THE UNIVERSITY OF HULL

HOLOCENE ENVIRONMENTS AND VEGETATIONAL CHANGE ON FOUR POLYNESIAN ISLANDS

being a thesis submitted
for the Degree of Doctor of Philosophy

in the University of Hull

by

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March 1994. Vol. I. (Text).

(89500 words in main text)

ABSTRACT

The specific research objectives of this study are: to look at environmental changes that have occurred on several Pacific island systems from the pre- to post-settlement periods; to see whether the observed changes are natural or anthropogenic; to test the latest Polynesian settlement theory; and to contribute to the understanding of the vegetation history on these islands.

This study reports the results of stratigraphic investigations from four Polynesian sediment sequences. The sediments of Lakes Lanoto'o (Upolu), Roto (Atiu), Temae (Mo'orea) and Vaihiria (Tahiti) have revealed a history of environmental and vegetational change during the Holocene, which include long-term climatic variations affecting broad scale vegetation changes on Upolu and Atiu; long term sea-level change influencing the local environment and vegetation on Atiu; localised disruption of vegetation in the Vaihiria basin of Tahiti resulting from natural landslides; and finally, major changes in local environment due to human activity, evident on all of the islands.

Records from Lake Lanoto'o and Lake Roto extend into the early Holocene and span both pre- and post-settlement periods, with the latter providing a continuous vegetation record from around 9000 yr BP. Sequences from Lakes Temae and Vaihiria originated in the late Holocene; the Temae record also spans the estimated period of Polynesian expansion into the Society Islands and, consequently provides some insight into the nature of indigenous floras.

Modifications attributed to human activity were recognised in the Lanoto'o catchment from 2425±70 yr BP (512 BC). Initial settlement of the Lake Roto basin has been dated from 1420±45 yr BP (AD 640), while a 1210±90 yr BP (AD 790) record of human influence has been determined from the Mo'orea sequence. Fossil pollen records indicate that Polynesian settlers modified the natural vegetation and encouraged the growth of open scrub and fernlands. However, declines in several primary forest plants, previously associated with anthropogenic deforestation, appear to have resulted from natural causes during pre-settlement times. The presence of coconut pollen in two of the lake sequences, dated at ~8600 yr BP in Atiu and prior to 1400 yr BP in Mo'orea, strongly suggests that the dispersal of this palm was by natural, as opposed to human agents, in contrast to previous theories. The Polynesian settlement date for Atiu, which is earlier than any previous archaeological records, is in conflict with the views behind the "Orthodox Scenario" of prehistoric settlement, and necessitates a re-think of this theory.

ACKNOWLEDGEMENTS

Research in Polynesia was an exceptional experience and I would like to express my sincere thanks to everyone who helped in some measure to make it all possible. Fieldwork would have been impossible without the tremendous team-work of Operation Raleigh and Hull University Mo'orea Expedition members, as well as the help and hospitality of the ever-smiling islanders.

I am most grateful to my supervisors; Dr. Sarah Metcalfe, for her continuous encouragement, sound guidance and patience, and; Professor John Flenley, for his inspiration and enthusiasm which initially sparked off this project. I am also much indebted to Dr. Paul Bahn who, not only gave stimulating advice on Polynesian prehistory, but also gave me access to his vast supply of Pacific literature, and helped me with editing and the translation of French literature. I would like to thank the assembled members of the School of Geography and Earth Resources, almost all of whom have assisted or advised in some way. Special thanks to Dick Middleton for his limitless help with geochemical analysis; Keith Scurr for drawing several pollen diagrams and John Garner who was always willing to take up a photographic challenge.

Thanks also go to Doug Harkness (NERC Research and Reactor Centre), Matt M^{c}Glone and Atholl Andersen for their willingness to undertake several radiocarbon dates; to Bob Knight for taking the core X-rays in the Physics department and; Arthur Whistler, Bill Sykes and Mark Merlin for their expert comments on the pollen data from Western Samoa and Atiu. Plant collections were identified with the assistance of Keith Ferguson (The Royal Herbarium in Kew), Clive Jermy and Roy Vickers (British Museum of Natural History). Identification of molluscs and tube worms were made by John Taylor (also British Museum of Natural History). I would also like to acknowledge the Natural Environment Research Council and British Academy for providing funds for the first two years of this study.

Special thanks go to my mum and sister who have been exceptionally supportive and understanding throughout this study. I am greatly indebted to Mike and Pete for their continuous friendship and encouragement through good times and bad.

I would like to dedicate this thesis to my wonderful dad who is dearly missed. His complete enthusiasm for all of my achievements, large and small, made any effort worthwhile.

Thank you.

To Dad

Always loved and never forgotten

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1 HOLOCENE ENVIRONMENTS AND VEGETATIONAL CHANGE

1.1. Introduction and research objectives

Large environmental changes are now known to have occurred on a global scale during the Holocene period both in the form of world-wide climatic fluctuations and as a result of human impact, and complex interactions of both (Roberts, 1989). There are, however, marked disparities in the regional cover of studies, for example, much work has been focused on the USA and north-west Europe but there is still relatively little information from the tropics, and especially from within the Pacific basin. The work presented here, from a group of Polynesian islands, provides a regional perspective of Holocene environmental change from a hitherto poorly studied area. (Figs.1.1 and Fig.1.2 show the location of Polynesia and the relative distribution of the islands studied).

The specific research objectives of this study are:

- to look at environmental changes that have occurred on several Polynesian island systems from the pre- to post-settlement periods;
- to see whether the observed changes are natural or anthropogenic whilst recognising that both may exist;
- to test the latest Polynesian settlement theory (the 'Orthodox' Scenario) which has been compiled mainly from archaeological investigations;
- to contribute to the understanding of the vegetation history on these islands.

During the 1990s there has been a rapid expansion of knowledge of the short-term climatic changes that affect the Pacific region. A more complete understanding of the complex coupled ocean/atmosphere system, and in particular the influence of El Niño-Southern Oscillation events (ENSO) (e.g. Glantz *et al.*, 1991; Diaz & Markgraf, 1992), have helped to identify the main factors controlling short-term, and often dramatic, climate variations in the Pacific region (i.e. on time-scales ranging from ~1-100 years). High resolution palaeoenvironmental studies of marine and terrestrial sediments (e.g. Anderson *et al.*, 1992; M^{c}Glone *et al.*, 1992), as well as coral monitoring studies (e.g. Cole *et al.*, 1992), are successfully determining the character and timing of recent ENSO occurrences and their related interannual variability, yet the long-term history of this system in the equatorial Pacific still remains poorly documented. Attention has also been turned to the impacts of short-term variation in rainfall intensity and seasonality as factors presently influencing island ecosystems (Stoddart, 1992). Important contributions to the investigation of longer-term (10^{-3} years) climate variability within the Pacific region include the reconstructions of sea-surface temperatures through oxygen isotope indicators; past sea-level changes identified through coastal geomorphology; and localised palaeolimnological studies.

Until recently, there have been few attempts to undertake archaeological studies with an environmental bias, i.e. with the specific objective of determining the effects of human colonists on island ecosystems, whilst also recognising the signs of natural environmental changes which may have been significant in post-settlement times (Nunn, 1990a). Studies of the relationship between natural environmental change and anthropogenic change include environmental reconstructions from Easter Island (Bahn & Flenley, 1992) which show a complex interaction of elements whilst acknowledging the difficulties involved in deciphering the historical record. Nunn's (1990a) appraisal of natural versus human impact on Pacific island systems in general, also recognises these complexities.

The Pacific remains a zone of archaeological interest particularly in relation to the question of Polynesian dispersal. Whilst a post-4000 yr BP settlement of Polynesia is now accepted by most investigators, many questions about the direction and chronological sequence of voyages into Remote Oceania still remain unanswered. Although many 'straight' archaeological investigations have been undertaken there is a paucity of data in areas where unfavourable geomorphological conditions hinder the discovery of early occupation sites (Kirch, 1986; Spriggs, 1985). In these cases there has been the need to resort to alternative methods such as palaeolimnological studies.

The relatively late settlement of Polynesia (estimated dates shown in Fig.1.3) provides the opportunity to examine human impact on relatively 'pristine' island environments and allows for the study of natural environmental variations which have occurred throughout the Holocene prior to human colonisation i.e. before ~4000 years ago on western islands such as Samoa, and before~1000 yr BP on the more easterly located Cook and Society Islands. It was hoped that the study of vegetation changes and lake environments on the islands of Upolu (Lake Lanoto'o), Atiu (Lake Roto), Mo'orea (Lake Temae) and Tahiti (Lake Vaihiria), would reveal if, and when, earlier human activity had occurred. Estimated settlement dates could then be assessed in the light of the present views on Polynesian prehistory (Chapter 2).

Although investigations of relict vegetation surviving today in undisturbed areas such as Niue (Sykes, 1970) or on the *makatea* limestone of the Ngaputoru group and Mangaia, Southern Cook Islands (Sykes, 1976a, b and c; Merlin, 1991) give some insight into the nature of pre-settlement vegetation, these areas are fairly restricted and rarely totally untouched. An alternative to these present vegetation studies is the analysis of the fossil pollen flora, deposited and preserved in the anaerobic environments of swamps and lake sediments. If the sediment sequence is complete and pollen preservation good then, information about the nature of pre-settlement vegetation can be obtained. The palynological data presented in this thesis, apart from providing the first records from the islands of Upolu, Atiu, Mo'orea and Tahiti, will more specifically provide information on 1) the origin of Pacific island savannas- the question still remains as to whether these fern and grassland associations had formed naturally during periods of greater aridity, or whether they originated from anthropogenic deforestation and burning in post-settlement periods?; 2) the dispersal of the coconut (*Cocos nucifera*)- was this palm introduced to the Pacific islands by Polynesian voyagers as presently suspected or did it occur naturally prior to human settlement?; and 3) the decline of several primary forest taxa believed to have been more extensive in the past- was the decline purely the result of anthropogenic activity or were other natural forces involved?

Vegetation (environmental) records from these four islands will also complement the few available records from the south-west and central Pacific, notably from Fiji (Southern, 1986), Mangaia (Lamont, unpublished; Ellison, in prep.), Rarotonga (Peters, unpublished), Tonga (Ellison, 1989), and from Aneityum (Hope & Spriggs, 1982). Records also exist for Easter Island (Flenley, 1979a; Flenley & King, 1984; Flenley *et al.*, 1991) and the Galápagos Islands (Colinvaux, 1972; Colinvaux & Schofield, 1976) in the east-central Pacific and the Hawaiian islands in the northern Pacific (Selling, 1948; Athens & Ward, 1991), whilst the palynological work by M^{c}Glone (e.g. 1983a, b, c, d, 1988, 1990; Roger & M^{c}Glone, 1989) dominates the New Zealand records.

This dissertation, therefore, presents a range of sedimentary studies from two coastal and two inland sites on four islands of central Polynesia, selected for their potential to provide stratigraphic records of pre- and post-settlement environments and vegetation change, as well as the effects of human impact on island ecosystems. The continuing text is structured with an initial review of past and present environmental change in the Pacific region (Chapter 1). Chapter 2 reviews the information on Polynesian prehistory and outlines the development, and shortcomings of the latest colonisation theories. Together with Chapter 1 it will put the aims of the study into perspective and explain the need to concentrate studies in the south-west and central Pacific region. The third chapter describes and discusses the physical, geochemical and biological techniques used in this study to reconstruct Holocene environments and vegetation change. The construction and dating of sedimentary zones, which form the basis of the interpretation of core sequences, are also explained. The following three chapters present and discuss the data obtained from the four study sites. The upland site of Lake Lanoto'o on Upolu (Chapter 4) is the first site to be discussed since it is on the most westerly island of the four and is believed to have been the first to be settled (~4000-3000 yr BP). It yielded the longest of the four sedimentary records extending back well into the pre-settlement period. This sequence is, however, incomplete and a continuous historical record could not be obtained. The ~8000 year record from Atiu, perhaps the most significant and complete sequence of the four, is examined in Chapter 5. This record is believed to span the range of estimated settlement dates for the Cook Islands (i.e. ~1000 to 1600 yr BP). Chapter 5 also includes the less conclusive record from the neighbouring island of Miti'aro within the brackish water lagoon of Rotonui. The two shorter stratigraphic records from Mo'orea and Tahiti in the Society Islands (eastern-most records), are discussed together in Chapter 6. The coastal site on Mo'orea provides a continuous record of environmental change over the past ~1600 years, which is again believed to cover both pre- and post-settlement periods in the Society Islands. The five hundred year record from inland Tahiti only provides information on post-settlement environments, since the occupation of the Society Islands is believed to have taken place around 1200 yr BP. In the final discussion chapter (Chapter 7) an attempt is made to synthesize the environmental information from Polynesia and to assess the extent to which inter-island comparisons can be made. Suggestions for future research in this area are also made.

1.2. Past Pacific environments

1.2.1. Climates of the late Pleistocene to early Holocene

There is a developing concensus of opinion about the causes of global climatic change, the major forcing factors identified being orbital variations, changes in the atmospheric composition and changes in sea-surface temperatures and oceanic circulation (Berger *et al.*, 1984; Overpeck *et al.*, 1989). There is, however, still uncertainty about which of the forcing factors has instigated change particularly in the Southern hemisphere where Milankovitch forcing is asychronous with the timing of glaciation (Denton *et al.*, 1986). All that is generally agreed about the major features of the atmospheric circulation in the Southern hemisphere during the last glacial is that: the trade winds were strengthened; there was a disruption of the summer monsoon due to the lower thermal gradient between the continents and the oceans which would have displaced the Intertropical Convergence Zone (ITCZ) southwards to a position more coincident with the geographical equator; and that there was a displacement in the westerlies, although the direction of this displacement is still hotly debated (Heusser vs. Markgraf, 1989).

The greater Pacific basin is of particular interest to the reconstruction of past climate and circulation in the tropics because it appears to contain the most active components of the Southern Oscillation. At 18,000 yr BP the sea level was lower and much of the presently shallow shelf areas in the Indonesia-North Australian region became land (Quinn, 1971; Bowler *et al.*, 1976; Webster & Streten, 1978), thus preventing cooler waters of the Equatorial Pacific upwelling regions from entering the Malay-Indonesia area. This has been suggested by Quinn (1971) as a factor for an intensified Walker circulation (Fig1.11) which would entail enhanced upwelling in the Eastern Equatorial Pacific and a westward extension of the Equatorial Pacific Dry Zone, as inferred from deep-sea core evidence of more vigorous marine biological activity and steepened sea surface temperature gradients, as well as from phosphate deposits indicative of large guano bird populations. However, conflicting conclusions on the intensity of the Walker circulation at 18,000 yr BP have been drawn from the interpretation of spatial patterns of palaeo-vegetation in New Zealand (Salinger, 1980a, 1980b, 1981 and 1984). Salinger proposes a weaker Walker cell for 18,000 which would have resulted in less persistent south-east trade winds and a reduction in the available precipitation. Webster and Streten (1978) suggested that at the height of the last glaciation, an enlarged area of sea ice surrounding Antarctica would have enhanced the latitudinal temperature gradient and caused a shift and strengthening of the westerly winds towards the equator and an incursion of cold mid-latitude water into the tropics. Lower sea surface temperatures would have resulted and thus reduced the available heat and moisture resources to promote cyclone genesis and maintain the smaller tropical disturbances which provide much of the wet season rainfall in this area. Generally cooler sea surface temperatures would also have reduced the moisture carrying capacity of the south-east trade winds.

Two mutually incompatible conclusions on the latitude position of the Intertropical Convergence Zone at 18,000 BP have been proposed from the same palaeolimnological evidence on the Galápagos Islands (Colinvaux, 1972; Newell, 1973) with Colinvaux argueing for a more northerly position for the Intertropical Convergence Zone (based on a core from the crater of El Junco) and Newell for a more southerly postion during the period of major glaciation (based on 20,000 yr BP polar ice core data (Johnsen *et al.*, 1972). Newell's suggestion of a greater steepening of meridional temperature gradients in the Northern hemisphere is, however, supported by the most recent reconstructions of global sea surface temperature patterns at 18,000 BP (CLIMAP project members, 1981). In the Eastern Pacific the cold water tongue immediately to the south of the Equator which is so prominent in the modern sea surface temperature pattern (Fig.1.10) during boreal summer, also appears enhanced at 18,000 yr BP (CLIMAP project members, 1981). This seasonal sea surface temperature feature of the present is believed to be the result of wind-stress forcing by the cross-equatorial surface wind from the Southern hemisphere and it is suggested that similar surface wind pattern were active during the last glacial maxima.

A general review of the sea-water temperature evidence (CLIMAP Project Members, 1981) has suggested that on a world basis the average anomaly between present and glacial surface-water temperatures was in the order of 2.3°C; however, environmental data from equatorial mountains, including Papua New Guinea, suggest temperature depressions in the order of 5-6°C occurred. Webster and Streten (1978, 1981) consider frequent and short-lived cold air invasions into the New Guinea highlands as a partial explanation for the apparent discrepancy in these glacial temperature estimates; however, in the light of plausibly different lapse rates in dry as compared to moist climatic regions, it appears difficult to compare temperature around the 5000m level with sea surface conditions. Moreover, in view of the widely spaced coring stations and other factors associated with calibration (e.g. Van Campo *et al.*, 1990), the sea surface temperature reconstructions from deep-sea cores may be open to revision (Hastenrath, 1991).

The nature of the last glacial maximum in the Pacific region, from about 18,000 to 15,000 yr BP, has also been determined from palaeoenvironmental records from Australasia (e.g. Kershaw, 1974, 1976, 1978, 1981; Colhoun *et al.*, 1982; Singh & Geissler, 1985) and deep sea cores from surrounding seas (CLIMANZ proceedings; Chappell & Grindrod, 1983). This period is believed to have been characterised by widespread aridity (Hope, 1978; Dodson, 1979; Bowler, 1983); reduced temperatures (Walker & Hope, 1982; Hope, 1983); depression of the treeline in upland areas, and expansion of grasslands and herbfields (Walker & Flenley, 1979; Kershaw *et al.*, 1983a; Martin & Polach, 1983). Palynological and stratigraphic evidence from Easter Island indicates cooler conditions from 21,000 to 12,000 BP (Flenley, 1979a; Flenley & King, 1984), whilst the last glaciation in Hawai'i has been bracketted by radiocarbon dates of 29,000 and 9100 BP (Porter, 1979).

Information on the post-glacial climatic amelioration from the Pacific basin is extremely limited; however, generalized oxygen-isotope curves from the deep ocean Pacific cores indicate a gradual increase in temperature from about 15,000 BP to a maximum at about 8000 BP (Shackleton & Opdyke, 1973; Hays, 1983). The isotope studies noted by Bard *et al.* (1990) suggest that deglaciation started at around 16,500 to 13,000 yr BP in the Southern Ocean. A period of climatic amelioration between 15,000 and 10,000 BP, is indicated by ice retreat in the mountains of New Guinea (Löffler, 1982) and the migration upslope of montane forests which reached their present distribution between 13,000 and 8300 BP (Hope & Peterson, 1976; Walker & Flenley, 1979; Hope, 1976, 1980). Walker and Flenley (1979) consider that the retreat of the glaciers and upward movement of the treeline suggest a fairly rapid increase in temperatures between 16,500 and 13,000 BP, followed by a slower increase, achieving present temperatures by 9000 BP. In south-eastern Australia and New Zealand, climatic amelioration was marked by the onset of organic deposition in the highlands and rapid expansion of the forests (Kershaw *et al.*, 1983b). Kershaw's (1976) analysis of material from Lynch's Crater in Queensland (Australia) implied that sclerophyllous plants including *Eucalyptus* and *Casuarina* dominated the vegetation of the last glacial maximum and persisted until the rainforest angiosperms became dominant between 9500 and 6000 yr BP. Dodson's (1977) palynological work on the Wyrie Swamp of south-eastern South Australia indicated that it "probably was drier during the period from 50,000 to 11,000 yr BP". In New Zealand M^cGlone (1983b) recorded rapid afforestation within 500 years in the South Island and believes that this was due to the widespread survival of forest trees in New Zealand during the glaciation. Subsequent vegetational changes then depended upon how rapidly individual taxa were able to take advantage of the change and expand their population.

Porter *et al.* (1977) recorded the disappearance of the last glacial ice cap from Mauna Kea, in Hawai'i, by 9000 yr BP. The vegetation records of windward Fiji (Southern, 1986) suggest that from 13,000 to 9000 yr BP rainfall was at least 50% lower than present and showed more distinct seasonality. Southern postulated that these changes were brought about by a substantial reduction in regional sea surface temperatures and less persistent south-east trade winds. After 13,000 yr BP the vegetation near the Lake Tagimaucia site on Taveuni, Fiji (Southern, 1986) gradually approached its present composition, although this process was not completed until about 6300 yr BP. According to Salinger (1981), however, the post-glacial climatic amelioration generally resulted in an increase in the sea surface temperatures and increased available moisture for transport by wind. This in turn led to greater cloud cover, orographic rainfall, major and minor tropical summer storm activity, and a stronger Southern Oscillation with persistent south-east trade winds.

During the past 18,000 years or so one of the most significant events to occur throughout Oceania was the low glacial sea-level followed by the rapid post-glacial marine transgression. While relative sea-level varies in different places due to local isostatic and tectonic movements, glacio-eustatic sea-level records indicate that at the last glacial maximum sea-level was anything from -120m (Fairbanks, 1989) down to -175m below present day levels (Veeh & Veevers, 1970). A universal sea-level drop of -175m, some 45m deeper than hitherto suspected, was suggested on the basis of dates from coral and associated material in the Great Barrier Reef (Australia), California, and south-east Carribean sea areas. However, one of the best available records of the progress of the Flandrian Transgression provided by the study of radio-carbon- dated samples drilled from submerged coral reefs on the Barbados shelf in the Atlantic (Fairbanks, 1989) indicates that the last glacial maximum shoreline was at -120m (Fig.1.4). A gradual rise started shortly afterwards, and accelerated to a rate of 24m rise in less than 1000 years beginning in 12,500 yr BP.

1.2.2. Pre-settlement environments of the Holocene period

The ending of the last glacial period did not mark the end of significant climate and sea-level changes. Environmental fluctuations throughout the Holocene, although generally of lower magnitude, have nevertheless had significant effects on island ecosystems. Both broad-scale and abrupt events have been recognised, although the exact nature and timing of some of these periods are still the subject of dispute.

Many European Holocene studies have indicated that temperatures were appreciably higher during certain parts of the Holocene than at present. The term post-glacial climatic 'optimum' (Manley, 1966) was coined because of the more favourable conditions that prevailed in previously colder regions like the northern limit of Greenland; however, this ? same increase in temperature would be far from advantageous for plant growth in drier areas. Alternative terms such as the 'altithermal' and 'hypsithermal' have, therefore, resulted. The hypsithermal has been recorded through oxygen isotope measurements of an ice-core at Camp Century on the Greenland ice-cap. This had indicated that a warm phase lasted from about 8000 to 4100 yr BP with extremes close to 5000 and 6000 yr BP (Dansgaard *et al.*, 1970). However, when a comparable study was made of the Dome ice-cap in Antarctica (Lorius *et al.*, 1979) it was found that the warmest phase of the Holocene was between 11,000 and 8000 yr BP, and it was relatively cool between 8000 and 4000 years ago.

In Papua New Guinea, pollen evidence for an expansion of forest above the present treeline between 8600 and 5000 yr BP (Hope, 1976), has been attributed to higher temperatures and a lower frequency of intense frost, coinciding with increased 'cloudiness' and rainfall in the highlands. A subsequent depression in the treeline may have been due to more severe climatic conditions, the clearing activities of people (believed to be present from at least 40,000 yr BP: Groube *et al.*, 1986), or most likely a combination of both. Morley (1982), however, noted the absence of a climatic 'optimum' in the Sumatran pollen records, but suggested that pollen analysis may not have detected these minor vegetational changes in an area where the flora is so complex. In south-eastern Australia there was an expansion of wet sclerophyll forest in the early to mid-Holocene with a cluster of dates around 9000 to 7000 yr BP in the highlands, and 6000 to 4500 yr BP in the lowlands (Bowler *et al.*, 1976; Hooley *et al.*, 1980; Kershaw *et al.*, 1983c). Indications here are that conditions were wetter, at least in the lowlands, and perhaps warmer and wetter in the highlands than either before or since. In tropical Australia, however, vegetation patterns suggest rainfall may have been 50% higher than present from 7000 to 3000 yr BP and temperatures slightly lower due to increased cloud cover (Kershaw, 1983b). Since the Holocene vegetation records from Australasia and the western Pacific region are often difficult to interpret in terms of climate because of complications of human influences, attention needs to be turned to the south-west and central Pacific i.e. to the islands with relatively shorter occupation histories. Holocene climate data from this region are presently very sparse and sketchy. The un-dated pollen ? sequences from Hawai'i, Selling (1948) recognises three climatic periods. The first period is believed to represent the end of the last glacial and is characterised by a restricted rainforest in favour of drier types of vegetation including species of *Acacia*, *Dodonea*, *Myoporum*, *Sida* and *Sophora*. A warm post-glacial period is recognised with increases in rainforest taxa such as *Elaeocarpus*, *Metrosideros*, *Myrsine*, *Cheirodendron*, *Coprosma*, *Pritchardia* and *Pelea*. This period may well correspond to the temperature maximum at 8000 to 9000 yr BP suggested by the oxygen-isotope curves from deep ocean cores (Hays, 1983). A cooler period follows when the rainforest is again replaced by drier types of vegetation in part of the area.

In New Zealand M^{c}Glone (1988) has shown that during the early Holocene interval (10,000 to 7000 BP) plants characteristic of mild, moist climates, in particular *Ascarina lucida* and tree ferns (*Cyathea*), were widespread. Subalpine scrub and low forest was dominant where subalpine *Nothofagus* forests are now both widespread and abundant. Roger and M^{c}Glone (1989) suggested that annual rainfall during the early Holocene was somewhat lower than at present, as a result of lesser incursion of winter rainfall, but that summers were cloudy and moist. Cloudy conditions at high-altitude sites may have counteracted the generally higher annual temperatures experienced in the early Holocene. Many sites which now have permanent water or bog vegetation were dry in the early Holocene (M^{c}Glone, 1990), which supports the argument for low precipitation overall, while the presence of moisture-demanding vegetation over large areas of New Zealand favours summers with little or no moisture stress. Interestingly, the Fijian pollen record (Southern, 1986) does not indicate a Holocene warming ('optimum'), possibly because minor climatic changes did not elicit a vegetation response in the equable climates of windward Fiji where her studies were concentrated~~(Southern, 1986)~~. The late Holocene in New Zealand was characterised by the spread of vegetation communities tolerant of edaphic and climatic extremes. *Nothofagus* forest spread rapidly in central and southern North Island and northern South Island from about 7000 BP (M^{c}Glone, 1988; Rogers & M^{c}Glone, 1989). *Nothofagus* forest in general can tolerate more variable climates, poorer soils and more disturbance than conifer-broadleaved forests. In ~~the~~ northern North Island, *Agathis australis* forest spread from around 6000 BP, and expanded vigorously from about 3000 BP (M^{c}Glone *et al.*, 1984; M^{c}Glone, 1989; Newnham *et al.*, 1989). *Agathis australis* is favoured by dryish, warm summers (Ogden & Ahmed, 1989) and its rapid increase in the late Holocene probably represents the regular occurrence of summer moisture deficits. This pattern of increase is similar to that recorded for *Agathis* on the Atherton Tableland in northeastern Australia. Other trees which spread at the same time are also favoured by high solar radiation and relatively drier summer conditions.

Palaeoenvironmental records from Australasia as a whole show a drier and less variable climatic regime than that of the present during the early Holocene. From around 7000 yr BP effective moisture is believed to have increased, and the most consistently warm and mild climates were experienced in Australia between 7000 and 4000 BP. In New Zealand, mild, reliably moist but drier climates than present prevailed until about 7000 BP, after which the climate gradually cooled and became wetter overall. From 5000 BP to 3000 BP colder climates with drier summers similar to the present became established in both Australia and New Zealand; evidence of drought, fire, erosion, and the spread of stress- and disturbance-tolerant vegetation indicate more variable climates. It has been suggested (M^{c}Glone *et al.*, 1992) that this increased variability may be linked to an increasing frequency of ENSO events during the last 5000 years.

1.2.2.1. Post-glacial rise in sea level

Studies on the coral reefs of Barbados (Fairbanks, 1989) indicate that the rate of sea-level rise between 11,000 and 10,500 yr BP (the Younger Dryas) decreased. Thereafter, an acceleration is indicated until 8000 BP, when the shoreline was at a depth of around -25m. The curve of sea-level rise flattens out 5000 years ago at -7m. The main problem that arises with the interpretation of the Holocene transgression lies in what happened globally after about 6000 yr BP. There are several schools of thought on this, though as Goudie (1992) notes the arguments are about possible changes of the order of only a couple of metres. One point of view was that there had been a continuously rising sea-level to the present, though the rate of rise has diminished with time (i.e. Shepard's hypothesis, 1963). Godwin *et al.* (1958) on the other hand hypothesised that sea-level rose steadily until about 3600 yr BP, since when it has more or less remained constant. There is, however, convincing evidence that the pattern of Quaternary sea-level change has varied relative to different points on the globe. Geophysical modelling which considers the importance of changes involving hydro-isostacy and glacio-isostacy in determining the response of sea-levels to glacio-eustay, predicts that the record of Holocene sea-level change will differ not only between different oceanic regions, but also between individual islands in the Pacific (Clark *et al.*, 1978; Clark, 1980; Nakibaglu *et al.*, 1983; Hopley, 1987; Nakada & Lambeck, 1988). Clark and Lingle (1979) identified six different zones with certain distinctive sea-level change characteristics. Their predictions, which were based on deglaciation and a resulting eustatic sea-level rise of 75.6m between 17,000 and 5000 years ago, shows that much of the western and central Pacific lie within Zone V (Fig.1.5). This zone would be characterised by an initial submergence followed by slight emergence of up to 2m beginning when water was no longer added to the oceans from the melting ice sheets. This theoretical support for the high Holocene sea-level concept is substantiated by the presence of small raised terraces in many parts of this region; however, in addition to the regional-trends predicted by such modelling, individual tectonic histories, related to plate tectonic location, and individual island geometries, resulting in local hydro-isostatic compensation, contribute to some discrepancies between islands (Bloom, 1980; Nakada, 1986).

There is evidence of Holocene emergence on several of the Cook Islands (Woodroffe *et al.*, 1990). On Suwarrow Atoll there are outcrops of emergent reef which have a radiocarbon-date of 4680-4310 yr BP. Also, fossil algal ridges occur which indicate up to 1m of emergence. The most landward of these ridges has been dated to 4220 yr BP. On Miti'aro there are emergent reefal deposits in the centre of the reef flat dated 5140-3620 yr BP. There are a number of erosional coastal features which also indicate Holocene emergence. On the northeast coast there is a conspicuous cliff-foot notch at a height of 0.5-1.0m above mean low water. Near Parava on the east coast there is a higher notch, with a floor at 1.79m and its deepest part 2.27m. On Mauke the only coral of Holocene age that appeared to be slighly above the present limit to coral growth came from a reef flat on the northeast of the island and dated 2900±85 yr BP. The record for Atiu is unfortunately less clear than the other islands in this area. No evidence of Holocene emergence was seen on the narrow reef flats; however, there are several notches and benches around the island which may be Holocene in age. One group of benches reach 2.8m above mean low water and are believed to represent features controlled by a contact between the lower and upper Pleistocene reefal limestones (Stoddart *et al.*, 1990; also referred to in Chapter 5). A lower group of benches occur at around 1.8m above mean low water may be indicative of Holocene emergence. A detailed chronology of late Holocene sea-level fluctuations in Mangaia (Yonekura *et al.*, 1986, 1988) indicates that there was possibly a higher sea-level than the present in the mid-Holocene, and that a maximum level of +1.7m occurred around 4000-3400 yr BP. An emergence is then considered to have occurred between 3400 and 2900 yr BP. Some conflicting evidence for Holocene emergence in the Cook Islands is presented from Aitutaki. Whilst Shepard (1961) and Wood and Hay (1970) described an emergent reef or shoreline of Holocene age Yonekura (1988) reported on a micro-atoll near the airstrip at a height of +0.4m dated 1530±210 yr BP which is considerably later than evidence reported from the other Cook Islands. Nevertheless, most of the data reported from the Cook Islands by Woodroffe *et al.* (1990) indicate that emergence has been widespread and broadly synchronous between the islands. This implies that emergence was controlled by a regional sea-level trend rather than local island uplift. Most of the emergent Holocene features in this area fell into the age range 5100-3400 yr BP.

Emergence at this time is generally consistent with that predicted by the geophysical models (i.e. Clark *et al.*, 1978; Nakada & Lambeck, 1988). These records, however, appear to be slightly different to those identified in French Polynesia where sea-level relatively higher than present persisted from between 6000 and 5500 yr BP until at least 1200 yr BP (Pirazzoli *et al.*, 1985, 1988). The late Holocene mean sea-level reached a maximum elevation at between +1.0m (at Makatea island) and +0.5m (Societies) and remained above the present m.s.l. The slight differences in 'relative' elevations from island to island is believed to be a consequence of the active flexuring of the lithosphere (M^{c}Nutt & Menard, 1978) caused by the weight of the most recent volcanic islands (i.e. the windward islands of Mo'orea, Tahiti and Mehetia). It is on these windward islands, therefore, that the Late Holocene change in 'relative' sea-level is least expressed since their active submergence partly cancels out the eustatic fall in sea-level. It is questionable as to whether one can fully decipher lithospheric flexure effects over the Holocene timescale and in an area where a reasonable tidal range exist; however, with stronger time controls and more accurately determined island topographies as well as an increased knowledge of island geomorphology the mechanical properties of the oceanic lithosphere may be ultimately deciphered (Spencer *et al.*, 1987).

The evaluation of dates from emerged Holocene shorelines in Fiji led Nunn (1990b) to conclude that the Holocene transgressive maximum reached 1-2m above present mean sea-level some 3000-2000 years ago; however the history of sea-level change in Fiji cannot be deciphered on modern coastlines without reference to local tectonic regimes.

1.2.3. Post-settlement environments (Post ~4000)

1.2.3.1. Polynesian impact

It was generally accepted that most Pacific island ecosystems immediately prior to human settlement had reached a state of 'relative' stability (Fosberg, 1963), despite climate changes since the last glacial period. Island vegetations were represented by 'climaxes' of primary succession (Nunn, 1990a), varying from grasslands in arid areas or on poor soils, such as those found on recent volcanic ash slopes of Mangareva (Fosberg, 1960), to rainforest in moist tropical regions. Remnants of primary forest, containing endemic species such as *Dysoxylum forsteri*, *Macarangaseemennii* and *Syzygium inophylloides* (Sykes, 1970), still exist in areas of tropical Niue which have never been settled. Pollen analysis on sub-tropical Easter Island (Flenley & King, 1984; Bahn & Flenley, 1992) indicated that pre-settlement vegetation was probably dominated by palm forest, the endemic *Sophora toromiro* and shrubs, while the original forest vegetation on the leeward regions of Fiji consisted of *Acaciarichii*, *Syzygium richii*, *Mussaenda raiateensis* and *Morindacitrifolia* according to Parham (1972) and Southern (1986).

The arrival of the first people on the Pacific islands (earliest known settlement dates shown in Fig.1.3) brought about immense changes in island biota (e.g. Olson & James, 1982, 1984; Kirch, 1982; Merlin 1985, 1991; Steadman, 1989; Dye & Steadman, 1990), for not only did the colonists introduce a range of wild and domesticated flora and fauna but they cleared areas of existing vegetation principally in order to plant crops (Nunn, 1990a). This was achieved mainly through shifting cultivation involving slash-and-burn (Cameron, 1962), and within 1000 years of initial settlement the original forests on most Pacific islands were severely altered (Nunn, 1990a). Activities such as these, resulting in erosion, loss of topsoil and reduced soil fertility, are believed to be the main contributory factors in the forming of the grasslands and fern scrublands (savannas) recognised on many Pacific islands today, including Fiji (Parham, 1972; Latham, 1979; Southern, 1986), Aneityum in Vanuatu (Spriggs, 1982), Futuna and Alofi, Horne and Wallis Islands (Kirch, 1981), Hawai'i (Kirch, 1982a), Huahine, 'Uvea, Mangaia, Borabora and Mangareva in west-central Polynesia (Kirch, 1982b), and parts of New Zealand (M^c^Glone, 1983d). Although the names of these open vegetation communities differ from island to island, they are all characterised by the dominance of the fern *Gleichenia linearis* (synonym: *Dicranopteris linearis*), or grassland species such as mission grass (*Pennisetum polystachyon*), wire grass (*Sporobolus indicus*) and blue grasses (*Dicanthium* spp.). Other characteristic taxa include the clubmoss *Lycopodium* *cernuum*, the fern *Nephrolepis hirsutula* (especially on the island of Niue) and the ironwood, *Casuarina equisetifolia.*

An alternative school of thought, strongly put forward by P. Nunn (1990a), is that natural forces were at least as influential as anthropogenic forces in the shaping of Pacific islands during post-settlement periods. One of the aims of this thesis is to explore these two schools of thought.

In the Hawaiian Islands, much of the palaeoenvironmental evidence for forest clearance and the anthropogenic origin of the extensive grasslands below an altitude of 440m is derived from the investigation of fossil landsnails (Kirch & Kelly, 1975; Christensen & Kirch, 1981; Hunt, 1981; Kirch, 1982a). The native gastropod assemblage contained in the basal deposits of the Halawa Valley on Molokai, suggested that the slopes, now supporting a grassland community, were originally covered in open native forest. The subsequent appearance of charcoal in these valley sediments and the increased rate of sediment accumulation, from about 800 yr BP, suggest that clearance by fire was followed by erosion. At this stage in the sequence native landsnails are replaced by 'anthropophilous' species believed to have been introduced in domestic crops such as taro.

Direct evidence for prehistoric forest clearance by fire and the origin of the vegetation communities in Fiji has been obtained from geomorphological and palynological studies by Southern (1986) and Hughes *et al.* (1979). Records of pollen and carbonised particles from coastal Viti Levu (Southern, 1986) detected burning from 4300 yr BP which resulted in the removal of forest vegetation and subsequent replacement by secondary forest and grassland by 3000 yr BP. Hughes *et al.* (1979) have documented increases in sedimentation rates from about 2000 yr BP in lowland swamps on the islands of Lakeba, which coincide with estimates of human arrival on Lakeba by Rowland and Best (1980). The presence of charcoal in the sediments suggests that fire was probably used to clear the forest for shifting cultivation. The investigators (Hughes *et al.*, 1979; Hughes, 1985) maintain that the formation of these lowland swamps began only after the arrival of people and subsequent massive catchment erosion. While the destruction of the vegetation may have ultimately rendered the valley slopes unfit for shifting cultivation, the creation of extensive swamps and alluvial flats provided an ideal environment for the cultivation of hydrophytic crops such as taro (Spriggs, 1982). This may well have initiated the shift from dry, hillside cultivation to intensive use of the valley bottoms and swamplands with the associated use of large scale irrigation systems, recognised in Spriggs' informative summary of human-induced landscape change (1985).

Pollen analysis and geomorphological techniques were also used to determine the sequence of environmental change on Aneityum in Vanuatu (Spriggs, 1982; Hope &

Spriggs, 1982). A preliminary pollen sequence from Anawau swamp indicated that the island was forested prior to 2940±80 yr BP, but that the following period saw a dramatic change to open grass and fernland with scattered trees. Corresponding increases in the concentration of carbonised particles in the sediment indicated that fire was again the dominant tool in the removal of the forest. As seen in Fiji, deforestation resulted in massive erosion and the deposition of extensive fertile alluvial plains at the mouths and along the valleys of many streams. Valley floor aggradation was accompanied by as much as 300 metres of coastal progradation at valley mouths (Spriggs, 1981, 1986).

The anthropogenic nature of the alluvial plains on Aneityum is questioned by Nunn (1990a), who believes that rapid tectonic uplift of the island could account for soil loss, valley-floor aggradation and coastline extension. Nunn also questions other apparently straightforward examples of the results of anthropogenic burning. For example, Kirch (1981) interpreted lowland deposits laid down around 1315±175 yr BP, from Tavai on Futuna in the Horne Islands, as having been derived from upland soils exposed by forest clearance. Nunn (1990a) stresses the fact that the island of Futuna is emerging at a rate of around 1mm/yr. He argues that the uplift of reef-fringed islands such as Aneityum and Futuna would cause shallowing of lagoons between coastlines and offshore reefs, resulting in reduced sediment mobility just offshore. This would contribute to coastal progradation and might result in the accumulation of fluvial sediment in lowland areas. This perhaps emphasises the need to concentrate further studies in tectonically stable areas.

The discovery of an aggradational terrace in the Nijiemhang valley on Aneityum, Vanuatu, dated at 22,400±250 yr BP, also led Spriggs (1981) to question the anthropogenic origin of the Aneityum savanna. The terrace is believed to indicate a period of aridity which may have seen the natural replacement of rainforest by savanna in some areas. The anthropogenic origin of Pacific savannas was also questioned by Bartlett (1956) and more recently by Fosberg in a personal communication to P. Nunn (1990a). While accepting the pyrophytic origin of the shrubland (talasiga) on Lakeba island in eastern Fiji, Latham (1983) also questioned its anthropogenic origin and suggested instead that such vegetation may have developed during pre-settlement periods of aridity. Evidence for such a period on nearby Taveuni island 14,300-13,000 yr BP was reported by Southern (1986). There seems little doubt about the effect of anthropogenic burning on the spreading and maintenance of Pacific island savannas but evidence is increasingly emerging of their possible pre-settlement origins (Nunn, 1990a). It was hoped that the analysis of pre-settlement vegetation in central Polynesia undertaken in this study would bring more information to light.

Further studies of the influence of human occupation on the islands of Polynesia have been made in New Zealand and Easter Island. Evidence from New Zealand indicates that few areas below the climatic treeline were devoid of forest or woodland vegetation prior to human settlement. Since the arrival of the Polynesians some 1000 years ago, approximately 50% of this indigenous forest has been destroyed by fire (M^c^Glone, 1983d). Perhaps the most extreme case of anthropogenic land degradation, which ultimately led to the decline of an entire culture, was experienced on remote Easter Island where records of deforestation began around 1200 yr BP (Flenley *et al.*, 1991; Bahn & Flenley, 1992). The pollen records from the volcanic craters of Rano Raraku, Rano Aroi and Rano Kao show that the decline of palm-like trees (possibly the Chilean wine palm, *Jubaea chilensis*) and the tree/shrub *Sophora toromiro* (from which a type of rope was woven) corresponded to a period of extensive erosion and soil impoverishment, as well as the extinction of the endemic Achatinellidae land snails (Kirch & Christensen, in press) dependent on forest cover for survival. The removal of trees is believed to have been linked with the building and transportation of massive stone statues, *moai* (Mulloy, 1970; Flenley *et al.*, 1991; Bahn & Flenley, 1992), and the subsequent regeneration of the palm was greatly hindered by introduced fruit-eating rodents. At the time of European contact in 1722 total deforestation had occurred and the megalithic culture was starting to collapse (Bahn & Flenley, 1992), possibly as a result of food shortage and subsequent warfare for which there is strong evidence in the prehistory of Easter Island (Routledge, 1919; Métraux, 1940; Heyerdahl & Ferndon, 1961).

1.2.3.2. **European contact**

One of the most important and widespread effects of early European contact with the Pacific islands (from the mid-1700s) was the sharp decline in their indigenous populations as a result of introduced diseases. This led to an initial reduction in forest clearance because of reduced demand, which in turn encouraged the growth of secondary forests or savanna on many uplands and reduced soil loss (Nunn, 1990a). Burning of forest cover, however, resumed in the few decades after contact to meet the increasing demands for commercial crops, grazing and insect control. This again resulted in soil loss and slope instability (Cochrane, 1969; Scott, 1975). Cochrane gave the example of a regularly burned area of 243 hectares at Tubenasolo in western Viti Levu, Fiji on which 20 landslides occurred a few weeks after burning. An increase in the susceptibility of slopes to failure increases with increasing devegetation and soil loss. Scott (1975) quantified these relationships for Oahu, Hawai'i.

New exotic animals and plants, notably rabbits (Watson, 1981), goats (Hamann, 1975) and weed species (Florence, 1982), lead to further landscape change. Environmental degradation, due to inappropriate land management (e.g. Drysdale, 1988), urbanization and mining has continued in the last few decades, perhaps exacerbated by the effects of the increased frequency of tropical cyclones experienced recently in the south and central Pacific (Grant, 1981; Nunn, 1990a; referred to in section 1.3).

Two main periods of anthropogenic influence have, therefore, been recognised on many islands of Polynesia. An initial prehistoric Polynesian settlement, by a predominantly Asian population, possibly modified the vegetation and natural environment through forest clearance, induced slope erosion and the introduction of exotic taxa. Further landscape degradation, along with new introductions of competitive taxa and disease, which resulted in the decline of indigenous plants, animals and people, characterised the historical period of European contact. While the dates of European contact with the islands of the Pacific are well recorded, no precise information on Pacific prehistory and island colonisation are documented. A variety of archaeologically-based investigations, forming the subject of the following chapter, have been undertaken to in order to reveal this prehistory.

1.2.3.3. Natural climate change during the post-settlement period

Two major climate changes, for which there is evidence from most parts of the world (Lamb, 1977; Goudie, 1992), occurred within the post-settlement, pre-European history of most Pacific islands: The Little Climatic Optimum (LCO or Medieval warm epoch), when temperatures were 0.5-1.0°C above present, occurred around 1200-650 yr BP (~AD800 to 1350) and the Little Ice Age (LIA or neoglaciation), when temperatures averaged 1.5°C below those of the LCO, occurred around 650-50 yr BP (~AD1350 to 1950).

Nunn (1990) noted that the beginning of the LCO coincided with the period of Polynesian migration in all directions out from a dispersal centre in the Marquesas (Sinoto, 1970; see Chapter 2). It has been argued that comparatively favourable conditions (persistent trade winds, clear skies and few storms) existed for sea voyaging during the LCO which could explain the contemporary increase in the rate of initial colonisation of the Pacific islands (Bridgman, 1983). The onset of the LIA, on the other hand, coincided with the end of long-distance Polynesian voyaging (Bridgman, 1983), and the end of settlement expansion periods on many islands (e.g. Nuku Hiva, Marquesas: Suggs, 1961).

Within the Pacific Basin there is little clear evidence of the effect of either the LCO or the LIA, and much of it is contradictory (Nunn, 1990a). A pause in swamp deposition some 900 years BP, perhaps associated with drier conditions and soil formation, was noted from the Waitabu swamp sediments on Lakeba, Fiji (Hughes *et al.*, 1979), whilst on Tikopia, Solomon Islands, the LCO was marked by increased upland erosion and coastal progradation (Kirch & Yen, 1982). Salinger (1976) has, however, been able to show that New Zealand experienced a climatic deterioration starting at about AD 1300, which was most severe between 1600 and 1800. This ties in well with the situation in Europe and North America (Roberts, 1989; Wright, 1984).

There is evidence from tide-gauge records to suggest that following on from the current post-neoglacial (Little Ice Age) amelioration in climate there has been a corresponding rise of sea-level. Nunn (1990a) concludes that a sea-level rise has been in progress for at least the last 90 years, perhaps in response to global warming. Short term tide gauge readings also show recent sea-level rises of the order of 1.6 mm/yr at Wellington, New Zealand (Hannah, 1988) and 2 mm/yr at Pago Pago in American Samoa (Pirazzoli, 1986).

1.3. The modern Pacific environment

1.3.1. The modern climate system

The major environmental factors affecting the modern ecosystems of Pacific islands are inevitably influenced by their location within the Pacific basin. For instance, proximity to areas of precipitation maxima influenced by the Tropical Convergence Zones (Fig.1.6) or principal areas of rainfall anomalies (Fig.1.7) particularly positive anomalies due to increased storm frequency, which themselves fluctuate with the state of the Southern Oscillation (section 1.3.1.1). The position of islands relative to tropical cyclone tracks (Fig.1.7) or the markedly dry conditions imposed by the Equatorial Dry Zone, must also be considered.

On a smaller scale the altitude and topography of individual islands will inevitably modify the affects of climate on the ecosystems. For instance the topographic-interactions with trade winds of day-periodic circulations in mountainous terrain and across coastlines (detailed in Hasterath, 1991) often result in wet windward and dry leeward slopes on high islands such as Tahiti, Mo'orea and Western Samoa. Low lying island ecosystems such as those on Atiu and Miti'aro will be less affected by orographic factors.

The distinctive tropical Sea Surface Temperature patterns (SST shown in Fig.1.10) in the Pacific feature an extensive warm pool in the west, with the warmest surface water anywhere on the globe extending to depths of more than 100m, and a cold tongue in the east near the equator that is strongest in about October and weakest in March-April. These SST patterns are brought about by the patterns of winds and the strong solar radiation in the tropics. In the west, the relatively light winds allow solar heating to warm the ocean and minimise heat loss from evaporation while water tends to pile up from the surface westward flowing ocean currents driven by the strong trade winds further east. At the same time the southeast trade winds from the Southern Hemisphere cause upwelling of bottom cold water along the coast of South America and along the equator in the eastern Pacific. The result is an upward slope in the sea level to the west of about 60cm across the equatorial Pacific and a corresponding deep thermocline (100-200m) in the western Pacific, but a shallow (~40m deep) thermocline in the east. This east-west variation in the depth of the thermocline is believed to be the key ingredient in the El Niño-Southern Oscillation variation (ENSO-discussed below).

The main current systems of the Pacific ocean include the South Equatorial Current and North Equatorial Current (NEC) flowing westward from 10-20°N and the narrow eastward Countercurrent, centred near 7°N (shown in Fig.1.8). These currents owe their existence to the pattern of surface winds, whose complexity arises from the presence of the southeast and northeast tradewind systems and their convergence region of much lighter but more variable winds in between. The distribution of strong convection in the atmosphere is also largely determined by the SST pattern with the convergence of the trade winds favoured by the presence of warmer water. Thus, the Intertropical Convergence Zone (ITCZ) and South Pacific Convergence Zone (SPCZ) (Fig.1.6) preferably lie over the regions of water warmer than 27°C. Seasonality in the Cook Islands is largely determined by the latitudinal shift of the South Pacific Convergence Zone. This boundary moves south over the Cooks, giving wet weather (yielding two-thirds of the annual precipitation) during November to April, and retreats north, giving dry weather during the Trades, from May to October. The climate of Western Samoa is strongly influenced by the proximity with the ITCZ.

Warm moist air rises and latent heat is released aloft by the precipitation in the extensive convection in the west. A return eastward flow in the upper atmosphere provides the link to the dry cool air sinking in the east. The 'dry zone' present along the equator in the eastern Pacific coincides with the cold tongue evident in SSTs. This Equatorial Dry Zone contrasts sharply with the zonally oriented band of strong convergence and abundant precipitation only a few 100km to the North. Annual rainfall increases from less than 500mm in the vicinity of the Equator to more than 4000mm in the band of strong convergence centred at about 5°N, and to about 2500mm in a band to the South of the Equator. The distribution of mean annual rainfall in the central South Pacific Ocean (shown in Fig.1.9) clearly illustrates the gradient of rainfall towards the Equatorial Dry Zone positioned north of the Cook Islands. In these annual average figures it is worth noting that all of the five islands considered in this study occur in close proximity to the 2000mm contour, although seasonal variability has not been taken into account.

1.3.1.1. Environmental variability and extremes

Marked interannual variations of the atmosphere-ocean system are an essential characteristic of tropical climate. Instrumental in various regional climate anomalies is the surface pressure see-saw of the Southern Oscillation, which occurs on a time scale of 2-10 years. The Southern Oscillation is measured by observing the pressure differences between Tahiti and Darwin. When the difference is positive, the Southern Oscillation is in *high phase* (otherwise known as normal or cold phase), sea surface temperatures are high over the Indonesian region and pressure is low. Over the eastern Pacific sea surface temperatures are low and the pressure is high. The Walker Circulation (Fig.1.11) then develops a descending limb over the eastern Pacific and an ascending limb over Indonesia. During the low phase of the Oscillation (otherwise known as abnormal or warm phase) the surface ocean water over the eastern Pacific undergoes warming to the extent that the pressure gradient between that region and Indonesia reverses. Surface pressure over Indonesia is now relatively higher than over the eastern Pacific.

Whereas the causes of the Southern Oscillation are not well understood, its climatic consequences are more obvious. The global-scale precipitation patterns associated with the Southern Oscillation have been studied by Ropelewski and Halpert (1987, 1989) and Kiladis and Diaz (1989). Fig 1.7 illustrates the regions where rainfall anomalies are particularly sensitive to the alternation between the high and low phases of the Southern Oscillation. During the high Southern Oscillation phase, precipitation tends to be abundant in the greater Indonesia - Australasian region and in the realm of the average position of the Intertropical Convergence Zone over the northern equatorial Pacific, contrasting with dry conditions in the Equatorial Dry Zone. In the low Southern Oscillation phase, the circulation is characterised by a southward displacement of the ITCZ and a northeastward shift of the South Pacific Convergence Zone, resulting in a reduced Equatorial Dry Zone and enhanced rainfall along the Equator in the central and eastern portions of the basin, contrasting with decreased precipitation over Indonesia.

Tropical hurricanes, defined as low pressure systems with wind speeds in excess of 120km/h (Stoddart & Walsh, 1992), are probably the single most important catastrophic event regularly experienced in the western Pacific (hurricane belt shown in Fig.1.8), though it is clear from geomorphological evidence that hurricanes have occurred in the recent past in areas where there is no historical record of them. The six storms that occurred in the Tuamotu-Society Islands area between December 1982 and April 1983 are particularly noteworthy with rainfall in Tahiti reaching eight times the average. The increased frequency of central Polynesian storms is now believed to be directly linked to El Niño events (i.e. low phase of the SO) which result in southwest Pacific storms tracking somewhat further eastwards than normal (Hastings, 1990). During the intense 1982-83 ENSO many more tropical cyclones (8 systems) formed east of 180^{o} in the South Pacific than in any previous year on record.

The winds that accompany hurricanes, which may exceed 275km/h, can cause extensive damage to forests and economic crops (e.g. in Western Samoa in 1990, Whistler, 1992). Wind generated storm surges can also raise the local level of the sea 5m or more above its tidally-predicted position and cause overtopping of islands and widespread inundation (e.g. hurricane 'Sally' on Rarotonga in January 1987; Stoddart & Walsh, 1992). Wind-driven waves can lead to severe reef destruction, mobilisation of coarse sediment and its depostion on reef flats, and erosion of existing shorelines and land surfaces. Reef blocks 4-6m in diameter were deposited on reef flats on Raroia Atoll in 1903 and Rangiroa in

1906. Increases in sea-level may also lead to the encroachment of sea-water into the Ghyben-Herzberg freshwater lenses of small islands which could have had profound effects on the terrestrial vegetation (Woodroffe, 1989). Rainfall, especially in near stationary storms can reach extraordinary levels and serve as a catalyst in accelerating change (Stoddart, 1971a). Ash (1992) noted that heavy rainfall associated with cyclones had caused severe landslides on the Serua hills of southern Viti Levu. Massive forest disturbance resulted in the creation of bare patches ranging in size from 10^2 to $10^4 m^2$. Sand cays and low limestone islands may suffer substantial additions or losses to their coastline during tropical cyclones (e.g. Woodroffe, 1983- on Tonga; Stoddart, 1971b; and Fitchett, 1987- on Tuvalu). A coral-rubble bank 19km long and up to 4m high formed on the ocean-facing side of Funafuti Atoll, Tuvalu, following the passage of Cyclone Bebe in 1972. The land area increased by about 20% as a result of this bank forming (Baines *et al.*, 1974).

Short-period fluctuations in sea-level have been associated with both meteorological conditions or seismic events. In the Pacific such conditions frequently correlate with El Niño-Southern Oscillation events (Stoddart & Walsh, 1992). Over the period 1981-1983 these fluctuations had amplitudes of 55-60cm at Jarvis, Kiritimati and the Galapagos Islands, and 80cm at Nauru (Lukas *et al.*, 1984). El Niño sea level fluctuations at Truk have an amplitude of ca. 30cm, compared with 10cm on non-El Niño years (Cane, 1986). During the 1972 event monthly mean sea-level at Guam fell 44.2cm below mean sea level, in an area with a tidal range at springs of 1m. This resulted in extensive mass mortalities of emersed reef-flat organisms, particularly corals, echinoderms and molluscs (Yamaguchi, 1975).

Tropical storms vary greatly in their size and intensity. Kerr (1976) used 'minor', 'moderate', and 'severe' to describe the magnitude of the storms' impact on island systems, rather than referring them to the absolute intensity of the meteorological event. Although subjective, this may be a more appropriate measure of intensity when considering the island ecosystems. Based on such estimates for the 30 year period (1939-69) for the Fiji group as a whole, about one storm in five can be classified as 'severe', one in four as 'moderate' and remainder as 'minor'. Thus in the last century the Fiji islands may have experienced 20-30 severe hurricanes. The lower frequency of storm events outside the cyclone zone does not mean that the ecological effects are any less severe than in areas of higher cyclone frequency. Indeed, it can be argued that the massive changes to reef and island landforms and biota at Funafuti during hurricane 'Bebe' were not only the result of the intensity of that particular event but also a result of the long time lag between it and any predecessor. In areas of more frequent hurricane activity, however, where time lags between events are shorter, island ecosystems may well be more adjusted to periodic high magnitude perturbations (McLean, 1980).

In addition to ENSO there are other global-scale meteorological factors whose slowly varying properties are also strongly reflected in both the seasonal frequency and intensity of hurricanes. One of these factors is the Quasi-biennial Oscillation (QBO) of stratospheric zonal wind anomalies that occur near the equator during the summer seasons of both hemispheres. When stratospheric winds on the equator are from the west and weak easterlies occur at 10ºN (i.e. the westerly phase) the frequency of intense storms is greater in the northwest and southwest Pacific.

It is clear that the major enviromental hazards affecting the Pacific island ecosystems vary in magnitude and occur on differing spatial and temporal scales. Stoddart & Walsh (1992) note that variability in rainfall was the climate factor which had the greatest influence on the ecology of the Pacific islands, while recognising that the most extreme climatic disturbances experienced were hurricanes, which vary in frequency in space and time. This inherent environmental variability and associated extreme conditions has major consequences for the establishment and survival of plants and animals on islands today, especially through the control of vegetation growth by rainfall. As recognised in Stoddart's (1992) biogeographical division of the Pacific Ocean local topographies and geologies also have a profound effect on the distribution and diversity of plants and animals.

Stoddart makes the distinction between the biogeographic characteristics of atolls and other reef islands, elevated limestone (*makatea*) islands, and high (often volcanic) islands, and notes that whilst the distance from the source of propagules and island area (as originally proposed by MacArthur and Wilson, 1963) effects biotic diversity on the high islands the main controls on atoll biota are ecological, i.e. there is a limited pool of trees, shrubs and herbs that can colonise and survive in the habitats on atolls (for example, *Scaevola*, *Tornefortia*, *Suriana* and a handful of other species). Atoll vegetation is also noted to respond asymmetrically to rainfall extremes: it is more sensitive to drought than to wetness (Stoddart, 1992).

The raised limestone islands, which reach a maximum elevation of 329m at Eua, are noted as having a relatively uniform environment (Stoddart, 1992). Fosberg (1976) however, remarked on the dramatic increase in biotic diversity associated with even small increases in elevation of reef islands. Many raised islands in the Pacific have unfortunately been devastated by phosphate mining and consquently it is difficult to reconstruct their native biota. In the eastern Pacific, however, the island of Henderson maintaines 67 species of vascular plants, including four introductions, whereas the neighbouring atolls of Oeno and Ducie have a total recorded flora of 15 and 4 species respectively (Fosberg *et al.*, 1983; Fosberg *et al.*, 1989).

With the exception of the easternmost Pacific islands, which show a marked American influence, the Pacific high islands have two main characteristics: in terms of distance from source areas of propagules (i.e the Indo-Malayan region) they show marked diminution in species diversity from west to east, and in terms of area and elevation they exibit considerable ecological diversity. Within the distribution of the high islands, west to east, the most basic divide is at the Tonga Trench which relates to the 'andesite line' (shown in Fig.1 and discussed in section 2.1): there is no more dramatic biogeographical boundary in the Pacific than that between the southern Cook Islands and the southern Tongan islands (Stoddart, 1992). The latter have mangroves and seagrass and a distinctly West Pacific aspect; whilst the former lack them.

1.4. **Questions arising**

It is evident from the review of environmental variability in the Pacific basin that the island ecosystems on Upolu (Western Samoa), Atiu and Miti'aro (Cooks), Mo'orea and Tahiti (Societies) are presently influenced by unique sets of climatic, topographic and geological factors and that no two islands are strictly comparable. Is it, therefore, possible to find a common environmental history between isolated cores from widely spread geographical locations and different island types?

Certainly any attempt to draw general conclusions about the vegetational history from these individual islands is in danger of overgeneralisation; nevertheless, the data available, although not great ~~is~~ are sufficient to demand that at least an attempt be made. While it is necessary to be aware that site specific variations do occur it may still be possible to distinguish large regional trends. i.e. if there is a global or regional event one might expect some consistency between the records even though the depositional environments of wholly volcanic catchments (i.e. Upolu and Tahiti) may differ from volcanic and coralline catchments (i.e. Atiu and Mo'orea). Some islands on the other hand, by virtue of their location, may be more receptive to climate changes than other. Samoa's proximity to the Tropical Pacific Convergence Zone (Fig.1.6) and principal area of rainfall anomalies in the western Pacific is perhaps best situated to register climatic variability and short-term changes in moisture conditions. Irregular movements of the South Pacific Convergence Zone which correlate with the Southern Oscillation may be detected in the island biota of the Cooks. At the other extreme the Society Islands, which lie outside the zone of persistent cyclone activity (Fig.1.8) and the principal area of rainfall anomalies, may register the more subtle changes in climate. They may also be more responsive to low frequency high magnitude perturbations due to the greater lag time between events (referred to above).

Further questions which are particularly relevant to this exercise are: to what extent can fossil pollen studies actually be linked to climate, through vegetation change on these relatively small and often low lying islands?; and are there techniques available which can distinguish between natural and anthropogenic modification of these island ecosystems.

Whilst the contribution of vegetational history to the revelation of climatic change has already been immense in temperate regions, and several classic studies have now been made near the equator (equatorial Africa, Latin America and Indo-Malesia, summarised in Flenley, 1979b), it is necessary to bear in mind that the interpretation of former vegetation in terms of climate depend absolutely on our understanding of the present relationship between vegetation and climate. Near the equator this understanding is unfortunately all too uncertain. Most studies of the equatorial fossil pollen floras, noticeably concentrated in mountainous regions above 4000m, rely heavily on the detailed information (i.e. temperature and moisture regimes) from altitudinal sequences of present vegetation communities. Tahiti (which reaches 2237m) is the highest islands refered to in this study, followed by Mo'orea (1207m), Upolu (1100m) and Atiu which reaches a maximum altitude of only 71m and although altitudinal zones have been recognised to some extent on the three higher islands, factors such as slope angle, aspect and the degree of anthropogenic disturbance (in turn inter-related with accessibility) appear to be as important in determining vegetation type as temperature and rainfall. This study, therefore, cannot fully rely on climatic reconstructions from altitude sequences on individual islands; nevertheless, the information gleaned from the available botanical studies across a whole range of Pacific island geomorphologies and locations (summarised in Appendix 3), show that several taxa and plant communities occur consistently in similar habitats. A system of 'indicator' species or communities with known restricted environmental requirements has, therefore been used in this study to infer changes in climatic conditions.

This technique is clearly not as satifactory as those performed on the fossil pollen flora of North America and Europe where precise mathematical models are available to clearly define the relationships between fossil pollen data and climatic variables. Whilst recognising the limitations and imprecision of this techniques it does at least provide a basic start on islands where no previous palaeoclimatic reconstructions have been attempted from pollen studies.

Understanding the environmental setting and way of life of prehistoric human cultures depends upon the collation of information from a wide range of evidence, among which pollen analysis ranks very highly (Dimbleby, 1985). The detection of human modification of the environment may even provide evidence of a human presence before archaeological evidence is available. The precision with which human influence can be detected from the pollen record of Pacific island vegetation is greatly facilitated by the practice of agriculture by Polynesian colonists. In agricultural communities one expects to find elements of destruction of the natural vegetation, the introduction of crop species, the presence of weed species associated with arable and pastoral activities (Behre, 1981) and the recovery of the vegetation following the abandonment of the site, often in different proportions from the original vegetation cover (Delcourt, 1987). Initial populations may, however, have been so small as to not elicit a clear vegetational response and in these cases one needs to consider the pollen evidence alongside additional evidence from charcoal, inwashed soils and evidence for nutrient flushing (such as algal blooms) in order to reconstruct local human influence.

The review of the present knowledge of Polynesian prehistory outlined in the following chapter (Chapter 2) will provide the framework from which to start deciphering both natural and anthropogenic impacts on the island ecosystems.

2. REVIEW OF POLYNESIAN PREHISTORY

With no definite system of writing known before European contact the Polynesian people preserved their history by oral tradition alone. They took pains to hand on these traditions in the form of genealogies and records of the more dramatic events of the past. This information, later to be written down by missionaries, provides at least an outline of their pre-European history. Nevertheless, accounts of their ancestral arrival on the islands of Polynesia are often conflicting or totally lacking. The advent of radiocarbon dating and genetic tracing, along with linguistic, biological, archaeological and past environmental studies, have now added a new dimension to Polynesian prehistory, and combined efforts are slowly unravelling many of the unsolved mysteries of Polynesian wanderings. This chapter reviews the history of Polynesian settlement as we know it so far, outlines the development of the Orthodox settlement theory, and tries to determine areas where detailed information is lacking and a concentration of research, such as attempted in this dissertation, is needed.

2.1. The Pacific in perspective

The division of the Pacific on biogeographical grounds (Stoddart, 1992- referred to in the first chapter) is not only relevant to the understanding of plant distributions and the factors that most effect island ecosystems but also to an appreciation of Polynesian migrations into and across the open Pacific. Recognised enthnic boundaries, are also informative when considering Polynesian prehistory. Oceania comprises the three conventional geographic, and broadly ethnic, regions of Melanesia, Micronesia, and Polynesia (Fig.1.1) which together contain 789 habitable island units. Polynesia, with its 287 islands, is the largest subdivision of Oceania, although its total land area is much smaller than that of Melanesia. Two additional Pacific components are the regions of Island Southeast Asia ('The Malay Islands') situated to the west of Oceania, and the large continent of Australia to the south-west. The complex migration patterns which took place from the western Pacific eastwards have given rise to a gradation of ethnic regions with varying cultures, languages and ancestry, which loosely cluster into the three geographical groups.

Oceania has alternatively been divided into two parts, namely Near Oceania and Far Oceania (Pawley & Green, 1973), on the basis of geographical location and island density. Near Oceania encompasses all the islands on the west side of the Pacific from New Guinea to San Cristobal and are characteristically separated from each other by relatively narrow gaps of water. Many of the islands are also relatively large. Far, or Remote, Oceania comprises all the islands that are separated from the islands of Near Oceania by water gaps greater than 350km. These islands are generally smaller in area, are more widely dispersed and remote from other islands and archipelagos. These features have resulted, to a large extent, from the geological characteristics of the Pacific Basin, which is divided by the 'Andesite Line' (Fig.1.1), i.e. the zone of demarcation of the western margin of the Pacific plate, separating the predominantly continental landmasses to the west from the entirely basaltic and/or coralline landforms to the north and east. West of the line lies the stable continent of Australia and the large Melanesian islands running eastwards to Fiji. The geological formations in the Melanesian region are highly varied and include sedimentary and metamorphic rocks, as well as a great deal of vulcanicity in the volcanic arcs extending from Indonesia to Japan. The islands east of the Andesite Line are smaller and geologically less complex, with the majority lacking sedimentary rocks other than recent alluvial deposits. A large number of coral atolls also occur to the east which have formed at sea level as volcanic islands have eroded or sunk below the surface of the ocean. Stoddart (1992) notes that these are generally poor in soil, vegetation diversity and available freshwater. In terms of basic resources it is very apparent that populations which migrated beyond the Andesite Line found themselves in increasingly impoverished and remote environments. Several of the food plants, including breadfruit, sugar cane, certain aroids and yams, which grew naturally in the New Guinea-Bismarck Archipelago region prior to human contact, were absent from the remote eastern islands. Polynesians (and Micronesians), therefore, had to transport most of their domestic plants and animals with them in their voyaging canoes as they crossed the vast expanses of Remote Oceania.

The Polynesian region (Fig.1.1), may be further divided into the Polynesian triangle, with apices in the Hawaiian Islands, New Zealand and Easter Island, and Outlier Polynesia, which includes a number of small islands with Polynesian-speaking inhabitants in Melanesia and the southern fringes of Micronesia (Fig.2.1). Cultural divisions based on linguistic (Green, 1968) and archaeological (Burrows, 1939) studies, follow the rather different boundaries termed Western and Eastern Polynesia. The basic implication of this division is that the two areas have undergone rather separate sequences of development e.g. several different culture traits, house building techniques as well as religion.

2.2. Ancestry and settlement patterns of the Polynesian people

2.2.1. Remote Polynesian ancestry

Speculations as to Polynesian origins began almost immediately after their discovery by Europeans in the eighteenth century. It was not until 1938, however, when Sir Peter Buck published 'Vikings of the Sunrise', that the weight of evidence convinced most scientists that Polynesian origins lay in the west rather than the east, possibly in Southeast Asia and/or South China (Kirch, 1986). The colourful theory that Oceania was colonised from the Americas was no longer seriously entertained, except by Thor

Heyerdahl whose theories, put forward in his 'American Indians in The Pacific' (1952), appear to ignore the bulk of accumulated evidence.

The recognition of several language traits in Pacific populations has been widely used in an attempt to trace Polynesian origins. On the broadest scale, this involved the separation of languages into the two major classes of Papuan and Austronesian. Papuan languages are spoken mainly on the island of New Guinea but scattered pockets have been found in eastern Indonesia, the Bismark archipelago and the Solomons. The Austronesian languages, in contrast, have a far wider distribution and can be found throughout most of island Melanesia and Indonesia, parts of coastal New Guinea, and all of Polynesia, Micronesia, and the Philippines (together with parts of South Vietnam, Malaya and Madagascar). It is now accepted that these two classes of languages reached the Pacific during two separate periods of human migration (Pawley & Green, 1973; Shutler & Marck, 1975; Bellwood, 1978b, 1980). During the first 'pre-Austronesian' period, small Papuan-speaking populations of hunter-gatherers were able to cross sea gaps to reach Australia, New Guinea (Pearce & Barbetti, 1981; Groube *et al.*, 1986) and the Bismarck Archipelago, and the northern Solomons between 50,000 and 30,000 yr BP, during periods of relatively low Pleistocene sea levels (Birdsell, 1977). New Ireland supported a human population as early as 32,000 yr BP (Allen *et al.*, 1988) and the island of Buka in the northern Solomons by 28,000 yr BP (Wickler & Spriggs, 1988). Since there is inter-island visibility from Buka to San Cristobal in the south-eastern Solomons (Swadling, 1976) it is likely that further discoveries of Pleistocene date will soon be made in this archipelago.

The discovery and occupation of the more remote island chains to the east required more sophisticated voyaging and colonisation strategies (Lewis, 1972) which were adopted by the second wave of migrants, between 3600 and 3000 yr BP (Bellwood, 1990) or earlier, according to Pawley (1981) and Tryon (1982). This phase saw Austronesian-speaking, horticultural populations, with a high degree of inter-island mobility, entering western Melanesia from eastern Indonesia. They rapidly dispersed eastwards as far as Samoa and Tonga, and eventually throughout the rest of Polynesia. This rapid movement of Austronesian people, from Melanesia to Polynesia, became associated with a distinct pottery culture known as 'Lapita' (Green, 1979; Kirch, 1982, 1984; Allen, 1984; Spriggs, 1984) and was seen to represent the founding group ancestral to later Polynesian groups. The archaeological evidence of long-distance transport of obsidian and other exotic materials by these Austronesian speaking Lapita people indicated that they had both the navigational technology and the craft to travel over distances of 3700km (Ambrose & Green, 1972; Best, 1987). Gifford and Shutler (1956), Golson (1959) and Bellwood (1985) all point out that Lapita ceramics have close parallels with certain island Southeast Asian pottery assemblages, and that the limited skeletal and dental remains associated with the Lapita sites in the Bismarck Archipelago (Kirch, 1988) also point to Southeast Asian rather than apparently indigenous Papuan populations. The genetic evidence of Serjeantson and Hill (1989) leaves little doubt that the Polynesians, direct descendants of the Lapita colonisers, are basically of Island Southeast Asian origin. Nevertheless, Lapita populations may have adopted some cultural traits from the older 'Papuan' populations they encountered in the Bismarck archipelago.

Thor Heyerdahl's (1952) theory supporting an initial settlement of eastern Polynesia by South American Indians, prior to the arrival of Polynesians, was briefly revived by Langdon (1982) and Langdon and Tryon (1983), who argued that evidence for such contact comes from the transfer of the Andean sweet potato into prehistoric eastern Oceania. The recent discovery, however, of 1000 year old sweet potato remains in Mangaia, Cook Islands (Hather & Kirch, 1991), is now believed to represent two-way voyaging of the Polynesians to South America and back again and could adequately explain the distribution of sweet potato right across the Pacific.

In conclusion, at 3000 yr BP the immediate Polynesian ancestry can be placed with certainty in the Tonga-Samoa region (Fig.1.3), with more remote origins in southeast Asia. Polynesian culture then apparently developed in the island groups around Samoa and Tonga (West Polynesian Homeland) for approximately 1500 years before moving further east. Some view this long pause as representing the time required for the discovery of the more dispersed islands beyond (Jennings, 1979), while others (notably Kirch, 1986) suggest that the long pause is partly the result of inadequate archaeological exploration of islands east of Samoa, and that further studies will eventually indicate a continuous dispersal. This pattern of migration and subsequent dispersal from the West Polynesian homeland has become the subject of much debate and dispute in recent years and one basic model has emerged, with alternative views (Kirch, 1986; Bellwood, 1989) rising mainly out of criticism of the 'Orthodox' view. Perhaps the most widely accepted theory to date is the 'Orthodox Scenario' of Polynesian settlement developed in the 1960s from archaeological work by Emory and Sinoto (1965), concentrated in the Marquesas Islands. This well established theory (described below) has been questioned recently in the light of new archaeological evidence (Kirch, 1986; Bellwood, 1989; Spriggs & Anderson, 1993), and several prehistorians believe a re-think is in order.

2.2.2. Development of the 'Orthodox Scenario' of Polynesian settlement

Before 1950, the prevailing theory for Polynesian settlement was that summarised by Buck (1938), in which the Society Islands were regarded as the 'hub of the Polynesian universe', the primary dispersal centre from which other East Polynesian groups derived. The model relied largely on the comparison of cultural traits, oral tradition and partial linguistic comparison, but the lack of precise dating techniques left plenty of room for error. The development of radiocarbon dating stimulated a wealth of subsurface archaeological investigations (e.g. in New Zealand by Duff, 1956; Easter Island by

Heyerdahl & Ferdon, 1961; Marquesas by Shapiro, 1958), which would ultimately lead to a questioning of the older theories.

Suggs (1960) attempted to rewrite Polynesian prehistory based on the newly acquired archaeological data (in particular the Haatuatua sequence from the Marquesas), and stressed the following points: (1) the occupation of Eastern Polynesia 'began before the Christian era and was underway by at least 200 BC'; (2) the Marquesas and Society Islands were both settled at approximately the same time, around the second or third century BC'; (3) both of these central archipelagos played important roles as 'main dispersal points' for the subsequent settlement of peripheral East Polynesian islands and archipelagos; (4) the settlement of Hawai'i was achieved by AD 124±120 and New Zealand was settled by AD 1000. He rejected Heyerdahl's theory of New World origins of early Easter Island culture and maintained that Easter Island was settled about the fourth century AD from the Marquesas. These proposals were, however, soon to be revised and elaborated as a result of K.P. Emory and Y.H. Sinoto's excavations in central East Polynesia. After detecting several procedural errors in Suggs' field methods, Sinoto revised the settlement date for the Marquesas to AD 300 using the cultural sequence derived from the Hane Dune Site (Sinoto & Kellum, 1965). This date became the key element of the 'Orthodox' view presented by Emory and Sinoto (1965) in the form of a diagram, which outlined a 7-stage sequence for the settlement of Eastern Polynesia. This graphic model has subsequently been modified (Fig.2.2 shows original and modified dates) in a variety of syntheses of Polynesian prehistory including Bellwood (1978), Jennings (1979) and Kirch (1982). After modifications, the key elements in the 'Orthodox' model are:

1. The West Polynesian archipelagos of Tonga and Samoa (along with certain of the smaller islands such as Futuna and Niuatoputapu) were colonised by members of the Lapita cultural complex late in the second millennium BC.

2. Ancestral Polynesian Society developed in this western 'homeland' over the ensuing 1500 years, a period during which there were apparently no further attempts at eastwards colonisation.

3. The Marquesas were the first islands in Eastern Polynesia to be settled at about AD 300, directly from Western Polynesia (possibly Samoa).

4. The Marquesas subsequently served as a major 'dispersal centre', the source for colonizing parties to Hawai'i (about AD 750), Easter Island (as early as AD 400), the Society Islands (by AD 800) and New Zealand (between AD 800 and 1000).

5. The Society Islands served as a secondary dispersal centre, with later 'migrations' to Hawai'i and New Zealand.

Language analyses by Green (1966) appeared to support the Emory-Sinoto model in suggesting that the Marquesas were the location of an ancestral Proto-East Polynesian speech community (PEP), from which the Easter Island language diverged. The subsequent split between Proto-Marquesic and Proto-Tahitic branches of this language could then be correlated with the colonisation of the Society islands from the Marquesas. Likewise, Green demonstrated that the Hawaiian language should be subgrouped with Marquesan, but that certain innovations uniquely shared between Hawaiian and Tahitian implied later borrowing. Thus, the two stage colonisation of Hawai'i was also supported. Green did, however, point out that there was no linguistic evidence to preclude either the Society Islands or the Cook Islands as the location of PEP.

In 1972 the accidental discovery of a partially submerged site at Vaito'otia on Huahine in the Society group (Sinoto & M^cCoy, 1975) added new archaeological data which had to be incorporated into the Emory-Sinoto model. However, ^{14}C dates of similar cultural phases appeared to be too recent in comparison with the Marquesan sequence and Sinoto and M^cCoy noted that the materials from Vaito'otia might necessitate a 're-evaluation of the hypothesis of the Marquesas Islands as the primary dispersal centre of East Polynesia' (1975).

2.2.3. Problems with the 'Orthodox' model

The 'Orthodox Scenario', although widely accepted (Jennings, 1979), has been challenged on several counts, particularly by Bellwood (1970); Biggs (1972); Hunt (1979); Irwin (1981), and an interesting review of these criticisms has been made by Kirch (1986). Kirch notes that both theoretical and substantive objections have been raised against the Orthodox Scenario including: (1) the uneven nature of archaeological survey and excavation in Eastern Polynesia, and consequent problems of sampling error; (2) the differences between the earliest dated East Polynesian assemblages and those known from West Polynesian sites of comparable age; (3) the problem of sufficient time for the development of shared cultural and language innovations in an ancestral East Polynesian community before dispersal; (4) theoretical arguments against a simple A to B to C settlement sequence; (5) radiocarbon ages from Hawaiian sites which appear unacceptably early in the light of the accepted Marquesan chronology.

1) Bellwood (1970) questioned the claims for the Marquesas as a 'primary dispersal centre' and noted that the simplicity of the model (in the sense of a minimum number of settlement steps), could well be the result of limited archaeological activity. Bellwood and Kirch (1986) both noted that the environmental setting of the Marquesas favoured the discovery of early settlement sites in coastal sand dunes and rock shelters. However, geomorphological conditions, such as gradual tectonic submergence, coastal aggradation and deposition of alluvial sediments on coastal plains, prevalent in islands such as the Society Archipelago, often result in site burial, making discovery difficult (the three

earliest sites notably being accidental discoveries). Evidence of archaeological site submergence was obtained not only at Vaito'otia-Fa'ahia and Vaihi but also at two midden deposits on Mo'orea (Green *et al.*, 1967). The Society Islands are also a likely candidate for the burial of early occupation sites under alluvium resulting from human-induced burning and erosion, as argued by Spriggs (1982).

Irwin (1981) questions the 'discontinuous' model of Polynesian settlement (in which there was a gap of 1500 years between the settlement of Western and Eastern Polynesia) and, like Bellwood, suggests that the absence of predicted early evidence in Eastern Polynesia can be explained in terms of 'patchy archaeological field work and sampling error'. Also, as the Lapita people moved eastwards and became 'aceramic' there was less archaeological material to find.

2) Bellwood and Davidson (1976) were troubled by the lack of similarities between the earliest artifact assemblages in the Marquesas and those in West Polynesia which were supposed to be directly ancestral. 'If we are to accept that eastern Polynesia was colonised from Western Polynesia, there must have been a point at which a pioneering Eastern Polynesian culture was indistinguishable from the Western Polynesian culture of at least one island group' (Davidson, 1976). It is possible that sites containing similar artifact assemblages are yet to be found.

3) The Orthodox Scenario also poses a problem for the accepted subgrouping model of Eastern Polynesian languages (Green, 1966). The model does not appear to allow sufficient time for new linguistic traits, common to all Eastern Polynesian languages, to have developed in the ancestral East Polynesian community before the primary split between Tahitic and Marquesic languages. The same can be said of other aspects of culture as well, for it is clear that Eastern Polynesian societies share many features which must have been developed in an ancestral community before dispersal to various East Polynesian islands and archipelagos.

4) Biggs (1972) observed that a simple A to B to C settlement model (such as that from Marquesas to the Societies to New Zealand) was unrealistic. ' Any simplistic view of Polynesian settlement passing from A to B to C in a sequence which never retraces its steps will be false' (Biggs, 1972), leading him to propose a theory of 'multiple intra-Polynesian migration and settlement'. This idea of multiple settlement is supported by linguistic data from various Polynesian islands, such as Uvea, Rotuma, Rurutu and Niuatoputapu.

Further objection to the Orthodox Scenario centres on the difficulties of voyaging direct from Western Polynesia to the Marquesas, given the 2880km distance and the generally opposing winds and currents (shown in Fig.1.8). This objection, raised by Biggs (1972) and others, suggests that 'islands which were closest would be settled first in the upwind struggle to the east'. Finney (1985), however, emphasises the importance of summer westerlies in equatorial latitudes in the western Pacific, and has also suggested that the occasional El Niño phenomenon (Ramage, 1986), which can draw winds and currents eastwards across the Pacific towards South America (as described in Chapter 1: 1.3), could have made direct voyaging from Samoa to the Marquesas possible. Nonetheless, a chain of settlement leading through the Cook Islands and Society group to the Marquesas would be more in keeping with what is known of the process of oceanic colonisation in the south-western Pacific (Irwin, 1989).

5) Other serious challenges to the Emory-Sinoto model have been those posed by the presence of several sites in Hawai'i that pre-date the supposed AD 750 Marquesan settlement of the archipelago (Kirch, 1985). An initial Hawaiian settlement by perhaps the fourth century AD has been proposed by Kirch, but as he comments (1986) such a date 'greatly strains the model, in which the Marquesas themselves were just colonised'. While reconsidering the archaeological evidence from the Marquesas, Kirch (1986) notes that 'although early sites have not been difficult to locate in the narrowly-confined Marquesan valleys, archaeological coverage of the archipelago has by no means been complete'. Even Sinoto (1983) cautions that 'it is probable that the early part of the initial period of Marquesan culture has not yet been discovered'. Such an earlier stage might well be expected to fill the gap between the Hane-Ha'atuatua material and that known from comparable West Polynesian sites, as suggested by Bellwood (1970) and Davidson (1976), and allow time for the development of eastern Polynesian language and culture traits and account for the earlier Hawaiian settlement dates.

The question of whether earlier sites were to be found on these islands was more recently answered by Ottino (1985) whose work suggests a 200 BC settlement date for the Marquesas. However, the date from the cultural deposit at Anapua of 390 BC-AD 80 (Ottino, 1985) is contradicted by a much later shell date from the same context (Ottino, 1991). A further three shell dates suggest that settlement did not begin until about AD 1100-1200 (Leach *et al.*, 1990). The use of driftwood resulting in the very early date is a distinct possibility on this almost inaccessible beach (Ottino, 1985). The Hane site on Uahuka has produced the most complete sequence of dates from the Marquesas (Sinoto, 1970). Although level VII is undated, there is an acceptable shell date (WSU-516) of 360 BC-AD 630 for level VI, and a charcoal date from the same context of AD 259-1030 (WSU-490). Other dates from the early levels are: 100 BC-AD 690 (WSU-491) and AD 340-990 (WSU-492), plus shell dates of AD 510-1290 (WSU-512) and AD 1-670 (WSU-524). Culturally equivalent is the Hanatukua shelter on Hiva Oa, plausibly dated to AD 567-890 (Gak-1962) and AD 600-990 (Gak-1963). A third much earlier date from this shelter (Gak-1964) was stratigraphically inverted and has been rejected. In Spriggs and Andersons' (1993) reappraisal of the Marquesan dates only three met their sampling criteria (i.e. those with standard deviations of 150 radiocarbon years or less), one of whose calibrated ages starts at AD 1 at 95% confidence limits and the other two at AD 567 and AD 600. They conclude that initial habitation of the Marquesas in the period AD 300-600 seems likely. However, although the chronological case for earlier settlement is weak it cannot be entirely dismissed.

According to Spriggs and Anderson (1993) the best dated early site in Hawaii is the Wai'ahukini shelter on Hawai'i Island where a shell and charcoal series suggests an initial occupation beginning around AD 650-850. The overall pattern of dates from Hawai'i suggests a relatively late settlement, probably after AD 600. There is a further date from Fanning Island (Sinoto, 1973), a possible stop-over point in voyaging to Hawai'i. This single date is, however, questionable and may well be on driftwood (Spriggs & Anderson, 1993).

The earliest acceptable radiocarbon date for the settlement of Easter Island is AD 410-1270 (WSU-1146) from *Thespesia populnea* charcoal from an inland house site (M^{c}Coy, 1973). *Thespsesia* is believed to be a Polynesian introduction to the island (Flenley *et al.*, 1991). Other dates that have been questioned by Spriggs and Anderson (1993) include dates of AD 570-1280 (M-710) from Ahu Vinapu and AD 780-1180 (Ua-618) from Rano Raraku. Present evidence thus suggests colonisation towards the end of the 1st millenium AD, later than proposed by the Orthodox Scenario. The wealth of New Zealand data has recently been considered by Anderson (1991) who concludes that the first settlement of mainland New Zealand most probably occurred in the period AD 1000-1200 (slightly later than previously proposed), the Karmadecs in the 13th century at the earliest and the Chatham Islands not before the 14th century. In the eastern archipelagoes there are only post-1000 BP dates published for the Tuamotus, Mangareva, Pitcairn and Henderson Island, although a preliminary report of recent work on Henderson notes new calibrated radiocarbon ages extending back to the late 8th century AD (Weisler *et al.* 1991).

2.2.4. Settlement of the Society Islands

The earliest known sites in the Society Islands (see Fig.1.3 for details of dates) are the burial ground at Maupiti (Emory & Sinoto, 1964, 1965), the extensive, waterlogged village site of Vaito'otia-Fa'ahia on Huahine (Sinoto & McCoy, 1975; Sinoto, 1979, 1983a, b, c), and the Vaihi site on Ra'iatea (Semah *et al.*, 1978). It was concluded from these that the Society Islands were occupied by the 9th century AD at the latest, by several communities with a culture similar to that found in the upper levels of the Marquesan sites. Sinoto interprets these assemblages as evidence for a 'migration' from the Marquesas to the Societies, but is criticised by Kirch (1986) for not considering that these may alternatively indicate the diffusion of traits from the Societies to the Marquesas, or that they represent a period of frequent contacts between these two archipelagos. To move beyond accidental discovery of buried sites and seek to answer the question of whether yet earlier assemblages exist in the Societies, a programme of sub-surface sampling must be initiated, using an explicit geomorphological model of site formation processes'. Alternatively, some other independent 'innovative approach' is needed to overcome the geomorphological problems of site discovery in the Society Islands (Kirch, 1986). It seems quite plausible to Kirch 'that we have yet to discover the first millenium or so of Society Islands prehistory...', and since archaeological investigations in the Societies are beset with sampling problems on geomorphological grounds, it was hoped that lake sediment analyses from Lake Temae would overcome these difficulties and be able to detect any earlier signs of human activity.

Spriggs and Anderson (1993) recent reassessement of all the available pre-1000 yr BP colonisation dates for East Polynesia rejects the date (GXO-207) from the Maupiti burials and the Gak-4629 date from the Vaito'otia-Fa'ahia site on Huahine on the grounds that they were on human and whale bone. They argue that these materials can be grossly affected by the uptake of old carbon in sea-water or from limestones and coral, or may be subjected to other forms of contaminant (Anderson, 1991). Other dates from the Vaito'otia-Fa'ahia site were, however, accepted and gave age ranges of AD 680-1020 (I-10770), 690-1030 (I-10769) and 770-1152 (I-9650) with high probabilities that the true ages are later than AD 750. A further date from the same layer, thought by the excavator to represent a habitation site overwhelmed by a tidal wave, gave an even later age of AD 980-1260 (Gak-5244, 910±75 yr BP). An earlier date (1650±270 yr BP/349 BC-AD 2240 calibrated) recorded from an archaeological site at Onetahi in Teti'aroa (Sinoto & M^{c}Coy, 1974) was also rejected by Spriggs and Anderson (1993). The basis for this rejection was that the date was 'clearly anomalous compared to more acceptable dates from the same cultural material from other sites'.

Lepofsky *et al.* (1992) recently reported two dates on coconut (*Cocos nucifera*) recovered from swamp sediments in the Opunohu Valley on Mo'orea, of AD 590-780 (Beta-41160) and AD 650-890 (Beta-41159). Beta-41160 consisted of a whole coconut considered to represent a hybrid of wild and domesticated forms. It was, therefore, believed to be of cultural origin.

2.2.5. Settlement of the Cook Islands

According to the 'Orthodox Scenario', the Cook Islands were settled from the Society group, as originally proposed by Buck (1938, 1944); however, as Kirch (1986) points out, very little is known of the subsurface archaeology of the Cooks. The few investigations that had been undertaken prior to the 1990's were concentrated on surface surveys of *marae* (stone temple platforms) and other structural features (Trotter, 1974; Bellwood, 1978). Bellwood's excavations at the Ngati Tiare site on Rarotonga and the Ureia site on Aitutaki have yielded the earliest stratified materials, dating to around the 10th-13th centuries AD. The Ureia dates (AD 810-1170) are supported by a good sequence of later dates (Allen & Steadman, 1990) and a comparable date from an earlier excavation (Bellwood, 1978b; NZ-1252, 969±83 yr BP, AD 890-1240), and a site on Rakahanga with three cultural dates in sequence beginning AD 780-1160. Dates from the Tangatatau shelter on Mangaia (Kirch *et al.*, 1991) suggest a somewhat disturbed stratigraphy in a sequence begining AD 900-1220 (Beta-32826, 980±70 yr BP), a date which does not quite overlap at 2 standard deviations with a second sample from the same lowest stratigraphic zone of AD 1250-1633 (Beta-32816, 550±120 yr BP). There is no reason to believe, however, that these sites represent a colonisation or settlement phase in the Southern Cooks. Several artifacts from these limited sites have shown similarities with the later layers described from the Vaito'otia-Fa'ahia and Hane sites suggesting that earlier sites have not been found. Also of interest is the fact that both sites yielded 'Samoan' type adzes, the presence of which remains to be adequately explained.

Evidence of human occupation, possibly dating from the late first millennium BC, has been found on the atoll of Pukapuka in the Northern Cook Islands, directly between Samoa and the Marquesas (Chikamori & Yoshida, 1988). The cultural context of these dates was called into question by Spriggs & Anderson (1993) because they are all single dates on marine shell or unidentified charcoal or wood and no artifacts were recorded from the excavations. They also noted that Pukapukan is a Samoic (i.e. West Polynesian) language rather than an East Polynesian one, in contrast to languages spoken in the other Cook Islands. This in itself suggests a somewhat different settlement history from the rest of East Polynesia.

In view of the latest archaeological dates, Bellwood (1989) proposed the following adjusted sequence of Polynesian settlement. The Marquesas Islands were perhaps the first to be settled in eastern Polynesia around 200 BC (Ottino, 1985; Kirch, 1986), from Samoa if the evidence of adze typology is any guide (Green & Davidson, 1974). By AD 500 settlement seems to have reached the Hawaiian Islands (Kirch, 1985) and possibly also Easter Island (Ayers, 1971). During the later first millenium AD people had certainly reached the Society Islands (Sinoto, 1982), the Southern Cooks (Bellwood, 1978), and finally the large temperate landmass of New Zealand (Davidson, 1984).

The only way to test alternative hypotheses of Eastern Polynesian settlement is to continue to fill in the critical gaps which 'lie particularly in the central archipelagos (of) the Cooks, Societies, and the Australs' (Kirch, 1986). Until the early settlement phases of these islands are known, any attempts at producing a sufficient account of Polynesian dispersals will be premature. The palaeoecological studies undertaken in Atiu (S. Cooks), and Mo'orea (Societies) during this study, are intended to provide information to help close these data 'gaps' and to answer the question inferred by Kirch (1986) as to whether Polynesian voyagers took the more direct route across the Pacific and landed in the Cook Islands and the Societies before arriving in the Marquesas. An estimated date of early human activity in the inland Lanoto'o basin on Upolu (Western Samoa), which may also reflect the initial colonisation of this island, could verify, or perhaps contradict, the earliest settlement date of 3251±150 yr BP (Leach & Green, 1989) derived from coastal archaeological sites, known to be beset by geomorphological problems. The palaeoecological techniques used in this study will now be described (Chapter 3).

3. RECONSTRUCTION OF LATE HOLOCENE ENVIRONMENTAL HISTORIES: TECHNIQUES

A range of field and laboratory techniques have been used to reconstruct Late Holocene environments and the vegetation history on Upolu, Atiu, Mo'orea and Tahiti. These include the study of present-day plant distributions, analysis of the physical and geochemical properties of accumulated lake sediments, and the analysis of fossil pollen and diatoms preserved in these sediments. The fossil pollen content of sediments was analysed to detect responses of island vegetation to natural environmental variation and to more recent anthropogenic influences, and to build up a chronological picture of past environments with the aid of radiocarbon dating. Surveys of present vegetation and environments to some extent provided an anologue on which to base such environmental reconstructions (referred to in section 1.4). Analysis of the fossil diatom flora of Lakes Roto and Vaihiria was undertaken to provide insight into past lake conditions, such as changes in water salinity, alkalinity, and nutrient status, while the study of physical and chemical characteristics of the lake sediments was undertaken to reveal more about the origin and nature of accumulated material.

3.1. FIELD TECHNIQUES:

3.1.1. Collection of lake sediment cores

The collection of sediment cores for palaeoecological and sedimentary studies was undertaken during three separate visits to the Pacific islands. Cores were collected from Lake Vaihiria by Professor J.R. Flenley and Professor J.T. Teller during an expedition to Tahiti in July 1983. The collection of sediment cores from Lake Temae was undertaken during the Hull University Mo'orea Expedition of 1985 when the author also had the opportunity of visiting the Lake Vaihiria site on neighbouring Tahiti. Lake Lanoto'o in Upolu, Lake Roto in Atiu, and Lake Rotonui in Miti'aro were cored by the author during the summer of 1986, with the help of venturers from the Operation Raleigh Expedition (Pacific crossing).

With the exception of Upolu, which has several inland crater swamps and lakes at varying altitudes, all of the other islands visited had only one lake that was suitable for coring. All of the lakes involved in this study are relatively small (i.e. less than 1km in diameter), and since the effective size of lakes and their catchment areas determine the amount of pollen and sediment influx to a lake (Tauber, 1965), the accumulated sediments were expected to reveal changes in local catchment and island environments more readily than regional scale changes. Nevertheless, it was hoped that these sensitive catchments would respond to any large-scale regional variations. Long-distance dispersal of pollen which often complicates the pollen sequences from larger lakes was not expected to be a major component of the fossil pollen spectra from these lakes.

At each lake, depth soundings were taken to find the general shape of the lake bed and to find the greatest water depth which invariably coincides with the deepest sediment deposits. Further advantages of coring in deeper water (usually found near to the centre of the lake) are gained from the reduction in water turbulence (Davis, 1968) which often disrupts the surface sediments, and re-suspends pollen in shallow lake margins (Moore & Webb, 1978), and also the reduced possibility of over-representation of local peripheral vegetation which may deposit entire anthers into the marginal lake areas. Re-deposition of pollen and spores brought into lakes by peripheral streams or in-washed slope material (which was expected to be higher from the volcanic as opposed to the limestone slopes) is also likely to be reduced with distance from the lake shore; however, it is this in-wash of sediments that can also provide valuable information on catchment stability, and since re-bedded grains can usually be distinguished on the basis of exine deterioration (Cushing, 1964; Birks, 1970) this factor was not considered too problematic.

One of the major considerations when analysing sediment cores is whether the main core site selected is typical of the general area to which the interpretation will be applied, and for this reason a transect of sediment cores was taken across the lakes and compared. Cores were collected using a hand operated stationary piston sampler (modified Vallentyne Sampler: Walker, 1964), worked from a floating platform (shown in Figs.4.3 and 4.4) and anchored into position. The sampler and extension rods were worked through a central hole on the platform and aluminium casing pipes were used to prevent sediment slumping and also help in the relocation of the sampling borehole. A vice, built onto the collar around the central hole, was used to keep the stationary piston wire taut while the cores were being taken. This apparatus enabled core segments 1m in length and 35mm in diameter to be obtained at each drive and, with the addition of 1m extension rods, allowed up to 16m of sediment to be collected (e.g. Lake Roto). Using the transect of cores it was possible to predict where the most complete sequence of sediment would be found, and from these locations (shown in Figs.4.1, 5.1, 6.9, 6.22) the following five main cores were collected for laboratory analysis: a 3m core from Lake Lanoto'o beneath 15m of lake water; a 16m core from Lake Roto at a water depth of 6.8m; a 7.25m core from Lake Rotonui at a depth of 1m; a 14.5m core from Lake Temae at a water depth of 11.3m; and a 5m core from Lake Vaihiria at 25m water depth.

The material recovered was then described in simple terms based on the Tröels-Smith notation (Tröels-Smith, 1955) which included a description of sediment composition, degree of darkness (nig.), stratification (strf.), elasticity (elas.) and degree of drying (sicc.). Six main categories of sediment composition are recognised by Tröels-Smith, three being biogenic, two minerogenic, and a further one either chemical or biogenic. In summary these are: *Substantia humosa*, undifferentiated disintegrated organic matter; *Turfa*, macroscopic plant remains of below ground origin (e.g. roots) and mosses;

Detritus, macroscopic plant remains of above ground origin (e.g. leaves); *Limus*, lake mud of biogenic or chemical origin (e.g. marl); *Argilla*, fine grained minerogenic particles (e.g. clay); and *Grana*, medium or course grained minerogenic particles (e.g. sand). The advantage of dividing sediments into these categories is appreciated when considering the origin of the accumulated sediments. Biogenic sediments, comprised primarily of organic carbon, are more often autochthonous in origin, i.e. formed *in situ*, and hence the organic content is usually a good indicator of lake productivity. More rarely, however, organic matter may be allogenic, as when soils are eroded and washed into streams and lakes, or when leaves are blown directly into water bodies. On the other hand, minerogenic sediments, comprising rock particles, are invariably allochthonous in origin, i.e. brought to the point of deposition from elsewhere.

The other four descriptive measurements were estimated on a 0 to 4 scale where 0 indicated the lightest shades (e.g. clear quartz sand; lake marl); complete homogeneity; total absence of elasticity (e.g. plastic clay, sand, diatom deposits, and fen peat); and clear water respectively. At the other end of the scale, 4 represents sediments of the darkest shades (e.g. dy, and completely disintegrated *Sphagnum* peat); consisting of very thin minor layers, and/or that is easily split into thin horizontal layers; showing the highest degree of elasticity (e.g. fresh *Sphagnum* peat, swamp peat and cyanophyceous gyttja); and that are air dry. It was necessary to make this provisional stratigraphic record soon after the cores had been exposed because the processes of oxidation and drying rapidly bring about an alteration in the sediment characteristics.

After completing sediment descriptions the five main cores were extruded into PVC piping, wrapped in polythene to avoid moisture loss and the development of aerobic conditions, and returned to the laboratory at The University of Hull where they were then stored at 2^{o}C to prevent microbial activity.

3.1.2. Levelling of the coral ridge between Lake Temae and the sea

Lake Temae, being situated on the coastal plain of Mo'orea and separated from the sea by only a narrow coral *motu*, was well positioned for the use of standard levelling techniques to establish its elevation above sea level. Measurements were made along a transect (shown in Fig.6.9) from the lake to the sea across the width of the coral *motu*, and the elevation of the lake and ridge was determined. Elevations of the other lakes, which either were situated too far inland or, as in the case of Lake Rotonui (Miti'aro), had been levelled previously (D. Stoddart, pers. comm.), were obtained from maps and other information sources.

3.1.3. Present vegetation and ecological surveys

Palaeoecology is the study of fossil organisms in order to reconstruct past environments (Roberts, 1989); however, accurate palaeoenvironmental reconstruction depends on modern ecological data and is consequently only as good as our knowledge of present day ecosystems. For this reason vegetation surveys and ecological collections were made whenever possible on the islands under study to supplement ecological data from previous botanical studies. The fundamental assumption that has to be made in such palaeoecological studies is that relationships which can be observed at the present time also held good in the past. This is clearly a tenuous assumption in areas where anthropogenic modification of many vegetation communities is believed to have occurred; however, it is the best estimate we can get, and it must be used as a benchmark. This principle is known as uniformitarianism and has been systematically discussed and questioned in a vast literature, including Birks & Birks (1980) and Lowe & Walker (1984).

A small vegetation survey was undertaken on the island of Mo'orea, by the members of the Hull University Mo'orea Expedition, in order to assess the effects of certain environmental and anthropogenic factors on plant distribution, and also to detect any specific ecological indicators that could be used in later reconstruction of the island's environments from pollen records. The survey was based on 29 sample plots (see Appendix 1 for locations) subjectively chosen to include as wide a range of vegetation types as possible. These ranged from relatively undisturbed upland forests, to highly disturbed coastal sites dominated by fernlands and grasslands. At each site, a number of environmental variables were recorded, including altitude, aspect, humidity, slope angle, and estimates of drainage conditions and the degree of shading (a summary of variables is shown in Appendix 1). Plants that could not be positively identified in the field were collected and later determined by the author with help from the staff of The British Museum (Natural History), London, and The Herbarium of The Royal Botanic Gardens, Kew. A detailed description of this vegetation survey, and statistical analysis of plant distribution on Mo'orea, have been covered in Parkes and Flenley (1990) and will, therefore only be briefly summarized in this dissertation (Statistical analyses summarized in Appendix 1).

During the vegetation survey on Mo'orea, moss polsters (small moss hummocks) were collected from those plots with distinctive vegetation types. It was hoped that these polsters would have acted as natural traps for pollen and spores from the surrounding vegetation (Flenley, 1973; Bradshaw, 1981), thus giving a measure of the modern pollen rain and an indication of which taxa were high or low pollen producers. Unfortunately, later analysis (preparation technique detailed in Appendix 2B) showed that pollen preservation in these polsters was very poor and concentrations too low to be statistically significant. It is believed that particularly dry conditions may have been responsible for this poor preservation in the usually moist micro-environments of the polsters. The author, therefore, has had to rely on previously published information on pollen production to determine which plant taxa were likely to be over- or under-represented in the fossil pollen spectra. Fortunately, present day palynological studies undertaken in the Fijian Islands by Southern (1986) provided some qualitative information on the representation of several pollen and spore taxa common to the islands studied. However, the limitations of using data from a geographically and often geomorphologically distinct island needed to be appreciated. No quantitative correction factors (~~i.e.~~ as the pollen representation values of Davis, 1963; or pollen production factors of Andersen, 1970) were, therefore, available to adjust the fossil frequencies.

Although no extensive vegetation surveys were undertaken on the Cook Islands and Western Samoa, due to time restrictions and because similar studies had already been undertaken (e.g. Whistler 1978, 1980a, 1980b, 1983a, 1983b, 1990; Sykes, 1976a), several plant collections were made on these islands and ecological preferences recorded, particularly within the lake catchment areas under study. A range of habitats were studied, including the undisturbed, elevated central regions of Rarotonga (Cook Islands) and Upolu (W. Samoa), the heavily disturbed cultivated regions of Atiu and Miti'aro (Cook Islands), the relatively sheltered and moist lower valley of the dissected volcanic cores and the exposed, thin and dry soils of the *makatea* limestone regions (Atiu and Miti'aro). Plant ecologies were also studied on the islands of Eua (Tonga) and Aunu'u (American Samoa), and the raised coral island of Henderson also provided a range of plant communities relatively undisturbed by human activity. Plant collections made during this study are presently stored in the University of Hull Herbarium (School of Geography and Earth Resources). Several specimens, however, were donated to the Kew Herbarium on request. Reference pollen slides were also made from the positively identified plant specimens to aid identification of fossil pollen and spores, and followed the procedure outlined in Appendix 2C.

Collections and surveys from all of the above islands, along with previous botanical work undertaken on these, or neighbouring islands, most notably by Whistler (Samoa and Cooks), Sykes (Cooks), Merlin (Cooks), Florence and Papy (Society Islands), provided the main source of information on which to base a reconstruction of past vegetation types and environments. A summary of ecological and ethnobotanical notes for the taxa identified in the fossil pollen and spore records, has been compiled in Appendix 3 from all of the above mentioned sources.

Due to the mainly qualitative nature of the available botanical information, and the lack of quantitative present pollen studies, it was impossible to reconstruct the former vegetation by the use of modern analogues or indeed to apply transfer functions (Birks & Birks, 1980) for the reconstruction of former climates. It was, therefore, necessary to have recourse to 'indicator' species, using pollen taxa whose source plants had ecological preferences which were reasonably well established (full ecological descriptions are included in Appendix 3). The intuitive approach recommended by Livingstone (1967) for East Africa was also applied.

Since the detection of human activity in the lake catchments was one of the main aims of the pollen analysis it was necessary to clearly define which taxa could be definitely associated with a Polynesian agricultural community. Whilst plants such as *Ipomoea batatas* (the sweet potatoe), *Colocasia esculenta* (taro), *Morinda citrifolia* (Indian mulberry), *Musa paradisiaca* (banana), *Sida rhombifolia* and *Terminalia catappa* are strongly associated with Polynesian introduction and can be used as reliable indicators, the origins of several other taxa are less certain. A system of codes has been included in the ecological notes on taxa determined from the pollen record (Appendix 3). Taxa which have been identified as clearly of Polynesian introduction are coded with 'A'- Aboriginal introduction; the taxa suffixed 'R' are believed to be recent or historical introdutions, e.g. the weeds such as *Ageratum conyzoides* or *Ludwigia octovalvis.* Some taxa also have recorded arrival dates which can provide useful chronological markers e.g. *Lantana camara*, introduced into Mo'orea and Tahiti in 1830 and first reported from Samoa in 1895; *Psidium guajava* was recorded as being introduced to the Society Islands in 1815. Other taxa have been identified as 'E'- Endemic or 'I' Indigenous to an island or group of islands, whilst the origin of some taxa is unknown (i.e. no code) or uncertain (i.e. with a combination of codes). One notable species in this combination group is *Cocos nucifera* which was regarded in the botanic literature as either of aboriginal introduction or indigenous to several Pacific islands. The pollen profiles in this study strongly suggests that the coconut was actually indigenous to Atiu and Mo'orea (Chapters 5 and 6) which highlights the need to only rely on taxa whose origin is certain.

3.1.4. **Analysis of airborne pollen and spores**

During an ocean crossing from Valparaiso, in western Chile, to Fiji, in the western Pacific Ocean, an attempt was made to estimate the importance of long-distance pollen dispersal between several Pacific islands. If long-distance dispersal between island vegetations proved to be a major component of the pollen rain, then much care would need to be taken when interpreting the existence of low percentage fossil pollen frequencies in lake sediments from these islands. However, as already mentioned, the catchment areas of the lakes studied were probably not large enough to incorporate a major long-distance component (Tauber, 1965).

The aim of this study was to collect airborne pollen and spores over a determined route from the east Pacific islands of Juan Fernandez to the west Pacific island of Fiji, via Easter Island, Henderson, Pitcairn, Cook Islands, Samoa and Tonga. Collections were made by running a Burkard volumetric pollen sampler from a platform situated on board the ship. The sampler, containing a built-in vacuum pump, was designed to sample airborne particles, including pollen and fungal spores, continuously for periods up to seven days without attention. The theory is that particles are impacted on adhesive coated transparent Melinex tape supported on a clockwork-driven drum, which moves at

2mm/hr past an orifice 2mm wide. The volume of air drawn through the trap could be calculated, and the concentration of pollen estimated, if enough grains were sampled. The tapes were periodically removed and examined on board under a Wild light microscope, while the distance from the islands, as well as weather conditions and wind direction, were recorded from the ship's log book. It became apparent after two months of sampling that long-distance dispersal appeared to be a negligible factor since no pollen or spores were recorded beyond a radius of 5km from the nearest island. Several insects and soot particles were, however, sampled which indicated that the sampler was working effectively. Only twelve pollen grains and two fern spores were collected over the entire trip and they were sampled while the ship lay at anchor less than 5km off two of the islands. Two Urticaceae/Moraceae pollen and a single spore of *Gleichenia linearis* were recorded off Alexander Selkirk (Juan Fernandez), while nine grains of *Casuarina equisetifolia* (typical strand trees), one grain of the family Myrtaceae, an unidentified monolete fern spore, and two fungal spores were recorded within sight of the Island of Rarotonga (Cook Islands). From this study it was concluded that wind-bourne, long-distance dispersal of pollen and spores would form an insignificant component of the pollen rain over the islands studied. This study does not, however, assess the possibility of long-distance transport of grains and spores by animals such as sea birds and bats. The relatively short period of time over which the samples were collected may also have underestimated the pollen counts.

3.2. Laboratory techniques:

3.2.1. Physical investigations:

3.2.1.1. Magnetic susceptibility analysis of lake cores

Magnetic susceptibility measurements (Thompson & Oldfield, 1986) were recorded in an attempt to trace changing erosion rates within the catchments, and to link these with variations in sediment properties and vegetation. Readings were expected to show variations in the input of allogenic mineral matter, derived from the basaltic rocks of the drainage basins (common to all of the lake catchments studied), and later incorporated into the lake sediment. Since the in-washed minerogenic material has a greater susceptibility than the organic-based muds generated mainly from within the lake, the susceptibility profile is believed to reflect the extent of slope disturbance and soil erosion (Thompson & Oldfield, 1986), perhaps in response to short-term natural events such as landslides, severe storms or human-induced phenomena such as large scale clearance of vegetation within the catchment.

Susceptibility readings were measured along each of the four main cores (i.e. excluding Lake Rotonui), at 2.0cm intervals, using a Low frequency Core Scanning 'Loop' Sensor (Bartington Instruments Code M.S.1C) which was fixed horizontally to a non-magnetic surface. The sensor was immobilized so that insertion and removal of the core would not lead to significant movement. Care was also needed to avoid temperature variations during the measurements. The susceptibility meter was initially set to zero and the drift rate checked over 5 successive readings. The mean rate over this sequence should be 0.2 or less (whether + or -) and the variation no more than +0.1. Once the readings had stabilised (after at least 5 minutes) the S.I. units and 0.1 scales were chosen. Because of the low ferrimagnetic content of some of the organogenic sediments the more sensitive 0.1 scale was chosen in preference to the faster 1.0 scale. The 0.1 scale integrates susceptibility readings over 5-6 seconds and is ten times more sensitive provided drift is linear and reasonably slow.

The procedure for taking results involved reading a 'blank' before core insertion, doing a run of measurements at successive 2cm depths down 1m lengths of core, reading 2 blanks after full passage of the core downwards. Then a run, at the same intervals and the same speed, was made up the core, closing the sequence with a final blank. The series of 'blank' readings, i.e. when no sediment was in the coil, were used to estimate and correct for direction and variation of drift rate. They were also used to adjust the raw figures to a base reading, thus allowing comparison throughout individual cores. However, since the calculated readings are in arbitrary units comparisons could not be directly made between separate cores. A note was made of any recorded sample that was damaged or where the thickness of the core varied significantly and these readings were excluded from the final susceptibility profiles.

3.2.1.2. X-ray photography of sediment cores

Prior to the extraction of samples for geochemical and pollen analysis the sediment cores, still in PVC tubing, were X-rayed along their lengths in order to show major and minor variations in sediment density which may have resulted from in-washed clays, algal laminations, coral-sand bands etc. The X-ray process was undertaken in the Physics department of the University of Hull, and the X-ray sheets were then used as negatives from which to print positive photographs (e.g. shown in Figs.5.7 and 6.14). X-ray analysis also provided a non-destructive opportunity to examine the cores for structural integrity and suitability for further analysis. The preservation of fine laminations in the four sediment cores indicated that natural stratification had been undisturbed since deposition, a prerequisite for a clear chronological sequence. The absence of laminations noted in some sections may have occurred as a result of burrowing animals such as molluscs or as a result of the collection procedure. The X-ray technique also proved useful in the detection of fossil barnacles, molluscs (marine and freshwater) and tube-worm casts, which in turn provided additional information on environmental conditions within the lake catchment.

Magnetic susceptibility measurements and X-ray analysis both provided non-destructive, close sampling techniques, that had the potential to detect any short-term events not sampled in the following geochemical and biological analyses.

3.2.2. Geochemical investigations:

3.2.2.1. Analysis of major element oxides by X-ray fluorescence (XRF)

In order to establish the bulk chemical composition of the sediments from the four main lake sequences, analysis by X-ray fluorescence was carried out. Samples were prepared according to the fusion method of Norrish and Hutton (1969), and analyzed using a Philips PW 1212 XRF Spectrometer. During the preparation for XRF analysis the percentage loss-on-ignition, at 600°C (refered to in the data sets as L600), was measured to establish the amount of organic material present in the samples. Each sample was initially oven dried at a temperature of 90°C, and weighed using a Cahn TA 4100 scale balance, which has an accuracy of ±0.0001g. Samples were then heated to 600°C in a furnace and re-weighed, with care being taken to prevent temperatures exceeding 600°C since further loss-on-ignition, due to the release of CO_2 and CO_3 from carbonates and the loss of interlayer water from clay minerals, would result at around 700°C (this lose-on-ignition is refered to as LOI in the data sets). The difference between the sediment weight before and after burning constituted the organic content of the sample, which provided some measure of the internal lake production of sediment as well as the deposition of organic materials such as leaves from the surrounding catchment area (also indicated by the organic carbon content measurements shown in Appendix 4).

The remaining inorganic sample was ground down into a fine powder, added to spectroflux (following the method outlined in Appendix 5) and made into glass discs for analysis in the XRF spectrometer where the unique X-ray signature of individual oxides could be measured. Percentages of the total inorganic fraction could be calculated in this way for all the major element oxides, except sodium-dioxide (Na_2O). Calculation of Na_2O was obtained by making a pellet of boric acid crystals and pressing a thin layer of the inorganic sediment sample on the top surface using a hydraulic press at a pressure of 15 tons inch^{-2}. The resulting pellet was then analysed in the spectrometer and percentages of the total sample calculated.

Sample depths for geochemical analysis were chosen, whenever possible, at regular intervals down the core (extra samples being added later to increase detail in sections of particular interest). In some cases sample distance was slightly adjusted to avoid areas of damaged sediment. 21 samples were analysed from Lake Lanoto'o, 77 from Lake Roto, 46 from Lake Temae and 26 from Lake Vaihiria. Geochemical profiles and sample depths are shown in Figs.4.10, 5.10, 6.16 and 6.24 and described in the following chapters. Samples from the Rotonui (Miti'aro) sequence were also prepared for geochemical analysis but the nature of the sediment rendered the analysis unacceptable. Because of the high organic content of the neckron mud which dominated this core (often 90-99%) there was not enough inorganic material available to be analysed for oxide content i.e. without sampling in access of 20cm lengths of core. Three samples which did contain sufficient inorganic content to make up a glass disc were found to contain extremely high concentrations of Na_2O. Na_2O is the one element-oxide that can significantly distort the ability of the technique to detect the other oxides, this is because of the unavoidable inaccuracies involved in making the boric acid pellets as opposed to the more accurate glass disc preparations. Because of the low resolution of samples that would have necessarily resulted from this sequence and the inaccuracy of any XRF-analyses the core from Rotonui was abandoned for this technique.

Several assumptions, outlined below, have been made in the interpretation of the geochemical data from the four main islands.

1) Due to the nature of the geology of these islands, sediments rich in the oxides of silica, aluminium, titanium and iron, in ratios similar to those measured in basaltic rocks and lateritic soils of Western Samoa (Kear & Wood, 1959), Atiu and the Society Islands (Marshall, 1930; Wood & Hay, 1970) and Mangaia (Dawson, unpublished), were interpreted as being allogenically derived from the basalt interior. These basalt derived minerals (mainly derived from silicate minerals) will be collectively referred to in the text as the basalt-oxides.

2) The presence of thin veins of manganese in the soil profiles on Atiu have frequently been noted by geologists (eg. Wood & Hay, 1970), and may account for any high percentages of this mineral in the sediments of Lake Roto.

3) In the Atiu and Mo'orean sequence sediments rich in calcium carbonate (i.e. CaO and CO_2 + H_2O) and/or magnesium-oxide (MgO) are likely to be derived either from the calcitic and dolomitic limestones of the *makatea* surrounding Lake Roto, or reef material in the lagoons and barriers surrounding Lake Temae. These two oxides frequently also form a component of basalt rock, but usually at relatively low concentrations. According to Round (1973) magnesium may also be associated with algal deposits.

4) The presence of high percentages of sodium-oxide in a sediment sequence gives a general indication of salt (sodium-chloride) content derived from marine sources or evaporites. Sodium, however, also occurs in the basalt rocks and is renowned for its solubility in water. Interpretation of the sodium-oxide curve, therefore, must take these factors into account.

5) High percentages of organic material in the sediment may result from the formation of peat deposits in a lake basin (e.g. Lake Roto) and the accumulation of organic lake mud (gyttja) from internal lake production by the 'resident' biota. Organic material may also

be derived from the flora and fauna outside of the lake, but is more likely to be associated with a certain amount of mineral in-wash.

6) Silica-oxide occurring in excess of the other basaltic-oxide ratios (mentioned above) may be an indication of high diatom concentrations within the lake. Since these algae are capable of 'fixing' free silica in solution they could affectively retain the silica, which would otherwise be lost to the system, by incorporating it into their frustules. This theory is investigated later in the section on diatom analysis from Lake Roto (5.8.3.3).

7) A further possible source of silica in the system is from decaying organic matter. In a stable system any excess is quickly taken up from the soil by the next generation of plants and never actually reaches the drainage system; however, as a result of mass forest destruction the cycle of silica-oxide retention will be broken and an increase in SiO_2 inwash may be expected as a result.

8) P_2O_5 also occurs in significant quantities in the basalt rocks of these islands but high levels may also be present as a result of guano deposits (which exist fairly extensively on the *makatea* regions of the Cook Islands) or other faunal sources. A close relationship also often exists between P concentration and primary productivity (possibly due to the high trophic status of a lake environment).

9) The abundance of iron is determined not only by the conditions of the catchment but also by conditions within the lake. Fe_2O_3 may occur in a residual form i.e. contained within the structure of the silicate minerals or in an extractable form as authigenic oxides, iron sulphides, carbonates and organic complexes. When interpreting Fe_2O_3 profiles in sediments it is important to consider both rate of supply which is controlled by environmental processes and preservation potential which is controlled by limnological conditions because authigenic forms of Fe in the lake are potentially labile. Fe has a low solubility under oxidising conditions but solubility is increased under reducing conditions. Usually it is only the uppermost few cm of sediment that is exposed to oxidising conditions in the lake. Below this oxygen is depleted due to microbial activity. Reduction of iron as it is buried may cause it to go into solution but subsequent upward migration of Fe may lead to increased values in the upper parts of the core which have no association with a change in the erosional history of the catchment.

10) A close association of iron and sulphur has often been linked with the initial stages of slash and burn agriculture within a lake catchment.

3.2.2.2. Analysis of charcoal content

The presence of charcoal in lake sediments has often been considered as an indicator of anthropogenic activity within a catchment area (Clarke, 1983). Forest clearance, by burning, is considered to have been a common practice of the Polynesian people

(M^c^Glone, 1983d, 1989; Southern, 1986), however, evidence also exists for the occurrence of natural fires (Latham, 1979) perhaps resulting from lightning strikes particularly during dry conditions. Charcoal 'peaks' are, therefore, only regarded as an indicator of human activity if they correspond to other lines of evidence such as the presence of cultivars in the fossil pollen record.

Independent charcoal analyses of sediments from the four main sediment cores were undertaken using nitric acid digestion of organic material, followed by heat extraction of remaining charcoal (after Winkler, 1985). 10ml concentrated HNO_3 was added to 0.5g of oven dried sample (A) in a large polypropylene centrifuge tube. The sample was lightly boiled in a water bath for 1hour, or until effervescence ceased. The test tubes were swirled around occasionally to include material that had collected on the sides. After the contents had cooled the sample was centrifuged and the supernatant decanted three times, or until the supernatant was clear. The remaining sediment was washed into a pre-weighed ceramic crucible and completely dried in an oven at approximately 90°C. After cooling in a desiccator the dry sample and crucible were re-weighed (B). The sample was then placed into a furnace, at 550°C for 3 hours, or until a constant weight was maintained. After the samples were cooled again in a desiccator, the weight was recorded (C) and the percentage of charcoal in the sample was calculated using the formula:

$$\% \text{ charcoal in sample} = \frac{B\text{-}C}{A} \times 100$$

The idea behind this method is that the nitric acid would burn off all organic matter which would otherwise be burned off in the furnace; the three hour furnace treatment then burns off the charcoal and nothing else, so this weight loss equals the weight of charcoal alone. It must be noted that the amount of charcoal (expressed as a % dry weight) may be influenced to some extent by the sedimentation rate and weight of any heavy inorganic material in the sample. This technique was undertaken on 12 samples from Lake Lanoto'o, 43 from Lake Roto, 45 from Lake Temae and 26 from Lake Vaihiria.

3.2.3. Biological investigations:

3.2.3.1. Palynology: The principles and problems

The principles and problems of pollen analysis have been comprehensively described in several publications including Godwin (1934), Erdtman (1943, 1963, 1969), West (1971), Faegri & Iversen (1989), Moore, Webb & Collinson (1991), Birks & Birks (1980), Lowe & Walker (1984) and will, therefore, be dealt with here only briefly.

Pollen analysis has been extremely widely applied since it was first used in stratigraphic studies by Lennart von Post at the start of the twentieth century (Faegri & Iversen, 1975), and remains one of the principal techniques used in the reconstruction of Quaternary environments for several reasons (Birks & Birks, 1980). Pollen is usually the most abundant fossil preserved in Quaternary sediments since only a small fraction of the many released pollen fulfil their natural reproductive function and the majority, therefore, fall to the ground. The exines of pollen grains are highly resistant to decay in non-oxidizing situations such as bogs, lakes, fens; and because they are abundantly produced by plants, they tend to be deposited universally as the 'pollen rain', and thus they have the chance of being preserved in many sedimentary situations. Atmospheric turbulence results in a more or less uniform pollen rain over an area. Consequently pollen can be counted, and the resulting pollen spectrum should represent statistically all the pollen grains in the sediment of that age at that place. The proportion of each pollen type is dependent on the number of parent plants and hence, the pollen rain is a function of the composition of the vegetation. Because vegetation is responsive to environmental factors, these factors can be deduced from a reconstruction of the past vegetation. The taxonomy of pollen grains is also relatively well known, and the major types are readily identifiable under the light microscope due to their unique shapes, sizes and exine patterns. Because pollen grains are small (5-100μm) and abundant, only small amounts of sediment are needed for an adequate sample. This contrasts with fossils such as molluscs, vertebrates and plant macro-fossils, where relatively large amounts of sediment are needed to provide an adequate sample of the fossil population.

The technique of pollen analysis, however, is not without its problems. These may occur throughout the processes of pollen production, dispersal, deposition and preservation and can result in (fossil) assemblages being significantly different in composition from the initial life assemblages. For example, different plants produce different quantities of pollen, and it is generally believed (Birks & Birks, 1980) that wind-pollinated species produce more pollen than insect-pollinated species, while flowers that do not open (cleistogamous species) have a very low pollen production. Entomophilous plants (i.e. insect-pollinated) often have highly ornamented pollen grains which tend to clump together, whereas anemophilous species (i.e. wind-pollinated) tend to have smooth, light, and round or winged pollen grains.

Pollen dispersal involves many pathways, notably via high- and low-level air-borne transport and via a water-borne route in runoff and streams (Tauber, 1965), and each pathway introduces its own selective bias into the dispersal process. High-level wind dispersal, for example, leads to a well-mixed pollen 'rain' with the pollen of some taxa being carried over long distances, notably the conifers (gymnosperms) whose pollen grains have sacs to help keep them air-borne (Roberts, 1989). Tauber (1965) also recognised several forest components that could be influenced by local factors such as wind velocitiy, convection turbulence, canopy density and catchment size. Once deposited in a lake basin, pollen can also be redistributed as a result of wind-turbulence or overturn when water temperatures are changing. Redeposition is perhaps most significant in the shallow environments typically found around lake margins (referred to in section 3.1.1). Pollen exines are known to be very resistant to decay, due to their high sporopollenin content, however, they can be easily corroded by biological or chemical oxidation in aerobic sediments, such as soils or dry lake beds. This in turn may lead to varied levels of preservation and even under-representation of the less resistant taxa. Spores are frequently more resistant to oxidation and corrosion than pollen grains and often form the predominant plant microfossil component of river bourne sediment. In such cases the fossil pollen/spore spectra may be the result of differential transportation or preservation (Taylor, pers. comm.).

Many of the problems associated with pollen representation and analysis can usually be avoided, or at least minimalised, by careful choice of sample sites. However, some problems are unavoidably inherent to the technique and must be taken into consideration during the interpretation of fossil assemblages.

3.2.3.1.1. **Preparation of fossil pollen and spore samples**

In order to concentrate the pollen and spores in a sediment sample and to remove as much of the sediment matrix as possible, the standard palynological preparation techniques of Faegri and Iversen (1975) were followed, along with 5μm ultrasonic sieving (Tomlinson, 1984). This allowed for the removal of fine clay-sized particles, thus facilitating the counting and identification of pollen grains and spores. These techniques are described in detail in Appendix 2, and were carried out on 14 samples from the Lake Lanoto'o core; 38 from Lake Roto; 42 from Lake Temae and 25 samples from Lake Vaihiria (sample levels are shown in the pollen diagrams of Figs.4.12, 5.11, 6.17 and 6.26). Pollen samples were also prepared from the sediment of Lake Rotonui (Miti'aro) but proved to be extremely poor in fossil content. This was mainly due to nature of the nekron mud which characterised most of this sequence. The acetolysis and oxidation treatment was unable to breakdown and remove the algal/bacterial material sufficiently to allow for the concentration of fossil pollen grains and spores. The volume of sample used for a further analysis was increased and a nitric acid treatment was also added but the concentration of pollen was still not sufficient for counting and the nekron 'emulsion' made the identification of the few visible grains near impossible. Palynology on this core was regretably abandoned. The nekron mud from Miti'aro could not be positively identified but a smear sample observed under the microscope showed the material to be filamentous in character which implied that it was some sort of algal-cyanobacterial association. Similar material was noted in the shallow brackish water lakes of Aunu'u island (American Samoa) as well as some levels of the Mo'orea core. Its proliferation may be related firstly to salinity and perhaps also to a high trophic status and warm shallow conditions.

The method of Benninghoff (1963) was also followed in order to determine the concentrations of pollen and spores in a sample. This involved the addition of a known quantity of an exotic taxon to the sample. In this case, two tablets containing 12,500±500 *Lycopodium* spores each (Batch No. 201890), were dissolved in distilled water and added to the sample before chemical preparation (Stockmarr, 1971). Grains of *Lycopodium clavatum* were then counted with the fossil pollen, and proportions of each in a weighed sample allowed for the calculation of the number of fossil grains per gram of sediment, using the following equation:

$$Pa = \frac{L \times Tp}{Tl} \times \frac{1}{wt.}$$

Where Pa = absolute number of grains per gram of sediment.

L = number of *L. clavatum* spores added to sample (i.e. 25,000±500).

Tp = total number of fossil pollen counted from the sample.

Tl = number of *L. clavatum* spores counted from the sample.

wt = Dry weight of sample before pollen preparation.

It is possible that *Lycopodium clavatum* may occur naturally in the fossil pollen samples from the Pacific as the species is known to occur there (Brown, 1935). However, the use of this spore as an exotic marker was not considered to pose a problem in calculation of absolute pollen because the added tablets contained pre-acetolysed spores. After a second acetolysis treatment during the pollen preparation, their exines became darkly stained and were easily distinguished from lighter grains that were only acetolysed once.

3.2.3.1.2. Identification and counting of pollen and spores

Pollen and spores were identified and counted using a Zeiss Photomicroscope at a magnification of x400, with a x25 objective, x10 eyepieces and x1.6 optovar magnification. Identifications were also made at x500 magnification, by increasing the optovar to x2, or under oil immersion using a x100 objective, achieving a total magnification of x2000. A Wild comparison eyepiece attached to a Meopta microscope enabled direct comparison of fossil and reference material. Traverses were made at 1mm intervals down the slide in order to avoid overlapping fields of view, and whole slides were counted to avoid non-random distribution of grains on the slide, since the lighter grains tend to be more mobile and migrate to the edges of the coverslips (Brookes & Thomas, 1967).

Pollen and spore taxa were determined mainly by comparison with modern reference material from the field collections previously mentioned, and from herbarium specimens held at the The Royal Botanic Herbarium (Kew), and British Museum (Natural History), London. Further identifications were made through personnel communications with Tropical/Pacific palynologists including Prof. J.R. Flenley (now of Palmerston North, New Zealand), Prof. D. Walker and Dr. G. Singh (Australian National University, Canberra), M. Bush (Duke University) and R. Morley (Robertsons Research).

A modification of the Benninghoff and Kapp (1962) notation was used to denote the level of identification of the pollen and spore taxa (indicated in the pollen diagrams). An absolutely positive identification of a fossil grain to genus or species should in practice involve thorough comparisons with all existing genera or species within a family or genus. However, in terms of availability of material and the time needed to study each taxa, this practice is often unrealistic. In this study, reference material has been restricted to genera and species that occur today in the Pacific/Australasian region and Antarctica. Since the oldest sediments studied do not exceed 10,000 years of age it is unlikely that any changes in the general floral composition of the Pacific region due to extinctions or major climatic variation would have occurred, and the likelihood of European, African and American species occurring in the Pacific before ~200 yr BP is small. With this in mind, if a genus is named on a pollen diagram without a suffix then the identification is reasonably certain within the confines of Oceania. In certain cases identifications to species level has been attempted, especially when species within a genera are known to have variable ecological preferences. In these cases reference material of the species most likely to occur, or have occurred, on a particular island group has been prepared for comparison with fossil pollen. Further comparisons with other available species known to occur in the Oceanic region will also have been made but not always to the same degree as the local species. Therefore, if a species has been identified with a degree of certainty, i.e. without a prefix, it usually means that the fossil species compares strongly with a species most likely to occur on that island group. In other words there has not been a diffinitive comparison with all known species within the genus in question. If a named taxon is followed by the suffix 'comp.' then the fossil pollen type is believed to compare favourably with the indicated taxa but cannot be conclusively assigned to it. If the named taxa is followed by 'sim.' then it is similar to the taxon indicated, but this is, or is suspected of being, representative of several indistinguishable taxa within a certain Pacific area. Pollen and spore characteristics of the important and identifiable fossil taxa have been described and included with the photomicrograph plates in Appendix 6.

Faegri and Iversen (1975) suggest that a minimum pollen count of 150 grains is required for analysis of samples from temperate areas. However, because of the greater diversity of species present in the tropics, a larger count is recommended, particularly if a representative count is to be obtained for those taxa recorded at low frequencies. Morley (1976) showed in a pollen trapping study in Malaysia that while common taxa were well represented with counts of 150 grains, the percentage of rare types did not stabilise until

300-500 grains had been counted. Similar conclusions were reached by Hamilton (1972) who suggested that 500 grains need to be counted to give accurate frequencies for rarer pollen types. Diversity of plant species in the islands of Polynesia are seen to decline quite rapidly with distance away from the source areas in south-east Asia and Australia. In view of this variable richness, counts of between 200 and 400 grains were made at each sample level depending on the taxa diversity. In samples with a high diversity of pollen and spore types the counts were continued above 400 grains and until no new types were identified in a further 25 consecutive counts.

3.2.3.1.3. **The fossil pollen diagram**

The pollen diagram is the conventional way of illustrating palynological results which are represented in this study in two forms: Firstly, as relative proportions of the different pollen and spore types, expressed as percentages of the total sum of pollen and spores, and secondly, as the concentration of pollen grains per gram of sediment. Total counts for some taxa can reach awkwardly high figures, and for ease of reference a square-root scale has been used. This also has the effect of reducing extreme peaks in the profile. Pollen and spores from obligate aquatic plants are also included in the percentage 'pollen sum' since they only form a small proportion of the total counts and consequently are unlikely to over represent local taxa. In the pollen sequence from Lake Vaihiria (Tahiti), counts of pteridophyte spores were exceptionally high and, in order to avoid obscuring trends in the spermatophyte profile, a second pollen sum (excluding pteridophytes) was also used.

The percentage profiles of individual taxa and ecological grouping of taxa provide information about the relative importance of individuals or ecological preferences within the plant community through time (if the sequence is dated); however, the advantage of pollen concentrations is that different taxa are independent of each other. Nevertheless, the value of pollen concentrations in a study of past vegetation are also limited since it cannot be assumed that changes in the levels of pollen expressed as grains/gram dry weight of sediment necessarily indicate changes in the density of the vegetation, or even the productivity/density of individual taxa. The density of vegetation may remain the same, but the amount of pollen deposited may vary as a result of changes in the pollen productivity of individual taxa (due to, for example, the onset of more amenable climatic conditions) or the replacement of existing taxa with less/more productive species. The levels of 'absolute' pollen are also partly a function of changes in the rate of sedimentation and sediment focussing, and not just a reflection of the amount of pollen produced by a population of plants (Taylor, pers. comm.). High resolution dating of sequences may eleviate the distortions imposed by variable sedimentation rates, but unfortunately not enough dates were obtained for the cores under study in this project to enable influx calculations.

3.2.3.1.4. **Identification of coconut pollen**

It seemed clear from the early stages of pollen counting that the palm, *Cocos nucifera* (coconut), was a particularly significant tree in the vegetation community of the Pacific islands under study. Archaeologists and botanists previously believed that the coconut was introduced by Polynesian voyagers migrating through the islands; this was mainly because no pre-Polynesian evidence had been found to the contrary. However, the presence of this species in the pollen records from Atiu and Mo'orea (this study), prior to recorded Polynesian arrival, greatly increased the importance of an accurate identification of this palm. The pollen of coconut is quite variable and needs to be distinguished carefully from other similar palm species. The higher magnifications of a Scanning Electron Microscope (SEM) were, therefore, used to compare fossil pollen from the Atiu core (the oldest record) with reference pollen of coconut collected from the nearby island of Mangaia and also with several other palms that have similar characteristics. This allowed more detailed comparisons of the exine pattern of grains to be made.

Preparation of material for the SEM followed techniques used for analysis by the light microscope (Appendix 2) but with the omission of alcohol dehydration and silicon oil mount. A small quantity of the prepared pollen sample was added to a circular cover slip and allowed to dry on a slide warmer. The cover slip and sample were then glued to an SEM stub and spatter-coated with gold. The sample was scanned and photographs were taken using a Nikon camera mounted onto the microscope. Fossil pollen preparations from depths of 8.40m and 12.05m, which contained grains identified under the light microscope as *Cocos nucifera*, were compared under the SEM with reference coconut pollen from Mangaia (see Appendix 6, Plate 15). Twenty fossil grains were compared with twenty reference grains and apart from the slightly greater size of the fresh reference pollen (which was expected), the grains were strongly comparable in shape, form and exine pattern. Other reference palms observed under the SEM included *Pritchardia vuylstekeana* (the only *Pritchardia* species found today in the central Pacific), *Pritchardia pacifica*, *Jubaea chiliensis* (the Chilean wine palm believed to have been growing on Easter Island before its extinction due to human over-exploitation or climate change) and *Livistona* spp. The descriptions of these and other monocolpate palm genera which were compared and distinguished from the fossil *Cocos nucifera* grains are included in Appendix 6).

The sizes of coconut grains in the fossil pollen record were seen to vary quite considerably, both within the same levels and throughout the core, and so a study calculating the average length and breadth of 25 reference grains was made to ensure that the fossil pollen fell within the size range. An average length of 49μm (in silicon oil mount) and average width of 32μm was calculated, with lengths ranging from 40-55μm, and widths from 20-42μm. All of the fossil grains identified under the light microscope fell within this range. The author is therefore confident that the identification of *Cocos* *nucifera* in the Lake Roto sediment core is accurate. It must be noted, however, that some palm morphologists (notably Hugh Harries of the International Coconut Cultivar registration Authority in Dar es Salaam) are slightly sceptical about the reliability of identifying 8600 year old coconut pollen and believe that only 'an educated guess can be made'. Collaborative work with the palynology Unit at Kew (with John Dransfield and Madeline Harley) is now in progress to address this question. Their initial reaction to the Light and Scanning Electron Micrographs of the grains in question was that the pollen does indeed have the characteristics of *Cocos nucifera*.

3.2.3.2. Diatom analysis in the sediment sequence of Lake Roto, Atiu

Diatoms are particularly useful palaeoecological indicators since they have distinct ecological tolerances and a substantial amount of autecological information is available. Diatom assemblages can frequently be divided into several specific habitats within a lake: pelagic or planktonic species float in the water, usually in the upper layer of the lake; epiphytic species grow attached to higher aquatic plants; epipelic species live on the surface of the mud; while epilithic species live on stones (Birks & Birks, 1980). In addition, lake sediments may contain representatives of two other habitats, streams and soil, which have been washed in by stream-flow or soil disturbance. Diatoms from each habitat are also sensitive to conditions of pH, water chemistry (Rawson, 1956), and salinity (e.g. Alhonen, 1971), to climate and to light intensity, which is itself related to water depth, turbulence, presence of other planktonic organisms and currents. The resistant silica shell (frustule), readily preserved in most lake sediments (except under extreme alkaline or acidic conditions), the uniquely sculptured valves which can be readily identified down to species level, and their abundance as fossils, make diatoms highly suitable for palaeoecological studies. Nevertheless, several difficulties are encountered in their use, and these have been adequately reviewed by palaeolimnologists such as Round (1964) and Bradbury (1975).

3.2.3.2.1. Preparation of diatom samples from Lake Roto

32 diatom samples from the Lake Roto sequence were prepared following Battarbee (1979). In order to determine whether the diatom content of Lake Roto was connected to silica concentrations, (shown in the sediment chemistry), a simple analysis of diatom concentration was also undertaken, which involved the removal of organic material from sediment samples, of known dry weight. To achieve this, hydrogen-peroxide was added to the sample, in a pyrex beaker, and heated on a hot plate until all organic material had been removed and effervescence ceased. The sample was then allowed to dry out completely, before 200 ml of distilled water was added and mixed thoroughly into a suspension. A micro-pipette was used to remove 100μl of the suspension which was placed onto a circular cover slip and dried naturally. The sample was then mounted in

Naphrax and allowed to cool until solid. Since the concentration of the sample in suspension was known and the area of the slide looked at under the light microscope could be calculated, an estimate of the number of diatom frustules per gram of sediment was made. Diatom identifications were made, mainly to genus level, with reference to standard floras. Relative frequency of diatom taxa as a percentage of all counted valves, and taxa concentrations in valves/g, are shown in Figs.5.15 and 5.16.

The diatom content of the Lake Vaihiria core was analysed by Michael Johnston using the methods of Mannion (1978) and Barber and Haworth (1981). Weighing of the samples enabled the diatom content to be expressed in absolute terms (i.e. valves/cm^3 of sediment) as well as a percentage of the total diatom count. A conversion from valves/cm^3 of sample to valves/g of sample (as calculated for Lake Roto samples) would have been preferable and would have eliminated any possible distortions due to variations in sediment compaction. Unfortunately the available figures did not allow for this conversion.

SEM techniques were used to help identify several diatom taxa present in the Lake Roto core. Sample suspensions were prepared (as above) and were plated onto cover slips and left to evaporate. The cover slips were glued to SEM stubs before being spatter-coated with gold.

3.2.3.3. **Identification of macro-remains**

Macro-remains were determined in order to provide further information about the lake environment and the origin of the sediments. Coarse sieving of sediment in preparation for pollen analysis (Appendix 2) isolated all material greater than 1mm from the main sample. These macro-remains included mollusc shells, coral fragments, seeds, fern sporangia and coarse volcanic-derived material. Mollusc shells and tubeworm cases were identified with the help of J. Taylor (British Museum of Natural History), while the volcanic-derived material was identified using a geochemical micro-probe at the University of Hull.

3.2.3.4. **Examination of clay laminations in the sediments of Lake Roto**

A closer examination of the fine clay laminations in the upper sediments of Lake Roto was undertaken using SEM techniques. This was simply done by glueing a dried thin section of the core, cut vertically, directly onto a stub and spatter-coating it with gold. This enabled a detailed examination of the laminations and Appendix 6, Plate 12 (1-4) and Plate13 (3) show photographs of the clay minerals and associated diatoms. The dominant clay mineral appeared to be chlorite (Plate 13), and the dominant diatoms were the centric diatom *Thallassiosira weissflogii*, *Diploneis smithii* and several species of *Nitzschia*.

3.3. Construction and dating of sedimentary zones

3.3.1. Stratigraphic zonation

In order to aid description, discussion and interpretation of the often complex geochemical, pollen and diatom diagrams, stratigraphic zones were constructed on the basis of similar geochemical or biological assemblages. The grouping of adjacent sediment samples of consistent character was undertaken by carrying out principal components analysis (pca) on the percentage data. Thus, the sediment sequence was divided into geozones or biozones of defined geochemical or fossil content. Some identified zones which consisted of only a single or a few sample levels within a larger zone, are referred to in the text as intra-zonal divisions (or sub-zones) and may, for instance, result from brief episodes of catchment disturbance within an generally stable period. The identified zones have a code which firstly identifies the Lake from which the core is derived (i.e. L-Lanoto'o; R-Roto; T-Temae; and V-Vaihiria) and secondly identifes the type of analyses undertaken (i.e. g-geochemical zone; p-pollen and spores; and d-diatoms). The number of the zone is denoted by Roman numerals beginning at the base of the core, whilst sub-zones are given lower-case letters.

Ordination by pca allows for the representation of the multidimentional data in a few dimensions by positioning each core sample depth (or biological and geochemical components) in relation to the principal components axes in such a way that the new distances reflect, as accurately as possible, the original distances or dissimilarities between the sample depths (or components). Multivariate analysis of the palynological and diatom data can often help to detect gradients of biological change that may ultimately reflect changing environmental conditions. It is a property of the principal components axes that they are selected along the major directions of variation within the data. Accounts of the complex mathematics involved in principal components analysis are presented by Jöreskog *et al.* (1974) and Seal (1964) and are not ventured into here.

The principal components analysis program in the Factor analysis/Stats-view package of the Apple Macintosh computer was run on nine percentage data sets (i.e. geochemistry, fossil pollen and spores and diatoms) from the four main sites. The XRF analysis of sediment from Lake Temae will, however, be used in the following worked example.

The raw percentage data table for this analysis (Fig.3.1) shows that 13 geochemical components were measured at 46 sample depths throughout the sequence. Correlations between the 13 components were calculated and a correlation matrix formed (Fig.3.2). This matrix showed that strong positive correlations existed between the basalt-oxides, for example Fe_2O_3 and K_2O (97%), TiO_2 and K_2O (98%), SiO_2 and K_2O (87%), and Fe_2O_3 and Al_2O_3 (99%). Conversely, strong negative correlations exist between the basalt-oxides and organic content (LOI), in particular SiO_2 and LOI (-95%), as well as the basalt-oxides and CaO content (SiO_2 versus CaO with -95% correlation). A graph of the unrotated orthogonal plots (Fig.3.3 derived from factor scores of unrotated solution in Fig.3.2C) displays the relative associations of the 13 components along two axes and emphasises these disimilarities. A pca was next performed on the resultant correlation matrix and the eigenvalues and eigenvectors (i.e. Factors) were extracted. A measure of the sampling adequacy was given and in all cases indicated that transformation of the data sets was not necessary. The no-transformation option was therefore used, which dramatically reduced the memory size needed for the calculations of the larger pollen/spore data sets. The analysis calculated the proportion of data variation (i.e. at individual sample depths) included in the first seven principal components (values 1-7 in Fig.3.2B) and invariably showed that the most significant variation occurred in the first two principal components. For example, Fig.3.2B shows that the first principal component of the Temae geochemical data contains ~73% of the variation, whilst the proportion of data variation in the second principal component is ~16%. Because of the high proportion of variation within the first two principal components it was possible to plot the first two pc axes (Factors 1 and 2 shown in Fig.3.4) against each other to accommodate 89% of the data variation on a single graph. This effectively plotted sample depths with similar compositional variation in both the first and second principal components together, whilst separating sample depths with disimilar compositions. 5 zones and 3 sub-zones were then subjectively selected from the resulting sample distribution (shown in Fig.3.5) which then formed the basic units for the Lake Temae geochemical sequence description and interpretation (in Chapter 6).

The pc distribution of the sample depths from the Temae geochemical sequence appeared to be strongly influenced by the variable content of basalt and calcareous material (zone TgI samples containing a high calcareous content and zone TgII samples with high basalt-oxide content). This variation was mainly accommodated in the first principal component (Factor 1) and when Factor 1 is plotted against sample depth, as shown in Fig.3.6A, there is a clear comparison with the profile of percentage basalt-oxides (Fig.6.16). The second principal component (Factor 2) appears to mainly account for the variation in the MgO content of the samples (as can be seen when comparing Fig.3.6B with the percentage profile for MgO in Fig.6.16). In the case of the Temae geochemical profile the principal components analysis appeared to verify the straigraphic description of the core. In the case of other cores, such as the Lake Roto core, similar analyses have been able to identify more subtle changes in the geochemistry which were not immediately obvious from the field and laboratory notes.

The pollen and spore percentage data for Lake Temae showed a very complex distribution of samples on the two principal components axes. Because of the low proportion of variance accommodated in the first two principal components it was difficult to distinguish clear zones from the complete data set (possibly due to the high number of taxa occurring at low percentages). A reduced set of selected taxa was therefore analysed which excluded ruderal species that only occurred in the sediments above 3.07m and that were considered significantly relevent to warrant their own separate zone (i.e. TpV and TpVI, in Fig.3.7 key to sample depths). Taxa that formed ≤1% of the total counts throughout the sequence were also excluded. The pca identified several distinct zones (Fig.3.7A) within this second data set but there were still many 'outlier' samples not accounted for. Further sub-sets were constructed in order to identify any additional units of consistent assemblage. The first included only arboreal and arboreal/shrubs (Fig.3.7B) and the second included only shrubs, herbs and pteridophytes (Fig.3.7C). Six zones were eventually recognised along with four sub-zones, one of which was the sand layer at 4.56m that contained no pollen.

The pca of the percentage geochemical data from Lake Roto excluded the data from sample depth 4.95m because its composition was clearly distinct from the rest of the core (shown in Fig.5.10) and was already recognised as a separate unit (Sub-zone RgVa). The exclusion of this sample enabled the more subtle changes in the stratigraphic sequence to be detected which would have othewise been masked by the strong variation signal from the sample. As with the Lake Temae sequence, the correlation matrix (Fig.3.8) of geochemical variables shows that strong positive correlations existed between the basalt-oxides (with the notable exception of Fe_2O_3). SiO_2 and K_2O showed 80% correlation, TiO_2 and Al_2O_3 97%, SiO_2 and TiO_2 80%, and an 85% correlation exists between SiO_2 and Al_2O_3. Conversely, SiO_2 and organic content (L600), and TiO_2 and SO_3 are shown to be negatively correlated (i.e. -90% and -84% respectively). No correlations appear to exist with Fe_2O_3, MgO, MnO and CaO. Factor 1 accounted for 46% of the variance in the geochemical data whilst Factor 2 accommodated 19% (i.e. 65% in total). These first two principal components axes are plotted in Fig.3.9 and show the distribution of samples within the seven recognised zones and two sub-zones (including level *4.95m which was excluded from the analysis). The presence of the basalt-oxides appears to account for most of the variation and can be clearly seen when comparing Factor 1 plotted against depth (Fig.3.10A) with the percentage profiles shown in Fig.5.10. The variation in Factor 2 is less obvious (Fig.3.10B) but appears to be influenced by a combination of the varying Fe_2O_3 and organic content.

The pca of percentage pollen and spore data from Lake Roto is shown in Fig.3.11. European taxa which only occurred in the top two levels of the core were excluded from the analysis and were designated a separate zone (Zone RpVII). This omission reduced the distortion of the rest of the data, resulting from the strong variation signal from the European taxa. Taxa accounting for ≤1% of the total counts were also excluded from the PC data set. Seven pollen zones and one sub-zone were identified. The correlation matrix resulting from the analysis is shown in Fig.3.12.

The pca of percentage diatom data from Lake Roto is shown in Fig.3.13 and seven zones and one sub-zone were identified. Diatom taxa accounting for ≤1% of the total counts were excluded from the pc data set. The correlation matrix resulting from the analysis is shown in Fig.3.14.

Pca was also attempted on a data set which combined 78 major components of the geochemical, pollen and diatom data, as well as magnetic susceptibility readings from the Lake Roto core. Although the first two resultant factors of this analysis only accounted for 40% of the proportion of original variance (24% and 16% respectively) and no clearly distinct units were identified, the display of the unrotated orthogonal plot did show some interesting groupings (Fig.3.15). Components 1-28 appeared to be associated with a group reflecting high salinity levels within the system. This group included oxides of sodium, the salt-tolerant *Achrostichum aureum* and the resting spores of *Chaetoceros* sp. The environmental influence on the grouping of components 29-43 are not so clear but this group does contain several pollen taxa e.g. *Weinmannia rarotongensis* and *Glochidion* sp., which are associated with less disturbed forest-type vegetation. Components associated with catchment disturbance (Nos. 42-48), on the other hand, such as the dominant presence of basalt-oxides, high magnetic susceptibility and the sedge *Cyperus pennatus* were also grouped together by the analysis. The last two groups appear to be dominated by components associated with human contact and disturbance i.e. components 49-60 are possibly associated with the Polynesian contact period and includes the sweet potato (a known Polynesian introduction), whilst components 61-78 are possibly influenced by European contact and include introduced weeds such as *Ageratum conyzoides*, *Sida rhombifolia* and *Elephantopus mollis*. The correlation matrix of the 78 components is shown if Fig.3.16.

The data set used in the analysis of the geochemical data from Lake Vaihiria excluded sample depths 4.45m and 1.05m. The high CaO content of the former and high MnO and MgO component of the latter sample strongly distorted the rest of the geochemical data (as shown in Fig.3.17A) along the x-axis. The two depths were designated the separate sub-zones VgIb and VgIIIc respectively. The exclusion of these samples resulted in a slightly clearer distribution of the remaining samples (Fig.3.17B) and an attempt at zonation was undertaken. The gradation of samples levels 14-16 from basalt-rich through to organic rich sediments resulted in Zone II being a weakly linked unit. The correlation matrix (Fig.3.18) and unrotated orthogonal plot (Fig.3.19) (both formed from 26 geochemical sample levels) shows that although positive correlations exist between the basalt-oxides the relationships are relatively complex. Na_2O and CaO show an 80% correlation with each other and are also strongly linked with the TiO_2 and Al_2O_3 component. SiO_2 on the other hand has closer associations with K_2O, MgO, MnO and Fe_2O_3. As with the other island cores the organic content shows strong negative correlations with all the basalt oxides, but appears to be more closely associated with SO_3

and P_2O_5. The factor controlling the main variation in the data is not obvious, but appears to result from the complex interaction of the two basalt groupings and organic content. The widescale variation in the geochemistry throughout the Vaihiria profile is reflected in the large number of sub-zones identifed (eight in total) within three main zones (a rather vein attempt to display the relative positions of these zones and sub-zones is made in Fig.6.24 and described in Chapter 6).

The original Lake Vaihiria data set used for the analysis of the pollen excluded any taxa which accounted for ≤1% of the total pollen and spore assemblage. All sample levels were included and the resultant axis of variance is shown in Fig.3.20. The proportion of variance accounted for in Factor 1 was only 24% and 13% in Factor 2, nevertheless, three zones and and four sub-zones were identified. A similar restriction on taxa accounting for ≤1% of the total was imposed in the diatom data set and the three zones and two sub-zones are shown in Fig.3.21.

The pca of the percentage geochemical data from Lake Lanoto'o included data from all sample depths. The correlation matrix (Fig.3.22) of geochemical variables shows that strong positive correlations existed between most of the basalt-oxides. Conversely, the basalt-oxides are negatively correlated with organic content (L600). There is a notable strong correlation between CaO and Na_2O which will be discussed in the following chapter. These first two principal components accounted for 60% of the data variance and are plotted against each other in Fig.3.23. Four geozones and two sub-zones were identified and appear to be distinguished mainly by the variation in basalt-oxide versus organic content.

Five zones were recognised within the pollen and spore sequence from Lake Lanoto'o (Fig.3.24) although the distribution of samples within the pc axes did not always fit into particularly tight groupings and zonal boundaries were perhaps more prone to subjectivity. The zonal units do, nevertheless, provide a basis on which to describe the core sequence. The correlation matrix resulting from this pca is shown in Fig.3.25.

The dating of the zonation boundaries identified in this section is based on a series of radiocarbon dates and estimated age-depth profiles which are described in the following section (and shown in Figs.3.26 to 3.29) and incorporated into the discussion of individual core sequences (Chapters 4-6). The accuracy of the age-depth profiles, and the subsequent age-determination of the zones, inevitably depend on the total number of radiocarbon dates obtained for a sequence, the potential for contamination and the period of time that these dates cover. The single date obtained from the Tahiti (VHA) core, therefore, provides very little basis for age-determination of zone boundaries and any interpretation must inevitably include a high degree of inaccuracy. On the other hand, the 8 radiocarbon dates obtained for the Lake Roto sequence allows for a far more accurate determination of the zonal divisions. In the following chapters any estimated date (i.e.

extrapolated or interpolated from the age-depth profiles) for the zonal boundaries or specific single events will be suffixed by 'estd.'

3.3.2. **Chronology of the sediment cores**

Chronology and correlation between the separate lake sediment cores were achieved by radiometric dating. A series of 17 sediment samples (detailed in Appendix 4) were extracted from the lake cores under study and radiocarbon dated by conventional methods at the NERC Radiocarbon Laboratory at East Kilbride. One AMS date from the Lake Roto sequence, at a depth of 3.53-3.52m, was undertaken with the kind support of M. M^{c}Glone and A. Anderson (DSIR Land Resources, NZ.). The length of core extracted for dating ranged from 4.0cm to 20cm, the size being determined mainly by the amount of datable carbon available in the sediment (also shown in Appendix 4). At the laboratory samples were pre-treated with 0.5M HCl to remove any old carbonate material, which might otherwise have contaminated the date. The three organic-rich samples extracted from the 3m Lake Lanoto'o core (which appeared to have been deposited relatively slowly) were kept to a minimum size in order to achieve the best resolution of dates. However, because of the low amount of datable carbon in the top two samples a known percentage of geologically old (carbonate) carbon was added to prepare sufficient benzene for radiometric dating. This method was recorded as having no adverse effect on the dates (D. Harkness, pers. comm.). Stable isotope enrichment values (δ^{13}C), which can indirectly indicate how much biogenic material is present in a sediment (S. Metcalfe, pers. comm.), were determined using the independent 'semi-micro' method and are also listed in Appendix 4.

The reported sample ages were calculated in conventional ^{14}C years before present (yr BP) followed by an error function representing one standard deviation about the mean (+1$^{\emptyset}$). In practice, the present is taken as AD 1950 in order to prevent dates appearing to be older simply because they were analysed more recently. The calculation of conventional ^{14}C years assumes that the specific activity of ^{14}C in atmospheric CO$_2$ has been constant, and this is known to be untrue. The ^{14}C activity in the atmosphere and other reservoirs, and thus the initial activity of the samples dated, has varied over time (eg. Stuiver, Pearson, & Braziunas, 1986), and a calibration curve is necessary to convert radiocarbon ages into calibrated years before present (cal. yr BP) and calibrated calendar years (BC/AD). By measuring the radiocarbon age of tree rings of known age it is possible to construct calibration curves for the last 9200 years for samples in equilibrium with atmospheric CO$_2$. The conventional dates of this study have, therefore, been corrected for secular variations using the 'Quaternary isotope lab radiocarbon calibration program 1987, Rev. 2.0, University of Washington' based on the technique of Stuiver and Pearson (1986). The oldest sample from the Lake Lanoto'o sequence was, however, not corrected since the date of 8920±80 yr BP was near the limit of the calibration curve.

Results and initial discussions in this thesis will follow the convention of quoting uncalibrated dates, expressed in yr BP. In the concluding sections, however, when reference is made to previous archaeological chronologies which invariably use the calendar system, dates are expressed in calibrated calendar years BC or AD for ease of comparison. All uncalibrated and calibrated dates are included in Appendix 4 for cross reference of these dating systems. Whilst constructing the age-depth profiles for Lanoto'o, Roto, Temae and Vaihiria, it has been assumed that overlying sediments are younger than the underlying sediments, in the absence of any evidence for sediment disturbance or reworking and that the top of the section is assumed to be present day. The steepness of the profile from the Miti'aro sequence suggest, however, that some of the uppermost sediments may have been removed (section 3.3.2.5).

3.3.2.1. Lake Lanoto'o age-depth profile

The three radiocarbon dated sediment samples from the Lanoto'o core (at 2.90-2.80m, 1.62-1.58m, and 0.94-0.88m; Appendix 4 and Fig.3.26) occur in chronological sequence. The two uppermost dates (2425±70 yr BP/SRR-3716 and 3575±65 yr BP/SRR-3086) however, suggest that the sedimentation rate in the top 2m of the core was significantly faster than the lower metre, implied by the basal date of 8920±80 yr BP (SRR-3085). An in-wash of clay material detected in the top two metres perhaps explains this higher rate, while the apparent lack of in-washed clays below 2.50m implies that the accumulation of the organic gyttja was more gradual, and perhaps occurred during a period of catchment stability. The three stable isotope enrichment values measured from the three dated samples (-23.7/SRR-3716, -23.8/SRR-3717 and -24.6/SRR-3086) are all similar and provide no further information on ratios of authogenic and allogenic material. Several more dates would ideally be required in this slowly accumulated sequence; however, these three dates do provide a general chronological framework from which to interpret the stratigraphic information.

3.3.2.2. Lake Roto age-depth profile

The eight radiocarbon dates detailed in Appendix 4 (and shown in Figs.5.10 and 5.11-insert) show that the Lake Roto sediment sequence extends from before 7820±70 yr BP to the present. This sequence, therefore, spans the range of dates estimated for Polynesian arrival to the Southern Cook Islands, i.e. from 969±83 yr BP in Aitutaki (Bellwood, 1978) to ~1600 yr BP in Mangaia (Lamont, unpublished; Steadman & Kirch, 1990). Apart from two exceptions (SRR-3714 and SRR-3283) the radiocarbon dates appear to be in correct sequence. The sample collected from 5.32-5.52m and dated at 3380±70 yr BP (SRR-3714) unfortunately coincided with levels rich in mineral slope material which may well explain the discrepancy of several hundred years with the 3100±150 yr BP date from level 6.50-6.55m (SRR-3283). Because of this possible contamination, the SRR-3714 date has been excluded from the age-depth profile drawn in red (Fig.3.27 and Fig.5.8). The Lake Roto sequence (red-line) shows that sedimentation rates between 13.98m and 10.30m (approx. 0.33cm/yr), and in the upper 3.50m of the core (averaging 0.25cm/yr) are generally higher than average rates in the central core section, i.e. from 10.30m to 3.50m (0.13cm/year). These two zones of 'accelerated' accumulation coincide with material high in magnetic minerals, in-washed clay bands, and (as described later in the geochemistry section 5.8.2) sediment rich in basalt-derived oxides such as iron, aluminium, titanium and silica. The highest rate of accumulation throughout the core, i.e. 0.88cm/yr, occurs between 2.90m and 1.58m, again corresponding to the major clay horizons shown in the stratigraphy (see Fig.5.10 and 5.11-insert).

Due to the insufficient organic content of the sediments below 14m, the lower 2.5m section of this core is not dated and can only be tentatively estimated from the projection of the other seven dates. Using the average sedimentation rate of the upper 14m of the core, i.e. 0.18cm/yr, the estimated date of the sediment at the base of the core is ~9000 yr BP. However, since the lower material is significantly different in composition from the dated sediments above this extrapolated estimate may be very inaccurate.

3.3.2.3. **Lake Temae age-depth profile**

Only two radiocarbon dates (shown in Appendix 4) were obtained from the Lake Temae sediment sequence which, nevertheless suggest that very rapid sedimentation had occurred in the lake basin, particularly in the lower sections of the core. A radiocarbon date of 1540±100 yr BP (SRR-3288) was recorded at 11.50m, while a radiocarbon date of 1210±90 yr BP (SRR-3088), was measured at a core depth of 6.85m. Using the average ^{14}C years this indicates that a rapid accumulation rate of ~1.4cm/yr, occurred between 11.50m and 6.85m, while a slower sedimentation rate of 0.57cm/yr occurred from 6.85m to the top of the core.

No radiocarbon date was obtained from the lowest levels of the Temae core since there was very little datable carbon available in the calcareous muds below 11.50m. However, by taking the average rate of sedimentation of the calcareous mud recorded between 11.50 and 6.85m (i.e. 1.4cm/year) an extrapolated date of approximately 1750 yr BP was estimated for the base of the core at 14.50m. One must recognise the potential inaccuracy of this estimated date when considering further interpretations. This sequence, nevertheless, is believed to pre-date the time of Polynesian arrival in the Society Islands (i.e. ~1100 yr BP) as suggested by a great proportion of the archaeological data from the island (described in Chapter 2). The sediment record should, therefore, give insight into pre-settlement environments as well as changes related to human settlement once the population had reached detectable levels. The average sedimentation rate between 11.50 and 6.85m was used in the estimated basal date (as opposed to the average rate from the whole core above 11.50m) because of the consistent nature of the sediment below 7m i.e. calcareous mud.

3.3.2.4. Lake Vaihiria age-depth profile

Although the two cores (VHA and VHB) extracted from Lake Vaihiria have comparable stratigraphic records, the two radiocarbon dates (Fig.3.29) from their basal sediments appear to conflict with each other. Core VHB had a radiocarbon date of 540±90 yr BP (Beta-10100) at a depth of 5.05-5.14m, while core VHA (analysed in this study) had a radiocarbon date of 1290±120 BP (SRR-2552) at a depth of 4.65-4.75m. A second date from the VHB core, at a depth of 2.46-2.50m, was measured at 320±200 BP (GX-10697). This difference between the two cores casts some doubt on the accuracy of the VHA date which contained a high percentage of in-washed mineral material that may have introduced some old carbon into the sample (Harkness, pers. comm.; Pennington *et al.*, 1976; Nambudiri *et al.*, 1980). Since there was such a strong similarity between the two core stratigraphies it was decided that the two dates from core VHB could be related with caution to the VHA sequence, although the alternative profile which accounts for the 1290±120 BP date is also shown in Fig.3.29 for comparison. It must be noted that the range of significance for the 320±200 BP date appears to be extremely large; nevertheless, a date ~300 BP does comply with the sedimentation rate inferred from the lower date, and in the absence of a more complete radiocarbon sequence will be used to provide a very tentative chronology for this sequence.

The two available VHB dates indicate that the rate of sedimentation was slightly greater in the lower 2.5m of sediment, averaging 1.20cm/year, while the upper 2.5m averaged a rate of 0.78cm/year. These are particularly high rates of sedimentation, although not unreasonable given the climate and topography of this watershed. A potentially inaccurate estimated date of 530 yr BP from the lowermost sediments of the VHA core (derived from VHB dates) suggests that the entire record lies within the post-settlement period on Tahiti. It is expected, therefore, that both human and natural influences could have played important parts throughout this sequence. It must be reiterated that the chronology of this short sequence is very unsatisfactory.

3.3.2.5. Lake Rotonui age-depth profile

Four radiocarbon dates were determined from the 7.25m core collected from Lake Rotonui, Miti'aro. The two lower dates (SRR-3085/7.22-7.12m = 6970±70 yr BP; SRR-3287/6.90-6.85m = 6170±120 yr BP) were determined from sediments rich in lake mud and peat and implied that deposition was relatively slow. The two upper dates (SRR-3286/5.55-5.45m = 5340±110 yr BP; SRR-3285/2.60-2.50m = 4380±100 yr BP) were derived from highly organic nekron mud samples and strongly suggest that there was an increase in the sedimentation rate during this time. Although the four radiocarbon determinations occur in chronological sequence the extrapolated profile from the upper most date (at 2.55m) to the origin is rather steep and implies that the sedimentation rate was considerably reduced in the upper unit of the core. An alternative extrapolated profile from the four dated samples (red-lined) could imply that the top sediments had somehow been removed. This suggestion is investigated further in section 5.8.3.3.

4. STRATIGRAPHIC STUDIES FROM LAKE LANOTO'O, UPOLU, WESTERN SAMOA

4.1. Location and physiography of the island of Upolu, Western Samoa

The island of Upolu (Fig.4.1) belongs to the territory of Western Samoa, along with the island of Savai'i and six small adjacent islets. The two main islands, plus Apolima and Manono, are populated, whilst the four islets off south-east Upolu shelter only seabirds. The territory lies between longitude 171° 20' and 172° 50' W and latitude 14° 10' and 13° 20' S and is approximately 840km east of Fiji and 2400km north-north-east of New Zealand (Kear & Wood, 1959). Western Samoa occupies the western portion of the Samoan archipelago (Fig.4.1), the other main islands being in American (Eastern) Samoa. The Samoan archipelago is volcanic in origin, with eruptions occurring as recently as 1911 in Savai'i (Whistler, 1983b) and form an irregular line from northwest to southeast, following the trend of most of the archipelagos of the Pacific Ocean. Unlike the other archipelagos, however, the youngest volcanoes are at the west end, and the only atoll (Rose atoll) is at the east end. Upolu, the most developed and populous island of Western Samoa, contains the capital, Apia. The island is narrowly elliptical in outline, approximately 75.5km by 25.7km, with an area of 1110 km^2. A rugged chain of volcanic cones forms a crestal ridge which rises to a maximum height of 1200m (shown in Figs.4.1 and 4.2). This spine of extinct shield volcanoes slopes more steeply on the south than the north. The eastern part of the island is rough and broken, while broad plains are characteristic of the western region.

4.2. Outline of geology and soils of Upolu

The predominantly basaltic rocks of Upolu have been ejected from a great number of volcanic cones throughout much of the upper Quaternary period. Kear and Wood (1959) divided the volcanic rocks of Western Samoa into six formations based on age. The distribution of these formations on Upolu are shown in Fig.4.2. They also recognised a series of marine tuffs, and three sedimentary formations which are generally confined to the outer islands and coastal areas respectively. The oldest rocks, the Fagaloa Volcanics, occur most plentifully in the north-eastern district and the central mountains of Upolu and to a lesser extent in south-western Upolu. According to Kear and Wood (1959) they consist of basaltic lava flows which are either non-porphyritic or contain phenochrysts of olivine, augite and feldspar, with associated dykes, tuffs and cone deposits. They characteristically form steep-sided high mountains with slopes of 25° to 50° similar to the older volcanic rocks in Rarotonga and Tahiti. Rocks of the four most widely distributed volcanic groups, (Salani, Mulifanua, Lefaga and Puapua) rest unconformably on, and fill valleys eroded in, the Fagaloa rocks. Petrographically they strongly resemble one another, being mainly olivine basalts; however, they differ in the extent of weathering and thickness of overlying soil. Salani volcanics have characteristically deeply weathered soils, while the Puapua volcanics maintain only thin soils. The general structure of Upolu, therefore, is that of a deeply eroded Pliocene or early Pleistocene volcanic terrain, flanked and largely buried by late Pleistocene and Recent lavas.

The soils of Western Samoa were briefly described by Hamilton and Grange (in Kear & Wood, 1959), and have been mapped in detail by A.C.S. Wright (1963), of the New Zealand Soil Bureau, who supplied Kear and Wood (1959) with some of the following comments. Soils are predominantly stony latosols of varying fertility, but most have a good structure and sub-soils are not usually compact. The deepest sedentary soils are found over the Fagaloa Volcanics, while soils on recent lava flows are sparse but very fertile. The factor most likely to affect agriculture on these soils is deficiency of potash and/or potassium, however, they do have unusually high amounts of titanium-oxide (7.8 to 12.6%). The soils along the coasts and in valleys are mostly alluvial and are often composed of calcareous sand, silt, and even coral rubble (Whistler, 1980b).

4.3. The general climate of Upolu

The climate of Western Samoa is tropical and strongly influenced by the proximity with the Intertropical Convergence Zone (referred to in Chapter 1). Two distinct seasons occur; a wet summer, with winds varying from west to north (November to April); and a drier winter with cooling southeast trade winds (May to October) (Kear & Wood, 1959; Whistler, 1983b; Stanley, 1989). Because of its maritime situation temperature ranges, both daily and seasonal, are slight, with the mean daily temperature remaining at about 26.6°C, and rarely falling below 15°C. Over the last 65 years the average maximum temperature at Apia has been 29.4°C, average annual precipitation 2800mm, and the average yearly relative humidity 83.6%. On the island of Upolu the southern region (windward) tends to get more rain than the northern region (leeward); for example the village of Lotofaga on the southeast coast receives an annual precipitation of 4000mm, whilst Mulifanua on the northwest coast receives 2200mm. Nevertheless, no area receives less than 2000mm rainfall a year, which limits the severity of the 'dry' season. This is largely due to the east-west alignment of the mountains reducing the rainshadow effect. The wettest period is from December to March, when tropical storms often cause heavy downpours and flooding. Samoa lies within the hurricane belt of the southern Pacific, and tropical storms periodically hit the islands with devastating results (Wood, 1970; Whistler, 1992). Another important factor affecting rainfall is elevation. Although specific data on rainfall are lacking, Angenheister (in Wright, 1963) suggested that there was an increase in rainfall of as much as 21-29% for every increase of 100m in elevation.

4.4. The present vegetation of Upolu

The flora of Samoa is regarded as being more closely related to that of Fiji and Tonga to the west, than it is to that of Rarotonga and Tahiti to the east (Whistler, 1980b), with the majority of the Samoan species having Indo-Malesian (Malay) affinities. Due to the filter effect, there is a gradual decrease in the number of genera and species eastwards across the Pacific from southeastern Asia, and a number of Indo-Malesian taxa reach their easternmost extent in Fiji and Samoa (Smith, 1955).

Until the last few years the most significant work on the vegetation of Samoa was probably that undertaken by K. Rechinger (1907-1915), who spent up to six months on the islands and provided the first comprehensive discussion of Samoan vegetation. E. Christophersen collected extensively on Upolu and Tutuila in 1929 and 1931, and his detailed list of collections (Christophersen, 1935, 1938) remained the most complete list of Samoan plants published until recent collections by A. Whistler (1978, 1980b, 1983b). On the basis of his collections, and quantitative analyses, Whistler (1980b) divided the Samoan vegetation into sixteen climax communities and four disturbed communities. The climax communities are grouped into four categories based on general habitat characteristics: littoral, wetland, rainforest, and scrubby summit vegetation. Disturbed communities recognised by Whistler were managed lands, *Kula* (*Gleichenia/Dicranopteris*) fernland, disturbed forest, and *Rhus* secondary forest.

The littoral vegetation of Samoa, similar to that found on many other southern Pacific islands, has been divided on the basis of varying sub-stratum and degree of marine exposure (Whistler, 1980b). The narrow zone of herbaceous vegetation on the rocky shores, dominated by sedges, grasses, succulents, and creepers, is called the *Lepturus* rock strand. Characteristic species of this community are the grass *Lepturus repens* and the sedge *Fimbristylis cymosa*. The *Ipomoea* sand strand is a creeper-dominated herbaceous vegetation occurring on sandy shores, and characterised by the presence of *Ipomoea pes-caprae*, *Vigna marina*, and *Canavalia maritima*. Elsewhere in the Pacific this community is commonly referred to as the '*pes-caprae* formation' (van Steenis, 1961). The littoral shrubland (referred to as the *Scaevola* scrub by Stoddart, 1975b) is a shrub dominated vegetation on rocky or sandy shores, with *Scaevola taccada*, *Wedelia biflora* and *Desmodium umbellatum* forming the main components. The scrubby forest vegetation occurring in a narrow zone along the shore and dominated entirely by *Pandanus tectorius* is referred to by Whistler (1980b) as the *Pandanus* littoral scrub. A similar formation, 'the *Pandanus* woodland,' was noted by Stoddart (1975b) on Aitutaki. A mixed littoral forest, not dominated by any particular tree species, occurs in a narrow zone along the shore, with tree species including *Barringtonia asiatica*, *Pisonia grandis*, *Hernandia nymphaeifolia* and *Hibiscus tiliaceus*. A *Pisonia* littoral forest and a *Barringtonia* littoral forest also occur when either *Pisonia grandis* or *Barringtonia asiatica* dominate over the other tree species.

The two wetland communities recognised on Samoa by Whistler (1980b) are the coastal marsh community and the mangrove forest community. The coastal marsh is a herbaceous wetland vegetation occurring in flat, low-lying coastal areas where soils are saturated with slightly brackish to fresh water. Undisturbed marshes are usually dominated by the fern *Cyclosorus interruptus* and the sedge *Eleocharis dulcis*, along with the swamp fern *Acrostichum aureum*; however, under disturbed conditions *Ludwigia octovalvis* and *Rhynchospora corymbosa* become abundant. This community is also found growing along the margins of crater lakes of Upolu at 700-1000m elevation (Ollier *et al.*, 1979). The mangrove forest community occurs most frequently along coasts protected by reefs or offshore islands. It is common on mudflats, along estuaries, and in sheltered lagoons where sedimentation is occurring. The arboreal component is dominated by the salt-tolerant *Bruguiera gymnorhiza* and *Rhizophora samoensis*, whilst ground cover species include the salt-tolerant *Acrostichum aureum* and the grass *Paspalum distichum*. American Samoa marks the easternmost extension of the natural mangrove community in the Pacific, although some biogeographers believe that mangroves have had a wider distribution across the Pacific in the past (Woodroffe, 1991; Ellison, 1991).

The rainforest vegetation is considered by Whistler (1980b) to be the natural forest of Samoa extending from the edges of the mangrove and littoral forests up to, and including, the high-altitude forests. Rainforest is believed to have originally covered the majority of the land area on Samoa, but after centuries of human activity forest areas have been greatly reduced with the only remaining undisturbed forest existing on inaccessible or rugged terrain. Whistler (1980b) divided the rainforests of Samoa into six communities (of which five occur in W. Samoa) based primarily on differences in floristic composition, which in turn are related to variations in rainfall and temperature (both dependent on elevation), edaphic factors, and topography. The communities are referred to by the name of the dominant species, followed by a descriptive topographic word. The *Diospyros* spp.-*Syzygium* spp. coastal forest, is an undisturbed low-stature forest of coastal areas which covers a narrow zone between the littoral forests on the shore and the lowland forests of the interior. It differs from the littoral forest by being dominated primarily by trees with seeds not dispersed by seawater including *Diospyros samoensis*, *Diospyros elliptica*, *Syzygium clusiifolium*, and *Syzygium dealatum*. The *Syzygium inophylloides* ridge forest is the natural forest found on foothills and inland ridges, while the *Dysoxylum samoense* lowland forest is that part of the rainforest covering the flat to moderately sloping lowlands, particularly on deep alluvial soils of coastal valleys. This forest is then replaced by the *Dysoxylum huntii* montane forest at higher elevations after a broad transition zone.

The *Dysoxylum huntii* montane forest which occurs above 1000m on Upolu is the most extensive undisturbed type of vegetation remaining in Western Samoa and has been alternatively referred to as 'upper montane rainforest, and fern forest' by Rechinger (1907-1915), and 'primary high forest of uplands' by Wright (1963). On Upolu this forest is dominated by *Dysoxylum huntii*; however, other important canopy trees include *Myristica hypargyraea*, *Syzygium samoense*, *Canarium samoense*, *Canthium merrillii*, *Calophyllum samoense*, *Palaquium stehlinii* and *Polyscias samoensis*. Compared to the lowland forests the montane forest floor is less exposed due partly to the higher density of trees, and partly to the greater ground cover. Common ground ferns include *Lomagramma cordipinna*, *Polypodium samoense*, *Nephrolepis biserrata*, and *Asplenium nidus* (on the ridges). Also present are *Angiopteris evecta* with spreading fronds up to 4m or more, and tree ferns (*Cyathea* spp.) ranging from ground cover up to 'trees' 10m in height. *Cyathea* spp. are particularly common in secondary or disturbed montane forests of Samoa. Climbing plants include *Piper graeffei* and *Freycinetia* spp., while common epiphytic ferns include *Lomagramma* and *Antrophyum alatum* with *Procris pedunculata*, of the Urticaceae family, also frequently found as an epiphyte. The climate of this community is both wetter and cooler than that of the lowland forests below, with mean temperatures probably 2-4°C cooler than at sea level. The soil is usually moist all year round and drought conditions are rare. These factors, along with a constantly high humidity, contribute to the profusion of ground cover and epiphytic species, particularly mosses and ferns.

In Western Samoa a *Pometia pinnata* lowland forest occurs on recent lava flows of the lowlands and middle slopes. However, the high altitude cloud forest, recognised by Whistler (Whistler, 1980b) in Eastern Samoa and containing several subtropical 'austral species' (e.g. of the genera *Ascarina* and *Weinmannia*), is believed to be absent from the western islands. A montane scrub vegetation, noted on the poorer soils of the weathered trachyte plugs of Tutuila, and dominated by *Pandanus reineckei*, *Rapanea myricifolia*, and *Syzygium brevifolium*, is believed also to occur on some summit areas of eastern Upolu (Whistler, 1980b) but has not been readily recognised.

Four disturbed vegetation communities, influenced by both past and present human activity, are recognised by Whistler. Vegetation actively maintained by current human activities (managed land), such as plantation agriculture, shifting agriculture and grazing, are concentrated mainly in the coastal regions of Western Samoa. Disturbed (secondary) forest, i.e. woody vegetation no longer under the influence of human management but still changing in structure and species composition, is found from disturbed littoral forests all the way up into storm damaged summit forests. These secondary forests have no typical floristic composition, and vary according to the original forest composition. Several species are, however, generally associated with the secondary forests of Samoa and include: canopy trees such as *Rhus taitensis*, *Neonauclea forsteri* and *Macaranga stipulosa*; subcanopy trees such as *Hibiscus tiliaceus*, *Cananga odorata*, *Glochidion ramiflorum* and *Cyathea* spp.; and trees or shrubs in areas exposed to intense sunlight such as *Psidium guajava*, *Melastoma denticulata*, *Morinda citrifolia*, *Trema orientalis*, and *Wikstroemia foetida*. Because of the openness of the canopy, there is a profusion of ground cover, dominated mostly by weedy species like the composite *Mikania micrantha*, the grass *Paspalum conjugatum*, and the fern *Nephrolepis hirsutula*.

Before the arrival of the Polynesians, all of the disturbance to vegetation was by natural causes. At present tropical storms or hurricanes that periodically hit the island are one of the most common cause of vegetation damage, accutely exemplified by the hurricane of 1990 which did extensive damage to the native and plantation forests on Samoa (Whistler, 1992). Strong winds can uproot or break trees, sometimes resulting in large areas of 'windfall' vegetation (Wood, 1970). Landslides on steep slopes, particularly after heavy rains, are another natural sourceof disturbance. Volcanic eruptions and lava flows can completely destroy the vegetation and cover the ground with basalt, requiring centuries for forest regeneration. Although eruptions have been recorded recently on the island of Savai'i (~1760 and 1902-11), no significant activity has occurred on Upolu recently. Since their arrival, humans have also been a major source of disturbance on Samoa, with agricultural practices greatly modifying the natural vegetation, leading to the creation of large areas of secondary forest. Before the European era of Samoan history, most of the destruction of the native forest was caused by shifting or 'slash-and-burn' agriculture. This practice was largely replaced by plantation agriculture during the European phase (i.e. since about 1830), due to the need for cash crops such as coconuts and taro.

The *kula* fernland community is the low, disturbed, fern-dominated vegetation found on the highly eroded soils of lowland ridges and coastal bluffs. *Kula* fernland, dominated by *Gleichenia linearis* (*Dicranopteris linearis*), covers large areas at Luatuanu'u on the north-central Upolu coast, and between the villages of Amaile and Tiavea on the northeastern corner of the island (Fig.4.2). Woody species typical of this habitat on Upolu include *Hibiscus tiliaceus*, *Psidium guajava* and *Morinda citrifolia*, with *Wikstroemia foetida* and *Melastoma denticulata* also present. The soil associated will the *kula* fernland is a leached clay poor in essential nutrients and is relatively acidic (pH measured at 5.6 by the USFWS inventory, 1978). Wright (1963) also noted that available phosphates and exchangeable potassium were low. The rainfall in this community was estimated by Whistler (1980b) to be in the range of 2500-3250mm per year. However, because of the impoverished nature of the soil and lack of tree cover, the ground is often dry, favouring xerophytically adapted plants. The lack of tree cover also resulted in relatively high temperature and low humidity in the direct sun. Wright (1963) attributes the origin of the *kula* fernland on Upolu to repeated and periodic burning of the vegetation, resulting in poor soils that are unsuitable for most mesophytic forest species. In pre-European times, many villages with associated fortifications were located inland, particularly in areas with easily defended ridges and bluffs near to the coast. According to Wright, the land around the fortifications would have been periodically burned to maintain a clear view. Although all fortifications and inland sites have long since been abandoned, the fernland vegetation is still maintained by random periodic burning for no other apparent reason than 'idle amusement' (Wright, 1963; Whistler, 1980b).

4.5. Settlement patterns and agricultural practices on Upolu

Archaeologists believe that the Polynesians had settled in Samoa at least 3000 years ago (Davidson, 1969; Green & Davidson, 1974; 3251±150 BP date from Leach & Green, 1989) and evolved a distinct culture whilst maintaining regular contact with Fiji and Tonga. Stratigraphic sequences at several major sites and 45 radiocarbon dates provide evidence of continuous occupation in both coastal and inland areas from sites containing pottery, dating to approximately 2000 years ago, through a long aceramic period to sites of the European contact period in the late eighteenth to early nineteenth century. However, with the exception of the pottery, found only in the early part of the known Samoan sequence, the range of artefacts from excavations is restricted. Although archaeological evidence shows settlements both inland and on the coast (Green & Davidson, 1974), Wright (1963) believed that the majority of the island's inhabitants were initially forced to live in the high interior of the island to avoid recurrent raids by sea-faring groups from other Pacific islands. Warfare, accompanied by the building of fortifications, seems to have been rife in Samoa for at least the first 1500 years of settlement (Green & Davidson, 1974). Villages were usually sited at, or close to, easily defendable strong points and were always within reach of a permanent water supply, i.e. rivers or freshwater lakes. Site locations were apparently not controlled by soil types (Green & Davidson, 1974). When the situation along the coast became more amenable, the Samoans of the interior were probably keen to leave the cool, wet climate of the uplands for the more pleasant living conditions of the coast (Kear & Wood, 1959). In the 1830s, under the impact of European contact, nearly all occupation returned to the coast (Green & Davidson, 1974), where it was documented by Watters (1958).

The first European to see the islands of Western Samoa was the Dutch seaman, Jacob Roggeveen, in 1722. The French explorer Bougainville observed the islands in 1786 and was so impressed by the Samoans as navigators that he bestowed upon the islands the name 'Navigator's islands'. Missionaries, from The London Missionary Society, became established on the islands in 1830 and are today still the strongest religious and educational influence. The census of October 1956 recorded a population on Upolu of 69,206, while in 1981 the figure had risen to 112,901. The total population of the Territory as a whole had apparently tripled since 1900 when the indigenous population was recorded at 32,875 (census department, Apia). The present distribution of population and developed land is virtually confined to a narrow strip around the coasts; however, with the pressure of this increasing population and the urge to plant more land in bananas (Kear & Wood, 1959), taro and other export crops (W. Gerlach, pers. comm.), there is a growing need to utilise soils of the foothills and high interior (Whistler, 1983b).

4.6. Lake Lanoto'o, its location and surroundings

Most of the extinct volcanic craters on Upolu are flat-floored and contain swamps underlain by red clay, but a few, including the Lanoto'o cone, contain a crater lake. Lake Lanoto'o (or Lanuto'o) is situated in the centre of the island of Upolu at 740m above sea-level (Fig.4.3 and 4.4). The volcanic rocks which characterise this region are the Salani volcanics (Fig.4.5) dating from between 310,000 yr BP and 64,000 yr BP (Kear & Wood, 1959). The lake is like an obtuse triangle in shape with a maximum distance across of approximately 400m, and a maximum depth near the centre of 17.5m (Fig.4.1). It is surrounded by the extremely steep inner slopes of the volcanic crater which reach a maximum elevation of 790m in the west, and an average height of 770m (Fig.4.1). Bathymetric recordings (measured in 1986) indicate that the floor of the lake basin dips gently from the north and south shores, whereas the gradient from the west and east shores is much steeper and falls rapidly to depths of 10m only 5m from the lake edge. Deltaic deposits may well account for the gentle gradients to the north and south of the lake.

The soil on the inner slopes, a highly weathered slippery red lateritic clay (Fig.4.6), is surprisingly deep considering the angle of slope. This soil is relatively rich in titanium and magnetic minerals derived from the groundmass (e.g. titan-augite and magnetite) of the olivine basalts which dominate the geology of this area (Kear & Wood, 1959). The soils within the crater support a dense cover of relatively undisturbed *Dysoxylon huntii* moist montane forest (Fig.4.7), with common trees including *Syzygium* spp., *Elaeocarpus tonganus*, *Palaquium stehlinii*, *Myristica* spp., *Alphitonia zizyphoides* and members of the families Araliaceae and Myrsinaceae. However, the abundance of tree ferns (*Cyathea* spp.), characteristic of young secondary forests (Whistler, 1980b), suggests that recent local catchment disturbance may have occurred. The trees and ground are almost completely covered by a multitude of ground and epiphytic ferns, including *Asplenium nidus*, *Pteris*, *Hypolepis* and *Cyclosorus* species, plus filmy-ferns (Hymenophyllaceae), climbing shrubs such as *Freycinetia* sp., and a variety of orchids.

Around the lake margins, where the light levels are higher and the ground very wet, *Pandanus* spp. dominate the vegetation almost to the exclusion of everything else (Fig.4.4). During 1986 weed taxa such as *Euphorbia hirta*, *Triumfetta* and *Mimosa pudica* were only seen in significant quantities along the disturbed pathway leading down to the lake (Fig.4.6), whilst a thin band of aquatic sedges was noted on open areas of flat peripheral lake mud. A few coconut and banana trees had also been recently planted around the rim of the crater. Drainage of rainwater from the outer crater slopes is concentrated into two river systems, the Leafe river to the south and the Soaga river to the north (Fig.4.2), which then flow directly to their respective coasts. These fertile outer slopes are quite heavily cultivated in the lower region and maintain taro and fruit tree plantations which dominate over the sparse stands of native hardwoods (Fig.4.8).

4.7. Sedimentary analyses of Lake Lanoto'o, Upolu

4.7.1. Physical investigations:

4.7.1.1. Sediment core stratigraphy

Two short cores were collected from Lake Lanoto'o at the two locations shown in Fig.4.1. A 3m core (core-1) was collected in 15m of water and consisted predominantly of brown, highly organic lake mud (Ld_2/Sh_2 of the Tröels-Smith notation, 1955) with three grey-coloured zones of mud and fine clay ($Ld_2/Sh_1/Ag_1$) at 1.88-1.38m, 0.90-0.84m, and 0.62-0.56m (see Fig.4.12, insert). The clay units are believed to represent periods of in-washed material from the catchment slopes and contrast sharply with the autochthonous mud. Red iron staining was also noted in the sediment core between 1.88-1.38m.

Two sections of core-1 (1.0-1.30m and 2.0-2.50m) unfortunately fell out during collection and so a second core extraction (core-2) was attempted in 9m of water. On the third, metre the piston-corer became irretrievably wedged in the sediment and had to be abandoned. This second core was generally similar in appearance to the first two metres of core-1 but both cores showed little visual variation in the field for a clear comparison to be made. The first and longer core was later used for laboratory analyses, but is believed to represent only the top of a much longer sedimentary record since the base of the sediment fill was not reached. It is possible that sediments have been accumulating in Lake Lanoto'o since the cessation of volcanic activity during the last interglacial (or penultimate glacial according to Kear & Wood, 1959). The author believes that this site could still contain important information on the nature of pre-glacial vegetation (not covered by this study) and would definitely warrant further collection of sediments with stronger coring and retrieving equipment. Due to the gaps in the data a continuous sedimentary history could not be obtained from this sequence.

4.7.1.2. X-ray photography

The X-ray photographs of the 3m Lanoto'o core showed no abrupt transitions and very little variation in density with the exception of the units rich in clay material. The occurrence of fine laminations throughout the sequence indicated that the core had not been significantly disturbed. The only significant macro-remains found in the sediments of Lake Lanoto'o were fossil leaf fragments present in the clay-rich band between 1.88m and 1.38m. The core X-rays showed that the fragments were confined only to this zone and may have resulted from higher influx of slope debris during this period.

4.7.1.3. Magnetic susceptibility analysis

The magnetic susceptibility profile for the Lanoto'o sequence (Fig.4.9) shows negative susceptibility readings from the basal section of the core, i.e. between 3.00m and 2.50m, as well as three susceptibility peaks (i.e. higher than 10 arbitrary units), occurring between 1.88-1.38m (maximum of 51 arb. units at 1.70m), 0.90-0.84m (maximum of 14.75 arb. units), and 0.62-0.56m (maximum of 15.25 arb. units). The negative readings imply a low influx of mineral-rich sediments during the early part of the record, whilst the subsequent peaks, which closely correspond to the three clay zones described in the stratigraphy, again indicate episodes of greater terrigenous in-wash.

4.7.2. Sediment geochemistry

Percentage profiles of mineral oxides, organics, and charcoal are shown in Fig.4.10, and indicate that significant geochemical variation has occurred through the core sequence. As described in section 3.3.1. strong correlations exist between the basalt-oxides, SiO_2, TiO_2, Al_2O_3 and Fe_2O_3 (all over 90% correlation. Fig.3.22) as well as minor basalt components such as MnO, and P_2O_5. The profile for CO_2/H_2O is also strongly linked with the basalt-oxides. Since there appears to be no direct correlation of CO_2/H_2O with the CaO profile (i.e. CO_2 derived from calcium-carbonates) water from clay mineral latices probably formed the main component of this profile. Strong correlations also exist between CaO, K_2O and Na_2O with a weaker link with MgO. These oxides also occur in small amounts in the basalt rocks of Samoa but do not appear to correlate directly with the major basalt-oxides mentioned above. The correlation matrix (Fig.3.22) indicates that SO_3 content does not correlate with any of the other oxides or organic material. Although there are significant peaks in the basalt-oxide profiles the sediment composition is dominated by organic material throughout. Only six samples contain less than 40% organics, the lowest percentage being 33% at a depth of 0.60m. Fluctuations between organic rich sediments and samples rich in basalt-oxides are believed to represent fluctuations in the accumulation of autogenic and allogenic material, and indirectly indicate periods of catchment stability and instability repectively. Four zones and two sub-zones (shown in Fig. 4.10) were detected by the factor analysis of the geochemical data (Fig.3.23).

The first zone, **LgI**, extends from the base of the core at 3.00m to 1.90m and spans the data gap between 2.50m and 2.00m. The sediment is dominated by organic lake mud forming between 63-77% of the total geochemical composition. The main basalt-oxides make up the rest and show no major variation throughout this zone, except at the upper level of 1.95m when there is a slight increase. SO_3, possibly derived from a build-up of hydrogen-sulphide in the anaerobic environments of the peripheral swamps, shows a small peak of 1.2% at a depth of 2.64m. Interestingly, the highest recorded charcoal levels in the Lanoto'o profile (reaching 15.6%) occur in this zone and closely correspond with a radiocarbon date of 8920± yr BP for the sediments at 2.80-2.90m. Since there is no evidence for human occupation during this period of the island's history the charcoal must represent natural fires within the catchment. Dry ground conditions and/or increased lightning occurrence are factors that could favour the onset of natural fires; however, the geochemical data alone cannot verify these conditions. The low mineral content of the lake may be influenced by a dense ground-cover of vegetation restricting soil erosion from these steep slopes.

The second zone, **LgII** extends from 1.90m to 1.45m and spans a stratigraphy of gyttja-with-clay. The zone also yielded a radiocarbon date of 3575±65 yr BP from the sediments at 1.58-1.62m. The geochemistry is characterised by a sharp increase in the percentages of basalt minerals at the expense of organic content. At 1.75m, SiO_2, TiO_2, Al_2O_3 and Fe_2O_3 reach peaks of 7.5%, 7.8%, 22% and 15.5% respectively. The second lowest percentage levels of organic material (38%) are also recorded at this depth. The relative ratio of TiO_2 and Fe_2O_3, as compared with SiO_2 and Al_2O_3, seem much higher than would normally be found in weathered olivine basalts (as indicated by the analyses of Marshall, 1927). The high titanium is likely to be derived from the deeply weathered titan-augites which form a major component of the groundmass of olivine basalts common to Upolu (Kear & Wood, 1959), whilst the excess of iron may have resulted from the in-wash of well developed, and previously stable, iron-rich soils (possibly laterites) which have accumulated ferric bands. It is interesting to note a progressively decreasing Fe_2O_3 content, relative to SiO_2, from the lower to upper sediments (Fig.4.11). This situation could result from progressively less weathered soil material being brought into the lake during times of prolonged slope disturbance. The zone as a whole represents a period of increased slope disruption resulting in the in-wash of mineral-rich soils. Factors which may have encouraged such an increase in slope erosion include an intensification or increased seasonality of rainfall (especially if the vegetation cover had already been broken as a result of storm damage or small scale openings from natural die-back). The natural slumping of regolith ,when the thickness of weathered soil exceeds it threshold limit, may also account for the pulses of catchment material reaching the lake; however, one might expect such cycles to occur more frequently and over a shorter time period. 100-year cycles of soil build-up and failure were described by Wentworth in Hawai'i and were merely the product of high rainfall on steep slopes. Anthropogenic activity such as forest clearance may have, alternatively, exposed the previously undisturbed iron-rich lateritic soils. An estimated date for the beginning of this zone (Fig.3.26 ~5000 BP est.) however, implies that this activity occurred 2000 years earlier than any archaeological sites so far recorded. If large scale vegetation removal (natural or anthropogenic) was responsible for the exposure of catchment slopes then this chain of events is likely to be manifested in the pollen record discussed in the following section. It is, however, only possible at this stage to identify phases of catchment instability and stability.

After the peak of basalt-oxides at 1.75m there follows an equally abrupt decrease in mineral content which continues into zone LgIII. **LgIII** ranges from 1.45m to 0.55m and spans the gap in data between 1.30m and 1.00m. The stratigraphy initially reverts to a dark brown organic gyttja with organic levels increasing from a maximum of 47% in LgII to 79% in LgIII; however, the two distinct sub-zones at 0.88-0.83m **(LgIIIa)** and 0.65-0.55m **(LgIIIb)** mark an abrupt increase in basalt-oxides which correspond to the clay laminations recorded in the field descriptions. Measured organics fall to 49% and 33% at 0.85m whilst SiO_2, TiO_2, Al_2O_3 and Fe_2O_3 percentages increase to 7.7%, 5.8%, 18.9% and 11.3% at 0.85m, and 10%, 8.7%, 25.2% and 11.7% at 0.60m. The lower ratio of iron-oxide in the mineral peak at 0.60m (compared with 0.85m and shown in Fig.4.11), may have resulted from a shorter period of weathering of newly exposed rock in the catchment following the preceding disturbance event (recorded in LgIIIa).

The final zone **LgIV** ranges from a depth of 0.55m to the top of the core and like LgI and LgIII (with the exception of the clay-rich sub-zones) is dominated by lake mud. Percentages levels of the basalt-oxide are not much higher than those found in LgI and organics dominate the sediment. This is again believed to represent a period of catchment stability. The main distinction between this upper-most zone and zones LgI and LgIII is the slight increase in percentages of CaO, Na_2O and K_2O, although they do not exceed 0.37%, 0.03% and 0.7% respectively. All of these oxides are components of the basalt geology of the catchment. The practice of Polynesian settlers to spread coral fragments on the slightly acidic and potash-deficient soils of the upland areas to render them more fertile for agriculture may provide an alternative explanation for this increase. This practice was recorded by Kauta'i *et al.* (1984) on the island of Atiu, Cook Islands, and may well have occurred in Samoa.

4.7.3. Biological investigations: The palynological record

Whilst the percentage fossil pollen record (Fig.4.12, insert) shows that changes have occurred in the composition of the pollen and spore flora over approximately the last 9000 years of the lake catchment history, the profiles showing pollen and spore concentrations (Fig.4.13 insert) show no significant change. This does not, however, necessarily imply that the vegetation density has remained constant, since the concentration of fossil grains in the deposit is also dependent on the sediment accumulation rate, amongst other factors. Summary diagrams of the fossil pollen flora composition (Fig.4.14) show that only subtle changes occurred between 9000 to 3000 yr BP (i.e. estd. dates from the lower 1.65m), but that the last 2500 years or so (i.e. estd. from the top 1m) was characterised by more obvious composition changes, with primary taxa alternating with the secondary taxa in relative importance. Variations during the period from 9000 to 3000 yr BP have been attributed to natural influences on the vegetation in and around the Lanoto'o basin. The fall in primary and arboreal taxa around 2500 years ago, which corresponded to increases in the fernland (most notably *Gleichenia*), grassland and Polynesian weed taxa, has been attributed to the first significant anthropogenic disturbance in the sedimentary record. It must be noted, however, that an important section of the record is missing immediately below this date and may well have shown a earlier disturbance-assemblage. Factor analysis of the percentage and absolute pollen and spore profiles detected the presence of the five vegetation zones (Fig.3.24) which are shown in relation to the pollen profile in Figs.4.12 and 4.13 (inserts).

The lowermost zone of the fossil flora analysis, **LpI**, extends from 3.00m to 2.30m and roughly corresponds to zone LgI of the geochemical analysis. Trees and pteridophytes dominate throughout with the ferns declining slightly in the uppermost sample. A wide diversity of primary tree and shrub taxa form 30-32% of the spermatophyte flora (i.e. excluding pteridophytes) and include the indigenous tree *Elaeocarpus tongensis* (7.3% to 9.7%) today found in the *Dysoxylum huntii* montane forest of Samoa (Whistler, 1980b), and members of the Araliaceae family ranging from 4.3% to 5.7%. Present day pollen studies by Southern (1986), have shown that *Elaeocarpus tongensis* was frequently underestimated in the pollen rain of sites on Fiji, while Hamilton (1972) also noted that pollen from the Araliaceae family was invariably poorly dispersed.

Other primary tree taxa which each make up less than 3% of the pollen and spore composition of this zone include: *Weinmannia affinis*, a small to medium sized tree rarely found below 500m in the vegetation of Eastern Samoa (Whistler, 1980b), where it occurs in the constantly damp and cool forest communities; *Palaquium* sp., almost certainly *Palaquium stehlinii* (W.A. Whistler, pers. comm.), is a large tree of the foothills and montane forests and forms an important canopy component of the *Dysoxylum huntii* montane forest; *Ascarina* sp., most probably *Ascarina diffusa*, a small tree of the high-altitude and constantly wet cloud forests of Eastern Samoa (Whistler, 1980b) and *Alphitonia zizyphoides*, a very large indigenous tree which prefers areas of high light intensity i.e. high ultraviolet radiation (Papy, 1954) and often found on Samoa on almost vertical cliffs, and on steep slopes at high altitude (Setchell, 1924). This species of *Alphitonia* was also noted by Whistler (1980b, 1984) in both primary montane communities and secondary lowland forests in the eastern Samoan islands. *Dysoxylum* sp. is also present, one of three species of *Disoxylum* (*D. Samoense*, *D. moata* or *D. Huntii*) but most likely to be *D. huntii*, which extends above 1000m on Upolu (Whistler, 1980b) and is common today in the undisturbed forest around the slopes of Lake Lanoto'o (W.A. Whistler, pers. comm.). Present pollen rain studies in Fiji (Southern, 1986) indicate that the genus *Dysoxylum* is also likely to be under-represented in the fossil pollen record. This may account for the surprisingly low recorded levels throughout the Lanoto'o sequence, especially when considering the dominance of this tree in the upland forest communities today. Also occurring in the record of this zone are members of the palm family (but not coconut) and *Allophylus* sp., possibly *Allophylus vitiensis*, a tree associated with dry, exposed hillslopes of low- and mid-altitudes on Rarotonga (Wilder, 1931). The species of *Ixora* is most probably *Ixora samoensis*, usually a small tree of the lowland to montane forest, but occasionally found in the high-altitude montane scrub community of Eastern Samoa (Whistler, 1980b) where low temperatures and high light intensities are common. *Rapanea* and *Celtis*, which are both regarded as secondary genera in south-east Asia but have been found in undisturbed forests of Samoa, were also noted.

The myrtle family (Myrtaceae) contains species of both trees and shrubs, but it is likely that the taxa present here (forming 2.0-4.4% of the pollen flora) are of the genus *Syzygium*, primary trees typical of the Samoan upland forests today. *Syzygium samoense* and *Syzygium brevifolium* are the two species that were noted by Christophersen (1935) growing on the crater rim around Lake Lanoto'o. Other taxa occurring in this unit which are associated with undisturbed forests include the parasitic shrub *Loranthus insularum*, often attached to native forest trees, and the small succulent herb *Procris* (accounting for 4.7% at 2.55m). This species of *Procris* is most likely to be *Procris pedunculata*, commonly found at high altitudes at the base of trees and on rocks.

Arboreal taxa associated with disturbed forest conditions which are commonly to rarely found in the pollen flora include *Trema orientalis*, which ranges from 15% to 25% of the total flora, and a species of *Grewia* which forms 2.2% at 2.70m. Both of these taxa are believed to be successionary taxa often occurring in newly exposed areas of forest clearance, natural small scale disruptions of the forest canopy by tree falls, landslides etc. The pteridophytes which form a major component of the forest cover during this period include the tree ferns (Cyatheaceae), accounting for up to 23%, members of the Polypodiaceae family and species of *Pteris*, *Cyclosorus* and *Hypolepis*. The robust 'false-tree-fern' *Angiopteris evecta* also forms up to 3% of the pollen and spore flora. Whistler (1984) records species of *Cyathea* in both the undisturbed cloud forests as well as the disturbed forests of Samoa today and, therefore, they provide little information about the stability of this catchment.

Whilst the diversity of primary species in the fossil flora suggests that this zone represents a period of catchment stability (also implied by the geochemistry and magnetic measurements), the presence of some successional taxa such as *Trema*, suggests that catchment disturbance may have occurred. Since these phases were not detected in the sedimentary record it is most likely that they were localised and of small scale, having resulted perhaps from the natural dynamics of the forest and lake catchment (i.e. natural decay or wind-throw of older trees, localised land-slips on moisture-laddened slopes etc.). Apart from the presence of the subtropical 'austral species' of *Ascarina* and *Weinmannia*, which may indicate cool conditions, the vegetation community believed to have been growing in the catchment during this period does not provide any clear information about the climatic regime. Moisture availability does not appear to have been a major restricting factor, since many cloud forest taxa were recorded. The slight increase in the uppermost pollen level of Araliaceae and Myrtaceae, as well as the appearance of the epiphytic herb *Procris pedunculata*, apparently at the expense of 'cool' indicators such as *Weinmannia* and *Ascarina*, may be in response to an increase in temperature and humidity towards the close of this zone. There is, however, no quantitative ecological data to verify this deduction which is only based on single indicator species rather than recognised pollen assemblages.

The genus *Ilex*, present in one sample of this zone at less than 1%, has never been recorded in the vegetation of Samoa (W.A. Whistler, pers. comm.) and may have arrived by long-distance dispersal from the Society Islands where it is known to occur; however, in view of the fact that *Ilex* pollen is poorly dispersed (Hamilton, 1972; D.M. Taylor, pers. comm.) this genus may formerly have occurred on the island, but has since become locally extinct. *Englehardtia* sp. and *Pittosporum* sp. also detected in the pollen record of zone LpII, are both unlikely to have occurred on Upolu (W.A. Whistler, pers. comm.).

LpII spans from 2.30m to 1.15m and loosely corresponds to LgII in the geochemical analysis. This period sees the dramatic appearance of *Pandanus* pollen at 1.95m, forming between 26% and 43% of the pollen and spore flora. *Pandanus*, not detected at all in the previous zone, dominates the spermatophyte flora throughout LpII. The same primary forest species present in LpI decline only slightly in both fossil grain concentrations and percentage terms, possibly in response to the relative *Pandanus* increase. The most significant decreases in taxa, however, occur in the percentages of *Trema* sp. and the tree ferns. Both taxa, nevertheless, remain in the record. A species of *Rapanea* pollen increases in abundance at 1.95m. The environmental significance of this is, however, difficult to interpret due to the occurrence of this genus in a range of habitats i.e. from undisturbed moist forests to successional communities (see Appendix 3). The presence of sedges (Cyperaceae) and the swamp reed *Typha latifolia*, during this period could have been encouraged by the formation of openings in the forest canopy, or the development of new peripheral areas resulting from an increased input of catchment material (inferred from the geochemistry). The gently shelving deltas on the north and south shores, evident during the bathymetric survey, may have been formed or enlarged during this period, enabling these opportunistic aquatic plants to get a foot-hold on the otherwise steeply sloping lake shores. The pioneering qualities of *Pandanus* may also have favoured the natural increase of this tree around the extended lake margins, and account for the high pollen percentages of this plant which is known to be a prolific producer. Selective cultivation of this valuable tree at the expense of *Trema* and the tree ferns may have been undertaken by Polynesian settlers. This may have resulted in increased slope disruption, but may also be expected to have encouraged pioneer weed and fern species. Such pioneer plants and introduced cultivars, which could have verified the presence of human activity, do not appear in the pollen record at this stage. Considering the date of 3575±65 yr BP (3880 cal. yr BP) estimated from the centre of this zone, it seems more likely that slope disturbance and vegetation change were the result of natural forces.

LpIII extends from 1.15m to 0.85m and corresponds to the horizon of in-washed clays detected in the stratigraphic, magnetic and geochemical records between these depths. At the beginning of this zone the summary diagram (Fig.4.14) shows a decline in primary taxa, and trees in general, which corresponds to an increase in pteridophytes, herbs and the first signs of recognisable weed taxa of Polynesian origin. *Weinmannia* sp. falls to around 1%, while the Araliaceae group, accounting for 5.3-6.8% in LpII, reach a maximum of only 2%. Decreases in percentages are also found in *Myrsinaceae*, *Elaeocarpus* and the Myrtaceae group, as well as *Pandanus*, now forming only 11% of the count at 0.96m. Palm pollen, which accounted for up to 3% in LpII, is totally absent from LpIII to the top of the core. The low pollen producers, *Inocarpus* sp., *Dysoxylum* sp. and *Coprosma* sp. are also undetected above this sub-zone (although they are all known to occur on Upolu today). In contrast *Macaranga stipulosa*, one of the main canopy trees associated with Samoan secondary forests (Whistler, 1980b), increases to 2.8% at a depth of 0.90m. Also regarded as a typical sub-canopy tree of disturbed forests is the aboriginally introduced Indian mulberry (*Morinda citrifolia*) which appears in the pollen record for the first time, although only at low frequencies. A significant increase is also recorded in the tree-fern family Cyatheaceae.

The change from a vegetation dominated by trees to one dominated by pteridophytes, including the notable disturbance indicator *Gleichenia linearis* (dominant taxa of the *kula* fernland community), and the first significant appearance of grasses (Gramineae) and weed taxa (e.g. the aboriginally introduced *Acalypha* sp., *Portulaca* sp., and the species of *Euphorbia*), suggest that the vegetation structure had been modified by human intervention. *Acrostichum aureum*, a large leathery fern, with pinnate fronds up to 4m long, occurs in the pollen record for the first time at a depth of 0.90m. This fern is often found growing near rivers and in swampy areas and is capable of colonizing disturbed moist areas and tolerating saline conditions. It is interesting to note that the XRF analysis showed a slight increase in Na_2O above this zone; however, the source is unkown.

Zone **LpIV** from 0.85m to 0.60m is characterised by a return to darker organic gyttja and significantly lower amounts of mineral material compared with LpIII. The summary diagram (Fig.4.14) indicates that there was a possible regeneration of primary taxa and trees. *Weinmannia* sp. increasing to 5.4%, Araliaceae to 3.2-5.7%, and *Elaeocarpus* reaching a maximum of 6.9% at 0.70m. Increased percentages are also seen in the profiles of *Ascarina* sp., *Guioa rhoifolia*, Myrtaceae and *Procris* which suggest that the stable forest community was able to redevelop quickly after the phase of disruption. *Gleichenia linearis* also falls below 1%. *Pandanus*, however, remains the most important single species in the vegetation and reaches percentages of 26-40% at 0.80-0.70m (probably still taking advantage of new alluvial land formed in the preceding period). The species of *Freycinetia* occurring for the first time above 1%, is most probably *Freycinetia samoensis*, a climbing shrub occurring at altitudes between 300-500m in both primary and secondary forests of Upolu and Savai'i (Whistler, 1980b). Its presence may be indicative of an incomplete canopy cover allowing light to penetrate down to the shrub layer. The presence also of *Lycopodium cernuum* (2.2% at 0.80), a terrestrial clubmoss commonly found on open, dry hills and generally growing with other ferns and grasses (Wilder, 1931), suggests that the disruption of vegetation cover in the previous zone may have encouraged the development of the fernlands and grasslands typical of the mid-altitude regions of Upolu today (Fig.4.15).

LpV (0.60-0.00m). Although the top sample of this zone was not recognised as a separate pollen unit in the principal components analysis (Fig.3.24), the flora does appear to be different to the rest of the zone and may represent another brief period of forest and catchment disturbance similar to LpIII. This upper level also corresponds to sub-zone LgIIIb in the geochemical analysis. Primary taxa and trees decline slightly, while *Gleichenia*, grasses and other secondary taxa such as *Trema*, increase. *Cocos nucifera* appears for the first time in the pollen record, although only at very low levels. The occurrence of coconut in the Lanoto'o catchment area must have resulted from Polynesian planting since it is most unlikely to have dispersed naturally into this inland site.

Zones LpIII and the top of LpV appear, therefore, to represent two periods of disturbance in and around the catchment which occur either side of a relatively stable period. The presence of the aboriginally introduced *Acalypha* and *Morinda citrifolia* in LpIII, and the later appearance of coconut and other introduced weeds, strongly suggest that Polynesians were present in the Lanoto'o catchment area (which presumably provided a good defensive position and source of freshwater), and were most probably responsible for the changes in vegetation during this period. The evident lack of in-washed clays from 0.80-0.60m, and the abrupt nature of the disturbance horizons, perhaps supports the idea that anthropogenic factors were more significant than natural factors. Increased rainfall or storm intensity would more likely have resulted in a more even deposition of clay laminations within the lake, as seen in zone LpII of the geochemical analysis. There is not enough evidence, however, to discount possible natural influences on vegetation composition during this period, and it is quite likely that both anthropogenic and natural factors were acting antagonistically to promote vegetation changes and catchment disturbance.

The lower levels of LpV, from 0.40m to the top of the core, spans a stratigraphy dominated by organic gyttja. The summary diagram shows that the primary forest taxa fell slightly in percentage terms in the lower sample, but recovered in the uppermost sample. Perhaps the most significant feature of this upper zone is the first appearance (at less than 1%) of highly competitive weed species of known European introduction. These include *Triumfetta rhomboidea*, a pantropic weed, common in bush fallow, pastures, disturbed places and roadsides, and first reported from Samoa in 1905 (Whistler, 1983), and *Euphorbia hirta*, an erect to ascending herb, common in gardens, croplands, and on roadsides, and first reported from Samoa in 1839 (Whistler, 1983). Cyperaceae percentages also increase slightly in this zone and probably represent an increase in newly introduced sedges such as *Cyperus rotundus*, *Fimbrystylis dichotoma* and *Kyllinga brevifolia* (first noted from Samoa in 1868, 1895 and 1905 respectively). All these sedges are common in croplands and waste places. The 'sensitive mimosa,' *Mimosa pudica*, occurs along with the highly prolific *Lantana camara*, in the upper sample level of this core. *Mimosa pudica* is a spreading, sub-woody, perennial herb up to 40cm in height which is locally abundant in lawns, various crops and disturbed places, and often dominates in pastures. This widespread weed, native to tropical America, was first reported from Samoa in 1839 (Whistler, 1983). *Lantana camara* is an erect, branching shrub native to tropical America and was first reported from Samoa in 1895 (Whistler, 1983). It may originally have been introduced as an ornamental, but is now a noxious weed of coconut plantations, pastures and waste places. Pollen from the combined families of the Urticaceae/Moraceae, which represent herbs, shrubs and trees, on the whole offer little information for the reconstruction of vegetation and environments; however, their slight increase in the upper zone may represent an increase in herbaceous species now associated with expanding grasslands and fernlands. Pteridophytes still form a major component of the vegetation of zone LpV, with percentages of 51% and 36% at 0.30 and 0.10m, but there appears to have been a slight reduction in the diversity of species since the two preceding disturbance phases. Tree ferns dominate the pteridophyte flora with *Cyclosorus/Hypolepis*, *Pteris* sp. and members of the Polypodiaceae also occurring in significant percentages. *Gleichenia linearis* declines in the upper level while species of the family Marratiacae (usually shade-tolerant ferns) reach 1.5%.

The pollen assemblage of this uppermost zone appears to represent the European contact period on Upolu, with the extension of croplands, and the initial introduction of weed species typically found on Upolu today. A relatively stable forest formation of both primary and secondary taxa, however, appears to exist in the vicinity of the lake, and perhaps represents a shift of settlement from interior highlands to the coastal strip as suggested by Wright (1963).

4.7.4. The sedimentary record from Lake Lanoto'o: Overall conclusions

The organic-rich sediments of the Lake Lanoto'o sequence appear to have accumulated very slowly over the past ~10,000 years or so; however, several episodes of more rapid allogenic deposition were identified and have been attributed to increased activity (anthropogenic and natural) within the catchment. Changes in floral composition over this period, implied by the fossil pollen and spore spectra, have also been linked to these episodes of increased catchment disturbance. Two key sections were unfortunately missing from the sedimentary sequence and since the resolution of dates is also low, only tentative chronological conclusions can be drawn (using estimated dates from the age-depth profile shown in Fig.3.26).

Prior to 8920±80 yr BP the Lanoto'o catchment, which was geomorphologically stable, supported a primary and secondary forest vegetation, dominated by high altitude, 'cool' taxa such as *Weinmannia* and *Ascarina*. The presence of cloud forest species also implied that moisture availability was not a restricting factor. It is interesting at this stage to note the findings of McGlone *et al.* (1992) on New Zealand during this early part of the Holocene. Between 10000 and 7000 yr BP they record the presence of plants characteristic of mild, moist climates, in particular *Ascarine lucida* and tree ferns (Cyatheaceae). Rainfall was believed to be lower than present due to decreased winter rainfall but summers were cloudy and moist.

Although the stratigraphic record from Lake Lanoto'o is disrupted between ~7600-5200 yr BP, there is some evidence to suggest that stable conditions were maintained within the catchment up until ~5000 yr BP. The period between 5000 and 3500 yr BP is marked by a significant increase in slope in-wash with relatively iron-rich soils reaching the lake, perhaps in response to unstable weather conditions (since anthropological influence was unlikely). The sudden appearance of *Pandanus* and other stress tolerant taxa in the pollen record of this period and the slight decline in primary forest taxa, imply some degree of forest disturbance. Peripheral lake muds may have been extended during this period and allowed aquatic reeds and sedges to colonise. The expansion of *Pandanus* may have also been encouraged by the extension of the lake margin, as this pioneer tree is well adapted to colonising open areas where light can penetrate.

McGlone *et al.* (1992) describe a spread of vegetation communities tolerant of edaphic and climatic extremes as well as taxa favoured by high solar radiation and relatively drier summer conditions. They believe that this combination along with evidence of drought, fire and slope erosion are indicative of more variable climates possibly related to ENSO phenomenon, especially after about 5000 yr BP. The records from Lake Lanoto'o do not contradict this description, but the evidence for climatic change is not in itself strong enough to stand alone.

Around 2500 yr BP estd. a decline in several primary forest taxa, and corresponding increases in secondary plants such as *Macaranga stipulosa*, *Acalypha* (an aboriginal introduction), *Morinda citrifolia* (also aboriginally introduced), *Gleichenia linearis*, tree ferns and species of *Euphorbia*, are associated with human activity and subsequent catchment erosion which spans the next 300 years or so. Although there is archaeological evidence of Polynesian settlement on coastal regions of Upolu since 3251±150 yr BP (Leach & Green, 1989), occupation of inland sites may only have been encouraged during periods of inter-island warfare, accounting for the relatively brief period of activity recorded. Stable conditions resume in the following ~700, years after which a further disturbance phase is indicated from ~1600 to ~1400 yr BP. This may represent a further wave of inland activity or short term climatic or geomorphological disruption (a distinction cannot, however, be made). European contact is represented in the record by the occurrence of weed taxa of known introduction and a slight recovery of a stable forest community indicated in the upper levels of this sequence.

5. STATIGRAPHIC STUDIES FROM LAKE ROTO, ATIU, SOUTHERN COOK ISLANDS

5.1. The Cook Islands archipelago

The Cook Islands archipelago is situated in the centre of Polynesia nearly midway between Tahiti and Samoa (Fig.1.1) and is spread across the south Pacific Ocean between latitude 8° and 23°S and longitude 156° and 167° W. The archipelago consists of twelve inhabited and three uninhabited islands, with a total land area of 240km^2, scattered over 1,830,000km^2 of ocean and fall geographically into two groups: The Southern Cook Islands and the Northern Cook Islands.

The Southern Cooks (Fig.5.1) form a compact group of islands, originating from submarine volcanoes rising from the sea floor at depths of 4500-5000m (Summerhayes, 1967). The islands differ widely in their form, structure and relief, making it difficult to deduce a geological history consistent for the whole group (Wood & Hay, 1970). They include a high mountainous island, Rarotonga; four raised coral islands with volcanic cores: Atiu, Mangaia, Ma'uke and Miti'aro; one atoll, Manuae; one near-atoll with a volcanic core, Aitutaki, and a sand-cay on a coral foundation, Takutea (Wood & Hay, 1970). Several are isolated sub-marine mountains, but those between Aitutaki and Ma'uke (including Atiu) form a distinct chain that trends north-west parallel to the much larger major chains of the Line Islands, the Austral Group, the Society Islands, and the Tuamotu archipelago (Wood & Hay, 1970). The Cook Group of volcanoes lies within the nephaline-bearing zone of the Pacific basin (Chubb, 1934) where continental rocks are absent (Marshall, 1924). The islands of the Northern Cooks form a more widely spread group of atolls, with the exception of Nassau, which is a sand-cay on a coral-reef foundation (Wood & Hay, 1970). Their surrounding bathymetry indicates that some are parts of submarine ranges of volcanic mountains, and others are summits of single volcanic cones rising 4600-6700m above the ocean bed (Summerhayes, 1967).

The inhabitants of the Cook Islands call themselves *Maori*, as do the aboriginal Polynesians of New Zealand whose ancestors are believed to have come from the Cook Islands. Maori legends strongly indicate that there is a western Polynesian element present in the Cooks. In an ethnobotanical study of the Cook Islands, Whistler (1990), notes that legends credit Samoan voyagers with settling on the western part of Rarotonga, while Pukapuka was colonised from either Samoa or Tokelau, and Atiu, Ma'uke and Miti'aro may have been colonised from the Manu'a Islands of Samoa; the 'Orthodox ' Scenario (described in Chapter 2) suggests otherwise. Because of this apparently diverse origin and because of the great distances between islands, the Maori culture is not homogeneous and each of the islands, or group of islands, has its own dialect. Atiu, Ma'uke, and Miti'aro, however, have a common dialect and are together called the Ngaputoru group.

The European discovery of the Cook Islands can probably be attributed to Alvaro de Mendaña, who sighted Pukapuka in AD 1595, but the first recorded landing was by Pedro Quiros on Rakahanga in AD 1606. The next recorded contact was not until nearly 175 years later when Captain James Cook landed on Atiu (Beaglehole, 1967). In 1789, the Bounty mutineers are believed to have discovered Rarotonga, an account of which was later recorded by the Rarotongan convert and missionary Maretu (Crocombe, 1974) who lived ca. AD 1802-1880, but the first landing is attributed to Captain Goodenough during a sandalwood expedition there in 1816. The beginning of the westernisation of the islands began a few years later with the arrivals of the missionaries from the London Missionary Society based in the Society Islands.

5.2. Location and physiography of the island of Atiu, Southern Cooks

Atiu, located at latitude 20°S and longitude 158° 10'W, is the third largest island in the Cook Islands (Fig.5.1), with an area of 26.9km^2 and a circumference of 20km around the coast. The island is roughly quadrilateral in shape and may be divided into three distinct physiographic regions: the highly weathered volcanic interior, the raised coral limestone rim or *makatea*, and the swampy lowland depression that separates the two former regions in most areas (Fig.5.2).

The deeply weathered central volcanic plateau, the site of much agricultural activity both recently and in pre-contact times (Sykes, 1976a), rises from moderately steep and badly eroded clay slopes to a maximum altitude of 71m (Hunt, 1969). The upper surface of the volcanics is horizontally bevelled, a feature attributed to marine erosion. Streams draining from the central uplands to the surrounding lowlands, cut deep gullies into the slopes, and then disappear at the base of the *makatea* cliff through sinkholes. The clays on the slopes, weathered from coarse augite-olivine-labradorite basalts containing phenochrysts of feldspar (Marshall, 1930) support little but the 'false stag-horn' fern *Gleichenia linearis* and guava. In road cuttings the red-friable soil is seen to contain thin veins of manganese-oxide. Conspicuous terraces, possibly formed from high sea level stands, have been described on the volcanic slopes of Atiu at 45m, 20m, and 7-15m (Campbell *et al.*, 1978). Schofield (1967) identified a further level at 4.6m. Although these features have often been used to reconstruct erosional histories for the island based largely on inferred sea-level change, Stoddart *et al.* (1990) emphasise that none of the terraces has been rigorously mapped or levelled, and that there is no direct evidence for a marine origin. Potassium-argon dates of the basalts on Atiu (Dalrymple *et al.*, 1975; Turner & Jarrard, 1982) estimate the age of the island at between 8 to 10 million years.

The *makatea* limestone is believed to have developed during the early Tertiary on slowly subsiding foundations and, according to Wood and Hay (1970), may well have covered the volcanic rocks of Atiu entirely. McNutt and Menard (1978) hypothesised that uplift of the Cook Island and their reefs resulted from crustal loading through the formation of the nearby younger volcano of Rarotonga (mean date of 1.65Ma) and consequent deformation of the crust. On Atiu the limestone forms 3-6m cliffs on the seaward margin, rising to an elevation of 30m on the inland margin. In places the inner margin of the *makatea* grades smoothly into the volcanic slopes (Grange & Fox, 1955), but elsewhere, especially adjacent to the swamps, it is formed by a vertical cliff 10 or so metres high (Campbell *et al.*, 1978; Campbell, 1982). Analyses by Marshall (1930) showed that the *makatea* mainly consists of calcite and aragonite of both primary and secondary origin, while the inner regions consist of irregularly dolomitised limestone. These different geologies correspond to a transition between the main mass of *makatea*, of early Pliocene age (Marshall,1930), and a peripheral fringe of much younger Pleistocene limestones along the coast (Stoddart *et al.*, 1990). The *makatea* is deeply dissected with individual karst pinnacles and towers ranging in height from 3-4.5m, but locally exceeding 6m (Stoddart *et al.*, 1990). There is also substantial internal limestone corrosion and Stoddart *et al.* (1990) surveyed one sinkhole which descended 22.5m from the pinnacles on the *makatea* surface, the lower 11m being a vertical fall to a freshwater pool. The upper surface is distinctly convex in cross-profile (Stoddart *et al.*, 1990), a character which is believed to be indicative of post-uplift erosion. The degree of post-emergence modification on Atiu is, however, unknown but in the case of Mangaia (an island larger than Atiu but of similar morphology and geology) Stoddart *et al.* (1985) argued that the development of the swamplands by limestone retreat effectively isolated the surface of the *makatea* from fluvial dissolution as the streams draining the central volcanics exit through the limestone close to the present sea level. Therefore most of the karst erosion in the *makatea* is confined internally. This has important implications when considering the relative input to the lowlands and lake of sediment and the fluvial-transport of pollen from the volcanic slopes and limestone surfaces.

Much of the *makatea* is covered with red colluvial clays, believed to have been deposited downwards as the 'moat' between the volcanics and the *makatea* was incised by erosion. However, there is the possibility that the swamp levels were at higher elevations during the Pleistocene high stands of the sea and that the colluvium may be relict from that time. The pockets of lateritic clay soil are able to support a largely intact native forest cover in areas regarded unsuitable for cultivation (Sykes, 1976a; Franklin & Merlin, n.d.). As described by Kauta'i *et al.* (1984), this encircling band of *makatea* was once a rich source of resources for the Polynesians. 'From here our ancestors obtained fine building wood for houses (from) *toa* (*Casuarina equisetifolia*) and *ano* (*Guettarda speciosa*) and timber for the great double canoes from *tamanu* (*Calophyllum inophyllum*) and *miro* trees

(*Thespesia populnea*)...' *Pandanus* was also obtained for thatching, and coconut palms for torches for land crab hunting (Kauta'i *et al.*, 1984).

Between the *makatea* and the central plateau is a discontinuous lowland where streams flowing from the dissected volcanics are ponded back by the peripheral limestones to form swampy areas, the most extensive of which extend for 3.5km in the northeast (Stoddart *et al.*, 1990). A single lake, Te Roto (Fig.5.1), is present on the southwest part of the island. The conspicuous trash line noted at the Tamarua sink on Mangaia at 2m above the swamp level suggests that the underground conduit networks of the *makatea* are sometimes unable to cope with flood discharges and result in higher water levels in the marginal swamps. Chemical analyses of streams within the *makatea* rim on Mangaia suggested that the water draining the central volcanics are under-saturated with respect to calcium carbonate and are thus capable of substantial limestone erosion (Stoddart *et al.*, 1985). Such action may be enhanced by the presence of the taro marshes adjacent to the limestone, supplying organic acids and raising carbon-dioxide concentrations through higher partial pressures in soil air. In particular sulphate levels are high at swamp sites and may lead to acidic drainage where periodic drying and thus oxidizing conditions are encountered (Thornton & Giglioli, 1965). Taro is cultivated in some of the lowlands of Atiu whilst the vegetation community of others is dominated by *Inocarpus edulis*, *Ludwigia octovalvis* or sedges.

5.3. **Soils of Atiu**

Five main soil types have been recognised on Atiu by Grange and Fox (1953) and their distribution is shown in Fig.5.2. The *Tamarua* clay loam is a grey, frequently waterlogged soil principally used for taro cultivation where the water is not stagnant. Today most of the valley flats are extensively modified by artificially impounding stream water to form taro plots. A second type of soil, the *Mokoera* clay loam, occurs as a narrow belt on the inner margin of the *makatea*. This soil is derived from weathered basalt alluvium carried from the central highland probably at the time when the *makatea* surface was close to sea-level. Deposition of this kind is presently occurring on the *makatea* surrounding the low volcanic hills of Takuae Foodland on Miti'aro Island (see Fig.5.17). The *Mokoera* clay is the most fertile soil in the Cook group, being rich in humus and all plant nutrients except phosphate. The full utilization of this soil, however, is impeded by the presence of limestone outcrops which cover 40% of the area of this soil type. Where the soil is not used for the cultivation of citrus and other small crops the vegetation is composed of coconut palms, *Hernandia peltata*, *Hibiscus tileaceus*, and *Aleurites moluccana*. A rocky phase of the fertile *Mokoera* soil occupies the greater part of the *makatea* but its utilisation is restricted by the limestone outcrops. Coconut palms grow notably well on this soil.

The moderately fertile *Tetoa* clay loam is found on the terraces and the gentle slopes on the south-eastern side of the central volcanic hill. Next to the *Mokoera* soil, this is the most fertile soil on the island, and in addition there are no limestone outcrops to impede cultivation. The presence of many fragments of coral indicates that the terraces were sites of villages for many years and that coral had been added to soils to increase pH values and aid cultivation. In contrast, the *Te Autua* clay loam that occurs on the upland flats is highly infertile. It is regarded as the poorest of the lateritic soils in the Southern group, and has a low potash and lime content as well as low available phosphates. It maintains a very poor vegetation dominated by *Gleichenia linearis* and guava, with the occasional *Casuarina* tree. Several healthy fruit trees are, however, found around the villages on the central plateau (Fig.5.3), and occur in pockets of improved soil which may have resulted from the addition of refuse from the houses (Grange & Fox, 1953). The final soil type, the *Te Kapi* clay loam, is found on the moderately steep slopes extending from the gentle land outside the *makatea* up to the margin of the upland flats. This soil is also infertile, and supports little but coconut palms near to the *makatea* while *Gleichenia* and guava occur on the upper slopes.

5.4. **The general climate of Atiu**

The present day climate of Atiu is tropical and is characterised by persistent north-east, east and southeast trade winds, and a mean annual temperature around 25°C, with a diurnal range greater than the annual range. Mean annual rainfall on Atiu since 1958 (Thompson, 1986) is 1970mm, but this is subject to local topographic control. Interannual variability in rainfall is considerable, both in annual and in monthly totals (Stoddart *et al.*, 1990) with the greatest monthly range of between 752 and 0mm occurring in the month of May. To some extent this variability is explained by irregular movements of the South Pacific Convergence Zone which correlate with the Southern Oscillation (refered to in Chapter 1). When the SPCZ is unusually far north, rainfall in the Southern Cooks may only be 30-40% of the yearly average (Stoddart *etal.*, 1990).

The Southern Cook Islands lie within the South Pacific hurricane belt and although little is actually known about the frequency of hurricanes prior to satellite surveillance, it is generally clear from the records of Visher (1925) that storms of exceptional severity have occurred. Since surveillance began in 1969 hurricane frequency has averaged 1.4 per annum in the area of the southern Cooks. Tropical hurricanes, engendering average winds from 100 to 200km/hr, occur most frequently during January to March, and approach from the north-east, curving round to the south and the north-west. Tsunamis also occur in this area but no major ones have been recorded and they are regarded less important than hurricanes in causing coastal inundation (Stoddart, 1975).

5.5. The present vegetation of Atiu

There have been few floristic studies, and fewer ecological studies of native forest vegetation in the Cook Islands (Sykes, 1980). Most published floras and botanical studies have been based on collections from Rarotonga (Cheeseman, 1903; Wilder, 1931; Philipson, 1971; Fosberg & Sachet, 1972; Stoddart, 1972), and Aitutaki, an almost-atoll (Fosberg, 1975; Townsend, 1975; Stoddart, 1975a and b). There have, however, been some good descriptive botanical studies of the Ngaputoru group, providing invaluable information on ecology and ethnobotany, (Sykes 1976 a, b and c, 1980b; Whistler, 1988, 1990) and of *makatea* islands elsewhere in the Pacific (Wilder, 1934). A study on the 'species-environment patterns of forest vegetation on the uplifted reef limestone of Atiu, Miti'aro and Ma'uke' has also been undertaken by J. Franklin and M. Merlin (n.d.) and on the woody vegetation on the limestone of Mangaia and upland region of Rarotonga by Merlin (1985, 1991).

Alien plant species, along with the 'false staghorn' fern *Gleichenia linearis*, dominate the interior volcanic plateau of Atiu, the site of much agricultural activity both recently and in pre-contact times (Sykes, 1976). The native vegetation is, nevertheless, found largely intact on the rugged *makatea* areas (Sykes, 1976) as the karst topography is unsuitable for most forms of cultivation and is difficult to traverse. In general this *makatea* vegetation grades from littoral strand and coastal scrub communities (similar to those described on Upolu, Chapter 4) to the taller forest of the upland *makatea*. The canopy consists mainly of widespread Polynesian littoral species, and a few endemics (Whistler, 1988, 1990; Merlin, 1991). Merlin recognised four forest types on the *makatea* of Atiu: a *Pisonia* littoral forest dominated by *Pisonia grandis*, *Pandanus tectorius*, and *Guettarda speciosa*, and in some areas also containing *Casuarina equisetifolia*; a *Hernandia* littoral forest, dominated by *Hernandia nymphaeifolia*; a *Barringtonia* littoral forest, composed of almost pure stands of *Barringtonia asiatica*; and a *makatea* forest, dominated by *Elaeocarpus tonganus*, *Hernandia moerenhoutiana*, and *Calophyllum inophyllum*. Although *Calophyllum inophyllum* is referred to as a littoral species by Whistler (1983), Franklin and Merlin (n.d.) did not find this tree immediately adjacent to the coast and believe it may have been transplanted into interior forests because of its value as a timber tree (Whistler, 1990; Merlin, 1991). The *makatea* forest was further divided into those with and without the following introduced species: *Aleurites moluccana*, *Hibiscus tiliaceus*, *Cordyline fruticosa*, *Cocos nucifera* and *Syzygium jambos*. These different *makatea* forest types appear to be influenced by a combination of geographical attributes such as position to prevailing winds, elevation, and proximity to the coast or roads.

Franklin and Merlin (n.d.) noted that the tropical forests of the Ngaputoru group have a relatively low diversity of native species compared to the more elevated island of Rarotonga. Only 31 species were recorded during their surveys (Franklin & Merlin, n.d.) on the uplifted reef limestone of these islands. According to the records of

Brownlie and Philipson (1971) the immediate relationship of the pteridophyte flora of the Cook Islands is with the Society Islands. On a broader scale, however, affinities of both the pteridophyte and spermatophyte floras are with the floras of the Indo-Malesian region, characteristic of the South Pacific island region as a whole (Copeland, 1932; Christensen, 1943; Brownlie, 1965).

5.6. Settlement patterns and agricultural practices on Atiu

Originally most of the natives of Atiu lived on the lower ground just inside the lowland swamp areas, and terraces were excavated for houses from the sides of the radiating spurs of volcanic rock (Marshall, 1930). Captain James Cook, however, recorded seeing some buildings up on the plateau during his first visit in 1777 (Beaglehole, 1967). The population of Atiu today lives on the central plateau of the island in five villages (Fig.5.2), representing the pre-European contact organisation into land-holding districts. The amalgamation of the villages was brought about, in about 1823, by the Tahitian pastors of the London Missionary Society who induced the people to move for health reasons. Location on the central plateau did, nevertheless, have its drawbacks, notably the lack of natural water and the poor quality of the soils.

The population of Atiu was estimated by Captain Cook (Beaglehole, 1967) to be at least 2000 in 1777, while John Williams (1837) estimated that it was 'something under 2000' in 1823. Rapid reduction of the population, however, followed European contact, largely as a result of the lack of immunity to western diseases. By 1842 there were only 985, and the population dropped to its lowest recorded level of 759 in 1916. Numbers increased again to 1225 by 1981.

In pre-contact times, the most important species of food plant cultivated on Atiu were taro, banana, breadfruit, coconut, sweet potato, and yam. Nowadays this has been augmented by cassava, but the extensive taro swamps are still very important in providing the staple food on the island. Many dryland foods are also still grown on the lowland areas, including coconut, breadfruit, banana, citrus, pawpaw and mango (Kauta'i *etal.* 1984). Piggeries are also situated in these areas but there are now only a few bush houses on the plantations themselves.

5.7. Lake Roto, its location and surroundings

Lake Roto (also known as Tiroto or Tiriroto) is a small lake situated in the lowlands of the south-west quadrant of Atiu (Figs.5.1 and 5.4) and which abuts onto the inner cliff of the *makatea* limestone (Fig.5.5). It is generally oblong in shape (~183m x 228m) and has a maximum depth, measured in 1986, of 8.4m (Fig.5.1). The lake is 0.9m above sea-level (Hunt, 1969) and is connected to the sea by a sub-*makatea* tunnel through which water is exchanged (Fig.5.5). The lake level is reported to fluctuate slightly with the tides and becomes slightly saline after heavy storms (Kauta'i *et al.*, 1984). The inner wall of the *makatea* which bounds the lake on the west side is deeply notched, with a characteristically horizontal notched roof 1-1.5m above the swamp surface implying a higher than present water-level. The vegetation immediately surrounding the lake is today dominated by *Pandanus tectorius*, *Hibiscus tileaceus* and groves of coconut palms, with reeds and aquatic sedges growing in abundance around the lake margins. A taro plantation is situated immediately to the north of the lake (next to the coconut grove in Fig.5.4) on fine alluvial deposits transported from the basalt slopes above. Fern scrub and grassland occur on the plateau slopes to the north. The lake provides a home for wild duck, fishing grounds for the kingfisher or egret, a favoured haunt of eels, kokobully, and more recently the *tilapia* fish, which was intentionally introduced and now abounds in the shallow margins.

5.8. Sedimentary analyses of Lake Roto

5.8.1. Physical investigations:

5.8.1.1. Sediment core stratigraphy

The composition of the two main sediment cores (core 1, 0-15m and core 2, 0-16m) collected from Lake Roto is shown in Fig.5.6 and, apart from the thicker band of laminated gyttja on the top of core 2 (possibly due to the closer proximity of deltaic in-wash), it appears that a comparable sequence of sediment types exists. Core-2 was eventually used in the laboratory analyses mainly because it was the longer of the two records, but also because of its closer proximity to the deltaic area to the north believed to provide a main source of allochthonous material in periods of catchment disturbance. This could then be used as an indication of catchment stability. The stratigraphy of this 16m sediment core, is described in detail in Appendix 7 and shown in detail in Fig.5.11 (insert) and generally indicates a changing sequence from a terrestrial to a lacustrine environment. A well structured (i.e. with recognised peds) mineral horizon with iron staining occurs at the base of the sequence (16-14m), and is believed to have resulted from a 'lateritic' soil formed *in situ*. Between 14.00-14.15m, this highly mineral deposit gives way to a thin horizon of organic lacustrine mud, indicating greater moisture retention within the catchment. The depression may have contained a lake at this time, a suggestion also supported by the fossil diatom flora (section 5.8.3.3.). Between 14.00m and 10.23m moss/sedge peat deposits, alternating with distinct bands of in-washed mineral clay of increasing thickness, have been attributed to episodic, high energy events (resulting in increased catchment erosion), followed by more stable periods when the growth of mosses and sedges was able to resume. An alternative explanation for this sequence is that there may have been a natural build-up of weathered material derived from the volcanic interior due to a periodic ponding-back of water behind the *makatea* limestone. After a transition zone of peat and organic lake mud between 10.23m and 9m, a predominantly organic based gyttja with some fine in-washed clays occurs up to a depth of 3.52m. This again implies that the water-level in the basin continued to rise leading to the formation of a permanent lake. Above 3.52m, major in-washed mineral clays again occur in the sequence, perhaps during another phase of catchment disturbance (either natural or anthropogenic). The uppermost metre of the core is characterised by a return to an organic-rich lake mud with only a few fine clay laminations, implying that catchment erosion was less significant during this final period.

5.8.1.2. X-ray photography

X-ray photographs of the Lake Roto core showed clear laminations (clay and algal) throughout the sequence (e.g. Fig.5.7a and b), with the exception of the uppermost 5cm of the core. The dense clay horizons seen in the stratigraphy (described above) were also clearly detected in the X-ray photographs, and their extent has been noted in the stratigraphic description in Appendix 7, and shown in relation to the lithology and pollen content in Figs.5.10 and 5.11 (insert). X-ray photographs also detected the presence of the freshwater snail, *Melania incisa* Reeve, associated with the upper 3.30m of sediment (Fig.5.7b). These molluscs are believed to prefer nutrient enriched muds (J. Taylor, pers. comm.) and appear to coincide with the occurrence of in-washed mineral clays in the sequence. A mineral-rich pebble, containing large quartz crystals was also detected in the X-ray photographs at 3.47m (Fig.5.7b), and lends support to the view that slope erosion was particularly significant at this time.

5.8.1.3. Magnetic susceptibility analysis

The magnetic susceptibility profile from the Lake Roto core (Fig.5.9a and b) shows that sediments with relatively high susceptibility occur between 16-13m and above 3.50m, while readings between these zones are much lower and often show a negative susceptibility. The relatively high readings below 14m have been attributed to the iron-enrichment evident in the stratigraphic record. Two notable susceptibility peaks occur between 15.66-15.56m and 14.90-14.30m. Negative susceptibility readings were recorded between 14.10m and 14.02m and correspond to the thin layer of organic-based lacustrine mud. Susceptibility increases again above 14m in response to in-washed mineral clays; however, the readings become progressively less significant towards 12m, perhaps responding to a declining mineral in-put (indicated by the basalt-oxide profiles described in section 5.8.2.) or a migration of magnetic-mineral oxides such as Fe_2O_3 responding to anaerobic conditions within the sediment profile. The second explanation is only weakly supported by the Fe_2O_3 profile (Fig.5.10) which shows a dramatic increase in percentage towards the top of this unit. Levels fluctuate only slightly about zero in the next 8.5m, and appear to be slightly positive in the zones rich in clay laminations, and slightly negative when peats or organic gyttjas dominate. Magnetic mineral content significantly increases again above 3.50m (Fig.5.8b) to the top of the core, with sharp peaks between 3.50-3.46m, 3.20-3.16m and 2.52-2.48m, closely corresponding to major mineral clay horizons. Again these probably represent brief episodes of increased catchment activity.

5.8.2. Sediment geochemistry

The main objectives of the geochemical analysis were to distinguish those sediments formed within the lake habitat (i.e. autochthonous sediment), from material deposited into the lake from the surrounding volcanic, *makatea* and marine habitats (allochthonous material), provide support for the susceptibility profile with regards to the importance of magnetic minerals, and also to determine the fire regime of the catchment through charcoal analysis.

Factor analysis undertaken on the results of the sediment geochemistry (section 3.3.1.; Fig.3.10) indicated that the most significant factor influencing variance within the sediment was the presence or absence of basalt-oxides. The next most influential factors were the presence of Fe_2O_3 and absence of MgO, K_2O and Na_2O. Statistical analysis also indicated the presence of seven distinct zones, and two sub-zones, within the sediment profile (Fig.3.9). These zones are shown in relation to the geochemical profile in Fig.5.10. and in relation to the age-depth profile in Fig.3.27.

The first zone, **RgI**, extends from the base of the core at 16m to 13.29m and contains a transitional sub-zone (RgIa) between 14.02 and 13.29m. The lower 2m of this zone was identified as a red coloured, coarse basalt-derived soil, and its basalt origin is verified in the geochemical anaysis. Silica-oxide reaches levels up to 39% and titanium up to 6%, which suggests that the source rock of this sediment was probably a titan-augite basalt, noted by Marshall (1930) as being common in the central plateau region of Atiu. Aluminium-oxide reaches levels of 23%, and P_2O_5 up to 0.74% at a depth of 14.20m. The relatively high content of Fe_2O_3, which reaches 21% in the base level, strongly suggests that this material is a weathered lateritic sediment, either formed as a soil *in situ* or transported from the interior slopes. As previously noted the visible ped structures would favour the first mode of origin. The sediment between 13.84m and 13.36m appear to represent a transition from the coarse basalt-dominated soil below, to sediments rich in fine clays and peat above. An increase in organic content (to around 30%) just below this transition correlates with the lacustrine horizon recognised in the core stratigraphy. Sub-zone (RgIa: 14.02-13.29m), indicates a sudden revertion back to basalt-dominated oxides and incorporates the large peak of SiO_2, TiO_2 and Al_2O_3 at 13.50m. These samples contain a lower ratio of iron-oxide compared with the coarser mineral soil below. These sediments may have been leached of their iron content before deposition or as a result of post-depositional conditions which may have become increasingly anaerobic as water level within the lowlands increased.

Zone **RgII** extends from 13.29m to 10.20m, and spans a stratigraphy characterised by alternating fine, dense-clay and peat layers of increasing thickness. This zone is, therefore, not of homogeneous composition (as can be seen from the pca axes in Fig.3.9). The alternating stratigraphy is reflected in the 'peaks' and 'troughs' of the basalt-oxides, similarly occurring inversely, in the organic profile (representing the peat content). Basalt-oxides collectively decrease in significance through the zone at the same time as organic percentages increase. The fine grained nature of the clay bands throughout RgII, along with their occurrence successively on top of peat or gyttja deposits, implies that these are in-washed, rather than *in situ* deposits, possibly resulting from progressively less severe episodes of slope erosion. This may have occurred during a period when the water level in the Roto basin was also rising (i.e. relative to the land) to accommodate the developing peat. The sequence may alternatively be explained in terms of perodic flooding of the lowlands when the underground conduit network of the *makatea* was unable to cope with the discharges. This could have resulted in a periodic rise in water level within the marginal swamps. At this stage it is interesting to note that this alternating unit is bounded by two radiocarbon dates of 7820±70 yr BP (8611 yr BP calibrated) and 6730±90 yr BP (7579 yr BP calibrated) i.e. during the period of post-glacial sea-level rise (noted in section 1.2.2.1.). It is possible that a rising sea-level in some way necessitated the relocation (upwards?) of the conduit passages which discharged drainage water from the central plateau and lowlands. If this were the case then the lowlands could have become periodically flooded during the periods when new sub-makatea passages where being dissolved to accomodate this discharge. The predominantly clay units could have been developed during this time either directly from the central highlands or as a result of secondary redistribution of clays within the lowland areas. Once new conduit passages had been formed at the new level and drainage resumed the water level may have fallen slightly. This could have encouraged the intervening deposition of peat until the level was high enough to initiate a new cycle. Stoddart *et al.* (1990) noted that the 20-25m cliffs at Kurekure were conspicuously notched at their base, with a 1m high notch extending to a horizontal depth of 10m in places. Whilst this feature along with similar basal notches on the inner side of the *makatea* near Lake Roto, imply higher water-levels, there is little substantial evidence to suggest lower base levels. During a visit to the 500m long Anetaketake cave Woodroffe (Stoddart *et al.*, 1990) noted the uneven floor and lack of evidence of either wave-cut features or changed base level. The cave does, however, extend below the present water-level and there are pools of standing water. The impressive stalactite, stalagmite and flowstone deposits, with sequences of rimmed terracettes imply that the caves are predominantly solutional structures (Stoddart *et al.*, 1990).

Also of interest in this geochemical zone is the occurrence of a dramatic peak of Fe_2O_3 (40%) at 10.90m, followed shortly by peaks of Na_2O (7.9%), MgO (2.8%), CaO (2.5%) and K_2O (0.25%) at a depth of 10.45m, just below the upper limit of the peat.

This concentration of minerals may have resulted from a period of increased evaporation, with mineral precipitation at the surface of the peat, possibly resulting from warmer and/or drier conditions; alternatively, the iron concentration could have resulted independently of outside factors and merely represent changes in the oxygen status of the sediment column. The peaks of sodium, calcium and magnesium could alternatively be accounted for by an influx of saline water, reaching the lake back through the *makatea* passage. Seawater encroachment may be the result of several factors including short term storm surges, increased atmospheric pressures or higher relative sea-levels (long term). These explanations do not, however, account for the peak in iron-oxide percentages. Interpretations from the pollen analysis, and analyses of the fossil diatom flora, will attempt to answer the question of whether the increasing sodium content of the lake was due to saltwater intrusion, salt spray or was a result of other factors such as increased evaporation or just a relative decrease in the other oxides.

RgIII spans 10.20m to 7.30m and incorporates the transition from peat dominated sediments to lake mud with fine in-washed clay laminations. This zone is characterised by a gradual increase in basalt-oxides along with relatively high percentages of calcium-oxide, which reach a peak of 3.6% at 8.65m. The highest basalt-oxide levels at the top of this zone correspond directly to a horizon of denser clay-laminations and probably represent a decrease in slope stability during the closing stages of this period. Two peaks of silica-oxide (23%) occur at 9.66m and 8.36m which are in excess of the other basalt-oxide ratios. It is possible that these peaks represent increases in diatom concentrations within the lake in some way related to the enrichment by CaO and/or P_2O_5 which both show increases in relative percentages. If the CaO was derived from calcitic-limestone entering the lake system, an increase in the alkalinity of the lake might have occurred, favouring the development of an alkaliphilous diatom flora (see 5.8.3.3. below). Phosphate is often regarded as a limiting nutrient to diatom growth. Diatom 'blooming' and the occurrence of eutrophic tolerant species may have occurred if P_2O_5 was no longer limiting within this unit.

RgIV spans levels 7.30m to 5.05m and like RgIII below has a stratigraphy dominated by an organic lake mud containing fine clay laminations. The basalt-oxides decline in importance through this zone with the noticeable exception of SiO_2, which remains at levels around 20-26%. This surplus of 'free' silica is again believed to be due to increases in diatom concentrations (to be verified in section 5.8.3.3.). Sodium-oxide increases dramatically in this unit from 3.8% at a depth of 7.20m, up to 8.2% at a depth of 5.60m and corresponds to a peak of 2.4% in MgO as well as an increase in K_2O. Iron is not a significant component within this unit. Interestingly, sodium, magnesium and potassium are important constituents of seawater and this zone is believed to represent another period of increased salinity within the lake and its catchment. The mechanism resulting in such an increase in salinity is, however, not clear at this stage.

RgV occurs between 5.05m and 3.35m and spans a stratigraphy of organic lake mud with clay laminations, the latter occurring most noticeably from 4.60m to 4.65m. Na_2O and MgO percentages fall considerably from the start of this zone corresponding to an increase of basalt-minerals, especially rich in iron. The sample at 4.95m (sub-zone **RgVa**) has a geochemical composition very different from the surrounding sample levels and consists mainly of CaO (31%), P_2O_5 (15.5%) and CO_2 + H_2O (6%). X-ray photographs of this sediment section show a small pebble-sized deposit which was later identified as a fragment of limestone, and is the likely cause of these high percentages of calcite. The peak of phosphate in this level may possibly have resulted from an in-wash of guano deposits, commonly found on the *makatea* limestone; however, phosphate is generally limited within the colluvial deposits and the erosional processes active in the *makatea* limestone (i.e. predominantly solutional) are unlikely to have resulted in a re-deposition of colluvial soils into the swamplands. Although there is only a single level which shows this peak of minerals it is interesting to note that it coincides with one of the two main increases in charcoal level (Fig.5.10) described below. However, if, for some reason the vegetation on the raised *makatea* areas close to the inner cliff-line was disrupted during this period, then the limestone and pockets of iron-rich lateritic soils may have become exposed, and vulnerable to aerial processes. If a large-scale clearance of vegetation did occurr at this time it is likely to be detected in the pollen record (discussed in section 5.8.3.1.).

Alternatively, the chemical composition of the streams within the makatea rim may have became more conducive to limestone erosion i.e. became under-saturated with respect to calcium carbonate (as described on Mangaia by Stoddart *et al.*, 1985), or 'aggressive' water flows parallel to the cliff foot which may have resulted in a more physical undercutting of the limestone during periods when the underground network was unable to cope with discharge.

The next section of the core from 3.35m to 1.03m, **RgVI**, is dominated by major clay laminations in a matrix of organic lake mud. Basalt-oxides rise sharply at the beginning of this zone and remain high throughout the rest of the core, again implying increased soil erosion and catchment instability. Percentages of Na_2O, CaO, MgO and SO_3 all continue to decline throughout the upper units of the core.

The final zone, **RgVII** extends from 1.03m to the top of the core, and is characterised by unlaminated mineral clay and organic mud. The geochemistry exhibits similar levels of basalt-oxides to RgVI with the addition of high percentages of iron-oxide, manganese-oxide and phosphate, all likely products of volcanic weathering.

Charcoal analysis of 44 sediment samples from the Lake Roto core, undertaken independently of the X-ray fluorescence analyses, were made with the initial aim of identifying periods of catchment burning. These could then be compared with the pollen record to see if there was any link to agricultural activity. However, only low percentages of charcoal were recorded in the samples, and the resulting profile (in Fig.5.10) has an uncanny resemblance to the profiles of basalt-oxides (also Fig.5.10). This, unfortunately suggests that the levels of charcoal reaching the lake were most probably dictated by the amount of in-washed slope material and were not necessarily indicative of the amount of burning within the catchment. Nevertheless, once the underlying trend related to the basalt minerals had been removed, two periods of higher charcoal percentages were detected. Although these analyses are inconclusive on their own, it is interesting to note that the first charcoal peak, comprising the two samples at 4.70m and 4.40m, (8.86% and 8.82% respectively), corresponds closely to the dense band of clay laminae from 4.60-4.65m identified in RgV. The other peak in charcoal occurs in the 4 samples from 3.19m to 1.60m and corresponds strongly with the opening samples of RgVI, again dominated by in-washed clay laminations. The following palynological investigations strongly suggests that this unit contains the first signs of a significant human population within the catchment.

5.8.3. **Biological investigations:**

5.8.3.1. **The palynological record**

Percentage and concentration diagrams of the fossil pollen flora from Lake Roto are shown in Figs.5.11 and 5.12 (inserts), and initial observations of the pollen records as a whole suggest that the vegetation on the island has changed significantly during the past 9000 years at least (estimated date from Fig.3.27). These changes are seen both through the composition of the pollen flora (best shown by the percentage diagram, Fig.5.11), and indirectly by the absolute counts of grains reaching the lake (shown in the absolute diagram, Fig.5.12), which loosely approximate to vegetation cover in the lake catchment when deposition rates and other external conditions are constant. The percentage summary diagram (Fig.5.13) clearly shows that the vegetation prior to 6730±90 yr BP was generally dominated by fernlands which reached levels of up to 98% of the total pollen and spore counts and never fell below 45%. Arboreal, shrub, herb and aquatic taxa gradually increased during this early period but did not dominate the vegetation until around 6000 years ago (estd. date). The period from 6730±90 yr BP to 1420±45 yr BP saw dramatic increases, first in the swamp fern *Acrostichum aureum*, and then in coconut trees (from ~5000 yr BP estd.), both dominating the vegetation. A notable decrease in primary tree taxa also occurred during this period of the islands history. The vegetation composition changed abruptly again from 1420±45 yr BP with the decline of coconut, corresponding to increases in grasses, sedges and the 'false-staghorn' fern *Gleichenia linearis*.

Principle components analysis of the palynological sequence (Fig.3.11) indicated the presence of seven main composition zones (RpI-VII) and one sub-zone (RpIIa) which are shown in relation to the pollen profiles in Figs 5.11 and 5.12. The lowermost zone **RpI** extends from 16m to 14.55m and corresponds to the dense and coarse, mineral-rich 'soil', of high magnetic susceptibility at the base of the core. Perhaps the most notable point about this zone is the comparatively low concentrations of pollen and spores compared with the upper zones (shown in the absolute record, Fig.5.12), and also the higher proportion of pteridophyte spores compared with pollen. The low counts could be the reflection of a relatively sparse vegetation cover in the region, perhaps as a result of exposed conditions which might have favoured low-lying ferns.

Other possible explanations for the low concentrations of pollen and spores in this zone must be considered. Firstly, since absolute figures are based on counts of grains per gram of sediment the lower density of grains in the sediment may be related to the higher density of the sediment from which these pollen preparations were made. Dry weights of sediment samples used in pollen analyses (see Fig.5.12) clearly show that sediments in the lower 2m of the core were of the highest density (ranging from 0.55 to 0.94g/cm^3). Nevertheless, the dry weight of sediment from, for example, level 3.05m was also relatively high at 0.67g/cm^3, and total counts from this level do not appear to be particularly low. This is reassuring and implies that the effects of sediment density is not over-riding other factors. Another possible reason for low counts in this zone may be the result of poor pollen and spore preservation in the coarse, basaltic material of the lower sediments. The stratigraphic record does not indicate whether this horizon had been permanently waterlogged prior to the formation of the peat above, and oxidizing conditions may well have occurred. As mentioned in the section on stratigraphy and geochemistry, it is thought that this coarse basaltic horizon/soil developed *in situ*, forming in the depression between basalt plateau and *makatea*. If this was the case, it is quite likely that available moisture from the central highland would collect in the depression providing the anaerobic conditions needed for grain preservation. If, on the other hand, the horizon had not been waterlogged, or the basalt material had been deposited in the depression from the surrounding hill slopes, there is a distinct probability that the grains present in the samples would be degraded and pitted (an indication of oxidation). However, only one degraded trilete spore was counted in all three samples, which fortunately suggests that oxidation has not been a major problem in grain preservation. Rapid sediment accumulation in the lake basin during this period could also have resulted in the low concentrations of fossil pollen grains and spores recorded. This would not, however, result in selective deposition or preservation of grain types. Unfortunately, due to the inorganic nature of the sediments, this lower section of the core has not been dated and accumulation rates are therefore unknown.

The fern species which dominate this lower zone include *Pteris commans/tripartita*, species of *Cyclosorus* and *Hypolepis*, *Angiopteris evecta*, *Marattia* sp., and species of Cyatheaceae and Polypodiaceae. *Pteris commans/tripartita* is a very large fern, commonly found at high altitudes and associated with streams and rich alluvial soils on Tahiti (Florence, 1982), but is rarely found on Atiu today. *Angiopteris evecta*, the indigenous king fern, is also found in the inland valleys and high elevation rainforests of Rarotonga and Mangaia but is no longer found on the lower islands of Atiu and Ma'uke, perhaps as a result of human activity and/or higher average temperatures. The species of *Marratia* is most possibly *Marratia salicina*, a large fern common in deep valleys in Rarotonga as well as at altitudes of 300m (Wilder, 1931). Tree ferns, of the Cyatheaceae family, are often associated with cool, but moist upland forest regions of the south-west Pacific islands, as well as occurring in some secondary forests, such as noted by Whistler (1980b) in upland Samoa. The same is generally true for most species of *Cyclosorus* and *Hypolepis*, although they are by no means confined to these habitats. Species of the family Polypodiaceae are today found over the whole range of altitudes and habitats and consequently provide little information about the influence of environment on the vegetation. Although the pteridophyte flora in this zone appear to be common in the cool (and moist) climatic regimes of today the low levels of upland tree pollen which are usually associated with these fern-forests is somewhat confusing.

The only tree present in this zone which reaches over 1% of the total pollen and spore count, but only at the lowest level, is a species of *Trema*, believed to be *Trema cannabina*, an indigenous species still very rare in the Cook Islands (only found in small pockets on the *makatea*) but common elsewhere in the region. Members of the Urticaceae/Moraceae families reach 2% at level 15.80m and probably represent a sparse herbaceous cover underneath the dominating ferns. No other taxa reach levels in excess of 1% in the vegetation of this zone but it interesting to note the possible presence (i.e. under 1%) of *Pritchardia vuylstekeana*, *Pandanus tectorius* and *Calophyllum* sp. in this zone. All three taxa are capable of surviving today in the most severe habitat types such as the *makatea* and coastal regions.

Pritchardia vuylstekeana, now listed as an endangered palm of the Cook Islands (Whistler, 1988), was recently recorded on the south part of Miti'aro (Cook Islands) growing in scattered clusters on the rugged *makatea* (Sykes, Whistler & Merlin, pers. comm.). This fan palm was previously thought to be solely endemic to the nearby island of Makatea, where it was noted by Wilder in 1932 as growing on coral rocks at 200' (~65m) elevation. The new Miti'aro record has now widened the range and status of *Pritchardia vuylstekeana* to a Polynesian endemic (Whistler, 1988), and the presence of pollen from this palm in the Roto sequence indicates that it was also growing on Atiu in the past. The indigenous 'screw-palm,' *Pandanus tectorius*, also has xerophytic adaptations which allow it to withstand the harsh coastal locations on rocky and sandy shores where it is now found abundantly. This tree often forms the chief vegetation above high-water mark in many Polynesian islands, but has also been found growing on the hills in Rarotonga to at least 275m (Cheeseman, 1903), and in the high altitude formations of Tahiti (Florence, 1983; Papy, 1954), where it adapts to all terrains and all types of soils. *Pandanus* is a known prolific producer of pollen which is subsequently dispersed quite readily. Therefore, the pollen in this zone could quite feasibly have originated from a source location other than Atiu. The species of *Calophyllum* is most likely to be *Calophyllum inophyllum*, an indigenous spreading tree also common in the littoral forest on sandy beaches of most atolls and high islands (Whistler, 1980a). Unlike *Pandanus* this genus has been recorded by Southern (1986) as probably under-represented in the fossil pollen record. The parent plant, therefore, most likely grew in the vicinity of the lake, or at least on the island.

The presence of these three trees, although very sparse, supports the view that zone RpI represents a relatively inhospitable environment; however, unlike the pteridophytes they imply that dry conditions prevailed. It must, however, be reiterated that taxa that form less than 1% of the pollen rain of a sample may not necessarily be present on the island. Long-distance dispersal of pollen and spores may account for the presence of Podocarpaceae/Pinaceae and *Alnus japonica* in the pollen samples of this zone, since no records of these taxa have been made for the Cook Islands or indeed any nearby islands and are very unlikely to have been growing locally during this time (Whistler, pers. comm.). Both taxa are also renowned for their ability to disperse pollen over great distances (Flenley, pers. comm.); this fact, along with the relatively low absolute counts of grains in this zone, may have inadvertently resulted in a higher concentration of exotic pollen.

RpII, extending from 14.55m to 12.30m, includes a radiocarbon date of 7820±70 yr BP (SRR-3084) between 13.88-13.98m and a pollen sub-zone (RpIIa) between 14.33 and 13.97m. The base of this zone appears to coincide with the transition from dense basaltic material below into the thin horizon of lake mud (gyttja) above, which is then overlaid by alternating humified peat and dense basaltic clay layers of increasing thickness. This alternation of clay and peat occurs five times within this zone and continues into zone RpIII.

The percentage summary diagram (Fig.5.13) shows that although pteridophytes still dominate the vegetation, percentages have fallen slightly due to increases in primary trees and aquatic taxa. However, absolute counts for ferns, as well as trees and aquatics, actually increase overall and could possibly indicate that climate conditions were more amenable to pollen production and/or vegetation growth compared with zone RpI. This could have resulted from an amelioration of climatic conditions (i.e. warmer and wetter) which enabled a greater range of taxa to grow. The ferns dominating the vegetation of this zone are the same taxa as RpI; however, *Angiopteris evecta* and Cyatheaceae are seen to decrease in absolute terms towards the top of this zone, possibly replaced by members of the fern family Aspleniaceae. Species of this family are found in shaded and moist situations and may have been encouraged by the greater arboreal cover afforded during this period.

The abrupt occurrence of *Cyperus pennatus* (at level 14.30m), an indigenous sedge commonly found in wet coastal places throughout the Pacific, corresponds with the thin level of lake mud in the stratigraphy (RpIIa). This is believed to mark the period when the lake/marsh was initially formed as a result of increased moisture in the lowland depression. Other sedges (Cyperaceae) appear significantly for the first time in this zone, accounting for 32% of the vegetation at level 12.55m. *Cladium jamaicense*, a large indigenous sedge, probably formed the greatest component of this sedge cover. *Cladium* is found today dominating the brackish marshes of Miti'aro but is less common on Atiu. The occurrence of Cyperaceae, as well as the emergent aquatic reed *Typha latifolia*, again imply that wetter conditions prevailed, at least locally around the site. In the pollen record *Typha latifolia* occurs only in very low counts (less than 1%) which would normally be regarded as not significant; however, since the pollen is formed in heavy tetrads the pollen grains are most likely to have been disperse locally.

Mosses appear to be the main component of the peat material, both in RpII and RpIII, and consequently occur in higher percentages in these layers as compared with the intervening clay horizons, occasionally forming up to 50% of the total pollen and spore counts (i.e. excluding mosses). The clay horizons, on the other hand, are associated with lower pollen and spore counts as well as containing several degraded monolete and trilete spores. This perhaps supports the idea that these clay bands were deposited fairly rapidly and were derived from the slopes of the central highlands, where oxidation could have readily taken place. The absence of degraded pollen grains in these samples may imply that the central uplands were dominated by ferns, while the pollen producing plants were confined to the *makatea* (from where there is only aerial transport of pollen). However, because fern spores are very resistant to oxidation/corrosion and often form the predominant microfossil component of river bourne sediment, the fossil pollen/spore spectra may actually be a result of differential transportation/preservation (Taylor, pers. comm.).

The arboreal component of RpII is dominated by *Trema*, *Calophyllum*, and *Pandanus tectorius*. *Trema* reaches 8% at 14.15m and then falls to between 2% and 4%, while the other two taxa remain around 2-4%. Other arboreal taxa, including *Pritchardia vuylstekeana*, *Glochidion*, *Weinmannia rarotongensis* and *Coprosma*, are generally all below 1% but the diversity of species is noticeably greater than in RpI. Members of the Urticaceae/Moraceae group also increase, but it is difficult to deduce whether these taxa are trees, shrubs or herbs due to the similarity of pollen throughout this group.

The alternating stratigraphy of this zone, and the following zone (RpIII), suggest that a fluctuating environmental regime existed during this period, however, it is difficult to deduce whether this has resulted from climatic fluctuations such as rainfall or storm frequency or from local hydrological cycles. Periods of peat deposition may have occurred during moist but stable climates followed by a rapid deposition of slope material in more unstable periods. If storm frequency or severity had increased at this time then salt spray from the sea may have been an influencing factor on plant growth, particularly on the windward side of the island where the Lake Roto catchment is situated. The close proximity of the lake to the sea and the presence of a sub-*makatea* tunnel connecting with the sea, also make the Roto basin a suitable site for detecting any sea-level changes, with associated changes in lake salinity. As previously mentioned, the geochemical analysis of the lake sediment shows several peaks of Na_2O occurring above a depth of 13.84m. The first signs of *Cocos nucifera* and *Acrostichum aureum* also occur within this zone at levels 13.80m and 13.15m respectively (the significance of this record of *C. nucifiera* is discussed later in section 5.8.3.2.). Both of these species are capable of tolerating, and perhaps prefer, slightly saline conditions. The presence of *Cladium jamaicense*, mentioned above as being common in the brackish to saline marshlands of Miti'aro (see Fig.5.17) again supports the idea of an environment influenced by saline conditions. A further indication of increased salinity, through either sea spray or marine encroachment via the sub-*makatea* tunnel, is the presence of three marine dinoflagellates in the lake sediment.

It is believed that pollen zone RpII represents a vegetation under more amenable conditions (perhaps warmer and wetter than RpI) with a small proportion of saline tolerant plants representing the first signs of salt intrusion into the system. The fluctuating horizons either represent a local hydrological response possibly to a regional rise in sea-level or result from episodic storm events which may account for the salt-tolerant vegetation evident in this unit.

RpIII spans the depths of 12.30m to 10.05m and has the same alternating stratigraphy as RpII except that the peat and clay horizons are thicker. The dominant fern taxa of the previous two zones appear to decline in both absolute and percentage terms in this zone. The clubmoss *Lycopodium cernuum*, on the other hand, is seen to increase dramatically throughout, from 14% at 12.05m to 81% at 10.29m. In the Cook Islands this terrestrial clubmoss is commonly found in open, dry hills. The dominance of *Lycopodium cernuum* in level 10.29m, also closely corresponds to the iron-rich horizon in the surface layers of peat (as indicated in the geochemical profile, Fig.5.10), believed to have resulted from higher evaporation over precipitation. The 'false staghorn' fern, *Gleichenia linearis*, is also detected at low levels in zone RpIII, and is today found abundantly on all the dry hills of Rarotonga (Wilder, 1931) and open fernlands of Atiu, where it is generally regarded as an indicator of disturbed, dry, sterile soils.

Whilst the presence of *Lycopodium cernuum*, *Gleichenia linearis* and the iron-rich horizon suggest that a relatively dry (possibly disturbed) environment may have existed during this period, the formation of peat and the presence of aquatic sedges, mosses, *Typha latifolia* and *Acrostichum aureum* imply that the local area in and around Roto basin was still wet enough to support a marshland community. The increase in absolute counts of *Acrostichum aureum*, as well as coconut, may represent an increasing influence of salt spray on the vegetation, or salt intrusion into the ground water.

Pandanus tectorius and *Pritchardia vuylstekeana* are again represented in this zone with counts fluctuating from 1% to 11% of the total flora (the lower counts being associated with the clay-based samples). These two species are known to be able to withstand low moisture availability, a factor characteristic of the *makatea* regions where they are found today. *Calophyllum* and *Trema* appear to be less well adapted to dry, hot habitats and are seen to decline in RpIII. Other arboreal taxa present in low amounts in this zone include *Allophylus vitiensis* (at 10.55m), a large native tree, common in all the valleys on Rarotonga and on the dry hillsides at the lower elevations; also a species of *Rapanea*, possibly *Rapanea cheesemani*, a small spreading tree common at altitudes between 300-400m in Rarotonga; *Pipturus* sp., probably *Pipturus argenteus* a small, indigenous tree, occasionally found in disturbed places and in the *makatea* forests of the Cook Islands. *Weinmannia rarotongensis*, an upland forest species of Rarotonga, is present only at 12.05m, and *Celtis paniculata*, a small tree commonly found in lowland valleys and slopes of Rarotonga reaches no more than 3%.

RpIV covers pollen levels between 10.05m to 8.47m and coincides, at its lower limit, with the transition zone of peat and clay to lake mud. The progression to a lake from a peat-swamp indicates even wetter local conditions than zone RpIII below. The percentage summary diagram (Fig.5.13) shows a definite increase in the proportion of pollen from arboreal and shrubby species, especially primary trees, at the expense of ferns (with the exception of *Acrostichum*), clubmosses and sedges. There are significant increases in *Pritchardia vuylstekeana* (up to 20.5%), *Pandanus tectorius* (up to 16%), *Calophyllum* (up to 7.5%), *Rapanea* sp. (up to 5%), as well as small increases in *Elaeocarpus tonganus* (up to 3%), *Ficus tinctoria* (up to 2.5%), *Glochidion* sp. (up to 1.5%), and a species of *Canthium* (up to 1.5%). The last five taxa are today associated with relatively undisturbed conditions and prefer warm and humid conditions. Other primary trees present above 1% in some of the levels of this zone are *Allophylus vitiensis*, *Weinmannia rarotongensis*, *Coprosma laevigata*, and a species of *Homalanthus*, possibly *Homalanthus pedicellatus*, a small tree found on the undisturbed slopes of the highest mountains in Rarotonga (Wilder, 1931). The main constituents of the increased shrub component are *Celtis paniculata*, which increases in both absolute and percentage terms, and a species of *Guettarda*. A more diverse herb cover has also developed in this zone which includes *Triumfetta procumbens*, *Heliotropium* and *Cyathula*. Interestingly, these herbs are all strand taxa commonly found on sandy beaches of most atolls and high islands, where they appear to thrive in the saline habitats.

The presence of these littoral strand species, along with the dramatic increase of the fern *Acrostichum aureum* (up to 42% at 9.55m.), may have been influenced by a further increase in salt intrusion indicated by the Na_2O profile (Fig 5.10). Grasses are also recorded at levels of 1.5% at a depth of 9.30m. The presence of the indigenous 'bird's nest' fern, *Asplenium nidus*, is perhaps made possible by the increased arboreal cover, since this fern is commonly found growing on trees in the woodlands of all the valleys of Rarotonga, especially along moist hillsides (Wilder, 1931). Also present in the pollen record for the first time is *Jasminium didymum*, an indigenous climbing vine common today from the lowland forest to the montane scrub on Rarotonga. This zone is believed to represent a warmer, and perhaps more humid period than RpIII, stable enough to have allowed for the development of an undisturbed forest community.

RpV extends from a depth of 8.47m to 3.30m and spans a stratigraphy dominated by lake mud and fine clay laminations throughout. The most obvious and abrupt change in the vegetation of this zone is the dramatic increase of *Cocos nucifera.* Percentages of coconut pollen increase from 4% at 8.55m, to 50% at 8.40m, and remain at high levels throughout the zone (ranging from 25% to a high of 76% at 3.55m.). The absolute pollen profile for coconut also shows an increase (with the highest concentrations found at 7.80m). The increase in pollen concentrations of *Cocos* and the tree fig, *Ficus tinctoria/rarotongensis*, is believed to represent a true increase in vegetation density. This increase corresponds to an equally dramatic decline in most of the other arboreal taxa including *Pritchardia vuylstekeana*, *Pandanus tectorius*, *Calophyllum*, *Canthium* sp., *Elaeocarpus tonganus* and *Rapanea.* In the percentage summary diagram the pteridophyte flora are collectively seen to be at their lowest ever percentage levels of around 15-30%. However, ferns still form a significant part of the vegetation as a whole and are dominated by *Acrostichum aureum* and *Pteris commans/tripartita.*

The presence of *Acrostichum* and *Cocos* pollen in such high concentrations, and apparently at the expense of other taxa, suggests that they were capable of out-competing the other plants which may have been under stress from extreme environmental factors. In the light of the sediment geochemistry results, it is suspected that high salinity levels were the main cause of this stress. It may be appropriate at this stage to consider the possible mechanisms which could have led to such increases in salinity and the apparent gradual increase in water level in the Roto basin. It seems feasible to suggest that the increase in basin water level, influencing the progression from soil to peat-swamp and finally to lake, could have been independent of the local climate or at least not totally controlled by rainfall and temperature. Other possibilities which could have resulted in rising lake levels include a reduction in permeability of the underlying material perhaps due to the deposition of fine clays into the basin, and/or a change in the relative sea-level which may have directly influenced the lake level via the sub-*makatea* channel. An increase in relative sea-level might also have indirectly effected the lake level, through its influence on the islands' freshwater-table or as a result of the ponding back of drainage water until new conduit passages had formed (as referred to in section 5.8.2).

If reduced permeability was the cause for lake level rise in the Roto basin the salinity of the water may be expected to have remained more or less stable throughout the rest of the sequence, that is unless saltwater was periodically entering the lake via the channel as a result of strong storms or tidal surges. Short-term increases in water salinity resulting from such events are likely to have affected local lake biota, including diatoms, and local vegetation, such as the aquatics and marsh ferns, but would be less likely to have a direct effect on the floral composition of the whole region. However, salt spray may have became an important controlling factor of floral composition if wind strengths had increased or became more consistent, as a result of increased storm frequency or more consistent prevailing winds. Under these conditions slope erosion might be expected to have increased significantly during this period; however, after an initial period of catchment instability the sediment stratigraphy indicates relatively stable conditions.

If, on the other hand, a consistent post Holocene sea-level rise (either eustatic or relative to island subsidence) had caused the lake level increase (i.e. via the channel), saltwater intrusion would probably have occurred making the water of Lake Roto brackish over longer periods. This would certainly effect the local aquatic taxa and vegetation around the lake periphery, and also the lake sediment and resident lake biota. A rise in sea-level may also have had an indirect effect on the regional vegetation through increases in soil salinity and contamination of the freshwater system (as noted by Woodroffe (1989) in the Maldive islands). In order to shed light on this situation, and to discover if salt was in fact present in significant quantities in the lake water over long or short periods, an analysis of diatoms was undertaken and is described in section 5.8.3.3.

The penultimate zone, (**RpVI**) occurs between 3.30m and 0.80m and spans a stratigraphy dominated by gyttja. However, major clay laminations are characteristic of the lower half of this zone indicating that there was possibly a further period of increased catchment disruption. One of the most significant changes in the island flora during the beginning of this period is the dramatic decrease in coconut, with percentage counts falling very abruptly from 76.5% at 3.55m, to 5.4% at 3.05m, and then remaining around 5-7% for the rest of the record. A similar decline is seen initially in the absolute pollen counts for coconut (from 78,800 grains/g to 12,000 grains/g), but a recovery to a concentrations of 32,400 grains/g is seen around 2.05m. Corresponding decreases in *Acrostichum aureum* occur in zone RpVI, whilst *Celtis paniculata* declines to undetectable amounts. On the other hand very significant and abrupt increases in *Gleichenia linearis* (from 1% at 3.55m to 41% at 3.05m), Cyperaceae and Gramineae occur from the onset of this zone. The presence of these taxa, but most notably *Gleichenia*, strongly suggests that large scale disturbance has occurred, resulting in the opening up of the vegetation cover to accommodate a grassland-fernland type vegetation.

The increases in *Cyperus pennatus* may have been encouraged by the development of alluvial areas in the moist lowlands, probably resulting from the increased slope erosion. The summary diagram (Fig.5.13) shows that *Gleichenia* and other pteridophytes including *Polypodium phymatodes*, *Cyathea affinis*, *Pteris commans*, *Cyclosorus/Hypolepis* and members of the Cyatheaceae and Polypodiaceae, again dominate the vegetation with *Acrostichum aureum* still accounting for up to 3% of the vegetation cover.

In RpVI it is interesting to see the first occurrence of cultivated grasses (i.e. Gramineae in excess of 40μm), and also the significant appearance of other taxa associated with Polynesian introduction including *Casuarina equisetifolia* and *Ipomoea batatas* (the sweet potato) (Whistler, 1991). *Hibiscus tileaceus*, regarded by Franklin and Merlin (n.d.) as probably an aboriginal introduction to the Cooks, also occurs for the first time in the record. It seems quite feasible that the decline of the coconut was in fact due to clearance by a newly arrived Polynesian population. Clearing areas for settlement and cultivation may have resulted in an increased rate of soil erosion accounting for the high density of basaltic-clay laminations at the onset of this zone. A sizable fragment of coarse basalt, containing large crystals of quartz, was found in the sediment core at a depth of 3.47m, i.e. just between the boundaries of zones RpV and RpVI. This provides another small piece of evidence to support the idea that erosion was a significant factor affecting the central volcanic slopes during this period. The new areas of disturbed soil provided ideal sites for the establishment of pioneer fern, grass and sedge species, all becoming well established in this zone.

The ironwood (*Casuarina equisetifolia*), a favoured tree of the Polynesians (Wilder, 1931, Whistler, 1991), appears to have been introduced, or actively cultivated, during this period, and reaches up to 9.5% of the pollen and spore rain reaching the lake. This pine-like tree, often referred to as 'iron-wood' because of its durable wood, is today common in littoral and lowland forests and on fernlands. Whistler, (1980, 1990) suggests that this tree is an aboriginal introduction to Polynesia, while Franklin and Merlin (n.d.) suggest that *Casuarina* may be indigenous to the Cook Islands. A single grain of *Casuarina* was found at 12.05m in the pollen record from Lake Roto, but the morphology and high production of *Casuarina* pollen are likely to have encouraged long-distance dispersal. This single record was, therefore, disregarded, with the rest of the record strongly supporting a Polynesian introduction. *Casuarina* has many reported uses in Polynesia and would be an ideal tree to cultivate on a newly colonised island. It was the favoured wood for making war clubs, and was also used for house posts, tools, and outrigger booms for canoes. The bark is also reported to have been used for preparing a medicine (Whistler, 1980a). *Hibiscus tileaceus* is another tree regarded favourably by the Polynesians. This characteristic secondary forest tree, capable of resisting fire, is presently found in abundance in the littoral forest and mangrove forest margins of most atolls and high islands (Whistler, 1980), and was recorded in disturbed inland sites on the raised *makatea* of the Ngaputoru group by Franklin and Merlin (n.d.). The Polynesian people often use the soft wood of this tree in construction, the making of canoe parts, and for many other purposes (Whistler, 1980). The bast fibre from the bark is also used to make cordage, mats, and kava strainers, while the large leaves are used as coverings for the native ovens. The aboriginally introduced sweet potato (*Ipomoea batatas*) was, and still is, extensively cultivated for its edible root, and is regarded as one of the most important food crops in the Cook Islands (Whistler, 1991). It is also the only plant definitely known to have been aboriginally introduced into Polynesia from the New World.

Apart from *Casuarina*, *Hibiscus* and coconut, the only other trees which are significant in the pollen record of this zone are *Pandanus tectorius* (reaching 2%) and *Ficus tinctoria* (recorded at 3% at 3.05m). Both are highly valued as a source of material and may also have been actively cultivated during this period. Throughout Polynesia *Pandanus* is regarded as second only to the coconut palm in importance and is regularly collected (Fig.5.14) for thatching, the making of fans, hats, mats, and baskets, and formerly for sails (Whistler, 1990). The fruits are often used to make colourful and fragrant necklaces, while the male flowers are used to scent coconut oil. The indigenous wild fig, *Ficus tinctoria*, is a tree commonly cultivated today by the natives as a shade tree. Its tough bark was formerly used to make a coarse cloth, while the dried stems, which will smoulder for a long time, were taken by fishermen in their canoes to light their cigarettes (Whistler, 1990).

The presence at 1.05m of *Bidens pilosa* and *Ageratum conyzoides*, both cosmopolitan weeds recorded as early European introductions, implies that the end of this zone marks the initiation of the European contact period. Both of these 'weedy' composites are natives of tropical America and are common in waste places and croplands. *Bidens pilosa* is most common in dry areas where it often becomes dominant, while *Ageratum conyzoides* prefers moist habitats like taro swamps (Whistler, 1983).

The opening of this zone marks the first clear evidence of Polynesian presence on the island whilst the close of the zone sees the first influence of European contact. Although the lower pollen zone boundary has been placed at 3.30m, and corresponds to an estimated date of ~1300 yr BP, further smear samples (i.e. not statistically counted) were analysed to identify precisely where the change in floral composition occurred. This was placed at 3.54m. An AMS date was subsequently undertaken on the 1cm sediment sample between 3.52-3.53m and a date of 1420±45 yr BP (1310 cal. BP/AD 640) resulted. These additional analyses provided the most accurate means of dating the earliest significant effects of Polynesian activity within the catchment. Following this period, the vegetation underwent a dramatic change from a coconut-dominated flora to a scrubland vegetation dominated by ferns, grasses, and sedges. This floral composition is very typical of the vegetation found on Atiu today, which was described by Marshall (1930) as probably being the natural vegetation cover of the central uplands. The pollen record here strongly indicates otherwise. It is also interesting to note that the main period of primary forest decline (with the exception of the coconut decline), so often associated with the Polynesian settlers, had apparently already occurred as a result of natural forces during an earlier period. This is not to say that the Polynesian settlers did not have a significant effect on the island vegetation and environment, but when they arrived on this island the diverse native forests originally believed to have existed, were already in the late stages of natural decline.

The final zone, **RpVII**, from 0.80m to the top of the core has a stratigraphic record dominated by unlaminated lake mud. The general vegetation composition is similar to RpVI except that this zone is characterised by a significant increase in the diversity of new weed species. Species occurring for the first time at level 0.55m, include *Passiflora quadrangularis*, *Mikania micrantha*, *Bidens* sp., and *Psidium guajava*. *Passiflora quadrangularis* is a strong climbing weed, common in woods, but also often cultivated. Similarly, the composite, *Mikania micrantha*, is a rapidly spreading creeping or twining vine which occurs in nearly every type of disturbed habitat including coconut plantations and taro fields. With its rapid growth, rooting at the nodes, and periodic but prolific seed production, it quickly covers open land and retards the growth of crops or natural vegetation. This species is native to tropical America and was first reported from Samoa in 1924 and from Tonga in 1979 (Whistler, 1983). The introduced guava, *Psidium guajava*, is a shrub or tree originally native to Mexico, but now naturalised in most tropical countries. This formidable weed, first reported from Tahiti in 1815 (Jacquire, 1960), from Samoa in 1893, and from Tonga in 1953 (Whistler, 1983), is commonly found growing in pastures, plantations and along roadsides, and is successfully dispersed by birds who eat the fruits and readily scatter the seeds.

Weeds present in the uppermost pollen level include *Sida rhombifolia*, *Acalypha*, and *Elephantopus mollis*. *Sida rhombifolia*, is a perennial shrub very common on roadsides, in plantations, and in sunny waste places, and is often a dominant species in these habitats. The species of *Acalypha* is most likely to be *Acalypha hispida*, an introduced shrub noted as commonly growing about settlements and disturbed areas on Rarotonga (Wilder, 1931). *Elephantopus mollis*, reported to be a noxious weed in many tropical countries is a composite native to tropical America, which also thrives in dry, sunny, disturbed places and plantations (Whistler, 1983). Most of these new weed species are well known European introductions (with the possible exception of *Sida*), well adapted to competition in disturbed open landscapes now typical of Atiu. European contact with Atiu occurred in 1777 which does not conflict with the age range of this zone.

Barringtonia asiatica, the indigenous fish-poison tree, also occurs for the first time in the pollen record of this zone. The pollen of this huge spreading tree is typically heavy and only dispersed locally, perhaps accounting for its absence in the lower pollen levels. Today *Barringtonia* occurs abundantly in the littoral forests of many Polynesian islands and is often the dominant tree on rocky coasts (Whistler, 1983). Its timber is used for building boats, but the wood is not particularly durable. The large seeds are commonly crushed and put into the lagoon to stupefy reef fish (Wilder, 1931; Whistler, 1991).

RpVII, therefore, appears to represent the main period of Western influence on the vegetation (and indigenous population). However, level 1.05m (in RpVI) probably represents the first arrival of Europeans to Atiu. The lack of clay laminations in the sediment stratigraphy in this uppermost zone may indicate a decline in agricultural activity around the lake basin resulting from a decrease in demand due to a declining population and/or the movement of main settlement sites away from the lowlands and onto the basalt plateau where today's villages are situated. This would have released a certain amount of pressure from around Lake Roto.

5.8.3.2. **Identification of coconut pollen**

One of the most surprising, and important, discoveries made from the pollen analyses was the presence of *Cocos nucifera* at a depth if 13.80m, a level which closely corresponds to the radiocarbon date of 7820±70 yr BP (SRR-3084; 8611 cal. yr BP). This record is crucial in considering the much-debated question of human or natural dispersal of the coconut in the Pacific. Bearing in mind present archaeological and biological data on Pacific migrations (e.g. Kirch, 1986; Bellwood, 1989; Steadman & Kirch, 1990), it seems inconceivable that people could have reached these islands and introduced the coconut at this early date. This pollen record, therefore, controversially suggests that natural dispersal was the mechanism for the establishment of coconut on Atiu.

Although it is generally agreed that the coconut can be dispersed naturally by ocean currents (Papy, 1954), many botanists, including Whistler (1990), have suggested that it was <u>probably</u> an aboriginal introduction over much of its range, as no truly wild plants have ever been found that could not have been carried by humans to the Pacific. However, Fosberg and Sachet (1972) have suggested that the coconut could have arrived by floating, probably from the Indian Ocean. The presence of coconut remains (5040±370 yr BP, 5420±90 yr BP and 5410±100 yr BP) from Aneityum Island, Vanuatu (Spriggs, 1984), also supports the natural dispersal theory of coconut to the West Pacific. Sediment analyses of the Aneityum core by Spriggs indicated that human colonisation of the island took place around 2900 yr BP, i.e. after the arrival of the coconut. A slightly earlier colonisation date for Vanuatu of 3150±70 yr BP was obtained from studies by Ward (1979), but this still does not affect the conclusion. These dates from Aneityum were previously the earliest date for coconut in the world, the next earliest being a date from Aitape on the north coast of Papua New Guinea (4555±80 yr

BP), associated with human skeletal remains (Hossfeld, 1965). Dates of coconut remains from the Solomon Islands by Kirch and Yen (1982) (3360±130 yr BP and 2695±90 yr BP), and by Yen (1973; 2830±90 yr BP) which were previously interpreted as evidence for natural dispersal before human settlement (Spriggs, 1984; Yen, 1973) have now been revised since the discovery of a Solomon settlement date of 28,000 yr BP by Wickler and Spriggs (1988).

Other possible early coconut remains have been recorded from Pagan in the Northern Marianas Islands of Micronesia, in the form of a leaf impression of a coconut seedling located in undated pyroclastic deposits (Fosberg & Corwin, 1958). Spriggs (1985) suggests that all of these dates support an Indo-Pacific, as opposed to a Central American, origin for *Cocos nucifera* (Child, 1964; Harries, 1978). Heyerdahl is now probably alone in his acceptance of a Central American origin with human dispersal as the agent for its spread in the Pacific (Heyerdahl, 1979). Child (1964) suggested an original home for the coconut may have occurred between New Guinea and Fiji, a position accepted by several other authorities (Dennis & Gunn, 1971; Purseglove, 1972; Sauer, 1971).

The 7820±70 yr BP date from Atiu (now the oldest record) strongly supports a SW Pacific origin but further palynological studies would be needed to narrow down the exact location. Perhaps, future archaeological studies in pre-settlement sites will reveal remains of an ancestral coconut that would provide the final piece of evidence. Since archaeological studies have, until now, concentrated on occupation sites it is not surprising that remains of a pre-colonisation type vegetation have not been found.

5.8.3.3. The diatom record

The general objective of the analysis of the diatom flora in the sediments of Lake Roto, was to provide information about changes in the lake environment and to aid the interpretation of the pollen and geochemical analysis. More specific aims were to detect changes in water salinity and nutrient content which would help distinguish between climatic and relative sea-level influences, as well as possible anthropogenic influences on the nutrient status of the lake. The main ecological references, and the basis for the following interpretation, were derived from Lowe (1974), Patrick and Reimer (1975), S.E. Metcalfe and H. Håkansson (pers. comms.). The percentage and absolute diatom concentrations from this sequence are shown in Figs.5.15 and 5.16, and the seven diatom zones and one sub-zone identified in the PCA (Fig.3.13) will now be discussed.

Diatom zone **RdI** occurs from the basal sediments at 16.00m to 11.05m and is characterised by a total absence of preserved diatom valves, except for the sample within sub-zone **RdIa** (14.28-13.98). Low concentrations were certainly to be expected owing to the nature of the sediment but a total lack of diatoms was quite surprising. Coarse iron-rich soils, which may have been periodically dry, and peat deposits low in available free silica, are not particularly favourable for diatom growth and preservation and probably account for their absence. Sub-zone RdIa, however, coincides with the thin layer of organic mud at level 14.15m. Only a few species of *Nitzschia*, *Navicula* and *Achnanthes* were present in very low absolute counts (shown in Fig.5.16). Species of these genera have widely varying ecological preferences and therefore, provide little environmental information if identified only to generic level. However, the actual presence of diatoms gives some indication that the basin was moist and probably permanently waterlogged during this period (this is also supported by the presence of the lake mud).

Zone **RdII** contains two levels between 11.05 and 9.05m. The lower sample level contains a similar diatom flora to that of unit RdIa, but in slightly higher concentrations. In the upper sample level of this zone the total absolute counts rise noticeably and floral diversity increases from two to six taxa, however, along with *Nitzschia* spp. and *Navicula* spp. the dominant taxa is *Chaetoceros* resting spores. This is the first record of *Chaetoceros* in the sequence and is a resting spore of a diatom usually characteristic of marine or saline lake environments (Round, 1973; Gasse, 1986). It is possible that the spores reached the lake from the sea via the sub-*makatea* channel. *Chaetoceros* makes up 39% of the total valves, while *Nitzschia* spp. and *Navicula/Achnanthes* spp. reach levels of 16% and 36% respectively. Other species present include *Amphora coffeaeformis* (1.3%), *Achnanthes exigua* (4%) and *Fragilaria brevistriata* (3%). (The genus *Fragilaria*, which was recently separated into five new genera by Williams & Round, 1987, is referred to here in its original capacity). *Amphora coffeaeformis* is an alkaliphilous diatom which has an optimum pH for growth of over 8. They are regarded as mesohalobous, i.e. brackish water forms occurring in salt concentrations of anywhere between 500 and 30,000 mg/l (Lowe, 1974). Simonsen (1962) has, however, classified this species as polyhalobous, occurring in salt concentrations over 40,000 mg/l. Patrick and Reimer (1975) also noted that this diatom is found only in habitats with rather high conductivity such as estuaries, springs and soil. *Achnanthes exigua* is also regarded as an alkaliphilous diatom with a pH range of 6.8-9.0, and an optimum pH around 8. This periphytic species is tolerant of small amounts of salt and usually occurs in water with a temperature greater than 30°C (i.e. eurythermal) (Lowe, 1974). The alkaliphilous diatom *Fragilariabrevistriata* has a pH range of 6.5-9.0, with an optimum pH of 7.5-7.8. On the nutrient spectrum it is regarded as eutrophic, i.e. characteristic of water with high nutrient concentrations and generally regarded as indifferent on the halobion spectrum (Lowe, 1974); however, Patrick and Reimer (1966) noted it as halophilous, i.e. stimulated by small amounts of salt. Its specific habitat is classified as periphytic and is noted as occurring in a wide range of conductivities (Lowe, 1974). The presence of both *Chaetoceros* spores and *Amphora coffeaeformis* strongly indicates the occurrence of high salt levels in the lake water of this period (apparently supporting the conclusions of both geochemical and pollen analysis). The presence of the other taxa does not conflict with this view. This zone has a peat stratigraphy, containing small amounts of organic gyttja, and as previously suspected represents the first signs of transition from a peat swamp to permanent lake environment.

RdIII, which spans around 1.5 metres of lake mud (9.05m to 7.40m) corresponding to the transition from a primary forest vegetation to a vegetation cover dominated by coconut. The diatom flora is characterised by a slight decrease in concentration of *Chaetoceros* and *Amphora coffeaeformis* and a corresponding dramatic increase, in concentration and percentages, of *Fragilariabrevistriata* and *Nitzschia* spp. *Fragilaria* accounts for up to 89% (at 7.80m) of the total valve counts while percentages of *Nitzschia* spp. reach 55% (at level 8.40m). Peaks in the absolute counts of these taxa occur concurrently with peaks in the silica profile indicated in the geochemical analyses. *Achnanthes exigua* is still present in low percentages (up to 1.4%) along with several new species which all occur below 1%. These include *Pinnulariagibba, Gomphonema angustatum, Caloneis* spp. and *Diploneis smithii.* This latter part of RdIII appears to represent a slight reduction in salt concentrations and perhaps an increase in the pH of the water encouraging the development of alkaliphilous species. Perhaps the decline of primary forest cover indicated in the vegetation has resulted in the exposure of *makatea* limestone accounting for the alkaline conditions in the lake. Nutrient rich conditions indicated by the presence of *Fragilariabrevistriata* could have resulted from higher levels of vegetal material reaching the lake.

RdIV, extending from 7.40m to 4.88m, is dominated by a dramatic increase in *Chaetoceros* spores which rise sharply to 73% at level 6.15m. There is an equally dramatic decline in *Fragilariabrevistriata* and *Nitzschia* spp. from the recorded flora. *Achnanthes exigua* increases to levels of 45% in the lower metre of this zone until it is replaced by *Chaetoceros*, species of *Navicula* and *Achnanthes*, plus *Amphora coffeaeformis* which reach their highest level of 7% at 5.55m. *Gomphonema angustatum*, which can tolerate a broad spectrum of salinity (Lowe, 1974), reaches a level of 2% in the lower two levels of this zone. This diatom is alkaliphilous and often occurs in eutrophic water conditions over a wide temperature range (0^o to $>15^o$), (Lowe, 1974). The eutrophication of lake water at these two levels may have again resulted from removal of the primary forest cover (indicated in the fossil pollen) releasing organic material into the lake. Other species which occur for the first time in the record, but at levels less than 1%, are *Achnanthes coarctata* and *Achnanthes inflata*, both tolerant of some salt and occur in neutral to alkaline conditions (Lowe, 1974).

This zone clearly represents a lake environment influenced by high levels of salinity which favoured the development of *Chaetoceros* and *Amphora*. The highest percentages and very high absolute counts of these two diatoms occur between levels 6.15m and 5.05m, closely corresponding to the peaks of Na_2O and MgO percentages in the geochemical profiles. Maximum diatom concentrations for the whole core were found at level 5.55m correlating strongly with the zone of excess silica-oxide.

Diatom zone **RdV**, occurring between 4.88m and 2.93m, shows a sharp decline in *Chaetoceros* and decreases in counts of *Amphora coffeaeformis*, *Navicula* and *Achnanthes*. *Nitzschia* abruptly increases again, but to even higher levels, reaching percentages between 77% and 96%. *Diploneis smithii*, a species that is found over a broad range of salt concentrations but is generally found between 500-30,000 mg/l (Lowe, 1974), occurs significantly for the first time in this zone, forming 3% of the flora at 3.55m.

The top of this zone also sees the initial occurrence of *Stauroneis phoenicenteron*, *Navicula confervacea* and *Thalassiosira weissflogii* in the record. *Stauroneis phoenicenteron* has a pH range of 6-8.2 and a nutrient range from eutrophic to oligotrophic conditions. It has a wide range of ecological tolerances and usually occurs in water with a temperature greater than 30°C (eurythermal). This diatom is also regarded as euryoxybiontic, i.e. capable of living in polluted water (Lowe, 1974), and perhaps supports the idea that the lake is becoming increasingly eutrophic. Also present is *Pinnularia gibba*, which can also withstand eutrophic conditions and is capable of living in oxygen-poor water (Lowe, 1974). It has a pH range of 4.3-8.2 (acidophilous) with an optimum pH around 6. *Navicula confervacea* has a pH range of 5-8.4 (alkaliphilous to indifferent), with an optimum pH at 8.4 (Lowe, 1974), and can tolerate small amounts of salt. It is usually found in non-submerged habitats (aerophilous), supporting the view that allochthonous material is a major component of the lake sediment at this time. *Thalassiosira weissflogii* has been classified as halophilous, but also as mesohalobous, is mostly found in rivers or at the river mouth where water-level changes or the tide has an influence and where concentrations of suspended sediments are generally high (H. Håkansson, pers. comm.). Such conditions could have resulted from an increased input of slope material or resuspension of bottom sediments.

The penultimate diatom zone **RdVI** extends from 2.93m to 1.30m and shows an increase in the significance of *Pinnularia gibba* (up to 28%), *Navicula confervacea* (up to 6%), *Thalassiosira weissflogii* (up to 5%), and *Fragilaria brevistriata* (reaching 30% at the top of the zone). These taxa point to a lake environment influenced by high nutrient levels and suspended sediments, perhaps poor oxygen status and pH levels ranging from 5-9. *Gomphonema angustatum* and *Stauroneis phoenicenteron* also reach levels of 1.5% and 3% respectively, and again indicate eutrophic conditions.

The final diatom zone, **RdVII**, spans the two levels between 1.30m and the top of the core. This unit contains a species composition similar to RdVI, with the addition of *Pinnularia acrosphaeria* which prefers littoral areas of circumneutral lakes and ponds (Patrick & Reimer, 1975) and may have reached the lake during periods of increased erosion of slope material from peripheral areas. *Nitzschia* species dominate level 1.05m while *Navicula/Achnanthes* spp., *Fragilariabrevistriata*, *Caloneis* spp., *Diploneis smithii* and *Pinnulariagibba* increase in significance in the uppermost level. Again high trophic status is implied in this final zone.

Geochemical analysis detected peaks of sodium-oxide around 10.45m (~6700 yr BP, estd.) and 7-4m (~3500-1500 yr BP, estd.), and although sodium is renowned for its solubility in water and also occurs in small amounts in basalt rock, it is believed, in the light of the significant presence of salt-tolerant and marine taxa, that these sodium peaks resulted from true increases in lake water salinity. This influx of saline tolerant diatoms and marine resting spores appears to be responsible for the 'excess' of silica also represented in the geochemical analysis between 7.20m and 5.20m. Diatoms are able to incorporate free soluble silica into their frustules, and therefore, any SiO_2 which would otherwise be lost to the system is retained in the sediment. The increased salinity inferred from the geochemistry and marine diatoms is now believed (by the author) to have resulted from seawater reaching the lake through the *makatea* passage, either as a result of increased wave action linked to storm surges or persistence of trade-winds, or higher relative sea-levels; however, the extended periods of salinity indicated by the diatoms perhaps favour the second explanation, although a short period of catchment instability was recognised between 5000 and 4000 BP estd. A higher relative sea-level would account for the transition of the Lake Roto basin from a terrestrial to lacustrine system, and for the changes to the floral compositions of lake diatoms and island vegetation. It is interesting at this point to review the sea-level profiles for this area of the Pacific (outlined in Chapter 1) which yield a wealth of evidence for a sea-level higher than present between ~4000 and 2000 yr BP; with records from the Societies and Tuamotus (Pirazzoli *et al.*, 1985, 1988) indicating a possible high sea-level stand between 6000 and 1200 yr BP. Although, the stratigraphic record from Atiu cannot in itself provide definite evidence for a sea-level change it does appear to support a regime of high relative sea-level between ~3500-1500 BP and possibly an earlier hiatus around 6700 BP. The 6700 BP salinity increase can alternatively be explained in terms of increased evaporation during a warmer period which resulted in the concentration of sodium (and other oxides) in the upper layers of the peat deposits.

Information derived from a 7.25m sediment core (core 1: Fig.5.17 and 5.18) extracted from Lake Rotonui (beneath 1m of brackish water) on Miti'aro is also of some interest with regard to possible relative sea-level change after ~7000 yr BP estd. This sequence, which unfortunately proved unsuitable for pollen analysis and geochemical analysis (explained in Chapter 3), was nevertheless dated by a series of four radiocarbon dates (Figs.3.30, 5.17 and Appendix 4) and showed a clear stratigraphic change from swamp to lake environment (i.e. from peat, to peat and organic mud, and finally to red algal/bacterial mud). This change could have been in response to a late Holocene sea-level rise, since the lake level is indirectly controlled by the sea-level. The transition from peat to algal mud occurs at a depth of 7.0-6.25m (or ~8.0-7.25m below sea-level) between 6970±70 yr BP and 6170±120 yr BP, roughly around the peat/gyttja transition period in the Roto sequence. A true lake environment, with a rising water level to accommodate 6m of algal mud, must have occurred from ~5500 yr BP estd. onwards. However, when considering the sedimentation rate and age-depth profile of this core, it is possible that the top 2.5m of the core (i.e. above the uppermost ^{14}C date) do not represent the last ~4380 years or so of deposition. Instead, it is possible that the lake level fell from a higher-than-present-level, resulting in the removal the upper sediments. Extrapolation from the dates of the lower sediments estimates the top of the core to be anywhere between 3500 and 2000 yr BP estd., which appears to coincide with the second period of saline conditions in the Lake Roto basin.

Although there does not appear to be any clear evidence for a higher than present lake level within the inner *makatea* rim (i.e. from the transects surveyed by Stoddart *et al.*, 1990), the presence of a raised notch at 2.3m (at Parava in Fig.5.17), anomalously high sectors of reef flat at 1.23m (possibly of Holocene age) and apparently anomalously high beachrock found up to 1.96m, all suggest a higher than present sea level. These features resemble similar emergence features described by Yonekura *et al.* (1986, 1988) on the northwest coast of Mangaia which all date from a high stand of the sea at 1.0-1.7m above present in the interval 5000-ca 3150 yr BP, after which sea level fell to its present level or less. Although no precise dates regarding relative sea-level change can be determined from this sequence it was interesting to note the general comparisons with the Atiu sequence, perhaps implying that the changes identified in Lake Roto were regional rather than local.

The Rotonui sequence also indicated the presence of four periods of disturbance between 5300 and 4300 yr BP estd., corresponding to levels of re-worked algal sediment. Since the depth of water above the algal sediment is everywhere less than 1m it is likely that any extreme climatic conditions, such as high winds and hurricanes, could cause enough water turbulence to disrupt the uppermost lake sediments. These levels of disturbance could alternatively have resulted from fluctuating lake levels responding to sea-level or local tectonic movements although again there is no geomorphological evidence to support this.

5.8.4. The sedimentary record from Lake Roto: Overall conclusions

The stratigraphic record from Lake Roto, Atiu, shows that several distinct changes have occurred in the lake environment and surrounding vegetation through the past 8611 years. Prior to 1420 yr BP (1310 cal BP/AD 640) changes have been attributed to natural variations in climate (small-scale) and salinity levels linked to relative sea-level change. In the lowest part of the sequence, i.e. before ~8000 yr BP estd., the vegetation was dominated by ferns and clubmosses possibly growing in exposed (perhaps relatively dry), conditions. The period from 8000 to 7200 yr BP estd. may have been characterised by an increase in temperature and/or moisture availability, which encouraged the growth of indigenous trees such as *Pritchardia vuylstekeana*, *Pandanus tectorius*, *Trema canabina* and *Cocos nucifera*. However, the geochemical record points to a relatively unstable catchment, with periodic disturbances checking the full development of the vegetation and causing severe soil erosion. A brief period of relatively dry and hot conditions may have occurred between ~7200 and 6700 yr BP estd.

An ameliorating and more stable climate is inferred from the development of indigenous forest taxa, including *Calophyllum*, *Trema*, *Elaeocarpus tonganus*, *Allophylus vitiensis* and species of *Rapanea*, from 6730 yr BP to ~5200 yr BP estd., with maximum development occurring between 6500-5500 yr BP estd.; however, during this same period diatoms, vegetation and geochemical records indicate a gradual increase in salinity within the lake and island system. Saline tolerant diatoms, including *Chaetoceros*, dominate the fossil records from around 5500 to 2300 yr BP estd., while saline tolerant plants such as coconut and *Acrostichum* dominate the vegetation from ~5200 to 1420 yr BP estd.. Increased salinity during this period has been attributed to a relative rise in sea-level affecting the diatom population within the lake and causing stress to intolerant plants. This stress resulted in the natural decline of several primary forest trees including *Pritchardia vuylstekeana*, *Calophyllum* sp., *Trema cannabina*, and *Elaeocarpus tonganus* around 5000 yr BP estd.. Decline of the major primary tree species associated with undisturbed forests of today, therefore, occurred long before the arrival of the Polynesians, contrary to earlier theories. While most of these primary taxa still exist in small pockets on the undisturbed and coastal regions of the *makatea*, *Pritchardia vuylstekeana* is no longer found on Atiu, although the pollen record shows that it occurred in some abundance prior to 5000 yr BP estd. The fossil pollen record covering the pre-settlement period on Atiu also indicates that natural dispersal was the mechanism for the establishment of the coconut on this island. This palm, associated for so long with Polynesian wanderings, should now be considered as an indigenous tree, naturally established prior to human settlement. Records from Mo'orea (Chapter 6) also support this view.

After 1420 yr BP (AD 640) a dramatic decrease in coconut trees and corresponding increases in aboriginal taxa, grasses, sedges and the fern *Gleichenia linearis*, are believed to represent the first detectable signs of human activity within the catchment. It is quite possible, however, that Polynesians arrived much earlier and that their activities are only marked in the sedimentary record once the population reached significant levels. The removal of coconut trees and the opening up of the vegetation, is believed to have resulted in increased soil erosion from the catchment slopes, and Lake Roto became slightly eutrophic. A reduction in population pressure and/or movement to the central plateau occurred in the period following European contact, which may have resulted in a decline in agricultural activity around the lake basin and allowed slopes to re-stabilise to some extent.

Since the time of human occupation on Atiu, (i.e. estimated at least by AD 650), it is difficult to recognise any underlying natural trends in climate which may have resulted from, for example, the Little Climatic Optimum increase in temperatures or the Little Ice Age increase in precipitation, recognised by Nunn (1990a). However, as Nunn points out, a great deal of Polynesian expansion into the central Pacific actually occurred during the LCO period (~1200-650 yr BP) when winds were more favourable and, as a consequence, any effects that temperature increase may have had on the vegetation and island environment were probably masked by concurrent anthropogenic activity.

6. STRATIGRAPHIC STUDIES FROM LAKE TEMAE, MO'OREA, AND LAKE VAIHIRIA, TAHITI, IN THE SOCIETY ISLANDS

6.1. French Polynesia and the Society Islands Archipelago

French Polynesia is located in the South Pacific Ocean between 7° and 27° S latitude and 134° and 155° W longitude, and consists of 120 islands whose total landmass is about 4000 km^2. The islands of French Polynesia are arranged in five linear, sub-parallel chains in a general NW-SE orientation and comprise islands whose exposed surface is dominated by volcanic rocks, such as the majority of the Society Archipelago, the Marquesas Islands, the Austral Islands, and the Gambier Islands, and those whose exposed surface is built of coral reef material, such as the Tuamotu Archipelago, and some of the Gambier Islands. Vulcanism which constructed the islands and seamounts of French Polynesia began in the Palaeocene and has continued intermittently until the present (Jarrard & Clague, 1977; Schlanger, 1981).

The Society Archipelago (Fig.6.1) covers an area of 720km^2 and consists of fourteen islands (9 high volcanic islands and 5 atolls) divided regionally by reference to the prevailing trade winds into the Windward group (Iles du Vent) to the east, and the Leeward group (Iles sous le Vent) to the west. The principal islands of the former are Tahiti and Mo'orea; of the latter, Huahine, Ra'iatea and Borabora.

6.2. Location, physiography and geology of the island of Mo'orea

The Island of Mo'orea, considered to be the geographical centre of the Pacific Ocean (Fig.6.1), is situated at latitude 17°30'S, longitude 149° 50'W. The island has an area of 132km^2 and is roughly triangular in shape with 61km of coastline (Galzin & Pointier, 1985). Mo'orea is actually the surviving south rim of an ancient and considerably eroded basaltic caldera which forms a jagged semi-circular ridge interrupted by a series of peaks, the highest of which is Mount Tohivea at 1207m (Fig.6.1). This old crater rim, approximately 1.2 million years of age (Jackson, 1976), encircles a central plain (Fig.6.2) which opens to the sea along the northern coast at Cook's Bay and Opunohu Bay. Although only 3km apart, these two bays are separated by Mount Rotui which rises to 899m from the floor of the caldera. On the seaward side of the main ridge, secondary ridges radiate towards the coast formed by deep valleys dissecting the former volcanic cone. The island is encircled by a barrier reef which encloses a generally shallow lagoon (Fig.6.3), 0.50-3.00m deep and 500 to 1500m wide (Galzin & Pointier, 1985). The reef is intersected by twelve passes which correspond to the main valleys on the island (for example the Vaiare pass, shown in Fig.6.3) and are also associated with deeper channels which lie parallel to the coast and act to expel the waters of the lagoon into the ocean. Fringing reefs frequently occur on the landward side of the lagoon abutting a coastal plain composed of both coral beach material and alluvial deposits and varying in width from 10m to 100m. Lake Temae, the only true lake on the island, is situated on the coastal plain in the north-east of the island (Fig.6.1).

6.3. Location, physiography and geology of the island of Tahiti

Tahiti is situated 25km south-east of Mo'orea (Fig 6.4) and is the largest island in the Society group, covering 1040km^2. The island is constructed from two volcanic cones of olivine basalt, connected by the low isthmus of Taiarapu, and surrounded by a single barrier reef. The larger cone, Tahiti-Nui, rises to an elevation of 2237m at Mount Orohena, whereas the highest peak on the smaller cone, Tahiti-Iti, is only 1323m above sea level. Like Mo'orea both volcanic cones are deeply gullied with gorges and valleys graded to Pleistocene low sea levels (Chevalier, 1975). Alluvial fans at river mouths are common, especially from the larger rivers such as the Papeno'o, on the north side, with its source near Orohena; the Punaruu on the west side; and the Vaitepiha, on the north-east of the Taiarapu peninsula. A flat coastal plain, barely a metre above sea-level, varies in width from a few metres to 900m, the widest plains being found on the protected western side of the island. The coastal plain is almost the only area of cultivation and settlement on the island today.

Geologically, the core of Tahiti-Nui is a deeply eroded 1km-wide plutonic plug of nepheline monzonite, theralite, and syenite, and is estimated to have crystallized about 2000m below the level of the original crater floor. Most exposed rocks are lavas, which are predominantly fluid alkaline basalts and basanites, with some ankaramites and oceanites (Chevalier, 1975). Radiometric dating of these rocks indicates that volcanic activity spanned much of the late Cenozoic and may have begun even earlier (Krummenacher & Noetzlin, 1966). A detailed account of the petrology of the rocks of Tahiti is presented in M^{c}Birney & Aoki (1968).

6.4. The general climate of Mo'orea and Tahiti

The climate of Mo'orea and Tahiti is characterised by high humidity, average temperatures between 25°C and 30°C, and an annual thermal variability that is less than the daily variability. However, a cool and dry season from June to September (mean temperature 24.5°C), can be distinguished from a hot (26.5°C) and humid rainy season from October to April. Mean annual rainfall recorded at the meteorological station at Poapoa (Mo'orea) is 2733mm, although rainfall varies considerably according to local factors such as altitude and aspect. On Mo'orea, for example, the average rainfall in high altitude areas often exceeds 4000mm, where orographic precipitation is frequent, whilst rainfall in the littoral areas rarely surpasses 2000mm. On Tahiti rainfall varies from 1000mm/year along the drier coast to as much as 10,000mm in the central mountains (Deneufbourg, 1965). In 1980 rainfall in excess of 10,000mm was recorded in the the valley of Papeiha on the east coast at an altitude of 500m, but the Punaruu valley, at the same altitude on the west and leeward coast received less than 3000mm (Florence, 1983). At higher elevations, such as in the Lake Vaihiria catchment area on Tahiti, temperatures are much cooler as a result of both elevation and greater cloud cover. Due to the oceanic influence on the island humidity is generally high (average 80% to 90%) and frequently reaches 98%.

The dominant winds reaching the islands of Mo'orea and Tahiti are the northeast to southeast trade winds which average between 20 to 40km/hr and may reach speeds up to 60km/hr in the winter. The refreshing, and relatively dry, southeast trade winds (the Mara'amu) blow consistently from May to August varying to easterlies from September to December. This wind reaches only the southeast and southwest regions of the islands. The moist northeast trades (the To'erau) blow from January to April coinciding with the hurricane season. Tropical cyclones, giving rise to average winds of 100-200 km/hr are generally rare (the high number of cyclones occurring between 1983-82 being exceptional (Chapter 1, section 1.2). Data from the National Meteorological Service from Tahiti suggest that 4-8 cyclone events per century occur in the Society Islands, and these storms are typically accompanied by heavy rainfall.

6.5. The present vegetation on Mo'orea and Tahiti

The Society Islands are located at the eastern extremity of the Indo-Pacific biogeographic province where species diversity of the flora is generally poorer than in the West Pacific. The flora of the Society Islands, like Samoa and the Cooks, has its most marked affinities with the Old-World and Indo-Malaysian floras. More subtle affinities, however, also exist with east-Malaysian and Australian floras (Florence, 1983), while the mountain floras of the Societies show some affinities with a sub-Antarctic flora.

The vegetation on the islands of Mo'orea and Tahiti is today dependent on a variety of environmental factors (including the effects of people) and varies from the highly modified coastal vegetation, to the isolated and relatively less disturbed forests of the upper valley areas. Florence (1983) and Fosberg (1992) described several vegetation types on Mo'orea that were fundamentally similar to vegetation stages recognised by Papy (1954) in Tahiti. These included a coastal vegetation; a mesotropical vegetation, receiving less than 2000mm of water per year, and several hygrotropical stages receiving more than 2000mm of precipitation per year.

The littoral vegetation present on gravels and coral sands of the coastal plain is typical of the strand vegetation of many other Pacific islands (such as that described on Upolu in Chapter 4). The primary littoral vegetation has been greatly degraded as a result of human occupation in the coastal regions of Tahiti and Mo'orea and a restricted native flora, including *Hibiscus tiliaceus*, *Thespesia populnea* or *Barringtonia asiatica* is found mixed with introduced species, such as *Terminalia catappa* or *Casuarina equisetifolia*. On the east coast of Tahiti, however, one can still find clumps of forest of *Barringtonia-Pandanus*, with *Morinda citrifolia*, *Vigna marina* and *Ipomoea* spp. forming the pioneer fringe. Other taxa characteristically growing on the coastal flats include coconuts, banyan trees, and the large shade tree *Calophyllum inophyllum*. On the shore the goat's foot convolvulus (*Ipomoea pes-caprae*) creeps over the sand and *Hibiscus* thickets stand in muddy waters in some areas. Natural mangroves are absent from both islands but *Rhizophora mucronata* has been introduced on the Vaiare coast of Mo'orea (Fig.6.5), in an attempt to stabilise the sediments. Cultivated crops are found on the best soils and include yam, sweet potato, taro, banana, and some Polynesian arrowroot.

Several mesotropical formations were recognised on the hillslopes of Mo'orea and Tahiti reaching up to 300-500m. Situated in the zone of intense human influence where fire, deforestation and soil erosion were, and still are, common the mesotropical vegetation is on the whole very degraded and modified. It is dominated by a *Psidium-Gleichenia* scrub, which is particularly well developed in the north-west sectors of Tahiti, but less extensive in the wetter sectors where fires are unable to take a hold. Since its introduction in 1815, the guava, *Psidium guajava*, has spread very rapidly to all disturbed areas, where it has mixed with sparse stands of indigenous species such as *Grewia crenata*, *Pandanus tectorius*, *Metrosideros collina* and *Wikstroemia foetida*, against a background of naturalized species like *Mangifera indica*, *Eugenia cuminii* and the weed *Lantana camara*. The herbaceous stratum of this formation includes almost pure stands of *Gleichenia linearis*, able to regenerate rapidly after fires (Papy, 1954), with some *Lycopodium cernuum*, *Nephrolepis hirsutula* and grass species.

In valleys protected from fires or cultivation on the east coasts of Tahiti, and to a lesser extent on Mo'orea, there survive areas of lowland primary forest made up of *Commersonia bartramia*, *Glochidion* spp., *Alphitonia zizyphoides* and a sub-forest of *Alyxia scandens* and *Canthium barbatum*. The crests also support stands of *Serinthes myriadena* and, more commonly in Mo'orea, *Casuarina equisetifolia*.

Two riparian forest formations are recognised on the lower valley slopes: an *Hibiscus tiliaceus* and *Ficus* forest and a monospecific forest of *Inocarpus fagifer* (the Tahitian chestnut). The former is commonly found at the entrance of the big valleys and contains indigenous trees such as *Neonauclea forsteri*, *Aleurites moluccana*, *Xylosma suaveolens*, the strangling fig, *Ficus prolixa* and the smaller *Ficus tinctoria*. Naturalized species include the avocado and mango tree, and a sub-vegetation of *Canthium barbatum* and *Wikstroemia foetida* are also characteristic. Herbaceous taxa include grasses and ferns such as *Angiopteris evecta* with epiphytic ferns such as *Antrophyum plantagineum*. The *Inocarpus fagifer* forest develops in sub-marshy areas at the mouths of large valleys or on acid substrates. *Inocarpus fagifer*, noted for its buttressed trunk, can reach a height of

20-25m, and its dense canopy results in very low light penetration resulting in sparse undergrowth.

The mid- and high-altitude vegetation formations belong to the hygrotropical stage and support the most diversified of all vegetation types on the islands. On the drier parts of Tahiti, extending from an altitude of 300 to 1000m, *Metrosideros-Dodonaea* forests occupy the interfluves of crests sheltered from the wind; however, in the wetter sectors, this forest formation does not extend beyond 200-300m. Tall isolated stands of *Neonaucleaforsteri*, *Fagraeaberteriana*, and *Rhus tahitensis* are found with *Metrosideros collina* and *Dodonaea viscosum* dominating the lower stratum. Shrubs include *Pittosporum tahitense*, *Wikstroemia foetida* or *Coprosma tahitensis*, with a poor herbaceous cover of *Gleichenia linearis* or *Lycopodium cernuum*. Where the *Metrosideros-Dodonaea* forest has been disturbed by humans, or because of restricting edaphic factors on the crests, a *Gleichenia* heath forms impenetrable thickets. In the past few centuries there has been an increase in the introduction of various aggressive taxa to the islands, but most notable was the introduction in 1930 of *Miconia calvescens* which has become naturalized. It is today seen progressively replacing species of the riparian vegetation and hygrophile forests and was seen growing in great profusion around the lower slopes of Lake Vaihiria in 1985 (Fig.6.6). Florence (1982) also recorded dense areas of *Miconia* during a survey of the lake catchment area.

In Tahiti a cloud forest of *Cyathea-Alstonia* occupies the middle and upper reaches of the valleys, the slopes, and crests between 500 and 1800m. This forest formation is less well developed in Mo'orea where it forms at a slightly lower altitude. The cloud forest is directly linked to the high orographic rainfall and high cloud moisture which forms under the summits, and is characterised by arborescent ferns, especially of the genus *Cyathea*, and the ligneous climbing shrub *Freycinetia impavida*. The discontinuous upper arborescent stratum is dominated by *Alstonia costata* and *Weinmannia parviflora*, along with *Ilex tahitensis*, while in the high valleys *Reynoldsia tahitensis* is also found. The shrub stratum is dominated by *Cyathea* along with *Glochidion* spp., *Crossostylis biflora*, or endemics such as *Sclerothecaarborea* and *Fitchianutans*. The herbaceous component is dominated by ferns including *Marattiasalicina*, *Asplenium nidus* and *Diplazium polyanthos*. A well developed epiphytic cover of bryophytes and filmy-ferns (Hymenophylaceae) along with clubmosses (*Lycopodium*) and the succulent herb *Peperomia* grow amongst the inter-twining *Freycinetia*.

A summit scrub of *Metrosideros-Weinmannia* is found on crests which rise above the cloud layer on Tahiti. Intense insolation, lower moisture and high exposure to winds are the factors which influence this thin band of scrub vegetation. The arborescent component consists of *Metrosideros collina*, *Weinmannia parviflora* and *Myrsine* spp., while shrubs include *Styphelia pomarae*, *Vaccinium cereum* and, on the more organic soils, *Asteliananadeaudi*. The lower exposed summit ridges on Mo'orea have a less well developed vegetation cover often characterised by stunted *Pandanus* trees and *Metrosideros* shrubs (Fig.6.7).

6.6. Settlement patterns and agricultural practices on Mo'orea and Tahiti

The earliest known sites of Polynesian activity in The Society Islands (Fig.1.3) are the burial ground at Maupiti (Emory & Sinoto, 1964, 1965), the water-logged village site of Vaito'otia-Fa'ahia on Huahine (Sinoto & McCoy, 1975; Sinoto 1979b, 1983a, 1983b), and the Vaihi site on Ra'iatea (Semah *etal.*, 1978). From these studies it was concluded by Kirch (1986) that by the 9th century AD at the latest the Society Islands were occupied by several communities sharing a material culture similar to that found in the Hane-Ha'atuatua site in the Marquesas. Archaeological investigations by Green *et al.* (1967) on Mo'orea, led them to conclude that the bulk of the island's population in the pre-contact period was not necessarily concentrated on the coastal flats as it is at present, nor were they necessarily aggregated into villages. Rather, for a people who relied essentially on cultivating food crops, the more scattered, homestead-like pattern of settlement described by the early European explorers, with focal concentrations in ecologically favourable zones inland, was perhaps more likely. However, the territorial base of the political and social unit involved both inland and coastal zones. Kirch (1982b, 1983), on the other hand, believes that initial coastal settlement on the flat plains was perhaps more significant than implied by Green *et al.* and that utilization of marine resources was as important as hillslope cultivation; however, Spriggs (1981) argues that these coastal plains were only formed after human-induced slope disturbance through forest clearance resulted in the relocation of upland soils to the coastal lowlands. This in turn stimulated the movement of a predominantly inland population out to the highly fertile coastal regions.

The English navigator Captain Wallis was the first European to stay on Tahiti in 1767; while Captain Cook was one of the first explorers to land in Mo'orea in 1777 when he gave his name to the Bay of Paopao, now Cook's Bay. The white occupation of these islands really began in 1797 with the arrival of missionaries from the Missionary Society of London. They brought Christianity to the islands and built the first church in the Pacific at Papetoai (Mo'orea). The first known census on Mo'orea was taken by the missionaries in 1804 at which time the population was 2533. Thirty years previously the population had been estimated to be 20,250. At the census in 1977 the island had a resident population of 5,788. In 1769 Captain Cook estimated the population of Tahiti to be around 40,000; but by 1829 it had dropped to 8,568 and a low of 7,169 was reached in 1865. The populations of Mo'orea and Tahiti today (1988 census) are 8801 and 131,309 respectively, and the majority of this population now lives on the coastal plains.

6.7. Sedimentary analyses of Lake Temae, Mo'orea

6.7.1. Lake Temae, its location and surroundings

Lake Temae (Figs.6.8 and 6.9), the only lake on Mo'orea, is situated in the north-east corner of the island and is separated from the sea by a coral ridge (the *motu*). Today this brackish water lake is approximately 1000m in length and 400m wide, with a maximum depth, measured in 1985, of 11.30m. However, a 1928 map of the island by Crossland (Fig.6.10) shows that Lake Temae was formerly larger in area and lay between two smaller lakes. Lake Motuiti, to the north-west, is now totally dry through most of the year and supports a vegetation dominated by *Pandanus* (Fig.6.11), whilst the sediments of Lake Varea, to the south-east, now lie beneath Temae airport. From its coastal position, it seems feasible that the lake had formerly been part of the lagoon system and that the coral ridge was once an island on the barrier reef. Now part of the mainland, the ridge supports a littoral vegetation along with a plantation of coconut palms and *tiare* plants (*Gardenia tahitensis*). Coconut groves and *Pandanus* trees have also been planted around the shores of the lake whilst the aquatic reed *Typha angustifolia* dominates the marshy lake margins and inland delta area (Fig.6.12). On the landward side of the lake the Temae valley rises dramatically up to Mt. Fairurani at 741m altitude (Fig.6.1). The two bordering ridges, which reach the coastal plain either side of the lake, maintain only a sparse cover of vegetation dominated by grasses and ferns (Fig.6.12). The village of Temae, which today consists of a few scattered houses situated at the base of the valley, was one of the main sites of ancient settlement on the island, along with Papetoi, Afareaitu and Opunohu. According to local accounts the lake was frequently used for executions prior to 1860, with the victim apparently being weighed down with stones and drowned!

6.7.2. Physical investigations:

6.7.2.1. Sediment core stratigraphy

The locations and general stratigraphy of the three sediment cores from Lake Temae are shown in Figs.6.9 and 6.13 respectively, and a detailed stratigraphic log of core-1 is included in Appendix 8. Fig. 6.13 shows that the stratigraphy of the two shorter cores was comparable to the upper sediment sequence from core-1, and since the latter core provided the longest (14.5m) and most complete sequence, and also coincided with the maximum lake depth of 11.30m (Fig.6.9), it was chosen for further laboratory analysis. This main core showed significant variation in sediment character throughout the sequence with the lower 7m dominated by a fine, but dense, buff-coloured calcareous material which changed abruptly to a dark brown, mineral-rich band, between 7.05m to 6.40m. Calcareous mud again dominated the sequence between 6.45m and 4.00m, whilst the uppermost 4.00m of sediment was characterised by algal laminations and a varying amount of organic and mineral material.

6.7.2.2. Level of Lake Temae and the coral ridge

The profile over the coral ridge dividing the lake from the sea (Fig 6.9 transect A-C), indicates that the surface of the lake was at sea-level, and that the coral ridge reaches a maximum height of 2.65m above sea-level, dipping steeply on the sea-ward side. A small storm beach, reaching a height of 0.75m a.s.l., was also recorded on the outer edge of the coral ridge. Since a narrow channel links Lake Temae to the sea (via Lake Motuiti) it is unlikely that the level of the lake would have risen above sea-level in the past and there appear to be no historical accounts of a lake level significantly lower than present.

6.7.2.3. X-ray photography

Apart from the uppermost 23cm, the X-ray photographs (e.g. Fig.6.14a-f) show clear light and dark laminations (algal, clay and coral-sand) throughout the core which suggest that, once the sediment was deposited, disturbance has been negligible. The top 23cm of sediment, however, contained a high proportion of water and may well have been disturbed during collection. This has been taken into account in the interpretation of data from this section.

Whilst the horizons and laminations rich in algal material appear light grey on the positive X-ray photographs (Fig.6.14c), the denser coral-sand bands (Fig.6.14d) and less dense mineral-rich laminations appear black to dark grey. The most significant bands are noted in the core log (Appendix 8), and show that algal laminations most commonly occur between 3.90m and 1.20m, while coral-sand bands are common from the base of the core to a depth of 3.68m. Fine allochthonous clay laminations are concentrated in the section between 0.75m and 0.45m, whilst thick zones of mineral clay, containing plant fragments, can be distinguished between depths 11.24m to 11.64m and 6.24m to 7.10m. X-ray photographs detected the presence of the marine mollusc, *Nassarius fraudulentus* (Marrat.), marine barnacles and brackish-water tubeworm cases of *Neopomatus uschakovi* Pillai (J. Taylor, pers. comm.), which were scattered throughout the lower calcareous sediments up to a depth of 7.10m; however, they were most often found concentrated in coral-sand bands and in particular the band extending from 9.65m to 9.91m. These marine gastropods usually inhabit intertidal sand flats and can probably tolerate slightly reduced salinities (J. Taylor, pers. comm.), but there is no published information that verifies this. Whole shells of fresh to brackish water molluscs (Fig.6.14a and b), identified as *Melania incisa* Reeve (J.Taylor, pers. comm.), appear to occur in bands in the upper sections of the core, between 1.10m and 1.80m (with the highest concentrations between 1.26m and 1.70m), 0.72m-0.77m, and 0.05m-0.09m.

No fresh/brackish water molluscs were found below 1.80m, which perhaps implies that the influence of the marine environment was more significant during this earlier period.

6.7.2.4. Magnetic susceptibility analysis

Susceptibility readings from the uppermost 36cm of the Temae core were not included in the magnetic profiles (shown in Figs.6.15a and b) because of variation in core thickness due to high water content. The magnetic profile (Fig.6.15a) clearly shows that susceptibility has varied through the sequence, and ranges from 1.5 to 3813 arbitrary units. Two susceptibility peaks (i.e. greater than 60 arb. units) occur at depths of 6.24m-7.10m and 11.24m-11.64m, and reach maxima of 3813 and 498 arb. units at 6.76m and 11.42m respectively. Fig.6.15b shows the susceptibility profile excluding readings greater than 60 arb. units and indicates the presence of four smaller susceptibility peaks at depths of 9.85m (40 arb. units), 8.98m (40.25 arb. units), 4.94m (43 arb. units), and from 1.32m-0.38m (maximum of 53.5 arb. units). The main peaks in susceptibility appear to correlate directly with the dark brown, minerogenic sediments identified in the stratigraphy (Appendix 8), again implying that the sediment must have originated from the basalt interior rather than being a product of autogenesis. The magnetic profile also detects several smaller peaks, not visibly identified in the stratigraphy, which perhaps indicate small-scale disturbance events within the catchment.

6.7.3. Sediment geochemistry

Analyses of the Lake Temae geochemical record (Fig.6.16) showed strong correlations (82-94%) between the profiles of all the major basalt derived oxides, as well as the minor basalt-oxides K_2O, MnO, and P_2O_5. Organic content was strongly correlated with Na_2O and SO_3, (86% and 71% correlation respectively), while Na_2O, SO_3 and organic content also appeared to be tenuously linked with the basalt-oxide profiles. The correlation matrix showed a 97% correlation between CaO and loss-on-ignition (excluding organics), which suggests that carbon-dioxide, derived from coralline-limestone ($CaCO_3$), was the main constituent of the LOI total (as opposed to H_2O from clay minerals). MgO, however, showed no significant correlation with any of the other oxides. Samples were statistically divided into the following five zones, and three intra-zonal divisions (Fig.6.16), based mainly on the variable content of basalt, organic and calcareous material.

Geochemical zone **TgI** extends from the base of the core, at 14.50m to a depth of 7.05m and corresponds to almost 7.5 metres of dense, calcareous mud (over 40% calcium-oxide), interrupted at intervals by coral-sand bands. Two sub-zones, **TgIa** (11.65-11.35m) and **TgIb** (9.92-9.62m) correspond to two bands of sediment rich in basalt-oxides, with SiO_2 reaching 23.4% and 9%, Al_2O_3 reaching 13% and 4.6%, and Fe_2O_3 reaching 11.5% and 3.8% respectively. These two sub-units, which also correspond to the peaks in magnetic susceptibility, are believed to indicate periods of catchment disturbance. Interestingly, these horizons still have a significant percentage of calcareous material, along with a coarse sand fraction, containing marine molluscs and barnacles, which indicates that material had been brought in from the marine environment as well as from inland. This perhaps supports a natural climatic disturbance as opposed to anthropogenic disturbance. The lower zone abruptly ends with the influx of terrigenous material at 7.10m.

TgII spans from 7.05m to 6.36m and corresponds to a significant band of increased basalt-oxide frequencies, with SiO_2 reaching a maximum of 34%, Al_2O_3 18%, Fe_2O_3 16% and TiO_2 4%. Na_2O increases from 0.75% to 2.6% and peaks are also detected in the minor basalt-oxides. Organic content increases briefly to 17.3% at 6.93m. Unlike the previous disturbance horizons there appears to be very little calcareous material (2%) and no marine organisms in the sediment of this zone, which might have been expected if a strong storm surges or high winds were responsible for the slope disruption. On the other hand, slope erosion may have been initiated by deforestation, perhaps by burning, since charcoal percentages increase significantly at this time to 8.6% (Fig.6.16). However, because the charcoal profile is significantly similar to the mineral oxide profiles (also described in the sequences from Lanoto'o and Atiu) it is difficult to determine whether the increases in charcoal are due to increased burning in the catchment or just reflect the amount of natural charcoal in the in-washed sediments.

TgIII incorporates the sediment between 6.36m and 3.61m and the geochemistry of this zone indicates a sharp transition back to a fine, calcareous based matrix interrupted by coral-sands. A sub-zone (**TgIIIa**) occurring between 4.68 and 4.38m corresponds to one of these coarse grained coral-sand bands which contain high percentages of $CaCO_3$ (47% CaO at 4.56m). These coral-sands are rich in leaf fragments and often contain low concentrations of pollen and spores (section 6.7.4.2). Throughout the rest of this zone there is a progressive change from a calcareous based mud to a predominantly organic-based mud.

The next zone, **TgIV**, occurs between 3.61m and 1.31m, and shows a continuing increase in all the mineral oxides associated with a volcanic source rock, which peak around 2.54m, and an increase in organic content, corresponding to a relative decrease in CaO and LOI percentages. Continuous, small-scale vegetation clearance, slope instability and in-wash may have influenced this gradual increase in allochthonous material. Natural cycles in the disposal of regolith from the steep slopes may also explain the high input of allogenic material at this time. Alternatively, it may have resulted from a relative decrease in the input of calcareous material from the lagoon, possibly blocked off during the final stages of lake formation.

Another significant change in this zone is the dramatic increase in MgO which reaches a peak of 6.5% at 2.54m after having remained stable between 2-3% in the lower core units. This increase appears to correspond to the zone rich in red and yellow algal material. The isolation of Lake Temae from the sea may have resulted in an increase in water temperature similar to that observed by Galzin and Pointier (1985) while considering the effects of coral-sand extraction on the reefs of Mo'orea: 'The dikes which constitute the dredging routes block the circulation of water and hinder its renewal in such a way that certain sectors of the lagoon are isolated and confined: the waters there reach temperatures of 40 -42°C.' An increase in temperature, along with an increase in the nutrient status of the lake, may have encouraged the growth of the red and yellow algae. The presence of similar red and yellow nekron mud has been noted from other coastal Pacific lakes including Lake Rotonui and Lake Rotoiti on Miti'aro, Cook Islands, and Lake Pala and The Red Lake on Aunu'u Island, American Samoa (Parkes, unpublished). This algal production may well indicate the onset of isolation of a lake from marine influence and could also account for the high organic and MgO content (Round, 1973) in this zone. The excess of SiO_2 in zone IV, relative to the other basaltic minerals, may have resulted from an increase in diatom concentration, again in response to increased temperature and nutrient levels in the lake; however, no diatom analyses were undertaken to verify this increase.

The final and uppermost zone, **TgV**, extends from 1.31m to to the top of the core and corresponds to another period of high mineral input. SiO_2 reaches 27%, Al_2O_3 13% and Fe_2O_3 11.5%. Organic content falls slightly, perhaps as a result of decreased algal content, and CaO falls to its lowest recorded level (0.9%). The peaks of basaltic mineral oxides, corresponding to high magnetic susceptibility readings, may yet again indicate a period of slope disturbance and soil influx. This is supported by the appearance of fine clay laminations shown in both the sediment stratigraphy (Appendix 8) and X-ray photographs of this section. Futher information about the nature of these disturbance events is provided by the palynological investigations in section 6.7.4.2.

6.7.4. **Biological investigations:**

6.7.4.1. **Present vegetation survey on the island of Mo'orea**

Results and statistical analyses of data from the vegetation survey undertaken on Mo'orea are covered in detail in Parkes & Flenley (1990) and will, therefore, only be summerised here. Vegetation plot locations, a summary of the measured environmental variables, association analyses and ordination plotted axes, two-way association table, and a list of the plant taxa used in the statistical analyses, are all included in Appendix 1.

In summary, the statistical analysis of the 29 vegetation plots (location map in Appendix 1) revealed that the main environmental variable influencing the vegetation on Mo'orea was altitude. The ways in which altitude affect vegetation, however, are not always straightforward. It may influence vegetation through its effects on temperature, precipitation, insolation and wind strength. Nevertheless, temperature decrease with altitude is usually regarded as the most important of the factors controlling floristic composition (Steenis, 1962). Complications can occur, however, when inversions of the normal temperature-altitude gradients are disrupted by the flow of cold air downhill (Flenley, 1969).

The angle of slope appears to be the second most important factor affecting the vegetation composition in Mo'orea. The effects of slope are also indirect, influencing for example, the depth of soil, moisture content and insolation with regard to aspect. Altitude and degree of slope, may in turn have affected the amount of human activity and subsequent disturbance of the vegetation. High altitude regions are less accessible compared with lowland coastal areas. Steep slopes are more difficult to cultivate and settle. However, Spriggs (1985) and Earle (1980), when considering sites on Aneityum and the Hawaiian Islands respectively, noted that the coastal plains which appear very fertile today may well have been susceptible to severe flooding at the time of the first settlers. Although much of the population of Mo'orea now lives on the flat coastal plain surrounding the island, signs of earlier anthropological disturbance can be found in the higher forested areas, for example above Afareaitu. These high altitude forests are no longer inhabited and it is the lower slopes of the valleys that are being increasingly cultivated.

The vegetation pattern on Mo'orea is further complicated by the effects of cyclones, which may override the usual ecological factors of soil and micro-climate; and instead of a stable forest, a disturbed community is found. Although Mo'orea does not experience frequent cyclones, that of 1983 caused considerable damage and the vegetation on Mo'orea may still have been recovering two years later when this survey was undertaken. Nevertheless, the vegetation survey provided a fair basis for the interpretation of the fossil pollen assemblages especially with regards to deducing the degree of vegetational disturbance, since a clear distinction was detected between the disturbed vegetation types, mainly at lower altitudes, and the relict primary forests, found mainly in the upland regions. Several disturbance indicators, most notably *Gleichenia linearis*, were also detected and have been incorporated into the ecological data.

6.7.4.2. The palynological record

Pollen and spore profiles from the Temae sediment core are shown in percentage form in Fig.6.17 (insert) and in absolute form in Fig.6.18 (insert). The percentage summary diagram (Fig.6.19) shows the proportions of trees, shrubs, herbs and pteridophytes, as well as the distribution of primary, secondary and 'weedy' taxa throughout the record. The outer plates of marine dinoflagellates, having a similar structure to pollen grains, were well preserved in the pollen preparations and were also counted to provide further information on the marine influence. The percentage profile of dinoflagellates, represented as percentages of total pollen and spore counts, is also shown in Fig.6.17. Factor analysis of the fossil pollen and spore record (Fig.3.7) indicated the presence of six zones and four sub-zones, which in most cases closely coincide with the geochemical zones described above.

Zone **TpI** extending from the base of the sequence to 7.00m closely corresponds to zone TgI in the geochemical record, but contains three intra-zonal divisions as opposed to two detected in the XRF analysis. These sub-zones occur between 14.50-14.45m (**TpIa**), 11.65-11.35m (**TpIb**), and 9.92-9.62m (**TpIc**). The pollen record in TpI (excluding sub-zones) is dominated by *Pandanus tectorius*, constituting 39% to 86% of all pollen and spores. This hardy, salt-tolerant tree, a native to Polynesia, occurs throughout the island today and has successfully been cultivated on the coastal plain. Other taxa significant in this zone are *Cocos nucifera* (reaching 13%), *Trema orientalis* (up to 13%), *Ficus tinctoria* (up to 11%), *Macaranga tahitensis* (up to 7%), *Neonauclea forsteri* (up to 6%), and members of the Urticaceae/Moraceae family. All of these trees are today associated with secondary forest formations on Tahiti and Mo'orea, but *Neonauclea forsteri* and *Ficus tinctoria* (the indigenous wild fig) are found as isolated stands in mid-altitude hygrophile forests of *Metrosideros* and *Dodonaea* (up to an altitude of 1000m on Tahiti), where human disturbance is reduced (Florence, 1983). Both species are also found in the *Hibiscus-Ficus* forests at the mouths of large river valleys (Florence, 1983). The presence of *Cocos nucifera* pollen in these lower levels suggests that this palm was introduced to Mo'orea prior to the arrival of the Polynesians, favouring the concept of natural dispersal through the central Pacific islands. This tree therefore, can also be regarded as a primary tree in the period prior to extensive cultivation by humans.

Pollen samples associated with sub-zones TpIb and TpIc contain a significant percentage of degraded pollen grains and spores, mainly of taxa characteristic of primary upland hygrophile forest environments, such as *Ascarina polystachya*, *Weinmannia* sp., *Eugenia rariflora*, *Metrosideros collina*, and the shrub *Polyscias guilfoylei*. The species of *Weinmannia* is most probably *Weinmannia parviflora*, and along with *Metrosideros collina* forms the dominant species of the mid- and high-altitude hygrophile forests on Mo'orea and Tahiti today (between altitudes of 500 to 2200m on Tahiti). *Weinmannia parviflora* was also noted by Florence (1983) as occurring on the wind protected slopes in the cloud forests of Tahiti. Degraded upland ferns include the tree ferns *Cyathea affinis* and *Cyathea horrida*, both associated with the undisturbed cloud forests of the Society Islands, found particularly in deeply shaded areas on stream banks or near waterfalls; *Lycopodium phlegmaria*, a fern common at altitudes above 300m; and members of the *Cyclosorus/Hypolepis* group. *Macropiper* sp., possibly *Macropiper latifolium*, an indigenous shrub, present in the montane forests, also represents 8% of the grains in sub-zone TpIc. Pollen from the small tree *Meryta*, associated with both primary and secondary forest formations, is also present in these two sub-zones in a slightly degraded state. The presence of degraded grains of primary upland taxa in conjunction with much detrital material and the appearance of the disturbance indicator *Gleichenia linearis* (up to 4%), support the idea that two relatively severe events took place high up on the humid slopes of Mo'orea. These are believed to have resulted in the removal of the top soil, containing quantities of upland forest pollen and leaf litter, which was then re-deposited on the lower plains and in the lake/lagoon. There is also a noticeable decline in relative percentage and absolute counts of *Pandanus* pollen in these 'disturbance' sub-zones and littoral forest species, including *Barringtonia asiatica* and *Messerschmidia*, which occur at low levels in TpI, are noticeably absent. Dinoflagellate percentages are also significantly lower in TpIa, Ib, and Ic, indicating that the sediments have been derived mainly from inland. It is interesting to note that *Myrsine affinis*, a small tree of the high altitude hygrophile forests, is no longer detected in the pollen record above 9.96m. However, the main primary forest component does appear to have maintained low levels of counts in the periods following the catchment disturbance.

The lowest sub-zone (TpIa) contains some degraded upland taxa but also significantly high counts of sedge, grass, *Gleichenia* and coconut pollen. The sedge *Fimbristylis cymosa* accounts for 20% of the total count while other sedges (Cyperaceae) account for another 10%. Gramineae, at 4% and *Gleichenia linearis* at 6% all suggest that an open and newly disturbed vegetation existed, at least in the vicinity of the lake. This level may, therefore, represent the close of another episode of disruption on the upper slopes of the catchment which resulted in the formation of new alluvial areas down slope allowing for the colonisation of pioneer taxa and coconuts (which account for 9%).

TpII, extends from 7.00m to 6.45m and corresponds to the band of dark brown sediment rich in mineral oxides. The pollen record again shows a peak in degraded upland forest taxa, similar to those seen in TpIb and TpIc. Additional primary taxa which briefly occur in this zone include the endemic tree composite *Fitchia*, *Rapanea tahitensis*, *Eugenia* sp., *Alstonia costata*, *Astronia fraterna* and *Freycinetia impavida*, all found today in the high altitude hygrophile and cloud forests of Tahiti, but occurring less frequently on Mo'orea, where *Fitchia* is totally absent today. The tree ferns *Cyathea affinis*, *Cyathea horrida* and other Cyatheaceae increase to their highest levels at 17%, 3% and 8% respectively. After the initial increase in upland forest taxa in this zone, and unlike the periods following previous episodes of disturbance, several primary woody species decline to undetectable amounts. These include *Alstonia costata*, *Astronia fraterna*, *Fitchia* sp., *Premna tahitensis*, a species of palm, and *Metrosideros collina*. Other species, such as *Ascarina polystachya*, *Rapanea tahitensis*, *Weinmannia* sp. and *Weinmannia vescoi*, decline to some extent but appear to recover again towards the top of the core.

This second zone also sees a fall in the percentage and absolute counts of *Pandanus tectorius* and *Cocos nucifera*, along with several secondary taxa such as *Macaranga tahitensis*, *Neonauclea forsteri* and *Trema orientalis*. There is a corresponding appearance of the swamp reed, *Typha latifolia* (2%) and members of the Cyperaceae family (2%). *Colocasia esculenta* (taro), an aboriginal introduction and today widely cultivated throughout the alluvial swamplands of Polynesia, occurs for the first time in this zone (2%), along with *Cordyline terminalis* (at 3%), an erect shrub with an enlarged edible root. Although probably native to the western Pacific, *Cordyline* is believed to have been carried by Polynesians to the eastern island groups where it was subsequently cultivated. The presence of these two taxa, as well as the appearance of the introduced weed *Acalypha* (at 6.33m), strongly points to the influence of human agricultural activity within the Temae catchment.

The increase in alluvial swamp vegetation in this and the following unit probably resulted from the availability of freshly deposited alluvial material, derived from a large scale disturbance event in the upper catchment area. The redistribution of soil material from the steep, relatively inaccessible valley slopes to the flatter coastal areas would have provided newly arrived Polynesian settlers with a fertile, and elevated coastal plain, ideal for the cultivation of crops such as coconut, *Pandanus* and taro. The presence again of *Gleichenia linearis* from around 7.18m to the top of the core may be a direct response to vegetation and land disturbance.

Zone **TpIII** extending from a depth of 6.45m to 4.73m, corresponds to the return to calcareous mud in the lake sediment record. The reed, *Typha angustifolia*, the sedge, *Fimbristylis cymosa* (up to 23%), and grass species all increase in this zone, while two other swamp taxa, *Acrostichum aureum* and *Stenochlaena palustris* occur at low levels and perhaps represent the initial stage of a natural transition from the pioneer species of sedges to the slower colonising swamp ferns. The ironwood tree, *Casuarina equisetifolia*, occurs for the first time in the pollen record of this zone and supports the view that this tree was introduced by Polynesian voyagers. *Calophyllum inophyllum*, the highly regarded mape tree, also appears in the record at this time. Although an indigenous tree of the littoral forest, the Polynesians often planted mape trees around their sacred *marae* sites. In spite of being common on the island today, only very low counts of *Calophyllum* were found in the pollen record of the upper sediments, a fact that probably reflects the low pollen production of this tree.

Other significant changes in the pollen composition of TpIII include the fluctuations in coconut and *Pandanus* counts. Fluctuations between these two taxa may have resulted from changes in cultivation techniques by the Polynesians, and their preferences between these two trees. A peak in *Cocos nucifera* (24%) occurs around level 4.90m while *Pandanus* falls to a low of 6%. Coconut then falls dramatically in **TpIV** (4.73m to 3.07m) to be replaced by *Pandanus* (which increases to 64%), and other useful tree species such as *Hibiscus tiliaceus* and the introduced shade tree *Terminalia catappa*. Small scale edaphic changes may have alternatively encouraged the development of *Pandanus* or *Cocos*. This seems fairly unlikely since both species have very similar requirements and tolerants. At present, *Hibiscus* is common everywhere from sea-level to highlands, and grows particularly well at the mouth of large river valleys. This versatile tree was cultivated for its large leaves, its light wood and for the fibre of its bark.

A sub-zone (**TpIVa**) between 4.73m and 4.58m corresponds to a pure band of coral-sand and contains no pollen or spores. Marine dinoflagellate concentrations fall completely above this level and probably mark the end of marine contact with the lake.

TpV extends from 3.07m to 1.31m and closely corresponds to a stratigraphy dominated by algal material. The pollen record in this zone indicates the re-introduction, or recovery, of a few primary plant taxa, namely *Weinmannia* sp., species of the family Elaeocarpaceae, and *Eugenia rariflora*. Apart from *Pandanus* (at between 34 and 63%), however, it is the secondary trees and shrubs, including *Ficus tinctoria* and *Trema orientalis*, along with pteridophytes such as *Gleichenia linearis*, *Angiopteris evecta* and *Acrostichum aureum*, that dominate this unit. The robust king fern, *Angiopteris evecta*, today forms an important component of the valley and secondary upland forests on Mo'orea. Also noteworthy is the increasing diversity and percentages of ruderal herbs, including *Mimosa pudica* and *Bidens paniculata*, both introduced cosmopolitan weeds, common today in gardens, sunny open pastures, and on roadsides in Mo'orea. *Achyranthes aspera*, a weedy plant of coastal plantations, also occurs briefly at 2.54m. Significant increases in percentages and absolute counts of cultivated plants include *Colocasia esculenta* (5%); the banana, *Musa paradisiaca* (2%); the *tiare*, *Gardenia tahitensis*; *Cocos nucifera*; the large shade producing tree *Barringtonia asiatica*; and *Casuarina equisetifolia*. The slight recovery of primary upland taxa and the corresponding increase in swamp cultivars, e.g. taro, could indicate a shift of importance from hillslope activities to the lowland plains. This perhaps supports the idea (Spriggs, 1985) of a late intensification of agricultural activity on the now more extensive alluvial plains.

The final zone, **TpVI**, occurs from 1.31m to the top of the core and shows a further increase in introduced ruderal herbs. These herbs included *Bidens pilosa*, *Ludwigia octovalvis*, *Ageratum conyzoides*, *Elephantopus mollis* and the prolific *Stachytarpheta*, all of which are found in disturbed and open areas of Mo'orea today and have been strongly associated with European introduction. The highly competitive shrub, *Miconia calvescens*, also shows itself in these upper sediments. It is this extremely prolific species, which was introduced to Mo'orea only 60 years ago, that poses the greatest threat to the island's remaining natural vegetation. A further invasive plant, originally introduced in 1850 for its fruit and now occupying vast scrub areas with *Gleichenia* *linearis*, is the guava plant, *Psidium guajava.* The pollen of this plant occurs in the uppermost sample level of the core. The composition of pollen and spores found in this uppermost zone closely resembles the floral composition found on Mo'orea today.

The sudden influx of *Typha angustifolia* pollen into the lake (reaching up to 59%) again suggests that there was an increased availability of open, flat land. The increase in this freshwater reed may alternatively have resulted from a decrease in the salinity of the lake as the marine influence was cut off, with *Acrostichum* (more tolerant of saline conditions) being naturally replaced by *Typha angustifolia.* Today Lake Temae is almost surrounded by *Typha angustifolia* which has colonised nearly all the available peripheral mud.

6.7.5. The sedimentary record from Lake Temae: Overall conclusions

At this site the very existence of the lake in its present form is probably dependent on human activity. The location of the lake suggests that it could formerly have been part of the lagoon behind the coral barrier reef and that it has been cut off from direct marine influence by a massive influx of sediment at both ends of the lake. This sediment may have been derived from the seaward reef, as coral fragments were broken away during tropical storm surges and later accumulated in the lagoon (similar to that described by Stoddart & Walsh, 1992; Woodroffe, 1983 - on Tonga; Stoddart, 1971b and Fitchett, 1987 - on Tuvalu), or more probably from in-washed material from the steep basaltic slopes above the lake during periods of disturbance (anthropogenic and/or natural). The idea of a marine origin for the lake is strongly supported by several other lines of evidence. Firstly, the lake is at sea-level (Fig.6.9) and is still brackish. Secondly, the bulk of the lower part of the core consists of a dense, but fine grained, calcareous mud which is interrupted at intervals by thin bands of coarser coral and shell fragments (coral-sand). This calcareous mud is typical of sediments found in the sheltered lagoon environments of Mo'orea today, (Galzin & Pointier 1985), and the coarser coral fragments are probably derived from the outer barrier reef, by breaching waves, during short period fluctuations in sea-level associated with meteorological conditions (described in section 1.3.1.1). These lower calcareous sediments are also rich in marine dinoflagellates, barnacles, marine molluscs and tube-worms which disappear dramatically above 7.0m.

Based on the two available dates from the Mo'orea sequence several preliminary conclusions have been reached. During the period between approximately 1750 yr BP and 1210 yr BP there were apparently frequent small and medium scale disturbance events which scoured material from the seaward side of the barrier reef and deposited it into the protected lagoon environment. These manifest themselves in the formation of coarse coral-sand bands sandwiched between finer calcareous mud, deposited during calmer periods. A <u>very</u> rough estimate suggests that small scale events occurred once every 10 years. This order of magnitude roughly coincides cycles of the Souhtern Oscillation which have an estimated periodicity of 2-7 years. Medium scale events occurred once every 100 years. These episodes, however, were not severe enough to have dramatically affected the inland vegetation. Two or three major events also occurred within this time period at levels 11.50m (dated at 1540 yr BP), and 9.87m (~1420 yr BP estd.), and possibly also at the lowest level, 14.42m (~1750 yr BP estd.). These events were severe enough to affect both coastal and inland areas. This implies that disturbance was the result of a large-scale climatic perturbation rather than local factors. Upland vegetation was disrupted, and soil may have become exposed to strong winds and heavy rain resulting in slope erosion. Nevertheless, this upland vegetation generally recovered after these events and loss of taxa was minimal.

The disruption of vegetation, and resulting soil erosion (around 1210±90 yr BP estd.) have been attributed either to the presence of significant Polynesian activity on the island or perhaps to a shift to more intensive cultivation practices on the catchment slopes if an indigenous population already existed. Archaeological evidence from the Society Islands supports a Polynesian arrival somewhere around the 9th century AD, i.e. some 1100 yr BP estd., perhaps favouring the first explanation. Plant taxa associated with Polynesian migration also appear around this period. The coconut palm, on the other hand, appears to have become established prior to human arrival as indicated in the Lake Roto sequence from Atiu (Chapter 5). Throughout this period of increased soil erosion (1220-1100 yr BP estd.), the lake was slowly being isolated from the rest of the lagoon by material in-washed from the bluffs.

Increases in the indigenous population, from 1210 yr BP (AD 790) onwards, may have encouraged the practice of forest clearance, perhaps initially on the lower valley slopes where it was easier to settle and cultivate. Interesting questions, however, arise when considering why the upland vegetation, on steep, less accessible slopes, was also disrupted. Evidence from Tahiti and Mo'orea indicates the existence of cultivation high up in the interior of the island at least up to the time of Cook's visit (Beaglehole, 1967), and during times of inter-island conflict populations may well have retreated to the upland areas. Alternatively, the Polynesians may have purposely induced soil erosion in these upland areas to encourage the accumulation of fertile alluvial plains down towards the coast as suspected by Spriggs (1981) in Anietyum, Lakeba and Hawai'i. At this point it is also interesting to note the geoarchaeological research carried out in the Kawainui marsh, O'ahu, in the Hawaiian islands. Allen-Wheeler (1981) documents the transition of this area from a saltwater bay to a major area of taro irrigation and aquaculture. The process involved a complex mix of natural activity, i.e. the formation of an accretion barrier across the lagoon mouth, and human action, i.e. erosion associated with forest clearance. Drigot (1982) raises the possibility that the alluvial infilling of this marsh was a controlled, intentional process rather than an unintended consequence of cultivation within the catchment. The possibility exists that the formation of Lake Temae and surrounding elevated alluvial areas was also intentional.

Although the pollen evidence strongly suggests that there was a significant Polynesian influence on the island vegetation during this period one cannot rule out the possibility that slope erosion was purely the result of natural processes. For instance, natural cycles of regolith development and landsliding are well known from Hawai'i and fifty years ago Wentworth described a cycle of soil build-up and failure every 100 years or so, which were just related to a natural set of processes on steep slopes with high rainfall and not to climatic change or human activity.

In the period up to approximately 300 yr BP, there were further changes in the vegetation composition, believed to be the result of changing cultivation practices. The progressive anthropogenic influence may have resulted in the opening up of the landscape and influenced the colonisation of ruderal herbs and grassland species. The formation of new, flat and highly fertile land encouraged the cultivation of more coconut and *Pandanus* on the sandy areas, along with taro in the deltaic swamps. The lake was finally cut off from the surrounding lagoon during this period and is marked by a transition from calcareous based sediment to organic and mineral based sediments in the lake. Marine dinoflagellates, molluscs and barnacles also disappear from the sediments. Algal muds then developed in the lake with continuing inputs of nutrients and possibly higher water temperatures.

The arrival of the Europeans some two centuries ago is marked by the further introduction of aggressive weed species and a slight recovery in the primary forest taxa. The recovery of an upland forest may have resulted from a decline in the indigenous population. Alternatively, or in addition, the settlement of coastal, as opposed to inland, areas may have released pressure from the upland forests. Today, all the settlements are located around the coast, where most of the cultivation takes place. There is a continuous increase in mineral input during this period, which peaks towards the top of the core and perhaps, reflects the latest population increase during the 20th century.

Unfortunately the vegetation and sedimentary record from the Lake Temae core does not extend far enough back in time to see any natural trends resulting from long term climatic changes. The record does, however, indicate that some form of extreme natural events have had short term effects on the indigenous, pre-settlement vegetation, with taxa diversity appearing to recover fairly rapidly after the event. The record also indicates that Polynesian settlers may have had a considerable effect on the native floral composition, being responsible for both the decline of several upland forest taxa, and the formation of the shrub-fernland communities typical of the lower regions of Mo'orea today. The *Hibiscus-Ficus* forests characteristic of the lower valley regions were probably also formed during this period. Recovery of the forests was further jeopardised by the

Europeans with the introduction of highly competitive pioneer taxa such as *Miconia calvescens* and *Psidium guajava*.

6.8. Sedimentary analyses of Lake Vaihiria

6.8.1. Lake Vaihiria, its location and surroundings

Lake Vaihiria is located in the interior of the island of Tahiti at the headwaters of the Vaihiria (Tahiria) river (Figs.6.4, 6.20 and 6.21) It lies at an altitude of 460m a.s.l. and is surrounded by very steep slopes of basaltic lavas and conglomerates which generally have an angle of slope in excess of 45^o and reach altitudes up to 1219m. The lake has a surface area of $1.72km^2$ and a maximum water depth sounded at 28m (Becker, 1974), although the map by SEDEP (1981) indicates a maximum depth of 35m (Fig.6.22). The lake was originally thought to occupy the site of an ancient volcanic crater, but more recent studies by Becker (1974) show that Lake Vaihiria is a land-slip lake. Several episodes of mass movement, indicated by the exposure of large landslip scars on the valley sides, resulted in the formation of a debris dam that blocked the flow of the Vaihiria river near its headwaters (Fig.6.21). Associated with massive lavas and agglomerates to the west and north-west are two fault systems. The combination of these two fault systems was probably responsible for the weakening and subsequent collapse of the western flank, resulting in the damming of the valley and the formation of the lake. The resultant debris is composed of a permeable mixture of angular blocks, up to 30m in size, in a matrix of sandy to clayey sediment.

The Lake Vaihiria drainage basin, at an elevation of between 460 and 1600m, lies in the wet tropical zone and is frequently subjected to heavy rainfall; as much as 10,000mm/year can fall as a result of orographic effects. This amount of rainfall is likely to have had a significant effect on the natural cycles of regolith deveopment and landsliding within the catchment. At the upstream end of the lake a flat alluvial plain has formed (Figs. 6.6 and 6.21) which has been incised by a number of modern stream channels, exposing several metres of inter-bedded clay, sand, and gravel. Rainwater enters Lake Vaihiria through these channels, which in turn receive their waters from the many rock-walled tributaries feeding the system. Springs also emanate from between the basalt flows and plunge as waterfalls to the valley floor. The outflow of water from the lake is mainly through the permeable debris dam. Seepage at the toe of the dam occurs in several places and is concentrated down-valley in a single channel. Becker (1974) notes that seepage is from at least four springs at an elevation about 170m below the level of the lake, mainly along the contact of the bedrock with the overlying debris and alluvium. Rough calculations at one seepage site indicate that discharge is small, i.e. less than $2m^3s^{-1}$, although groundwater flow may be greater through alluvial sediment below the debris providing a hydrological link between the lake bed and the lower reaches of the valley. Becker (1974) also measured spring seepage between October 1973 and August

1974 and found flows to range from 0.4 to $1.3m^3s^{-1}$. He also found a close correlation between reduced discharge and lower lake level, but concluded that there was more water going into the lake than could be accounted for by discharge from beneath the debris dam. The lake is believed to overflow the dam periodically, when inflow exceeds the rate of seepage. This conclusion is supported by the winnowed surface of the coarse debris and the formation of a narrow, 10m deep channel along the contact of the debris dam with the bedrock of the valley wall. According to M. Ricard (pers. comm.), Lake Vaihiria is known to fluctuate within a range of about 5m, and the water was probably near to its lowest level in 1983.

The slopes of the Lake Vaihiria catchment naturally support a mid- and high-altitude hygrophile forest vegetation, which is today dominated by *Pandanus tectorius*. On the humid windward slopes *Crossostylis biflora*, *Alstonia costata*, *Freycinetia impavida*, *Cyathea* spp., epiphytic ferns and filmy-ferns form the main component with *Pandanus*. However, on the slopes protected from the wind, the arborescent stratum is dominated by *Weinmannia parviflora* and *Metrosideros collina*. Florence (1982) noted that these forests have today been greatly contaminated by aggressive introduced taxa, particularly *Psidium guajava* and *Miconia calvescens*. The endemic species *Pipturus vaihirianensis* and *Xylosma tahitense*, noted by Moore (1940), perhaps occur less frequently in the region today as a result of this competition. The *Psidium-Miconia* brush was particularly striking around the edges of the lake in 1985, where it had completely invaded the *Cyathea-Pandanus* forest (Fig.6.6). An aquatic vegetation, dominated by *Egeria densa*, formed an incomplete belt around the lake margin, particularly developed along the right bank where it forms a thick carpet several metres deep and up to 7m in width. A riparian vegetation has also developed on the flat alluvial areas, where ruderal species including *Commelina diffusa*, *Ludwigia erecta* and the grass, *Paspalum conjugatum*, have colonised. In the northern areas of sand and gravel *Hibiscus tiliaceus*, *Centotheca lappacea* and *Amomum cevuga* can also be found. Native floppy-eared eels, known as *puhi taria*, represent the only significant faunal resident in the cold waters of the lake and are known to reach up to 1.8m in length.

Up until 1984-85, Lake Vaihiria was the last natural lake in Tahiti. A smaller lake, Vaiufaufa, existed on Tahiti-Iti at an elevation of 630m, but was drained in 1983, and the sediments disturbed, during the construction of a larger reservoir. In 1984, the Vaihiria River was harnessed for hydro-electricity, which resulted in major disruption of the lake environment and its catchment. The cores collected in 1983 therefore represent the last undisturbed sediment records before this event.

6.8.2. Physical investigations:

6.8.2.1. Sediment core (VHA) stratigraphy

Two sediment cores (VHA, 0-5m, and VHB, 0-5.14m) collected from Lake Vaihiria, within 5m of each other and at a water depth of 25m, showed comparable stratigraphic sequences. The 5m sediment core shows no abrupt changes in stratigraphy, and consists of a dark reddish brown, finely-disseminated detrital mud (making up 10-30% of the sediment), with mineral deposits and fine grey, to olive-green clay laminations making up the rest. Laminations of nearly pure clay are most common between 2.15 and 4.45m. Occasional coarser sand bands are scattered throughout the core, but clusters were recorded between 1.0m and 2.0m, and between 4.0m and 5.0m. Possible algal laminations were also noted between 1.0m and 2.0m. Several laminae that occur between a depth of 3.50m to 5m are hard (lithified) and are in marked contrast to the soft nature of the rest of the core. These laminations appear to be associated with the levels rich in volcanic lava particles noted in the pollen preparation slides, and represented in Fig.6.27 (insert). There are abundant fine-grained fragments of organic matter scattered evenly through the sediment, such as leaves, vegetal fibres and bryophytes. Fern sporangia were the only macro-remains found in the sediment, and these occurred throughout.

The presence of sand in the mineral fraction, and a wide range of grain sizes throughout this lacustrine sequence is probably a reflection of the steep slopes bounding the lake, the high rainfall and the small drainage basin area, all of which combine to deliver coarse sediment to the valley floor and to limit the amount of sorting that occurs to the eroded soil. Because of the high energy environment in the Vaihiria catchment laminae that contain a high percentage of clay-sized material probably reflect periods of reduced runoff to the lake, or less catchment disturbance, unlike similar laminations in the previous three sequences, which implied increased run-off.

6.8.2.2. X-ray photography

The X-ray photographs of the Vaihiria core show distinct laminations throughout the sequence which implies that the sediments have been relatively undisturbed since the time of deposition; however, somewhat thicker and denser laminae were detected in the lowest 50cm of the core and at a depth of 3.45m. These appear to correspond to samples rich in volcanic lava particles.

6.8.2.3. Magnetic susceptibility analysis

Magnetic susceptibility measurements (Fig.6.23) were recorded in an attempt to trace changing erosion rates within the catchment and to link these with variations in sediment properties. Although values vary by an order of magnitude, there is no apparent trend;

the presence of several distinct peaks and the uniformly low values in the upper 0.8m are, however, notable. The most significant magnetic peak occurs between 4.42m and 4.56m, while four medium peaks are detected at 4.76m, 3.50m, 2.28m and 1.22m. Several smaller peaks occur around 3.94m, 3.68m, 3.32m, 2.92m, 2.74m, 2.62m, 1.78m, and 0.96m. It is believed that these susceptibility peaks represent a series of disturbance events within the catchment or result from the periodic landsliding of regolith build-up. Susceptibility readings are generally higher in the sediments below 3.28m (i.e. all above 1500 arb. units) indicating a high input of allochthonous mineral.

6.8.3. Geochemical analysis

The main objective of the geochemical analysis of sediment from Lake Vaihiria was to provide information on the amount, and frequency, of in-washed basaltic material reaching the lake. Statistical analyses (Fig.3.18) show that there are very strong (91%) correlations between the geochemical profiles of titanium-oxide and aluminium-oxide, while a 67% and 75% correlation exist between iron-oxide and TiO_2 and Al_2O_3 respectively. These three oxides form the main coherent group of basalt-oxides in this sequence. A slightly weaker correlation exists between this group and the profile for silica-oxide which appears to correlate most strongly (90%) with MgO and perhaps reflects a combination of both the in-washed basalt material as well as the population of algae resident in the lake (similarly found in Lake Temae). Weak correlations are found between CaO and Na_2O (68%), while no significant correlations exist for the profiles of SO_3, P_2O_5, organic content, and loss-on-ignition of H_2O and CO_2.

Factor analyses (Fig.3.17) indicated the presence of three loosely linked geochemical zones and eight sub-zones within the geochemical data (shown in Fig.6.24). This large number of single-level sub-zones reflects the fluctuating nature of this short sediment sequence and makes the description of this core quite complicated.

The lowest geochemical zone **VgI** which ranges from 5.00m to 3.15m contains samples which are generally dominated by the basalt-oxides, however, the variable organic content of several samples is recognised. Sub-zones **VgIa** (4.75-4.55m) and **VgIc** (3.75-3.55m) are distinguished by their higher organic content (>20%), whilst sub-zone **VgIb** (4.55-4.35m) is characterised by the highest levels of Fe_2O_3, Al_2O_3 and TiO_2 (15.9%, 16.5% and 4.3% respectively) recorded in the sequence. Sub-zone VgIb also correlates strongly with the highest recorded magnetic susceptibility readings (Fig.6.23) and the highest percentages of CaO and Na_2O (7.7% and 0.77% respectively) as well as a moderate peak of charcoal (reaching 4.6%). This sub-unit is, therefore, believed to represent a period of increased catchment erosion.

VgIc corresponds to a similar, but less severe, increase in basalt-oxides with readings of Fe_2O_3, Al_2O_3 and TiO_2 reaching 15.4%, 15.5% and 3.7% respectively. It is interesting to note that increases in the percentages of SiO_2 and MgO appear to follow on directly after the basalt-oxide increases in VgIa and VgIb, and may indicate expanding algal populations in the lake following nutrient inputs from the catchment possibly an indirect consequence of the slope and vegetation disturbance. Similar but less extreme basalt peaks occur within this zone at 4.85m and 4.05m.

Zone **VgII** ranges from 3.15-1.95m and is generally characterised by a rise and fall in organic content with fluctuations in the basalt content of the sediment which is mainly accounted for in sub-zone **VgIIa** (2.35m to 2.15m) where Fe_2O_3 reaches 15.3%, TiO_2 (3.7%)and Al_2O_3 (15.2%). The higher iron content may indicate the presence of well developed soil material or be the product of increased translocation by solution into the lake system. However, as iron is often very motile in these systems its presence may merely represent changes in post-depositional environments within the sediment core (referred to in section 3.2.2.1.). It is interesting to note that in the level immediately prior to VgIIa charcoal (4.8%) and organic content (26.7%) were comparatively high.

A smaller basalt peak also occurs around 2.65m and probably represents a small in-washed deposit. The geochemical profiles for P_2O_5, and SO_3 in the two lower zones both show a gradual increase in percentages levels moving up the profile. Since these oxides represent less than 1% of the total composition it is likely that there increase is the indirect result of a lower input of basalt-oxides.

Zone **VgIII** ranges from 1.95m to the top of the sequence and is generally characterised by significantly higher levels of SiO_2 and MgO.in the lowest 1m to be replaced by high organic content in the uppermost metre. This zone also contains four sub-zones: **IIIa** (1.80-1.70m), where silica-oxide increases to a maximum of 40% and MgO reaches 7.7%. The main basalt-oxides also increase followed directly by the highest recorded charcoal levels (5.8%) at 1.65m; in sub-zones **IIIb** (1.35-1.15m) and **IIIc** (1.15-0.95m) iron-oxide dramatically increases to between 15.3% and 15.8%, while Al_2O_3, and TiO_2 account for 14.9%, and 3.31% at 1.25m. MnO peaks at 1.05m along with CO_2 + clay mineral-water, increasing to 4.9%. Since there was unlikely to be any carbonaceous material entering the lake, this sudden peak in LOI may be related to the presence of hydrous clay minerals typically found in highly weathered soils. The highest percentages of magnesium-oxide also occur in sub-zone at 1.05m, and is believed to signify an increase in resident algae (verified in the diatom analyses in section 6.8.4.2.

Between depths of 0.84m and 0.04m there is an significant increase in organic material which reaches its maxima towards the top of the sequence and is represented by sub-zone **IIId** (0.04-0.0m). Basalt-oxides, after a brief hiatus, fall dramatically towards the top of the zone, while SiO_2 is seen to decline sharply from 0.84m upwards. The reduction in allogenic input suggests that the top of this zone represents a period of relative stability within the catchment.

X-ray diffraction analyses of core VHB (undertaken by J. Teller at the University of Manitoba and detailed in Parkes *et al.*, 1992) showed the presence of a similar suite of minerals throughout the sequence. Although no attempt was made to quantify the data, major minerals present were augite, olivine, haematite, plagioclase, and magnetite. Lesser proportions of quartz, potassium feldspar, and calcite were also present in most samples. The clay-sized grains appeared to be almost entirely expandable clays, mainly montmorillonite (smectite) with minor amounts of expandable chlorite and vermiculite. Augite and haematite were also present in the clay-sized fraction, but illite, kaolinite, and normal chlorite were absent. The absence of minerals such as kaolinite, commonly formed during weathering in the tropics, is a reflection of the high rainfall, steep slopes, and the immature nature of the soils in the Vaihiria basin. The presence of unstable mafic minerals in the sediment, such as olivine and augites, is further evidence for the rapid removal of incompletely weathered soil from the volcanic slopes around the lake (J. Teller, pers. comm.). In fact, today the steep slopes of the Vaihiria valley have only a very thin mantle of soil on them. The haematite and expandable clays were, on the other hand, formed by the weathering of basalt rock, and then later deposited into the lake.

The geochemical analysis (Fig.6.24), therefore, indicates the presence of several peaks in basalt-oxide percentages throughout the lower 4m of sediment, followed by a fairly sharp change to a more organic-based mud in the upper 1m. The basalt-oxides may be easily leached, or translocated in the form of clay minerals, from weathered soils under normal moist conditions. However, when extreme peaks in the percentage of these oxides occur, in combination with indicators such as high magnetic susceptibility and SiO_2, their input is believed to be a consequence of mass movement rather than solutional processes. The low elemental values probably relate to more stable phases in the watershed; however, there is not always a clear distinction between organic-rich and basalt-rich samples as exemplified by sub-zone VgIc which has high percentages of Al_2O_3 (15.5%) and TiO_2 (3.7%) as well as organics (20.4%), but low levels of Fe_2O_3, SiO_2, MgO. Also of particular interest in this sequence is the increase in SiO_2 and MgO between 1.85m and 1.05m in association with the maximum percentages of charcoal (up to 5.8% at 1.65m). Less extensive peaks of SiO_2 occur at levels 4.85m, 4.45-4.25m, 3.45-3.25m and 2.25m. Complete weathering of tropical humid soils invariably results in the formation of resistant silica residues and may indicate periods of intensive erosive activity within the catchment. This unit perhaps reflects the exposure of the soils to severe weather conditions through forest clearance perhaps by fire. A large increase in diatoms within the lake could provide an alternative explanation for the high SiO_2 levels and the possibility is examined in section 6.8.4.2.

6.8.4. Biological investigations:

6.8.4.1. The palynological record

General features of the pollen record (Figs.6.25; 6.26 and 6.27-inserts) are the relatively high taxa diversity and the extremely high values, both percentage and 'absolute', for pteridophytes. The first is not surprising in a tropical rainforest environment (Flenley, 1979); the second is, however, unusual. Pteridophytes represent over 50% of all fossil pollen and spores throughout the Vaihiria sequence, and up to 90% in some samples. This may be attributable to the exceptionally steep topography of the lake catchment area which allows innumerable ferns the opportunity to deposit their spores directly into the lake. Heavy rainfall (up to 10,000mm/annum) may also prevent the dispersal of lighter spores out of the lake catchment. The presence of a number of degraded fern spores in the samples suggests that some grains have been transported to the lake via streams, or as a result of slope in-wash. Since the levels of degraded grains (Fig.6.27-insert) do not fluctuate consistently with the zones of high allochthonous input described in the geochemistry, the source of these grains is most probably via inflowing streams. Fluvial transport may have resulted in a certain amount of differential preservation/transpotation of fossil pollen and spores, in favour of the more resistant fern spores. Because of the high percentages of pteridophytes in the sediment core, pollen percentages were calculated as both percentages of total pollen and spores, and percentages of total pollen only (Fig.6.26). The pollen percentages in the following text will refer to percentage of total pollen only, while spore percentages will refer to percentage of total pollen and spore counts in a sample.

The percentage summary diagrams shown in Fig.6.25 indicate that, although all the zones are dominated by pteridophyte spores, there is a detectable decrease in primary taxa from the lower sediments upwards. Once the pteridophyte counts have been removed from the summary calculations it is clear that both primary taxa and arboreal taxa have fluctuated significantly throughout the sequence. This is believed to be in response to periods of catchment disturbance, followed by periods of reduced activity. The diagrams also indicate a significant increase in aquatic taxa towards the middle of the sequence where percentages reach a maximum of 40% of total pollen. This increase may reflect the colonisation and exploitation of newly formed land, in the vicinity of the lake. Absolute counts of pollen (Fig.6.27-insert) indicate several zones where pollen and spore counts were relatively low, and appear to correlate closely with periods of slope disturbance described in the geochemical record. Unfortunately, the high variation in sediment density (i.e. weight of $1cm^3$ of sediment) often distorts the absolute figures, with the result that low counts do not always represent low pollen and spore production. Analysis of the palynological data (Fig.3.21) detected the presence of the three main vegetation zones and four sub-zones shown in Figs.6.25 and 6.26 (insert). These PCA-zones do not, however, appear to account for all of the variation within the pollen sequence, especially in relation to fluctuations of primary and secondary taxa. Several further units have, therefore, been subjectively identified and included in the following description.

Zone **VpI** ranges from 5.00m to 3.35m and is generally associated with a pollen flora typical of relatively stable conditions; however, a single sub-zone, **VpIa** between 4.55 and 4.35m, is believed to represent a clear disruption in the vegetation cover. Arboreal taxa most abundant in this lower zone include: *Ascarina polystachya*, a mid- to high-altitude forest species which accounts for between 12% and 60% of the spermatophyte palyno-flora; *Trema orientalis* (2-30%), often associated with secondary forest growth; and *Pipturus vaihirianensis* (up to 14%), a primary tree endemic to the region, but rarely found on Tahiti today. *Freycinetia impavida* appears to form the main shrub component, whilst *Procris pedunculata* (up to 17%) forms a significant part of the herbaceous flora. *Procris* is today often found growing epiphytically on the shaded branches of primary forest trees. A relatively high diversity of primary forest related species occurs at lower percentage levels and includes trees such as *Weinmannia parviflora*, *Weinmannia vescoi*, *Reynoldsia verrucosa*, and *Altingia* sp. *Weinmannia parviflora* is today regarded as one of the dominant taxa of the mid- and high-altitude hygrophile and cloud forest formations, and was noted by Florence (1983) growing best on the slopes protected from the wind. *Reynoldsia verrucosa* is a particularly large tree generally restricted to the cloud forests of Tahiti today, whilst *Altingia*, another cloud forest tree, is now rarely recorded throughout Polynesia. The smaller primary trees or shrubs in this zone include *Rapanea* spp. (no secondary species have been recorded from the Society Islands), several species of *Ilex* and *Metrosideros collina*. The latter tree presently dominates the shrub layer of Tahiti's mid- and high-altitude forest formations, and also occurs in association with *Dodonaea viscosa* in the drier regions of Tahiti. Of the ferns that were positively identified in this zone, tree fern species were the most abundant including *Cyathea affinis* and *Cyathea horrida*, both accounting for up to 15% of all pollen and spore counts. *Gleichenia linearis* is also present in this zone, but remains at a constant low level throughout.

Although the pollen taxa indicate a relatively diverse flora in this lower zone, there appears to have been one major period of vegetation disturbance (VpIa) which is characterised by a reduction in the total pollen count (see absolute diagram, Fig.6.27-insert), by the loss of particular species, or by the replacement of primary indicators by taxa associated with a secondary forest system. There is also a slight reduction in the hygrophile species including *Ascarina polystachya* (from 27% at 4.65m to 12% at 4.25m), *Weinmannia parviflora*, which falls to below 1% at 4.25m, *Pipturus vaihirianensis* (1% at 4.25m) and *Procris pedunculata*, which decreases slightly to 2%. Other taxa which show some decline include *Weinmannia vescoi*, *Trema orientalis* and species of *Rapanea*. Interestingly the cloud forest species, *Reynoldsia verrucosa*, *Altingia* sp. and *Astelia nadeaudi*, either remain stable or appear to show a relative increase. This perhaps suggests that only the lower and mid-catchment vegetation was disturbed, whilst the vegetation on the high altitude ridges remained unaltered. Taxa most obviously increasing in relative importance in sub-zone Ia are *Pandanus tectorius*, which increases from 2% to 14%, and the sedges (Cyperaceae), which increase from 3% to 15%. The presence of these two taxa, along with the increased occurrence of the native woody climber *Freycinetia impavida* and the shrub *Coprosma tahitensis*, may reflect a disruption in the canopy cover which allowed increased light penetration to the lower forest levels. Absolute counts for all pollen and spore taxa also decline significantly at 4.45m. However, as already mentioned, this decline may just be a reflection of the relatively high density of the sediment sample at this level. The dry weight of 1cm^3 of sediment was 0.81g, whereas all the other samples weighed below 0.59g/cm^3. Nevertheless, it is clear that a significant change in floral composition occurred during this period. Primary forest taxa do seem to recover to some extent throughout the rest of this zone, but the appearance of the secondary tree *Macaranga tahitensis* (representing 4%) indicates that this recovery was not complete.

Zone **VpII** extends from 3.35m to 1.15m and, like zone VpI, is believed to represent a floral composition indicative of relatively stable environmental conditions disrupted only by brief periods of instability. Sub-zone VpIIa (3.15-2.95m), which was recognised in the Principal Components axes (Fig.3.20), reflects one of these periods. Sub-zone IIa shows an abrupt decline in primary taxa (Fig.6.25) due mainly to a decline in *Ascarina polystachya* pollen from 39% at 3.25m to 14% at 3.05m, as well as a decline in *Pipturus vaihirianensis* pollen from 14% at 3.45m to undetectable amounts at 3.25m. Unlike sub-zone Ia, *Pandanus* is absent from the record, and instead there is an increase in Urticaceae/Moraceae pollen, which could represent trees, shrubs or herbs. The first significant counts of the king fern, *Angiopteris evecta*, occur above 3.25m. Today this fern often replaces the true tree fern species in the secondary upland forests of Mo'orea, and perhaps represents a further stage in the transformation to a secondary type vegetation. The two sub-zones (Ia and IIa) clearly correspond to levels containing high counts of volcanic lava fragments noted in the pollen samples (Fig.6.27-insert), and also approximate to peaks in the basalt mineral oxides and magnetic susceptibility.

Another period of primary taxa recovery occurs above sub-zone IIa with the pollen again dominated by *Ascarina polystachya*, accounting for 42% to 60% of the spermatophyte flora. However, this unit also sees the last occurrence in the pollen record of *Procris pedunculata*, which possibly declined with reductions in primary host trees and/or increased light penetration.

The occurrence of secondary taxa throughout zones I and II may have resulted from extreme weather conditions, human activity, and/or natural geological processes in the catchment. Extreme weather may have reduced the stabilising (and primary) vegetation cover in the watershed and also have produced anomalously high amounts of precipitation. As the lower valley slopes are relatively sheltered from strong winds, cyclone damage is likely to be concentrated on the upper slopes. However, the pollen record indicates that it is the vegetation of the lower slopes that is affected whilst the species characteristic of the exposed high altitude ridges appear to remain intact. Alternatively, secondary taxa may have grown on the landslide debris soon after it impounded the lake. Since these zones are associated with phases of high mineral input, volcanic fragments, and the highest magnetic readings, especially around 4.45m, this explanation seems quite feasible and would have resulted in a short-term, localised disruption of vegetation. The fairly rapid recovery of species after the disturbance phases also supports this explanation. A third possible explanation is anthropogenic activity. Archaeological investigations in the Vaihiria valley by Cristino *et al.* (1988) revealed some evidence for a small, migrant population around 400 to 300 years ago. An interpolated date for sub-zone Ib, at a depth of 3.45m, was placed very approximately around 400 yr BP (estimated from the two VHB dates in Fig.3.29). A stratigraphic survey undertaken in the Papeno'o valley (topographically similar to Vaihiria) on the north side of Tahiti (Orliac, 1984), also revealed the presence of charcoal in an alluvial sequence, dated at 580±60 yr BP. If human activity was prevalent in the Vaihiria valley during this phase, it was probably small and seasonal (and therefore, unlikely to be detected above the natural slope processes).

A further period of disrupted vegetation that is not recognised by the pc analysis occurs at level 2.45m. There is a marked change in the pollen composition, including declines in primary forest taxa such as *Weinmannia parviflora*, *Metrosideros collina*, the clubmoss *Lycopodium phlegmaria* and members of the Araliaceae family. *Weinmannia vescoi*, *Fitchia* (the indigenous tree composite), and an unidentified species of palm are no longer detected in the pollen record above 2.45m. The secondary tree *Trema orientalis* is also seen to decline above this depth. Interestingly, the cloud forest species *Reynoldsia verrucosa*, *Altingia* and *Astelia nadeaudi*, again show a slight relative increase; however, the greatest increases are seen in percentages of *Pandanus* (up to 14%), *Freycinetia* (up to 8%), and sedges (up to 39%) which appear to be progressively replacing the primary taxa. Other secondary taxa include *Premna tahitensis* (5%), *Dodonaea viscosa* (3%), *Cordyline* sp. and *Melastoma denticulata*. Although *Cyathea* is still the dominant fern genus in this zone, *Angiopteris evecta* and *Gleichenia linearis* now also form an important component. The increase in the abundance of Cyperaceae above 2.45m may signify continued activity, or natural disturbance in the catchment and, along with the appearance of *Typha latifolia*, *Typha angustifolia* and the marsh fern *Stenochlaena palustris* around 2.25m, indicates the formation or extension of level land, capable of supporting aquatic vegetation and reed swamp. Perhaps the delta, present today at the northern end of the lake (Fig.6.6), was extended at this stage by in-washed material from the slopes above. The first record of the introduced weed, *Bidens pilosa*, occurs at

1.85m. This pantropic weed, originally native to tropical America, was an early introduction to Polynesia and was first reported from Samoa in 1839 (Whistler, 1983). It may well have reached the Society Islands at an earlier stage, providing possible evidence of human influence in the area. It is very common in dry areas, particularly in waste places and croplands, and often becomes dominant where it occurs.

A short period of forest recovery is represented by the two samples at 1.65m and 1.45m. However, *Pandanus* still accounts for 21% of the pollen flora and the presence of grasses, sedges and new secondary taxa, including *Claoxylon tahitense* and *Homalanthus moerenhoutianus*, suggests that there were still areas of open vegetation. This recovery period is followed by two further phases of catchment disturbance in the uppermost pollen zone, **VpIII**. These phases are represented by sub-zones **IIIa** (1.15-0.94m) and **IIIb** (0.74-0.54m) and are again associated with reductions in primary taxa and increases in *Pandanus* (up to 24%) and *Freycinetia* (up to 18%). Grasses reach their highest recorded levels at 9%, and sedges are still abundant, accounting for between 5% and 28%. It is interesting to note that several fern species decline to undetectable levels in this zone. These include *Asplenium nidus* (often collected as an ornamental plant), *Stenochlaena palustris*, and species of *Alsophila*, *Jamesonia*, and *Cyclosorus*. This second phase of disturbance is believed to reflect an increase in human activity in the Vaihiria catchment resulting in forest disruption and increased slope erosion bringing weathered soil material into the lake. The presence of high altitude cloud forest taxa again suggests that it is the lower slopes of the catchment that have been subjected to some form of disturbance. The idea that people were affecting the inland forest gains support from two other lines of evidence. When Tahiti was discovered by Wallis in 1768 the island was densely populated. Cook (1777) presented evidence for a population of over 20,000 and described agriculture extending a long way inland. Archaeological investigations by Cristino *et al.* (1988) revealed the presence of two permanent occupation phases in the Vaihiria valley; the first was dated at 300±50 yr BP (AD 1600-1700) and a second period of significant activity, corresponding to a high island population, was dated to 170±50 yr BP (AD 1720-1830). The two disturbance phases in zone II have interpolated dates of 320-240 yr BP and 160-100 yr BP and may well represent the occupation phases described by Cristino *et al.* (1988). Neverteless, it is very risky to accept this chronology without further radiocarbon date from this sequence.

The top 0.5m of pollen zone VpIII, like zone VgIV of the geochemical record, possibly represents a period of reduced activity in the catchment. Primary trees and shrubs, such as *Ascarina*, *Weinmannia parviflora*, *Metrosideros*, *Rapanea* and species of *Ilex*, appear to make some recovery, whilst several secondary forest taxa also remain significant, including *Trema orientalis* (up to 32%), *Macaranga tahitensis* (7%), *Neonauclea forsteri* (5%) and *Melastoma denticulata* (4%). *Pandanus* spp., *Freycinetia impavida* and sedge species, so significant in the previous zone, are relatively less important in this upper section of the core. Although the forest vegetation makes a significant recovery in this unit, the increase in *Gleichenia linearis* (reaching 11%) and the first appearance of the invasive *Psidium guajava* (at 0.64m), *Miconia calvescens*, and *Ageratum conyzoides* (at 0.25m) suggest that full recovery may have been checked to some extent by these competitive, introduced species. The floral composition reconstructed from this zone is typical of the vegetation types found in the Lake Vaihiria catchment today, with primary forest taxa dominating the upper, less accessible slopes, and secondary formations, intermixed with a *Pandanus-Cyathea* forest, occurring on the lower slopes, along pathways and in the immediate vicinity of the lake.

The recovery of both primary and secondary taxa in the top of zone III is in keeping with the idea that a decline in human activity occurred on Tahiti towards the beginning of the nineteenth century. As in most Pacific islands, the introduction of western diseases and weapons led to a drastic population decline, and the population of Tahiti fell to 5000 by 1816 (Henry, 1928). Inland areas were subsequently abandoned in favour of the coastal flats, especially as colonial rule and missionary activity led to the expansion of coastal settlement. Prior to about AD 1650, forest clearance may have led to higher rates of soil erosion in the interior of the island and, in turn, to alluviation in coastal lagoons. This would have provided a coastal population with areas of flat, fertile, land, suitable for cultivation. This process of alluviation in coastal areas is well documented on other Pacific islands such as the Lakeba Isles, Fiji (Hughes, 1985), in the Aneityum, Vanuatu (Spriggs, 1985), and in Tikopia, Solomon Islands (Kirch and Yen, 1982). The deep burial of archaeological sites on Huahine (Sinoto, 1983a, b) suggests it also happened in the Society Islands. Sedimentary analysis of Lake Temae also supports this idea.

6.8.4.2. **The diatom record**

The results of the diatom analysis is shown in percentage and absolute forms in Figs.2.28 and 2.29 respectively. The most significant change in the floral composition occurs above a depth of 2.25m with a dramatic increase in the planktonic diatom, *Synedra ulna*. A further significant change in ecological types is seen in the top 84cm, while more moderate changes in species composition occurred in the lower sediment sequence. The lower sediments, however, show distinct fluctuations between the dominant diatom taxa, perhaps in response to changes in the nutrient status of the lake resulting from in-washed slope material with associated nitrates and phosphates. Three major diatom zones and two sub-zones were detected by pca (Fig.3.21) from the percentage diatom data; however, several distinct variations in diatom concentration not recognised by the pca are also included in the following sequence description.

Diatom zone **VdI** extends from 5.00m to 2.75m and contains one recognised sub-zone (**VdIa**) between 2.95-2.75m. The diatom flora from 4.85m to 4.65m, is dominated by

Navicula spp. which account for up to 46% of the total count. *Navicula* is a benthic genus frequently containing epipelic species (i.e. those living on mud). *Gomphonema* spp. (often present in shallow waters) and *Nitzschia* spp. (planktonic or benthic) are also abundant in this zone, and, along with the epipelic genus *Pinnularia* spp., strongly suggest a shallow lake environment. Other taxa present include *Achnanthes inflata* (epiphytic in neutral to alkaline water), *Achnanthes lanceolata* (a periphytic, alkiphilous diatom, with an optimum pH of 7.2-7.5, requiring high oxygen concentrations and often found in springs and streams), *Rhopalodia gibberula* (a periphytic or epiphytic species, of shallow, alkaline lakes), and species of *Eunotia* and *Stauroneis*. At 4.45m, there is a dramatic fall in total number of diatom frustules per cubic centimetre, along with a decline in the absolute figures for individual taxa. The percentage diagram shows that the species composition is largely unchanged across this zone, except for a fall in *Navicula* spp., and remains a dominantly shallow water assemblage. This brief interval corresponds to vegetation changes in the pollen record and with the period of catchment disturbance suggested by the geochemistry (Fig.6.24) and the increase in magnetic susceptibility (Fig.6.23). A higher input of clastic material from the watershed may have produced a hostile environment for benthic diatoms, at least until the water had cleared, reducing the absolute count of diatoms. Thereafter, diatoms appear to 'mop up' the excess nutrients and free silica brought into the lake, and dramatic increases in absolute counts of *Gomphonema* and *Nitzschia* immediately follow.

Between 4.05m and 3.05m *Gomphonema* spp. and *Nitzschia* spp. continue to fluctuate in response to a series of disturbance events. Overall percentages of *Nitzschia* spp., decrease towards the top of this period, while *Navicula* spp. increase. The continuation of this predominantly benthic assemblage still indicates a relatively shallow lake. *Stauroneis phoenicenteron*, also present in the diatom record between 4.25-2.85m, has a pH range of 6-8.2, has a periphytic habitat and usually occurs in water with a temperature greater than 30°C (Lowe, 1974). It can also tolerate low oxygen concentrations and may represent a slight eutrophication of the lake during this time. It is interesting to note that organic levels and percentages of phosphate, and SO_3 also reach high levels at this time. At level 2.85m (intra-zone Ib), absolute counts of most species again fall dramatically but immediately increase again, with *Navicula* spp. reaching 452 counts/cm^3 at the beginning of zone **VdII** (2.75-0.74m) and corresponding to sub-zone **VdIIa** (2.75-2.35m). *Achnanthes lanceolata*, a periphytic diatom, appears to also increase during 'blooms' of *Gomphonema* spp., *Navicula* spp., and *Nitzschia* spp., perhaps as a result of peripheral plant material being brought into the lake during slope disturbance. Large fragments of leaf material were indeed found in the macro-remains of these sediments. Phosphates, rather than nitrates, are likely to have been the limiting nutrients to diatom growth in the preceeding period.

The most significant change in the diatom flora occurs in zone VdII above sub-zone VdIIa. The record between 2.25m and 1.05m shows a dramatic increase in both percentage and absolute counts of *Synedra ulna*, up to 61% at level 2.05m. *Synedra ulna* is a planktonic diatom which thrives in eutrophic conditions and prefers high silica concentrations. The geochemical record for this period indicates that there is a significant increase in the percentage of SiO_2, along with peaks of basaltic oxides, especially iron. Lowe (1974), notes that *Synedra ulna* prefers 'dirty' water, has a pH range of 5.7-9.0, and can tolerate a wide range of temperatures (oligothermal to eurythermal). It is difficult to assess whether the dominance of SiO_2 in the sediment during this phase was actually the result of the high concentrations of diatoms incorporating silica into their valves or whether it was the initial presence of available silica that encouraged diatom growth. Nevertheless, there does appear to be a strong link between the two.

The diatom composition during this phase possibly indicates a deepening of the lake with progressive loss of the epipelic flora. The existence of a 10m deep channel along the contact of the debris dam and bedrock of the valley wall (which today has no flow of water) also supports the idea that the lake level has formerly been higher. Variations in the effective precipitation and runoff in the catchment may be responsible for lake level fluctuations during this period. Higher rainfall on the deforested slopes may have induced erosion and subsequent in-wash of sediment to the lake, accounting for the higher nutrient status of the lake and the extension of the delta area to the north. Alternatively, the deepening of the lake may have resulted from an increase in the height or impermeability of the debris dam, conceivably induced by the indigenous population, accidentally or intentionally. This diatom zone approximately corresponds to the two disturbance zones at 2.45m and 1.05m (i.e. VpIIIa) in the pollen record and the disturbance zones VgIIa, IIIa, IIIb and IIIc in the geochemical record. The high percentage of charcoal supports the idea that anthropogenic activity was an important factor during this period.

Like the pollen and geochemical records the final diatom zone, **VdIII**, from 0.74m to the top of the core, indicates a stable period in the lake catchment history. *Synedra ulna* decreases along with percentages of SiO_2 and the other basaltic mineral indicators, as the percentage of organic material increases. This increase in organics may have resulted from growing mats of aquatic and riparian vegetation now able to colonise the new, and undisturbed, delta areas. A reduction in lake level, as indicated by a progressive increase in *Rhopalodia gibberula*, would further expose the peripheral mud for colonisation by aquatics and herbs and may explain the sudden appearance of new epiphytic diatoms in this upper zone. These include *Cocconeis* sp., *Denticula* sp., and *Epithemia adnata* which are all epiphytic on aquatic plants. *Achnanthes inflata* is frequently epiphytic on *Polygonum glabrum*, an aquatic plant found on the peripheral muds of Lake Vaihiria today (Florence, 1982). The periphytic *Rhopalodia gibba* also increases in this zone and is often found associated with springs and stream habitats (Lowe, 1974). This alkaliphile diatom has an optimum pH of 7.8, which is slightly above the pH of 7.0 recorded in the lake in 1983 by Teller and Flenley. The change to unlaminated mud throughout this zone could represent the end of seasonal algal 'blooms' which result from high nutrient availability. A reduction in human activity within the lake catchment could have led to less soil erosion, and a reduced input of suspended and dissolved sediment, especially during the rainy season.

6.8.5. The sedimentary record from Lake Vaihiria: Overall conclusions

During the five centuries of history believed to be represented by the stratigraphic record, the geochemical and mineralogical nature of the sediment has changed very little and reflects rapid erosion and transportation to the lake of immature soils developed from the olivine basalts of the catchment. The presence of clay laminations indicates that there were brief episodes of reduced runoff, while occasional sand layers indicate that there were also episodes of distinctly stronger sediment influx to the lake, notably during the earlier part of the sedimentary record. Localised landslides, rather than human activity, were probably responsible for these brief episodes of watershed disturbance prior to ~300 BP estd., a conclusion supported by the rapid recovery of pollen and diatom taxa after the disturbance was recorded.

Above 2.45m in the core, diatoms suggest that the lake deepened. This appears to have coincided with an increase in disturbance to the vegetation cover in the basin, as indicated by a steady rise in some secondary pollen taxa. Interpolation from two radiocarbon dates tentatively places this unstable interval between about 300 and 120 years ago estd., or roughly during the time when the island population is thought to have been expanding inland from its coastal settlements in the 17th and 18th centuries. Alternatively, extreme weather events such as cyclones and heavy rain may have initiated or exacerbated watershed instability during this period. The presence of introduced species in the pollen flora, however, suggests that human influence was a significant factor. Whatever the cause, some primary forest taxa were unable to recover and instead gave way to secondary trees and shrubs. The lake became enriched in nutrients and algal 'blooming' and in-washed material may have led to sediment lamination. Newly extended delta areas were eventually colonised by pioneer species, reeds and aquatics.

Above about 1m depth in the sequence (i.e. ~post 120 yr BP estd.), disturbance of the lake catchment was greatly reduced. Some primary forest taxa recovered but there was a significant increase in herbs, especially introduced ruderals. Nutrient inputs to the lake fell and the lake became clearer and perhaps shallower. This in turn encouraged further growth of aquatic vegetation and the influx of epiphytic diatoms on the peripheral muds. These changes may well correspond to the abrupt decline in island population during the late eighteenth and nineteenth centuries, which came about after contact with Europeans.

The twentieth century saw a rapid increase in island population, but this time it remained largely concentrated on the coastal plain. The interior catchment of Lake Vaihiria was, therefore, little affected until recent construction work undertaken after collection of the cores in 1983.

7. CONCLUSIONS AND SUGGESTIONS FOR FUTURE RESEARCH

7.1. Holocene environmental records from Upolu, Atiu, Mo'orea and Tahiti

The stratigraphic and palynological evidence presented in the preceding chapters provides a broad framework for the assessment of environmental change in the west-central Polynesian region. Although it is important to be aware of the difficulties involved in trying to find a common environmental history between isolated cores from widely spaced geographical locations and different island types several consistencies in the records are worthy of attention. These aspects of environmental change occurred at several different temporal scales: a possible long-term climatic variation affecting broad scale vegetation changes on Upolu (Chapter 4) and Atiu (Chapter 5); a long term sea-level change influencing the lake environment and vegetation on Atiu and possibly Mo'orea (Chapter 6); a more localised disruption of vegetation in the Vaihiria basin of Tahiti (Chapter, 6) possibly resulting from natural landslides; and finally, abrupt changes to local environments due to human activity, evident on all of the islands. These distinct changes in turn provided a latest estimate of Polynesian settlement on Atiu and Mo'orea, and an indication of settlement patterns around the shores of Lake Lanoto'o on Upolu.

When one considers the immense expanse of the tropical Pacific and the relatively few palaeo-vegetational studies that have been undertaken, it is clear that the present network of sites is inadequate for any firm conclusions.

7.1.1. Long term variation in climate effecting broad scale vegetation

Although local changes in island systems often mask the effects of regional climatic variation, several underlying trends have possibly been recognised. Firstly, there appears to be some agreement about the occurrence of a cool and possibly stable period prior to 8000 yr BP as indicated by the vegetational composition and stratigraphy of the two older records (Lanoto'o in Upolu, Chapter 4 and Roto in Atiu, Chapter 5). Both island vegetations were dominated by upland ferns, and while Atiu maintained only a very sparse arboreal component, the forest cover of Upolu comprised mainly cool-indicating upland taxa. The level of moisture availability at this time is, however, not so clearly indicated by the vegetation record. The presence of cloud forest taxa on the one hand indicates relatively high moisture levels, while the scarcity of trees and the presence of taxa frequently found in dry open environments, imply reduced moisture levels. It is likely that the high altitude vegetation within the lake Lanoto'o catchment was receiving higher levels of moisture from orographic cloud formation than the lower elevations of Atiu and this could account for the denser cover of humid vegetation-types in the Upolu sequence and the depauperate arboreal cover on Atiu.

After ~8000 BP estd. (and up to ~5000 BP) the records from Upolu and Atiu are believed to indicate a contemporaneous increase in temperature and humidity, which resulted in the gradual development and diversification of forest. Data from Atiu, however, suggest that the full development of the forest vegetation was checked to some extent, between 7700 and 6600 yr BP, possibly by a relatively unstable climatic or hydrological regime which resulted in severe soil erosion within the catchment. These fluctuations became progressively less extreme, until stability was resumed around 6500 BP, following a possibly drier period between ~7200 and 6700 yr BP (although evidence for this is limited). The most extensive growth and maximum diversity of the indigenous forest taxa on Atiu was recorded between 6500-5500 yr BP, after which a slight forest decline is detected in the pollen sequence, initially due more to increases in soil salinity than to climatic change or other factors such as natural forest die-back. The Upolu record, although interrupted between 7600 and 5200 yr BP, provides some evidence for the end of stable conditions and undisturbed forest development around 5000 yr BP, but did not confirm the period of greater aridity or climatic fluctuation indicated in the Atiu sequence. Vegetation on Taveuni (Fijian Islands) apparently reached its present composition around 6300 BP in response to an ameliorating climate (Southern, 1986); however, like the Lanoto'o record there was no indication of the drier period between ~7200 and 6700 yr BP. This appears to strengthen the argument for a local hydrological forcing being the most important instigator of change around Lake Roto at this time.

The development of forests on Atiu and Upolu after 8000 yr BP is in keeping with other records of a general early- to mid-Holocene warming in the region (i.e. Dansgaard *et al.*, 1970; Hope, 1976; McGlone, 1983c, refered to in Chapter 1). Unfortunately, this diversification on Atiu was subsequently retarded by the effects of sea-level change and, in the absence of a continuous record from an inland site, it is impossible to deduce when this period of 'optimal' forest growth conditions ended. The earliest recorded evidence of the coconut was also determined from the sediments of Lake Roto around 7800 yr BP, supporting the natural dispersal of this palm to the central Pacific region. A pre-settlement record of coconut pollen was also determined from the Mo'orea pollen sequence around ~1700 yr BP.

5000 yr BP is believed to mark the start of an unstable period across the region, which is identified in the records of Lanoto'o and Roto by increased slope erosion, a definite decline in primary forest taxa, and their subsequent replacement by *Pandanus* in Upolu, and salt-tolerant coconut and swamp fern in Atiu. The stratigraphic record from Rotonui (Miti'aro) also indicates several disturbance events between 5300 and 4300 yr BP, in the form of re-worked sediments. Although the main cause of the composition change in the vegetation of Atiu (after 6700 yr BP) has been attributed to relative sea-level rise and salt intrusion within the freshwater system. An increase in storm frequency, or rainfall intensity may have exacerbated the effects of a concurrent sea-level rise. This period of catchment instability continues for the following 1000-1300 years, after which a further period of reduced activity is inferred until 2500 yr BP, on Upolu, and until ~1800 on Atiu. The palynological records from Fiji (Southern, 1986), and in particular the continuous sequence from Tagimaucia in Taveuni, apparently suggest that little or no climatic variation occurred from about 6300 yr BP to the present day that cannot be related to sea-level changes, tectonic and volcanic activity, or anthropogenic disturbance (from 4300 yr BP onwards). It is possible, however, that the islands to the east of Fiji, which were settled later and experienced little or no recent volcanic or tectonic activity were more suited to detect these periods of climatic instability.

7.1.2. Long term sea-level change

There is little doubt that the most dramatic change throughout the islands of the west and central Pacific during the last glacial/interglacial cycle was the massive fall and rise in sea-level. Islands disappeared as sea-level rose, while the extent of the remaining islands was diminished. However, because most islands have narrow and steeply shelving margins, the impact of an extended coastal area and subsequent submergence on both climate and vegetation was minimal. This is in contrast to the situation in Australia and New Guinea, for instance, where massive extension of the continental area occurred at the height of the last glaciation, affecting climates in certain regions. Other effects of rising sea-levels on the Pacific island ecosystems were, however, more significant and included changes in the level and availability of freshwater, changes in drainage conditions and altered patterns of erosion and sedimentation as new base levels were reached.

A gradual increase in salinity within the lake and island system of Atiu (noted above) was first recognised in the stratigraphic record of Lake Roto around 6700 years ago with an increase in the dominance of salt-tolerant plants. However, it was not until ~4000 yr BP that a dramatic increase was seen in marine and saline tolerant diatoms, as well as percentages of sodium-oxide in the sediment. These high levels of salinity are recorded in the Roto sequence up until ~2000 yr BP. As described in Chapter 5 the initial signs of increased salinity in the Atiu sequence closely correspond to the transition from peat to lake mud in both the lake Roto and Rotonui (Miti'aro, Chapter 5) sequences, perhaps implying that salinity levels were intrinsically linked to a regional rise in sea-level. The higher recorded salinity levels in Lake Roto between ~4000 and ~2000 BP may be in response to the higher than present relative sea-levels recognised by several geomorphologists in the region (e.g. Stoddart *et al.*, 1990; Woodroffe *et al.*, 1990). A possible link, due to a late Holocene sea-level fall, may also exist between the reduced salinity levels detected around 2000 years ago in Lake Roto.

7.1.3. Changes in local environment due to human activity

The period of reduced geomorphological activity (from ~3500 yr BP estd.) in the Lanoto'o basin is believed to have been abruptly halted around 2500 yr BP by the arrival of Polynesian settlers at this inland site. Their activity within the catchment, including the small scale disruption of undisturbed forest, resulted in an opening up of the vegetation cover, encouraging soil erosion and the development of secondary vegetation. The lake margins may have also been extended during this time. Weeds, grasses, sedges and ferns (*Gleichenia linearis* in particular) formed a significant part of the flora and probably marked the initial formation of the *kula* scrublands recognised in the disturbed areas throughout Samoa today (Whistler, 1992). This perhaps supports the view that these open scrublands were not only maintained by anthropogenic activities such as burning, but were originally formed as a result of human disturbance. Nevertheless, a vegetation record extending back at least 15,000 years would be required to see if natural grasslands prevailed on Samoa under the harsher environmental conditions of the last ? glacial as indicated by the leeward records on Fiji (Southern, 1986).

Archaeological studies have revealed evidence of continuous human occupation in both coastal and inland areas of Upolu from ~2000 years ago (Green & Richards, 1975), and of occupation of coastal settlements from as early as 3251±155 yr BP (Leach & Green, 1989); few definite inland sites have, however, been recorded from the period between 3251 and 2000 yr BP. This 2500 yr BP date of a significant human presence at an inland site is in keeping with Wright's (1963) view that the island's inhabitants were initially forced to migrate to the high interior of the island to avoid recurrent raids by sea-faring groups from other Pacific islands. After ~2300 yr BP anthropogenic activity falls within the catchment until a further period of landscape disturbance is detected between 1600 and 1400 yr BP. This 200 year period has been attributed either to a further episode of human influence or to a possible increase in storm frequency and/or intensity. Wright (1963) believes that after the initial ~1500 years of inland settlement on the island, the situation at the coast became less risky and the population migrated to these more amenable locations. The reduced activity within the Lanoto'o catchment after at least 1400 yr BP again seems to support Wright's view, however, inland occupation does not appear to have been continous prior to this date.

It is interesting to note a similar period of disruption in both vegetation and catchment stability in the Atiu sequence from ~1800 to ~1500 yr BP, which resulted in a decline of the fig tree and possibly slope erosion from both the central plateau and *makatea* region. This period also coincides with the two major erosion events recorded in the Mo'orea sequence at ~1750 yr BP and 1540 yr BP. In both the Atiu and Mo'orea records catchment disturbance occurred before the arrival of Polynesian settlers to the islands and may have resulted from periods of climatic instability within the region. The possibility that locally unstable hydrological conditions prevailed simultaneously within the individual catchments cannot, however, be ruled out. Because of the presence of Polynesians on the island it is more difficult to determine with confidence whether anthropogenic or natural factors played the most significant role in the modification of the landscape around Lanoto'o.

The settlement of Atiu occurred before or at 1420±45 yr BP (AD 640) and resulted in major changes in vegetation composition, increased catchment erosion and an increased eutrophication of Lake Roto. The coconut palm which had naturally dominated the island vegetation prior to 1420 yr BP, declined dramatically and was replaced by open grassland and fernlands now dominated by *Gleichenia linearis*. This again supports an anthropogenic origin of the *Gleichenia* scrublands on Atiu and not a natural development as suggested by Marshall (1930). Several new species of weedy composites and cultivars, such as the sweet potato, also clearly marked the arrival of people on Atiu. In this post-settlement period the coconut and *Pandanus*, along with the aboriginally introduced *Casuarina equisetifolia* and *Hibiscus tileaceus*, initially formed (and still form) the main component of the much reduced arboreal cover. The original coconut forests may have been cleared exposing the slopes to soil erosion. The diatoms from Lake Roto then indicate an increase in the suspended sediment and nutrient status of the lake.

A similar pattern of landscape modification occurred in post-settlement Mo'orea. A possible increase in the indigenous population, from 1210 yr BP (AD 790) onwards, appears to have encouraged the practice of forest clearance, both on the lower valley slopes and on the steep upland slopes, inducing severe erosion and loss of soil. The degradation of the upland slopes, however, resulted in the development of fertile alluvial plains down towards the coast and and it is suspected that this erosion may have been intentionally induced. The formation of new, flat and highly fertile land encouraged a change in the location of cultivation from hillslope to deltaic swamps. Lake Temae was finally cut off from marine influence during this period and, thereafter, began to show signs of increased nutrient status with the development of algal muds.

A least one period of inland occupation was determined from the ~500 year old core from Lake Vaihiria (Tahiti, Chapter 6), which corresponded to a permanent decline of primary forest taxa, and increasing secondary component. A rise in the level and nutrient status of the lake was inferred from the diatom flora, and an extension of the alluvial delta to the north was implied by a developing marginal swamp vegetation. Although the island was known to be occupied throughout the 500 year sequence, the brief episodes of watershed disturbance prior to ~300 yr BP estd. have been attributed to localised landslides, rather than human activity.

The arrival of Europeans in the Pacific some two centuries ago is marked in all the sequences (except Miti'aro which was not analysed for pollen content) by the further introduction of aggressive weed species, a gradual return to stable catchment conditions, and partial recovery of upland and indigenous forest species. This recovery of primary forest taxa is believed to have resulted from a decline in the indigenous population through introduced disease and war (a process vividly described in the popular book, 'The Fatal Impact', by A. Moorehead, 1966). Alternatively, or in addition, the settlement of coastal as opposed to inland areas may have released pressure from the upland forests on Upolu, Mo'orea and Tahiti, while on Atiu the movement of settlements from the lower volcanic slopes to the central plateau, along with a shift from slash-and-burn agriculture on the dry slopes to taro cultivation in the swamps, may have released enough pressure from the exposed volcanic slopes to allow them to stabilise. The period of increased erosion towards the top of the Mo'orea sequence is believed to reflect the latest population increase around the coast and lower slopes during the 20th century.

Very few palynological studies have been undertaken in the west-central Polynesian region to compare with the records described in this study. Several comparisons have already been made with the 14,500 year record from Taveuni, Fiji (Southern, 1986- in Chapter 1) which show some similarities in pre-settlement environments and a similar course of events associated with initial occupation. Perhaps the only other relevant and comparable study from central Polynesia is the 6000 year old stratigraphic record from Lake Tiriara on Mangaia, in the Southern Cooks (Lamont, unpublished). It is reassuring to note several similarities between this record and the upper 2/3 of the Atiu record, since both islands occur in the same region, have a very similar geology and geomorphology and the location and character of the two lake basins are almost identical. However, several distinct differences also occur between the records. The Mangaian pollen sequence (Pollen diagram redrawn in Fig.7.1 from Lamont, unpublished) appears to begin during zone IV of the Lake Roto pollen sequence, at a time of climatic amelioration and primary forest recovery when the vegetation of both islands were becoming less dominated by pteridophytes. Close similarities in floral composition exist within this initial period.

In the Tiriara sequence two major disturbance periods were recognised and attributed to human influence on the island. The earlier period, which occurs around 2800 yr BP, sees the decline of several primary tree species including *Weinmannia* and *Meryta* sp. This fall in tree taxa associated with undisturbed forests appears to correspond to the similar decline, attributed to saltwater intrusion, of *Pritchardia*, *Calophyllum* and species of *Elaeocarpus* noted at the end of zone V (i.e. ~5000 yr BP), in the Atiu sequence. It should be noted that the reference slides used to indentify the *Weinmannia* and *Meryta* pollen in the work on Mangaia, were later re-identified by the author as pollen from the genus *Elaeocarpus* and *Calophyllum* respectively. This resulted in an even closer similarity between the two pollen sequences. However, there is an obvious discrepancy in the dating of this event, which could possibly have resulted from a disruption of the Mangaian sediment sequence believed to have occurred between 13m and 10m, i.e. prior to the 3910±90 yr BP radiocarbon date (and clearly shown as a disjunct unit in the stratigraphy and x-ray photographs of this core). The dramatic increase in *Cocos* and *Acrostichum* pollen seen in the Atiu sequence around 5000 yr BP was apparently absent from the Mangaia sequence, although both of these taxa were identified as being present. *Pandanus*, another salt-tolerant tree, is however seen to increase and, along with the presence of mangrove plants recorded around the same period, perhaps support the alternative idea that increased salinity was responsible for this forest decline as opposed to human influence or storm activity.

A second period of vegetation disturbance was noted in the Mangaia sequence around 1600 yr BP (extrapolated date), which resulted in a further decrease in arboreal pollen and corresponding increase in grasses, sedges and ferns, most notably *Gleichenia linearis*. The pollen assemblages in this upper zone of the Mangaia sequence (Zone III) closely correspond to assemblages found in pollen zones VI andVII of the Atiu sequence and are strongly felt to represent the same event, namely the main arrival of Polynesians to the Cook Islands. Geochemical analysis of the Lake Tiriara core (Dawson, unpublished) also indicated an increase in catchment erosion during this disturbance phase, corresponding to increases in the basalt-oxide content of the Roto sequence. The small discrepancy between the two dates (1600 yr BP for Mangaia and 1420 yr BP for Atiu) may represent a real difference in the colonisation of these two islands or, more probably, just reflect the statistical variation or a slight inaccuracy in the extrapolated date from Mangaia.

Additional palynological work on several other lakes on Mangaia, have also been undertaken by J. Ellison (University of California at Berkeley). The 7240 yr BP record from Tamarua (adjcent basin to Lake Tiriara) indicates an increase in *Dichranopteris* (*Gleichenia*) at about 1640 yr BP which strongly correlating to the Lake Tiriara record (Ellison, pers. comm.). *Cocos* was also noted as being 'present before man'. Several shorter cores showed a disturbance event at 6500 yr BP, and sea-level fall 4000-3000 yr BP (Ellison, pers. comm.). Palaeoecological data from Rarotonga, undertaken by C. Peters (Massey University) will, it is hoped, also add to this picture of environmental and vegetation change in the Southern Cook Islands (detailed descriptions of this study is as yet unavailable).

Many accounts have been written about the devastation of indigenous floras and catastrophic increases in erosion which accompanied the arrival of Polynesians to previously 'pristine' island environments (e.g. Fosberg, 1963). However, the stratigraphic studies undertaken here show that quite abrupt changes in vegetation composition and density, as well as episodes of severe catchment erosion, have been occurring on the west-central Polynesian islands right up to the period of settlement and indeed long before that. For example, declines in primary taxa on Atiu, including *Pritchardia vuylstekeana*, *Calophyllum* sp., *Trema cannabina*, and *Elaeocarpus tonganus*, previously linked to Polynesian activity (Merlin & Sykes, pers. comm.), are shown to have resulted from natural stresses some 3600 years before the island was settled. While most of these primary taxa still exist in small pockets on the undisturbed and coastal regions of the *makatea*, the previously common indigenous palm (*Pritchardia vuylstekeana*) no longer grows on Atiu and is restricted to localised areas of *makatea* limestone on Miti'aro and Makatea island.

Polynesian settlers continued the modification of native floras and local environments mainly through forest clearance and the introduction of competative plants and animals. However, the landscapes they encountered on arrival, especially on the smaller and less elevated islands such as Atiu, are now believed to have been far from the 'pristine' and diverse habitats previously envisaged.

7.2. Re-interpretation of Polynesian prehistory

One of the main objectives of this study was to obtain accurate information on prehistoric settlement of Upolu, Atiu and Mo'orea in order to evaluate the presently contested theory of Polynesian settlement. Palynological and stratigraphic investigations from Atiu and Mo'orea were able to identify periods in the island histories that were undoubtedly influenced by human activity, and are in both cases believed to record the initial settlement period at least of significant population sizes. A latest-settlement date of 1420±45 (AD 640) was obtained from the Atiu sequence, while a ~1210±90 yr BP record of human influence (i.e. from AD 790) has been determined from the Mo'orea sequence. Modifications attributed to human activity were also recognised in the Lanoto'o catchment from 2425±70 yr BP (2461 cal. BP/512 BC), but a gap in the stratigraphic record immediately prior to this period meant that human influence in the catchment could have also occurred any time up to 900 years earlier (i.e. between 3300 and 2500 BP). This range of dates, however, does not appear to contradict estimates of Samoan settlement around 3251±150 yr BP derived from archaeological surveys (Leach & Green, 1989). It does, however, argue against the possibility of an earlier occupation date, i.e. before 3250 yr BP, as suggested by Tryon (1982), although a more widespread stratigraphic survey of Samoan island lakes and swamps wound be needed to rule this out confidently.

In the Orthodox Scenario of Polynesian prehistory, the Society group was settled by AD 800 by voyagers from the Marquesas. The Society Islands then served as a secondary dispersal centre for the Cook Islands, New Zealand and Hawai'i (Chapter 2). While the estimated settlement date for Mo'orea (this study) strongly supports an AD 800 occupation of the Societies, the AD 640 settlement of Atiu does not support an initial colonisation from the Society Islands. Polynesians instead appear to have reached the Cook Islands before arriving at the Societies. However, when the dating errors of the two sequences have been taken into consideration it is quite feasible that the Society and

Cook Islands were settled at the same time, either from the Marquesas or indeed directly from the Samoan Islands as predicted by Irwin (1990). The presence of 'Samoan' type adzes in the Cook Islands archaeological sites may also support a settlement directly from the west as suspected by Kirch (1986). The earlier settlement dates for the Southern Cook Islands (from this study and studies on Mangaia: Lamont, unpublished; Dawson, unpublished) open up a whole range of possible settlement scenarios. These include colonisation of both the Southern Cooks and Societies at the same time from the Samoas or Marquesas, or settlement of the Societies from the Southern Cooks. However, the possibility of the Southern Cook Islands being occupied before the Marquesas to the north-east (Kirch, 1986) seems less likely in the light of these new dates. Nevertheless, the Northern Cook Islands are likely candidates for pre-Marquesan occupation as indicated by the recent archaeological date of ~2200 yr BP from Pukapuka (Chikamori & Yoshida, 1988). It is possible that still earlier sites are undiscovered.

7.3. Future Research in this field

There is obvious potential for continued palynological and sedimentary research in the central Pacific region in relation to both an extension of the record of long-term environmental change and to expanding Polynesian settlement data. Long-term environmental records from the Samoan region should be made possible with further coring at Lake Lanoto'o, perhaps with stronger core-retrieval equipment. The stratigraphic investigation described in this study was unfortunately unable to realise the full potential of this site and further investigations should be rewarding. Apart from Lake Lanoto'o, several additional sites suitable for coring exist on Upolu including several upland crater lakes and swamps which occur at varying altitudes, for example the lake and swamp situated in the craters of Mt. Le Pu'e at 1166m (~330m above Lanoto'o), Lake Lanoanea and Lake Lanoataata (Fig. 4.2), both at elevations lower than Lanoto'o. Together with stratigraphic records from protected coastal swamp areas, these sites have the potential to provide a continuous log of environments from the penultimate or last glacial period (Kear & Wood, 1959) to the present day. Future studies could also play an important role in logging the erosional and vegetation changes that accompany well recorded destructive hurricanes such as the one that slammed into Savai'i and Upolu in February 1990. There was extensive damage to the native forest as well as to plantation forests and very few areas escaped devastation (Whistler, 1992). A comparative core from Lake Lanoto'o could improve our understanding the effects of such natural extreme events on upland ecosystems.

It is apparent from the four investigations undertaken in this study that the analysis of only one core from an island necessitates making far-reaching assumptions about climatic and vegetational change for the island as a whole. Although palaeoenvironmental studies frequently rely on single cores it is believed that the historical record presented here from

Upolu would have yielded a much broader, informative and accurate picture of island environments and indeed local settlement patterns if several core sequences had been collected from different sites. This would have enabled a more complete cover of local environments such as altitude, aspect, proximity to settlements etc. Nevertheless, the location and spacing of core sites would depend on the scale and type of investigation being made, i.e. regional climate, regional settlement or local changes in environment.

An altitudinal sequence from both windward and leeward areas on Upolu could reveal important information about zonal changes in vegetation, and the influence of aspect and orography on this high island. The pattern of settlement from inland to coastal regions, or vice versa, might also be revealed in such a concentration of studies, and add to the relatively sparse and often conflicting information from archaeological investigations. Several potential coring sites also exist on the neighbouring island of Savai'i where no studies of this type have previously been undertaken, perhaps as a result of the greater logistical challenge of working on this island.

The detailed history of human impact on the environment which was revealed in this study indicates the potential of the techniques used for elucidating such environmental histories on other Pacific islands which have suitable coring sites. Until recently, it has generally been thought that sediments accumulated in coastal areas of central Pacific islands, such as lagoons, mangrove swamps or deltaic deposits, were unlikely to reveal long or undisturbed stratigraphic records. Although sedimentation in Lake Temae probably resulted from late Holocene emergence of Mo'orea other studies, for example in Fiji (Southern, 1986), have revealed extensive deposits from deltaic regions and coastal swamps extending into the Pleistocene. Similar potential coastal sites exist around other high islands of Polynesia, which were previously regarded as unsuitable for environmental reconstruction because of the lack of inland lakes or swamps. One such site is the extensive swamp areas of northern Huahine, which could yield an older, and hopefully comparable, study to that undertaken on Mo'orea. Similarly, sites in the Marquesas islands, morphologically similar to the Societies, could provide the missing link in the argument of prehistoric settlement to this group of islands. Although the Northern Cook Islands are ideally situated geographically to answer disputes about Polynesian settlement, the islands are atolls or sand cays which only have exposed environments that are not particularly suited to palaeo-botanical investigations and any archaeological records that have survived are likely to be well buried. This island group also lies within a relatively stable climatic zone (the subtropical gyre) and is unlikely to be responsive to a climatic signal.

Another potential site for environmental reconstruction exists on the small island of Aunu'u, situated off the north-east coast of Tutuila (American Samoa). Faimulivae marsh is a lake-marsh area situated in a crater to the east of the island, and although the crater is incomplete and opens out to the sea, several metres of sediment are known to occur within the basin (investigated by the author in 1986). The top sediments, however, are composed of red algal material similar to that found in the Miti'aro sequence and may prove to be unsuitable for pollen analysis and geochemical investigations because of its high organic and sodium content. The lower sediments, on the other hand, appear to be composed of organic muds and peat, probably formed at a time of relatively lower sea-level. This sequence could, therefore, yield information not only on sea-level change (comparable with a more adequately dated Miti'aro sequence), but also on pre- and post-settlement environments from American Samoa.

Perhaps most important for the reconstruction of Pacific environments through palynological studies is the expansion of information on present day plant ecology and present day pollen studies. Although there is a growing literature on Pacific island floras and the identification of vegetation types, information on the precise ecologies and autecologies of vegetation communities and individual indicator taxa is still very sparse, often making the interpretation of fossil pollen profiles a daunting and fruitless task. Efforts should perhaps be concentrated on recognised indicator species and associated taxa, for example the *Gleichenia* scrub community or known subtropical 'austral species' such as *Ascarina* and *Weinmannia.*

Analyses of present-day pollen rain undertaken in this study proved to be totally unsuccessful due to the poor preservation of grains collected in the natural moss polsters. However, with a properly distributed and scheduled collection of pollen rain, using designed pollen traps, and detailed vegetation surveys, a data set of grain production and dispersal could easily be compiled. Using this data correction factors could be determined for over- and under-represented taxa under a variety of local conditions. A more complete collection of pollen types could also be made to aid future fossil pollen identifications.

This study unfortunately did not achieve all that was hoped in terms of regional palaeoclimatic reconstruction. In retrospect this is possibly because the islands were not chosen with a clear idea of the climatically sensitive areas of the Pacific and also an appreciation of the climatic amelioration imposed on these oceanic systems, which appear to subdue all but the major variations in climatic signals. There is, however, still potential for high resolution stratigraphic studies (i.e. on a 1-10 year cycle) on island ecosystems such as Samoa which lie within the principal areas of rainfall anomalies associated with ENSO events (referred to in Chapter 1 of this thesis and detailed in Hastenrath, 1991; Diaz & Markgraf, 1992). The stratigraphic sequences described in this dissertation were, however, unexpectedly informative in relation to sea-level change and local pre-settlement environments. The influence of sea-level and saltwater intrusion on the island systems of Atiu is perhaps most notable, as vegetation composition in the past and present appears to be intricately linked with the ocean environment. The study also yielded a range of information about the role of anthropogenic impact on island ecosystems and catchment stability, as well as providing new data on the distribution of plant taxa, either previously associated with Polynesian introduction or regarded as natural in origin.

On reconsidering the initial objectives, this study has provided valuable information about the environmental changes that have occurred on Upolu, Atiu Mo'orea and Tahiti and provides the first vegetation history records from all of these islands. The records cover the pre- to post-settlement periods, although making a clear distinction between natural and anthropogenic factors has not always been possible. In the light of the estimated settlement date for Atiu a reappraisal of the Polynesian settlement theories has been attempted with a recognition of the inadequacy of present theories. It is to be hoped that future studies of Pacific palaeoenvironments will provide additional pieces of information to the basic framework provided here and clarify some of the questions raised by this investigation.

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HOLOCENE ENVIRONMENTS AND VEGETATIONAL CHANGE ON FOUR POLYNESIAN ISLANDS

being a thesis submitted
for the Degree of Doctor of Philosophy

in the University of Hull

by

Annette Parkes, B.Sc.

March 1994. Vol. II. (Figures).

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Appendix 4

- A Radiocarbon dates from the sediments of Lakes Lanoto'o, Roto, Rotonui, Temae and Vaihiria.
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Appendix 5 Preparation of glass discs for XRF analysis based on the fusion method of Norrish and Hutton (1969).

Fig.1.1 Location of main island groups in the Pacific ocean, the geographical divisions of Melanesia, Micronesia and Polynesia and demarcation of the Andesite line.

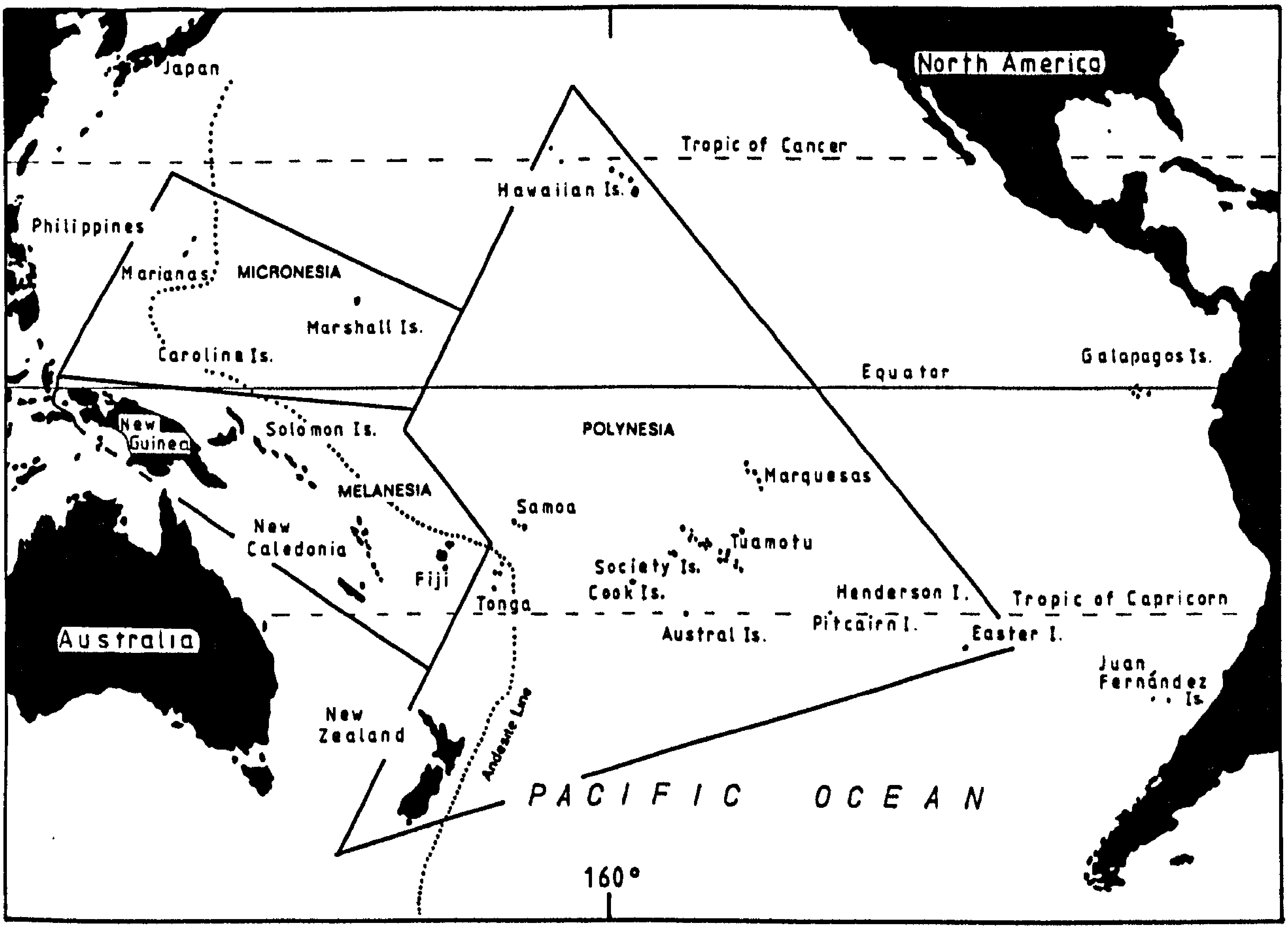


Fig.1.2 Relative distribution of the islands of Upolu, Atiu, Miti'aro, Mo'orea and Tahiti.

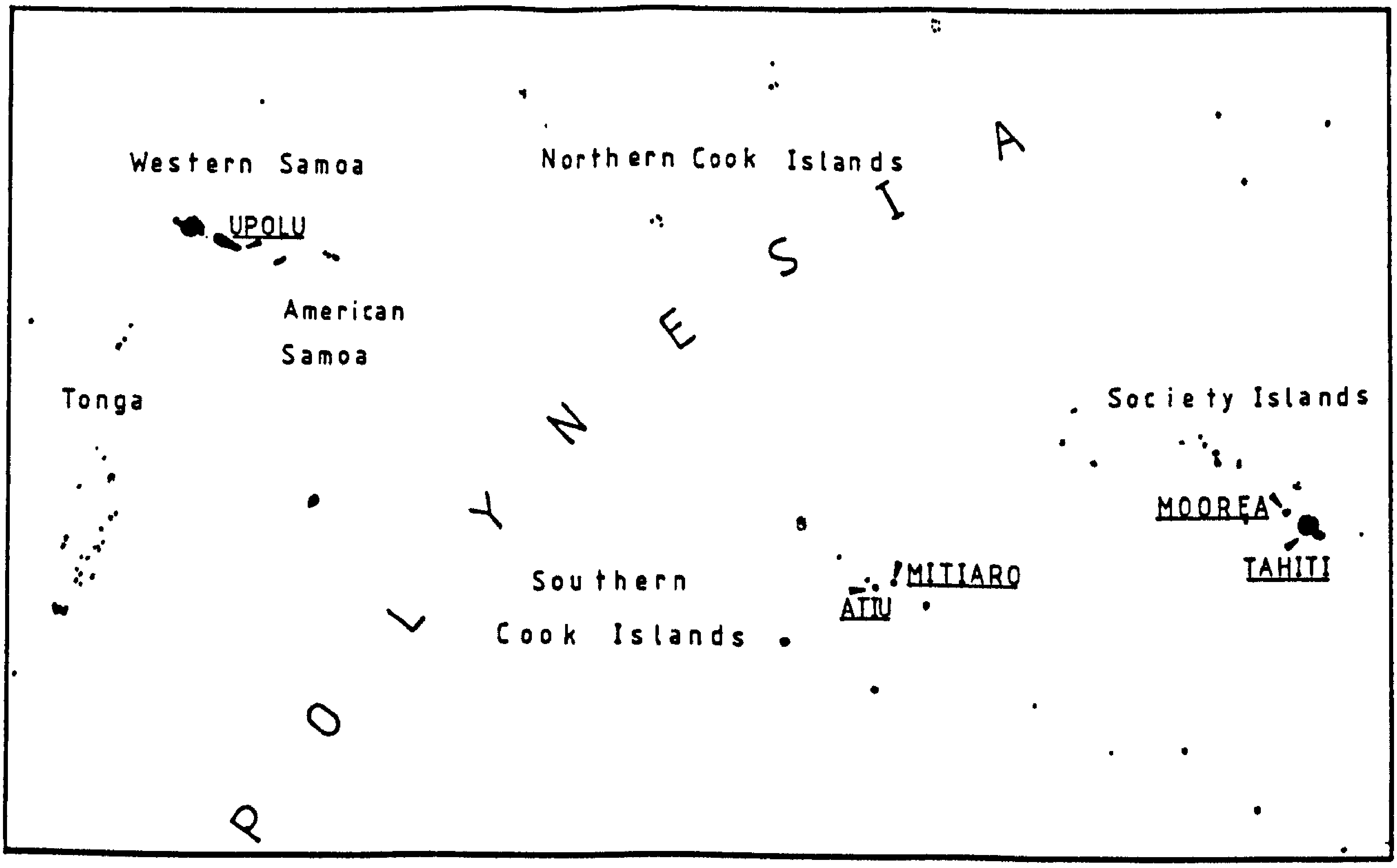
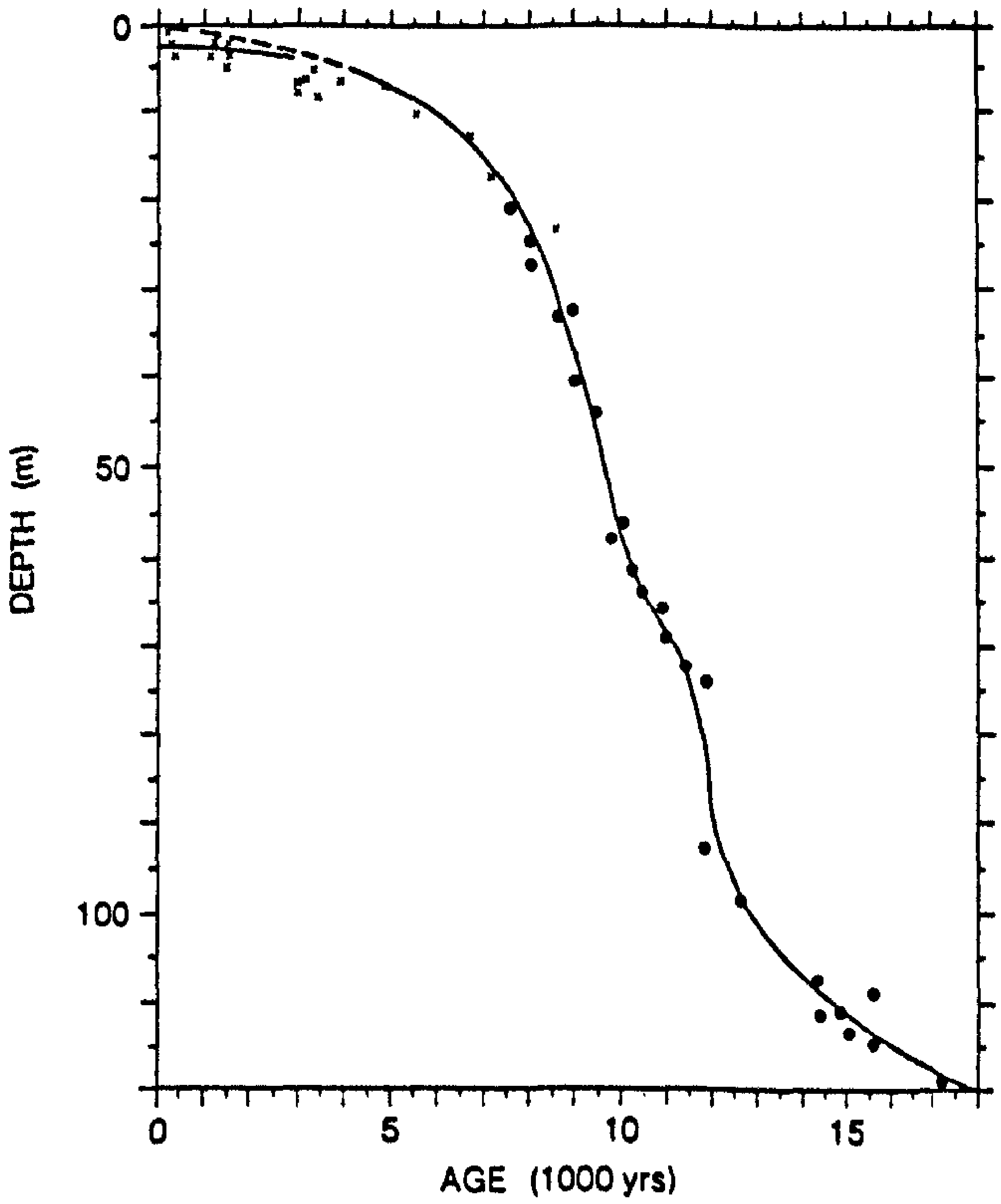


Fig.1.3 Earliest known settlement dates on selected Pacific islands based on Nunn (1990a).

Island group	Island site	Date (yr BP)	Source of data
Melanesia			
Papua New Guinea	Huon Peninsula	>40000	Groube *et al.*, 1986.
New Ireland	Matenkupkum cave	32700±1550	Allen *et al.*, 1988.
Solomon Islands	Kilu site	~28000	Wickler & Spriggs, 1988.
New Britain	Misisil cave	11400±1200	Specht *et al.*, 1981.
Fiji	Natunuku, Viti Levu	3240±100	Shaw, 1975.
New Caledonia	Naia	3165±120	Green & Mitchell, 1983.
Vanuatu	Malo	3150±70	Ward, 1979.
Polynesia			
Tonga	Tongatapu	3540±70	Poulsen, 1967.
Western Samoa	Ferry Berth, Upolu	3251±155	Leach & Green, 1989.
N. Cook Islands	Pukapuka	(~2200)	Chikamori & Yoshida, 1988.
Marquesas	Anapua, Ua Huka	2100±95	Ottino, 1985.
Hawai'i	Pu'u Ali'i, Hawai'i	1660±60	Bellwood, 1978.
Easter Island	Tahai	1260±130	Ayers, 1971.
Society Islands	Huahine	1100±70	Emory, 1979.
	Maupiti	1090±85	Emory & Sinoto, 1964.
S. Cook Islands	Tiriara, Mangaia	~1600	Lamont, unpubl.; Steadman & Kirch, 1990.
	Ureia, Aitutaki	969±83	Bellwood, 1978.
New Zealand	Wairau Bar, North Is.	~ 825	Bellwood, 1978.
Henderson Island	cave, north coast	790±110	Sinoto, 1979.
Mangareva		760±80	Shutler, 1971.
Micronesia			
Marianas Islands	Chalan Piao, Saipan	3479±300	Spoehr, 1957.
Caroline Islands	Bolipi, Lamotrek	3310±85	Fujimura & Alkira, 1984.

Fig.1.4 The sea-level curve for Barbados, based in radiocarbon dated corals (after Fairbanks, 1989).



The filled circles are data from Barbados corrected for estimated uplift. The crosses are data for four other islands in the Caribbean. The drawn curve reflects the depth range of live *Acroporapalmata*; the dashed line is adjusted to sea-level.

Fig.1.5 Estimated sea-level curve for zone V of Clark's (1980) model for the Pacific.

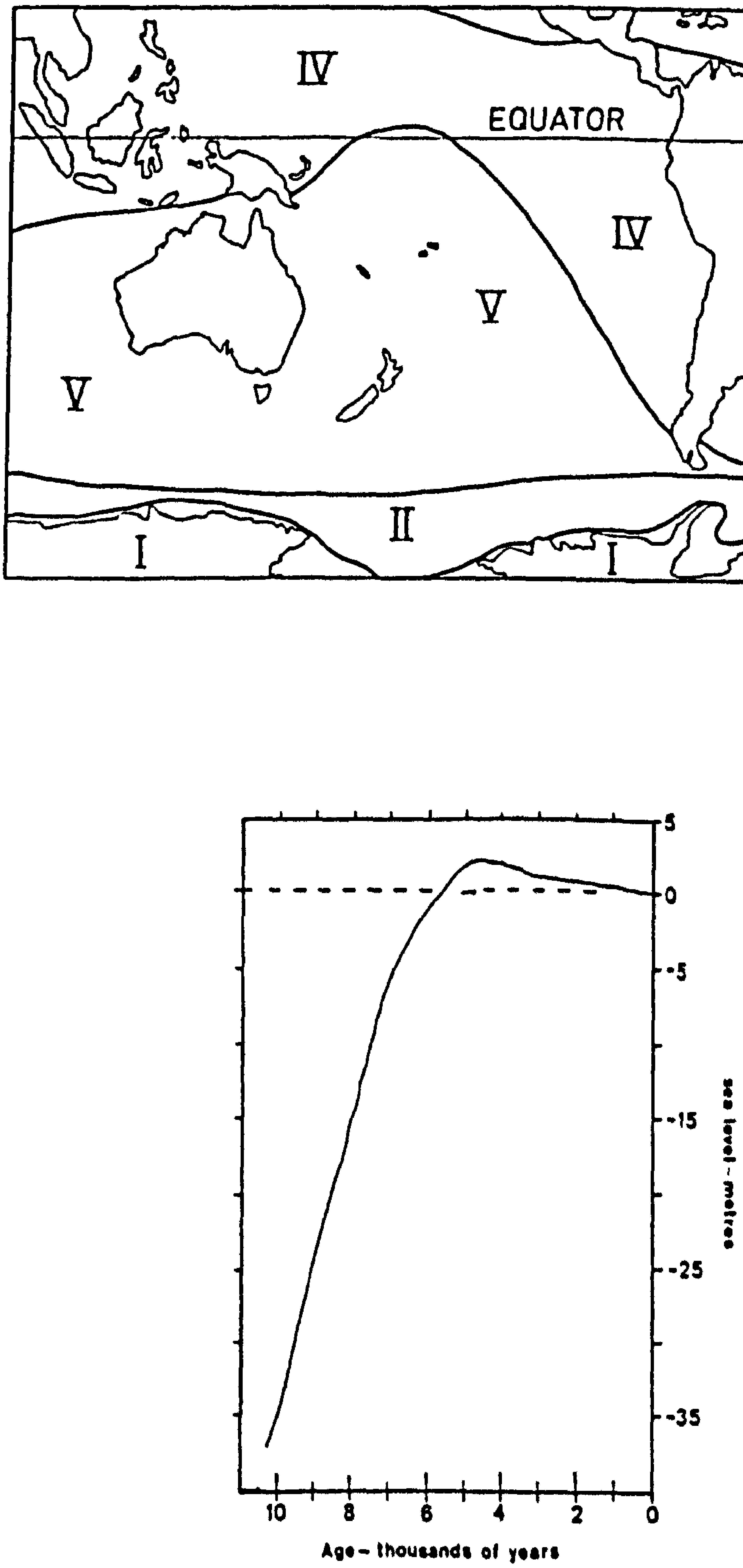


Fig.1.6 Schematic view of the main convergence zones, the ITCZ and SPCZ, along with the annual mean sea level pressure contours and surface wind streamlines.

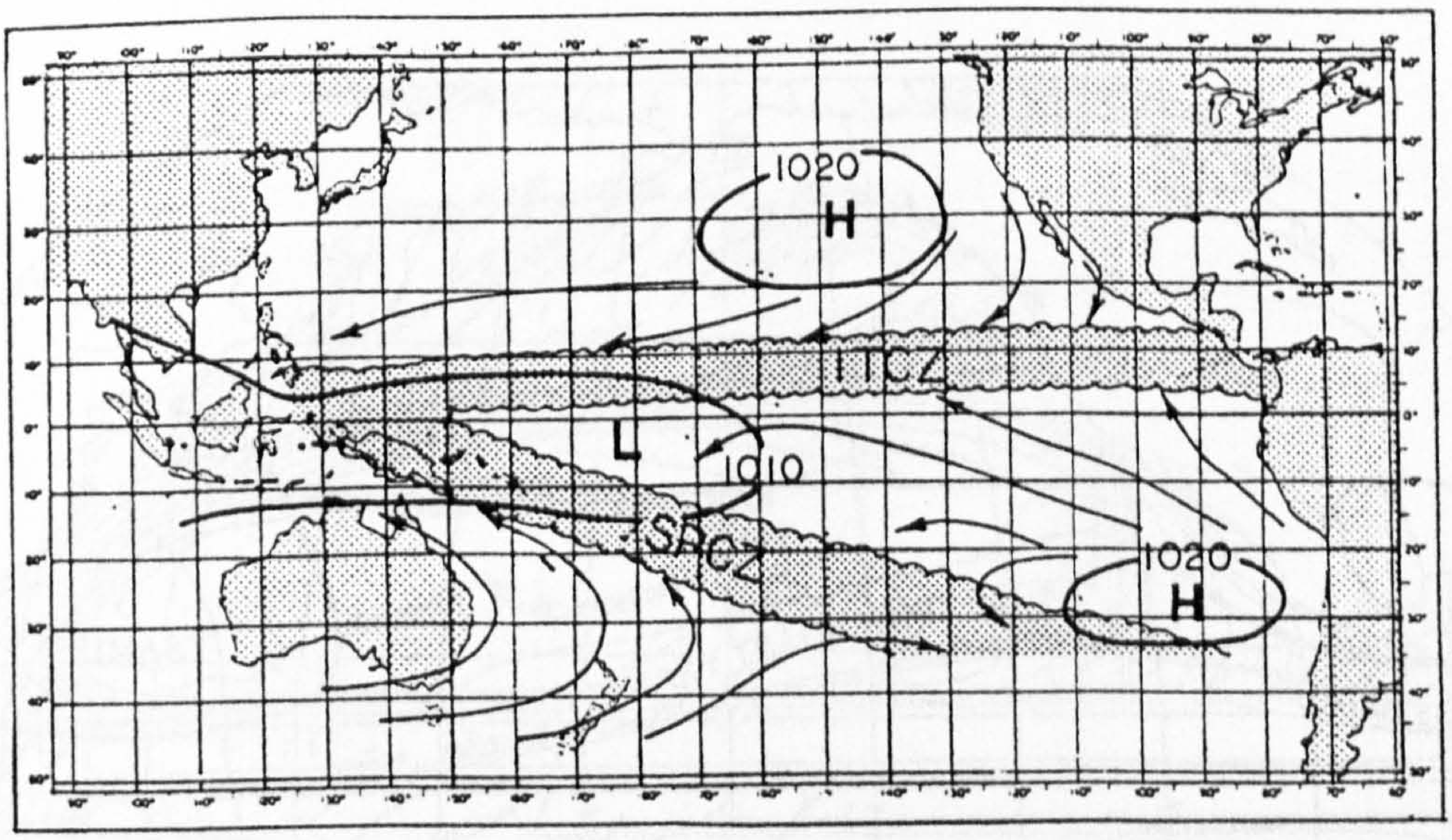


Fig.1.7 Schematic representation of the principal areas of rainfall anomalies during the high and low phases of the Southern Oscillation (after Ropelewski & Halpert, 1987; 1989).

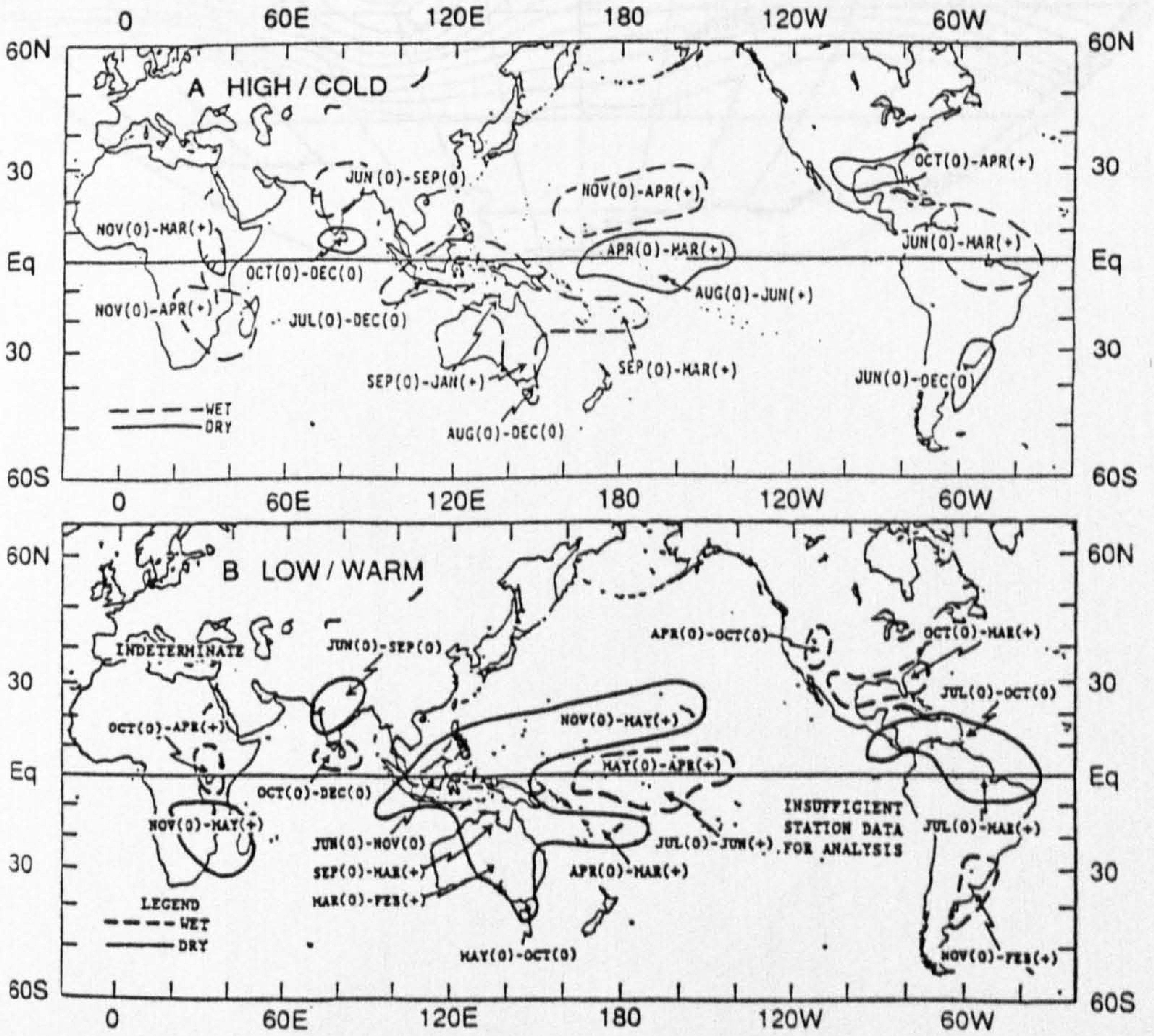


Fig.1.8 Distribution of atmospheric circulation regions and ocean current circulations of the Pacific. (Simplified zone of cyclone occurrence also shown).

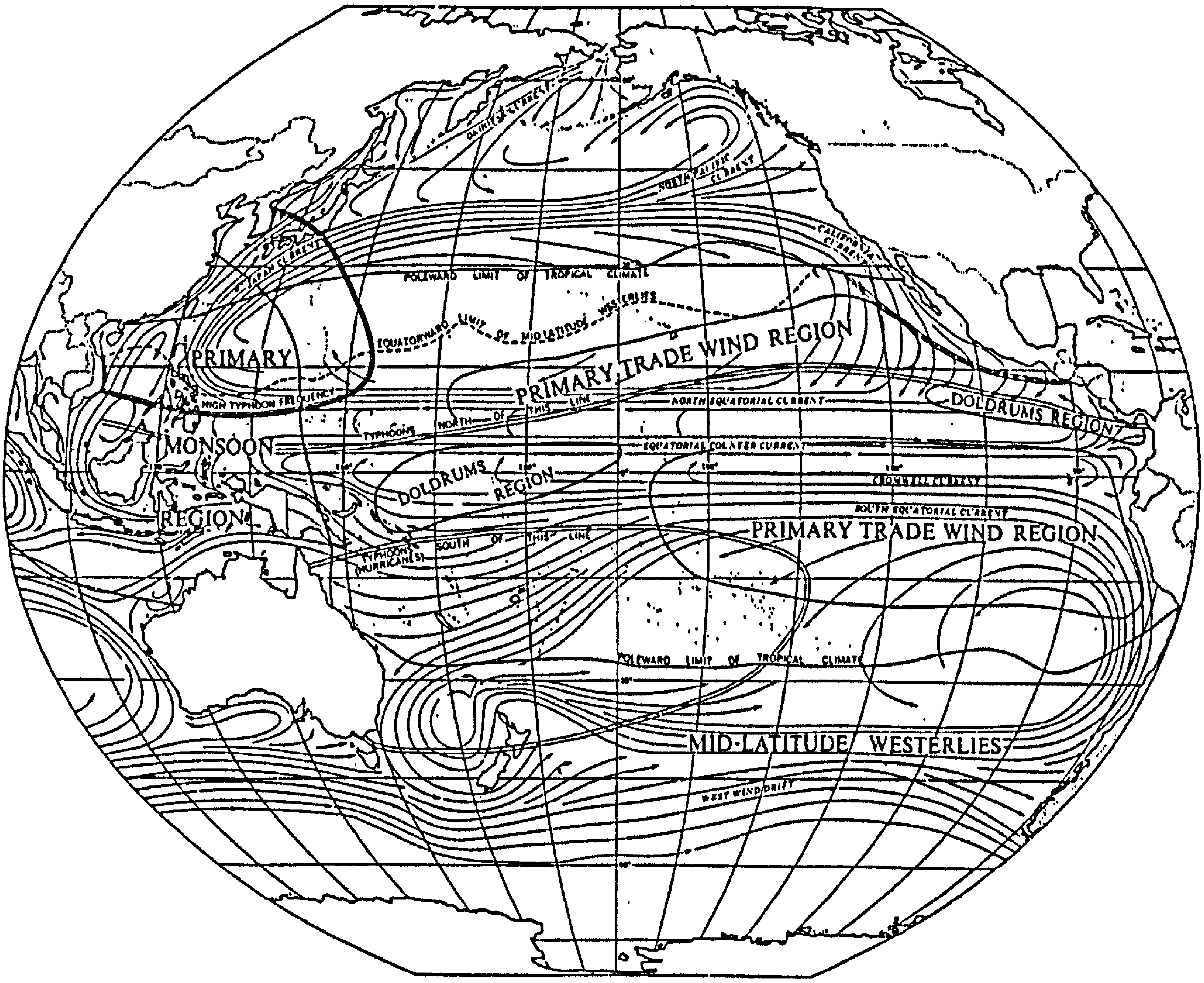


Fig.1.9 Distribution of mean annual rainfall (mm) in the central South Pacific Ocean (after Stoddart & Walsh, 1992).

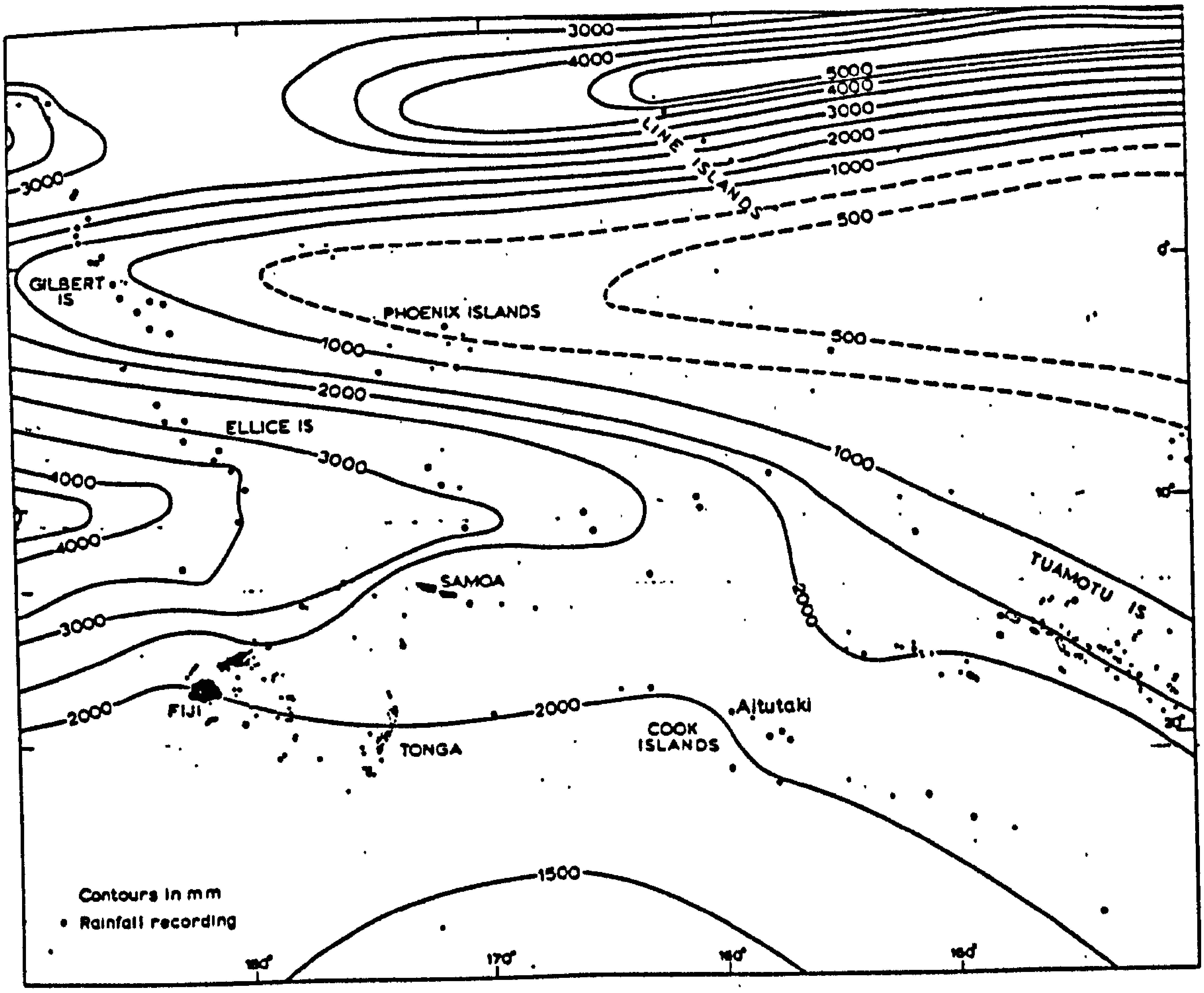


Fig.1.10 Mean annual sea-surface temperatures in °C (x10) (after Shea, 1986).

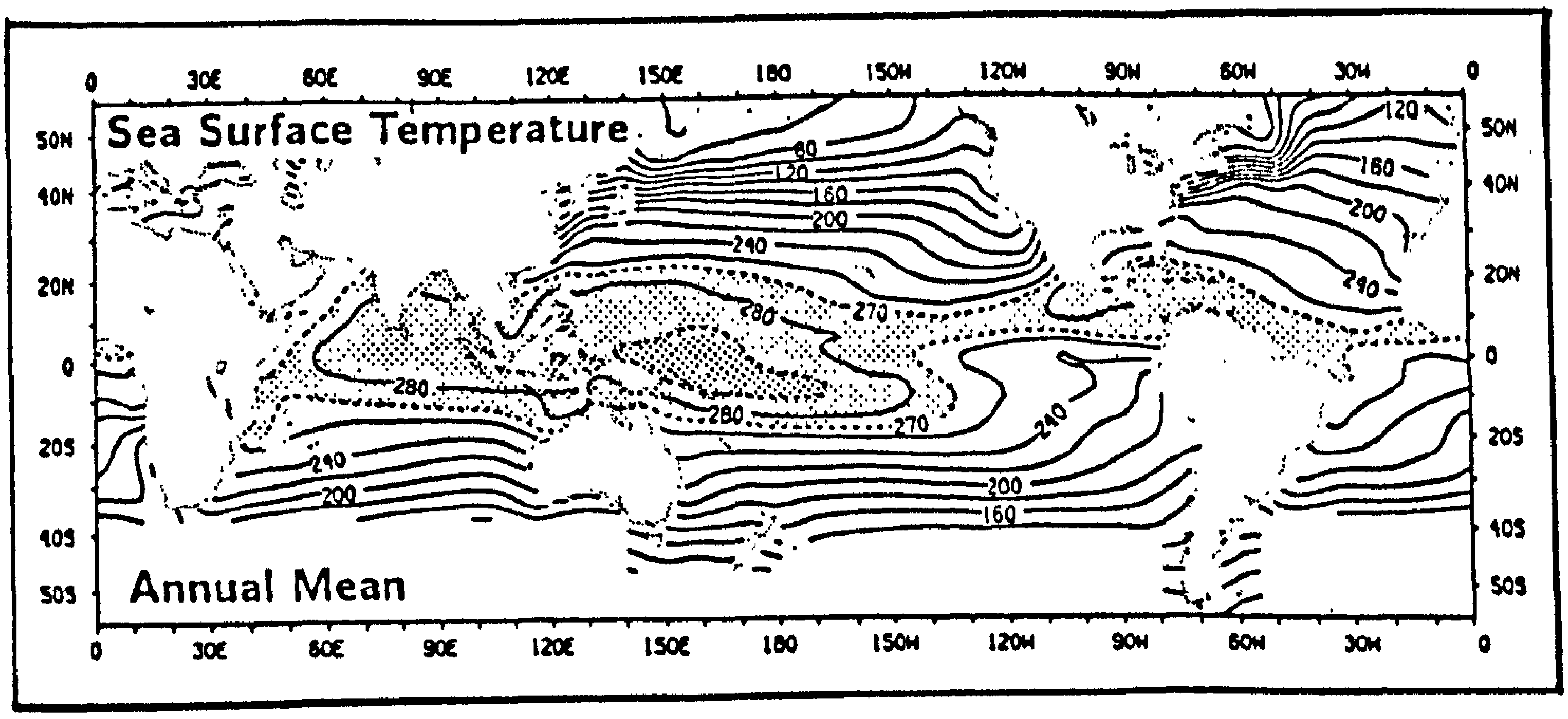


Fig.1.11 The Walker Circulation during high and low phases of the Southern Oscillation (after Lindesay, 1987).

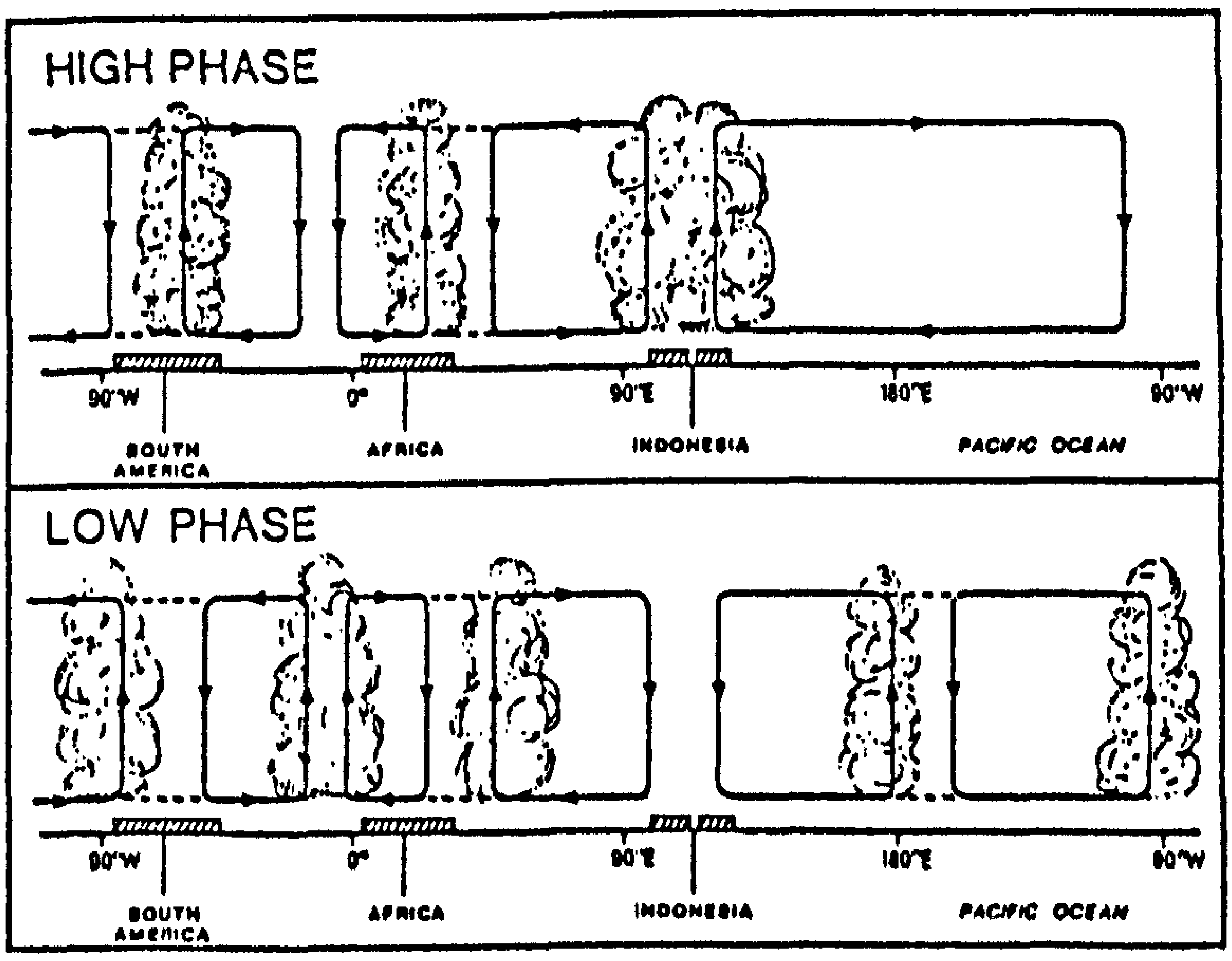


Fig.2.1 The Polynesian outlier islands in central Melanesia and southern Micronesia (after Bellwood, 1989).

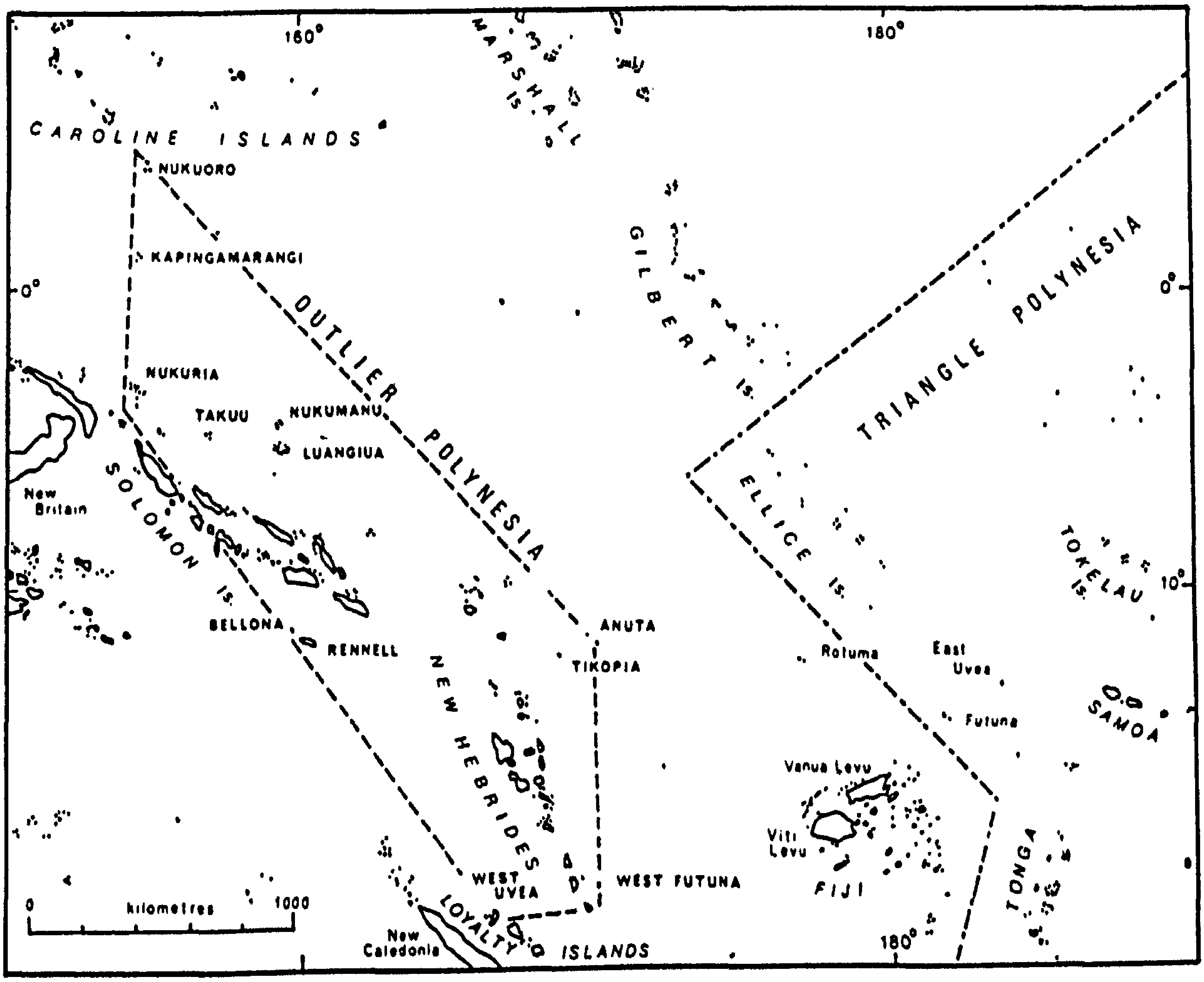
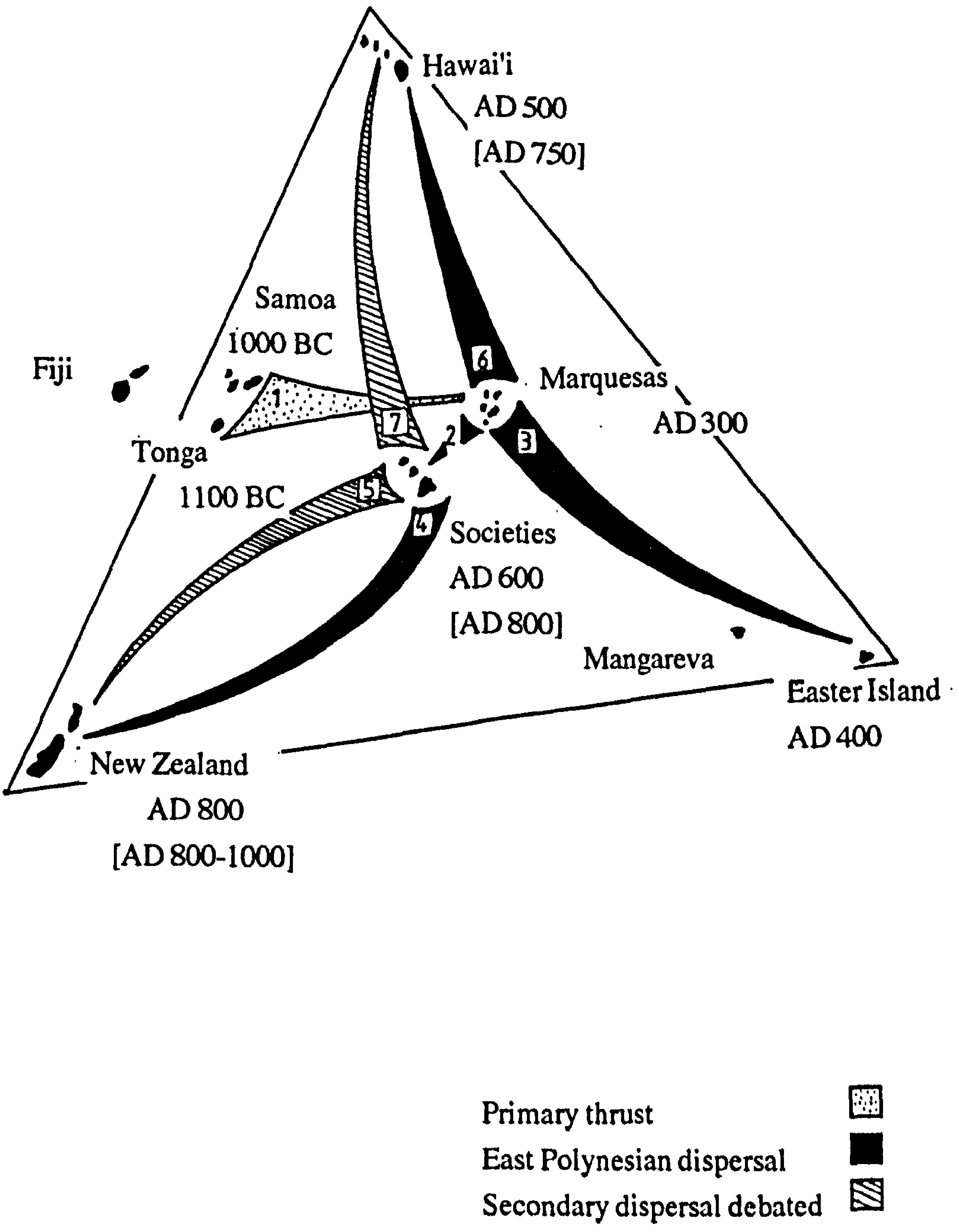


Fig.2.2 Emory & Sinoto model (1965) - plus revised dates (in brackets) used in the "Orthodox" Scenario of East Polynesian dispersals (after Jennings, 1979).



1) Colonization of the Marquesas from West Polynesia; 2) settlement of the Society Islands from the Marquesas; 3) settlement of Easter Island from the Marquesas; 4) initial colonization of New Zealand from the Society Islands; 5) secondary settlement of New Zealand from the Marquesas; 6) initial colonization of Hawai'i from the Marquesas; and 7) secondary settlement of Hawai'i from the Societies.

Fig.3.1 Geochemical analyses of sediment from Lake Temae: Percentage data.

	Depth	MgO_d	K2O_d	Fe2O...	MnO_d	TiO2_d	SiO2_d	SO3_d	CaO_d	P2O5_d	Al2O3_d	Na2O_d	LOI_d	L600
1	.25	1.86	.69	11.50	.07	2.21	26.85	6.64	2.23	.30	12.44	3.46	4.23	27.52
2	.39	1.73	.60	10.77	.08	1.93	27.44	6.06	1.64	.35	12.82	3.41	3.44	29.74
3	.76	1.79	.58	10.57	.05	1.69	24.89	4.90	.91	.35	12.02	3.42	3.85	34.97
4	1.06	2.83	.51	8.41	.05	1.41	22.38	5.68	1.22	.34	10.11	4.48	2.91	39.68
5	1.20	3.92	.54	8.11	.04	1.51	24.87	5.69	2.34	.34	9.88	3.95	2.77	36.02
6	1.42	4.66	.35	5.32	.04	.81	19.39	6.36	9.61	.26	5.51	4.17	4.51	39.01
7	1.76	5.54	.39	5.10	.08	.97	23.49	7.77	10.77	.25	5.68	3.46	4.90	31.59
8	2.11	6.04	.35	4.20	.07	.69	21.62	6.78	15.93	.30	5.03	2.59	7.28	29.11
9	2.54	6.45	.47	6.15	.06	1.19	26.99	6.39	7.51	.25	7.80	3.92	7.66	25.15
10	2.76	4.68	.43	5.51	.06	1.07	21.85	6.71	15.99	.25	6.75	2.91	8.59	25.20
11	3.37	4.64	.29	3.71	.05	.62	16.57	4.72	23.22	.24	4.70	2.50	10.34	28.41
12	3.50	4.55	.30	3.98	.04	.60	16.62	5.94	21.69	.24	5.12	2.22	8.58	30.12
13	3.72	3.68	.19	2.49	.02	.39	10.68	3.47	29.79	.19	3.22	2.02	21.07	22.78
14	3.90	3.46	.30	4.09	.03	.76	15.84	5.01	25.49	.21	5.17	1.76	15.74	22.16
15	4.16	2.50	.27	3.53	.03	.69	13.53	3.78	31.33	.19	4.47	1.22	14.81	23.66
16	4.30	2.43	.36	4.56	.04	.86	15.86	5.62	27.10	.20	5.94	1.48	18.32	17.22
17	4.46	2.96	.07	.35	.01	.05	1.19	1.25	46.86	.14	.43	1.62	36.08	9.00
18	4.90	2.47	.33	4.27	.04	.84	14.62	5.09	29.77	.20	5.08	1.33	19.26	16.68
19	5.20	2.43	.27	2.71	.02	.54	11.20	3.23	35.84	.18	3.11	1.19	27.13	12.15
20	5.62	2.34	.25	2.87	.04	.64	8.89	3.54	38.11	.18	3.38	.97	26.70	12.10
21	5.91	2.45	.27	2.77	.02	.63	8.12	4.23	37.74	.19	3.04	1.23	28.33	11.00
22	6.14	2.31	.22	2.52	.02	.58	6.28	3.22	35.16	.16	2.68	1.03	25.65	20.16
23	6.33	2.41	.49	5.92	.06	1.38	12.52	6.21	31.15	.23	6.31	1.12	17.52	14.68
24	6.40	2.02	1.35	15.44	.19	3.70	32.13	7.34	5.37	.35	17.00	2.42	3.27	9.42
25	6.58	2.80	1.42	16.18	.20	3.97	34.29	.89	2.14	.38	18.32	2.53	3.69	13.19
26	6.93	3.18	1.25	14.52	.22	3.39	30.52	.83	5.67	.31	15.02	2.60	5.20	17.29
27	7.18	2.45	.21	1.87	.02	.42	5.28	2.33	41.78	.19	2.10	.75	32.72	9.88
28	7.64	2.78	.14	1.06	0	.25	3.82	1.60	43.82	.20	1.18	.90	34.69	9.58
29	7.70	2.70	.10	.72	0	.16	2.41	1.46	45.51	.17	.72	1.21	34.33	10.50
30	8.28	2.71	.10	.91	0	.23	3.33	1.68	44.45	.18	1.06	.86	36.79	7.69
31	8.66	2.81	.10	.76	.01	.18	2.75	1.41	44.87	.19	.82	.98	37.38	7.73
32	9.36	2.88	.10	.93	0	.21	3.04	1.71	43.74	.18	1.06	.83	37.99	7.33
33	9.87	2.26	.37	3.75	.03	.87	8.96	6.03	36.03	.19	4.67	1.34	22.77	12.73
34	9.96	2.82	.11	.96	0	.22	3.08	1.99	43.14	.18	1.15	1.09	36.99	8.27
35	10.28	2.93	.10	.96	0	.22	3.12	1.22	44.32	.19	1.00	1.13	38.73	6.08
36	10.64	2.76	.12	1.01	0	.25	3.27	1.80	43.67	.17	1.15	.91	35.98	8.91
37	11.09	2.62	.04	.26	0	.07	.50	.63	47.74	.11	.20	1.60	39.85	6.39
38	11.18	2.92	.20	2.82	.02	.75	5.23	3.78	40.76	.17	2.58	1.01	30.10	9.66
39	11.51	2.39	.78	11.52	.13	3.10	23.36	6.41	15.77	.28	13.08	1.29	9.34	12.55
40	11.78	3.07	.09	.84	0	.21	1.91	1.27	45.17	.17	.82	1.02	37.21	8.23
41	12.24	2.91	.09	.81	0	.19	2.02	1.44	45.68	.16	.87	1.03	36.35	8.43
42	12.68	3.08	.10	.59	0	.16	2.10	.76	45.34	.19	.79	.95	37.18	8.75
43	13.20	2.97	.11	.91	0	.22	2.68	1.55	45.16	.19	1.04	1.00	36.27	7.90
44	13.68	3.00	.10	.58	0	.16	2.02	1.65	44.43	.20	.73	.94	36.09	10.10
45	14.23	3.05	.07	.39	0	.09	1.27	1.13	46.79	.17	.46	1.10	39.98	5.50
46	14.42	3.12	.09	.52	0	.16	2.34	.63	44.68	.18	.83	1.04	40.13	6.27

Fig.3.2 Pricipal Components Analysis on geochemical data from Lake Temae.

Factor Analysis for TEM xrf: $X_1 \ldots X_{13}$

Summary Information

Factor Procedure	Principal Component Analysis
Extraction Rule	Roots greater than one
Transformation Method	No transformation
Number of Factors	2

Unrotated Factor Scores: Columns 15 - 16

A

Correlation matrix

	MgO_d	K2O_d	Fe2O3_d	MnO_d	TiO2_d	SiO2_d	SO3_d	CaO_d
MgO_d	1							
K2O_d	-.066	1						
Fe2O3_d	-.081	.969	1					
MnO_d	.046	.967	.919	1				
TiO2_d	-.13	.984	.977	.95	1			
SiO2_d	.23	.871	.924	.845	.855	1		
SO3_d	.306	.396	.499	.375	.403	.687	1	
CaO_d	-.242	-.79	-.883	-.744	-.781	-.973	-.706	1
P2O5_d	.112	.827	.895	.761	.818	.906	.543	-.924
Al2O3_d	-.059	.958	.996	.904	.966	.939	.53	-.901
Na2O_d	.434	.511	.629	.466	.485	.793	.627	-.888
LOI_d	-.292	-.752	-.835	-.73	-.736	-.959	-.794	.968
L600	.426	.311	.459	.28	.289	.686	.714	-.799

Correlation matrix

	P205_d	Al203_d	Na20_d	LOI_d	L600
P205_d	1				
Al203_d	.908	1			
Na20_d	.765	.651	1		
LOI_d	-.859	-.856	-.835	1	
L600	.64	.492	.868	-.834	1

Partials in off-diagonals and Squared Multiple R in diagonal

	MgO_d	K20_d	Fe203_d	MnO_d	TiO2_d	SiO2_d	SO3_d	CaO_d
MgO_d	1							
K20_d	-.976	.999						
Fe203_d	-.999	-.972	1					
MnO_d	-.657	-.592	-.65	.985				
TiO2_d	-.989	-.961	-.987	-.641	1			
SiO2_d	-.999	-.975	-.999	-.66	-.992	1		
SO3_d	-1	-.976	-.999	-.664	-.991	-1	1	
CaO_d	-1	-.975	-.999	-.661	-.991	-1	-1	1
P205_d	-.867	-.822	-.87	-.588	-.889	-.875	-.872	-.874
Al203_d	-.999	-.975	-.997	-.672	-.989	-.999	-.999	-.999
Na20_d	-.998	-.972	-.998	-.662	-.992	-.999	-.999	-.999
LOI_d	-1	-.976	-.999	-.663	-.991	-1	-1	-1
L600	-1	-.976	-.999	-.662	-.991	-1	-1	-1

Partials in off-diagonals and Squared Multiple R in diagonal

	P205_d	Al203_d	Na20_d	LOI_d	L600
P205_d	.984				
Al203_d	-.866	1			
Na20_d	-.88	-.998	1		
LOI_d	-.872	-.999	-.999	1	
L600	-.873	-.999	-.999	-1	1

B Eigenvalues and Proportion of Original Variance

	Magnitude	Variance Prop.
Value 1	9.449	.727
Value 2	2.146	.165
Value 3	.666	.051
Value 4	.44	.034
Value 5	.122	.009
Value 6	.104	.008
Value 7	.033	.003

Eigenvectors

	Vector 1	Vector 2	Vector 3	Vector 4	Vector 5	Vector 6	Vector 7
MgO_d	.055	-.5	.8	-.11	-.123	-.078	.128
K2O_d	.29	.284	.165	-.049	.061	.056	-.176
Fe2O3_d	.309	.209	-.032	.035	-.005	.085	.118
MnO_d	.279	.263	.346	-.158	.317	-.029	-.557
TiO2_d	.287	.307	.085	-.078	-.012	.095	.089
SiO2_d	.322	-.028	.057	-.06	.058	-.013	.512
SO3_d	.219	-.305	-.327	-.771	-.293	.148	-.181
CaO_d	-.318	.114	.074	-.129	.01	-.053	-.264
P2O5_d	.304	.018	-.045	.3	-.676	-.518	-.257
Al2O3_d	.312	.182	-.05	.029	-.049	.039	.305
Na2O_d	.26	-.32	-.035	.43	-.104	.715	-.262
LOI_d	-.311	.16	.083	.123	-.311	.209	-.047
L600	.223	-.44	-.277	.222	.473	-.352	-.16

Unrotated Factor Matrix

	Factor 1	Factor 2
MgO_d	.169	.732
K2O_d	.893	-.416
Fe2O3_d	.95	-.305
MnO_d	.857	-.385
TiO2_d	.883	-.45
SiO2_d	.989	.041
SO3_d	.674	.447
CaO_d	-.978	-.166
P2O5_d	.934	-.027
Al2O3_d	.96	-.266
Na2O_d	.801	.469
LOI_d	-.957	-.234
L600	.685	.645

Communality Summary

	SMC	Final Estimate
MgO_d	1	.565
K2O_d	.999	.97
Fe2O3_d	1	.995
MnO_d	.985	.883
TiO2_d	1	.983
SiO2_d	1	.98
SO3_d	1	.654
CaO_d	1	.984
P2O5_d	.984	.873
Al2O3_d	1	.992
Na2O_d	1	.861
LOI_d	1	.97
L600	1	.885

C Factor Scores for Unrotated Solution

	Factor 1	Factor 2
MgO_d	.018	-.341
K2O_d	.094	.194
Fe2O3_d	.101	.142
MnO_d	.091	.179
TiO2_d	.093	.21
SiO2_d	.105	-.019
SO3_d	.071	-.208
CaO_d	-.103	.078
P2O5_d	.099	.013
Al2O3_d	.102	.124
Na2O_d	.085	-.219
LOI_d	-.101	.109
L600	.072	-.301

Fig.3.3 **Unrotated Orthogonal Plot: Factor 1 vs. Factor 2**

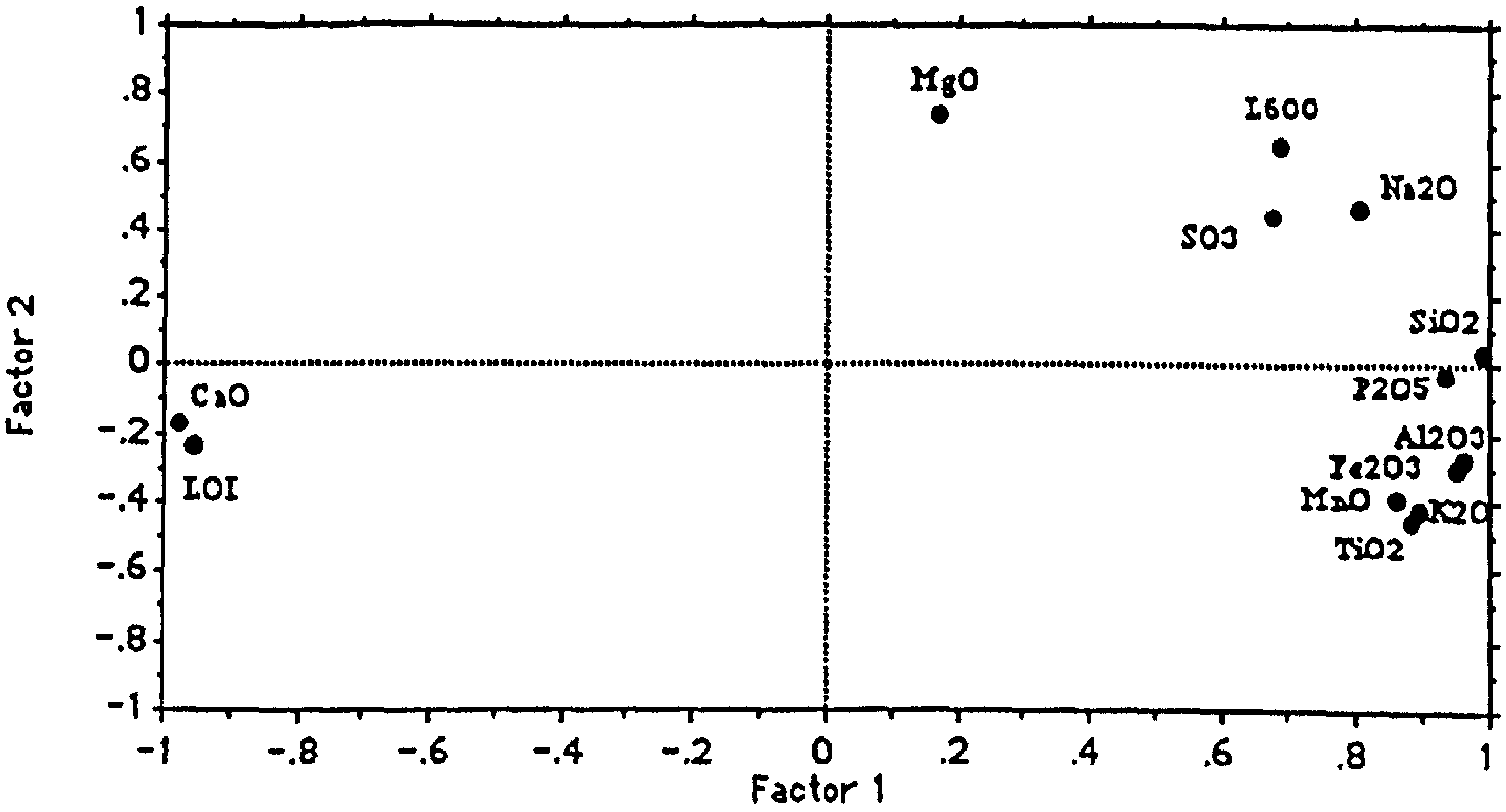
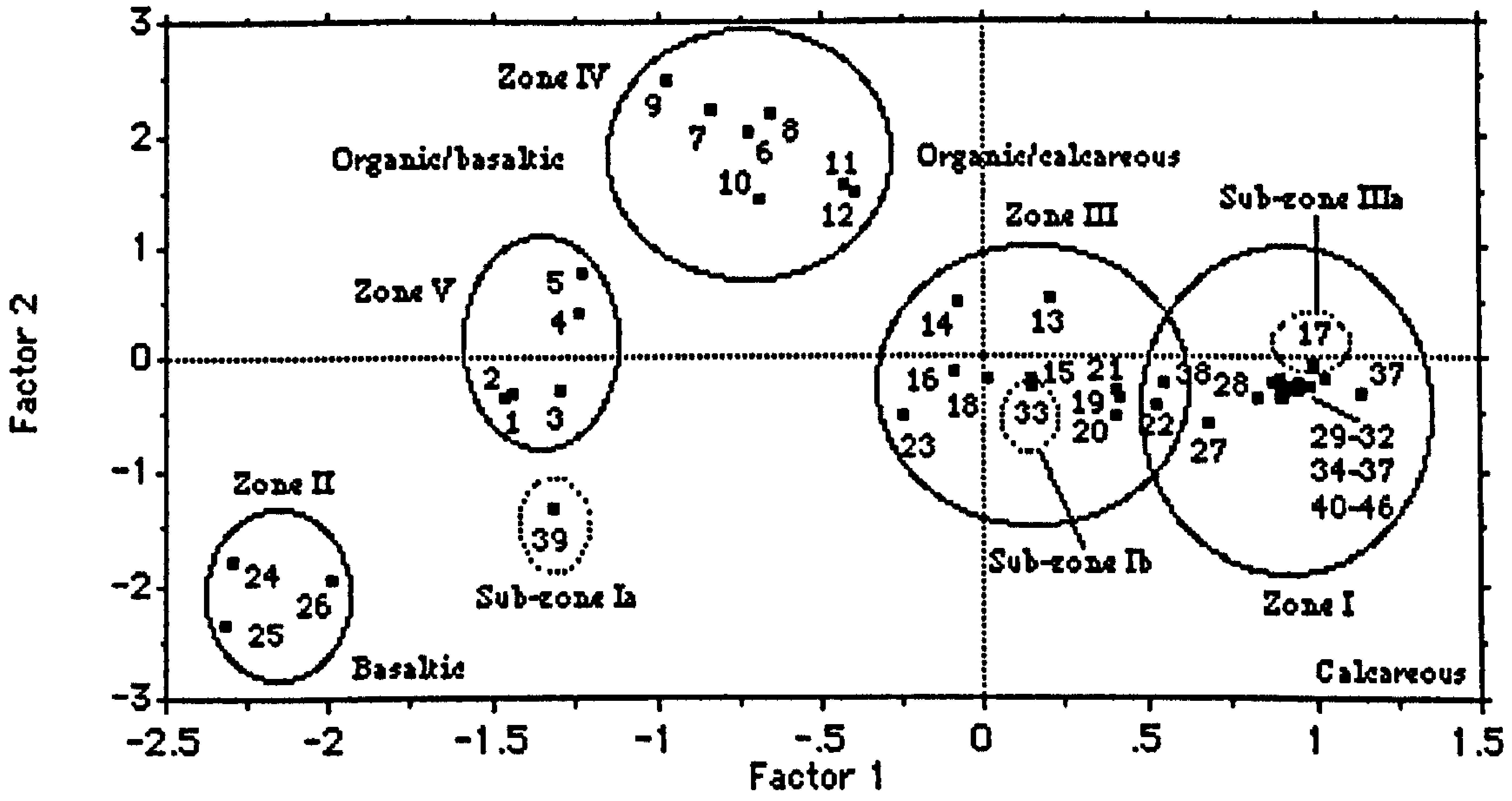


Fig.3.4 Factor scores derived from Lake Temae geochemical data.

	Depth	Factor 1	Factor 2
1	.25	1.450	.220
2	.39	1.488	.165
3	.76	1.364	-.096
4	1.06	1.350	-1.089
5	1.20	1.310	-1.239
6	1.42	.867	-2.102
7	1.76	.928	-1.961
8	2.11	.736	-1.891
9	2.54	1.006	-1.917
10	2.76	.734	-1.206
11	3.37	.347	-1.294
12	3.50	.396	-1.405
13	3.72	-.204	-.776
14	3.90	.127	-.558
15	4.16	-.086	-.116
16	4.30	.099	.079
17	4.46	-.999	.039
18	4.90	-.004	.129
19	5.20	-.426	.298
20	5.62	-.423	.447
21	5.91	-.428	.271
22	6.14	-.474	.083
23	6.33	.224	.518
24	6.40	2.111	2.238
25	6.58	2.152	2.622
26	6.93	1.835	2.091
27	7.18	-.698	.500
28	7.64	-.843	.270
29	7.70	-.923	.154
30	8.28	-.932	.330
31	8.66	-.923	.319
32	9.36	-.942	.292
33	9.87	-.167	.262
34	9.96	-.889	.206
35	10.28	-.934	.309
36	10.64	-.908	.267
37	11.09	-1.161	.261
38	11.18	-.570	.248
39	11.51	1.215	1.532
40	11.78	-.971	.190
41	12.24	-.979	.209
42	12.68	-.966	.223
43	13.20	-.910	.228
44	13.68	-.904	.117
45	14.23	-1.061	.244
46	14.42	-1.013	.288

Fig.3.5 Principal components analysis of XRF data from Lake Temae: Factor 1 versus factor 2.



<u>Key to sample depths within the identified geochemical zones:</u>

<u>Zone TgI (14.50-7.05m):</u>
46. 14.42m
45. 14.23m
44. 13.68m
43. 13.20m
42. 12.68m
41. 12.24m
40. 11.78m

Sub-zone TgIa (11.65-11.35):
39. 11.51m

38. 11.18m
37. 11.09m
36. 10.64m
35. 10.28m
34. 9.96m

Sub-zone TgIb (9.92-9.62):
33. 9.87m

32. 9.36m
31. 8.66m
30. 8.28m
29. 7.70m
28. 7.64m
27. 7.18m

<u>Zone TgII (7.05-6.36):</u>
26. 6.93m
25. 6.58m
24. 6.40m

<u>Zone TgIII (6.36-3.61):</u>
23. 6.33m
22. 6.14m
21. 5.91m
20. 5.62m
19. 5.20m
18. 4.90m

Sub-zone TgIIIa (4.68-4.38):
17. 4.56m

16. 4.30m
15. 4.16m
14. 3.90m
13. 3.72m

<u>Zone TgIV (3.61-1.31):</u>
12. 3.50m
11. 3.37m
10. 2.76m
9. 2.54m
8. 2.11m
7. 1.76m
6. 1.42m

<u>Zone TgV (1.31-0.0):</u>
5. 1.20m
4. 1.06m
3. 0.76m
2. 0.39m
1. 0.25m

Fig.3.6 First and second principal components of XRF analysis from Lake Temae plotted against core depth.

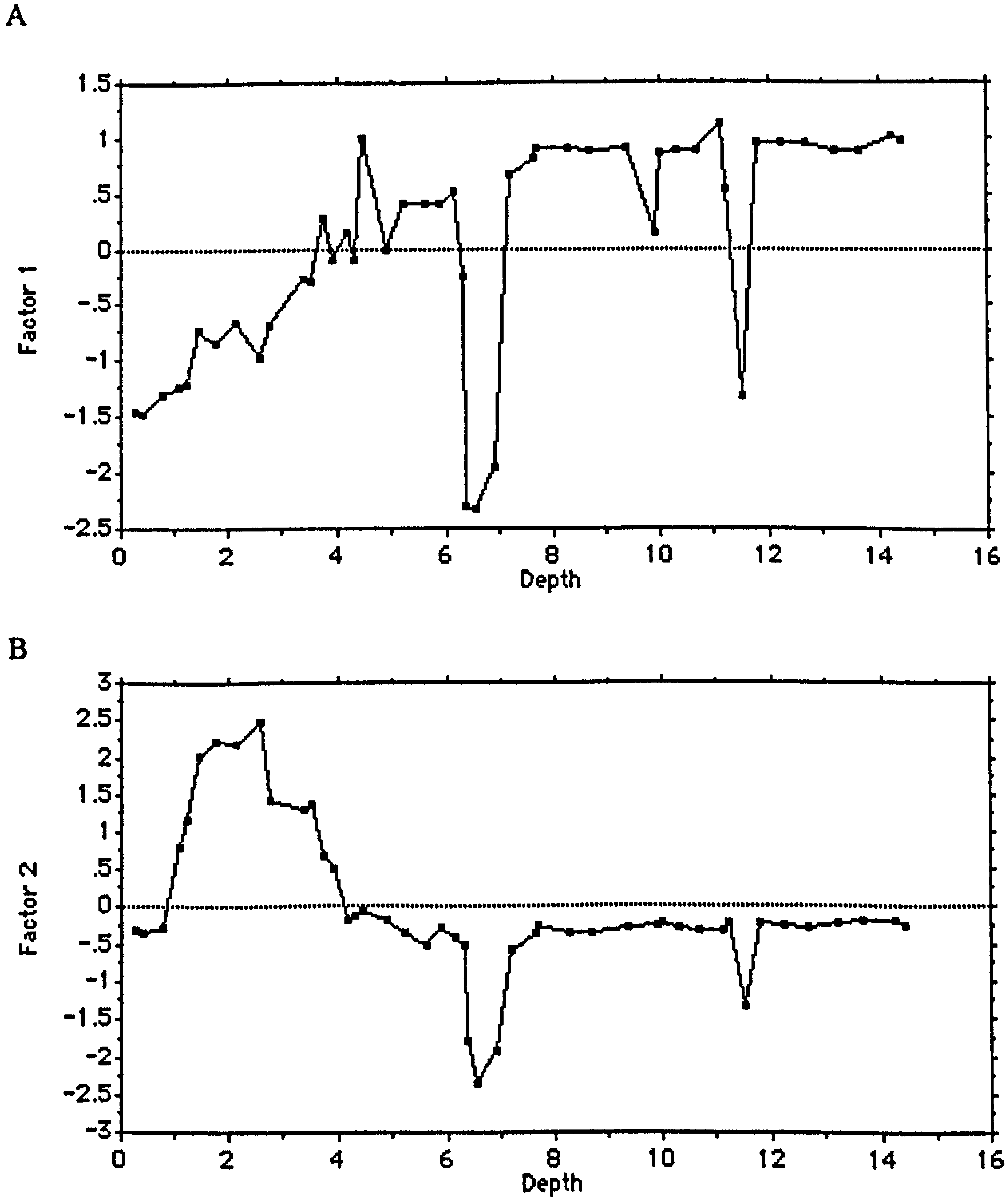
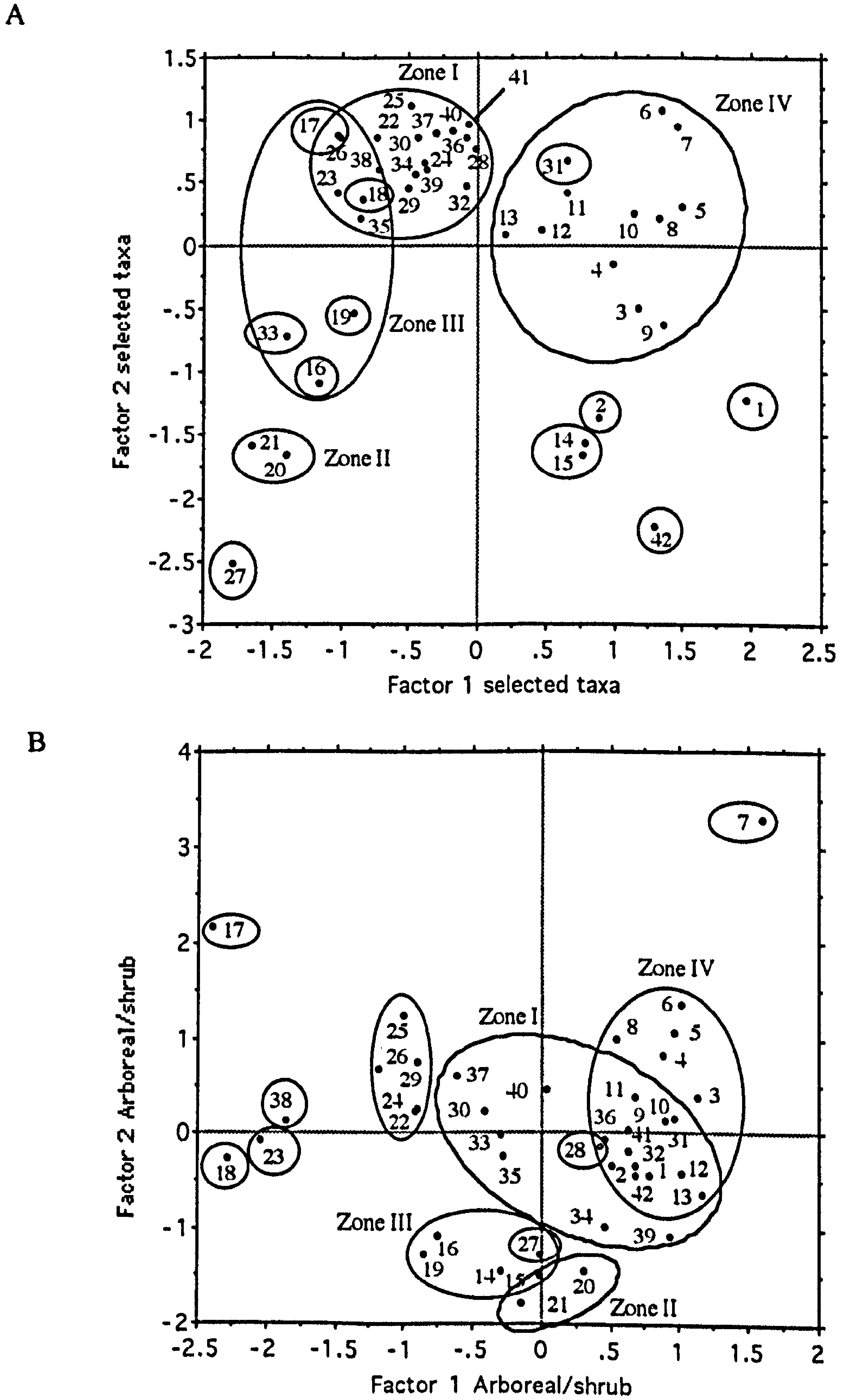
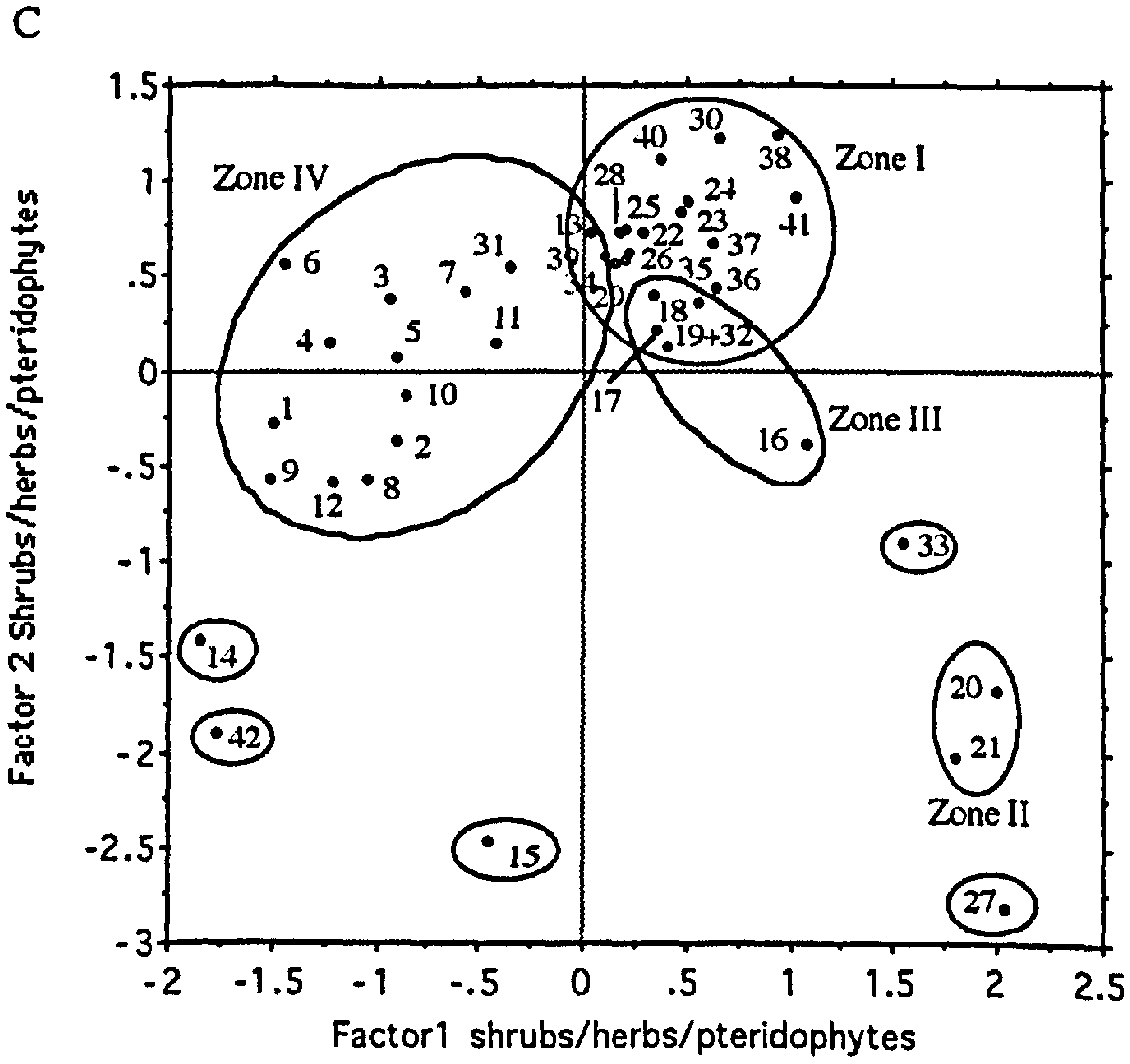


Fig3.7 Principal components analysis of pollen percentage data from Lake Temae: Factor 1 versus factor 2 (Selected taxa; arboreal or shrubs; shrubs, herbs and pteridophytes).




C
Factor 2 Shrubs/herbs/pteridophytes
Factor1 shrubs/herbs/pteridophytes
1.5
1
.5
0
-.5
-1
-1.5
-2
-2.5
-3
-2
-1.5
-1
-.5
0
.5
1
1.5
2
2.5
Zone I
Zone II
Zone III
Zone IV
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19+32
20
21
22
23
24
25
26
27
28
29
30
31
33
34
35
36
37
38
39
40
41
42

Key to sample depths within identified pollen zones:

Zone TpI (14.50-7.00m):

Sub-zone TpIa (14.50-14.45):

42. 14.48m

41. 14.42m
40. 14.23m
39. 14.03m
38. 13.68m
37. 13.20m
36. 12.68m
35. 12.24m
34. 11.78m

Sub-zone TpIb (11.65-11.35):

33. 11.51m

32. 11.18m
31. 11.09m
30. 10.64m
29. 10.28m
28. 9.96m

Sub-zone TpIc (9.92-9.62):

27. 9.87m

26. 9.36m
25. 8.64m
24. 8.28m
23. 7.64m
22. 7.18m

Zone TpII (7.00-6.45):

21. 6.93m
20. 6.58m

Zone TpIII (6.45-4.73):

19. 6.33m
18. 6.14m
17. 5.91m
16. 5.62m
15. 5.20m
14. 4.90m

Zone TpIV (4.73-3.07):

Sub-zone TpIVa (4.73-4.58):

13. 4.56m (sand layer: no pollen present)

12. 4.16m
11. 3.37m

Zone TpV (3.07-1.31)

10. 2.76m
9. 2.54m
8. 2.11m
7. 1.76m
6. 1.42m

Zone TpVI (1.31-0.0)

5. 1.20m
4. 1.06m
3. 0.76m
2. 0.39m
1. 0.25m

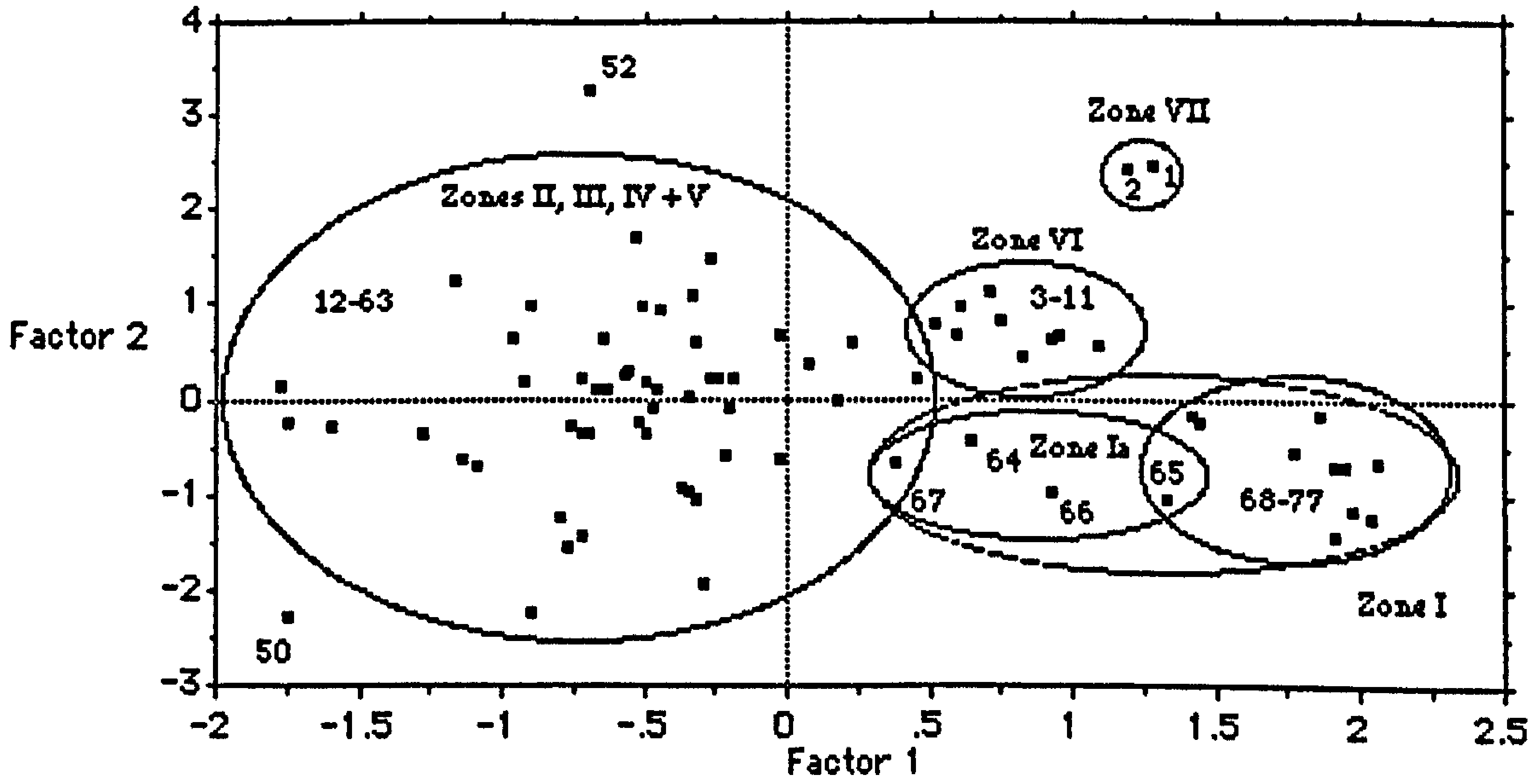
Samples identified within Zone TpIV of the Principal Components Analysis have been further divided into Zones IV, V and VI. based on the presence of ruderal herb and sedge pollen in these upper sediments.

Fig.3.8 Correlation matrix derived from Lake Roto geochemical data.

	Name	LOI	MgO_d	K2O_d	Fe2O3_d	MnO_d	TiO2_d	SiO2_d	SO3_d	CaO_d	P2O5_d	Al2O3_d	Na2O_d	L600
1	L600	1.000	-.089	-.686	-.288	-.168	-.696	-.901	.420	.212	-.679	-.781	.462	-.451
2	MgO_d	-.089	1.000	.586	-.374	-.406	-.129	.218	.003	.298	-.083	-.120	.543	-.277
3	K2O_d	-.686	.586	1.000	-.118	-.156	.488	.801	-.476	-.106	.417	.540	-.071	.220
4	Fe2O3_d	-.288	-.374	-.118	1.000	.293	-.020	-.072	.121	-.009	.207	.027	-.466	.125
5	MnO_d	-.168	-.406	-.156	.293	1.000	.080	.047	-.043	-.145	.385	.116	-.194	.366
6	TiO2_d	-.696	-.129	.488	-.020	.080	1.000	.809	-.847	-.388	.662	.973	-.695	.466
7	SiO2_d	-.901	.218	.801	-.072	.047	.809	1.000	-.652	-.338	.643	.856	-.392	.439
8	SO3_d	.420	.003	-.476	.121	-.043	-.847	-.652	1.000	.452	-.489	-.801	.544	-.477
9	CaO_d	.212	.298	-.106	-.009	-.145	-.388	-.338	.452	1.000	-.041	-.338	.169	-.321
10	P2O5_d	-.679	-.083	.417	.207	.385	.662	.643	-.489	-.041	1.000	.696	-.578	.449
11	Al2O3_d	-.781	-.120	.540	.027	.116	.973	.856	-.801	-.338	.696	1.000	-.697	.512
12	Na2O_d	.462	.543	-.071	-.466	-.194	-.695	-.392	.544	.169	-.578	-.697	1.000	-.454
13	LOI_d	-.451	-.277	.220	.125	.366	.466	.439	-.477	-.321	.449	.512	-.454	1.000

Fig.3.9 Principal components analysis of percentage XRF data from Lake Roto: Factor 1 versus factor 2. Zones RgI to VII.

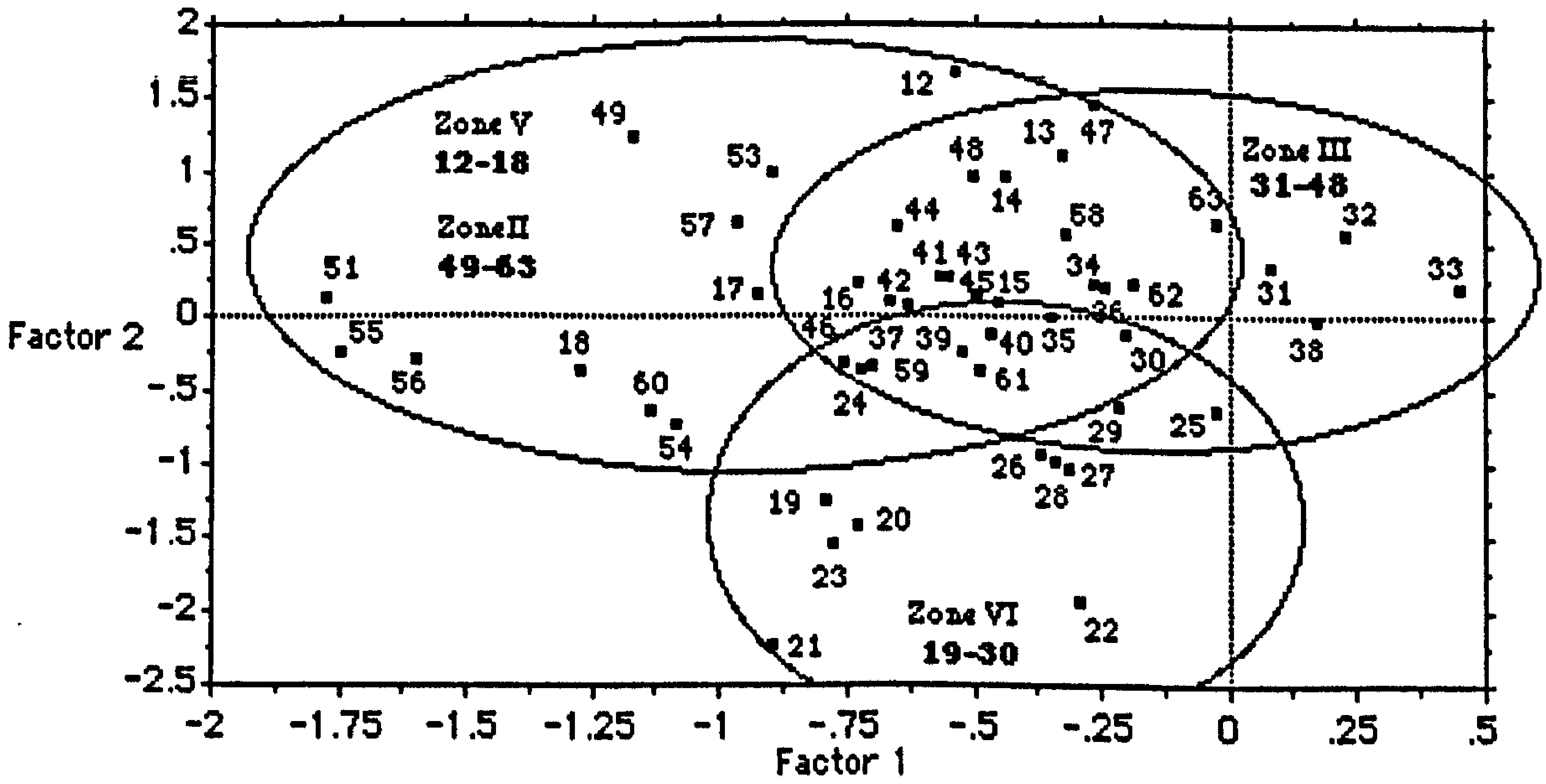
A



Peat / organic gyttja-----> organic gyttja ------> inorganic basalt-oxides

B

(Zones RgII, III, IV and V)



Key to sample depths within the identified geochemical zones

Zone RgI (16.0-13.29m):
77. 15.96m
76. 15.85m
75. 15.64m
74. 15.40m
73. 15.20m
72. 14.90m
71. 14.66m
70. 14.40m
69. 14.28m
68. 14.20m

Sub-zone RgIa (14.02-13.29):
67. 13.84m
66. 13.66m
65. 13.50m
64. 13.36m

Zone RgII (13.29-10.20)
63. 13.22m
62. 12.90m
61. 12.70m
60. 12.48m
59. 12.32m
58. 12.13m
57. 11.90m
56. 11.70m
55. 11.50m
54. 11.20m
53. 11.10m
52. 10.90m
51. 10.70m
50. 10.45m
49. 10.24m

Zone RgIII (10.20-7.30):
48. 10.16m
47. 9.90m
46. 9.76m
45. 9.66m
44. 9.46m
43. 9.24m
42. 8.90m
41. 8.75m
40. 8.65m
39. 8.46m
38. 8.36m
37. 7.97m
36. 7.93m
35. 7.84m
34. 7.76m
33. 7.70m
32. 7.50m
31. 7.40m

Zone RgIV (7.30-5.05):
30. 7.20m
29. 6.90m
28. 6.70m
27. 6.60m
26. 6.40m
25. 6.20m
24. 6.10m
23. 5.90m
22. 5.70m
21. 5.60m
20. 5.40m
19. 5.20m

Zone RgV (5.05-3.35):

Sub-zone RgVa (5.05-4.92)
* 4.95m

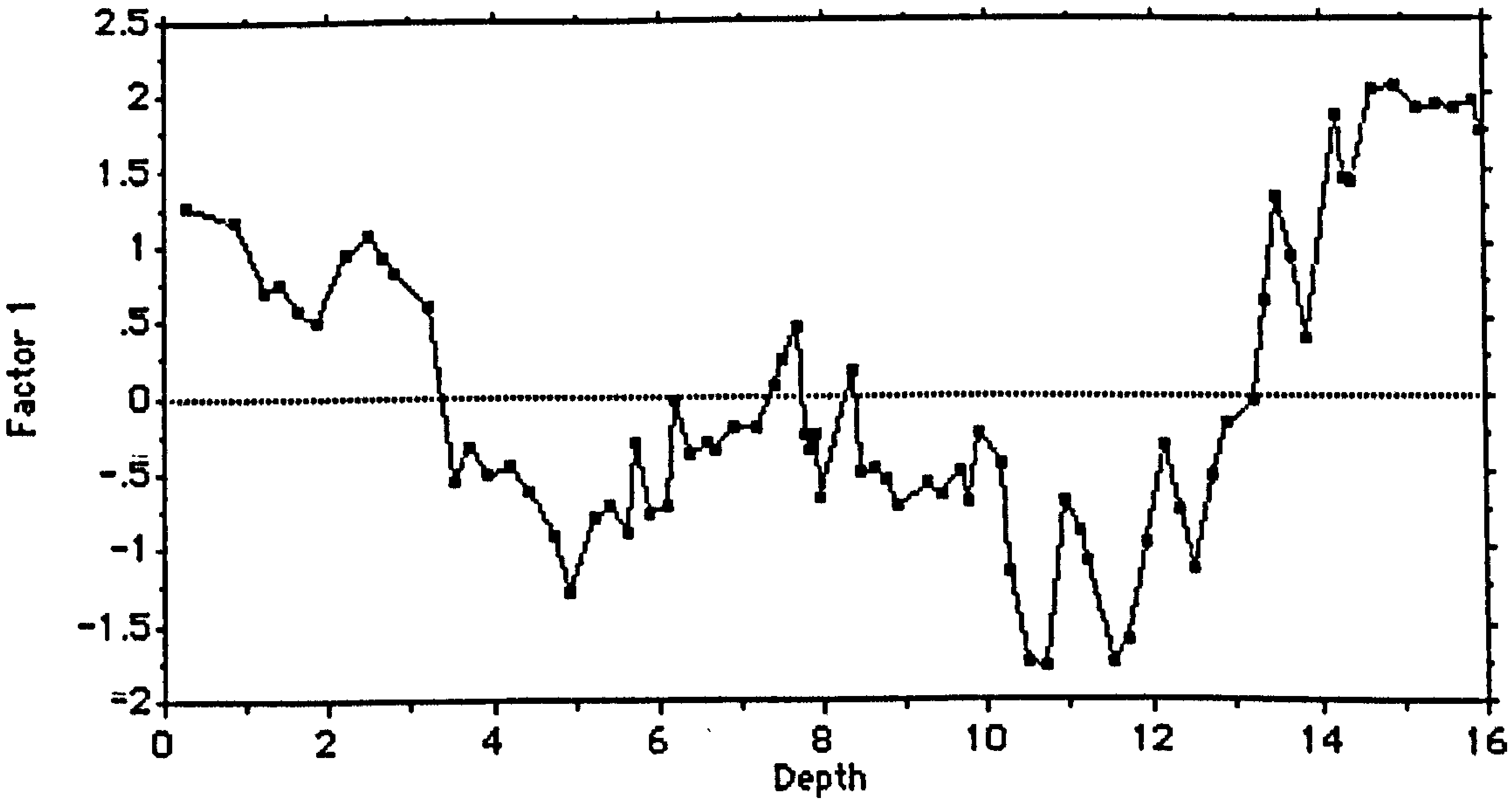
18. 4.90m
17. 4.70m
16. 4.40m
15. 4.20m
14. 3.90m
13. 3.70m
12. 3.50m

Zone RgVI (3.35-1.03):
11. 3.19m
10. 2.80m
9. 2.65m
8. 2.45m
7. 2.20m
6. 1.85m
5. 1.60m
4. 1.40m
3. 1.20m

Zone RgVII (1.03-0.0):
2. 0.85m
1. 0.25m

Fig.3.10 First and second principal components of XRF analysis from Lake Roto plotted against core depth.

A



B

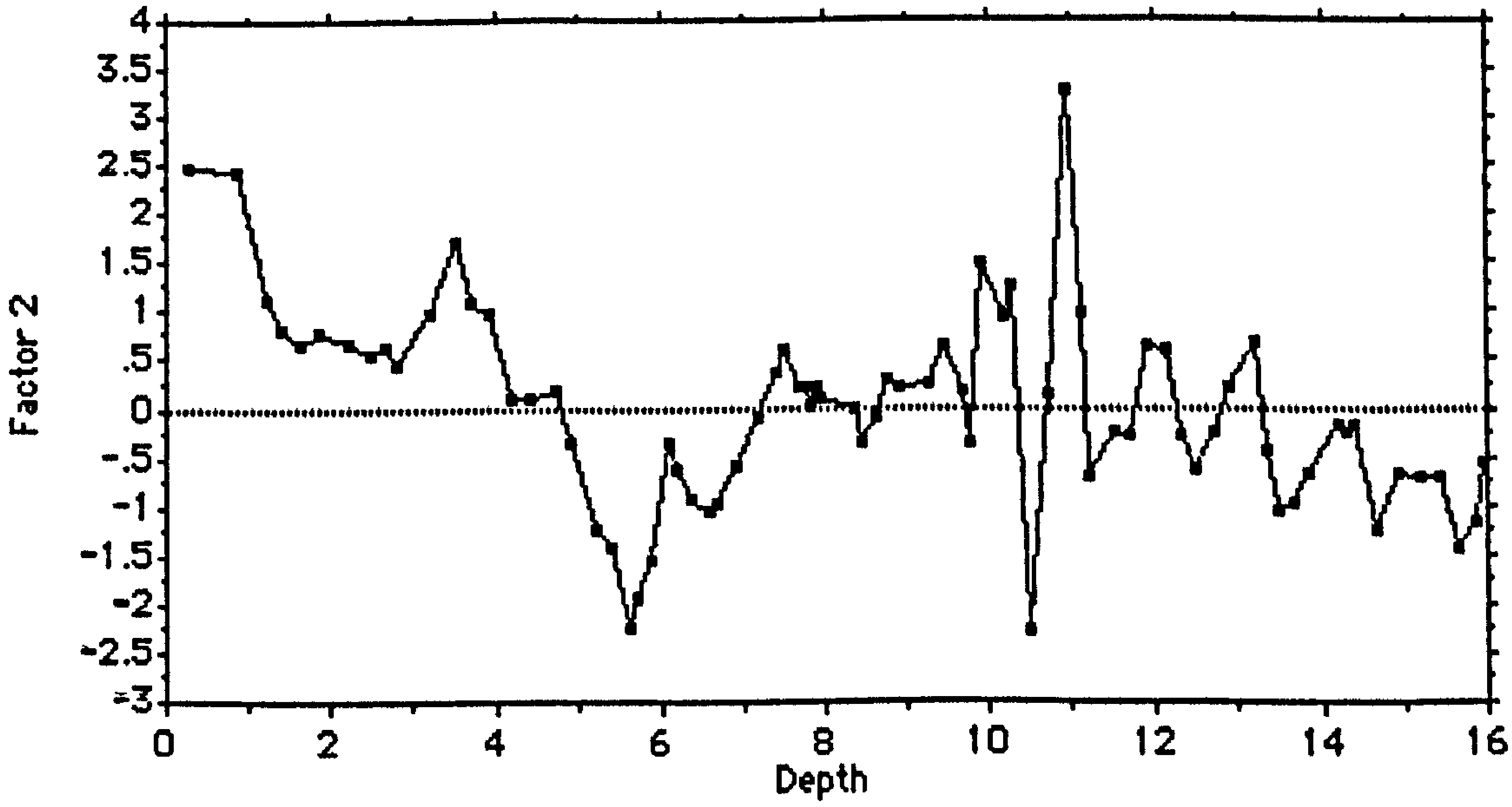
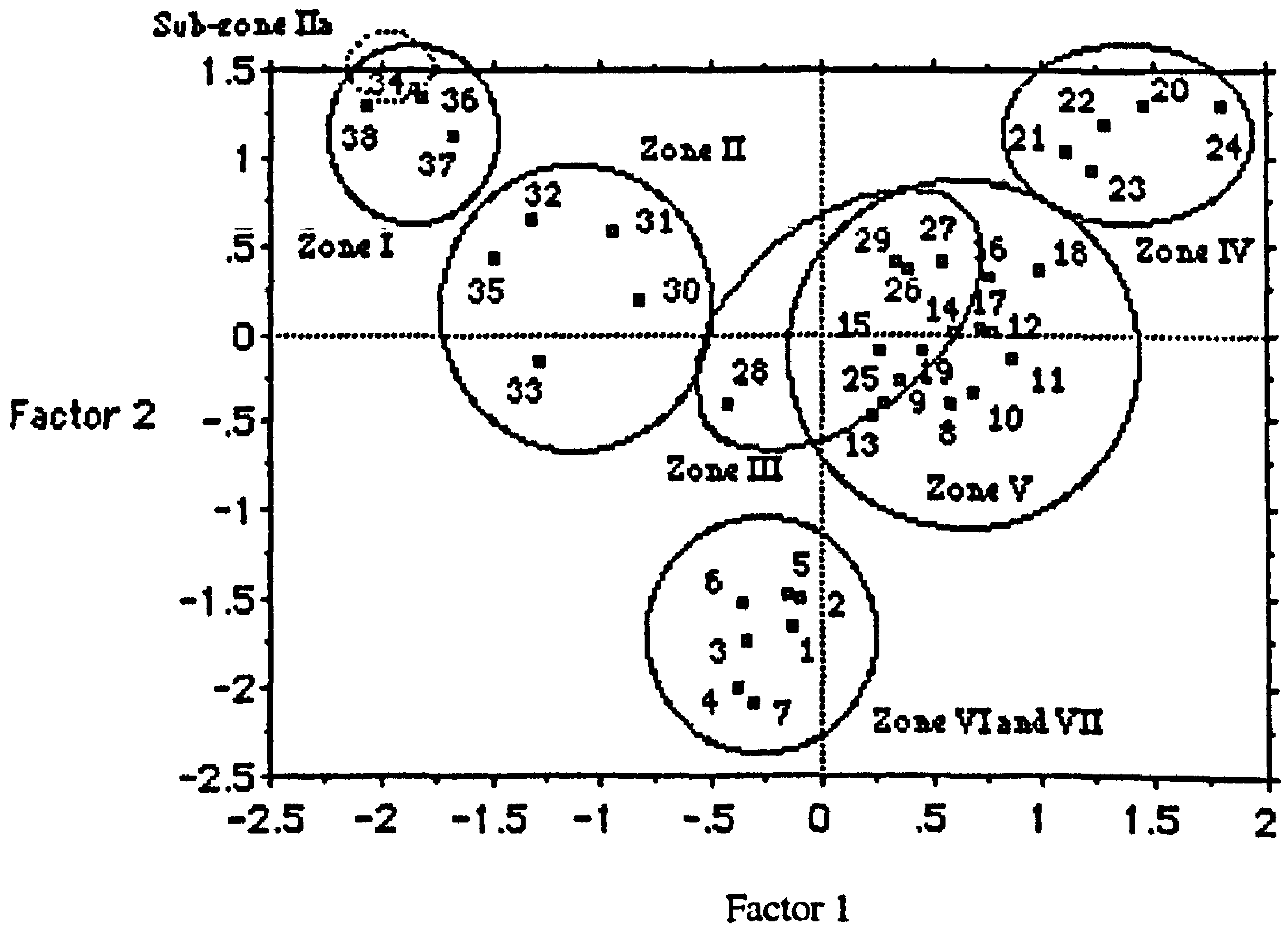


Fig.3.11 Principal components analysis of percentage pollen and spore data from Lake Roto: Factor 1 versus factor 2 (excluding European taxa). Zone RpI to VII.



Key to sample depths within the identified pollen zones:

Zone RpI (16.0-14.55m):
38. 15.80m
37. 15.30m
36. 14.80m

Zone RpII (14.55-12.30):
35. 14.30m

Sub-zone RpIIa (14.22-13.97)
34. 14.15m

33. 13.80m
32. 13.50m
31. 13.15m
30. 12.55m

Zone RpIII (12.30-10.05):
29. 12.05m
28. 11.55m
27. 11.05m
26. 10.55m
25. 10.29m

Zone RpIV (10.05-8.47):
24. 9.80m
23. 9.55m
22. 9.30m
21. 8.80m
20. 8.55m

Zone RpV (8.47-3.30):
19. 8.40m
18. 7.95m
17. 7.80m
16. 7.55m
15. 7.15m
14. 6.56m
13. 6.05m
12. 5.55m
11. 5.05m
10. 4.55m
9. 4.05m
8. 3.55m

Zone RpVI (3.30-0.80):
7. 3.05m
6. 2.55m
5. 2.05m
4. 1.55m
3. 1.05m

Zone RpVII (0.80-0.0):
2. 0.55m
1. 0.05m

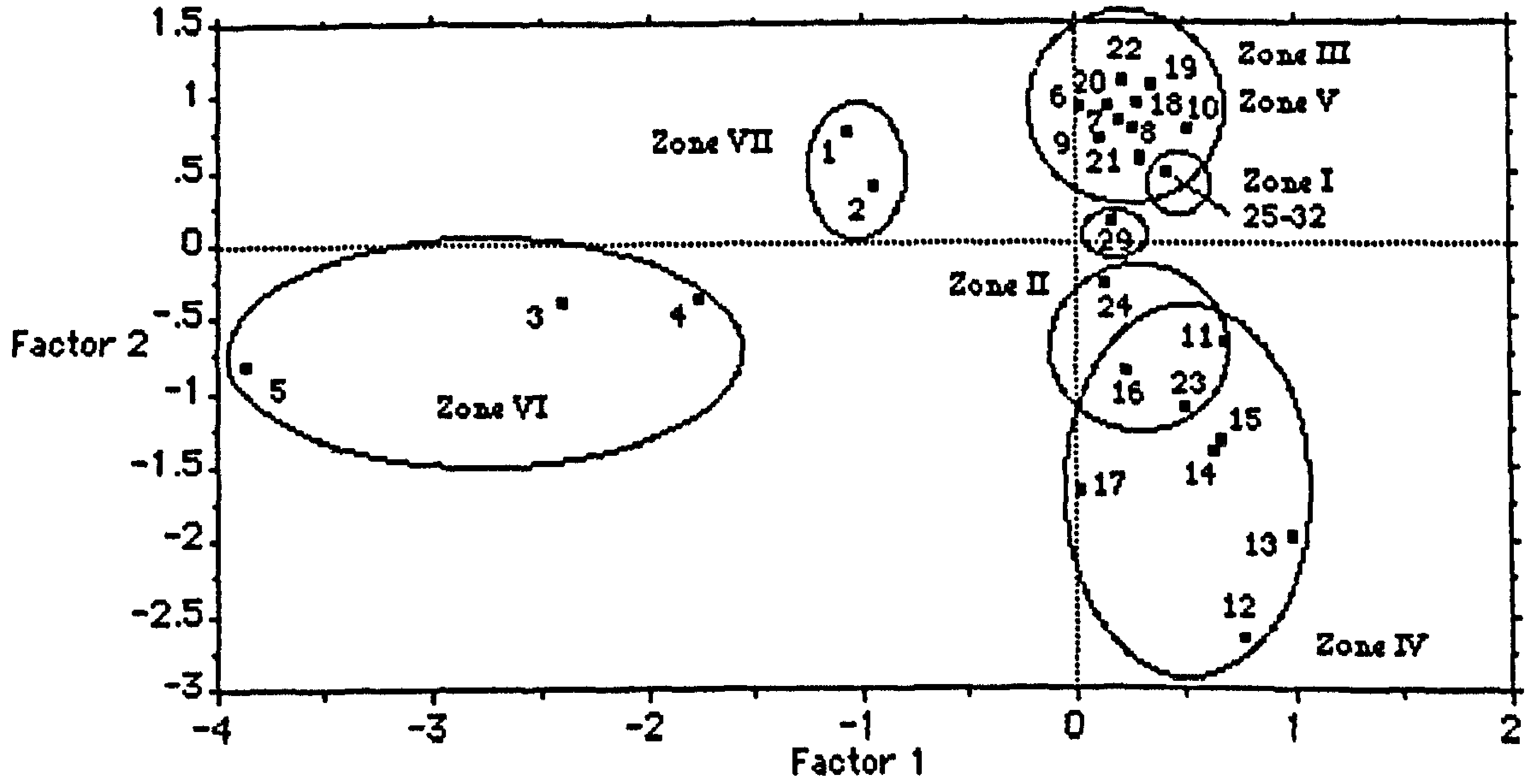
Fig.3.12 Correlation matrix derived from Lake Roto pollen data.

	Name	H. tiliaceus	Casuarina equi...	F. tinctoria	Cocos nuc...	Pritchardia vuyls...	Pandanus tector...	Calophyllum	E. tonganus	A. vitiensis	Trema	Glochidion	Homolanthus
1	H. tilia...	1.000	.526	-.074	-.148	-.168	-.080	-.122	-.163	-.088	-.157	-.167	-.105
2	Casuari...	.526	1.000	-.107	-.200	-.234	-.172	-.228	-.219	-.119	-.211	-.225	-.141
3	F. tinct...	-.074	-.107	1.000	.338	-.119	-.103	-.127	.267	.049	-.028	-.140	-.105
4	Cocos ...	-.148	-.200	.338	1.000	-.169	-.300	-.049	.073	-.121	-.232	-.127	-.221
5	Pritchar...	-.168	-.234	-.119	-.169	1.000	.639	.653	.525	.257	-.167	.539	.467
6	Pandan...	-.080	-.172	-.103	-.300	.639	1.000	.512	.248	.090	-.021	.338	.828
7	Caloph...	-.122	-.228	-.127	-.049	.653	.512	1.000	.528	.020	-.033	.569	.432
8	E. tong...	-.163	-.219	.267	.073	.525	.248	.528	1.000	.062	-.048	.184	.226
9	A. vitie...	-.088	-.119	.049	-.121	.257	.090	.020	.062	1.000	.021	.019	.015
10	Trema	-.157	-.211	-.028	-.232	-.167	-.021	-.033	-.048	.021	1.000	.260	-.039
11	Glochid...	-.167	-.225	-.140	-.127	.539	.338	.569	.184	.019	.260	1.000	.121
12	Homola...	-.105	-.141	-.105	-.221	.467	.828	.432	.226	.015	-.039	.121	1.000
13	Rapanea	-.092	-.124	-.035	-.188	.551	.768	.527	.283	-.012	-.075	.212	.712
14	W. raro	-.105	-.142	-.103	-.230	.140	.342	.063	-.186	-.049	.111	.325	.151
15	C. laevi...	-.076	-.103	-.056	-.167	.256	.127	.122	-.153	.030	.059	.335	-.103
16	Freycin...	.641	.190	-.087	-.117	-.142	.069	-.089	-.137	-.075	-.132	-.141	-.089
17	A. stellata	.521	.166	-.087	-.113	-.140	.092	-.095	-.135	-.073	-.130	-.138	-.087
18	C. pani...	-.166	-.224	.201	-.030	.575	.511	.417	.695	.153	-.032	-.064	.447
19	A. cony...	.815	.246	-.071	-.109	-.119	-.038	-.063	-.119	-.065	-.115	-.122	-.077
20	Heliotr...	-.117	-.158	-.132	-.087	-.043	.198	.207	.027	-.133	.432	.146	.313
21	Cyathula	-.063	-.084	.023	-.154	.326	.218	.249	.723	-.071	.046	-.099	.155
22	Gramin...	.344	.416	-.099	-.225	-.165	-.127	-.186	-.149	-.120	-.185	-.164	-.132
23	Cypera...	-.001	.016	-.159	-.261	-.117	.130	-.218	-.183	.193	.166	-.105	.121
24	Cyperu...	.207	.427	-.173	-.293	-.300	-.192	-.167	-.270	-.156	.177	-.060	-.175
25	Jameso...	.846	.488	-.122	-.169	-.195	-.033	-.149	-.188	-.102	-.181	-.193	-.121
26	Gleiche...	.514	.784	-.157	-.234	-.290	-.128	-.277	-.280	-.153	-.264	-.281	-.173
27	Acrosti...	-.141	-.225	.099	.184	.776	.277	.386	.637	.146	-.208	.147	.221
28	P. phy...	.758	.483	.057	-.261	-.068	-.044	-.091	.082	-.131	-.211	-.177	-.103
29	C. affinis	.576	.438	-.147	-.236	-.186	-.156	-.110	-.215	-.121	.016	.008	-.143
30	Cyathe...	.434	.351	-.262	-.368	-.206	-.066	-.069	-.238	-.183	-.150	-.174	-.173
31	P. com...	-.202	-.262	-.109	-.234	-.309	-.291	-.200	-.251	-.195	.287	.014	-.187
32	Cyclo/...	-.137	-.169	-.220	-.413	-.265	-.197	-.050	-.306	-.107	.595	.206	-.130
33	A. nidus	-.110	-.104	.005	-.104	.564	.207	.268	.363	.323	-.207	.184	.258
34	Lycopo...	-.172	-.132	-.079	.148	.174	.085	.252	.058	.647	.001	.066	.003
35	A. evecta	-.119	-.161	-.166	-.229	-.181	-.126	-.056	-.204	-.123	.741	.223	-.161
36	L. cernu...	-.070	-.094	-.103	-.167	-.037	.041	-.092	-.039	-.001	-.087	-.060	.106
37	Marattia	-.123	-.165	-.178	-.318	-.229	-.161	-.158	-.227	-.139	.458	.027	-.083
38	Cyathea	-.121	-.163	-.167	-.318	-.256	-.242	-.186	-.244	-.137	.254	-.044	-.140
39	Monole...	.017	.116	-.340	-.619	-.393	-.126	-.251	-.469	-.044	.323	-.060	-.080

	Rapanea	W. raro	C. laevigata	Freycinetia	A. stellata	C. paniculata	A. conyzoides	Heliotropium	Cyathula	Gramin≤40	Cyperaceae...	Cyperus pen...	Jamesonia	Gleichenia lin...
1	-.092	-.105	-.076	.641	.521	-.166	.815	-.117	-.063	.344	-.001	.207	.846	.514
2	-.124	-.142	-.103	.190	.166	-.224	.246	-.158	-.084	.416	.016	.427	.488	.784
3	-.035	-.103	-.056	-.087	-.087	.201	-.071	-.132	.023	-.099	-.159	-.173	-.122	-.157
4	-.188	-.230	-.167	-.117	-.113	-.030	-.109	-.087	-.154	-.225	-.261	-.293	-.169	-.234
5	.551	.140	.256	-.142	-.140	.575	-.119	-.043	.326	-.165	-.117	-.300	-.195	-.290
6	.768	.342	.127	.069	.092	.511	-.038	.198	.218	-.127	.130	-.192	-.033	-.128
7	.527	.063	.122	-.089	-.095	.417	-.063	.207	.249	-.186	-.218	-.167	-.149	-.277
8	.283	-.186	-.153	-.137	-.135	.695	-.119	.027	.723	-.149	-.183	-.270	-.188	-.280
9	-.012	-.049	.030	-.075	-.073	.153	-.065	-.133	-.071	-.120	.193	-.156	-.102	-.153
10	-.075	.111	.059	-.132	-.130	-.032	-.115	.432	.046	-.185	.166	.177	-.181	-.264
11	.212	.325	.335	-.141	-.138	-.064	-.122	.146	-.099	-.164	-.105	-.060	-.193	-.281
12	.712	.151	-.103	-.089	-.087	.447	-.077	.313	.155	-.132	.121	-.175	-.121	-.173
13	1.000	.196	.368	-.078	-.076	.573	-.067	.312	.307	-.109	-.047	-.151	-.106	-.157
14	.196	1.000	.385	-.089	-.087	.032	-.077	.267	-.085	-.160	.122	-.102	-.122	-.173
15	.368	.385	1.000	-.064	-.063	.063	-.056	-.017	-.061	-.090	-.107	.357	-.088	-.131
16	-.078	-.089	-.064	1.000	.980	-.140	.742	-.099	-.053	.269	-.002	.082	.790	.536
17	-.076	-.087	-.063	.980	1.000	-.138	.597	-.097	-.052	.275	.004	.090	.717	.545
18	.573	.032	.063	-.140	-.138	1.000	-.122	.079	.788	-.187	-.156	-.245	-.192	-.282
19	-.067	-.077	-.056	.742	.597	-.122	1.000	-.086	-.046	.163	-.003	.085	.833	.403
20	.312	.267	-.017	-.099	-.097	.079	-.086	1.000	.008	-.167	.094	-.005	-.135	-.203
21	.307	-.085	-.061	-.053	-.052	.788	-.046	.008	1.000	-.029	-.053	-.111	-.072	-.107
22	-.109	-.160	-.090	.269	.275	-.187	.163	-.167	-.029	1.000	-.025	.267	.288	.702
23	-.047	.122	-.107	-.002	.004	-.156	-.003	.094	-.053	-.025	1.000	-.081	.036	.032
24	-.151	-.102	.357	.082	.090	-.245	.085	-.005	-.111	.267	-.081	1.000	.309	.438
25	-.106	-.122	-.088	.790	.717	-.192	.833	-.135	-.072	.288	.036	.309	1.000	.692
26	-.157	-.173	-.131	.536	.545	-.282	.403	-.203	-.107	.702	.032	.438	.692	1.000
27	.261	-.068	.065	-.136	-.143	.673	-.091	-.109	.439	-.168	-.254	-.335	-.183	-.281
28	-.081	-.121	-.156	.457	.364	.048	.617	-.240	.237	.598	-.076	.133	.595	.547
29	-.121	-.144	-.088	.397	.294	-.215	.594	-.125	-.085	.131	-.092	.092	.489	.348
30	-.206	.198	-.045	.405	.344	-.279	.523	.073	-.111	.192	.193	.316	.558	.463
31	-.176	.048	.058	-.177	-.173	-.308	-.152	.102	-.153	-.223	-.070	.052	-.235	-.315
32	-.150	.233	.152	-.123	-.121	-.286	-.093	.435	-.118	-.181	-.019	.270	-.139	-.208
33	.065	-.003	-.007	-.093	-.091	.196	-.080	-.099	-.072	-.111	-.022	-.164	-.127	-.160
34	-.063	-.043	-.168	-.145	-.142	.154	-.126	-.135	-.004	-.211	.087	-.261	-.199	-.222
35	-.063	-.061	.199	-.101	-.099	-.187	-.087	.105	-.096	-.136	-.194	.267	-.138	-.203
36	-.008	.017	-.067	-.059	-.058	-.063	-.051	-.105	.003	-.106	.125	-.117	-.081	-.117
37	-.110	-.056	.081	-.104	-.101	-.215	-.090	.009	-.084	-.158	-.108	.148	-.142	-.209
38	-.137	.086	-.014	-.102	-.100	-.250	-.089	.158	-.097	-.172	-.134	-.020	-.140	-.208
39	-.191	.300	.025	-.032	-.023	-.436	-.055	.214	-.250	.183	.243	.309	-.014	.124

	Acrostichum au...	P. phymatodes	C. affinis	Cyatheaceae	P. comm/tri	Cyclo/Hyp	A. nidus	Lycopodium	A. evecta	L. cernuum	Marattia	Cyathea	Monoletes
1	-.141	.758	.576	.434	-.202	-.137	-.110	-.172	-.119	-.070	-.123	-.121	.017
2	-.225	.483	.438	.351	-.262	-.169	-.104	-.132	-.161	-.094	-.165	-.163	.116
3	.099	.057	-.147	-.262	-.109	-.220	.005	-.079	-.166	-.103	-.178	-.167	-.340
4	.184	-.261	-.236	-.368	-.234	-.413	-.104	.148	-.229	-.167	-.318	-.318	-.619
5	.776	-.068	-.186	-.206	-.309	-.265	.564	.174	-.181	-.037	-.229	-.256	-.393
6	.277	-.044	-.156	-.066	-.291	-.197	.207	.085	-.126	.041	-.161	-.242	-.126
7	.386	-.091	-.110	-.069	-.200	-.050	.268	.252	-.056	-.092	-.158	-.186	-.251
8	.637	.082	-.215	-.238	-.251	-.306	.363	.058	-.204	-.039	-.227	-.244	-.469
9	.146	-.131	-.121	-.183	-.195	-.107	.323	.647	-.123	-.001	-.139	-.137	-.044
10	-.208	-.211	.016	-.150	.287	.595	-.207	.001	.741	-.087	.458	.254	.323
11	.147	-.177	.008	-.174	.014	.206	.184	.066	.223	-.060	.027	-.044	-.060
12	.221	-.103	-.143	-.173	-.187	-.130	.258	.003	-.161	.106	-.083	-.140	-.080
13	.261	-.081	-.121	-.206	-.176	-.150	.065	-.063	-.063	-.008	-.110	-.137	-.191
14	-.068	-.121	-.144	.198	.048	.233	-.003	-.043	-.061	.017	-.056	.086	.300
15	.065	-.156	-.088	-.045	.058	.152	-.007	-.168	.199	-.067	.081	-.014	.025
16	-.136	.457	.397	.405	-.177	-.123	-.093	-.145	-.101	-.059	-.104	-.102	-.032
17	-.143	.364	.294	.344	-.173	-.121	-.091	-.142	-.099	-.058	-.101	-.100	-.023
18	.673	.048	-.215	-.279	-.308	-.286	.196	.154	-.187	-.063	-.215	-.250	-.436
19	-.091	.617	.594	.523	-.152	-.093	-.080	-.126	-.087	-.051	-.090	-.089	-.055
20	-.109	-.240	-.125	.073	.102	.435	-.099	-.135	.105	-.105	.009	.158	.214
21	.439	.237	-.085	-.111	-.153	-.118	-.072	-.004	-.096	.003	-.084	-.097	-.250
22	-.168	.598	.131	.192	-.223	-.181	-.111	-.211	-.136	-.106	-.158	-.172	.183
23	-.254	-.076	-.092	.193	-.070	-.019	-.022	.087	-.194	.125	-.108	-.134	.243
24	-.335	.133	.092	.316	.052	.270	-.164	-.261	.267	-.117	.148	-.020	.309
25	-.183	.595	.489	.558	-.235	-.139	-.127	-.199	-.138	-.081	-.142	-.140	-.014
26	-.281	.547	.348	.463	-.315	-.208	-.160	-.222	-.203	-.117	-.209	-.208	.124
27	1.000	-.047	-.237	-.242	-.386	-.423	.574	.136	-.270	-.122	-.324	-.336	-.627
28	-.047	1.000	.428	.295	-.251	-.244	-.135	-.208	-.206	-.010	-.127	-.155	-.005
29	-.237	.428	1.000	.337	.112	.236	-.125	-.110	.166	-.086	.169	.053	.198
30	-.242	.295	.337	1.000	-.009	.217	.052	-.207	-.139	-.149	-.109	.019	.440
31	-.386	-.251	.112	-.009	1.000	.566	-.131	-.189	.580	-.179	.751	.894	.630
32	-.423	-.244	.236	.217	.566	1.000	-.187	-.174	.572	-.087	.513	.536	.691
33	.574	-.135	-.125	.052	-.131	-.187	1.000	-.078	-.147	-.099	-.173	-.161	-.105
34	.136	-.208	-.110	-.207	-.189	-.174	-.078	1.000	-.154	-.036	-.099	-.112	-.159
35	-.270	-.206	.166	-.139	.580	.572	-.147	-.154	1.000	-.103	.740	.518	.398
36	-.122	-.010	-.086	-.149	-.179	-.087	-.099	-.036	-.103	1.000	-.072	-.108	-.166
37	-.324	-.127	.169	-.109	.751	.513	-.173	-.099	.740	-.072	1.000	.786	.545
38	-.336	-.155	.053	.019	.894	.536	-.161	-.112	.518	-.108	.786	1.000	.618
39	-.627	-.005	.198	.440	.630	.691	-.105	-.159	.398	-.166	.545	.618	1.000

Fig.3.13 Principal components analysis of percentage diatom data from Lake Roto: Factor 1 versus factor 2. Zone RdI to VII.



Key to sample depths within the identified diatom zones:

Zone RdI (16.0-11.05m):
32. 15.80m
31. 15.30m
30. 14.40m

Sub-zone RdIa (14.28-13.98)
29. 14.15m

28. 13.80m
27. 13.50m
26. 12.55m
25. 11.55m

Zone RdII (11.05-9.05)
24. 10.55m
23. 9.55m

Zone RdIII (9.05-7.40):
22. 8.55m
21. 8.40m
20. 7.95m
19. 7.80m
18. 7.55m

Zone RdIV (7.40-4.88):
17. 7.25m
16. 7.15m
15. 6.70m
14. 6.56m
13. 6.15m
12. 5.55m
11. 5.05m

Zone RdV (4.88-2.93):
10. 4.70m
9. 4.55m
8. 4.05m
7. 3.55m
6. 3.30m

Zone RdVI (2.93-1.30):
5. 2.55m
4. 2.05m
3. 1.55m

Zone RdVII (1.30-0.0):
2. 1.05m
1. 0.55m

Fig.3.14 Correlation matrix derived from Lake Roto diatom data.

	Name	Certos%	Thalass%	Nitz%	Nav/Ach%	NavB%	Dipl.smi%	Pinn su%	Staur p%	Gomph%	Achn ex%	Achn inf%	Achn co%	Frag brev%	Amph cof%	Calon%
1	Certos%	1.000	-.165	-.363	.348	-.211	-.125	-.198	-.151	-.022	.419	.164	.262	-.256	.609	-.089
2	Thala...	-.165	1.000	.083	.130	.893	-.087	.957	.364	.311	-.096	-.081	-.084	-.054	-.082	-.065
3	Nitz%	-.363	.083	1.000	.030	.150	.123	.071	.045	.203	-.271	.371	.250	-.030	-.250	.018
4	Nav/...	.348	.130	.030	1.000	.151	.057	.182	.135	.212	.132	-.159	-.090	-.197	.470	.110
5	NavB%	-.211	.893	.150	.151	1.000	-.112	.909	.566	.432	-.125	-.122	-.123	-.023	-.086	-.076
6	Dipl....	-.125	-.087	.123	.057	-.112	1.000	.129	-.079	.406	-.104	-.074	.188	.066	-.086	.909
7	Pinn ...	-.198	.957	.071	.182	.909	.129	1.000	.470	.440	-.118	-.108	-.114	-.012	-.095	.173
8	Staur ...	-.151	.364	.045	.135	.566	-.079	.470	1.000	.200	-.095	-.057	-.063	.126	-.060	-.062
9	Gomp...	-.022	.311	.203	.212	.432	.406	.440	.200	1.000	.271	-.075	-.041	-.091	.053	.456
10	Achn ...	.419	-.096	-.271	.132	-.125	-.104	-.118	-.095	.271	1.000	-.131	-.119	-.153	.085	-.017
11	Achn ...	.164	-.081	.371	-.159	-.122	-.074	-.108	-.057	-.075	-.131	1.000	.244	-.168	-.089	.008
12	Achn ...	.262	-.084	.250	-.090	-.123	.188	-.114	-.063	-.041	-.119	.244	1.000	-.168	.233	-.038
13	Frag ...	-.256	-.054	-.030	-.197	-.023	.066	-.012	.126	-.091	-.153	-.168	-.168	1.000	-.157	.043
14	Amph...	.609	-.082	-.250	.470	-.086	-.086	-.095	-.060	.053	.085	-.089	.233	-.157	1.000	-.081
15	Calon%	-.089	-.065	.018	.110	-.076	.909	.173	-.062	.456	-.017	.008	-.038	.043	-.081	1.000

25. *Typha angustifolia*
26. *Fragilaria brevistriata*
27. *Navicula/Achnanthes* spp.
28. *Nitzschia* spp.
29. *Nephrolepis* sp.
30. *Glochidion* sp.
31. *Weinmannia rarotongensis*
32. *Typha latifolia*
33. *Trema* sp.
34. Polypodiaceae
35. K_2O
36. *Coprosma laevigata*
37. *Pteris commans/tripartita*
38. *Angiopteris evecta*
39. *Cyathea* sp.
40. *Cyclosorus/Hypolepis*
41. *Marrattia* sp.
42. Magnetic susceptibility
43. Monolete spores
44. SiO_2
45. TiO_2
46. Al_2O_3
47. P_2O_5
48. *Cyperus pennatus*
49. *Thalassiosira weissflogii*
50. *Bidens pilosa*
51. *Ipomoea batatas*
52. *Stauroneis phoenicenteron*
53. *Navicula confervacea*
54. Fe_2O_3
55. *Pinnularia subcapitata/gibba*
56. Gramineae
57. *Casuarina equisetifolia*
58. Cyatheaceae
59. CO_2+H_2O
60. *Gleichenia linearis*
61. MnO
62. *Gomphonema angustatum*
63. *Polypodium phymatodes*
64. *Cyathea affinis*
65. *Jamesonia* sp.
66. *Hibiscus tiliaceus*
67. *Ageratum conyzoides*
68. *Caloneis* spp.
69. *Freycinetia* sp.
70. *Alyxia stellata*
71. *Sida* sp.
72. *Sida rhombifolia*
73. *Acalypha* sp.
74. *Elephantopus mollis*
75. *Passiflora quadrangularis*
76. *Colocasia esculenta*
77. *Barringtonia asiatica*
78. *Diploneis smithii*

Fig.3.16 Correlation matrix derived from Lake Roto combined sample data.

	Name	L600	MgO_d	K2O_d	Fe2O3_d	MnO_d	TiO2_d	SiO2_d	SO3_d	CaO_d	P2O5_d	Al2O3_d	Na2O_d	LOI_d	Certos	Thalas	Nitz
1	L600	1.000	.189	-.635	-.301	-.166	-.740	-.936	.433	.429	-.652	-.804	.529	-.289	-.035	-.160	.086
2	MgO_d	.189	1.000	.399	-.520	-.615	-.355	-.130	.254	.365	-.448	-.400	.739	-.609	.346	-.213	-.369
3	K2O_d	-.635	.399	1.000	-.109	-.316	.446	.706	-.373	-.158	.294	.449	-.062	-.136	.158	.022	-.437
4	Fe2O3_d	-.301	-.520	-.109	1.000	.608	.106	.079	-.018	-.081	.317	.200	-.485	.298	-.269	.097	.474
5	MnO_d	-.166	-.615	-.316	.608	1.000	.088	.044	-.096	-.260	.295	.121	-.321	.622	-.084	.376	.461
6	TiO2_d	-.740	-.355	.446	.106	.088	1.000	.825	-.857	-.560	.797	.978	-.766	.397	-.439	.256	-.092
7	SiO2_d	-.936	-.130	.706	.079	.044	.825	1.000	-.634	-.574	.640	.847	-.515	.286	.032	.160	-.276
8	SO3_d	.433	.254	-.373	-.018	-.096	-.857	-.634	1.000	.629	-.644	-.804	.616	-.448	.499	-.240	.143
9	CaO_d	.429	.365	-.158	-.081	-.260	-.560	-.574	.629	1.000	-.319	-.538	.338	-.538	-.036	-.271	.094
10	P2O5_d	-.652	-.448	.294	.317	.295	.797	.640	-.644	-.319	1.000	.807	-.741	.469	-.411	.111	.219
11	Al2O3_d	-.804	-.400	.449	.200	.121	.978	.847	-.804	-.538	.807	1.000	-.800	.432	-.425	.230	-.061
12	Na2O_d	.529	.739	-.062	-.485	-.321	-.766	-.515	.616	.338	-.741	-.800	1.000	-.509	.614	-.097	-.134
13	LOI_d	-.289	-.609	-.136	.298	.622	.397	.286	-.448	-.538	.469	.432	-.509	1.000	-.305	.268	.406
14	Certos	-.035	.346	.158	-.269	-.084	-.439	.032	.499	-.036	-.411	-.425	.614	-.305	1.000	-.152	-.351
15	Thalas	-.160	-.213	.022	.097	.376	.256	.160	-.240	-.271	.111	.230	-.097	.268	-.152	1.000	.087
16	Nitz	.086	-.369	-.437	.474	.461	-.092	-.276	.143	.094	.219	-.061	-.134	.406	-.351	.087	1.000
17	Nav/Ach	.040	.355	.009	-.226	.117	-.252	-.095	.256	-.023	-.122	-.264	.505	.020	.359	.137	.081
18	Nav B	-.145	-.290	-.021	.131	.417	.276	.157	-.296	-.332	.123	.248	-.162	.417	-.195	.893	.158
19	Dip Sm	.038	-.444	-.306	.392	.674	.008	-.110	-.076	-.092	.276	.032	-.252	.385	-.109	-.098	.129
20	Pinn su	-.161	-.326	-.026	.152	.501	.284	.159	-.293	-.344	.171	.265	-.173	.412	-.183	.957	.071
21	Staur p	.005	-.212	-.070	.022	.203	.092	.055	-.221	-.218	.024	.111	-.132	.395	-.139	.359	.046
22	Gomp	-.094	-.548	-.240	.353	.737	.139	.030	-.149	-.324	.217	.153	-.242	.570	-.070	.412	.328
23	Ach ex	-.073	.075	.112	-.138	-.103	-.162	.056	.256	-.108	-.231	-.110	.212	-.144	.455	-.072	-.187
24	Frag brev	.069	-.252	-.179	.043	-.040	-.104	-.162	.195	.430	-.016	.015	-.217	.033	-.236	-.069	-.034
25	Amph ...	.024	.316	.124	-.323	-.095	-.342	.029	.296	-.013	-.325	-.347	.540	-.142	.640	-.080	-.251
26	Calon	-.044	-.403	-.202	.289	.557	.112	-.003	-.162	-.228	.285	.139	-.254	.400	-.099	-.062	.012
27	B asiat	-.049	-.387	-.186	.259	.542	.128	.014	-.184	-.237	.287	.153	-.256	.391	-.096	-.057	-.033
28	H tiliac	-.038	-.447	-.165	.205	.534	.166	.037	-.256	-.338	.244	.183	-.289	.584	-.153	.105	-.020
29	Casuarin	-.009	-.419	-.184	.086	.432	.177	.051	-.292	-.356	.151	.176	-.258	.696	-.211	.183	.350
30	F tinct	-.048	.317	.285	-.279	-.093	-.305	.066	.318	-.090	-.357	-.292	.525	-.191	.715	-.092	-.229
31	Cocos	.168	-.045	-.242	.260	.107	-.542	-.306	.565	.189	-.326	-.454	.352	-.137	.407	-.205	.278
32	Pritch	-.002	.067	-.195	.050	-.095	-.285	-.195	.572	.564	-.160	-.215	.019	-.223	.032	-.147	.015
33	Pandan	.236	.056	-.024	-.156	-.206	-.205	-.306	.314	.681	-.043	-.207	-.015	-.287	-.132	-.149	-.050
34	Caloph	.057	-.186	-.139	-.056	-.208	-.065	-.142	.212	.404	.070	.009	-.174	-.038	-.185	-.168	.033
35	E long	.084	.119	.056	-.204	-.183	-.415	-.136	.497	.275	-.387	-.333	.283	-.242	.366	-.203	-.193
36	A vitien	.244	.578	.016	-.196	-.156	-.323	-.324	.292	.315	-.336	-.330	.482	-.309	.083	-.096	.026
37	Trema	-.119	.278	.265	-.404	-.389	.326	.258	-.337	-.101	.419	.260	-.053	-.083	-.108	-.170	-.143
38	Glochid	-.137	-.118	-.061	-.272	-.290	.287	.173	-.151	-.070	.248	.319	-.260	.033	-.220	-.163	-.024
39	Homolan	.071	.020	.062	-.033	-.098	-.166	-.164	.323	.626	-.054	-.158	-.078	-.195	-.037	-.083	-.080
40	Rapanea	.037	-.030	.143	-.036	-.110	-.078	-.121	.210	.619	.069	-.060	-.114	-.154	-.100	-.059	-.005
41	W raro	.168	.169	.037	-.449	-.330	.162	.009	-.231	-.063	-.107	.072	-.051	-.154	-.171	-.101	-.343
42	C laevig	-.244	-.083	.145	-.008	-.184	.441	.311	-.348	-.211	.239	.383	-.269	-.279	-.141	-.084	-.202
43	Freycin	-.049	-.387	-.186	.259	.542	.128	.014	-.184	-.237	.287	.153	-.256	.391	-.096	-.057	-.033

	Name	L600	MgO_d	K2O_d	Fe2O3_d	MnO_d	TiO2_d	SiO2_d	SO3_d	CaO_d	P2O5_d	Al2O3_d	Na2O_d	LOI_d	Certos	Thalas	Nitz
44	A stellata	-.049	-.387	-.186	.259	.542	.128	.014	-.184	-.237	.287	.153	-.256	.391	-.096	-.057	-.033
45	C pan	.093	.171	.037	-.004	-.109	-.410	-.259	.619	.683	-.240	-.376	.204	-.390	.215	-.190	.014
46	Urt/Mor	.358	.485	.069	-.355	-.261	-.314	-.381	.269	.254	-.389	-.358	.505	-.242	.075	-3.863E-4	-.030
47	Sida	-.049	-.387	-.186	.259	.542	.128	.014	-.184	-.237	.287	.153	-.256	.391	-.096	-.057	-.033
48	S rhom	-.049	-.387	-.186	.259	.542	.128	.014	-.184	-.237	.287	.153	-.256	.391	-.096	-.057	-.033
49	Acalyp	-.049	-.387	-.186	.259	.542	.128	.014	-.184	-.237	.287	.153	-.256	.391	-.096	-.057	-.033
50	E mollis	-.049	-.387	-.186	.259	.542	.128	.014	-.184	-.237	.287	.153	-.256	.391	-.096	-.057	-.033
51	P quad	-.049	-.387	-.186	.259	.542	.128	.014	-.184	-.237	.287	.153	-.256	.391	-.096	-.057	-.033
52	A conyz	-.055	-.409	-.212	.295	.583	.140	.020	-.212	-.247	.304	.168	-.276	.409	-.111	-.056	.012
53	B pilosa	-.037	-.149	-.164	.222	.265	.080	.037	-.170	-.070	.112	.095	-.133	.123	-.096	-.001	.260
54	C escul	-.049	-.387	-.186	.259	.542	.128	.014	-.184	-.237	.287	.153	-.256	.391	-.096	-.057	-.033
55	I batat	.040	-.149	-.034	-.036	.080	.035	.022	-.150	-.164	-.022	.054	-.094	.333	-.096	.191	-.045
56	Cyperac	.688	.286	-.371	-.291	-.242	-.337	-.581	.075	.190	-.399	-.426	.304	-.207	-.183	-.008	-.122
57	C. pen...	-.271	-.319	.024	.066	.130	.554	.361	-.546	-.414	.386	.502	-.414	.146	-.262	.147	.049
58	T ang	-.023	-.168	-.099	.018	-.059	-.018	-.025	.047	-.053	-.049	.076	-.091	.177	-.096	-.057	.057
59	T lat	-.173	.104	.206	-.294	-.152	.306	.258	-.234	-.099	.072	.266	-.150	-.007	-.096	-.057	-.193
60	Jameson	-.040	-.451	-.240	.297	.602	.156	.037	-.290	-.298	.280	.192	-.311	.521	-.161	.032	.063
61	Gleich ...	-.093	-.508	-.222	.235	.670	.269	.109	-.380	-.419	.256	.270	-.305	.689	-.232	.520	.354
62	Acrost ...	-.018	.059	-.233	.118	.103	-.448	-.163	.684	.375	-.290	-.383	.212	-.192	.331	-.141	.033
63	P phymat	-.128	-.499	-.114	.203	.623	.255	.114	-.281	-.464	.236	.251	-.271	.649	-.121	.439	.088
64	C affin	-.053	-.468	-.215	.156	.551	.205	.061	-.293	-.347	.367	.223	-.317	.617	-.171	-.009	.183
65	Cyatheac	.197	-.312	-.294	-.035	.204	.201	-.061	-.387	-.266	.135	.153	-.280	.198	-.317	.047	-.120
66	Polyp...	-.366	.231	.498	-.115	-.368	.404	.428	-.263	.021	.078	.363	-.236	-.425	-.083	-.055	-.571
67	P comm	-.444	.130	.560	-.073	-.420	.575	.580	-.541	-.270	.335	.542	-.367	-.126	-.157	-.167	-.423
68	Cyclo/...	-.258	.187	.368	-.304	-.382	.593	.445	-.607	-.224	.448	.504	-.305	-.069	-.289	-.137	-.319
69	A nidus	.086	.025	-.177	.008	.017	-.290	-.137	.395	.044	-.327	-.288	.083	-.151	.243	-.112	-.134
70	Lycopod	.343	.470	-.134	-.117	-.180	-.396	-.450	.323	.541	-.262	-.371	.445	-.226	-.136	-.173	.277
71	A evecta	-.460	1.012E-4	.419	-.004	-.216	.580	.536	-.519	-.307	.709	.552	-.376	.102	-.200	-.122	.022
72	L cernu	.305	.587	.038	-.211	-.202	-.225	-.350	.116	.344	-.233	-.252	.448	-.303	-.100	-.059	.091
73	Marattia	-.516	.129	.652	.150	-.247	.571	.606	-.576	-.271	.587	.557	-.402	-.001	-.208	-.123	-.231
74	Nephro	.213	.226	-.080	-.326	-.251	.020	-.094	-.092	.053	-.161	-.057	.029	-.076	-.133	-.079	-.267
75	Cyathea	-.512	.171	.678	-.020	-.298	.614	.642	-.615	-.222	.445	.586	-.403	.022	-.227	-.134	-.384
76	Monol...	-.096	.119	.361	-.258	-.288	.579	.326	-.729	-.341	.283	.460	-.320	.044	-.424	.207	-.354
77	Gramin	-.181	-.358	-.029	.136	.511	.330	.183	-.324	-.390	.207	.301	-.200	.464	-.205	.950	.158
78	Mag susc	-.536	.014	.578	.213	-.173	.620	.610	-.571	-.282	.369	.596	-.445	-.171	-.208	-.079	-.339

	Nav/Ach	Nav B	Dip Sm	Pinn su	Staur p	Gomp	Ach ex	Frag brev	Amph cof	Calon	B asiat	H tiliac	Casuarin	F tinct	Cocos	Pritch	Pandan
1	.040	-.145	.038	-.161	.005	-.094	-.073	.069	.024	-.044	-.049	-.038	-.009	-.048	.168	-.002	.236
2	.355	-.290	-.444	-.326	-.212	-.548	.075	-.252	.316	-.403	-.387	-.447	-.419	.317	-.045	.067	.056
3	.009	-.021	-.306	-.026	-.070	-.240	.112	-.179	.124	-.202	-.186	-.165	-.184	.285	-.242	-.195	-.024
4	-.226	.131	.392	.152	.022	.353	-.138	.043	-.323	.289	.259	.205	.086	-.279	.260	.050	-.156
5	.117	.417	.674	.501	.203	.737	-.103	-.040	-.095	.557	.542	.534	.432	-.093	.107	-.095	-.206
6	-.252	.276	.008	.284	.092	.139	-.162	-.104	-.342	.112	.128	.166	.177	-.305	-.542	-.285	-.205
7	-.095	.157	-.110	.159	.055	.030	.056	-.162	.029	-.003	.014	.037	.051	.066	-.306	-.195	-.306
8	.256	-.296	-.076	-.293	-.221	-.149	.256	.195	.296	-.162	-.184	-.256	-.292	.318	.565	.572	.314
9	-.023	-.332	-.092	-.344	-.218	-.324	-.108	.430	-.013	-.228	-.237	-.338	-.356	-.090	.189	.564	.681
10	-.122	.123	.276	.171	.024	.217	-.231	-.016	-.325	.285	.287	.244	.151	-.357	-.326	-.160	-.043
11	-.264	.248	.032	.265	.111	.153	-.110	.015	-.347	.139	.153	.183	.176	-.292	-.454	-.215	-.207
12	.505	-.162	-.252	-.173	-.132	-.242	.212	-.217	.540	-.254	-.256	-.289	-.258	.525	.352	.019	-.015
13	.020	.417	.385	.412	.395	.570	-.144	.033	-.142	.400	.391	.584	.696	-.191	-.137	-.223	-.287
14	.359	-.195	-.109	-.183	-.139	-.070	.455	-.236	.640	-.099	-.096	-.153	-.211	.715	.407	.032	-.132
15	.137	.893	-.098	.957	.359	.412	-.072	-.069	-.080	-.062	-.057	.105	.183	-.092	-.205	-.147	-.149
16	.081	.158	.129	.071	.046	.328	-.187	-.034	-.251	.012	-.033	-.020	.350	-.229	.278	.015	-.050
17	1.000	.160	.062	.193	.142	.125	.106	-.201	.450	.120	.128	.214	.017	.187	-.009	.156	-.028
18	.160	1.000	-.126	.908	.562	.569	-.098	-.042	-.082	-.072	-.073	.245	.408	-.101	-.265	-.197	-.148
19	.062	-.126	1.000	.119	-.088	.530	-.078	.052	-.083	.918	.916	.738	.132	-.100	.087	-.086	-.018
20	.193	.908	.119	1.000	.466	.578	-.088	-.029	-.091	.178	.183	.387	.308	-.107	-.247	-.179	-.145
21	.142	.562	-.088	.466	1.000	.273	-.082	.116	-.057	-.059	-.052	.445	.625	-.120	-.185	-.147	-.100
22	.125	.569	.530	.578	.273	1.000	.121	-.062	-.071	.563	.549	.638	.532	.094	-.086	-.233	-.107
23	.106	-.098	-.078	-.088	-.082	.121	1.000	-.108	.090	-.065	-.060	-.093	-.125	.673	.162	-.025	.018
24	-.201	-.042	.052	-.029	.116	-.062	-.108	1.000	-.155	.049	.052	.110	.002	-.186	.154	.458	.458
25	.450	-.082	-.083	-.091	-.057	-.071	.090	-.155	1.000	-.079	-.076	-.073	-.093	.279	.331	-.012	-.142
26	.120	-.072	.918	.178	-.059	.563	-.065	.049	-.079	1.000	.998	.826	.207	-.067	-.097	-.091	8.620E-5
27	.128	-.073	.916	.183	-.052	.549	-.060	.052	-.076	.998	1.000	.829	.195	-.069	-.127	-.089	-.002
28	.214	.245	.738	.387	.445	.638	-.093	.110	-.073	.826	.829	1.000	.512	-.091	-.204	-.154	-.045
29	.017	.408	.132	.308	.625	.532	-.125	.002	-.093	.207	.195	.512	1.000	-.133	-.282	-.224	-.144
30	.187	-.101	-.100	-.107	-.120	.094	.673	-.186	.279	-.067	-.069	-.091	-.133	1.000	.313	-.176	-.067
31	-.009	-.265	.087	-.247	-.185	-.086	.162	.154	.331	-.097	-.127	-.204	-.282	.313	1.000	-.068	-.257
32	.156	-.197	-.086	-.179	-.147	-.233	-.025	.458	-.012	-.091	-.089	-.154	-.224	-.176	-.068	1.000	.556
33	-.028	-.148	-.018	-.145	-.100	-.107	.018	.458	-.142	8.620E-5	-.002	-.045	-.144	-.067	-.257	.556	1.000
34	-.193	-.215	-.037	-.183	-.154	-.207	-.103	.614	-.169	-.026	-.024	-.099	-.211	-.154	.010	.562	.473
35	.135	-.259	-.171	-.241	-.185	-.237	.180	.447	.276	-.137	-.127	-.204	-.281	.375	.269	.460	.322
36	.625	-.122	-.102	-.118	-.087	-.199	.081	-.096	-.049	-.073	-.060	-.096	-.132	.031	-.162	.303	.113
37	.170	-.217	-.171	-.209	-.155	-.355	-.001	-.150	-.036	-.130	-.107	-.171	-.235	-.053	-.296	-.176	.049
38	-.115	-.208	-.131	-.198	-.149	-.263	-.071	.317	-.169	-.123	-.102	-.164	-.225	-.162	-.030	.149	-.030
39	-.077	-.106	-.060	-.095	-.075	-.117	-.042	.402	-.055	-.049	-.052	-.083	-.115	-.074	-.209	.568	.867
40	-.145	-.076	-.033	-.065	-.054	-.055	-.063	.462	-.080	-.030	-.037	-.060	-.082	-.037	-.141	.398	.881
41	-.319	-.129	-.110	-.125	-.092	-.247	-.107	-.172	-.136	-.080	-.064	-.102	-.140	-.119	-.288	-.141	.049
42	-.164	-.107	-.091	-.104	-.076	-.204	-.089	-.142	-.113	-.066	-.053	-.084	-.116	-.121	-.239	-.146	-.100
43	.128	-.073	.916	.183	-.052	.549	-.060	.052	-.076	.998	1.000	.829	.195	-.069	-.127	-.089	-.002

	Nav/Ach	Nav B	Dip Sm	Pinn su	Staur p	Gomp	Ach ex	Frag brev	Amph cof	Calon	B asiat	H tiliac	Casuarin	F tinct	Cocos	Pritch	Pandan
44	.128	-.073	.916	.183	-.052	.549	-.060	.052	-.076	.998	1.000	.829	.195	-.069	-.127	-.089	-.002
45	.136	-.243	-.080	-.228	-.173	-.184	.234	.362	2.415E-4	-.107	-.119	-.191	-.263	.258	.087	.678	.774
46	.487	.058	-.147	-.008	-.205	.022	.223	-.029	.064	-.095	-.092	-.047	-.089	.211	-.105	.065	.218
47	.128	-.073	.916	.183	-.052	.549	-.060	.052	-.076	.998	1.000	.829	.195	-.069	-.127	-.089	-.002
48	.128	-.073	.916	.183	-.052	.549	-.060	.052	-.076	.998	1.000	.829	.195	-.069	-.127	-.089	-.002
49	.128	-.073	.916	.183	-.052	.549	-.060	.052	-.076	.998	1.000	.829	.195	-.069	-.127	-.089	-.002
50	.128	-.073	.916	.183	-.052	.549	-.060	.052	-.076	.998	1.000	.829	.195	-.069	-.127	-.089	-.002
51	.128	-.073	.916	.183	-.052	.549	-.060	.052	-.076	.998	1.000	.829	.195	-.069	-.127	-.089	-.002
52	.115	-.027	.898	.182	-.027	.606	-.068	.043	-.089	.985	.985	.813	.230	-.083	-.149	-.106	-.006
53	-.072	.265	-.062	.003	.145	.359	-.050	-.050	-.076	-.026	-.036	-.057	.218	-.082	-.135	-.104	-.021
54	.128	-.073	.916	.183	-.052	.549	-.060	.052	-.076	.998	1.000	.829	.195	-.069	-.127	-.089	-.002
55	.159	.397	-.062	.320	.962	.154	-.060	.153	-.023	-.045	-.036	.482	.546	-.082	-.126	-.104	-.064
56	-.016	.025	-.071	-.009	.036	-.071	-.065	-.168	-.159	-.035	-.024	-.009	.008	-.160	-.311	-.097	.159
57	-.071	.302	-.068	.190	.388	.181	-.166	-.139	-.176	-.006	.002	.175	.397	-.208	-.405	-.290	-.163
58	-.077	-.073	-.062	-.070	-.052	-.139	-.060	.325	-.076	-.045	-.036	-.057	-.079	-.082	.131	.206	-.119
59	-.179	-.073	-.062	-.070	-.052	-.139	-.060	-.097	-.076	-.045	-.036	-.057	-.079	-.051	-.163	-.085	-.008
60	.145	.218	.719	.290	.423	.678	-.097	.087	-.106	.810	.812	.877	.486	-.128	-.217	-.163	-.037
61	.061	.677	.260	.631	.548	.758	-.145	-.049	-.122	.349	.340	.530	.842	-.178	-.326	-.267	-.174
62	.266	-.194	.006	-.170	-.166	-.161	.024	.299	.308	-.057	-.064	-.135	-.231	.071	.293	.812	.220
63	.218	.564	.574	.651	.319	.857	.100	-.018	-.077	.679	.676	.835	.547	.056	-.249	-.240	-.105
64	.110	-.002	.728	.203	.217	.524	-.108	.018	-.115	.818	.816	.789	.625	-.136	-.232	-.171	-.066
65	-.255	.114	.361	.161	.144	.328	-.204	-.083	-.239	.458	.468	.417	.322	-.293	-.472	-.128	.004
66	-.168	-.168	-.242	-.123	-.197	-.427	-.003	-.100	-.129	-.189	-.157	-.245	-.361	-.144	-.503	.250	.180
67	-.373	-.246	-.217	-.223	-.197	-.389	-.024	-.280	-.155	-.179	-.155	-.240	-.318	-.122	-.311	-.243	-.156
68	-.232	-.160	-.172	-.171	-.114	-.342	-.178	-.276	-.228	-.118	-.093	-.144	-.181	-.230	-.481	-.262	-.136
69	.211	-.147	-.111	-.140	-.099	-.209	.041	-.030	.035	-.084	-.073	-.117	-.112	-.011	-.133	.626	.179
70	.332	-.230	-.031	-.220	-.151	-.244	-.174	.159	.002	-.113	-.114	-.183	-.145	-.098	.131	.302	.098
71	.065	-.156	-.122	-.151	-.111	-.292	-.125	-.192	-.155	-.089	-.077	-.123	-.169	-.173	-.259	-.184	-.046
72	.526	-.076	-.065	-.073	-.054	-.145	-.063	-.101	-.080	-.047	-.037	-.060	-.082	-.086	-.170	.059	.093
73	-.160	-.158	-.134	-.153	-.113	-.301	-.131	-.210	-.166	-.097	-.078	-.124	-.171	-.176	-.354	-.205	-.107
74	-.248	-.101	-.086	-.097	-.072	-.192	-.084	-.134	-.106	-.062	-.049	-.079	-.109	-.099	-.224	-.121	-.017
75	-.336	-.172	-.146	-.166	-.123	-.328	-.143	-.228	-.181	-.106	-.084	-.135	-.186	-.183	-.385	-.223	-.158
76	-.234	.197	-.214	.189	.111	-.131	-.246	-.382	-.290	-.098	-.070	.003	.109	-.368	-.776	-.341	-.053
77	.156	.890	.082	.972	.386	.586	-.100	-.077	-.103	.147	.148	.327	.402	-.115	-.280	-.207	-.172
78	-.347	-.115	-.098	-.107	-.091	-.244	-.127	-.212	-.165	-.078	-.060	-.105	-.131	-.171	-.327	-.220	-.182

	Caloph	E tong	A vitien	Trema	Glochid	Homolan	Rapanea	W raro	C laevig	Freycin	A stellata	C pan	Urt/Mor	Sida	S rhom	Acalyp
1	.057	.084	.244	-.119	-.137	.071	.037	.168	-.244	-.049	-.049	.093	.358	-.049	-.049	-.049
2	-.186	.119	.578	.278	-.118	.020	-.030	.169	-.083	-.387	-.387	.171	.485	-.387	-.387	-.387
3	-.139	.056	.016	.265	-.061	.062	.143	.037	.145	-.186	-.186	.037	.069	-.186	-.186	-.186
4	-.056	-.204	-.196	-.404	-.272	-.033	-.036	-.449	-.008	.259	.259	-.004	-.355	.259	.259	.259
5	-.208	-.183	-.156	-.389	-.290	-.098	-.110	-.330	-.184	.542	.542	-.109	-.261	.542	.542	.542
6	-.065	-.415	-.323	.326	.287	-.166	-.078	.162	.441	.128	.128	-.410	-.314	.128	.128	.128
7	-.142	-.136	-.324	.258	.173	-.164	-.121	.009	.311	.014	.014	-.259	-.381	.014	.014	.014
8	.212	.497	.292	-.337	-.151	.323	.210	-.231	-.348	-.184	-.184	.619	.269	-.184	-.184	-.184
9	.404	.275	.315	-.101	-.070	.626	.619	-.063	-.211	-.237	-.237	.683	.254	-.237	-.237	-.237
10	.070	-.387	-.336	.419	.248	-.054	.069	-.107	.239	.287	.287	-.240	-.389	.287	.287	.287
11	.009	-.333	-.330	.260	.319	-.158	-.060	.072	.383	.153	.153	-.376	-.358	.153	.153	.153
12	-.174	.283	.482	-.053	-.260	-.078	-.114	-.051	-.269	-.256	-.256	.204	.505	-.256	-.256	-.256
13	-.038	-.242	-.309	-.083	.033	-.195	-.154	-.154	-.279	.391	.391	-.390	-.242	.391	.391	.391
14	-.185	.366	.083	-.108	-.220	-.037	-.100	-.171	-.141	-.096	-.096	.215	.075	-.096	-.096	-.096
15	-.168	-.203	-.096	-.170	-.163	-.083	-.059	-.101	-.084	-.057	-.057	-.190	-3.863E-4	-.057	-.057	-.057
16	.033	-.193	.026	-.143	-.024	-.080	-.005	-.343	-.202	-.033	-.033	.014	-.030	-.033	-.033	-.033
17	-.193	.135	.625	.170	-.115	-.077	-.145	-.319	-.164	.128	.128	.136	.487	.128	.128	.128
18	-.215	-.259	-.122	-.217	-.208	-.106	-.076	-.129	-.107	-.073	-.073	-.243	.058	-.073	-.073	-.073
19	-.037	-.171	-.102	-.171	-.131	-.060	-.033	-.110	-.091	.916	.916	-.080	-.147	.916	.916	.916
20	-.183	-.241	-.118	-.209	-.198	-.095	-.065	-.125	-.104	.183	.183	-.228	-.008	.183	.183	.183
21	-.154	-.185	-.087	-.155	-.149	-.075	-.054	-.092	-.076	-.052	-.052	-.173	-.205	-.052	-.052	-.052
22	-.207	-.237	-.199	-.355	-.263	-.117	-.055	-.247	-.204	.549	.549	-.184	.022	.549	.549	.549
23	-.103	.180	.081	-.001	-.071	-.042	-.063	-.107	-.089	-.060	-.060	.234	.223	-.060	-.060	-.060
24	.614	.447	-.096	-.150	.317	.402	.462	-.172	-.142	.052	.052	.362	-.029	.052	.052	.052
25	-.169	.276	-.049	-.036	-.169	-.055	-.080	-.136	-.113	-.076	-.076	2.415E-4	.064	-.076	-.076	-.076
26	-.026	-.137	-.073	-.130	-.123	-.049	-.030	-.080	-.066	.998	.998	-.107	-.095	.998	.998	.998
27	-.024	-.127	-.060	-.107	-.102	-.052	-.037	-.064	-.053	1.000	1.000	-.119	-.092	1.000	1.000	1.000
28	-.099	-.204	-.096	-.171	-.164	-.083	-.060	-.102	-.084	.829	.829	-.191	-.047	.829	.829	.829
29	-.211	-.281	-.132	-.235	-.225	-.115	-.082	-.140	-.116	.195	.195	-.263	-.089	.195	.195	.195
30	-.154	.375	.031	-.053	-.162	-.074	-.037	-.119	-.121	-.069	-.069	.258	.211	-.069	-.069	-.069
31	.010	.269	-.162	-.296	-.030	-.209	-.141	-.288	-.239	-.127	-.127	.087	-.105	-.127	-.127	-.127
32	.562	.460	.303	-.176	.149	.568	.398	-.141	-.146	-.089	-.089	.678	.065	-.089	-.089	-.089
33	.473	.322	.113	.049	-.030	.867	.881	.049	-.100	-.002	-.002	.774	.218	-.002	-.002	-.002
34	1.000	.545	-.022	-.028	.501	.472	.512	-.090	.024	-.024	-.024	.413	-.076	-.024	-.024	-.024
35	.545	1.000	.106	-.127	.261	.406	.349	-.139	-.169	-.127	-.127	.495	.096	-.127	-.127	-.127
36	-.022	.106	1.000	.029	-.080	.035	-.063	-.107	-.089	-.060	-.060	.270	.699	-.060	-.060	-.060
37	-.028	-.127	.029	1.000	.493	-.027	-.030	.201	.247	-.107	-.107	-.134	.051	-.107	-.107	-.107
38	.501	.261	-.080	.493	1.000	-.110	-.084	.298	.162	-.102	-.102	-.166	-.085	-.102	-.102	-.102
39	.472	.406	.035	-.027	-.110	1.000	.930	-.045	-.077	-.052	-.052	.786	.033	-.052	-.052	-.052
40	.512	.349	-.063	-.030	-.084	.930	1.000	-.066	-.046	-.037	-.037	.716	.037	-.037	-.037	-.037
41	-.090	-.139	-.107	.201	.298	-.045	-.066	1.000	-.014	-.064	-.064	-.213	.004	-.064	-.064	-.064
42	.024	-.169	-.089	.247	.162	-.077	-.046	-.014	1.000	-.053	-.053	-.103	-.197	-.053	-.053	-.053
43	-.024	-.127	-.060	-.107	-.102	-.052	-.037	-.064	-.053	1.000	1.000	-.119	-.092	1.000	1.000	1.000

	Caloph	E tong	A vitien	Trema	Glochid	Homolan	Rapanea	W raro	C laevig	Freycin	A stellata	C pan	Urt/Mor	Sida	S rhom	Acalyp
44	-.024	-.127	-.060	-.107	-.102	-.052	-.037	-.064	-.053	1.000	1.000	-.119	-.092	1.000	1.000	1.000
45	.413	.495	.270	-.134	-.166	.786	.716	-.213	-.103	-.119	-.119	1.000	.175	-.119	-.119	-.119
46	-.076	.096	.699	.051	-.085	.033	.037	.004	-.197	-.092	-.092	.175	1.000	-.092	-.092	-.092
47	-.024	-.127	-.060	-.107	-.102	-.052	-.037	-.064	-.053	1.000	1.000	-.119	-.092	1.000	1.000	1.000
48	-.024	-.127	-.060	-.107	-.102	-.052	-.037	-.064	-.053	1.000	1.000	-.119	-.092	1.000	1.000	1.000
49	-.024	-.127	-.060	-.107	-.102	-.052	-.037	-.064	-.053	1.000	1.000	-.119	-.092	1.000	1.000	1.000
50	-.024	-.127	-.060	-.107	-.102	-.052	-.037	-.064	-.053	1.000	1.000	-.119	-.092	1.000	1.000	1.000
51	-.024	-.127	-.060	-.107	-.102	-.052	-.037	-.064	-.053	1.000	1.000	-.119	-.092	1.000	1.000	1.000
52	-.042	-.148	-.070	-.124	-.119	-.060	-.043	-.074	-.061	.985	.985	-.139	-.116	.985	.985	.985
53	-.106	-.127	-.060	-.107	-.102	-.052	-.037	-.064	-.053	-.036	-.036	-.119	-.148	-.036	-.036	-.036
54	-.024	-.127	-.060	-.107	-.102	-.052	-.037	-.064	-.053	1.000	1.000	-.119	-.092	1.000	1.000	1.000
55	-.106	-.127	-.060	-.107	-.102	-.052	-.037	-.064	-.053	-.036	-.036	-.119	-.148	-.036	-.036	-.036
56	-.181	-.195	.218	.190	-.092	.058	-.058	.259	-.139	-.024	-.024	-.155	.330	-.024	-.024	-.024
57	-.127	-.338	-.174	.173	.069	-.151	-.095	-.076	.788	.002	.002	-.276	-.283	.002	.002	.002
58	.674	.525	.078	-.107	.588	-.052	-.037	-.064	-.053	-.036	-.036	-.119	-.006	-.036	-.036	-.036
59	-.106	-.127	-.060	.170	.381	-.052	-.037	.859	-.053	-.036	-.036	-.119	-.021	-.036	-.036	-.036
60	-.109	-.215	-.101	-.180	-.172	-.088	-.063	-.107	-.089	.812	.812	-.201	-.202	.812	.812	.812
61	-.252	-.347	-.164	-.289	-.279	-.142	-.101	-.173	-.143	.340	.340	-.324	-.150	.340	.340	.340
62	.249	.498	.138	-.272	-.015	.288	.088	-.242	-.210	-.064	-.064	.567	-.073	-.064	-.064	-.064
63	-.196	-.250	-.125	-.234	-.235	-.132	-.094	-.161	-.133	.676	.676	-.228	.150	.676	.676	.676
64	-.091	-.213	-.107	-.036	-.089	-.093	-.059	-.113	-.057	.816	.816	-.209	-.198	.816	.816	.816
65	-.015	-.282	-.192	-.182	-.116	-.167	-.143	.402	.082	.468	.468	-.330	-.220	.468	.468	.468
66	.033	.009	.172	.054	.021	.212	.127	.222	.480	-.157	-.157	.173	-.027	-.157	-.157	-.157
67	-.139	-.204	-.216	.334	.190	-.112	-.095	.276	.280	-.155	-.155	-.306	-.250	-.155	-.155	-.155
68	.007	-.337	-.095	.638	.324	-.101	-.094	.531	.455	-.093	-.093	-.311	-.177	-.093	-.093	-.093
69	.169	.501	.295	-.202	-.044	.289	.015	.025	-.086	-.073	-.073	.384	.003	-.073	-.073	-.073
70	.263	.066	.683	-.035	.137	-.057	-.019	-.185	-.168	-.114	-.114	.192	.487	-.114	-.114	-.114
71	-.023	-.197	-.129	.776	.357	-.112	-.042	-.053	.339	-.077	-.077	-.187	-.200	-.077	-.077	-.077
72	-.108	-.133	.907	.095	-.098	-.054	-.039	-.066	-.013	-.037	-.037	.094	.719	-.037	-.037	-.037
73	-.110	-.235	-.131	.604	.191	-.083	-.060	-.019	.335	-.078	-.078	-.223	-.194	-.078	-.078	-.078
74	-.125	-.177	-.083	.391	.284	.101	-.052	.599	-.073	-.049	-.049	-.166	-.013	-.049	-.049	-.049
75	-.140	-.285	-.142	.318	.104	-.091	-.080	.289	.094	-.084	-.084	-.269	-.219	-.084	-.084	-.084
76	-.206	-.457	-.031	.340	.010	-.077	-.073	.524	.280	-.070	-.070	-.431	.015	-.070	-.070	-.070
77	-.205	-.271	-.132	-.189	-.190	-.114	-.080	-.140	-.066	.148	.148	-.258	.016	.148	.148	.148
78	-.152	-.278	-.133	.168	.055	-.114	-.081	.052	.712	-.060	-.060	-.200	-.251	-.060	-.060	-.060

	E mollis	P quad	A conyz	B pilosa	C escul	I batat	Cyperac	C. pennat	T ang	T lat	Jameson	Gleich lin	Acrost aur	P phymat	C affin	Cyatheac
1	-.049	-.049	-.055	-.037	-.049	.040	.688	-.271	-.023	-.173	-.040	-.093	-.018	-.128	-.053	.197
2	-.387	-.387	-.409	-.149	-.387	-.149	.286	-.319	-.168	.104	-.451	-.508	.059	-.499	-.468	-.312
3	-.186	-.186	-.212	-.164	-.186	-.034	-.371	.024	-.099	.206	-.240	-.222	-.233	-.114	-.215	-.294
4	.259	.259	.295	.222	.259	-.036	-.291	.066	.018	-.294	.297	.235	.118	.203	.156	-.035
5	.542	.542	.583	.265	.542	.080	-.242	.130	-.059	-.152	.602	.670	.103	.623	.551	.204
6	.128	.128	.140	.080	.128	.035	-.337	.554	-.018	.306	.156	.269	-.448	.255	.205	.201
7	.014	.014	.020	.037	.014	.022	-.581	.361	-.025	.258	.037	.109	-.163	.114	.061	-.061
8	-.184	-.184	-.212	-.170	-.184	-.150	.075	-.546	.047	-.234	-.290	-.380	.684	-.281	-.293	-.387
9	-.237	-.237	-.247	-.070	-.237	-.164	.190	-.414	-.053	-.099	-.298	-.419	.375	-.464	-.347	-.266
10	.287	.287	.304	.112	.287	-.022	-.399	.386	-.049	.072	.280	.256	-.290	.236	.367	.135
11	.153	.153	.168	.095	.153	.054	-.426	.502	.076	.266	.192	.270	-.383	.251	.223	.153
12	-.256	-.256	-.276	-.133	-.256	-.094	.304	-.414	-.091	-.150	-.311	-.305	.212	-.271	-.317	-.280
13	.391	.391	.409	.123	.391	.333	-.207	.146	.177	-.007	.521	.689	-.192	.649	.617	.198
14	-.096	-.096	-.111	-.096	-.096	-.096	-.183	-.262	-.096	-.096	-.161	-.232	.331	-.121	-.171	-.317
15	-.057	-.057	-.056	-.001	-.057	.191	-.008	.147	-.057	-.057	.032	.520	-.141	.439	-.009	.047
16	-.033	-.033	.012	.260	-.033	-.045	-.122	.049	.057	-.193	.063	.354	.033	.088	.183	-.120
17	.128	.128	.115	-.072	.128	.159	-.016	-.071	-.077	-.179	.145	.061	.266	.218	.110	-.255
18	-.073	-.073	-.027	.265	-.073	.397	.025	.302	-.073	-.073	.218	.677	-.194	.564	-.002	.114
19	.916	.916	.898	-.062	.916	-.062	-.071	-.068	-.062	-.062	.719	.260	.006	.574	.728	.361
20	.183	.183	.182	.003	.183	.320	-.009	.190	-.070	-.070	.290	.631	-.170	.651	.203	.161
21	-.052	-.052	-.027	.145	-.052	.962	.036	.388	-.052	-.052	.423	.548	-.166	.319	.217	.144
22	.549	.549	.606	.359	.549	.154	-.071	.181	-.139	-.139	.678	.758	-.161	.857	.524	.328
23	-.060	-.060	-.068	-.050	-.060	-.060	-.065	-.166	-.060	-.060	-.097	-.145	.024	.100	-.108	-.204
24	.052	.052	.043	-.050	.052	.153	-.168	-.139	.325	-.097	.087	-.049	.299	-.018	.018	-.083
25	-.076	-.076	-.089	-.076	-.076	-.023	-.159	-.176	-.076	-.076	-.106	-.122	.308	-.077	-.115	-.239
26	.998	.998	.985	-.026	.998	-.045	-.035	-.006	-.045	-.045	.810	.349	-.057	.679	.818	.458
27	1.000	1.000	.985	-.036	1.000	-.036	-.024	.002	-.036	-.036	.812	.340	-.064	.676	.816	.468
28	.829	.829	.813	-.057	.829	.482	-.009	.175	-.057	-.057	.877	.530	-.135	.835	.789	.417
29	.195	.195	.230	.218	.195	.546	.008	.397	-.079	-.079	.486	.842	-.231	.547	.625	.322
30	-.069	-.069	-.083	-.082	-.069	-.082	-.160	-.208	-.082	-.051	-.128	-.178	.071	.056	-.136	-.293
31	-.127	-.127	-.149	-.135	-.127	-.126	-.311	-.405	.131	-.163	-.217	-.326	.293	-.249	-.232	-.472
32	-.089	-.089	-.106	-.104	-.089	-.104	-.097	-.290	.206	-.085	-.163	-.267	.812	-.240	-.171	-.128
33	-.002	-.002	-.006	-.021	-.002	-.064	.159	-.163	-.119	-.008	-.037	-.174	.220	-.105	-.066	.004
34	-.024	-.024	-.042	-.106	-.024	-.106	-.181	-.127	.674	-.106	-.109	-.252	.249	-.196	-.091	-.015
35	-.127	-.127	-.148	-.127	-.127	-.127	-.195	-.338	.525	-.127	-.215	-.347	.498	-.250	-.213	-.282
36	-.060	-.060	-.070	-.060	-.060	-.060	.218	-.174	.078	-.060	-.101	-.164	.138	-.125	-.107	-.192
37	-.107	-.107	-.124	-.107	-.107	-.107	.190	.173	-.107	.170	-.180	-.289	-.272	-.234	-.036	-.182
38	-.102	-.102	-.119	-.102	-.102	-.102	-.092	.069	.588	.381	-.172	-.279	-.015	-.235	-.089	-.116
39	-.052	-.052	-.060	-.052	-.052	-.052	.058	-.151	-.052	-.052	-.088	-.142	.288	-.132	-.093	-.167
40	-.037	-.037	-.043	-.037	-.037	-.037	-.058	-.095	-.037	-.037	-.063	-.101	.088	-.094	-.059	-.143
41	-.064	-.064	-.074	-.064	-.064	-.064	.259	-.076	-.064	.859	-.107	-.173	-.242	-.161	-.113	.402
42	-.053	-.053	-.061	-.053	-.053	-.053	-.139	.788	-.053	-.053	-.089	-.143	-.210	-.133	-.057	.082
43	1.000	1.000	.985	-.036	1.000	-.036	-.024	.002	-.036	-.036	.812	.340	-.064	.676	.816	.468

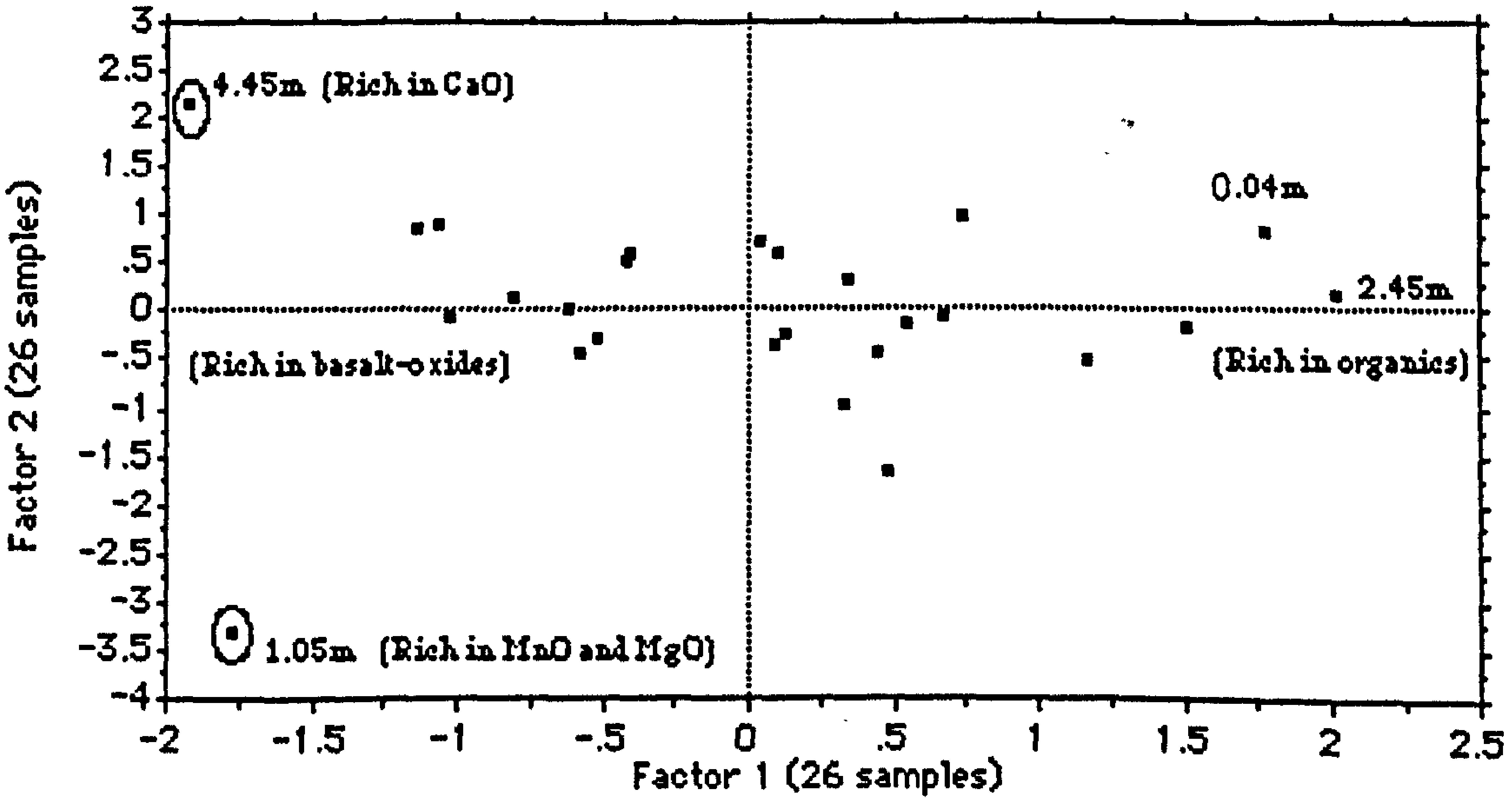
	E mollis	P quad	A conyz	B pilosa	C escul	I batat	Cyperac	C. pennat	T ang	T lat	Jameson	Gleich lin	Acrost aur	P phymat	C affin	Cyatheac
44	1.000	1.000	.985	-.036	1.000	-.036	-.024	.002	-.036	-.036	.812	.340	-.064	.676	.816	.468
45	-.119	-.119	-.139	-.119	-.119	-.119	-.155	-.276	-.119	-.119	-.201	-.324	.567	-.228	-.209	-.330
46	-.092	-.092	-.116	-.148	-.092	-.148	.330	-.283	-.006	-.021	-.202	-.150	-.073	.150	-.198	-.220
47	1.000	1.000	.985	-.036	1.000	-.036	-.024	.002	-.036	-.036	.812	.340	-.064	.676	.816	.468
48	1.000	1.000	.985	-.036	1.000	-.036	-.024	.002	-.036	-.036	.812	.340	-.064	.676	.816	.468
49	1.000	1.000	.985	-.036	1.000	-.036	-.024	.002	-.036	-.036	.812	.340	-.064	.676	.816	.468
50	1.000	1.000	.985	-.036	1.000	-.036	-.024	.002	-.036	-.036	.812	.340	-.064	.676	.816	.468
51	1.000	1.000	.985	-.036	1.000	-.036	-.024	.002	-.036	-.036	.812	.340	-.064	.676	.816	.468
52	.985	.985	1.000	.135	.985	-.041	-.009	.058	-.041	-.041	.869	.414	-.083	.675	.798	.517
53	-.036	-.036	.135	1.000	-.036	-.036	.088	.330	-.036	-.036	.376	.452	-.116	.031	-.064	.308
54	1.000	1.000	.985	-.036	1.000	-.036	-.024	.002	-.036	-.036	.812	.340	-.064	.676	.816	.468
55	-.036	-.036	-.041	-.036	-.036	1.000	.026	.312	-.036	-.036	.376	.363	-.120	.272	.200	.068
56	-.024	-.024	-.009	.088	-.024	.026	1.000	-.100	-.103	-.116	.028	.019	-.264	-.023	-.042	.208
57	.002	.002	.058	.330	.002	.312	-.100	1.000	-.104	-.053	.272	.413	-.354	.173	.190	.274
58	-.036	-.036	-.041	-.036	-.036	-.036	-.103	-.104	1.000	-.036	-.060	-.097	.039	-.090	-.064	-.093
59	-.036	-.036	-.041	-.036	-.036	-.036	-.116	-.053	-.036	1.000	-.060	-.097	-.142	-.090	-.064	.148
60	.812	.812	.869	.376	.812	.376	.028	.272	-.060	-.060	1.000	.629	-.153	.696	.745	.552
61	.340	.340	.414	.452	.340	.363	.019	.413	-.097	-.097	.629	1.000	-.263	.689	.601	.447
62	-.064	-.064	-.083	-.116	-.064	-.120	-.264	-.354	.039	-.142	-.153	-.263	1.000	-.210	-.167	-.222
63	.676	.676	.675	.031	.676	.272	-.023	.173	-.090	-.090	.696	.689	-.210	1.000	.644	.340
64	.816	.816	.798	-.064	.816	.200	-.042	.190	-.064	-.064	.745	.601	-.167	.644	1.000	.462
65	.468	.468	.517	.308	.468	.068	.208	.274	-.093	.148	.552	.447	-.222	.340	.462	1.000
66	-.157	-.157	-.186	-.181	-.157	-.157	-.096	.182	-.085	.195	-.274	-.360	.051	-.286	-.285	.044
67	-.155	-.155	-.179	-.149	-.155	-.143	-.023	.070	-.044	.222	-.254	-.366	-.365	-.301	-.208	-.044
68	-.093	-.093	-.097	-.028	-.093	-.085	.011	.344	-.095	.432	-.125	-.213	-.423	-.227	-.086	.249
69	-.073	-.073	-.085	-.073	-.073	-.073	.011	-.176	.154	-.073	-.123	-.161	.650	-.168	-.095	.073
70	-.114	-.114	-.133	-.114	-.114	-.114	.129	-.292	.259	-.114	-.192	-.227	.164	-.271	-.127	-.246
71	-.077	-.077	-.089	-.077	-.077	-.077	-.179	.293	-.077	.001	-.129	-.209	-.267	-.194	.019	-.157
72	-.037	-.037	-.043	-.037	-.037	-.037	.294	-.073	-.037	-.037	-.063	-.102	-.149	-.094	-.066	-.138
73	-.078	-.078	-.090	-.078	-.078	-.078	-.089	.231	-.078	.013	-.131	-.211	-.310	-.196	-.053	-.138
74	-.049	-.049	-.057	-.049	-.049	-.049	.588	-.118	-.049	.472	-.083	-.135	-.197	-.125	-.088	-.023
75	-.084	-.084	-.098	-.084	-.084	-.084	-.113	-.016	-.084	.313	-.142	-.230	-.337	-.214	-.118	-9.903E-5
76	-.070	-.070	-.074	-.030	-.070	.079	.321	.324	-.164	.310	-.038	.124	-.609	.043	.022	.440
77	.148	.148	.145	-.015	.148	.226	-.025	.231	-.078	-.078	.214	.687	-.199	.654	.253	.154
78	-.060	-.060	-.069	-.056	-.060	-.071	-.219	.518	-.078	.116	-.104	-.153	-.303	-.159	-.098	-.009

	Polypodiac	P comm	Cyclo/Hypo	A nidus	Lycopod	A evecta	L cernu	Marattia	Nephro	Cyathea	Monolete	Gramin	Mag susc
1	-.366	-.444	-.258	.086	.343	-.460	.305	-.516	.213	-.512	-.096	-.181	-.536
2	.231	.130	.187	.025	.470	1.012E-4	.587	.129	.226	.171	.119	-.358	.014
3	.498	.560	.368	-.177	-.134	.419	.038	.652	-.080	.678	.361	-.029	.578
4	-.115	-.073	-.304	.008	-.117	-.004	-.211	.150	-.326	-.020	-.258	.136	.213
5	-.368	-.420	-.382	.017	-.180	-.216	-.202	-.247	-.251	-.298	-.288	.511	-.173
6	.404	.575	.593	-.290	-.396	.580	-.225	.571	.020	.614	.579	.330	.620
7	.428	.580	.445	-.137	-.450	.536	-.350	.606	-.094	.642	.326	.183	.610
8	-.263	-.541	-.607	.395	.323	-.519	.116	-.576	-.092	-.615	-.729	-.324	-.571
9	.021	-.270	-.224	.044	.541	-.307	.344	-.271	.053	-.222	-.341	-.390	-.282
10	.078	.335	.448	-.327	-.262	.709	-.233	.587	-.161	.445	.283	.207	.369
11	.363	.542	.504	-.288	-.371	.552	-.252	.557	-.057	.586	.460	.301	.596
12	-.236	-.367	-.305	.083	.445	-.376	.448	-.402	.029	-.403	-.320	-.200	-.445
13	-.425	-.126	-.069	-.151	-.226	.102	-.303	-.001	-.076	.022	.044	.464	-.171
14	-.083	-.157	-.289	.243	-.136	-.200	-.100	-.208	-.133	-.227	-.424	-.205	-.208
15	-.055	-.167	-.137	-.112	-.173	-.122	-.059	-.123	-.079	-.134	.207	.950	-.079
16	-.571	-.423	-.319	-.134	.277	.022	.091	-.231	-.267	-.384	-.354	.158	-.339
17	-.168	-.373	-.232	.211	.332	.065	.526	-.160	-.248	-.336	-.234	.156	-.347
18	-.168	-.246	-.160	-.147	-.230	-.156	-.076	-.158	-.101	-.172	.197	.890	-.115
19	-.242	-.217	-.172	-.111	-.031	-.122	-.065	-.134	-.086	-.146	-.214	.082	-.098
20	-.123	-.223	-.171	-.140	-.220	-.151	-.073	-.153	-.097	-.166	.189	.972	-.107
21	-.197	-.197	-.114	-.099	-.151	-.111	-.054	-.113	-.072	-.123	.111	.386	-.091
22	-.427	-.389	-.342	-.209	-.244	-.292	-.145	-.301	-.192	-.328	-.131	.586	-.244
23	-.003	-.024	-.178	.041	-.174	-.125	-.063	-.131	-.084	-.143	-.246	-.100	-.127
24	-.100	-.280	-.276	-.030	.159	-.192	-.101	-.210	-.134	-.228	-.382	-.077	-.212
25	-.129	-.155	-.228	.035	.002	-.155	-.080	-.166	-.106	-.181	-.290	-.103	-.165
26	-.189	-.179	-.118	-.084	-.113	-.089	-.047	-.097	-.062	-.106	-.098	.147	-.078
27	-.157	-.155	-.093	-.073	-.114	-.077	-.037	-.078	-.049	-.084	-.070	.148	-.060
28	-.245	-.240	-.144	-.117	-.183	-.123	-.060	-.124	-.079	-.135	.003	.327	-.105
29	-.361	-.318	-.181	-.112	-.145	-.169	-.082	-.171	-.109	-.186	.109	.402	-.131
30	-.144	-.122	-.230	-.011	-.098	-.173	-.086	-.176	-.099	-.183	-.368	-.115	-.171
31	-.503	-.311	-.481	-.133	.131	-.259	-.170	-.354	-.224	-.385	-.776	-.280	-.327
32	.250	-.243	-.262	.626	.302	-.184	.059	-.205	-.121	-.223	-.341	-.207	-.220
33	.180	-.156	-.136	.179	.098	-.046	.093	-.107	-.017	-.158	-.053	-.172	-.182
34	.033	-.139	.007	.169	.263	-.023	-.108	-.110	-.125	-.140	-.206	-.205	-.152
35	.009	-.204	-.337	.501	.066	-.197	-.133	-.235	-.177	-.285	-.457	-.271	-.278
36	.172	-.216	-.095	.295	.683	-.129	.907	-.131	-.083	-.142	-.031	-.132	-.133
37	.054	.334	.638	-.202	-.035	.776	.095	.604	.391	.318	.340	-.189	.168
38	.021	.190	.324	-.044	.137	.357	-.098	.191	.284	.104	.010	-.190	.055
39	.212	-.112	-.101	.289	-.057	-.112	-.054	-.083	.101	-.091	-.077	-.114	-.114
40	.127	-.095	-.094	.015	-.019	-.042	-.039	-.060	-.052	-.080	-.073	-.080	-.081
41	.222	.276	.531	.025	-.185	-.053	-.066	-.019	.599	.289	.524	-.140	.052
42	.480	.280	.455	-.086	-.168	.339	-.013	.335	-.073	.094	.280	-.066	.712
43	-.157	-.155	-.093	-.073	-.114	-.077	-.037	-.078	-.049	-.084	-.070	.148	-.060

	Polypodiac	P comm	Cyclo/Hypo	A nidus	Lycopod	A evecta	L cernu	Marattia	Nephro	Cyathea	Monolete	Gramin	Mag susc
44	-.157	-.155	-.093	-.073	-.114	-.077	-.037	-.078	-.049	-.084	-.070	.148	-.060
45	.173	-.306	-.311	.384	.192	-.187	.094	-.223	-.166	-.269	-.431	-.258	-.200
46	-.027	-.250	-.177	.003	.487	-.200	.719	-.194	-.013	-.219	.015	.016	-.251
47	-.157	-.155	-.093	-.073	-.114	-.077	-.037	-.078	-.049	-.084	-.070	.148	-.060
48	-.157	-.155	-.093	-.073	-.114	-.077	-.037	-.078	-.049	-.084	-.070	.148	-.060
49	-.157	-.155	-.093	-.073	-.114	-.077	-.037	-.078	-.049	-.084	-.070	.148	-.060
50	-.157	-.155	-.093	-.073	-.114	-.077	-.037	-.078	-.049	-.084	-.070	.148	-.060
51	-.157	-.155	-.093	-.073	-.114	-.077	-.037	-.078	-.049	-.084	-.070	.148	-.060
52	-.186	-.179	-.097	-.085	-.133	-.089	-.043	-.090	-.057	-.098	-.074	.145	-.069
53	-.181	-.149	-.028	-.073	-.114	-.077	-.037	-.078	-.049	-.084	-.030	-.015	-.056
54	-.157	-.155	-.093	-.073	-.114	-.077	-.037	-.078	-.049	-.084	-.070	.148	-.060
55	-.157	-.143	-.085	-.073	-.114	-.077	-.037	-.078	-.049	-.084	.079	.226	-.071
56	-.096	-.023	.011	.011	.129	-.179	.294	-.089	.588	-.113	.321	-.025	-.219
57	.182	.070	.344	-.176	-.292	.293	-.073	.231	-.118	-.016	.324	.231	.518
58	-.085	-.044	-.095	.154	.259	-.077	-.037	-.078	-.049	-.084	-.164	-.078	-.078
59	.195	.222	.432	-.073	-.114	.001	-.037	.013	.472	.313	.310	-.078	.116
60	-.274	-.254	-.125	-.123	-.192	-.129	-.063	-.131	-.083	-.142	-.038	.214	-.104
61	-.360	-.366	-.213	-.161	-.227	-.209	-.102	-.211	-.135	-.230	.124	.687	-.153
62	.051	-.365	-.423	.650	.164	-.267	-.149	-.310	-.197	-.337	-.609	-.199	-.303
63	-.286	-.301	-.227	-.168	-.271	-.194	-.094	-.196	-.125	-.214	.043	.654	-.159
64	-.285	-.208	-.086	-.095	-.127	.019	-.066	-.053	-.088	-.118	.022	.253	-.098
65	.044	-.044	.249	.073	-.246	-.157	-.138	-.138	-.023	-9.903E-5	.440	.154	-.009
66	1.000	.660	.369	.302	-.071	.214	.097	.421	.017	.599	.490	-.136	.713
67	.660	1.000	.528	-.111	-.261	.557	-.151	.688	.211	.890	.583	-.226	.676
68	.369	.528	1.000	-.170	-.202	.542	-.008	.543	.384	.591	.696	-.162	.449
69	.302	-.111	-.170	1.000	-.101	-.144	-.076	-.158	-.101	-.160	-.079	-.144	-.154
70	-.071	-.261	-.202	-.101	1.000	-.164	.752	-.155	-.092	-.158	-.244	-.218	-.169
71	.214	.557	.542	-.144	-.164	1.000	-.069	.809	-.067	.514	.360	-.121	.430
72	.097	-.151	-.008	-.076	.752	-.069	1.000	-.065	-.052	-.083	.094	-.080	-.046
73	.421	.688	.543	-.158	-.155	.809	-.065	1.000	.079	.731	.509	-.135	.721
74	.017	.211	.384	-.101	-.092	-.067	-.052	.079	1.000	.231	.311	-.109	-.006
75	.599	.890	.591	-.160	-.158	.514	-.083	.731	.231	1.000	.610	-.173	.633
76	.490	.583	.696	-.079	-.244	.360	.094	.509	.311	.610	1.000	.219	.483
77	-.136	-.226	-.162	-.144	-.218	-.121	-.080	-.135	-.109	-.173	.219	1.000	-.083
78	.713	.676	.449	-.154	-.169	.430	-.046	.721	-.006	.633	.483	-.083	1.000

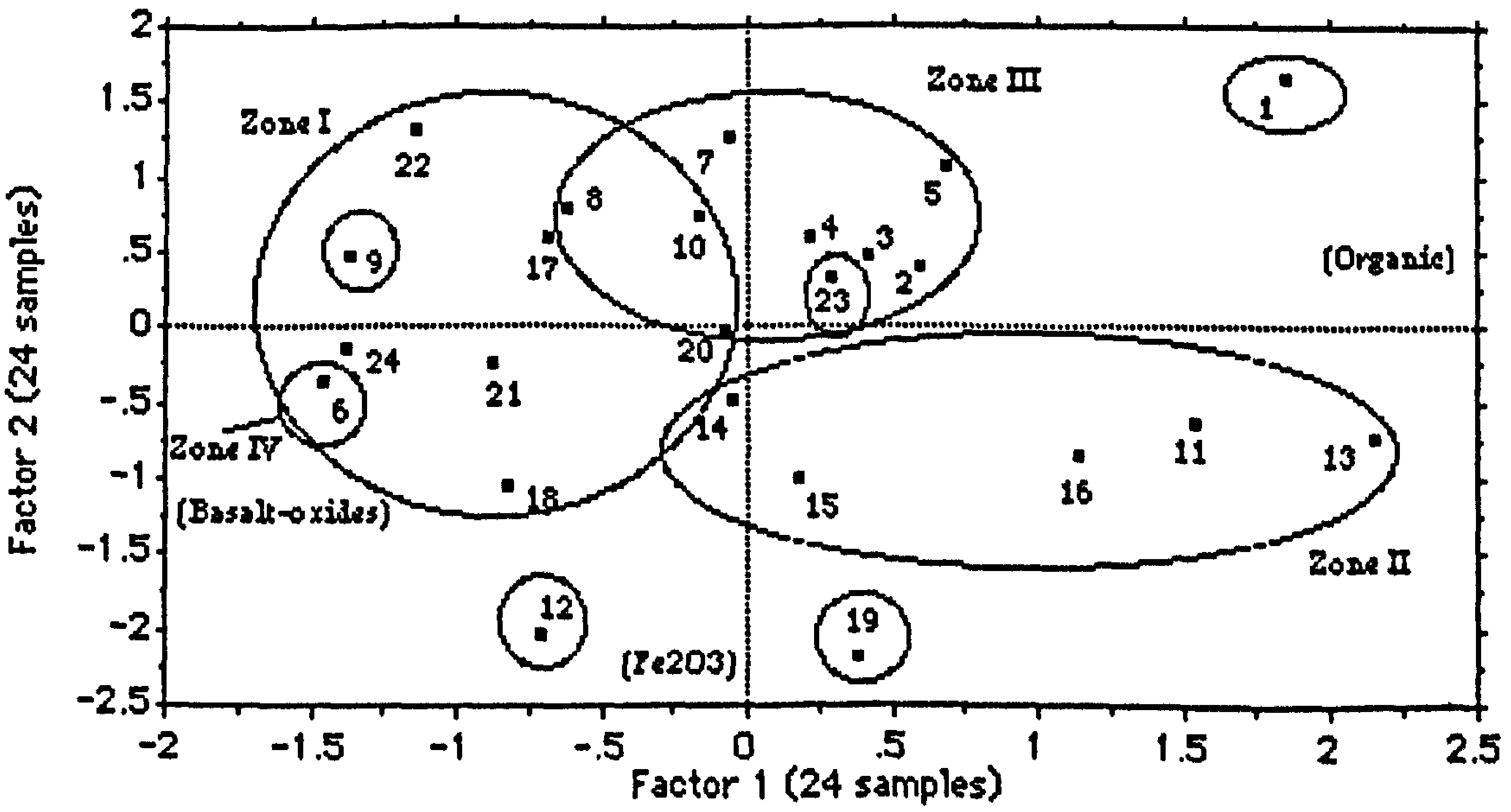
Fig.3.17 Principal components analysis of XRF data from Lake Vaihiria: Factor 1 versus factor 2. Data sets containing 26 and 24 sample depths.

A



B

Zones VgI to V



Key to sample depths within the identified geochemical zones:

Zone VgI (5.00-3.15):
24. 4.85m

Sub-zone VgIa (4.75-4.55m):
23. 4.65m
Sub-zone VgIb (4.55-4.35m):
* 4.45m

22. 4.25m
21. 4.05m
20. 3.85m

Sub-zone VgIc (3.75-3.55m):
19. 3.65m

18. 3.45m
17. 3.25m

Zone VgII (3.15-1.95m):
16. 3.05m
15. 2.85m
14. 2.65m
13. 2.45m

Sub-zone VgIIa (2.35-2.15m):
12. 2.25m

11. 2.05m

Zone VgIII (1.95-0.0m):
10. 1.85m

Sub-zone VgIIIa (1.80-1.70m):
9. 1.75m
8. 1.65m
7. 1.45m

Sub-zone VgIIIb (1.35-1.15m):
6. 1.25m
Sub-zone VgIIIc (1.15-0.95m):
* 1.05m

5. 0.84m
4. 0.64m
3. 0.44m
2. 0.24m

Sub-zone VgIIId (0.14-0.0m):
1. 0.04m

Fig.3.18 Correlation matrix derived from Lake Vaihiria geochemical data.

	Name	MgO_d	K2O_d	Fe2O3_d	MnO_d	TiO2_d	SiO2_d	SO3_d	CaO_d	P2O5_d	Al2O3_d	Na2O_d	LOI_d	L600
1	MgO_d	1.000	.757	.646	.524	-.132	.824	-.640	.225	-.776	.089	-.040	.680	-.778
2	K2O_d	.757	1.000	.627	.278	.006	.773	-.563	.249	-.742	.120	.289	.307	-.707
3	Fe2O3_d	.646	.627	1.000	.734	.607	.717	-.772	.408	-.452	.738	.334	.421	-.905
4	MnO_d	.524	.278	.734	1.000	.304	.341	-.540	.191	-.455	.429	.003	.503	-.538
5	TiO2_d	-.132	.006	.607	.304	1.000	.138	-.390	.557	.181	.911	.615	-.128	-.459
6	SiO2_d	.824	.773	.717	.341	.138	1.000	-.655	.319	-.547	.287	.140	.481	-.908
7	SO3_d	-.640	-.563	-.772	-.540	-.390	-.655	1.000	-.480	.595	-.486	-.322	-.294	.756
8	CaO_d	.225	.249	.408	.191	.557	.319	-.480	1.000	-.365	.402	.806	-.036	-.513
9	P2O5_d	-.776	-.742	-.452	-.455	.181	-.547	.595	-.365	1.000	.111	-.151	-.423	.518
10	Al2O3_d	.089	.120	.738	.429	.911	.287	-.486	.402	.111	1.000	.433	.083	-.595
11	Na2O_d	-.040	.289	.334	.003	.615	.140	-.322	.806	-.151	.433	1.000	-.286	-.334
12	LOI_d	.680	.307	.421	.503	-.128	.481	-.294	-.036	-.423	.083	-.286	1.000	-.520
13	L600	-.778	-.707	-.905	-.538	-.459	-.908	.756	-.513	.518	-.595	-.334	-.520	1.000

Fig.3.19 **Unrotated Orthogonal Plot: Factor 1 vs. Factor 2**

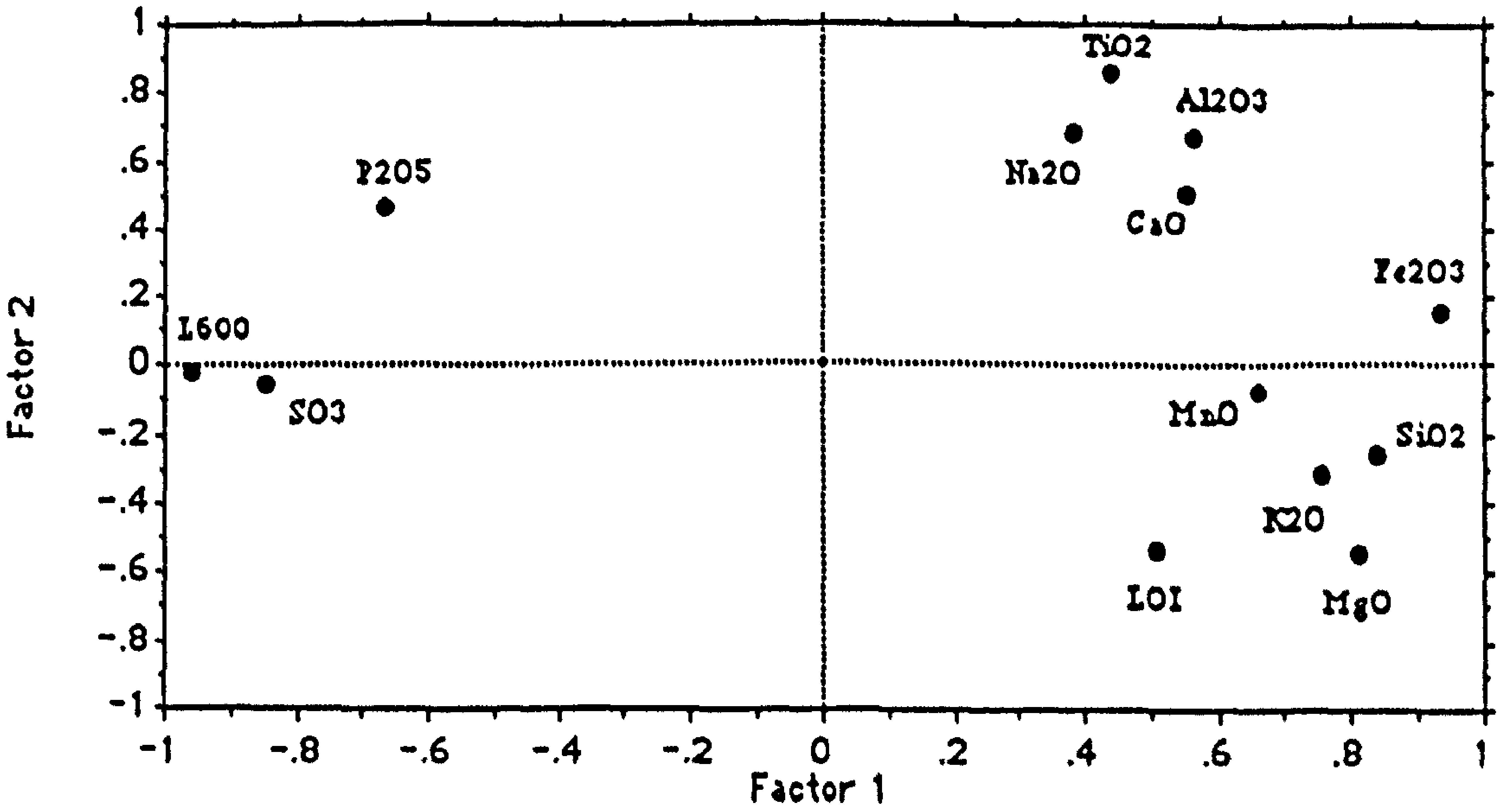
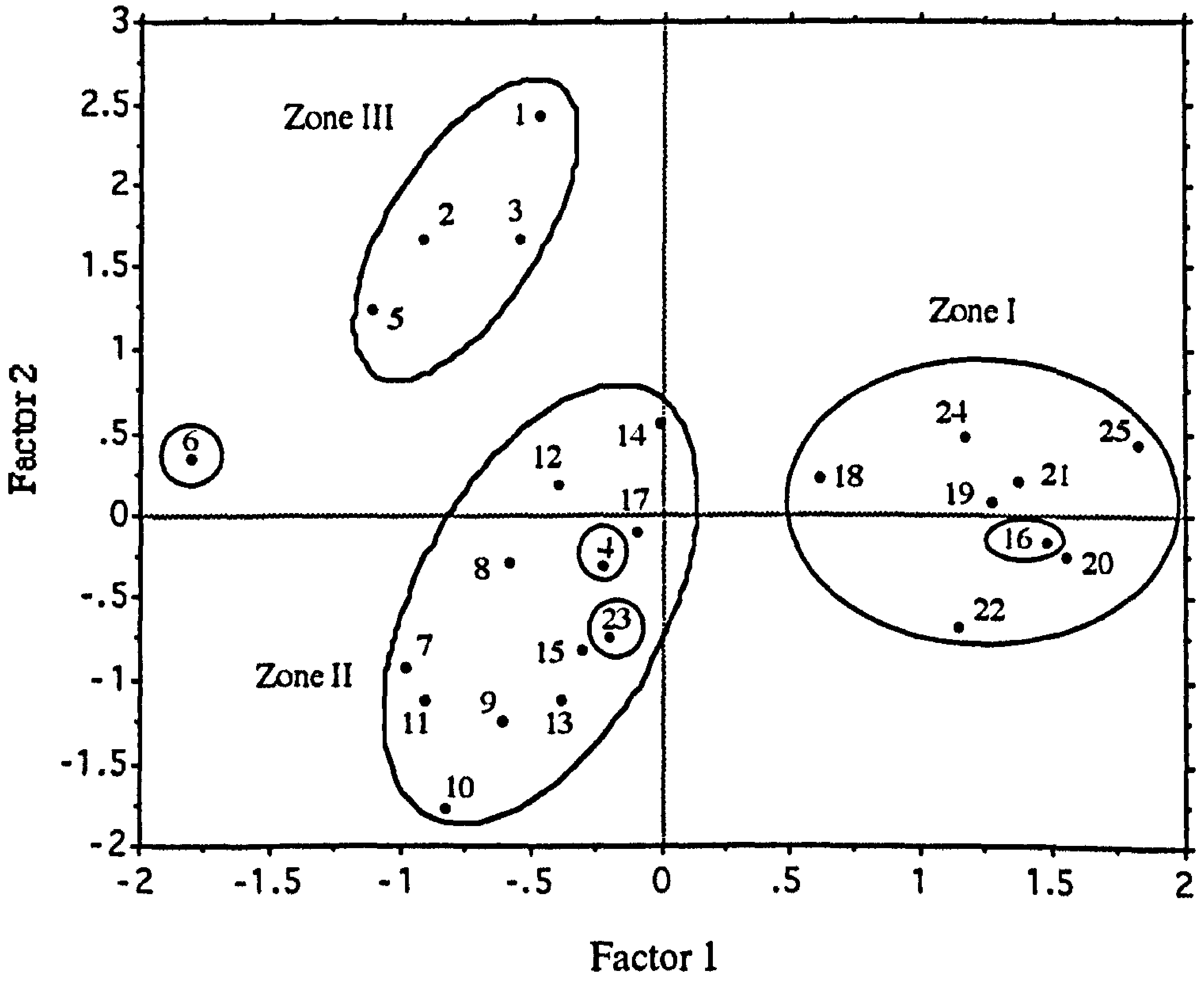


Fig.3.20 Principal components analysis of pollen data from Lake Vaihiria: Factor 1 versus factor 2. Zones VpI to III.



Key to sample depths within the identified pollen zones:

Zone VpI (5.00-3.35m):
25. 4.85m
24. 4.65m

Sub-zone VpIa (4.55-4.35):
23. 4.45m

Zone VpI (cont.)
22. 4.25m
21. 4.05m
20. 3.85m
19. 3.65m
18. 3.45m

Zone VpII (3.35-1.15):
17. 3.25m

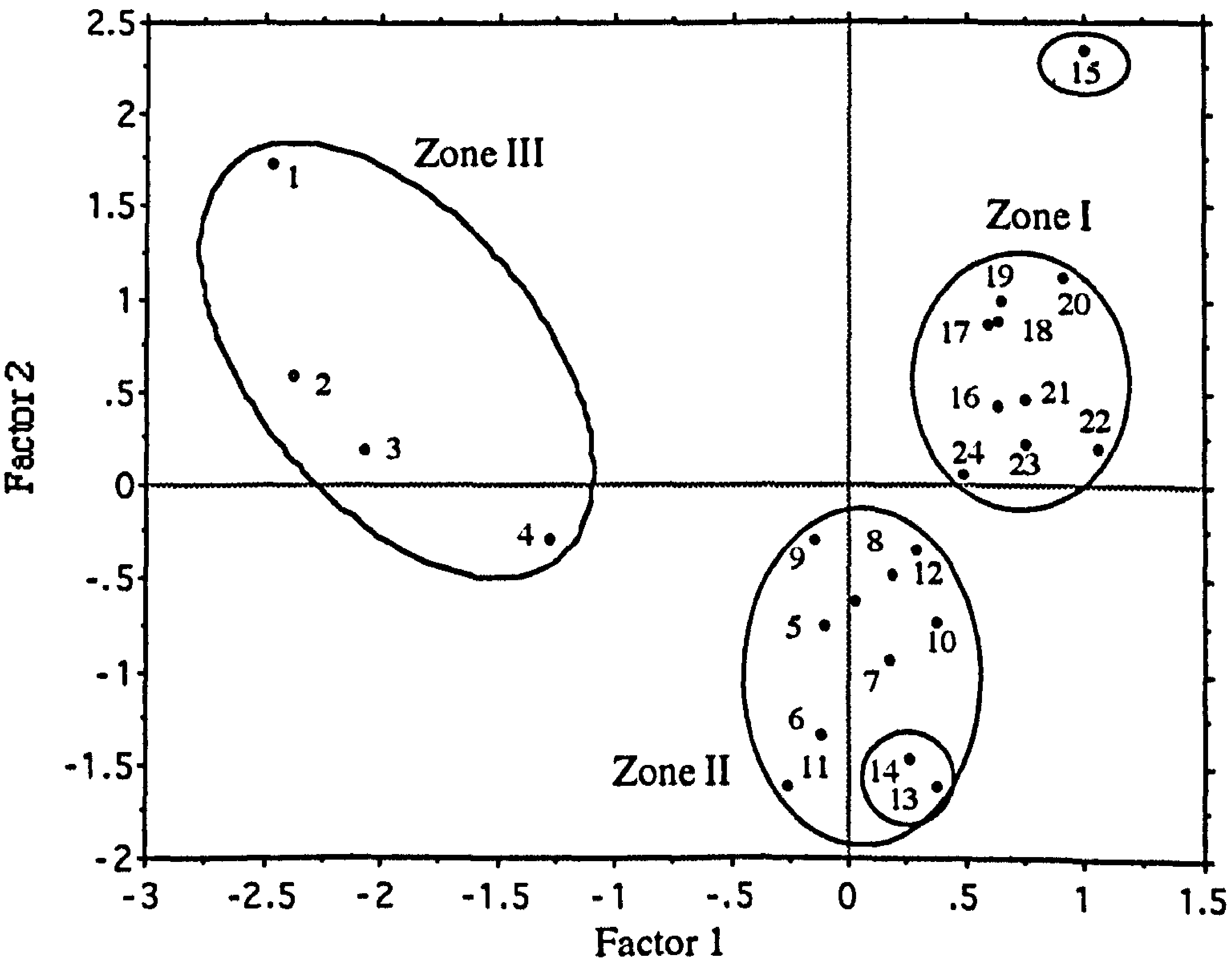
Sub-zone VpIIa (3.15-2.95):
16. 3.05m

Zone VpII (cont.)
15. 2.85m
14. 2.65m
13. 2.45m
12. 2.25m
11. 2.05m
10. 1.85m
9. 1.65m
8. 1.45m
7. 1.25m

Zone VpIII (1.15-0)
Sub-zone IIIa (1.15-0.94):
6. 1.05m
Sub-zone VpIIIb (0.74-0.54):
4. 0.64m

5. 0.84m
3. 0.44m
2. 0.24m
1. 0.04m

Fig.3.21 Principal components analysis of percentage diatom data from Lake Vaihiria: Factor 1 versus factor 2. ZonesVd1-III.



Key to sample depths within the identified diatom zones:

Zone VdI (5.00-2.75):

25.	4.85m
24.	4.65m
23.	4.45m
22.	4.25m
21.	4.05m
20.	3.85m
19.	3.65m
18.	3.45m
17.	3.25m
16.	3.05m

Sub-zone VdIa (2.95-2.75):

15.	2.85m

Zone VdII (2.75-0.74):

Sub-zone VdIIa (2.75-2.35)

14.	2.65m
13.	2.45m

12.	2.25m
11.	2.05m
10.	1.85m
9.	1.65m
8.	1.45m
7.	1.25m
6.	1.05m
5.	0.84m

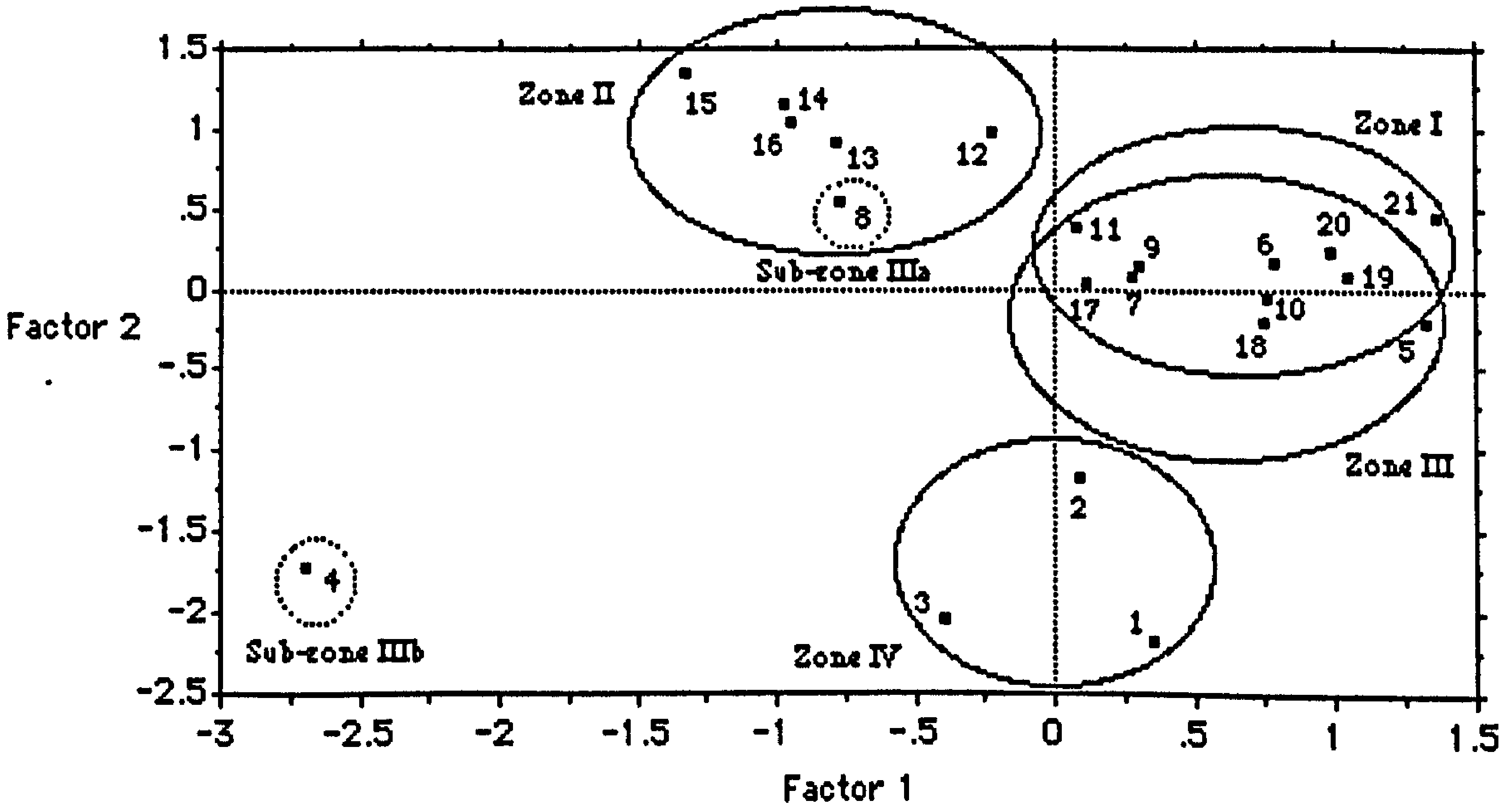
Zone VdIII (0.74-0.0)

4.	0.64m
3.	0.44m
2.	0.24m
1.	0.04m

Fig.3.22 Correlation matrix derived from Lake Lanoto'o geochemical data.

	Name	MgO_d	K2O_d	Fe2O3_d	MnO_d	TiO2_d	SiO2_d	SO3_d	CaO_d	P2O5_d	Al2O3_d	Na2O_d	LOI_d	L600
1	MgO_d	1.000	.820	.678	.763	.853	.877	.631	.497	.830	.858	.572	.837	-.858
2	K2O_d	.820	1.000	.268	.434	.557	.697	.457	.777	.786	.581	.756	.675	-.566
3	Fe2O3_d	.678	.268	1.000	.941	.923	.751	.551	-.211	.642	.918	-.103	.741	-.928
4	MnO_d	.763	.434	.941	1.000	.953	.833	.589	-.044	.754	.950	.086	.775	-.949
5	TiO2_d	.853	.557	.923	.953	1.000	.904	.653	.075	.844	.994	.176	.881	-.994
6	SiO2_d	.877	.697	.751	.833	.904	1.000	.585	.290	.840	.924	.344	.872	-.924
7	SO3_d	.631	.457	.551	.589	.653	.585	1.000	.196	.705	.647	.261	.510	-.647
8	CaO_d	.497	.777	-.211	-.044	.075	.290	.196	1.000	.397	.084	.921	.275	-.080
9	P2O5_d	.830	.786	.642	.754	.844	.840	.705	.397	1.000	.859	.416	.813	-.842
10	Al2O3_d	.858	.581	.918	.950	.994	.924	.647	.084	.859	1.000	.178	.887	-.998
11	Na2O_d	.572	.756	-.103	.086	.176	.344	.261	.921	.416	.178	1.000	.412	-.180
12	LOI_d	.837	.675	.741	.775	.881	.872	.510	.275	.813	.887	.412	1.000	-.897
13	L600	-.858	-.566	-.928	-.949	-.994	-.924	-.647	-.080	-.842	-.998	-.180	-.897	1.000

Fig.3.23 Principal components analysis of XRF data from Lake Lanoto'o: Factor 1 versus factor 2. Zones LgI to IV.



Key to sample depths within the identified geochemical zones:

Zone LgI (3.00-1.90m):
21. 2.80m
20. 2.76m
19. 2.64m
18. 2.55m
17. 1.95m

Zone LgII (1.90-1.45m):
16. 1.85m
15. 1.75m
14. 1.68m
13. 1.55m
12. 1.50m

Zone LgIII (1.45-0.55m):
11. 1.40m
10. 1.35m
9. 0.90m

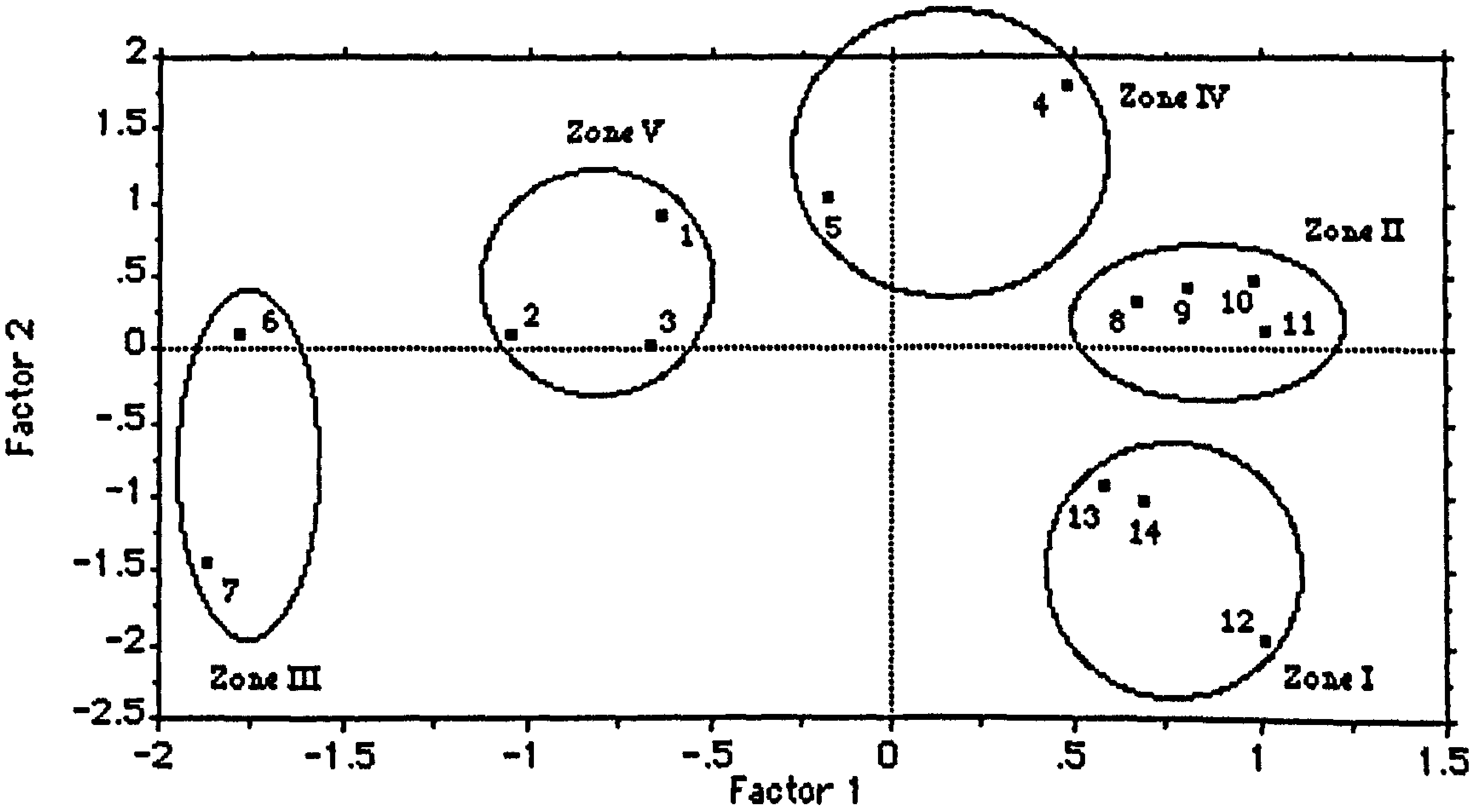
Sub-zone LgIIIa (0.87-0.82m):
8. 0.85m

7. 0.80m
6. 0.75m
5. 0.70m

Sub-zone LgIIIb (0.65-0.55m):
4. 0.60m

Zone LgIV (0.55-0.0m):
3. 0.50m
2. 0.30m
1. 0.10m

Fig.3.24 Principal components analysis of pollen and spore data from Lake Lanoto'o: Factor 1 versus factor 2. (Zones LpI to V)



Key to sample depths within the identified pollen zones:

Zone LpI (3.00-2.30m):
14. 2.95m
13. 2.70m
12. 2.55m

Zone LpII (2.30-1.15):
11. 1.95m
10. 1.75m
9. 1.55m
8. 1.35m

Zone LpIII (1.15-0.85):
7. 0.96m
6. 0.90m

Zone LpIV (0.85-0.60):
5. 0.80m
4. 0.70m

Zone LpV (0.60-0.0):
3. 0.50m
2. 0.30m
1. 0.10m

Fig.3.25 Correlation matrix derived from Lake Lanoto'o pollen data.

	Macaranga	Freycinetia	Ficus	Rapanea	Piperaceae	Morinda citr	Mimosa	Acalypha	Grewia	Triumfetta	Cyperaceae
1	.113	.251	-.060	.049	.438	.141	-.030	.071	-.653	-.058	-.100
2	.678	-.259	.640	-.039	-.027	.443	.791	.399	-.222	.885	.580
3	-.351	-.343	-.150	.212	-.497	-.503	-.169	-.163	.759	-.179	-.095
4	.161	-.251	-.265	-.415	-.281	.354	-.078	.672	.019	-.125	.019
5	.232	.857	.243	-.079	.307	.361	.212	-.228	-.127	.109	-.304
6	-.391	.209	-.440	.390	-.111	-.254	-.333	-.282	.427	-.436	-.317
7	-.298	-.005	-.005	.651	.130	-.145	.054	-.280	.644	-.067	-.219
8	.336	-.088	.001	-.207	-.349	-.183	.055	.179	.176	.305	.204
9	-.664	-.079	-.186	.441	.005	-.570	-.253	-.605	.532	-.404	-.447
10	1.000	.234	.329	-.332	.079	.604	.539	.688	-.170	.664	.255
11	.234	1.000	-.004	-.129	.347	.391	.008	-.131	-.072	-.034	-.370
12	.329	-.004	1.000	.173	.242	.170	.541	-.028	-.306	.549	.170
13	-.332	-.129	.173	1.000	.297	-.373	-.113	-.371	.363	-.193	-.305
14	.079	.347	.242	.297	1.000	.185	.164	-.327	-.297	.099	-.247
15	.604	.391	.170	-.373	.185	1.000	.720	.451	-.254	.610	.125
16	.539	.008	.541	-.113	.164	.720	1.000	.216	-.215	.918	.298
17	.688	-.131	-.028	-.371	-.327	.451	.216	1.000	-.058	.268	.161
18	-.170	-.072	-.306	.363	-.297	-.254	-.215	-.058	1.000	-.289	-.382
19	.664	-.034	.549	-.193	.099	.610	.918	.268	-.289	1.000	.559
20	.255	-.370	.170	-.305	-.247	.125	.298	.161	-.382	.559	1.000
21	.376	-.177	.258	-.465	-.383	.282	.057	.620	-.215	.038	.128
22	.539	.008	.541	-.113	.164	.720	1.000	.216	-.215	.918	.298
23	.659	-.066	.688	-.241	.010	.498	.834	.236	-.361	.951	.618
24	-.527	-.284	-.111	.220	-.051	-.449	-.210	-.292	.317	-.237	-.201
25	.222	-.129	.491	-.235	-.274	-.273	-.113	.010	-.314	.132	.488
26	-.399	-.315	-.407	.185	-.497	-.527	-.252	-.151	.474	-.260	-.094
27	-.327	.090	-.147	.169	-.141	-.120	-.141	-.216	.445	-.190	.038
28	.041	.724	-.240	-.115	.221	.197	-.230	-.261	.187	-.309	-.410
29	.112	.459	.215	-.320	.419	.077	-.104	-.160	-.192	-.140	-.192
30	-.062	.295	-.264	.382	-.061	-.175	-.176	-.270	.776	-.237	-.539
31	-.201	-.181	-.097	.637	-.045	-.278	-.152	-.234	.818	-.205	-.265
32	-.368	-.322	-.306	.136	.003	-.103	-.104	-.159	-.245	-.140	.266
33	-.583	-.363	-.311	.292	-.037	-.595	-.246	-.377	.148	-.331	-.309
34	-.357	-.167	.098	.561	-.084	-.274	-.113	-.174	.469	-.152	.006
35	-.356	-.146	-.255	.075	-.412	-.346	-.143	-.219	.770	-.192	-.224
36	.177	-.078	.265	-.213	-.448	-.459	-.256	.062	-.064	-.071	.096
37	-.369	-.117	-.203	-.074	.209	.163	-.134	-.225	-.141	-.175	.125
38	.039	-.252	.189	-.371	-.232	.088	.100	-.067	.062	.202	.403
39	-.518	-.170	-.316	.306	-.115	-.340	-.033	-.449	.546	-.133	-.173
40	-.094	.038	-.226	-.066	-.290	-.274	-.138	-.050	.547	-.147	-.408
41	.053	-.195	-.157	-.432	-.158	.374	-.023	.330	-.201	.005	.312
42	.315	.659	.056	-.248	.013	.496	.089	.055	-.274	.098	.074
43	.817	.575	.360	-.492	.173	.684	.468	.405	-.395	.581	.318
44	.055	-.133	.363	.255	.174	.028	.449	-.071	-.038	.432	-.036
45	.055	.096	-.047	-.344	.152	.167	-.174	.136	.089	-.254	-.303
46	.391	-.212	-.122	-.414	-.339	.350	-.037	.747	.100	-.025	.097
47	.224	.193	.069	-.358	-.111	-.002	-.074	.137	-.232	.174	.253
48	-.588	-.067	-.170	.057	.218	-.134	-.314	-.415	.050	-.320	.097
49	.211	.593	-.071	-.280	.591	.182	-.122	-.084	-.092	-.129	-.261

	Name	Pandanus	Urt/Mor	Trema	Euphorb	Weinmannia	Elaeocarp	Myrtaceae	Neonauclea	Araliaceae
1	Pandanus%	1.000	-.133	-.665	-.148	.187	-.044	-.318	-.389	-.262
2	Urt/Mor%	-.133	1.000	-.147	-.031	-.018	-.366	-.081	.265	-.461
3	Trema/para%	-.665	-.147	1.000	-.193	-.304	.353	.628	.277	.720
4	EuphorbA %	-.148	-.031	-.193	1.000	-.433	-.350	-.332	-.100	-.510
5	Weinmannia%	.187	-.018	-.304	-.433	1.000	.201	-.009	-.161	.038
6	Elaeocarp%	-.044	-.366	.353	-.350	.201	1.000	.542	-.201	.511
7	Myrtaceae%	-.318	-.081	.628	-.332	-.009	.542	1.000	-.224	.675
8	Neonauclea%	-.389	.265	.277	-.100	-.161	-.201	-.224	1.000	-.088
9	Araliaceae%	-.262	-.461	.720	-.510	.038	.511	.675	-.088	1.000
10	Macaranga%	.113	.678	-.351	.161	.232	-.391	-.298	.336	-.664
11	Freycinetia%	.251	-.259	-.343	-.251	.857	.209	-.005	-.088	-.079
12	Ficus%	-.060	.640	-.150	-.265	.243	-.440	-.005	.001	-.186
13	Rapanea%	.049	-.039	.212	-.415	-.079	.390	.651	-.207	.441
14	Piperaceae%	.438	-.027	-.497	-.281	.307	-.111	.130	-.349	.005
15	Morindacitr%	.141	.443	-.503	.354	.361	-.254	-.145	-.183	-.570
16	Mimosa%	-.030	.791	-.169	-.078	.212	-.333	.054	.055	-.253
17	Acalypha%	.071	.399	-.163	.672	-.228	-.282	-.280	.179	-.605
18	Grewia%	-.653	-.222	.759	.019	-.127	.427	.644	.176	.532
19	Triumfetta %	-.058	.885	-.179	-.125	.109	-.436	-.067	.305	-.404
20	Cyperaceae%	-.100	.580	-.095	.019	-.304	-.317	-.219	.204	-.447
21	Gramin%	-.069	.277	-.280	.663	-.075	-.442	-.563	-.118	-.613
22	Gardenia%	-.030	.791	-.169	-.078	.212	-.333	.054	.055	-.253
23	Cocos%	-.093	.915	-.193	-.156	.138	-.486	-.196	.303	-.465
24	Celtis%	-.418	-.267	.604	-.113	-.395	.345	.470	.196	.581
25	Euphorb hirt%	-.130	.333	-.082	-.147	.014	-.306	-.462	.263	-.370
26	Alphitonia%	-.149	-.308	.712	-.250	-.267	.239	.336	.231	.661
27	Procris%	-.257	-.272	.593	-.183	.017	.430	.737	-.366	.501
28	Ascarina%	-.028	-.362	-.272	-.075	.686	.340	-.096	-.173	-.039
29	Morinda%	.038	-.177	-.263	-.054	.577	-.231	-.178	-.270	.019
30	Guioa%	-.367	-.250	.388	-.267	.246	.459	.360	.303	.397
31	Disoxyl%	-.465	-.098	.476	-.064	-.177	.180	.555	.041	.390
32	Coprosma%	.139	.008	-.237	.034	-.139	.303	-.069	-.269	.026
33	Palmae%	.168	-.420	.476	-.367	-.345	.259	.273	.034	.722
34	Ixora%	-.240	-.119	.589	-.164	-.201	.230	.811	-.294	.505
35	Nympha%	-.764	-.227	.903	-.123	-.158	.452	.565	.331	.683
36	Mono%	-.154	.131	.157	-.225	.075	-.085	-.440	.512	-.087
37	Tril%	-.068	-.262	-.345	.478	-.281	-.304	-.165	-.347	-.238
38	Cyath%	-.662	.245	.017	.348	-.206	-.450	-.314	.246	-.322
39	Polypod%	-.473	-.197	.679	-.359	-.053	.558	.631	.153	.817
40	Angiopt%	-.574	-.188	.543	-.051	.022	.198	.121	.671	.443
41	Gleich%	-.148	.027	-.403	.827	-.348	-.482	-.472	-.122	-.634
42	Aspleniac%	.248	.061	-.518	-.032	.598	.210	-.291	-.213	-.520
43	Acrost%	.182	.487	-.499	.017	.566	-.287	-.327	.090	-.647
44	Marrat%	-.203	.413	.131	-.274	-.031	.056	.213	.431	.185
45	Cyclo/Hypo%	-.328	-.185	-.234	.601	.067	-.321	-.320	-.068	-.215
46	Alsophil%	-.224	.147	-.179	.922	-.322	-.402	-.376	.003	-.609
47	Pteris spp%	-.210	.113	-.103	.053	-.024	-.108	-.335	.663	-.348
48	Lycop ph%	-.269	-.419	.085	.202	-.267	.018	.284	-.352	.180
49	Lyco cer%	.154	-.276	-.302	-.030	.530	-.121	-.064	-.179	.006

	Gramin	Gardenia	Cocos	Celtis	Euphorb hirt	Alphitonia	Procris	Ascarina	Morinda sp	Guioa	Disoxyl	Coprosma
1	-.069	-.030	-.093	-.418	-.130	-.149	-.257	-.028	.038	-.367	-.465	.139
2	.277	.791	.915	-.267	.333	-.308	-.272	-.362	-.177	-.250	-.098	.008
3	-.280	-.169	-.193	.604	-.082	.712	.593	-.272	-.263	.388	.476	-.237
4	.663	-.078	-.156	-.113	-.147	-.250	-.183	-.075	-.054	-.267	-.064	.034
5	-.075	.212	.138	-.395	.014	-.267	.017	.686	.577	.246	-.177	-.139
6	-.442	-.333	-.486	.345	-.306	.239	.430	.340	-.231	.459	.180	.303
7	-.563	.054	-.196	.470	-.462	.336	.737	-.096	-.178	.360	.555	-.069
8	-.118	.055	.303	.196	.263	.231	-.366	-.173	-.270	.303	.041	-.269
9	-.613	-.253	-.465	.581	-.370	.661	.501	-.039	.019	.397	.390	.026
10	.376	.539	.659	-.527	.222	-.399	-.327	.041	.112	-.062	-.201	-.368
11	-.177	.008	-.066	-.284	-.129	-.315	.090	.724	.459	.295	-.181	-.322
12	.258	.541	.688	-.111	.491	-.407	-.147	-.240	.215	-.264	-.097	-.306
13	-.465	-.113	-.241	.220	-.235	.185	.169	-.115	-.320	.382	.637	.136
14	-.383	.164	.010	-.051	-.274	-.497	-.141	.221	.419	-.061	-.045	.003
15	.282	.720	.498	-.449	-.273	-.527	-.120	.197	.077	-.175	-.278	-.103
16	.057	1.000	.834	-.210	-.113	-.252	-.141	-.230	-.104	-.176	-.152	-.104
17	.620	.216	.236	-.292	.010	-.151	-.216	-.261	-.160	-.270	-.234	-.159
18	-.215	-.215	-.361	.317	-.314	.474	.445	.187	-.192	.776	.818	-.245
19	.038	.918	.951	-.237	.132	-.260	-.190	-.309	-.140	-.237	-.205	-.140
20	.128	.298	.618	-.201	.488	-.094	.038	-.410	-.192	-.539	-.265	.266
21	1.000	.057	.215	-.441	.467	-.369	-.290	4.770E-4	.205	-.359	-.235	-.107
22	.057	1.000	.834	-.210	-.113	-.252	-.141	-.230	-.104	-.176	-.152	-.104
23	.215	.834	1.000	-.297	.418	-.326	-.224	-.280	-.045	-.296	-.257	-.175
24	-.441	-.210	-.297	1.000	-.232	.224	.271	-.327	-.284	.094	.051	-.027
25	.467	-.113	.418	-.232	1.000	-.236	-.169	-.048	.200	-.258	-.223	-.152
26	-.369	-.252	-.326	.224	-.236	1.000	.354	-.339	-.341	.283	.358	-.007
27	-.290	-.141	-.224	.271	-.169	.354	1.000	-.025	.033	.052	.244	-.190
28	4.770E-4	-.230	-.280	-.327	-.048	-.339	-.025	1.000	.493	.536	.135	-.027
29	.205	-.104	-.045	-.284	.200	-.341	.033	.493	1.000	-.140	-.206	-.140
30	-.359	-.176	-.296	.094	-.258	.283	.052	.536	-.140	1.000	.711	-.237
31	-.235	-.152	-.257	.051	-.223	.358	.244	.135	-.206	.711	1.000	-.099
32	-.107	-.104	-.175	-.027	-.152	-.007	-.190	-.027	-.140	-.237	-.099	1.000
33	-.543	-.246	-.414	.535	-.360	.714	.133	-.422	-.333	.095	.077	.066
34	-.284	-.113	-.191	.289	-.166	.427	.812	-.338	-.153	.041	.495	-.153
35	-.327	-.143	-.241	.711	-.209	.508	.477	-.011	-.193	.515	.391	-.193
36	.362	-.256	.177	-.069	.808	.096	-.287	.009	.109	.076	-.161	-.241
37	.068	-.134	-.219	-.053	-.187	-.314	-.063	.130	.051	-.194	.130	.299
38	.396	.100	.321	-.035	.446	-.313	-.166	.122	.128	-.018	.153	-.028
39	-.651	-.033	-.267	.630	-.470	.560	.344	-.053	-.198	.412	.349	.313
40	-.227	-.138	-.204	.518	-.190	.369	-.140	.116	-.059	.587	.225	-.185
41	.555	-.023	.016	-.262	.054	-.409	-.244	.044	.003	-.336	-.071	.195
42	.253	.089	.184	-.506	.260	-.549	-.029	.640	.136	.062	-.295	-.059
43	.321	.468	.624	-.567	.323	-.575	-.111	.300	.401	-.218	-.456	-.311
44	-.355	.449	.344	.559	-.168	-.083	-.312	-.347	-.300	.057	-.099	.093
45	.472	-.174	-.215	-.072	-.013	-.455	-.312	.445	.573	.055	.063	-.019
46	.799	-.037	.008	-.330	.093	-.281	-.209	.029	.042	-.152	.052	-.085
47	-.015	-.074	.214	.325	.348	-.332	-.300	-.010	-.068	-.084	-.423	-.147
48	-.225	-.314	-.356	.427	-.165	-.160	.435	.020	.147	-.210	.101	.171
49	-.076	-.122	-.162	-.230	-.120	-.316	.051	.551	.872	.008	-.150	-.164

	Palmae	Ixora	Nympha	Monolete	Trilete	Cyath	Polypod	Angiopt	Gleich	Aspleniac	Acrost	Marrat
1	.168	-.240	-.764	-.154	-.068	-.662	-.473	-.574	-.148	.248	.182	-.203
2	-.420	-.119	-.227	.131	-.262	.245	-.197	-.188	.027	.061	.487	.413
3	.476	.589	.903	.157	-.345	.017	.679	.543	-.403	-.518	-.499	.131
4	-.367	-.164	-.123	-.225	.478	.348	-.359	-.051	.827	-.032	.017	-.274
5	-.345	-.201	-.158	.075	-.281	-.206	-.053	.022	-.348	.598	.566	-.031
6	.259	.230	.452	-.085	-.304	-.450	.558	.198	-.482	.210	-.287	.056
7	.273	.811	.565	-.440	-.165	-.314	.631	.121	-.472	-.291	-.327	.213
8	.034	-.294	.331	.512	-.347	.246	.153	.671	-.122	-.213	.090	.431
9	.722	.505	.683	-.087	-.238	-.322	.817	.443	-.634	-.520	-.647	.185
10	-.583	-.357	-.356	.177	-.369	.039	-.518	-.094	.053	.315	.817	.055
11	-.363	-.167	-.146	-.078	-.117	-.252	-.170	.038	-.195	.659	.575	-.133
12	-.311	.098	-.255	.265	-.203	.189	-.316	-.226	-.157	.056	.360	.363
13	.292	.561	.075	-.213	-.074	-.371	.306	-.066	-.432	-.248	-.492	.255
14	-.037	-.084	-.412	-.448	.209	-.232	-.115	-.290	-.158	.013	.173	.174
15	-.595	-.274	-.346	-.459	.163	.088	-.340	-.274	.374	.496	.684	.028
16	-.246	-.113	-.143	-.256	-.134	.100	-.033	-.138	-.023	.089	.468	.449
17	-.377	-.174	-.219	.062	-.225	-.067	-.449	-.050	.330	.055	.405	-.071
18	.148	.469	.770	-.064	-.141	.062	.546	.547	-.201	-.274	-.395	-.038
19	-.331	-.152	-.192	-.071	-.175	.202	-.133	-.147	.005	.098	.581	.432
20	-.309	.006	-.224	.096	.125	.403	-.173	-.408	.312	.074	.318	-.036
21	-.543	-.284	-.327	.362	.068	.396	-.651	-.227	.555	.253	.321	-.355
22	-.246	-.113	-.143	-.256	-.134	.100	-.033	-.138	-.023	.089	.468	.449
23	-.414	-.191	-.241	.177	-.219	.321	-.267	-.204	.016	.184	.624	.344
24	.535	.289	.711	-.069	-.053	-.035	.630	.518	-.262	-.506	-.567	.559
25	-.360	-.166	-.209	.808	-.187	.446	-.470	-.190	.054	.260	.323	-.168
26	.714	.427	.508	.096	-.314	-.313	.560	.369	-.409	-.549	-.575	-.083
27	.133	.812	.477	-.287	-.063	-.166	.344	-.140	-.244	-.029	-.111	-.312
28	-.422	-.338	-.011	.009	.130	.122	-.053	.116	.044	.640	.300	-.347
29	-.333	-.153	-.193	.109	.051	.128	-.198	-.059	.003	.136	.401	-.300
30	.095	.041	.515	.076	-.194	-.018	.412	.587	-.336	.062	-.218	.057
31	.077	.495	.391	-.161	.130	.153	.349	.225	-.071	-.295	-.456	-.099
32	.066	-.153	-.193	-.241	.299	-.028	.313	-.185	.195	-.059	-.311	.093
33	1.000	.210	.364	-.034	-.227	-.485	.535	.277	-.527	-.634	-.736	.209
34	.210	1.000	.347	-.293	-.024	-.210	.307	-.159	-.242	-.333	-.339	-.111
35	.364	.347	1.000	.074	-.232	.132	.771	.737	-.306	-.366	-.428	.267
36	-.034	-.293	.074	1.000	-.540	.179	-.215	.280	-.255	.095	.125	-.017
37	-.227	-.024	-.232	-.540	1.000	.519	-.140	-.308	.797	.019	-.213	-.273
38	-.485	-.210	.132	.179	.519	1.000	-.117	.093	.645	.059	.088	-.076
39	.535	.307	.771	-.215	-.140	-.117	1.000	.596	-.424	-.480	-.556	.445
40	.277	-.159	.737	.280	-.308	.093	.596	1.000	-.263	-.360	-.273	.467
41	-.527	-.242	-.306	-.255	.797	.645	-.424	-.263	1.000	.155	.092	-.336
42	-.634	-.333	-.366	.095	.019	.059	-.480	-.360	.155	1.000	.647	-.321
43	-.736	-.339	-.428	.125	-.213	.088	-.556	-.273	.092	.647	1.000	-.102
44	.209	-.111	.267	-.017	-.273	-.076	.445	.467	-.336	-.321	-.102	1.000
45	-.438	-.362	-.012	-.036	.469	.537	-.169	.238	.576	-.011	.072	-.152
46	-.554	-.185	-.163	.003	.311	.439	-.484	-.070	.762	.078	.200	-.379
47	-.268	-.375	.100	.358	-.059	.277	-.098	.374	.131	.178	.312	.419
48	-.031	.388	.175	-.495	.744	.343	.189	-.156	.421	-.146	-.306	-.129
49	-.270	-.179	-.171	-.156	.077	-.059	-.118	.010	-.027	.117	.427	-.257

	Cyclo/Hypo	Alsophil	Pteris spp	Lycop ph	Lyco cer
1	-.328	-.224	-.210	-.269	.154
2	-.185	.147	.113	-.419	-.276
3	-.234	-.179	-.103	.085	-.302
4	.601	.922	.053	.202	-.030
5	.067	-.322	-.024	-.267	.530
6	-.321	-.402	-.108	.018	-.121
7	-.320	-.376	-.335	.284	-.064
8	-.068	.003	.663	-.352	-.179
9	-.215	-.609	-.348	.180	.006
10	.055	.391	.224	-.588	.211
11	.096	-.212	.193	-.067	.593
12	-.047	-.122	.069	-.170	-.071
13	-.344	-.414	-.358	.057	-.280
14	.152	-.339	-.111	.218	.591
15	.167	.350	-.002	-.134	.182
16	-.174	-.037	-.074	-.314	-.122
17	.136	.747	.137	-.415	-.084
18	.089	.100	-.232	.050	-.092
19	-.254	-.025	.174	-.320	-.129
20	-.303	.097	.253	.097	-.261
21	.472	.799	-.015	-.225	-.076
22	-.174	-.037	-.074	-.314	-.122
23	-.215	.008	.214	-.356	-.162
24	-.072	-.330	.325	.427	-.230
25	-.013	.093	.348	-.165	-.120
26	-.455	-.281	-.332	-.160	-.316
27	-.312	-.209	-.300	.435	.051
28	.445	.029	-.010	.020	.551
29	.573	.042	-.068	.147	.872
30	.055	-.152	-.084	-.210	.008
31	.063	.052	-.423	.101	-.150
32	-.019	-.085	-.147	.171	-.164
33	-.438	-.554	-.268	-.031	-.270
34	-.362	-.185	-.375	.388	-.179
35	-.012	-.163	.100	.175	-.171
36	-.036	.003	.358	-.495	-.156
37	.469	.311	-.059	.744	.077
38	.537	.439	.277	.343	-.059
39	-.169	-.484	-.098	.189	-.118
40	.238	-.070	.374	-.156	.010
41	.576	.762	.131	.421	-.027
42	-.011	.078	.178	-.146	.117
43	.072	.200	.312	-.306	.427
44	-.152	-.379	.419	-.129	-.257
45	1.000	.608	.103	.289	.512
46	.608	1.000	.025	-.005	.012
47	.103	.025	1.000	.084	.005
48	.289	-.005	.084	1.000	.176
49	.512	.012	.005	.176	1.000

Fig.3.26 Age-depth profile and zones for the Lake Lanoto'o sediment sequence.

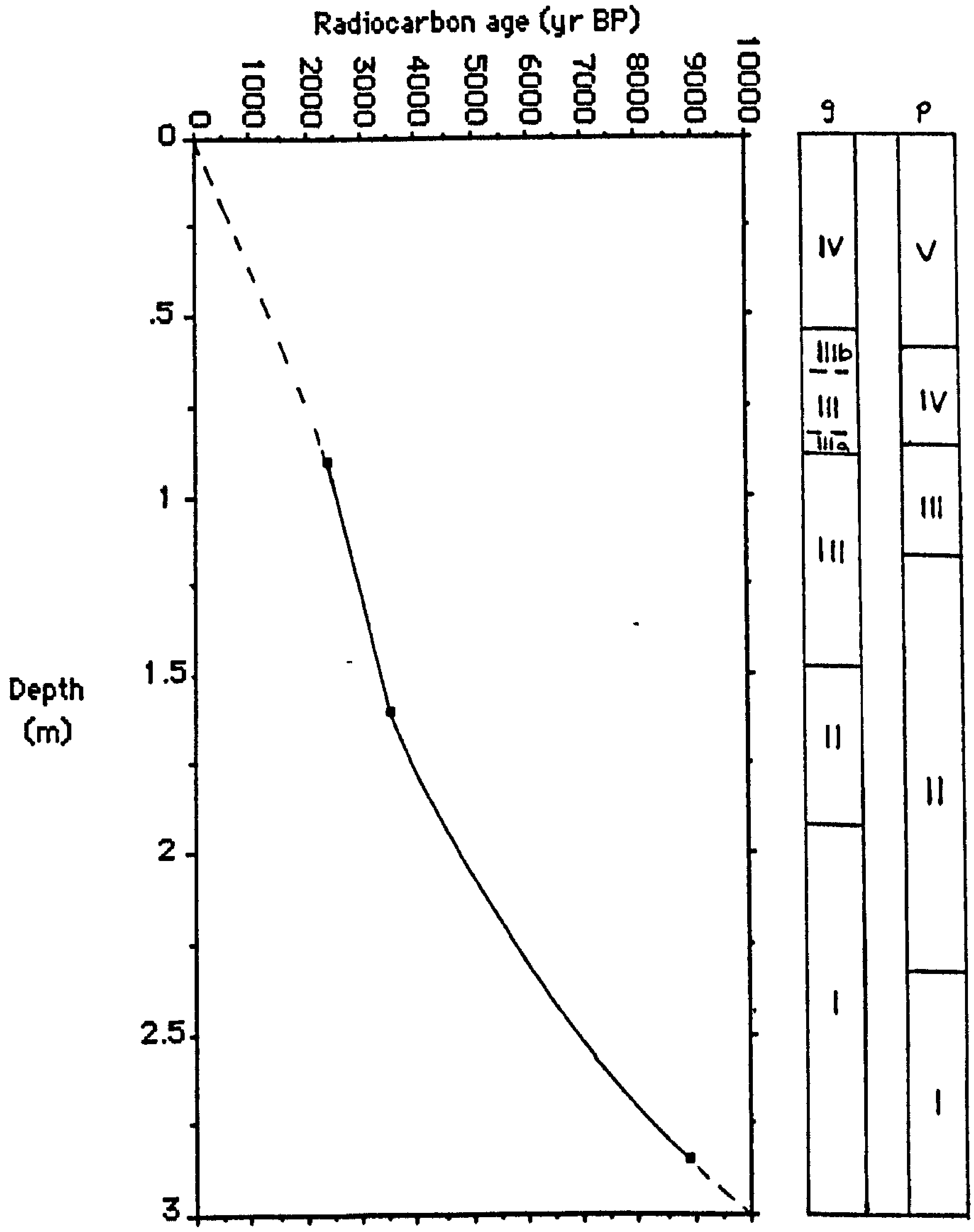


Fig.3.27 Age-depth profile and zones for the Lake Roto sediment sequence.

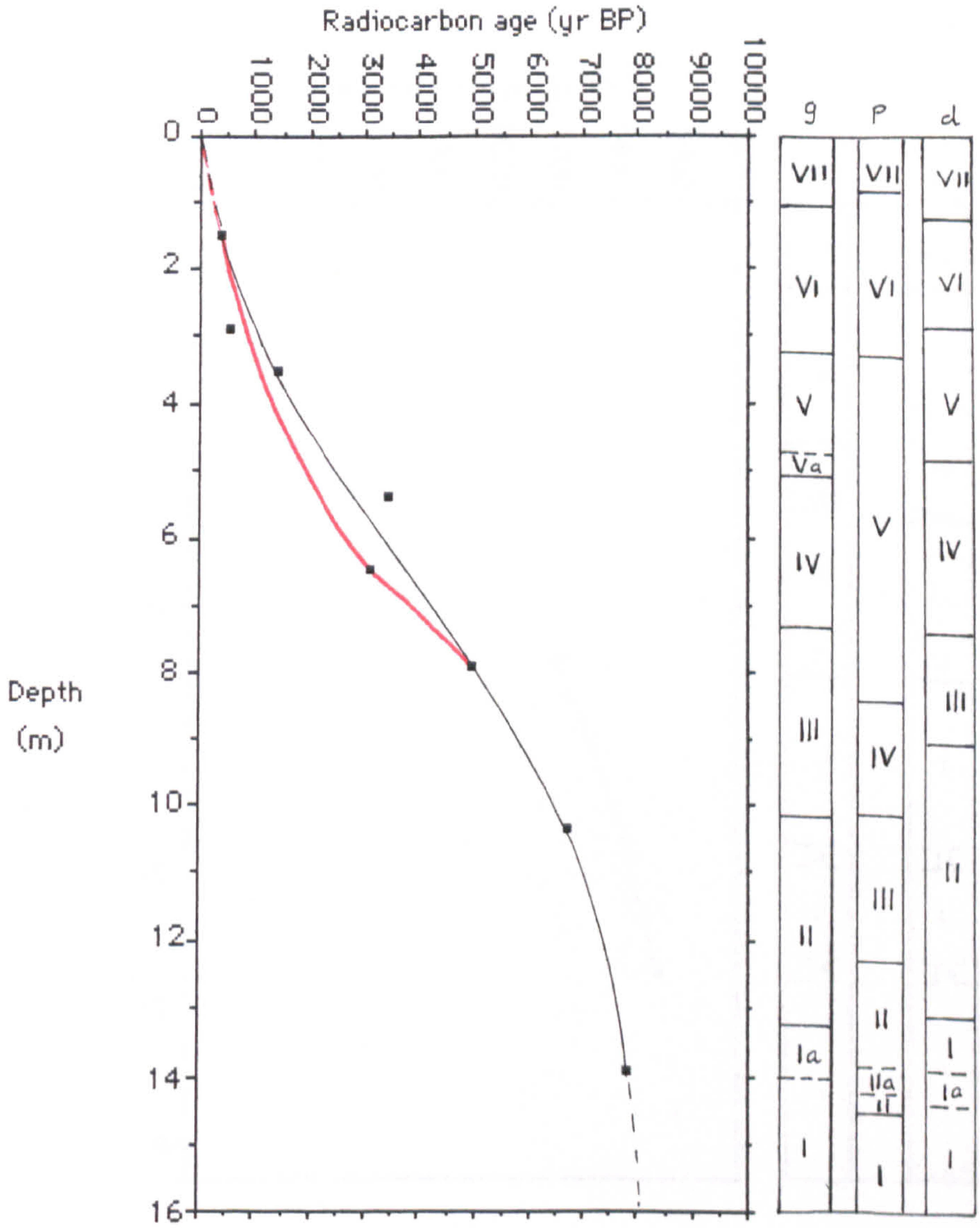


Fig.3.28 Age-depth profile and zones for the Lake Temae sediment sequence.

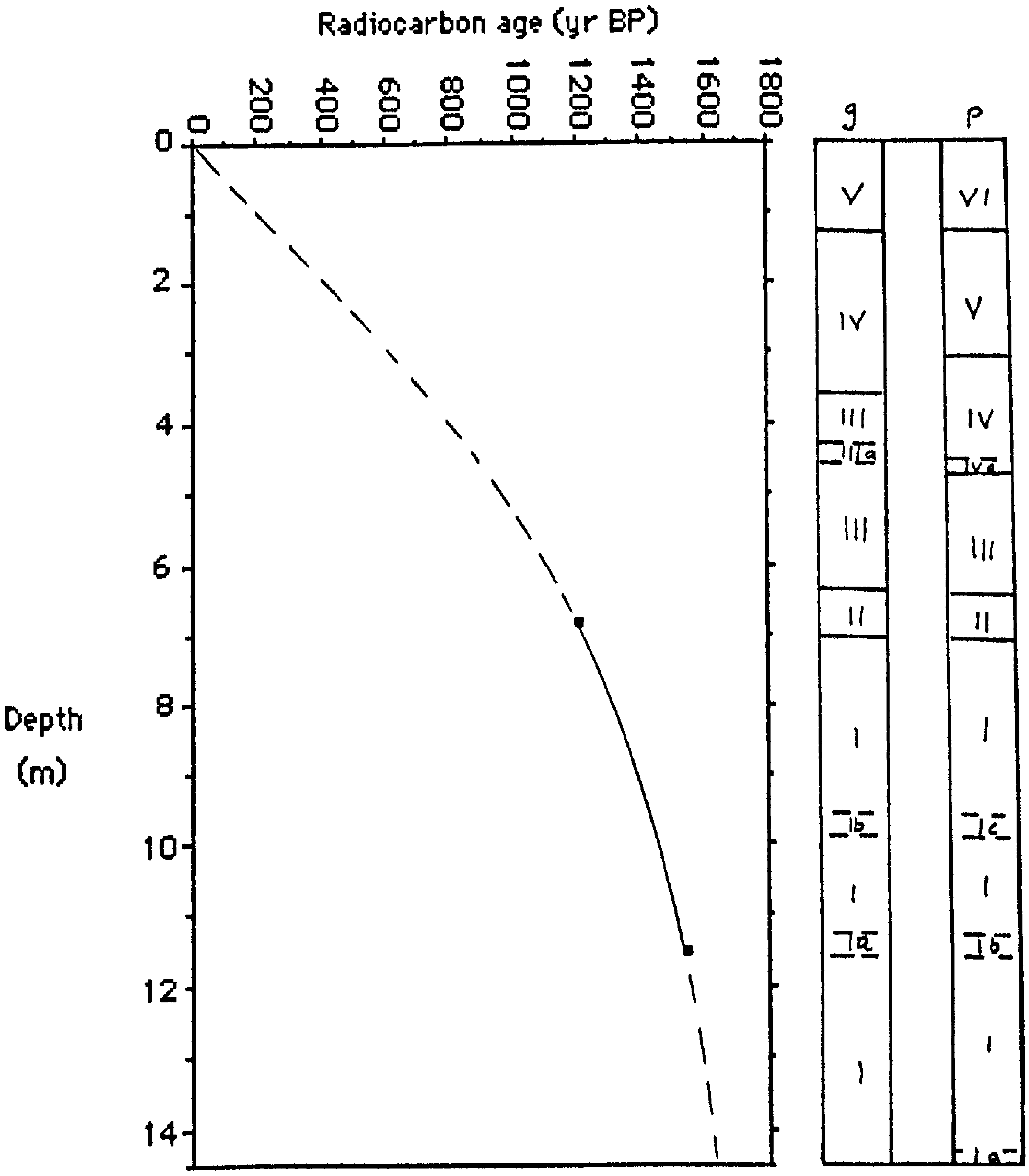


Fig.3.29 Age-depth profile and zones for the Lake Vaihiria sediment sequence.

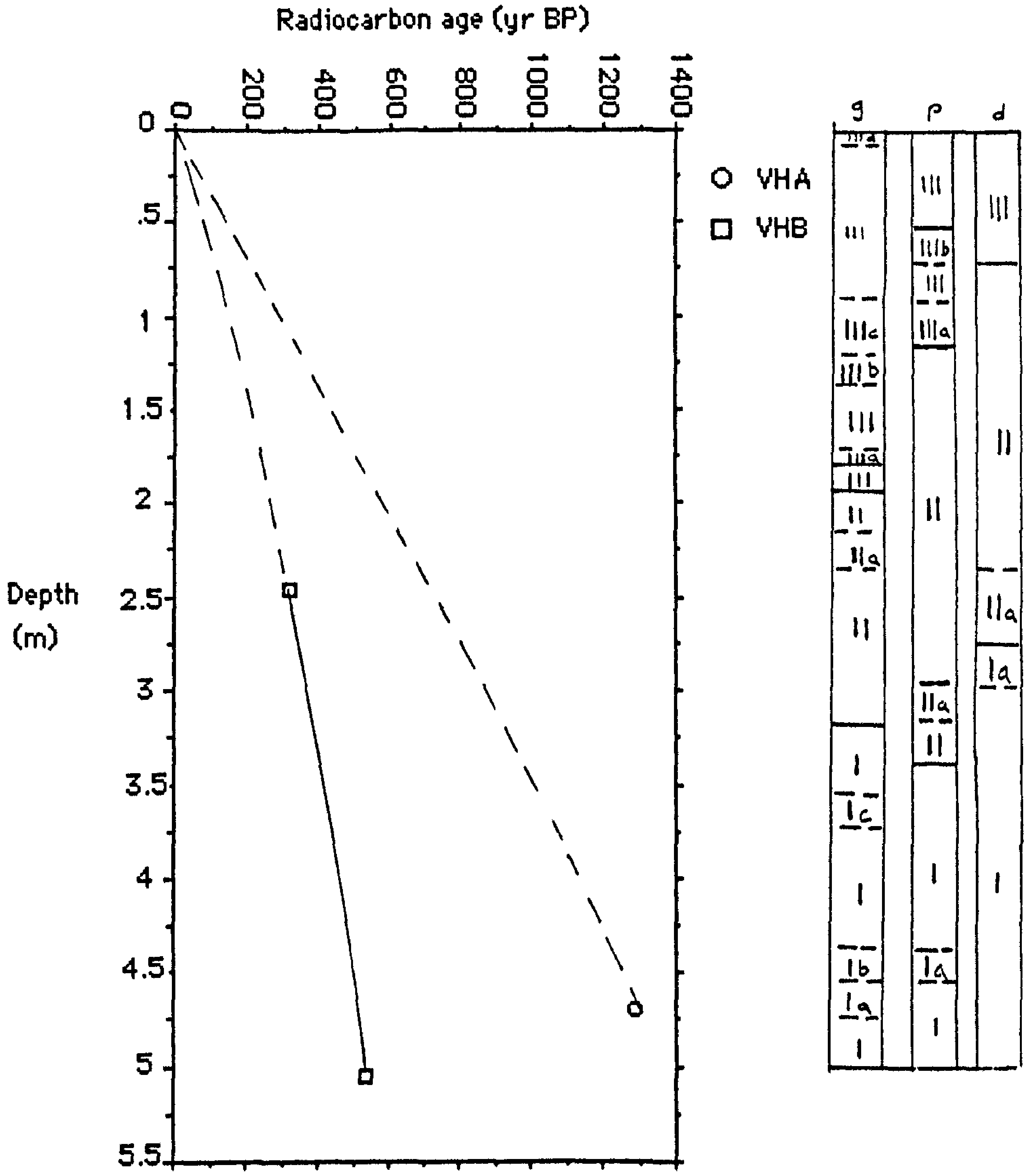


Fig.3.30 Age-depth profile for the Lake Rotonui (Miti'aro) sediment sequence.

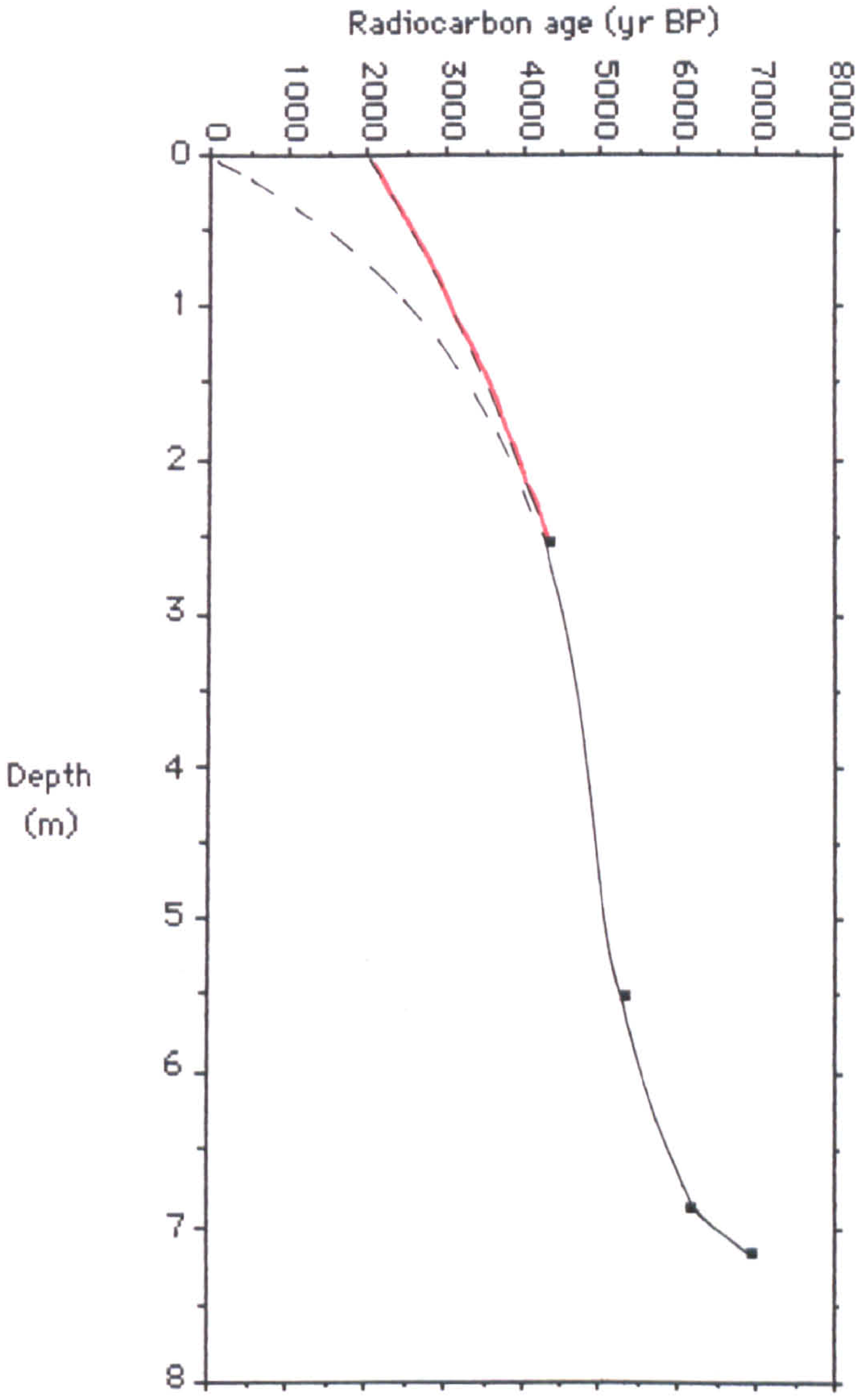
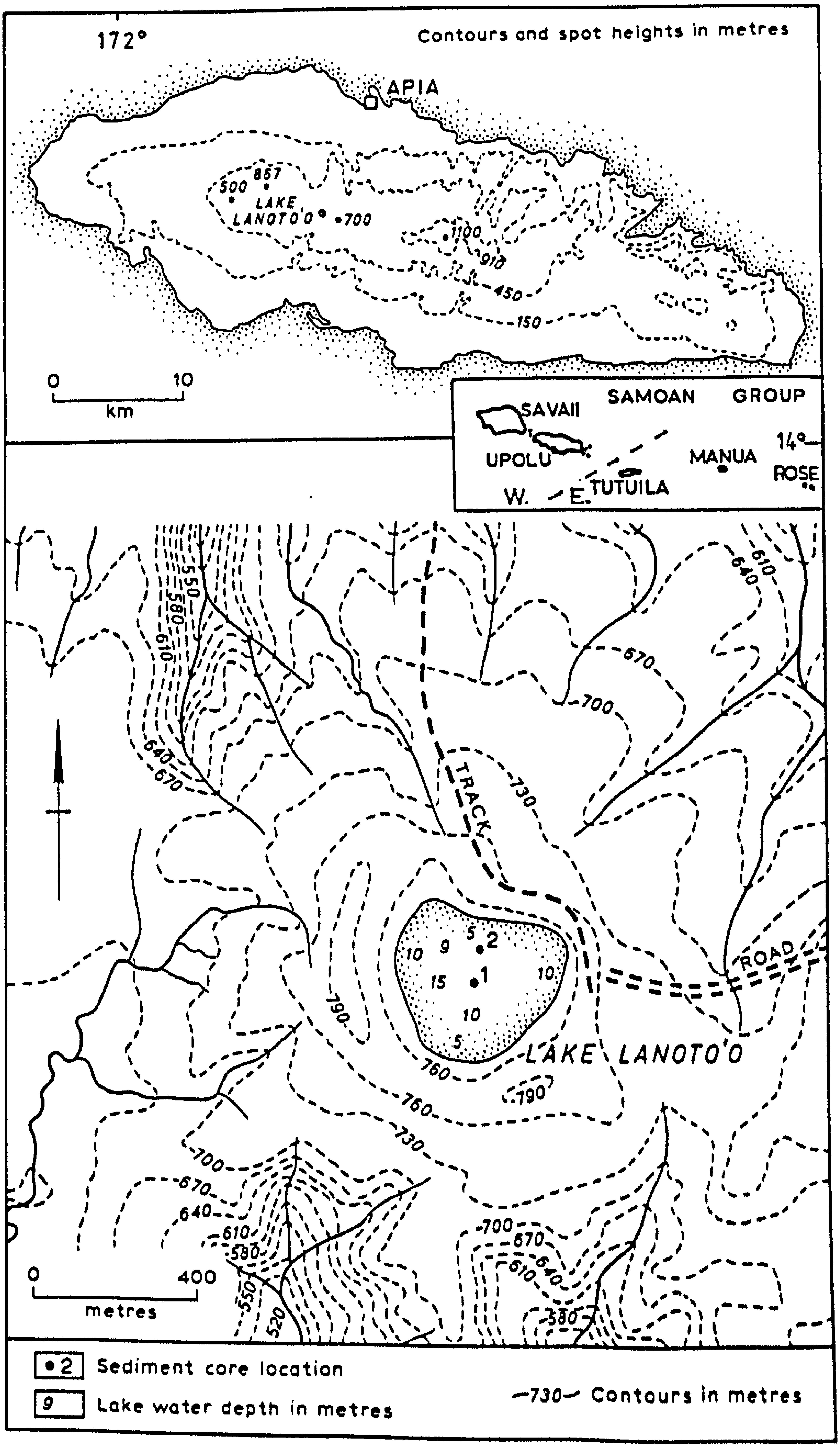


Fig.4.1 The island of Upolu and location of Lake Lanoto'o. Bathymetry of Lake Lanoto'o and position of core sites.



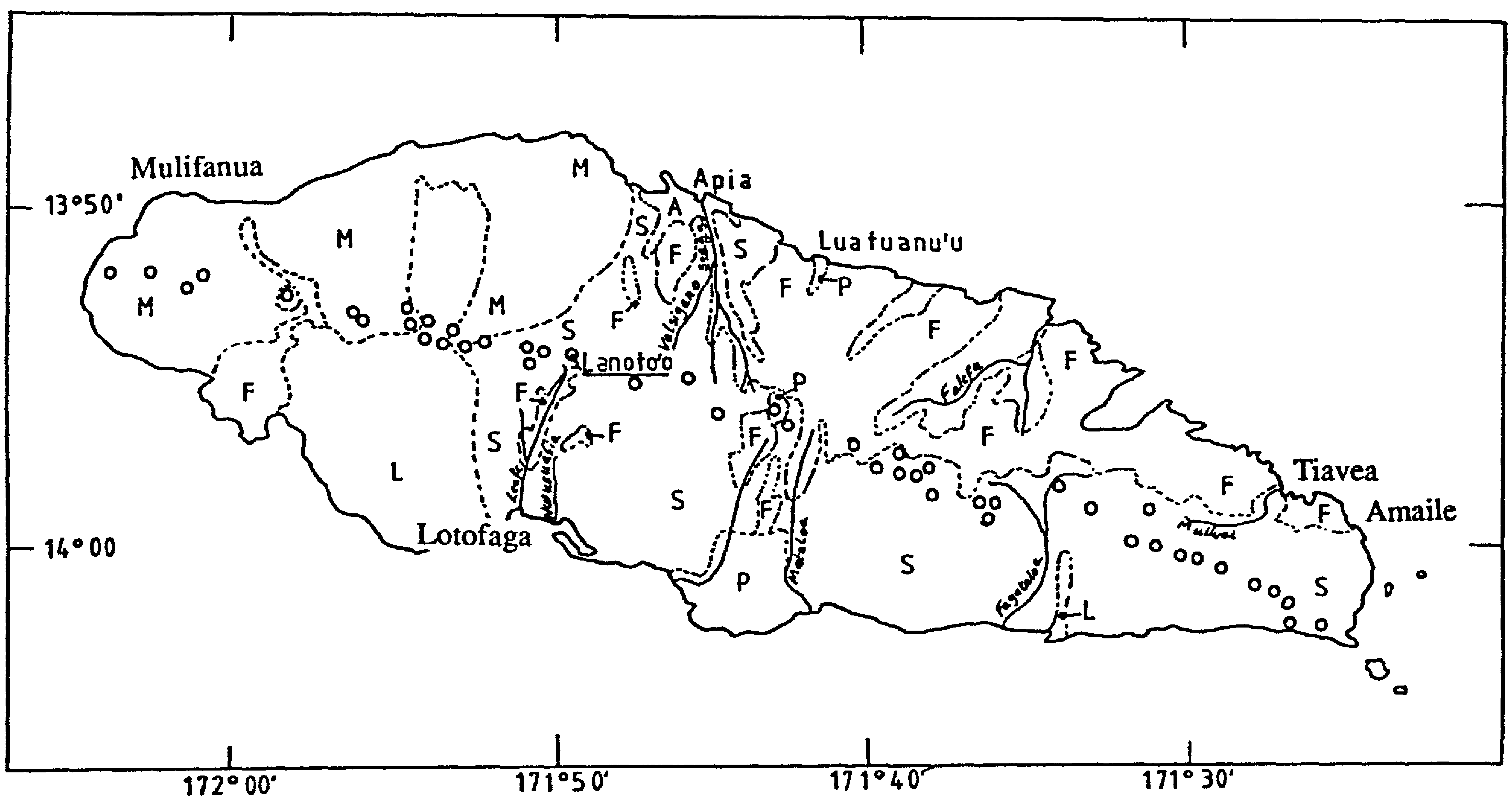


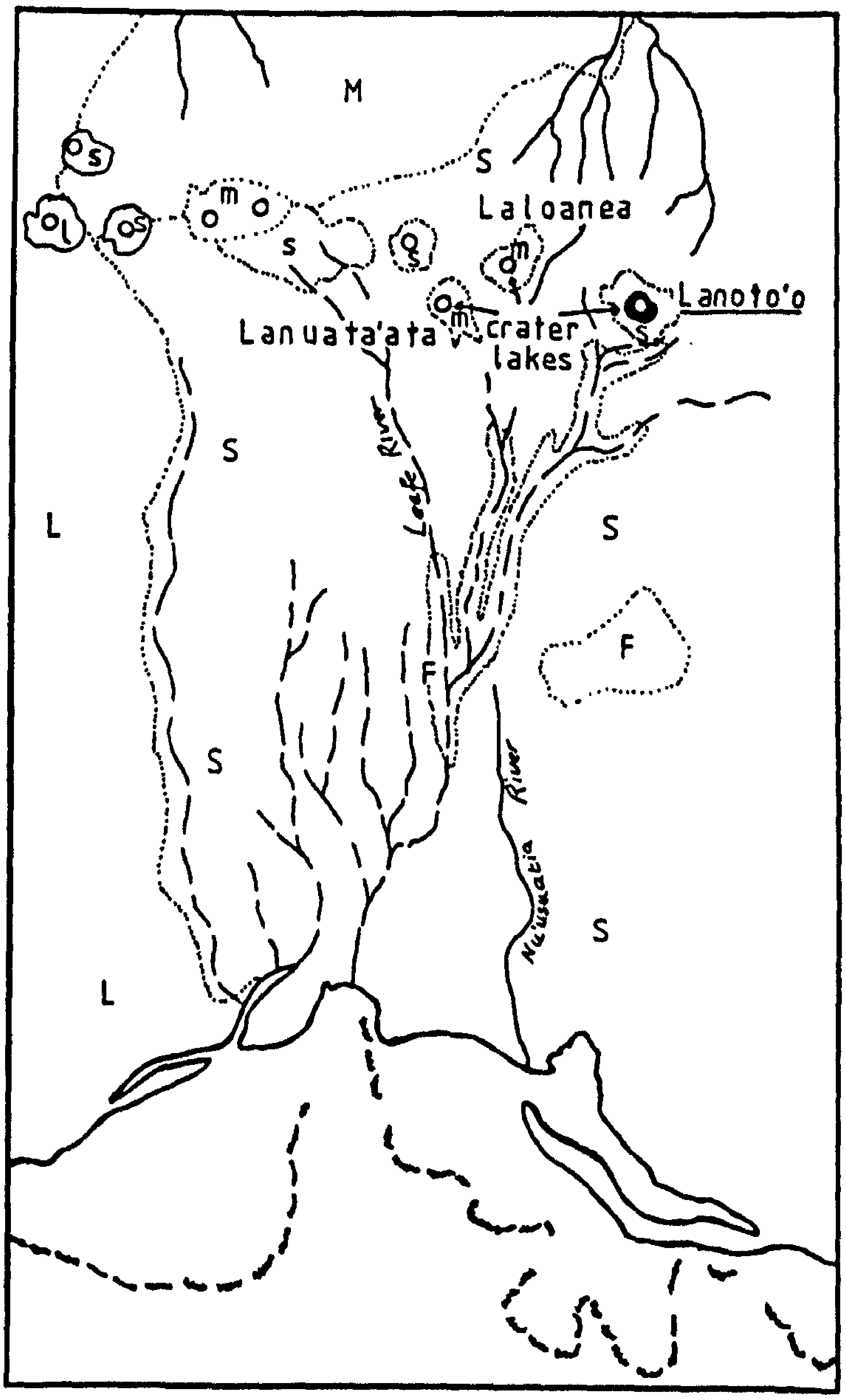
Fig.4.2 Geological formations on the island of Upolu.

Aopo Volcanics........	A	Historical
Puapua Volcanics......	P	Middle and Late Holocene
Lefaga Volcanics.....	L	Early Holocene
Mulifanua Volcanics.	M	Last Glaciation
Salani Volcanics	S	? Penultimate Glaciation to Last Interglacial.
Fagaloa Volcanics	F	? Pliocene to Mid-Pleistocene
Eruptive centres	o	

Fig.4.3 The Lake Lanoto'o crater showing coring platform and peripheral vegetation dominated by *Pandanus* and aquatic reeds.

Fig.4.4 While a diverse primary and secondary hygrophile forest vegetation grows on the inner slopes of the Lanoto'o crater, an almost monospecific band of *Pandanus* trees has developed on the marginal sediments of the lakes.

Fig.4.5 Geological setting of the Lake Lanoto'o crater.



Lefaga Volcanics.....	L	Early Holocene
Mulifanua Volcanics.	M	Last Glaciation
Salani Volcanics	S	? Penultimate Glaciation to Last Interglacial.
Fagaloa Volcanics	F	? Pliocene to Mid-Pleistocene

Fig.4.6 On the disturbed pathway leading to the lake a red, clay-rich laterite is seen. In the Lanoto'o crater weed taxa were found only in such areas.

Fig.4.7 Hygrophile forest, with dense ground cover, in the undisturbed parts of the Lanoto'o catchment.

Fig.4.8 In order to meet economic demands, indigenous forest trees are removed from the outer slopes of the Lanoto'o crater to make way for dryland taro cultivation.

Fig.4.9 Magnetic susceptibility profile from the Lake Lanoto'o sediment sequence, Upolu.

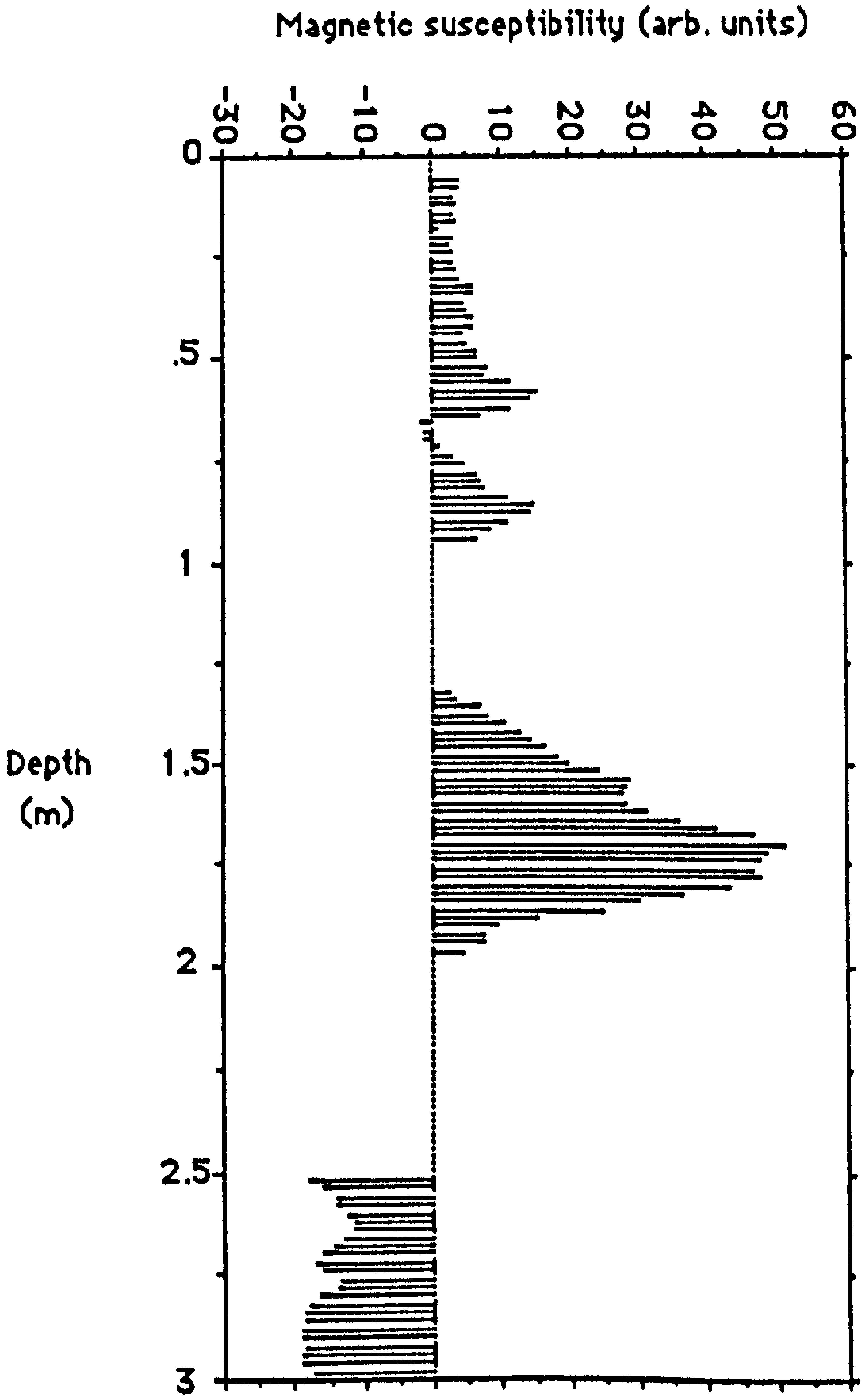


Fig.4.10 Geochemical analysis of the sediments from Lake Lanoto'o.

Fig.4.11 Iron-oxide and silica-oxide profiles from the Lake Lanoto'o sediment sequence, Upolu.

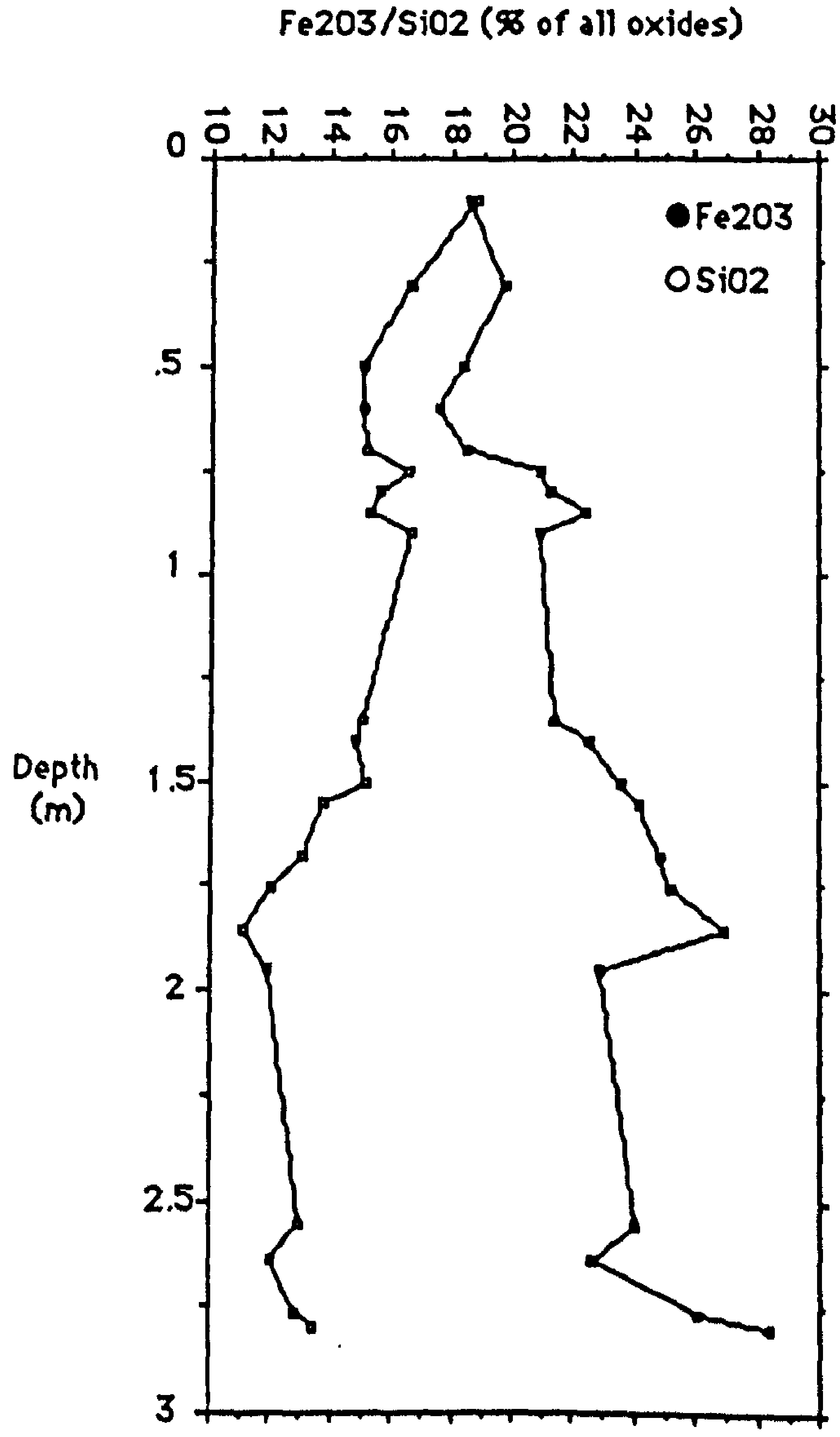


Fig.4.14 Percentage summary diagram of vegetation types from Lake Lanoto'o.

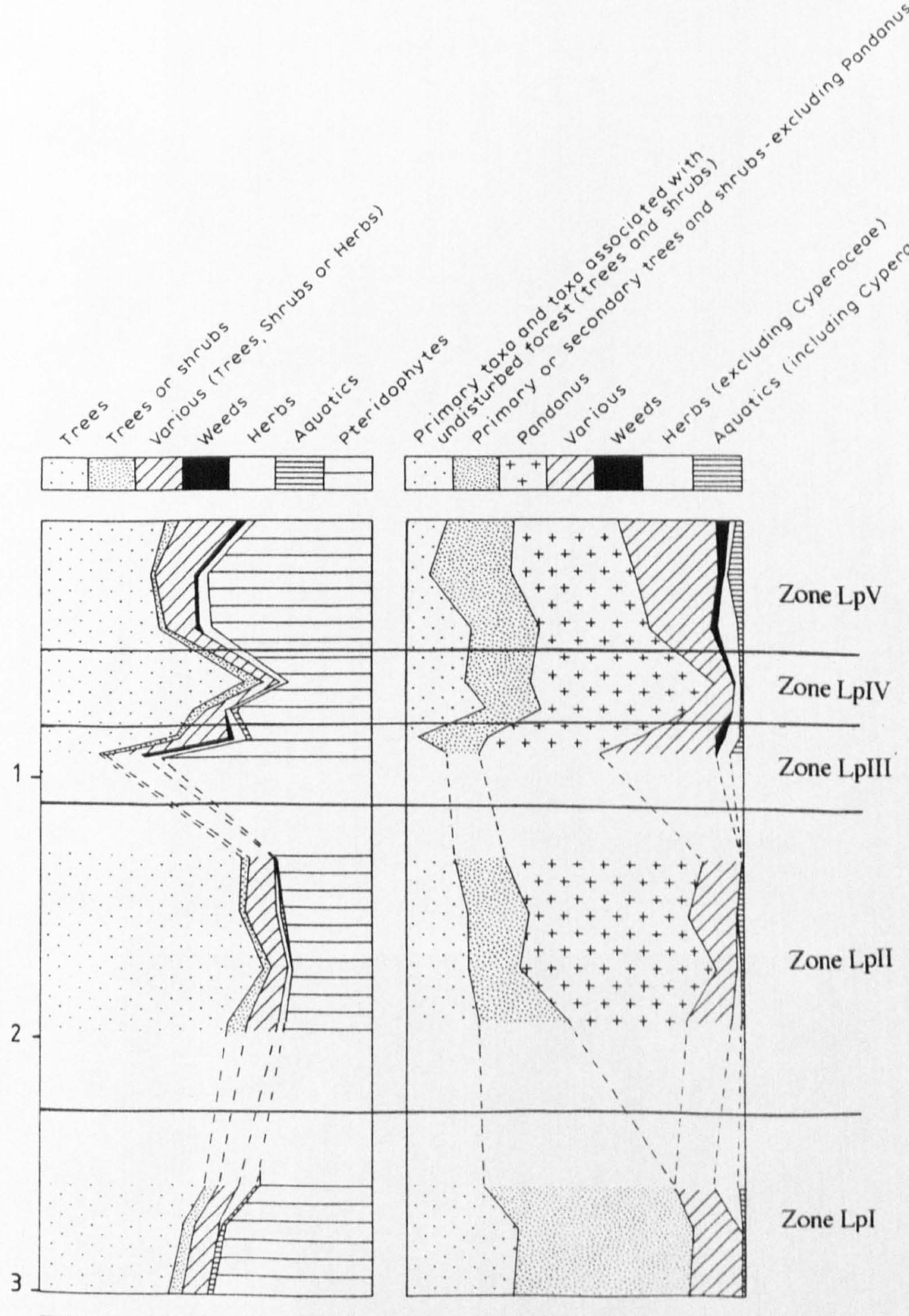


Fig.4.15 Typical vegetation of the disturbed mid- and low-altitude regions of Upolu where indigenous trees are found scattered among open grasslands and fernlands

Fig.5.1 The island of Atiu and location of Lake Roto. Bathymetry of Lake Roto and position of core sites.

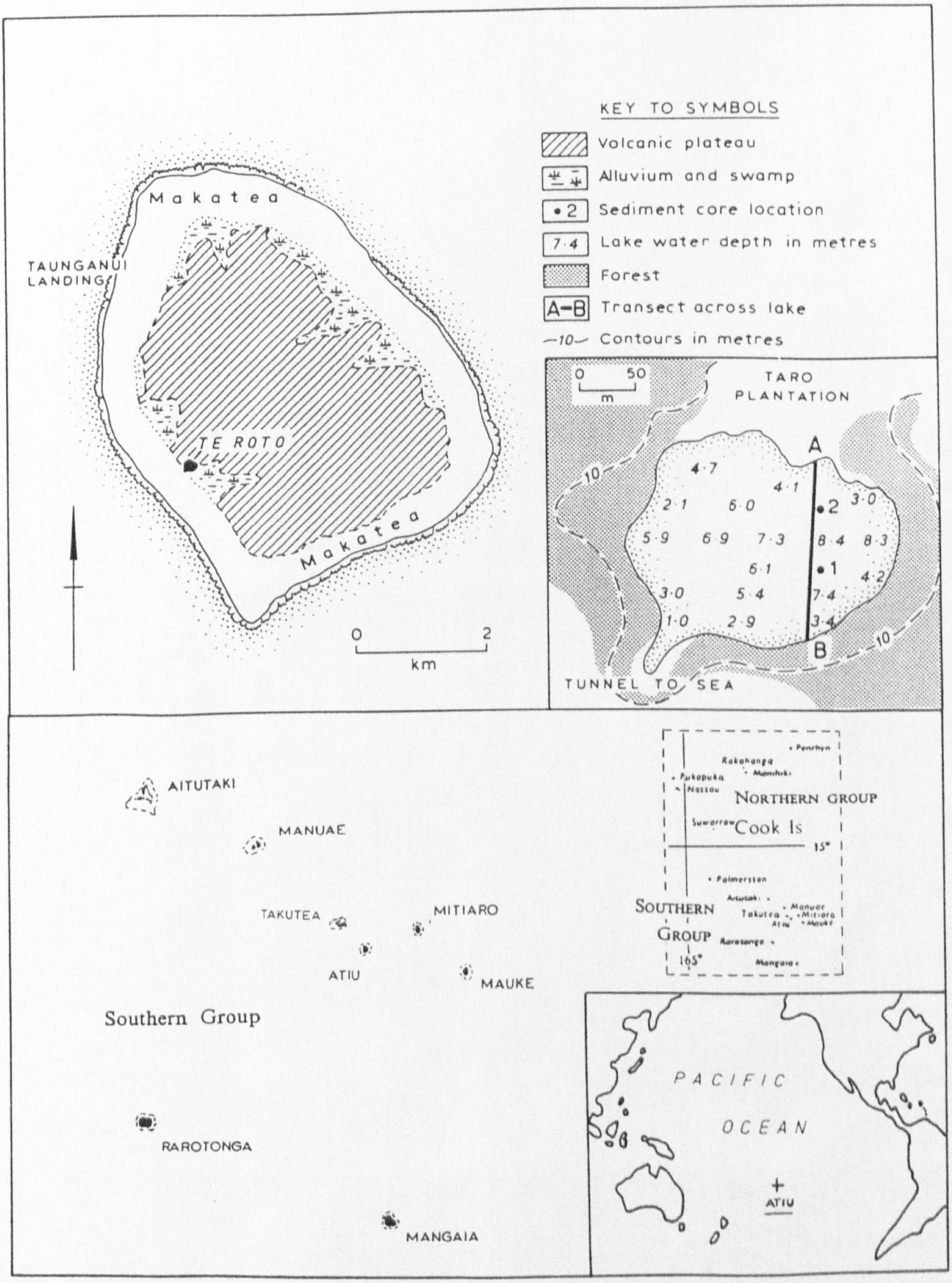


Fig.5.2 Soil types and the location of present-day village sites on Atiu.

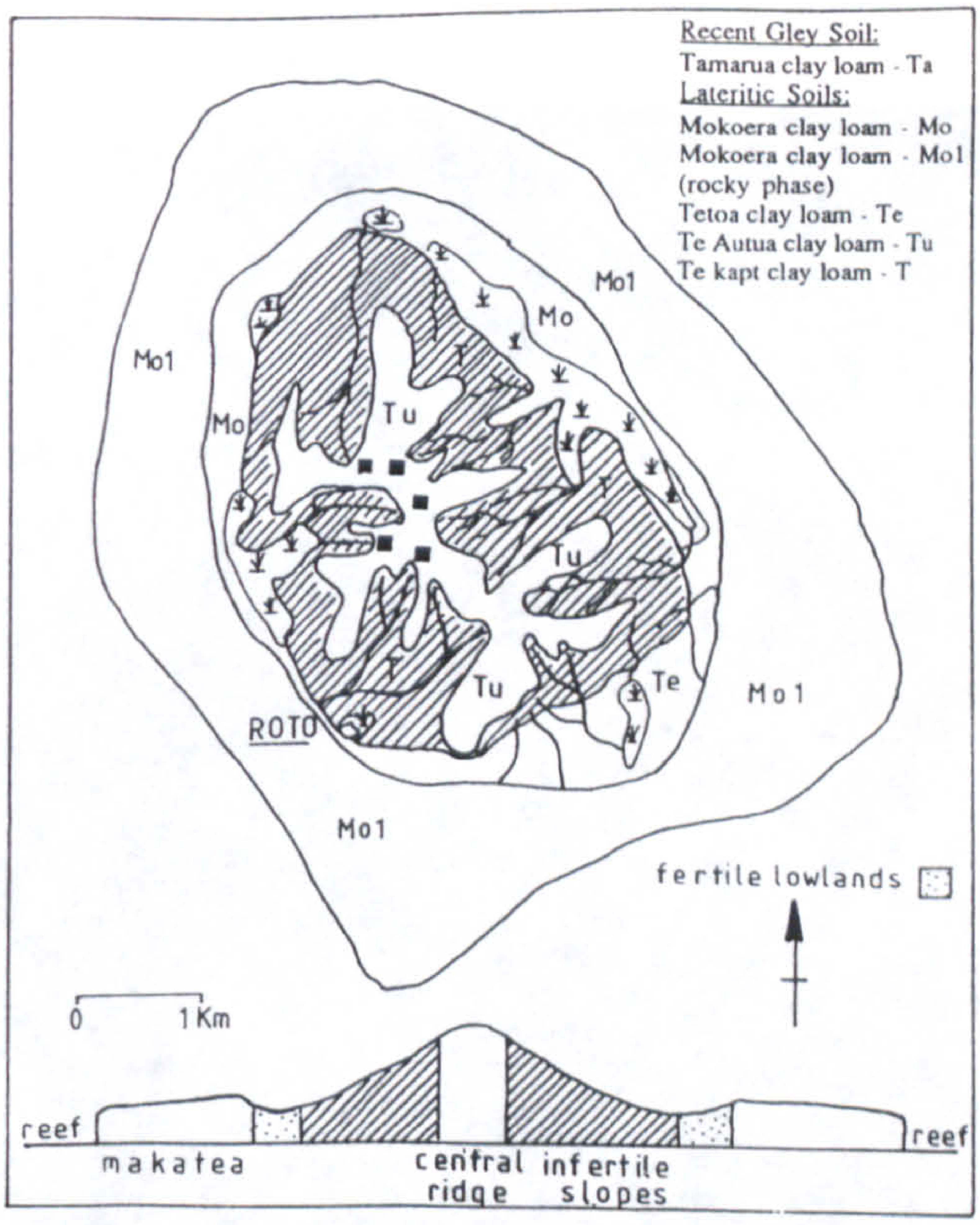
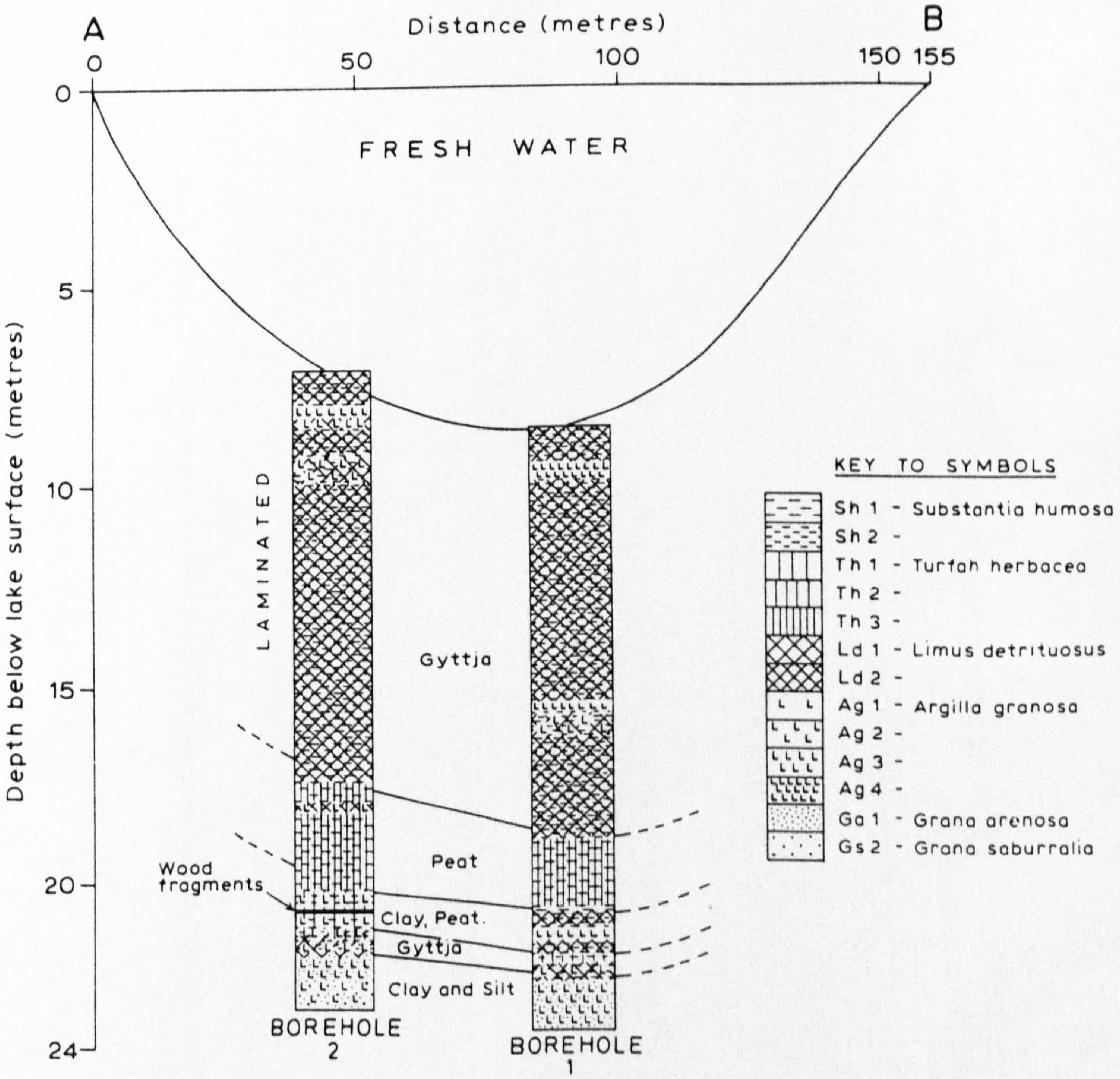


Fig.5.3 Present-day settlements are located on the central upland plateau of Atiu and although the soil is very infertile and moisture availability low, fruit trees appear to grow considerably well.

Fig.5.4 View of Lake Roto looking inland towards the central volcanic plateau with taro swamps and coconut groves in the marshy depression below.

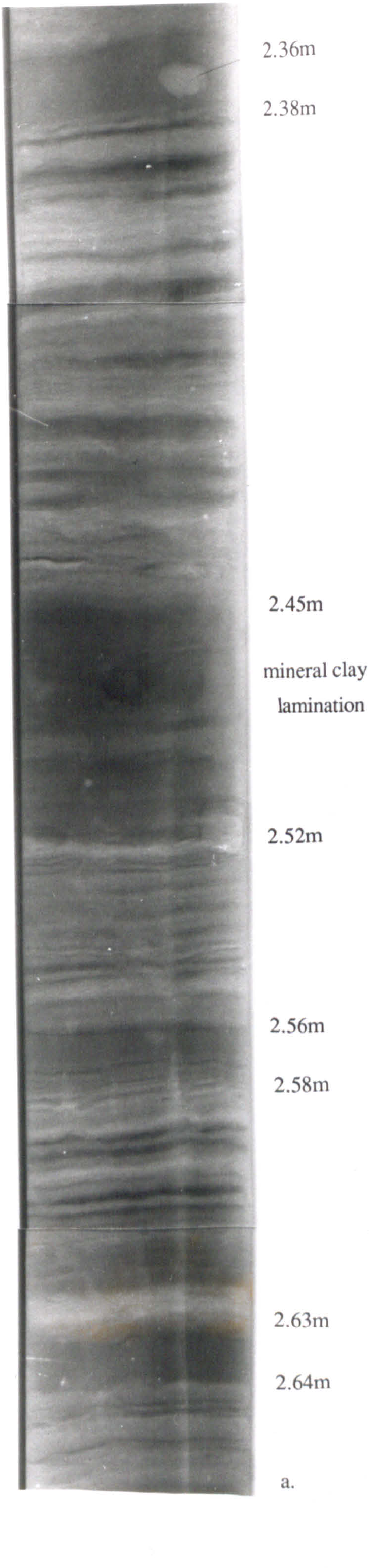
Fig.5.5 The solutional tunnel through the raised *makatea* limestone serves as an outlet for Lake Roto.

Fig.5.6 Stratigraphy of the two cores from Lake Roto.



Transect A-B is shown in Fig.5.1.

Fig.5.7. X-ray photographs from the Lake Roto sequence.


2.36m
2.38m
2.45m
mineral clay
lamination
2.52m
2.56m
2.58m
2.63m
2.64m

a.


3.30m
Mollusc
Melania incisa
40
3.47m
Basalt
pebble

b.

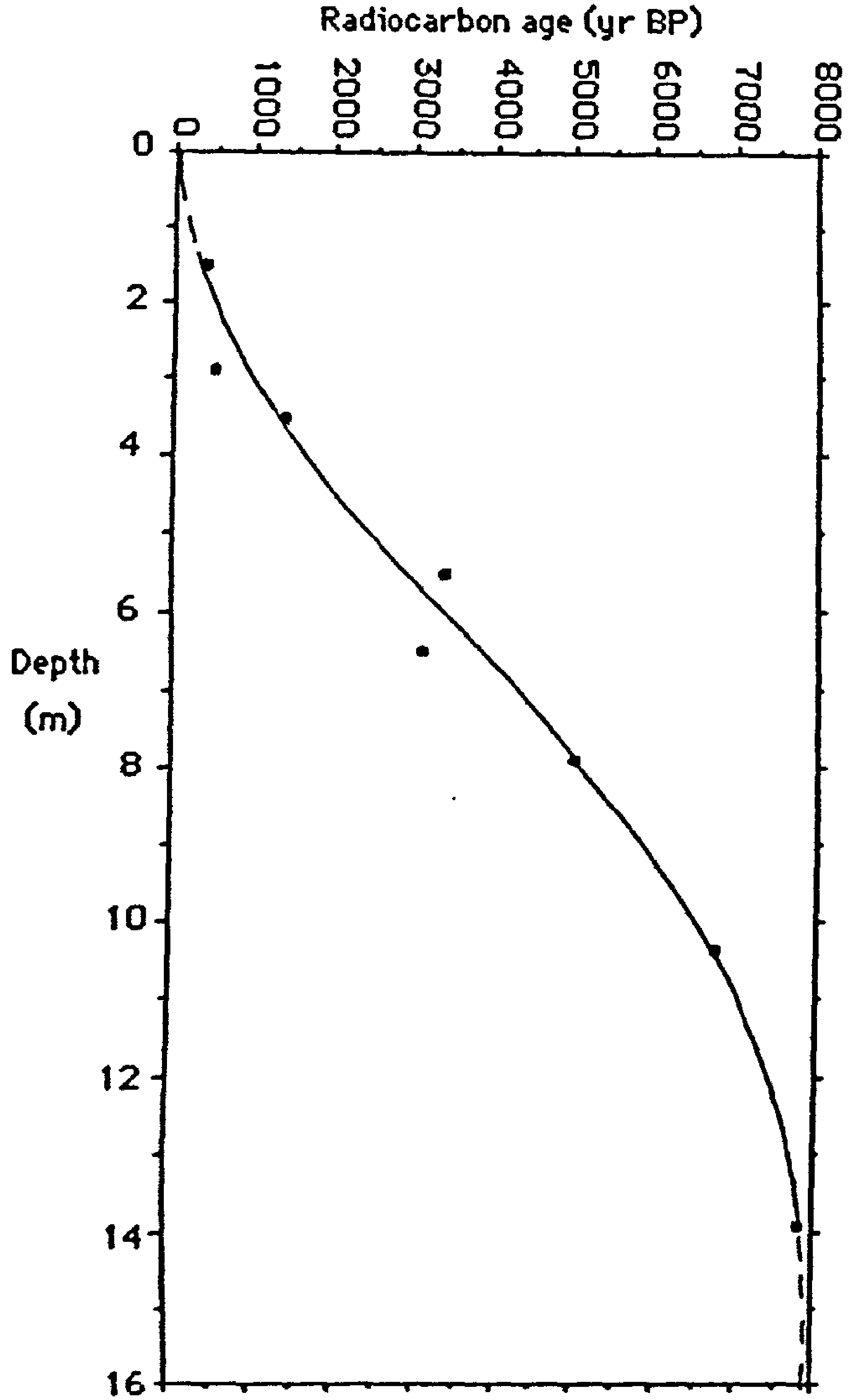


Fig.5.8 Age-depth sequence from the Lake Roto sediment core.

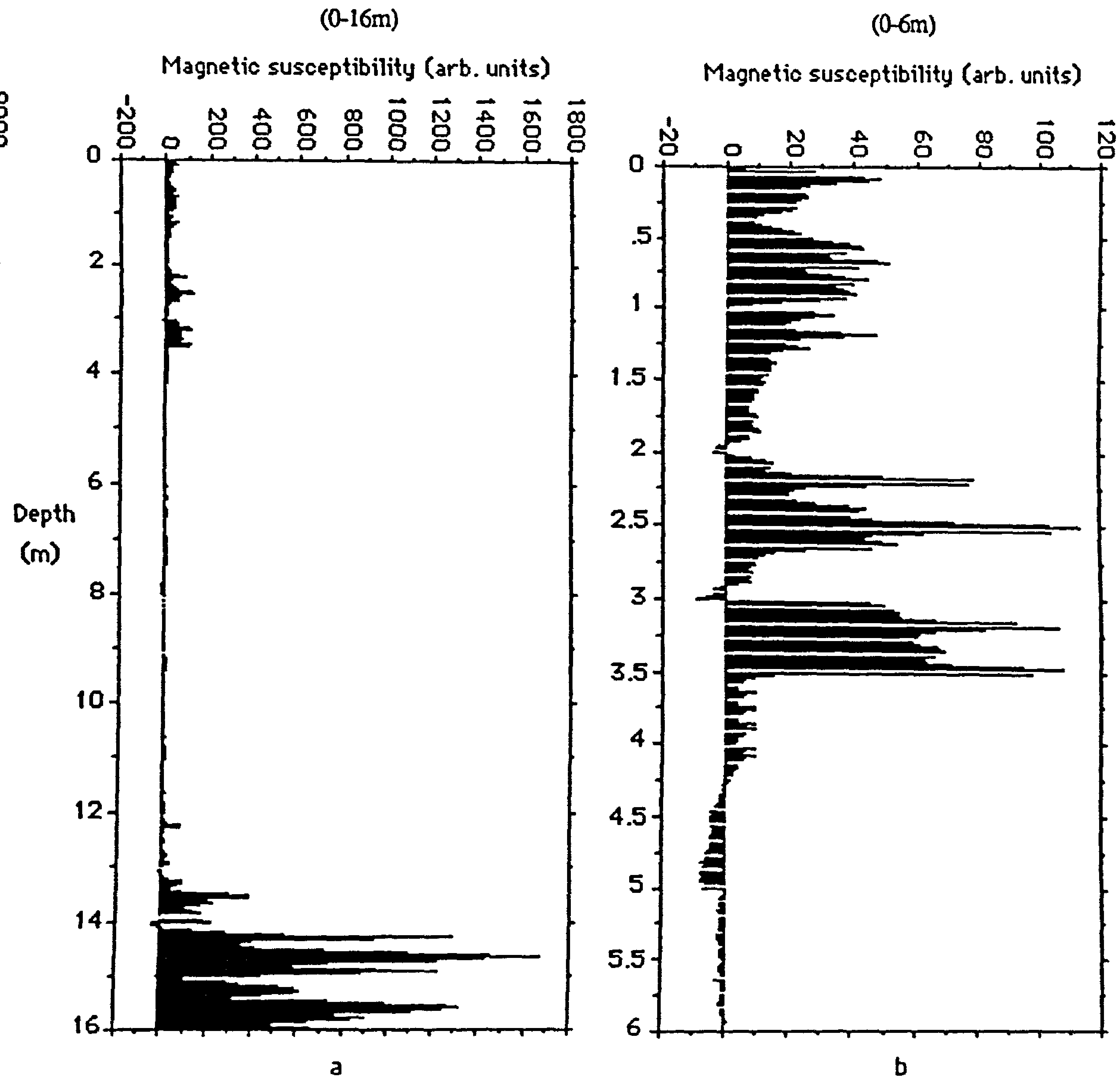


Fig.5.9 Magnetic susceptibility profile from the Lake Roto sediment sequence.

Fig.5.10 Geochemical analysis of the sediments from Lake Roto.

Fig.5.13 Percentage summary diagram of vegetation types from Lake Roto.

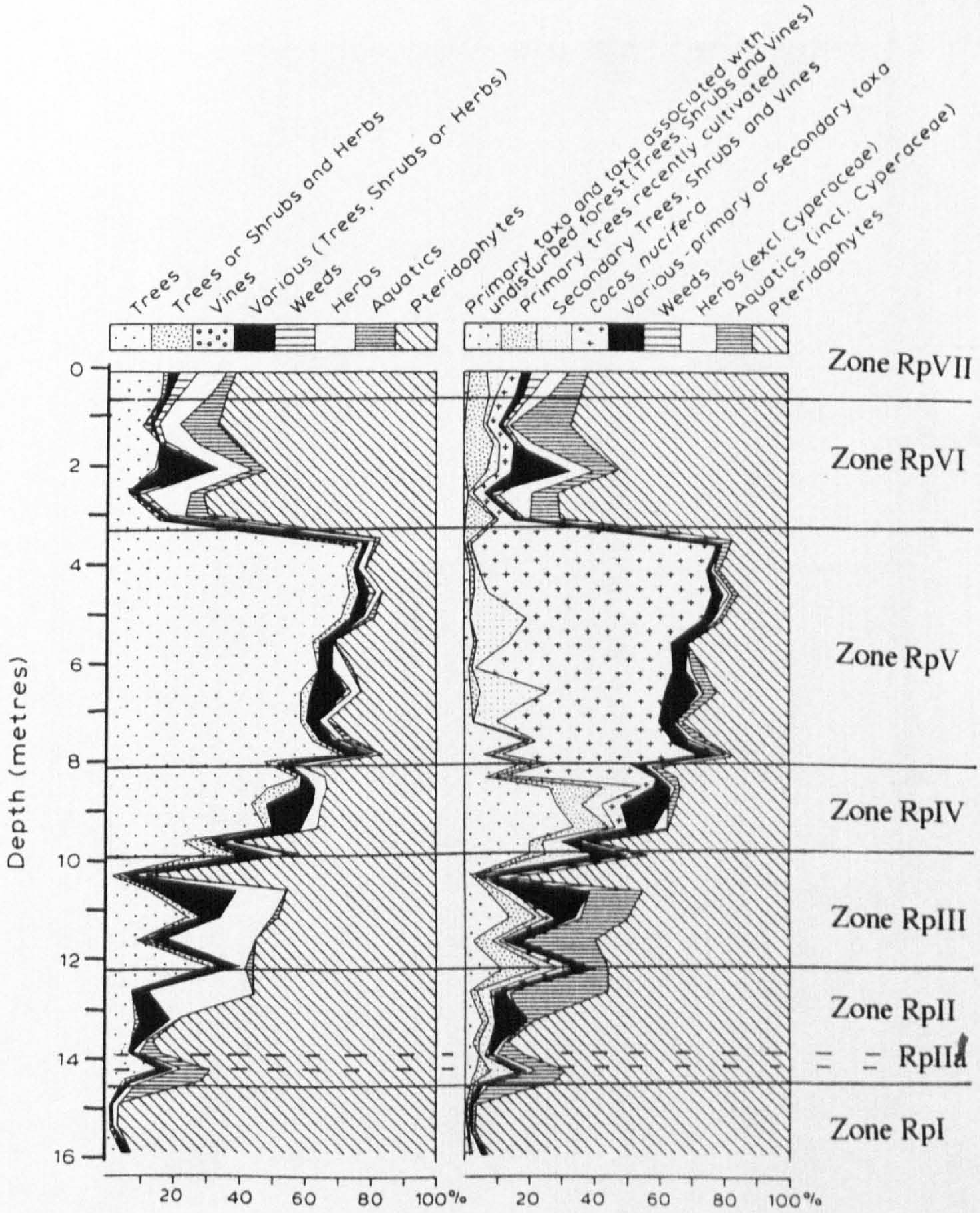
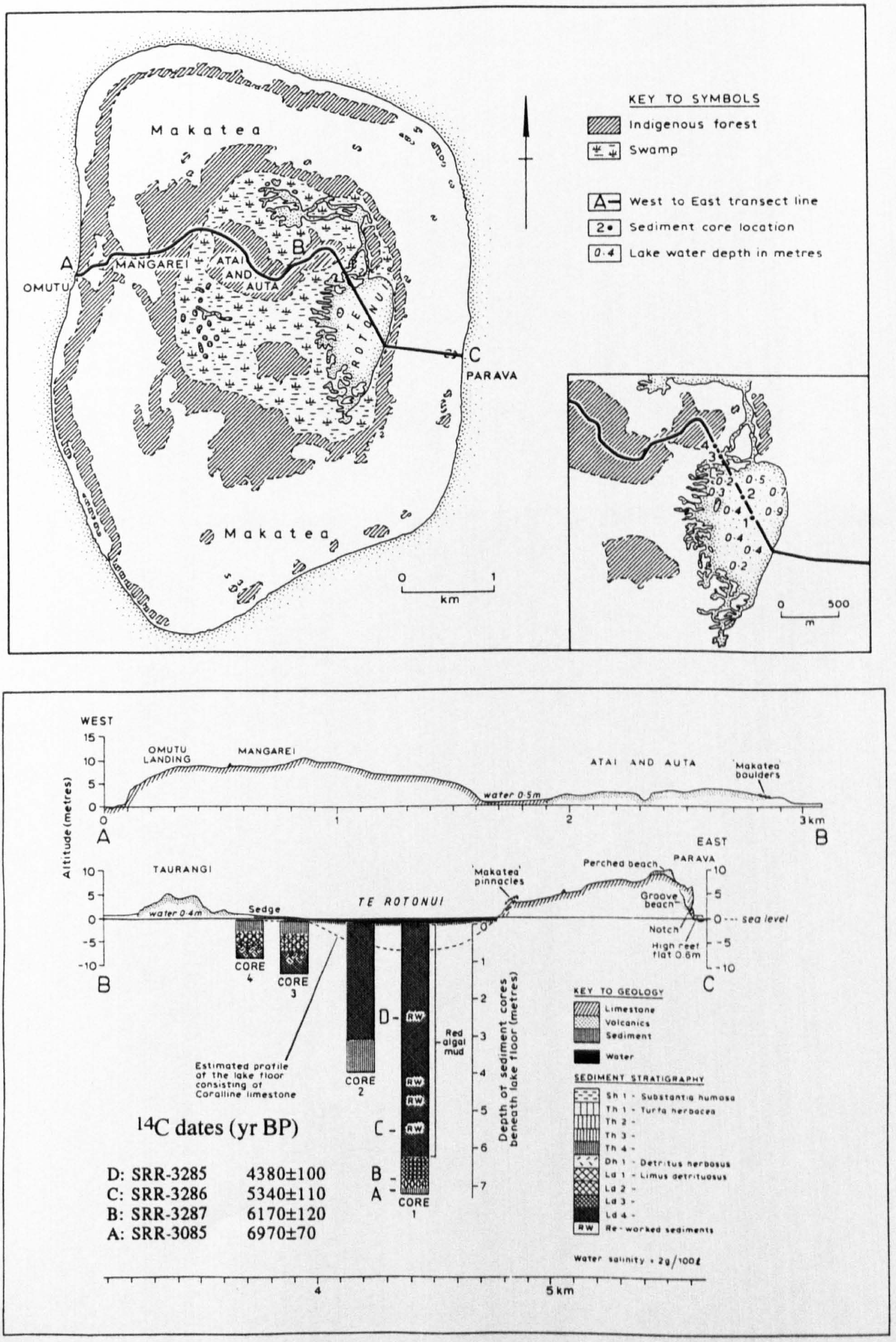


Fig.5.14 Collection of *Pandanus* leaves for thatching is still practiced today and remains the second most important source of material after the coconut.

Fig.5.15 Absolute fossil diatom concentrations in the sediment of Lake Roto, Atiu.

Fig.5.16 Percentage fossil diatoms in the sediment of Lake Roto, Atiu.

Fig.5.17 The island of Miti'aro, Southern Cooks. Location and bathymetry of Lake Rotonui and location and stratigraphy of sediment cores. Profile across the island based on survey by Stoddart, Spencer and Woodroffe.



^{14}C dates (yr BP)

D: SRR-3285	4380±100
C: SRR-3286	5340±110
B: SRR-3287	6170±120
A: SRR-3085	6970±70

Fig.5.18 Lake Rotonui, a shallow, brackish water lake in-filled with red algal mud.

Fig.6.1 The island of Mo'orea and location of Lake Temae.

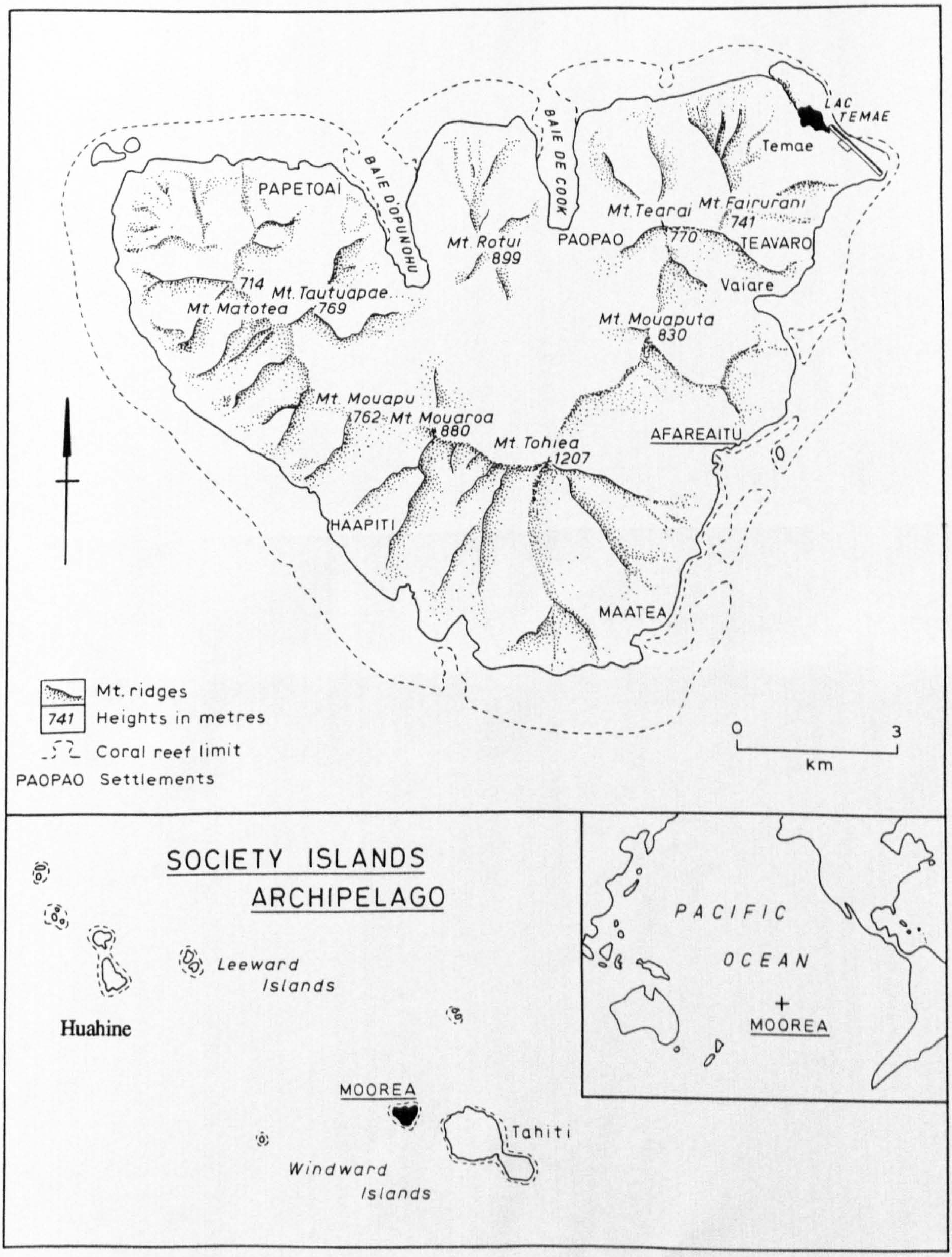


Fig.6.2 View towards the interior of Mo'orea as seen from Vaiare ridge. Remnants of old crater rim encircle the highly cultivated central plain.

Fig.6.3 The Vaiare Pass forms a passage through the outer barrier reef which almost encircles the island of Mo'orea and protects a sheltered lagoon where calcareous muds are deposited.

Fig.6.4 The island of Tahiti showing the location of Lake Vaihiria.

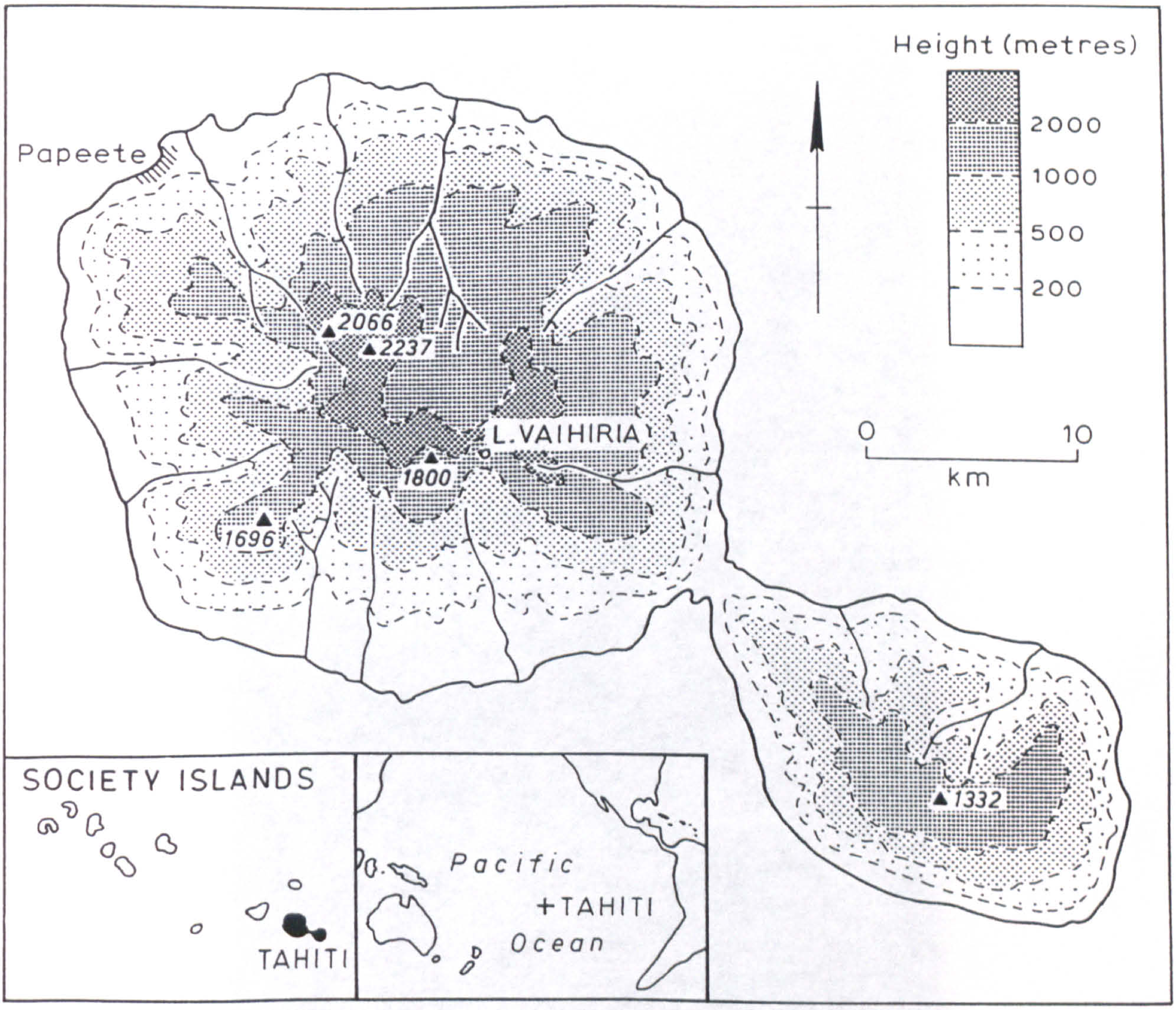


Fig.6.5 Mangrove trees planted on Mo'orea in an attempt to stabilize the coastal sediments. Coconut, *Pandanus*, *Casuarina* and *Barringtonia* trees form the main arboreal component of the coastal region, while inland slopes support grass and fernland scrub.

Fig.6.6 The broad-leaved *Miconia* shrub is clearly seen progressively replacing the hygrophile vegetation on the lower catchment slopes of Lake Vaihiria. The development of an alluvial plain to the north of the lake provided level ground for the colonization of aquatic plants and sedges.

Fig. 6.7 Stunted vegetation on the exposed ridges of Mo'orea is generally dominated by *Pandanus* trees, *Metrosideros* shrubs and a variety of grasses and ground ferns.

Fig.6.8 View of Lake Temae from the top of Temae valley. The coral *motu* supports cultivated coconuts and *tiare* plants, while *Pandanus* trees and aquatic reeds grow around the lake periphery. Lake Motuiti, now in-filled, indicates the former extent of the lake.

Fig.6.9 Bathymetry and location of core sites on Lake Temae. Profile over coral ridge which separates the lake from the sea.

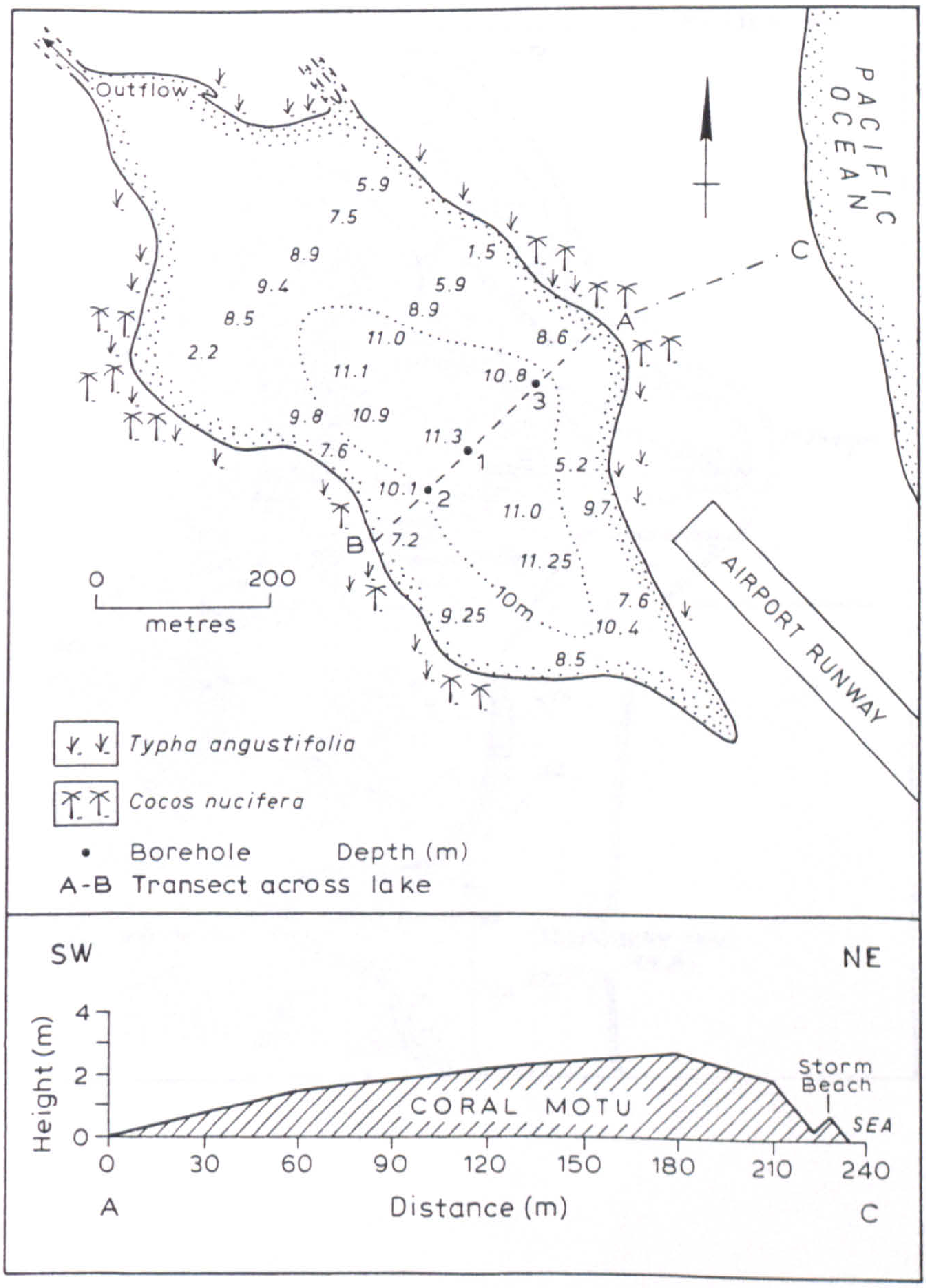


Fig.6.10 North-east corner of Mo'orea showing the former extent of Lake Temae: after Crossland, 1928.

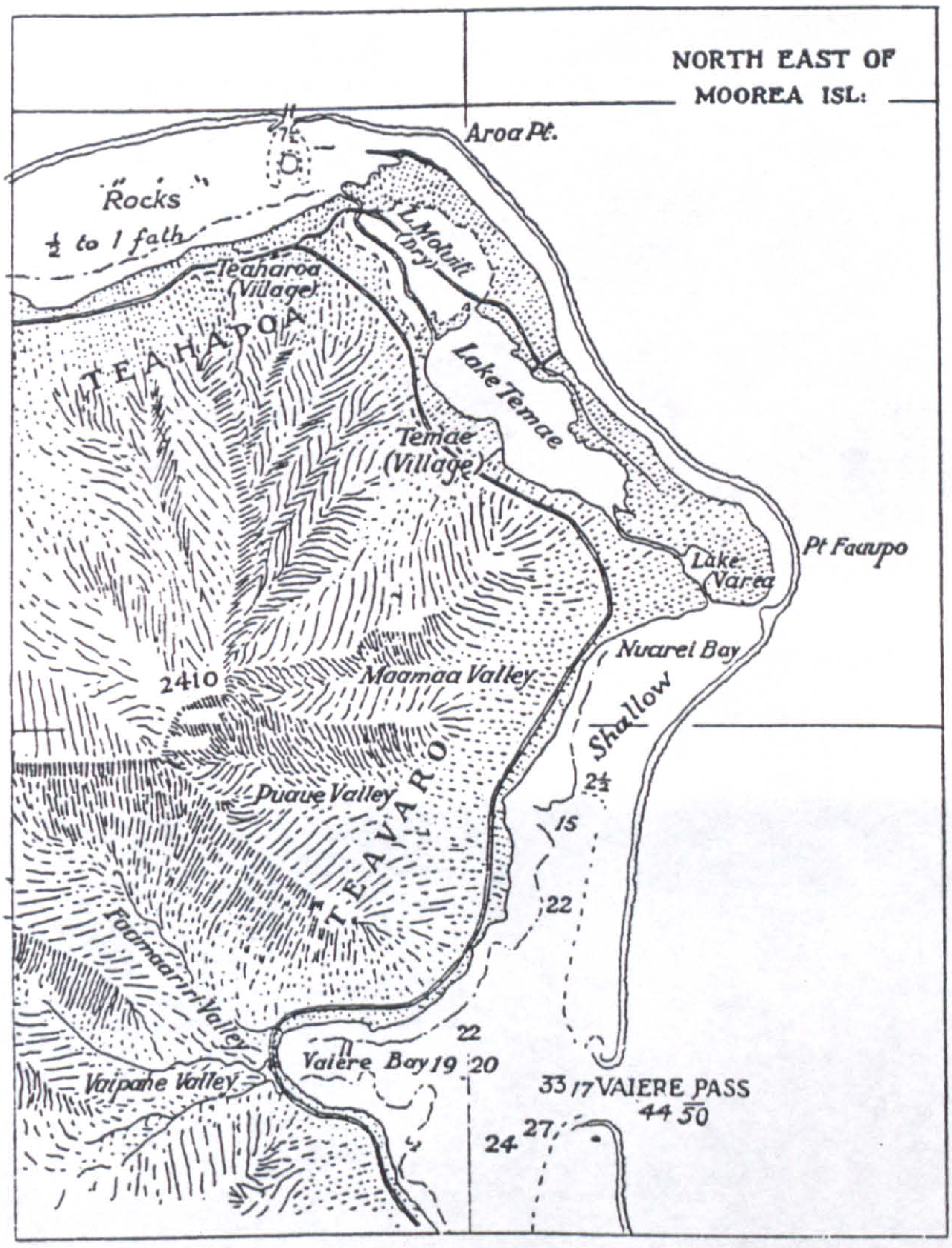
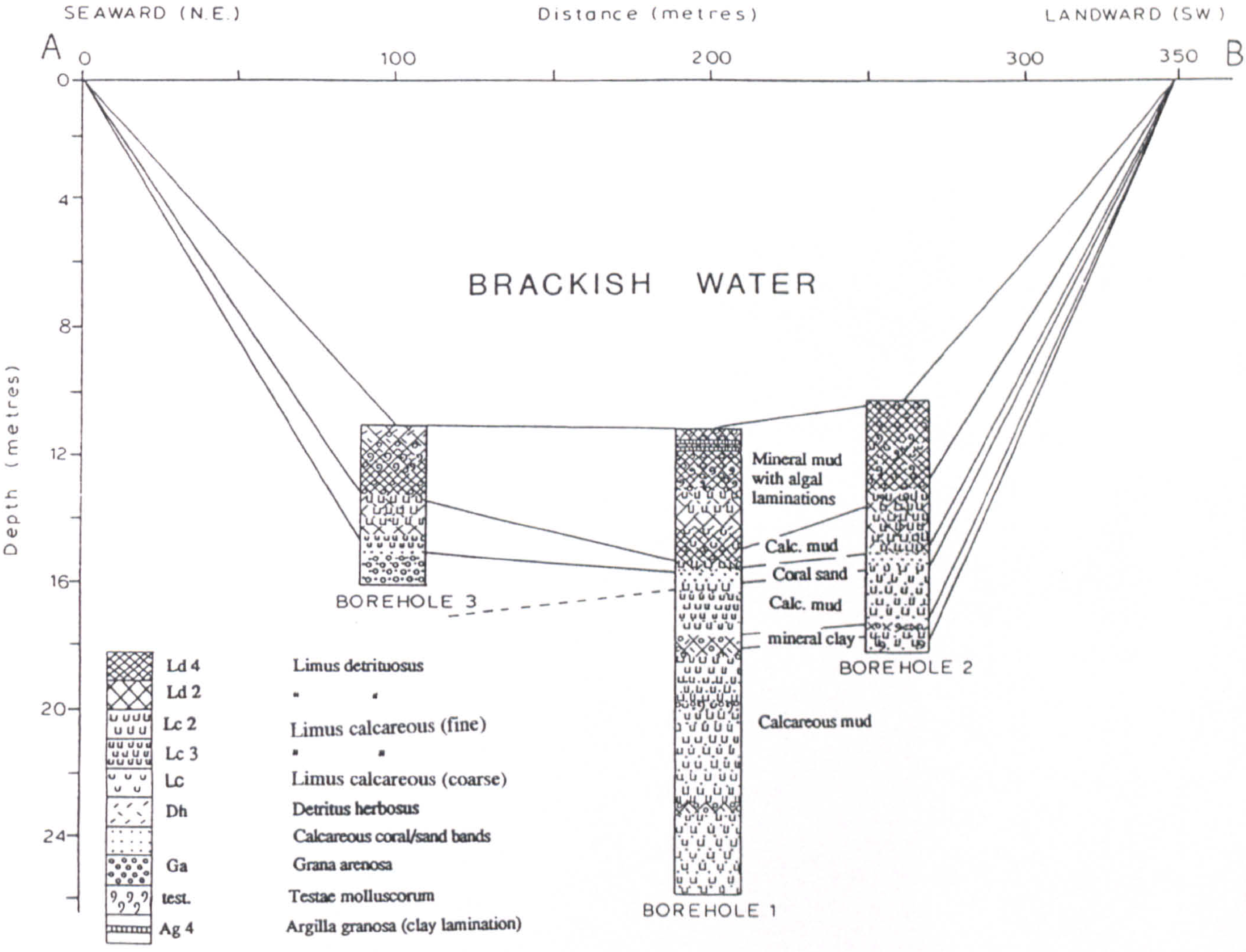


Fig.6.11 Dry lake basin of Motuiti with a littoral-type vegetation dominated by coconut and *Pandanus*.

Fig.6.12 Lake Temae looking inland towards Temae valley from the *motu*. The medium slopes of the catchment only support a discontinuous cover of scrub vegetation and the red basaltic soils are frequently exposed to the forces of erosion.

Fig.6.13 Stratigraphy and location of boreholes on Lake Temae.

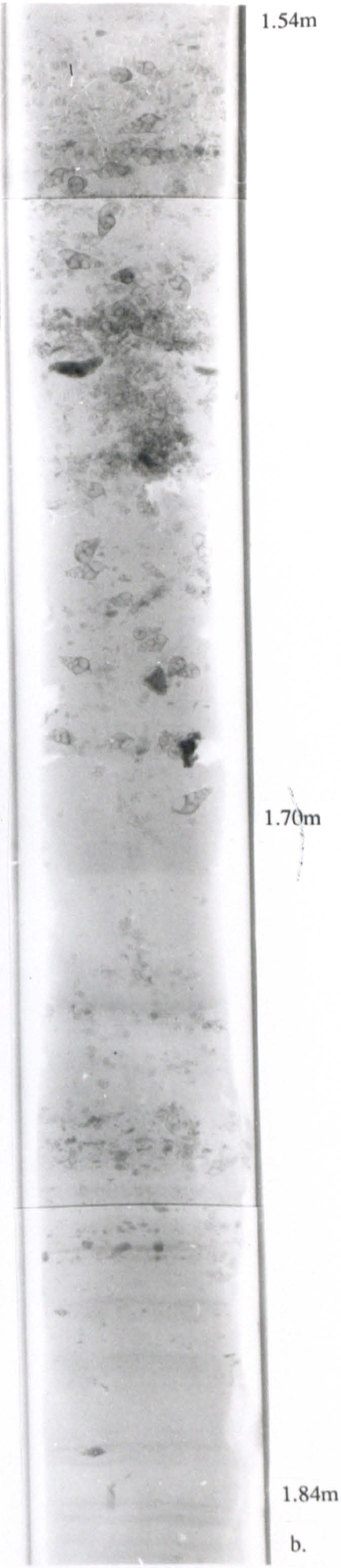


Transect A-B is shown in Fig.6.9.

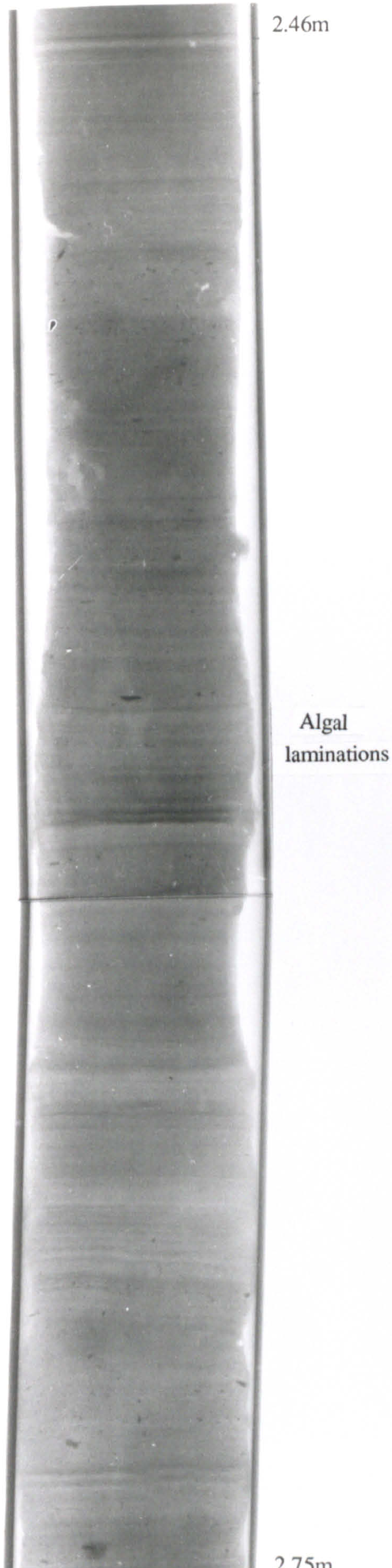
Fig.6.14 X-ray photographs from the Lake Temae sequence.

a.

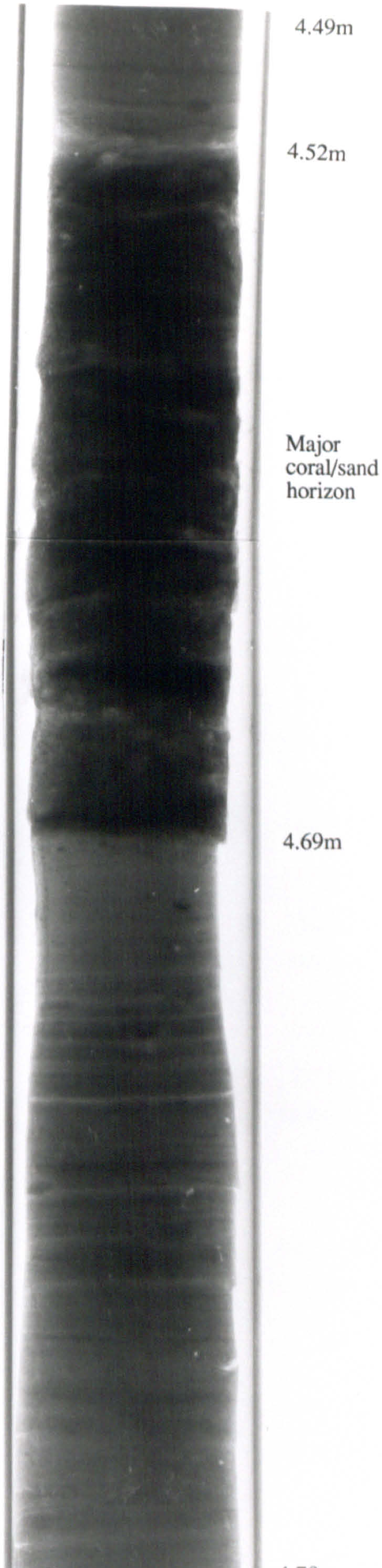
Freshwater molluscs



b.


2.46m
Algal laminations
2.75m

c.


4.49m
4.52m
Major coral/sand horizon
4.69m
4.78m

d.

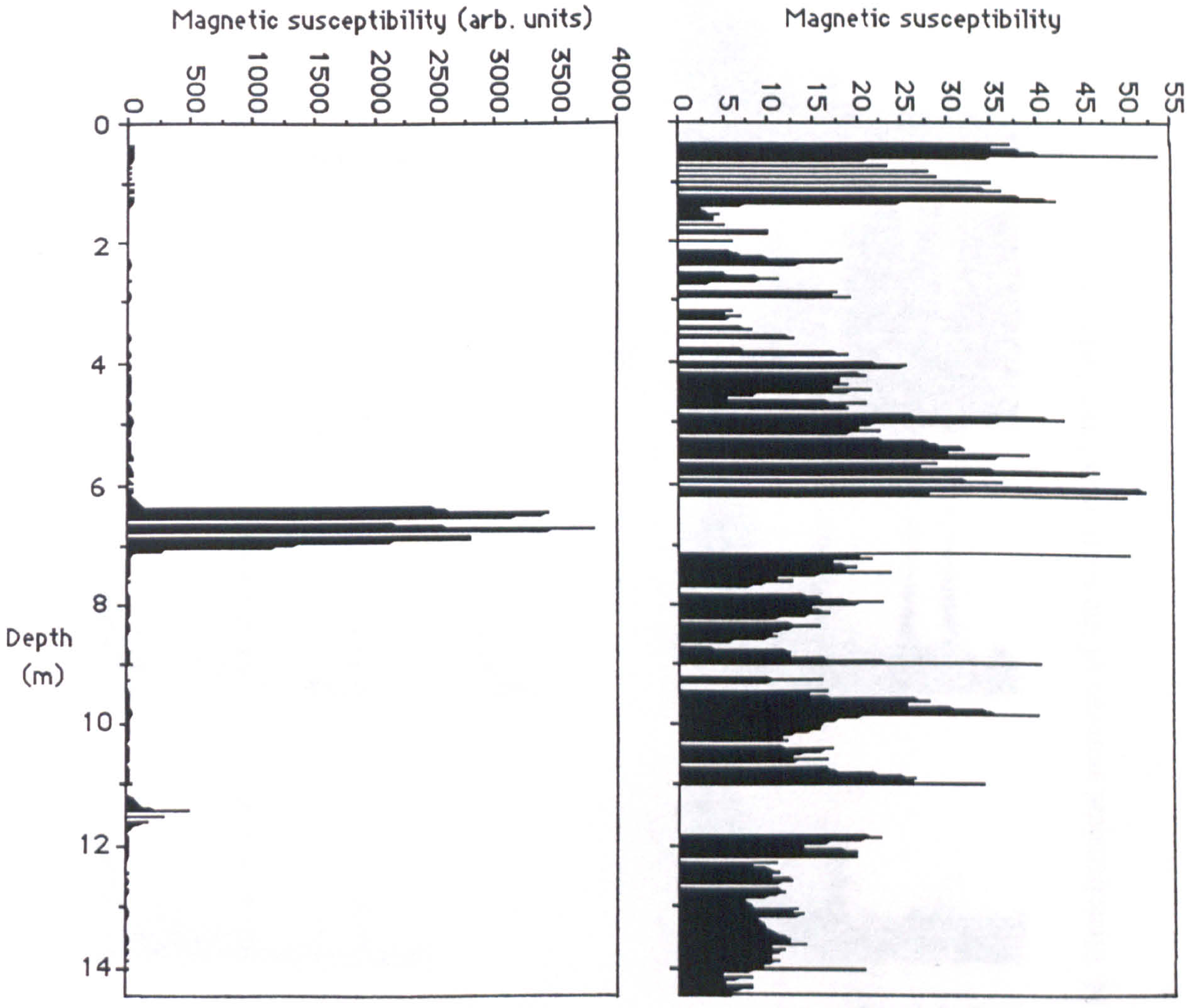

5.25m
5.29m
5.31m
5.33m
Medium coral/sand horizon
5.35m
5.51m
Medium coral/sand horizon
5.53m

e.


6.86m
Smooth mineral clay
7.00m
7.00m
Coarse mineral clay
7.04m
Abrupt transition
Calcareous mud
7.15m

f.

Fig.6.15 Magnetic susceptibility profile from the Lake Temae sediment sequence, Mo'orea.



a. b.

Fig.6.16 Geochemical analysis of the sediments from Lake Temae.

Fig.6.19 Percentage summary diagram of vegetation types from the fossil pollen and spore record of Lake Temae.

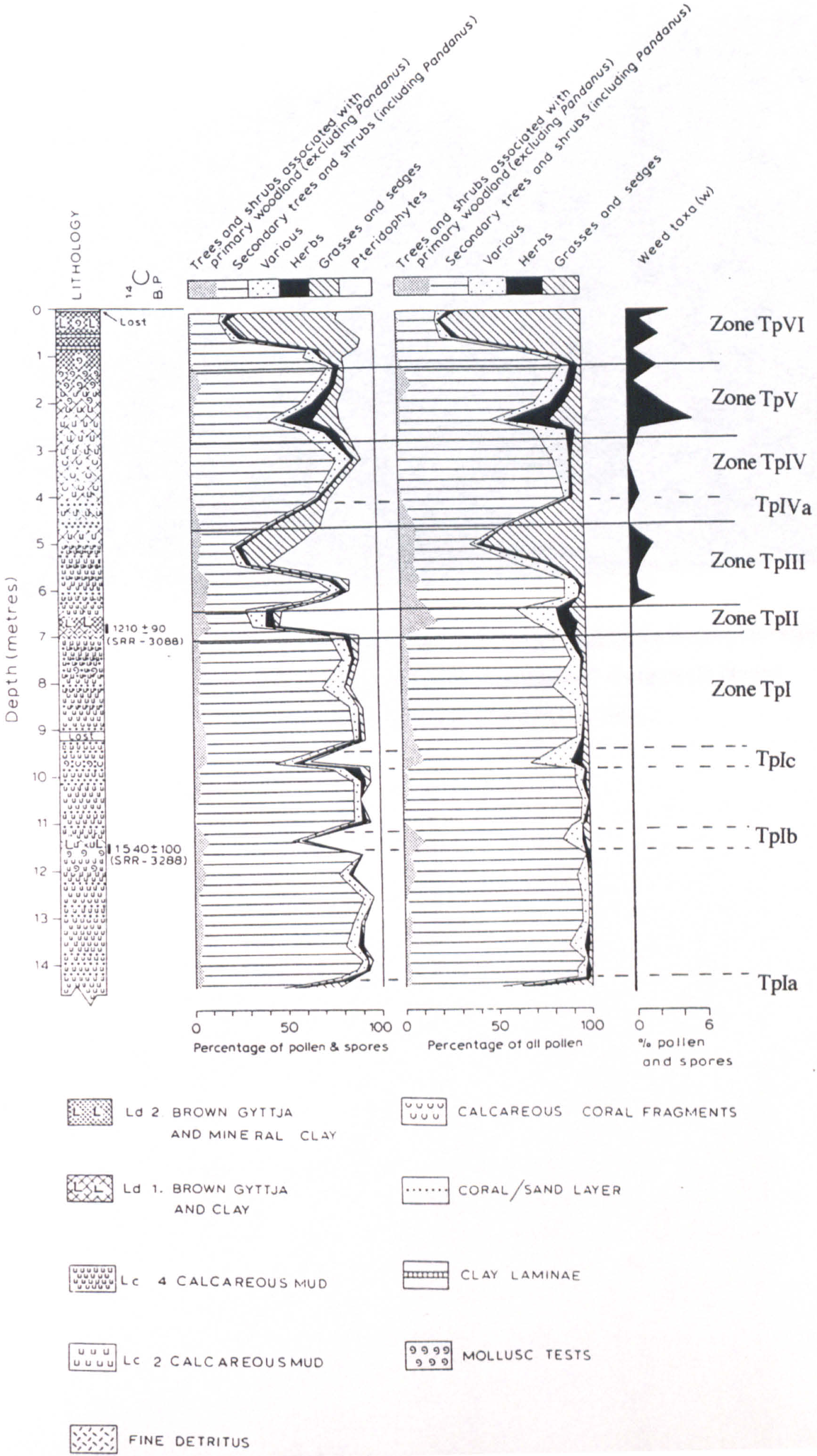


Fig.6.20 The steep slopes surrounding Lake Vaihiria still maintain a hygrophile forest in the undisturbed areas. However, recent "landscaping" completely altered the vegetation on the area of the debris dam.

Fig.6.21 Topographic map of the upper Vaihiria valley (after 1:40,000 Tahiti Sud-est topographic map), showing Lake Vaihiria and its dam of landslide debris, river alluvium, and landslide scarps (after Deneufbourg, 1965).

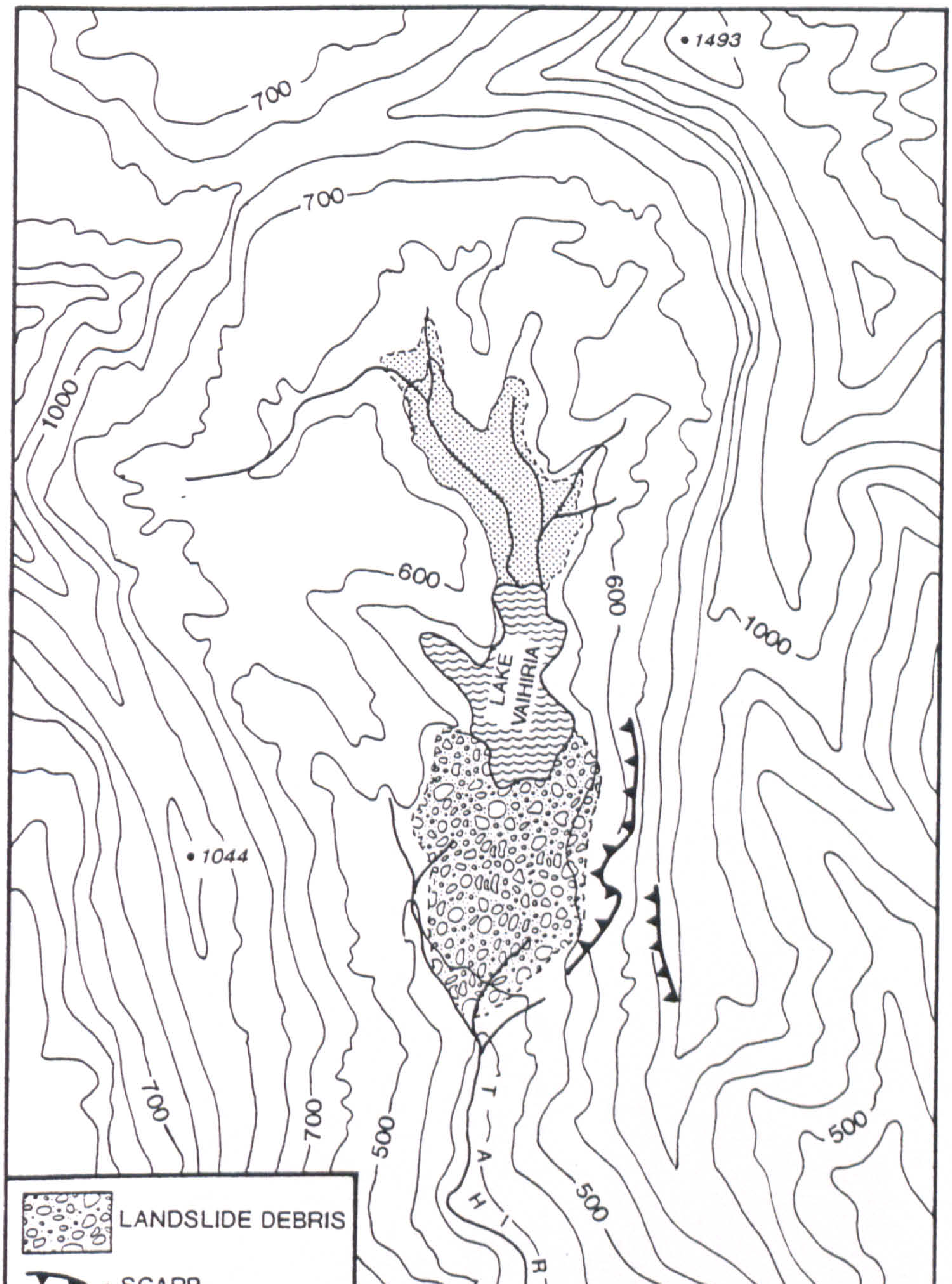


Fig.6.22 Bathymetry of Lake Vaihiria and elevation of surrounding area immediately surrounding the lake (after Becker, 1974 and SEDEP, 1981). Location of the core site also shown.

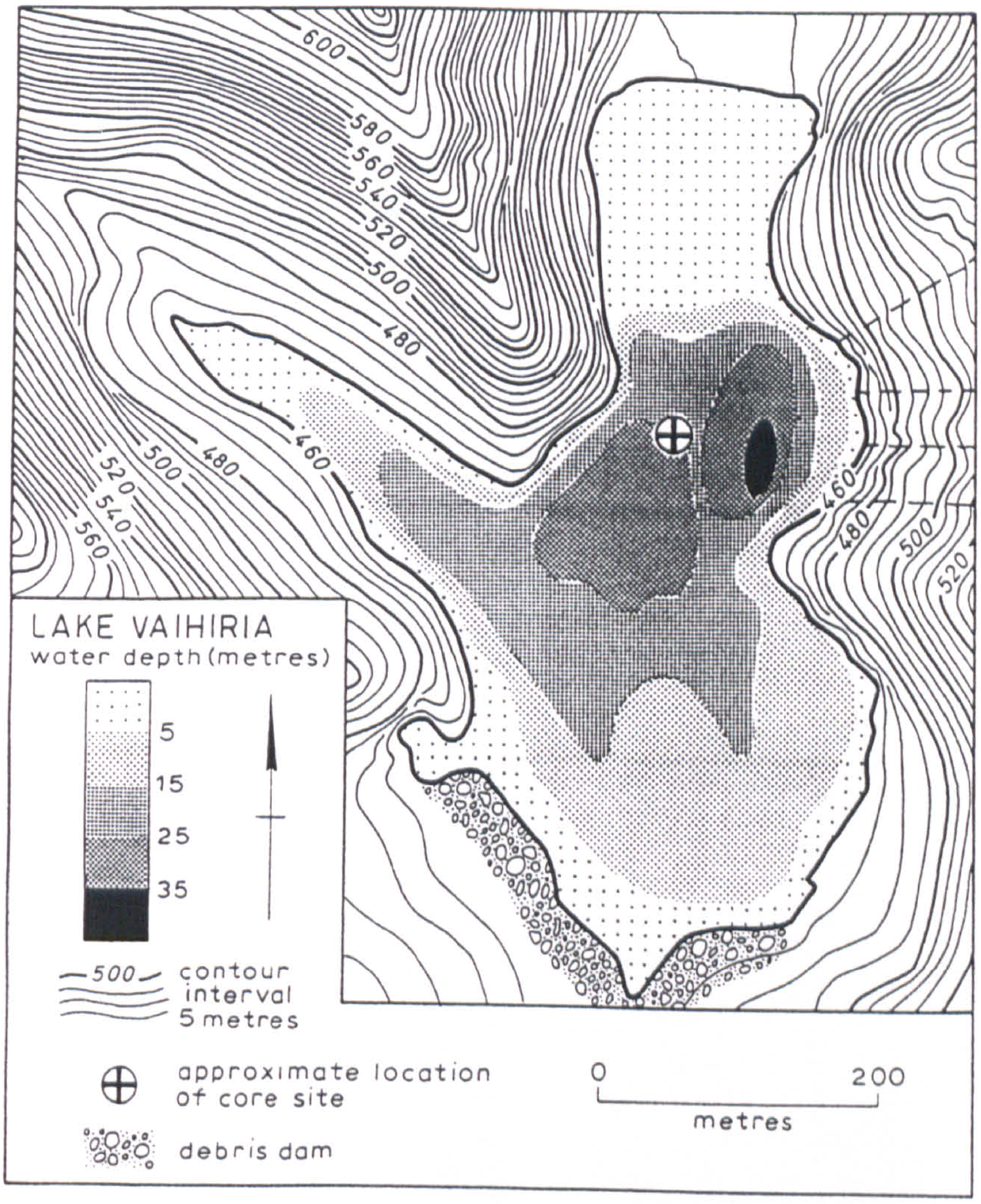


Fig. 6.23 Magnetic susceptibility profile from the Lake Vaihiria sediment sequence, Tahiti.

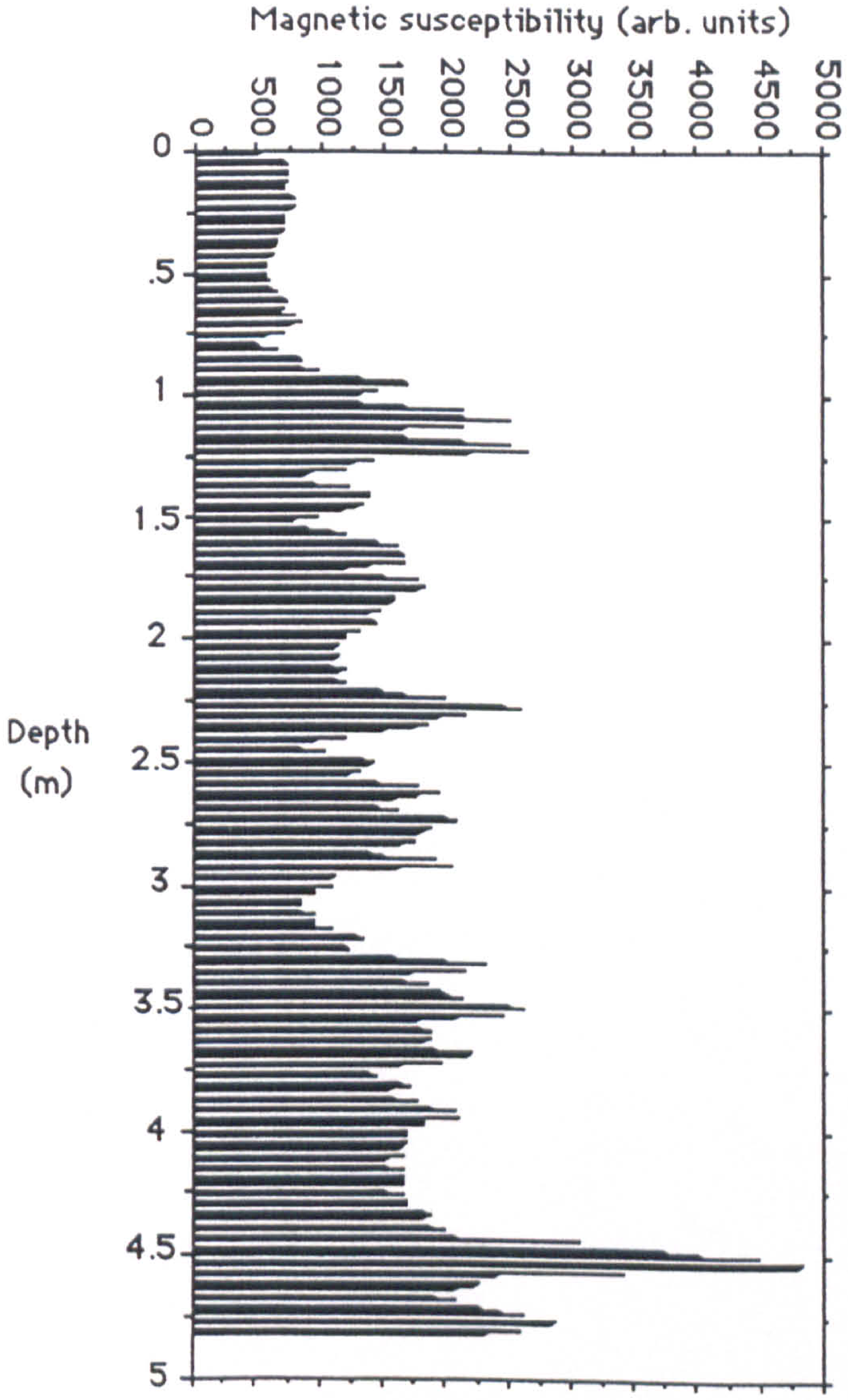
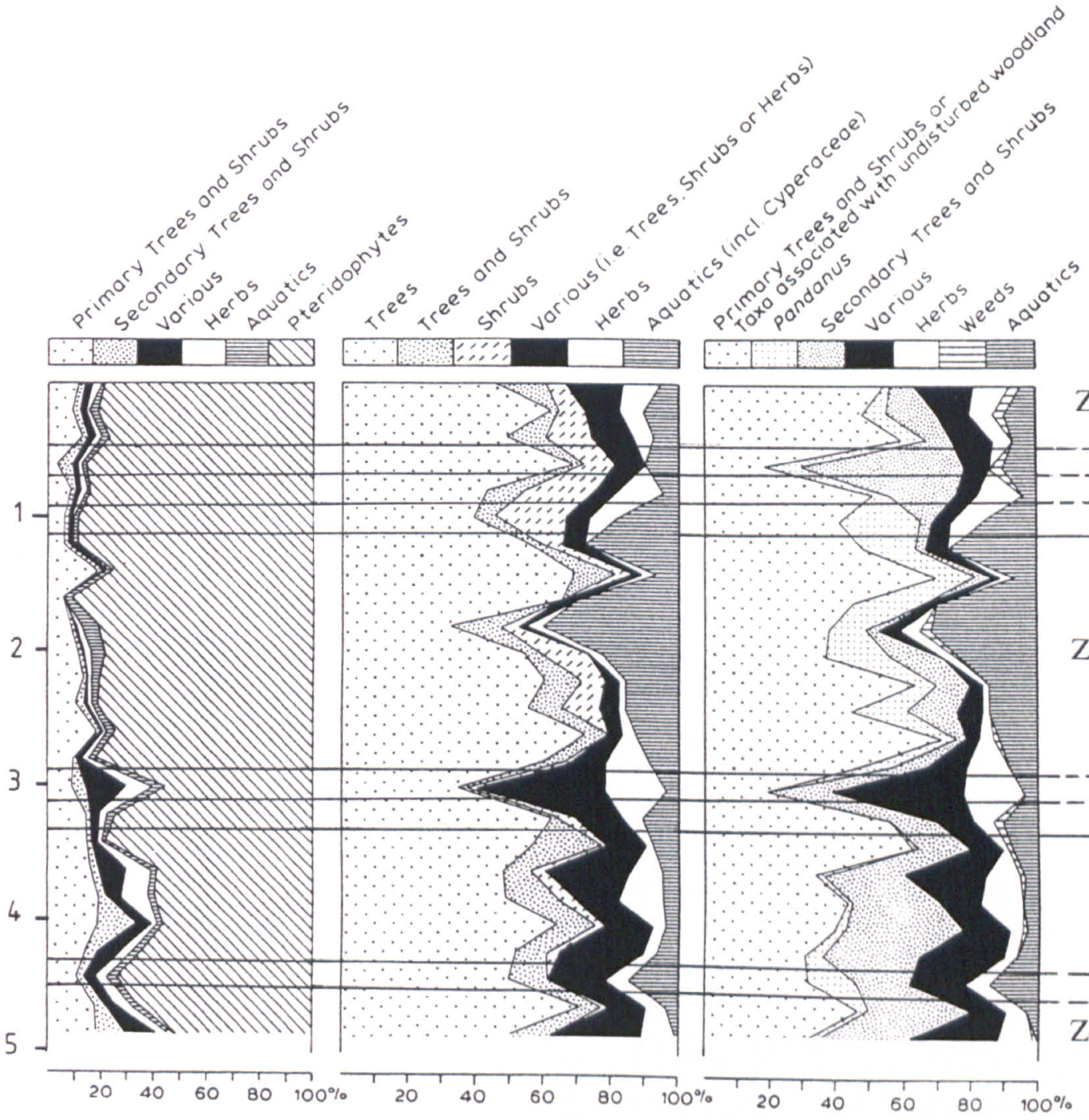


Fig.6.24 Geochemical analysis of the sediments from Lake Vaihiria.

Fig.6.25 Percentage summary diagram of vegetation types from the fossil pollen and spore record of Lake Vaihiria.



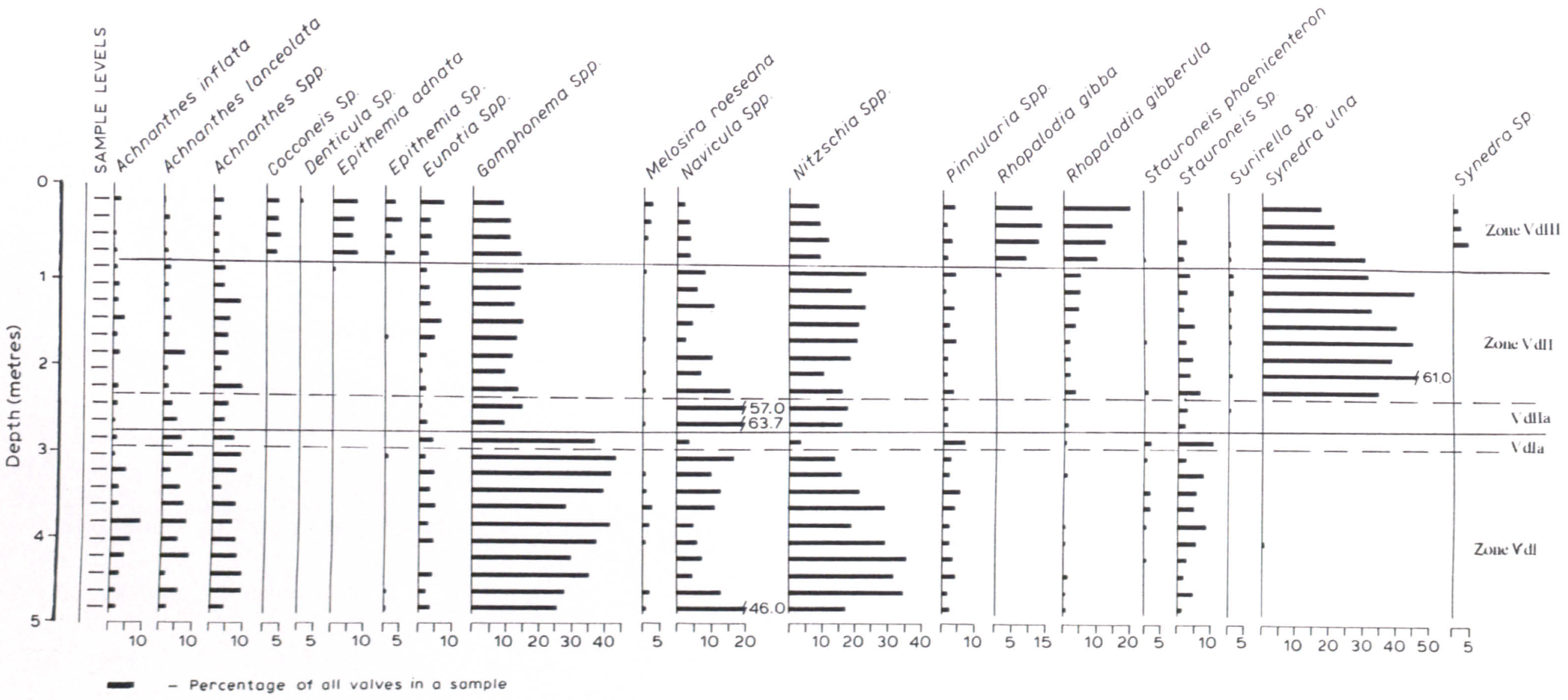


Fig.6.28 Percentage fossil diatoms in the sediment of Lake Vaihiria, Tahiti.

Fig.6.29 Absolute fossil diatom concentrations in the sediment of Lake Vaihiria, Tahiti.

Percentages of all pollen and spores.

Fig.7.1 Pollen diagram from Lake Tiriara, Mangaia. Redrawn from Lamont (unpublished).

APPENDIX 1

SUMMARY OF STATISTICS FROM THE VEGETATION SURVEY ON MO'OREA

A Environmental variables recorded for vegetation plots (see map) on Mo'orea.

Plot number	Vegetation type	Altitude in m. (a.s.l.)	Aspect	Mean slope (Deg.)	Dry bulb (Celsius)	Humidity (%)	Drainage conditions	Degree of shading	Mean soil pH. (0-5cm)		Loss on ignition (%)	Total number of taxa	Number of trees GBH = >0.3m	
									H_2O	0.01M $CaCl_2$			No. of taxa	Total no.
1	O	80	NW	9	-	-	G	L	4.3	3.9	13.2	6	-	-
2	O	80	W	23	-	-	G	L	-	-	-	4	-	-
3	F	160	SSW	13	-	82	M	I	5.4	5.4	19.2	15	2	4.
4	F	280	NNW	21	-	-	G	I	5.3	4.7	28.2	9	2	8
5	F	300	NW	11	-	-	G	I	5.8	5.5	26.0	16	-	-
6	F	500	NE	37	23	96	G	H	5.3	5.3	16.7	34	2	8
7	L	2	-	0	29	46	G	I	7.1	7.0	29.1	8	3	3
8	L	1	-	2	-	-	G	I	-	-	42.2	4	1	13
9	L	3	-	0	-	-	M	I	7.5	7.2	30.0	2	2	15
10	L	2	-	0	-	-	G	I/L	7.6	7.2	33.7	10	1	3
11	F	75	N	20	23	91	M	I	5.7	5.5	18.1	13	2	3
12	F	300	NE	34	23	91	G	I	5.8	5.6	22.1	14	-	-
13	F	270	SW	35	-	-	G	I	5.5	5.4	33.9	10	-	-
14	F	10	NE	25	24	83	G	L	6.2	6.2	17.5	8	-	-
15	O	50	E	17	24	83	M	I	5.3	5.2	23.1	6	-	-
16	O	7	ENE	9	24	83	G	I	5.8	5.5	14.2	10	-	-
17	F	-	-	21	-	95	M/B	I	5.3	5.2	24.1	11	1	7
18	F	200	-	15	23	91	M	H/I	5.3	5.2	25.1	16	3	9
19	O	100	SW	35	-	-	G	L	5.5	5.1	20.1	9	-	-
20	F	50	SW	27	-	-	G	I	6.3	6.0	18.4	14	-	-
21	O	30	W	5	-	-	G	L	5.6	5.2	10.1	13	-	-
22	L	1	W	10	-	-	G	I	7.6	7.2	37.2	10	5	15
23	F	75	NE	3	-	92	M	H	4.8	4.0	27.4	3	1	11
24	F	100	W	12	-	-	M	H	5.6	5.1	25.2	12	-	-
25	O	200	NNE	33	28	57	G	L	5.1	4.8	12.9	6	-	-
26	L	2	-	0	26	84	B	L	7.0	6.9	33.0	2	-	-
27	L	2	-	0	-	-	B	I	7.9	7.4	31.2	2	-	-
28	O	-	NW	25	26	69	G	I	6.3	6.1	11.2	9	2	4
29	F	500	-	30	-	-	G	I	6.3	6.3	33.3	26	4	10

Vegetation Type
L = Littoral
O = Open / disturbed
F = Forest / woodland

Drainage conditions
G = Good
M = Moderate
B = Bad

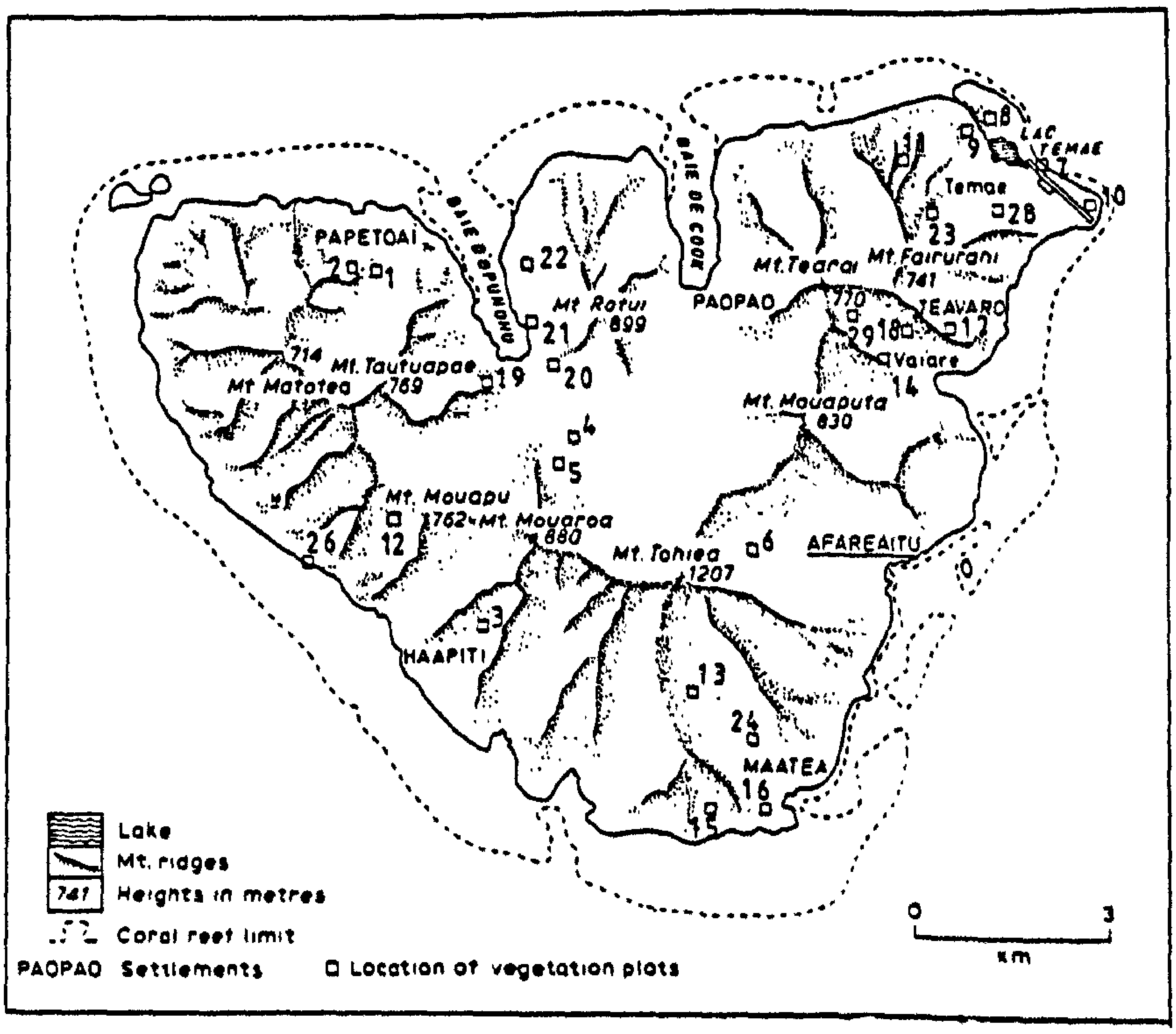
Degree of shading
H = High
I = Intermediate
L = Low

B List of collection numbers and taxa, from the vegetation survey on Mo'orea, used in statistical analyses.

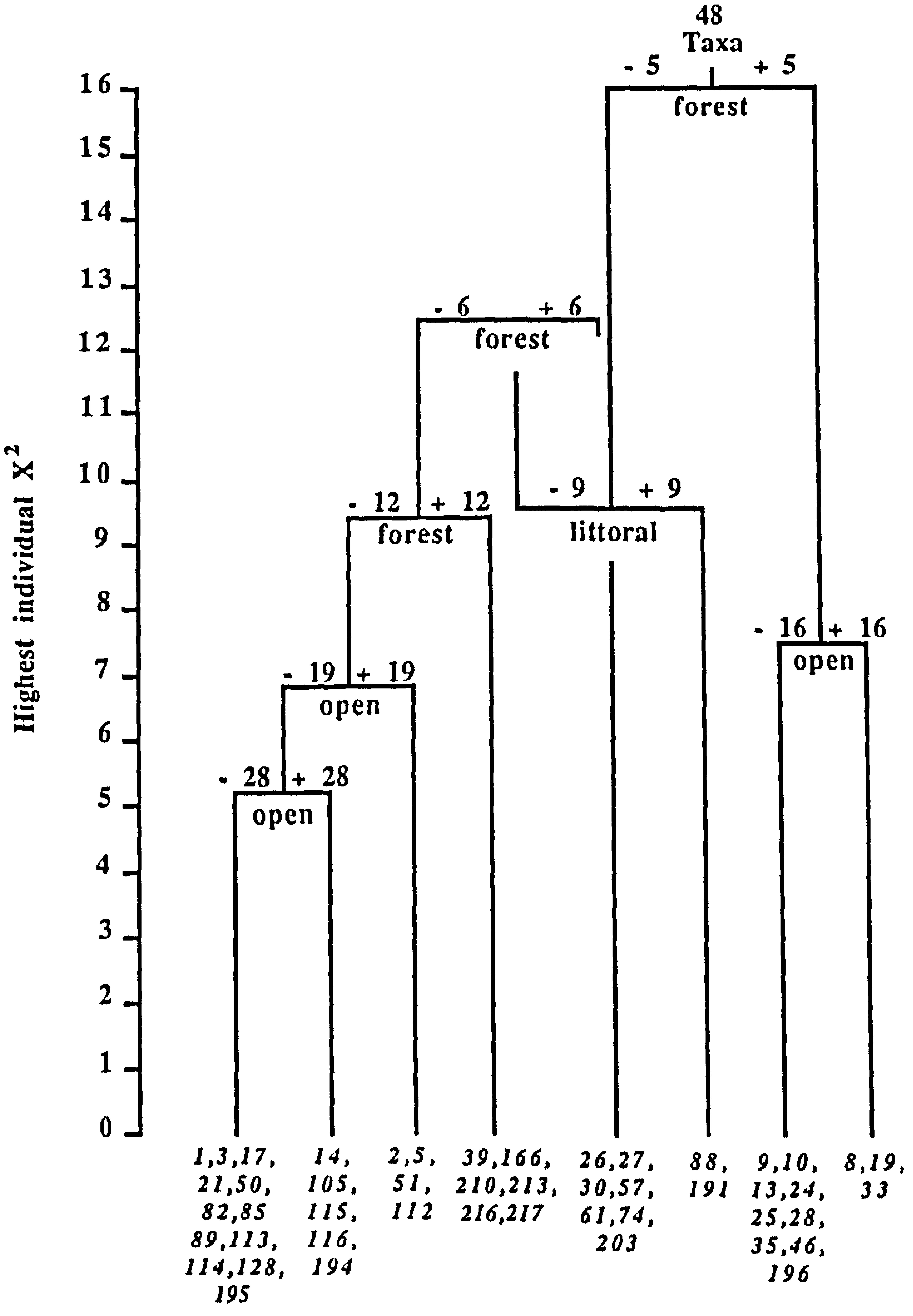
1. *Lycopodium cernuum*, Lycopodiaceae.
2. *Gleichenia linearis*, Gleicheniaceae.
3. *Emilia sonchifolia*, Compositae.
5. *Psidium guajava*, Myrtaceae.
8. *Eugenia* sp., Myrtaceae.
9. *Lomagramma wilkesiana*, Polypodiaceae
10. *Centotheca latifolia*, Gramineae.
13. *Stephania forsteri*, Menispermaceae.
14. *Mangifera indica*, Anacardiaceae.
17. *Bauhinia monandra*, Papilionaceae.
19. *Elaphantopus mollis*, Compositae.
21. *Diplazium polyanthos*, Polypodiaceae.
24. *Freycinetia arborea*, Pandanaceae.
25. *Aleurites moluccana*, Euphorbiaceae.
26. *Stenolobium stans*, Bignoniaceae
27. *Cordyline terminalis*, Liliaceae.
28. *Davallia solida*, Davalliaceae.
30. *Polypodium phymatodes*, Polypodiacaea.
33. *Nephrolepis exaltata*, Oleandraceae.
35. *Inocarpus edulis*, Papilionaceae.
39. *Hibiscus rosa-sinensis*, Malvaceae.
46. Zingiberaceae.
50. *Oplismenus compositus*, Gramineae.
51. *Lantana camara*, Verbenaceae.
57. *Davallia* sp., Davalliaceae.
61. *Asplenium nidus*, Aspleniaceae.
74. *Lygodium reticulatum*
82. Gramineae.
85. *Cassytha filiformis*, Lauraceae.
88. *Pandanus tectorius*, Pandanaceae.
89. *Morinda citrifolia*, Rubiaceae.
105. *Abrus precatorius*, Papilionaceae.
112. *Schizostachyum glaucifolium*, Gramineae.
113. *Adenanthera pavonina*, Mimosaceae.

114. *Eugenia* sp., Myrtaceae.
115. *Morinda citrifolia*, Rubiaceae
116. *Eugenia* sp. Myrtaceae.
128. *Barringtonia asiatica*, Lecythidaceae.
166. Hymenophyllaceae.
191. *Hibiscus tiliaceus*, Malvaceae.
194. *Cocos nucifera*, Palmae.
195. *Erythrina* sp., Papilionaceae.
196. *Angiopteris evecta*, Angiopteridaceae.
203. *Neonauclea forsteri*, Rubiaceae.
210. *Canthium barbatum*, Rubiaceae.
213. *Premna tahitensis*, Verbenaceae.
216. Cyatheaceae.
217. Cyatheaceae.

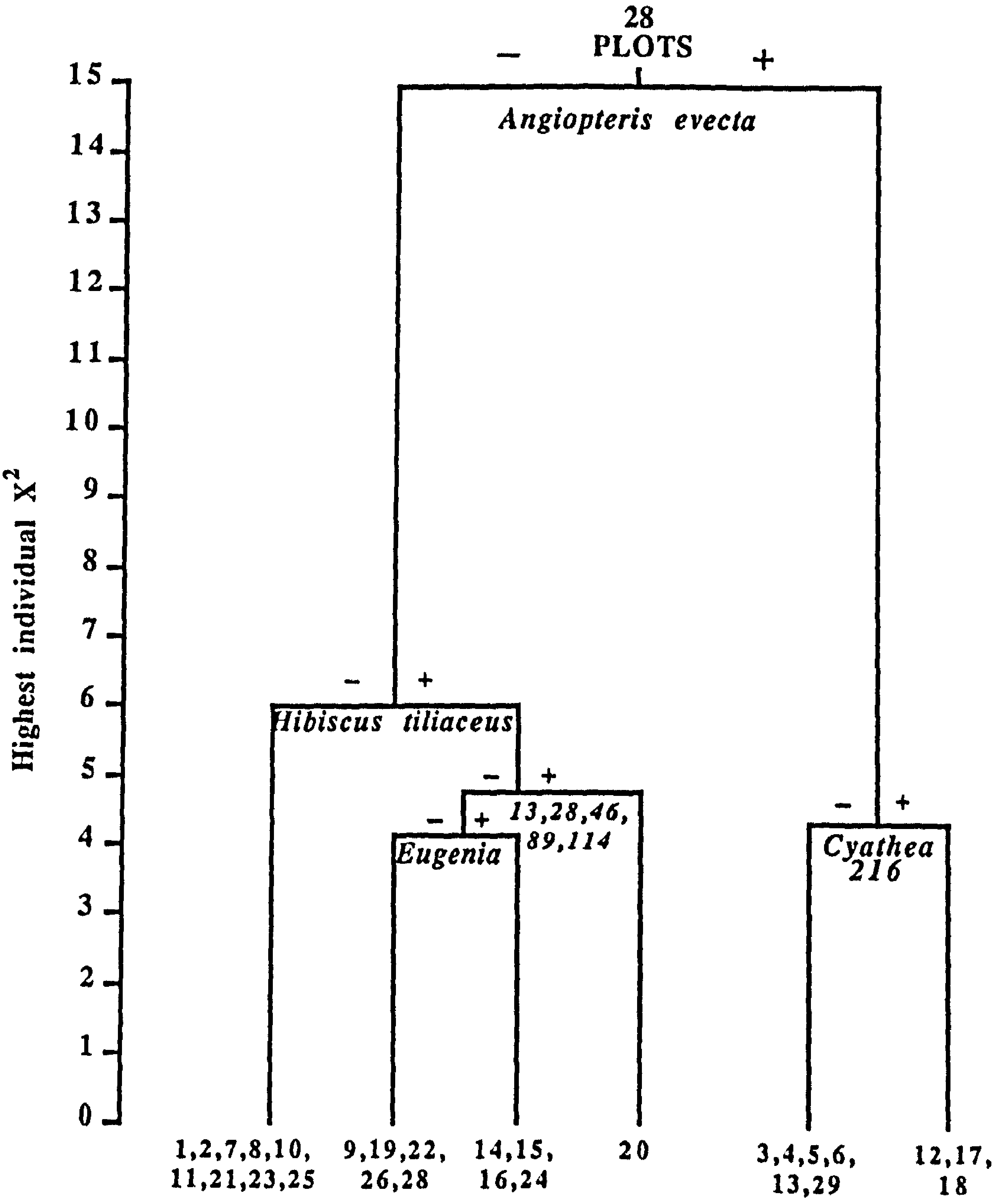
C Location of vegetation plots on the island of Mo'orea.

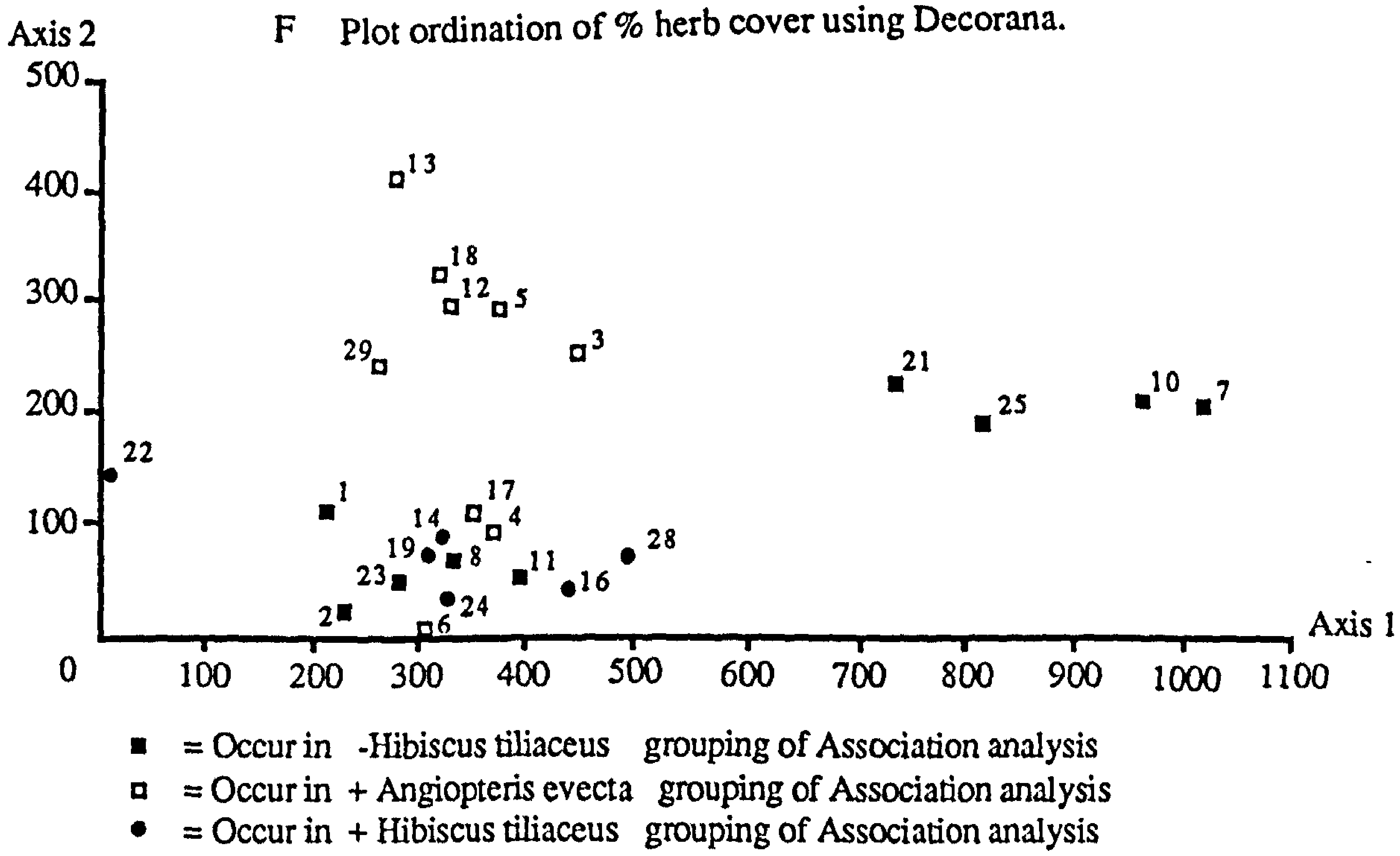


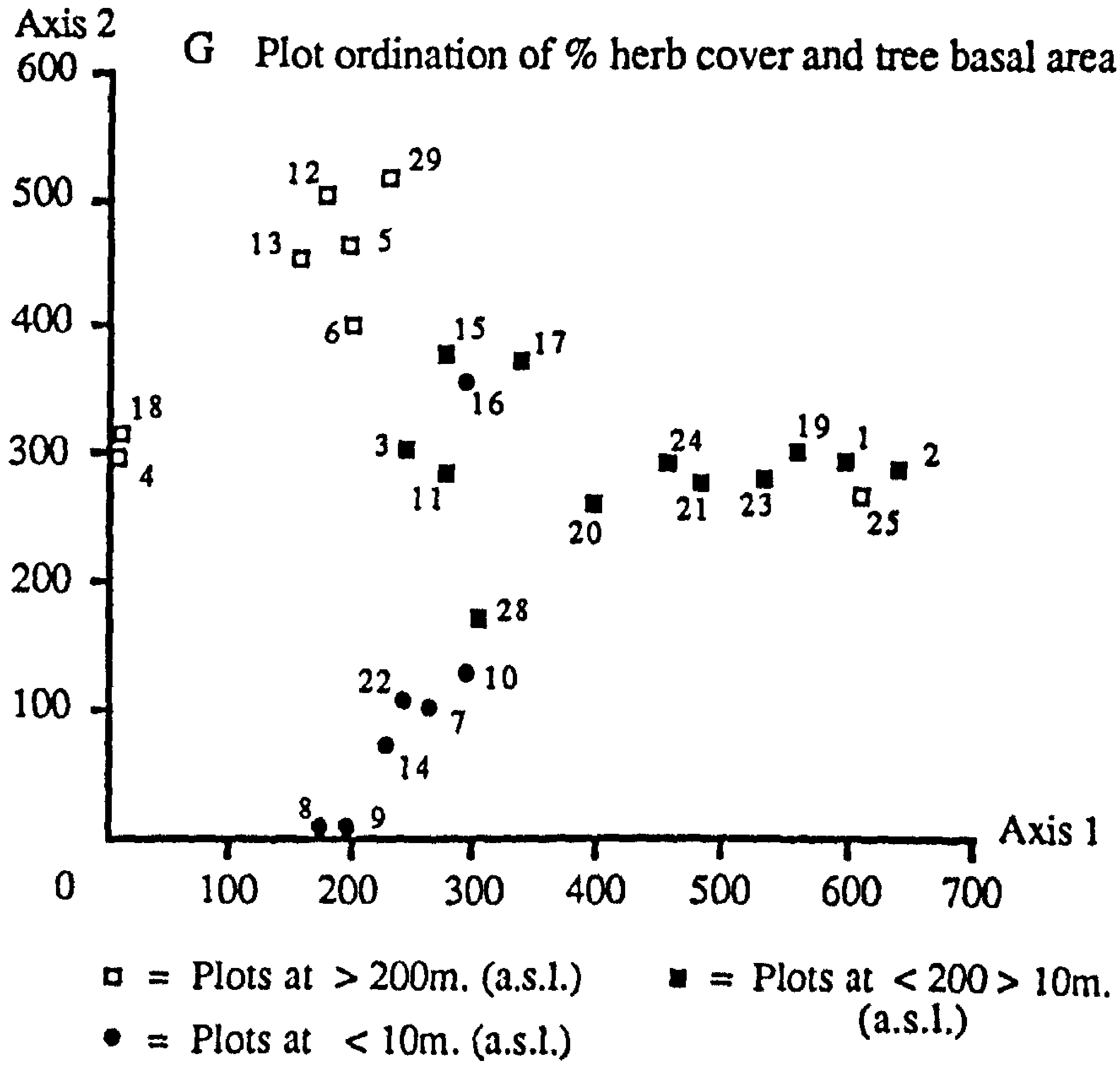
D Classification of taxa using Association analysis.



E Classification of vegetation plots using Association analysis.




F Plot ordination of % herb cover using Decorana.


G Plot ordination of % herb cover and tree basal area using Decorana

H Two-way Association analysis table for the vegetation survey on Mo'orea.

VEGETATION PLOTS

VEGETATION TAXA	5	3	6	28	4	13	18	17	12	20	14	15	16	24	9	26	22	19	27	1	2	7	8	10	11	21	23	25
9	I	I					I	I	I																			
10	I	I	I		I			I																	I			
13	I	I					I			I																I		
24	I			I		I			I																			
25	I				I				I		I			I											I			
28	I			I						I																		
35	I				I	I	I		I								I											
46	I									I																		
196	I	I	I	I	I	I	I	I	I																			
8	I	I			I						I	I	I	I														
19	I	I	I	I									I						I						I	I		
33	I		I	I			I	I	I	I	I	I	I	I				I							I	I	I	
88				I						I	I		I		I							I	I					
191							I		I	I	I	I	I	I	I	I	I	I	I									
26			I								I		I															
27			I	I														I							I			
30			I														I	I										
57			I	I							I			I														
61			I					I																				
74			I	I																								
203			I					I																				
39						I		I																				
166								I	I																			
210									I																I			
213							I		I																			
216							I	I	I																			
217								I	I																			
2																		I		I	I						I	
5																		I	I	I	I							I
51										I								I										I
112								I						I				I										
14		I					I						I						I									
105													I						I									
115										I									I									
116										I									I						I			
194											I						I		I			I		I	I	I		
1				I																I								
3																				I				I		I		I
17		I																			I				I			
21		I				I																						
50																										I		I
82																						I		I				
85																						I		I				I
89										I													I	I				
113										I							I									I		
114										I																		I
128														I			I											
195													I							I								

APPENDIX 2

POLLEN AND SPORE PREPARATIONS.

A. Preparation of fossil pollen samples based on the techniques of Faegri and Iversen (1974) and Tomlinson (1984).

1cm^3 of oven dried (90-100°C) sediment sample was weighed and placed in a polypropylene centrifuge tube in preparation for the chemical removal of the sediment matrix and slide preparation via the following nine steps.

1. Hydrochloric acid (HCl) treatment was used to remove free calcium carbonate.
2. Potassium hydroxide (KOH) treatment was undertaken to deflocculate and remove humic colloids i.e. unsaturated organic soil colloids.
3. Coarse seiving; to remove particles larger than 1mm and to isolate macro-remains for further observation.
4. Acetolysis; to remove cellulose in organogenic deposits and to excentuate features of the pollen exine to aid identification.
5. Hydrofluoric acid (HF) treatment; to remove siliceous material.
6. Oxidation; to remove lignin.
7. Ultrasonic seiving for the deflocculation and removal of fine clay particles.
8. Alcohol dehydration in preparation for sample mounting in silicon oil.
9. Slide mounting.

1\. Samples with free calcium carbonate present were washed in 5% HCl until effervescence ceased, and then neutralized with KOH in preparation for alkane digestion. This preparation was particularly important in the Lake Temae samples which were high in calcium carbonate and were later to be treated with HF.

2\. Approximately 5ml of 10% KOH solution was added to the tubes, which were then placed in a 'dri-block' heater at 100°C for 10 minutes and stirred frequently.

3\. Coarse material in the sediment was removed from the sample by seiving through a 1mm terylene gauze and washed with distilled water to remove as much adherent pollen as possible. Residue was retained for analysis of macro-remains. The liquid containing pollen was then centrifuged in large 100ml centrifuge tubes for 5 minutes at 2000 r.p.m. (revolutions per minute). Supernatant liquid was decanted and the sample transfered to 15ml centrifuge tubes.

4. The sample was washed in 10% acetic acid, stirred, centrifuged and supernatant decanted (= s.c.d.). This was followed by washing in glacial acetic acid, s.c.d.

In the fume cupboard, 2.5ml of a mixture of 9 parts acetic anhydride to 2 parts concentrated sulphuric acid was carefully added to the sample. Heated and stirred in a 'dri-block' heater for approximately 4 minutes at 100°C. An equivalent volume of glacial acetic acid was then added to stop the reaction, stirred, centrifuged and supernatent decanted. The sample was washed in 10% acetic acid, s.c.d., followed by washing in distilled water, s.c.d.

5. Silica was present in most samples and, therefore, for reasons of comparison all samples were treated with HF. The sample tube was placed in a fume cupboard and approximately 5ml of 40% HF was added. The tube was then sealed with a rubber cap and left overnight. Then the cap was removed and the contents heated at 100°C, for 15 minutes, in a 'dri-block' heater. The cap was then replaced and the tube centrifuged. The supernatant was decanted in the fume cupboard into a stream of running water. The sample was washed with hot 5% HCl to remove colloidal SiO_2 and silicofluorides, which would otherwise form a white precipitate, obscurring the pollen preparation. This treatment was kept brief since prolonged heating with this reagent entails risk of exine corrosion. The sample was stirred, centrifuged and supernatant decanted. This was then washed with distilled water, s.c.d.

6. For a number of the samples it was necessary to include an oxidation treatment to remove excessive lignin content. This was undertaken after the acetolysis treatment. In the fume cupboard 1ml of concentrated HCl was added to the sample and stirred. Then 2 drops of saturated sodium chlorate solution was carefully added. The sample was stirred gently until effervescence ceased. If effervescence was slight, more drops were added to a maximum of 6. After no more that 15 seconds distilled water was added to stop the oxidizing reaction. The sample was centrifuged and supernatant decanted. If, after further washing with distilled water the sample was bleached too much, the acetolysis procedure was repeated to re-stain the exine.

7. Deflocculation and removal of fine clay particles was achieved by a short ultrasonic treatment through a 5μm sieve. Aggitation proceeded no longer that 5 minutes since some exines are known to rupture under excessive ultrasonic treatment (e.g.

Cyperaceae). The resultant residue, containing the pollen and spores, was washed into polypropylene tubes, centrifuged and decanted.

8. Dehydration of samples was necessary to allow mounting in silicon oil. This was achieved by washing in 80% ethyl alcohol, 100% alcohol, 50:50 mixture of absolute alcohol and tertiary butyl alcohol (TBA) followed by pure TBA. Each process was followed by stirring, centrifuging and decanting of supernatant. The TBA solidifies in cool temperatures and frequently needed to be placed, in its container, into warm water to bring it back to its liquid state. The samples were then transferred to a small labelled tube with a small amount of TBA and about 1-2ml of silicon oil. (AK 2000). The samples were then stirred and centrifuged until the organic sediment was at the base of the tube. The TBA was then left to evaporate from the tubes in a warm oven.

9. Microscope slides and square cover slips (grade 0) were polished and placed on a slide warmer along with a beaker of molten paraffin wax. The pollen sample was stirred thoroughly with a glass rod. A small drop of silicon oil was placed in the centre of the slide and a small quantity of sample was mixed into it. The slide was inverted and placed, sample down, onto the cover slip. When the sample had spread the slide was sealed with molten paraffin wax which was run under the edge of the coverslip. The wax solidified when removed from the heat and the slide was labelled and ready for counting.

Silicon oil was used in preference to glycerol because of its more permanent property (Andersen, 1960) and relatively low refractive index, which differs significantly from that of pollen being studied (Christensen, 1954). Good contrast could therefore be achieved under the microscope. Glycerol mounts, on the other hand, are short-lived and tend to make the grains swell in size. The advantage a liquid mount, such as silicon oil, over a solid one is that grains may be turned over by slight pressure on the cover slip. This is often essential for the identification of some types which need both equatorial and polar projections or apertures seen both face on and obliquely etc.

B. Preparation of surface sediment pollen samples.

Moss polsters and other surface samples collected in the field area were prepared according to the technique outlined in section A. with the modifications described below.

No exotic pollen was added to the samples. Where samples comprised moss polsters or other bulky fibrous material they were first broken down by treatment in an Actomix blending machine. To do this the whole sample was placed in the container, covered with distilled water and run at half speed for 30 seconds. The sample was transfered to large centrifuge tubes and centrfuged for 5 minutes, at 2000 r.p.m. Subsequent procedure was as outlined from stage 2.

C. Preparation of reference pollen.

Plant material collected in the field was prepared for reference pollen slides. Anthers were removed from the flower and were subjected to KOH and acetolysis treatment. The addition of exotic pollen, HF, oxidation and ultrasonic sieving treatment was unecessary and consequently ommitted. The sample was dehydrated and mounted as described from stage 8.

APPENDIX 3

ECOLOGICAL AND ETHNOBOTANICAL NOTES FOR TAXA DETERMINED FROM THE FOSSIL POLLEN RECORD.

Taxa of fossil pollen and spores found in the sediment of Lake Lanoto'o (Lan), Lake Roto (Roto), Lake Temae (Tem) and Lake Vaihiria (Vh), are listed in alphabetical order. The probable origin of taxa are indicated by the following symbols: E - endemic; I - indigenous to an island or group of islands; A - aboriginal introduction; R - recent or historical introduction. Notes on the ecology of taxa and ethnobotanical points have been obtained from the listed botanical literature as well as vegetation studies on the islands by the author. Where the fossil pollen has only been identified to genus, ecological notes of the most likely occurring species have been noted for particular localities.

Main botanical literature referred to:

Brown, F.B.H. (1931, 1935); Chabouis, L. & Chabouis, F. (n.d.); Cheeseman, T.G. (1903); Florence, J. (1983); Fosberg, F.R. & Sachet, M.H. (1972); Franklin, J. & Merlin, M.D. (n.d.); Jacquier, H. (1960); Lamoureux, C.H. (1976); Maxon, W.R. (1924); Merlin, M.D. (1977, 1980, 1985, 1991); Merrill, E.D. (1981); Moore, J.W. (1940); Papy, H.R. (1954); Setchell, W.A. (1924); Vaupel, F. (1910); Whistler, W.A. (1980a, 1980b, 1983, 1984, 1988, 1990); Wilder, G.P. (1931).

***Acalypha* sp.**, Euphorbiaceae: (Lan, Roto, Tem-R) Possibly *Acalypha hispida*, an introduced, erect shrub common around settlements and disturbed areas on Rarotonga (Wilder, 1931). Alternatively, *Acalypha indica*, an erect herb up to 1.2m in height, and found occasionally on roadsides, in crops, and in waste places. This weed is a native to tropical Asia and was first reported from Samoa in 1905 and from Niue in 1981 (Whistler, 1983).

Achyranthes aspera, Amaranthaceae: (Tem-A) Synonym: *Achyranthes indica.* A little-branched woody herb or shrub up to 4m high, occasionally found in sunny coastal areas of littoral shrubland, and often becoming weedy in coastal plantations along roadsides. It is widespread in the Tropics, and is probably an aboriginal introduction throughout Polynesia (Whistler, 1980), but is generally of little value.

Acrostichum aureum, Pteridaceae: (Lan, Roto, Tem-I) The marsh fern is a large, leathery fern, with pinnate fronds up to 4m long, often growing near rivers and in swampy areas of the Ngaputoru group. Fosberg and Sachet (1972) describe *Acrostichum aureum* as a pantropical fern found in both fresh and saline marshes, water seeps, and swamps, especially around edges of mangrove swamps. Small patches of this fern were noted on the N-W coast, in a saline flat on Maupiti (Society Islands), and more commonly in littoral shrubland and coastal marshes, as well as on the face of maritime cliffs throughout Samoa (Setchell 1924; Whistler, 1980b, 1983) and Tahiti (Maxon, 1924). Since it is a shade-intolerant species, it does not occur in mature forest areas but only in openings and along the margins of the forest.

Ageratum conyzoides, Compositae: (Roto, Tem, Vh-R) Pantropic weed around 30-60cm in height and common on roadsides, in waste places, and in cultivated crops such as taro. Prefers moist habitats, but can survive in dry ones as well (Whistler, 1983). This herb was originally native to tropical America, and was first reported from Samoa in 1864 (Whistler, 1983).

Allophylus vitiensis, Sapindaceae: (Roto-I) A large native tree, common in all the valleys on Rarotonga, and on the dry hillsides at the lower elevations.

***Allophylus* sp.**, Sapindaceae: (Lan-I) Probably *Allophylus vitiensis* as above.

Alphitonia zizyphoides, Rhamnaceae: (Lan-I) A very large native tree, 25-30m high (Florence, 1983), and noted in Samoa (Setchell, 1924) occurring on steep slopes and almost vertical cliffs at high altitudes where it forms pure associations. Whistler (1980b, 1984) noted the presence of *Alphitonia* in both primary montane communities and secondary lowland forests on Samoa, and also found it associated with the *Rhus* secondary forests between 50 and 500m elevation. Papy (1954) noted that this species was present in the *Metrosideros* forests of the Society islands and preferred areas of high light penetration. The hardwood of this tree is valued for clubs, spears and tool handles.

Alsophila sp., Cyatheaceae: (Lan, Tem, Vh) Generally large, native tree ferns common in high mountain areas and damp forest.

Alstonia costata, Apocynaceae: (Tem) Small tree (8-10m) common on all hills and mountains of Rarotonga above an altitude of 80m. One of the dominant taxa of mid- and high-altitude hygrophile forest in the high islands of the Societies (Florence, 1983), especially in the cloud forests of Tahiti (up to an altitude of 1800m) and Mo'orea, where it occurs on the slopes and windward valleys. Often found growing with *Cyathea*, *Ilex* and *Weinmannia*.

***Altingia* sp.**, Altingiaceae: (Vh-I) Native tree which is rarely found today in the high-altitude hygrophile forests of Tahiti.

Alyxia stellata, Apocynaceae: (Roto-I) An indigenous climbing shrub which is common from the *makatea* to montane forest of Rarotonga. Commonly used to make garlands.

Angiopteris evecta, Angiopteridaceae: (Lan, Roto, Tem, Vh-I) Robust "tree" fern found in Samoa from near sea-level up to 200m altitude or more (Setchell, 1924), in lowland to montane forest (Whistler, 1984). This indigenous king fern is also common in inland valleys and rainforests of Rarotonga and Mangaia where it is referred to as *Angiopteris longifolia*. It also forms an important component of the valley and upland forests on Mo'orea and Tahiti, but is no longer found on the lower islands of Atiu and Ma'uke.

Antrophyum plantagineum, Vittariaceae: (Tem) An epiphytic fern frequently found in the *Hibiscus-Ficus* riparian forests which are typical of the lower valleys of Tahiti and Mo'orea.

Araliaceae: (Lan, Tem, Vh) Many species of the family Araliaceae are found at all three locations, and the majority of species are undisturbed forest plants. The Lanoto'o species may well include *Meryta macrophylla*, a small but common tree of the lowland to cloud forests (Whistler, 1984).

***Artocarpus* sp.**, Moraceae: (Tem-A) Probably *Artocarpus incisa*, the breadfruit tree, which reaches a height of 8-14m and is universally cultivated around villages to provide an important source of food.

Ascarina polystachya, Chloranthaceae: (Tem, Vh-E) Endemic tree of mid- and high-altitude hygrophile forests of Mo'orea and Tahiti (Papy, 1954; Florence, 1983).

***Ascarina* sp.**, Chloranthaceae: (Lan-I) Either *Ascarina diffusa* or *Ascarina lanceolata*, both trees of the high-altitude and constantly wet cloud forests. Christophersen (1938) notes the occurrence of *Ascarina lanceolata*: on Upolu at the top of Fao mountains at an altitude of 680m; and on Savai'i up to 1600m altitude. According to Powell (1868) the dried leaves of *Ascarina* were often used to scent coconut oil and to stuff pillows.

Asplenium nidus, Aspleniaceae: (Roto, Vh-I) The indigenous "bird's-nest fern" is common in woods from sea-level to the highest mountains, in all the valleys of Rarotonga. Grows on trees, rocks, old logs, and along the sloping banks of moist hillsides (Wilder, 1931). Either epiphytic or terrestrial, it grows best in the cloud forests of the Society Islands but is also common in the riparian forests of the lower river valleys (Florence, 1983). However, because of its popularity as an ornamental the numbers of this fern are declining rapidly. The large fronds are also used to wrap up food cooked in underground ovens, while the frond tips are sometimes baked and eaten.

Asplenium sp., Aspleniaceae: (Lan, Tem) One of several *Asplenium* species frequently found in moist and shaded locations.

Astelia nadeaudi, Liliaceae: (Tem, Vh-I) A native perennial herb, usually growing on the trunks and branches of native trees (particularly *Weinmannia* and *Metrosideros*) found in the wet, high altitude regions of Tahiti (Florence, 1983; Papy, 1954). Also found in pockets of organic soil in the summit scrub vegetation of Tahiti, where intense insolation, relatively low moisture and high exposure to winds prevail.

Astronia fraterna, Melastomataceae: (Tem-I) Native tree of the arborescent zone of vegetation between 900-1500m on the Society Islands, and frequently associated with windward slopes. Often found growing with the fern *Angiopteris* and climbing shrub *Freycinetia* (Papy, 1954).

Barringtonia asiatica, Barringtoniaceae: (Roto, Tem-I) Synonym: *Barringtonia speciosa*. The indigenous fish-poison tree grows up to 20m high and is commonly found in mixed littoral forest vegetation (Whistler, 1980), but often forms nearly pure stands on rocky coasts. The timber is used for building boats, but the wood is not very durable. Seeds are often crushed and put into the lagoon to stupefy reef fish.

Bidens paniculata, Compositae: (Vh-I) Native woody composite which reaches 1-2m in height and is found in the forest habitats of Tahiti (Florence, 1983; Papy, 1954).

Bidens pilosa, Compositae: (Roto, Tem, Vh-R) The introduced "beggar's tick", an annual herb around 20-90cm high and very common in dry areas, particularly in waste places and croplands. This pantropic weed was an early introduction to Polynesia, first reported from Samoa in 1839 and from Tonga in 1840 (Whistler, 1983), but was originally native to tropical America.

Bidens sp. Compositae: (Vh) Most probably *Bidens societatis*, an endemic composite present on the summit slopes of Tahiti (Papy, 1954).

Bischofia javanica, Bischofiaceae: (Roto A/I) A large, aboriginally introduced, or possibly indigenous tree, occasional in the valley and montane forests of Rarotonga (Whistler, 1990) and in forest openings in the low- to mid-altitude forests of Samoa (Christophersen, 1938). Although this tree was and still is important in Tonga and Samoa for the brown dye obtained from its trunk used to colour *tapa* cloth, no such use has been reported from the Cook Islands. Present pollen studies (Southern, 1986) show possible over-representation of this genus in the pollen rain.

Caesalpiniaceae: (Tem) Probably *Caesalpinia bonduc*, synonyms: *C. jayabo*, *C. bonducella*, and *C. crista*. A prickly, sprawling shrub or climber, found in disturbed coastal areas of Samoa (Whistler, 1984) and the Society Islands. A widespread species of the Tropics, but regarded as a pest due to the prickles and scrambling nature. The stems were used in some parts of Polynesia to trap fruit bats, and the hard seeds are still commonly used to make seed ornaments.

Calophyllum inophyllum, Guttiferae: (Tem-I) An indigenous spreading tree up to 25m in height, which is commonly found in the littoral forest on sandy beaches of atolls and high islands, and extending into the coastal forests of high islands. The fruits of this tree are ideally adapted for dispersal by water. Although *Calophyllum inophyllum* is referred to as a littoral species by Whistler (1983), Franklin and Merlin (n.d.) did not find it immediately adjacent to the coast in the Ngaputoru group of the Cook Islands, and Sabath (1977) also found *C. inophyllum* occurring away from the coast on the lagoon-edge of an atoll. Because of this, Merlin (1991) and Whistler (1990) suspect that *C. inophyllum* may have been transplanted into interior forests because of its value as a timber tree.

In pre-missionary times *Calophyllum inophyllum* was largely planted by the natives about their stone *marae*, or religious meeting-places, and their idols were carved from its wood. Great numbers of trees were consequently cut down by order of the first missionaries, hence its present scarcity. This is particularly true of the Society Islands and the Cook Islands. The wood was highly valued on account of its durability and canoes were frequently made from it, while the seeds, leaves, gum and bark are reported to have medicinal uses. A brown dye extracted from the fruit was used for colouring *tapa* cloth in Hawai'i, and an oil was obtained from the kernel for use in lamps (Whistler, 1980). Its native name in Tahiti and Rarotonga is *tamanu*. Present pollen studies (Southern, 1986) show that this genus may be under-represented in the pollen rain/fossil record.

***Calophyllum* sp.**, Guttiferae: (Roto) Most probably *Calophyllum inophyllum* as above.

***Cananga* sp.** Annonaceae: (Vh-A) Possibly *Cananga oderatum*, a large shade tree (Papy, 1954) common under cultivation in native gardens and often indicative of forest disturbance. The fragrant flowers are used for scenting coconut oil.

Canthium barbatum, Rubiaceae: (Roto-I) Synonym: *Cyclophyllum barbatum*. Tall shrub or small tree, common from seashore to the highest mountains in Rarotonga. The wood of this tree is hard and durable and used to make booms for attaching the outrigger to native canoes.

***Canthium* sp.**, Rubiaceae: (Roto) Possibly a variety of *Canthium barbatum*, as above.

Canthium merrellii, Rubiaceae: (Lan) Important canopy tree of the *Disoxylum huntii* forest of upland Upolu, Samoa (Whistler, 1980b).

Casuarina equisetifolia, Casuarinaceae: (Roto, Tem-A/I) Synonym: *Casuarina littorea*. A medium to large pine-like tree common in littoral and lowland forests and on fernland, but sometimes found occurring further inland, for example, high up on the hills of Rarotonga. It is a widespread tree, ranging from Malaysia to Polynesia and Micronesia, and widely cultivated elsewhere in the Tropics and is commonly planted around houses and along the shoreline. However, it cannot resist fire and is completely destroyed on burning (Papy, 1954). *Casuarina* is generally regarded as an aboriginal introduction to Polynesia, but Franklin and Merlin (n.d.) suggest that it may be indigenous to the Cook Islands. The "ironwood" tree has many reported uses in Polynesia and was the favoured wood for making war clubs, house posts, tools, and outrigger booms for canoes, while the bark is reported to have been used in Tonga for preparing a medicine. Native name: *toa*.

Celtis paniculata, Ulmaceae: (Roto, Tem, Vh) Small tree about 3m in height, commonly found in the valleys and on slopes up to an altitude of 300m in Rarotonga. When the foliage is bruised it emits a fragrant odour which is used in the making of wreaths (Wilder, 1931).

Christella dentata, Thelypteridaceae: (Vh) Synonyms: *Dryopteris nymphalis*, and *Cyclosorus dentatus*. Erect fern up to 120cm in height and commonly found in secondary forest, forest clearings, coconut plantations, and bush fallow. Widespread throughout the Old World Tropics and Subtropics and is native to Samoa and Tonga.

Claoxylon tahitensis, Euphorbiaceae: (Tem, Vh) Medium to large native tree (~10m) of the arborescent zone between 900-1500m on the Society Islands. Often found growing with the fern *Angiopteris* and climbing shrub *Freycinetia* (Papy, 1954).

Cocos nucifera, Palmae: (Lan, Roto, Tem A/I) Stately palm, often reaching a height of more than 30m. Whistler (1980) records this palm as the most common tree of inhabited shores, but is not often found in undisturbed littoral forest. The coconut is found throughout the Tropics and Subtropics of the world and although it is able to disperse naturally, Whistler (1990) suggests that it is probably an aboriginal introduction over much of its range, as it is in Hawai'i. Fosberg and Sachet (1972) suggest that the coconut was either introduced by humans or by floating from a probable Indian Ocean origin. Much controversy has surrounded the origin of this plant, as no truly wild plants are known that could not have been carried by people. The old argument that *Cocos nucifera* must be of American origin (Cook, 1910), because the other members of the Cocoineae are American, is no longer entertained as *Cocos* is now regarded as a monotypic genus more closely related to genera in South Africa. However, the association of *Birgus latro*, the coconut robber crab, with its dependence upon the coconut, provides a strong argument for an Indian or Indo-Pacific origin of both.

As Wilder (1931) relates "The coconut is doubtless the most useful of all trees to the people of the South Sea islands, furnishing as it does, not only nourishing food and drink, but wood for house-building, and leaves for thatching roofs. The shells are utilized for domestic utensils, and the oil for medicinal and personal purposes. The leaflets of the long flexible leaves are dexterously plaited together by the native people and form durable waterproof covering for their houses. From the exceptionally thick husk of a certain variety of coconut (*palmyraensis*), a strong and durable rope called sennit or coir is made. The coconut tree thrives best in sandy soil about sea level, it will, however, grow and bear fruit at higher elevations." The copra, from the dried endosperm, is also a very important commercial crop, being the source of coconut oil, used in soap-making and for food oils and fats. Whistler (1990) notes that while the leaves of coconut are very important to the maoris of the Cook Islands, they are generally regarded as inferior to the leaves of *Pandanus* species. Whistler (1983) also noted that, under disturbed conditions, coconut palms cannot successfully compete with coastal forest trees, unless tended or replanted.

Colocasia esculenta, Araceae: (Roto, Tem-A) The aboriginally introduced taro is a herb with tuberous edible roots (or corms) which "furnished the principal article of diet during times when the population of Rarotonga was larger than it is today" (Wilder, 1931). This plant is still extensively cultivated, sometimes on dry ground, but more generally in artificial ponds or swamps and is the favourite staple food in the Cook Islands where it is boiled or baked in earth ovens.

Commelina nudiflora, Commelinaceae: (Roto) A creeping herb common up to altitudes of 300m on Rarotonga, especially in damp places. Found as a pioneer plant on degraded and frequently burnt soils in the Society, where it was recorded as being introduced in 1850 (Papy, 1954). Often planted as an ornamental or collected for horse forage.

***Commelina* sp.**, Commelinaceae: (Tem) Possibly *Commelina diffusa*, the introduced water-grass, a common weed of taro patches and other wet habitats.

Coprosma tahitensis, Rubiaceae: (Tem, Vh) A small tree or shrub that grows on mid-altitude slopes and crests of Tahiti and Mo'orea. Often associated with the mesotropical *Metrosideros-Dodonaea* forests.

Coprosma laevigata, Rubiaceae: (Roto) Small tree 2 to 7m in height found up to altitudes of 400m in some relatively undisturbed districts of Rarotonga. When bruised, the leaves are fragrant and are used as garlands for personal adornment (Wilder, 1931).

Cordyline terminalis, Agavaceae: (Tem-I/A) Synonym: *Cordyline fruticosa*. Erect shrub with an enlarged edible root, which is today common in cultivation, but persists in the wild in many areas formerly cultivated. Noted in Samoa (Christophersen, 1938) in moist forests and openings from the lowlands to the highlands. This shrub is believed to be native to the western Pacific region, but carried by Polynesians to the eastern island groups.

***Cordyline* sp.**, Agavaceae: (Vh) Probably *Cordyline terminalis*, as above.

Cyathea affinis, Cyatheaceae: (Roto, Tem, Vh-I). Arborescent fern associated with the high-altitude undisturbed cloud forests of the Society Islands (Florence, 1983; Papy, 1954).

Cyathea horrida, Cyatheaceae: (Tem, Vh-I) Synonym: *Hemetelia horrida*. Tree fern of wet, usually montane, forests, growing in deep shade of forested slopes, on stream banks or near waterfalls. *Cyathea horrida*, whose stem can reach up to 4m tall, often occurs as an understorey species (Tryon and Tryon, n.d.).

***Cyathea* sp.**, Cyatheaceae: (Roto-I) Possibly *Cyathea parksiae* or *Cyathea decurrens*, both native species of tree fern common in the damp woods of Rarotonga (Wilder, 1931; Whistler, 1990).

Cyatheaceae: (Lan, Roto, Tem, Vh-I) Generally large, native tree ferns common in high mountain areas and damp woods. Whistler (1984) records the presence of *Cyathea* species both in the undisturbed cloud forests of Samoa as well as in disturbed forests.

***Cyathula* sp.**, Amaranthaceae: (Roto) Possibly *Cyathula prostrata*, a small erect herb of aboriginal introduction, occasional in disturbed places and common on sandy stretches near the seashore.

Cyperus pennatus, Cyperaceae: (Roto-I) Synonyms: *Mariscus javanicus*, *Cyperus javanicus*, *Mariscus pennatus*. An indigenous sedge up to 1m high, found in wet places and sometimes in sunny, littoral habitats. Common in the humid, central depressions of atolls in the Society Islands (Florence, 1983), and associated with the more disturbed coastal marshes on Samoa (Whistler, 1980b). The Maori name *mauku tatau tai* literally means "plant for squeezing coconut", a use to which the stem fibres are sometimes put. It was formerly used to strain *kava*, and parts of the plant are occasionally employed in native medicines (Whistler, 1990).

Cyperaceae: (Lan, Roto, Tem, Vh) The species from the Atiu sequence is possibly *Cladium jamaicense*, an indigenous sedge, dominating the marshes of Miti'aro but less common today on Atiu and Ma'uke. Found in Maupiti forming large pure stands in low wet spots in *motus*. Most species belonging to this family are associated either with moist, swampy areas, or are weedy species in open disturbed areas.

Davallia solida, Davalliaceae: (Tem, Vh) Most common fern throughout the island of Rarotonga from sea-level to high mountain (Wilder 1931) and common in shaded and moist places in the Societies (Papy, 1954). The Samoans call it the "coconut fern" since it is frequently found epiphytically on the trunks of Coconut trees (Setchell, 1924).

Dodonaea viscosa, Sapindaceae: (Tem, Vh-I) A shrub or small tree common on the dry hills, particularly in rocky places, between an altitude of 100-200m on Rarotonga, and in the lower mountains on dry, exposed, windswept ridges of Hawai'i (Merlin, 1977). Often found in association with *Metrosideros collina* in drier parts of Tahiti and Mo'orea from an altitude of 300-1000m (Florence, 1983; Papy, 1954).

***Dysoxylum* sp.**, Meliaceae: (Lan-I) Three species of *Dysoxylum* occur on Samoa. *D. samoense* and *D. maota* are both canopy trees of the climax forest which covers the flat to moderately sloping lowlands, particularly on deep alluvial soils of coastal valleys. This forest is replaced at higher altitudes by the *Dysoxylum huntii* montane forest, which extends above 1000m on Upolu and is found occurring around Lake Lanoto'o (W.A. Whistler, pers. comm.). *Dysoxylum huntii* is a tall tree (up to 20m) with a straight stem with green wood that readily burns and has consequently become a favoured fire-wood. Present pollen studies (Southern, 1986) show that this genus may be under-represented in the pollen rain/fossil record.

Elaeocarpus tonganus, Elaeocarpaceae: (Lan, Roto-I) Synonym: *Elaeocarpus rarotongensis*, a medium-sized, indigenous tree, common from the *makatea* to the montane forest in Rarotonga. Franklin and Merlin (n.d.) noted that *E. tonganus* tended to occur at higher elevations on the raised *makatea* regions of the Ngaputoru group of the

Cook Islands. Whistler (1980b) noted the presence of *E. tonganus* in the *Dysoxylum huntii* montane forest community of Samoa. Present pollen studies (Southern, 1986) show that this genus may be under-represented in the pollen rain/fossil record.

Elephantopus mollis, Compositae: (Roto, Tem-R). An erect herb, mostly 50-150cm in height, and common in dry, sunny, disturbed places and plantations. It is reported to be a noxious weed in many tropical countries and is capable of colonizing burnt and degraded soils (Papy, 1954). Originally native to tropical America, and was first reported from Tonga in 1953, but has not yet been reported from Samoa.

Eugenia rariflora, Myrtaceae: (Tem-I) A tree of the mid- and high-altitude hygrophile forests of Mo'orea and Tahiti, often associated with areas of *Metrosideros collina* (Florence, 1983).

Euphorbia hirta, Euphorbiaceae: (Lan-R) Synonym: *Euphorbia pilulifera*. Erect to ascending herb, 6-60cm in height, and very common in gardens, croplands, on roadsides, and open or disturbed areas generally. This cosmopolitan weed was an early introduction into Polynesia, and was first reported from Samoa in 1839 and from Tonga in 1840.

Euphorbia sp., Euphorbiaceae: (Tem-I) Probably *Euphorbia atoto*, synonym: *Euphorbia chamissonis*, a common weed along the seashore and also on dry hills (Wilder, 1931).

Fagraea berteriana, Potaliaceae: (Tem-I) A large indigenous tree, occasionally growing in the mountain ridge forests of Rarotonga, and in the *Metrosideros* forests of the Society Islands in areas of high light-intensity (Papy, 1954). It is common in the coastal to montane forests of Samoa where it becomes established as an epiphyte, develops as a strangler, and eventually becomes an independent tree (Whistler, 1980b, 1984). The timber is fine-grained but usually twisted, and is used for making handicrafts, while the fragrant flowers are sometimes used for adornment. According to Savage (1962), this tree was considered to be sacred in former times.

Ficus rarotongensis, Moraceae: (Roto-I) Large indigenous tree with only a small number of specimens now found on Rarotonga. Pollination by birds or insects and therefore slightly under-represented in the pollen record.

Ficus tinctoria, Moraceae: (Roto, Tem-I) Indigenous wild fig tree with aerial roots commonly found in all districts of Rarotonga, and also seen on the highest hills and mountains (Wilder, 1931). Also found in lowland valleys along river courses and in some humid mountain areas of Tahiti (Florence, 1983). Cultivated by the natives around their dwellings as shade trees. A coarse cloth was formerly made from the tough bark, while the dried stems, which will smoulder for a long time, were taken by fishermen in their canoes to light their cigarettes (Whistler, 1990). Pollination by birds or insects.

***Ficus* sp.**, Moraceae: (Lan) Probably one of the two large banyan species, *Ficus obliqua* or *Ficus prolixa*, naturally present in coastal to montane forests throughout the islands of Samoa, but also frequently planted.

Fimbristylis cymosa, Cyperaceae: (Tem) Synonyms: *Fimbristylis pycnocephala* and *Fimbristylis atollensis*. A perennial, clump-forming sedge with flowering stems up to 40cm high. Forms an important part of the rock strand vegetation and is often the dominant plant in this harsh habitat. Most species of the rock strand habitat are salt tolerant and require bright sunlight (Whistler, 1983b). *Fimbristylis cymosa* can withstand trampling and is the principal component of lawns around settlements. It is a widespread species, ranging from Tropical Asia to Eastern Polynesia and Hawai'i.

***Fitchia* sp.**, Compositae: (Tem, Vh-E) Either *Fitchia tahitensis* or *Fitchia nutans*, both small endemic tree composites (5-6m) found growing in the mesophile or hygrophile forests of Tahiti. Also recorded by Papy (1954) on the summit slopes of Tahiti.

Flacourtiaceae: (Lan, Tem) Possibly *Xylosma suaveolens*, a small tree widespread throughout Polynesia and found in high-altitude forests of Samoa (Whistler, 1980b), or *Hibiscus-Ficus* riparian forests of the Society islands (Florence, 1983).

Freycinetia arborea, Pandanaceae: (Tem-I) A native woody climber which spreads out over the floors of lowland and upland forests and wraps itself up around the trunks of the taller trees, often forming dense, impenetrable thickets. This tree forms a major component of the *Cyathea-Freycinetia* vegetation stage of hygrotropical forests of Tahiti and Mo'orea, particularly in areas of high humidity and low light penetration (Papy, 1954).

Freycinetia impavida, Pandanaceae: (Tem, Vh-I) Similar form and habitat to *Freycinetia arborea* above.

***Freycinetia* sp.**, Pandanaceae: (Lan, Roto) Samoan species is likely to be *Freycinetia samoensis*, generally widespread on the islands of Upolu and Savai'i and occurring in both primary and secondary forests. It climbs almost vertically up trees and holds on by means of attaching roots.

Fuchsia cyrtandroides, Onagraceae: (Vh-E) A tree 5m high, endemic to the Society Islands (Papy, 1954), and recorded in the rainforest of Tahiti on the south side of Mount Orohena, at an altitude of 1500m (Moore, 1940).

Gardenia tahitensis, Rubiaceae: (Tem-I) *Gardenia tahitensis*, the "Tahitian gardenia", is a fragrant-flowered shrub or small tree up to 6m high, which rarely occurs naturally on coastal rocks of the high islands. It is not a widespread species, being restricted to the area from the New Hebrides (Vanuatu) to the Marquesas, and is probably an aboriginal introduction over the eastern part of its range. It is, however, one of the few native Polynesian flowers which is commonly cultivated as an ornamental and has been extensively planted on the coral ridge separating Lake Temae from the ocean. The showy flowers are used to make garlands and for scenting coconut oil. Its native name in Tahiti is *tiareTahiti*.

***Gardenia* sp.**, Rubiaceae: (Lan-I) Samoan species is most likely to be *Gardenia lanotoensis* a widely distributed tree in the mountain forests of Upolu (W.A. Whistler, pers. comm.).

Gleichenia linearis, Gleicheniaceae: (Lan, Roto, Tem, Vh-I) Synonym: *Dicranopterislinearis*. The "false staghorn fern" is abundantly found on all the dry hills of Rarotonga (Wilder, 1931), and fernlands of Atiu, Mo'orea, Tahiti and Upolu (*Kula* fernlands), where it is regarded as an indicator of disturbed, dry, slightly acidic, sterile soils which have probably been maintained through periodic burning. *Gleichenia* regenerates rapidly after fire and is today found from sea-level right up to the highest peaks, being only absent in the cloud zone (Papy, 1954). Its ability to colonize poor soils, under poor climatic conditions, and its present widespread distribution have led Papy (1954) to believe that this fern must have occupied all the slopes in Tahiti and Mo'orea soon after the cessation of lava eruptions. Marshall (1930) also believes that this fern was the major component of the slope vegetation in Atiu prior to human contact, with its dense cover helping to prevent soil erosion. Pollen analysis from Lake Roto (this study) suggests that the cover of *Gleichenia* was probably less extensive than originally inferred by Marshall.

***Glochidion* sp.**, Euphorbiaceae: (Lan, Roto, Tem-I) Most probably *Glochidion ramiflorum*, an indigenous medium-sized (5-7m) spreading hardwood tree found occasionally in the *makatea* to montane forests of Rarotonga and undisturbed mid- to high-altitude forests of the Society Islands. Also reported in disturbed areas in Samoa (Whistler, 1984) in low- to mid-elevations, and regarded as one of the pioneers on the recent lava fields of Savai'i (Christophersen, 1938). This tree has a strong reddish wood often used to make furniture and house posts.

Gramineae: (Lan, Roto, Tem, Vh) The family of grasses contains many species which are found dominating open areas, pastures and disturbed places.

Grewia crenata, Tileaceae: (Lan, Tem) Synonym: *Grewia mallococca*. A small tree up to 12m high, found occasionally in the coastal forests of high islands (Whistler, 1980), but found growing at altitudes of around 150m on Rarotonga (Wilder, 1931). Also, infrequently found growing on the degraded slopes of *Psidium* and *Gleichenia* in the Society Islands (Florence, 1983). It is a widespread Pacific species, ranging from New Caledonia to the Society islands, but is of little use in the Pacific islands. Its wood is used in some light construction, but the tree is too small and too infrequent to be of much importance.

***Guettarda* sp.**, Rubiaceae: (Roto-I) Possibly *Guettarda speciosa*, an indigenous evergreen shrub or tree up to 20m high, mostly restricted to littoral habitats particularly in the littoral forest of rocky and sandy shores. It is a widespread species, extending from Tropical Asia to Southeastern Polynesia, but does not reach Hawai'i. The hard durable wood is used in construction, and a medicine is prepared from its bark. Flowers are sometimes used to scent coconut oil.

***Heliotropium* sp.**, Boraginaceae: (Roto, Tem) Possibly *Heliotropium anomalum*, a decumbent herb, common along sandy beaches just above high water mark.

Hibiscus tiliaceus, Malvaceae: (Roto, Tem-A) Synonym: *Pariti tileaceus*. A small to medium-sized tree up to 15m high and abundant in the littoral forest and mangrove forest margins, especially in windswept areas. The trunk and branches are often scrambling and sometimes form impenetrable thickets, particularly on the coast. It is regarded as a characteristic secondary forest tree, capable of resisting fire to some extent, and is often found in disturbed forests and plantations up into the mountains of the high islands. In Tahiti it has been noted from the littoral areas up to dry slopes at an elevation of 800-1000m, but finds optimum conditions in the riverine forests of the mesotropical zone (Florence 1983). Franklin and Merlin (n.d.) also recorded this tree in disturbed inland sites on the raised *makatea* of the Ngaputoru group of the Cook Islands. *Hibiscus* is one of the most useful trees in the littoral forests of Polynesia, with the soft wood being used in construction, canoe parts, and for many other purposes. The bast fibre from the bark is used to make cordage, mats, and *kava* strainers, and the large leaves are used as a covering for the native ovens.

Homalanthus moerenhoutianus, Euphorbiaceae: (Tem, Vh-I) Indigenous tree of the windward slopes in the Society Islands (Florence, 1983).

***Homalanthus* sp.**, Euphorbiaceae: (Roto) Possibly *Homalanthus pedicellatus*, a small tree found on the undisturbed slopes of the highest mountains in Rarotonga (Wilder, 1931).

Hymenophyllaceae: (Lan) Family of filmy ferns frequently attached to trees and around rocks, in a range of moist habitats from 200-600m altitude in Samoa (Setchell, 1924).

Ilex anomala, Aquifoliaceae: (Vh-I) A medium-sized tree present in the mid- to high-altitude rainforests of Tahiti. Present pollen studies (Southern, 1986) show that the genus *Ilex* may be under-represented in the pollen rain/fossil record.

Ilex cymosa, Aquifoliaceae: (Vh-I) A medium-sized tree present in the mid- to high-altitude rainforests of Tahiti.

Ilex tahitensis, Aquifoliaceae: (Vh-I) A tree of mid- to high-altitude rainforests attaining a height of 5-10m (Florence, 1983).

***Inocarpus* sp.**, Papillionaceae: (Lan) Possibly *Inocarpus fagifer*, the large Tahitian chestnut, with characteristic thin plank-buttresses. Found occurring as a canopy tree in the lowland forests of eastern Samoa (Whistler, 1980b) and on the wooded slopes and coastal lowland forests and thickets of Maupiti, Tahiti and Mo'orea. Whistler (1980b) believes that the Tahitian chestnut was an aboriginal introduction to Samoa, and commonly cultivated for its edible seeds and fire-wood.

Ipomoea batatas, Convolvulaceae: (Roto-A) The aboriginally introduced sweet potato, cultivated for its edible root. It is one of the most important food crops in the Cook Islands, and is the only plant definitely known to have been aboriginally introduced into Polynesia from the New World. The recent discovery of sweet potato remains, more than one thousand years old, in a rock shelter on Mangaia (Hather & Kirch, 1991) suggests that Polynesian contact with the Pacific coast of South America could have been established during the early first millennium AD.

Ixora bracteata, Rubiaceae: (Roto, Tem-I) According to Cheeseman (1903) and Eastman (1918) this small hardwood tree is commonly found above an altitude of 130m in all the valleys of Rarotonga but according to Whistler (1990) the plant is not well known except on Miti'aro.

***Ixora* sp.**, Rubiaceae: (Lan, Roto) The Lanoto'o species is likely to be *Ixora samoensis*, a small tree of the lowland to montane forest but occasionally also found in the montane scrub community of Eastern Samoa (Whistler, 1980b). Wood from this trees is used for tool handles and husking sticks (Whistler, 1984).

Jasminium didymum, Oleaceae: (Roto, Tem-I) Strong climbing vine common from the lowland forest to the montane scrub of Rarotonga where it often forms tangled thickets. The stems are used for tying thatch on native houses or are woven into freshwater eel traps.

Kyllinga brevifolia, Cyperaceae: (Vh) An opportunist sedge of moist waste places (Christophersen, 1938).

Lantana camara, Verbenaceae: (Lan-R). An erect, branching shrub 0.5-2.0m in height and believed to have originally been introduced by the Europeans as an ornamental, but has since become a noxious weed of coconut plantations, pastures and waste places. Also associated with the *Gleichenia* heath in Tahiti and Mo'orea (Florence, 1983) where it was introduced in 1830. It was first reported from Samoa in 1895 and from Tonga in 1953, but was originally native to tropical America.

***Lindsaya* sp.,** Polypodiaceae: (Lan) Possibly *Lindsaya decomposita,* a small tree fern noted by Setchell (1924) at between 200-300m altitude on Tutuila, Eastern Samoa.

Loranthus forsteri, Loranthaceae: (Tem) Shrub found in the mid-altitude *Metrosideros-Dodonea* forests of Mo'orea and Tahiti (Florence, 1983).

Loranthus insularum, Loranthaceae: (Lan) Parasitic shrub often attached to native species of forest trees, for example it has been observed on *Fitchia speciosa, Inocarpus, Ficus* and *Evodia* species in the high-altitude forests of Rarotonga (Wilder, 1931) and Samoa (Christophersen, 1938).

***Loranthus* sp.,** Loranthaceae: (Roto) Probably *Loranthus insularum* as above.

Ludwigia octovalvis, Onagraceae: (Tem-R) Synonym: *Jussiaea suffruticosa.* An erect, perennial herb up to 2m in height and locally abundant in wet pastures, roadside ditches, and taro fields. This pantropic weed is native to the Old World, and was first reported from Samoa in 1864 (Whistler, 1983) where it commonly grows in disturbed coastal marshes.

Lycopodium cernuum, Lycopodiaceae: (Lan, Roto, Tem, Vh-I) In Rarotonga (Wilder, 1931) and the Society Islands (Florence, 1983) this terrestrial clubmoss is commonly found on open, dry hills, growing with other ferns and grasses, (in particularly *Gleichenia linearis*). Setchell (1924) also notes *L. cernuum* growing from the dry slopes along the strand road up to altitudes of 700m on Tutuila. It is believed to be among the first plants to colonize new lava flows, after the establishment of *Gleichenia*, *Metrosideros* and *Dodonea* (Papy, 1954).

Lycopodium phlegmaria, Lycopodiaceae: (Lan, Roto, Tem, Vh-I) An epiphytic clubmoss common at altitudes of 300m on Rarotonga, and often found growing on trees along streams (Wilder, 1931) and in deep shade (Florence, 1983). Fairly common species in Samoa, increasing with altitude.

Macaranga tahitensis, Euphorbiaceae: (Tem, Vh) A tree often associated with the secondary forests of the Society Islands.

Macaranga stipulosa, Euphorbiaceae: (Lan) A canopy tree, associated with the secondary forests of Samoa (Whistler, 1980b).

***Macaranga* sp.**, Euphorbiaceae: (Roto) May well be *Macarangaharveyana*, a medium sized tree common in the lowlands of Rarotonga, especially in disturbed places and also found in the lower secondary forests of Samoa near the coast. This spreading tree, although apparently less common than previously, is valued for its wood, used for making boat planks, and often planted for shade near villages.

***Macropiper* sp.**, Piperaceae: (Tem-I) Possibly *Macropiperlatifolium*, an indigenous shrub, occasionally found in the montane forest of Rarotonga, and sometimes employed in herbal medicines.

Malvaceae. (Tem/Rot-R). Possibly *Malvastrum coromandelianum*, synonym *M. tricuspidatum*, a common weed of roadsides and waste places. Native to tropical America, first reported from Samoa in 1906 (Whistler, 1983).

***Marattia* sp.** Marattiaceae: (Roto) Possibly *Marattiasalicina*, a large fern common in deep valleys of Rarotonga up to altitudes of 300m. The root of this plant was used for food during times of famine (Wilder, 1931).

Melastoma denticulata Melastomataceae: (Lan, Tem, Vh-I) An indigenous shrub, occasionally found in open areas of fernlands and montane scrub on Rarotonga and Mangaia (Merlin, 1985, 1991). Also noted in the *Kula* fernlands of Upolu and on the montane scrub community associated with trachyte plug material on Tutuila (Whistler, 1980b). Present pollen studies (Southern, 1986) show that this genus may be under-represented in the pollen rain/fossil record.

***Meryta* sp.**, Araliaceae: (Tem) Most probably *M. salicifolia*, a small tree endemic to the Society Islands and recorded mainly from the summit slopes (Papy, 1954), e.g. from the south side of Mount Orohena, on a rocky knoll at 1400m altitude.

***Messerschmidia* sp.**, Boraginaceae: (Roto,Tem-I) Most probably *Messerschmidia argentea*, synonym: *Tournefortia argentea*, a small tree 2-12m high, common in open littoral forests of high islands and atolls (Whistler, 1980a). Widely distributed pioneer strand plant with floating fruits which provide a very effective means of dispersal. Requires bright sunny conditions and can withstand salt spray. It is a widespread species ranging from the Indian Ocean (Mauritius) to Southeastern Polynesia, but is not native to Hawai'i, and although it is a common tree, *Messerschmidia* is too small to be of much use for timber.

***Metrosideros collina*,** Myrtaceae: (Tem, Vh-I) This bushy tree or shrub is one of the dominant taxa of mid- and high-altitude forest formations in the high islands of the Society Islands, especially in shaded areas and on well drained slopes (Papy, 1954). It is often found in association with *Dodonaea viscosa* up to an altitude of 1000m in the drier regions of Tahiti. It is also the pioneer tree on new lava flows and is the dominant tree in the wettest rainforests of the Hawaiian Islands (Lamoureux, 1976). Florence (1983) notes that *Metrosideros* pollen is wind dispersed.

***Miconia calvescens*,** Melastomataceae: (Tem, Vh-R) Introduced ornamental tree which rapidly takes over native habitats. *Miconia* was introduced to Tahiti in 1930, but has since over-run many of the valleys and hillsides where it forms dense stands which exclude nearly all other species. Progressively replacing the high-altitude hygrophile forest by shading out all other plants and in some cases actually killing the trees (Florence, 1982; Parkes & Flenley, 1990).

***Mikania micrantha*,** Compositae: (Roto-R) This rapidly spreading, herbaceous, creeping or twining vine is the most common weed in Samoa and the Cooks where it occurs in nearly every type of disturbed habitat, particularly in coconut plantations and taro fields. With its rapid growth, rooting at the nodes, and periodic but prolific seed production, it quickly covers open land and retards the growth of crops or natural vegetation. It is native to tropical America and was first reported from Samoa in 1924 and from Tonga in 1979 (Whistler, 1986).

***Mimosa pudica*,** Papilionaceae: (Lan, Tem-A) This spreading, sub-woody, perennial herb, up to 40cm in height, is common to locally abundant in lawns, various crops, and in disturbed places, and often dominates in pastures (Whistler, 1980b). Commonly known as the sensitive plant as it folds back its foliage when disturbed. It is a widespread weed native to tropical America, but was an early introduction to Polynesia being first reported from Samoa in 1839 and from Tonga in 1840 (Whistler, 1986) and Tahiti in 1845 (Papy, 1954).

Morinda citrifolia**,** Rubiaceae: (Lan-A) The aboriginally introduced Indian mulberry is a small tree or shrub common about dwellings and in the coastal forests of Samoa (Whistler, 1984). It is also a characteristic sub-canopy tree of disturbed secondary forests of Samoa (Whistler, 1980b). Widely distributed, extending from India through Malaysia and Oceania, even to tropical Australia. The universal spread of *Morinda citrifolia* through the Pacific islands originally led people to believe that seeds were naturally dispersed by water in the buoyant fruits. It is now thought, however, to be mainly spread by Polynesian travellers. Originally introduced to the Cook Islands as a dye plant, with red or yellow dye being extracted from the roots. The fruit is also a famine food and is commonly used in medicines.

Musa paradisiaca**,** Musaceae: (Tem-A) The aboriginally introduced banana is commonly cultivated, primarily for its edible fruit, but the sap is sometimes used in remedies for shingles and the large leaves are sometimes used for mulch.

Mussaenda **sp.,** Rubiaceae: (Roto) Possibly *Mussaenda frondosa*, a low erect shrub or bush common in Rarotonga on all the dry, open hillsides above an altitude of 50m (Wilder, 1931).

Myrsine affinis**,** Myrsinaceae: (Tem, Vh-I) Medium sized tree associated with the moist, high-altitude hygrophile forests of the Society Islands (Papy, 1954; Florence, 1983).

Myrsine **sp.** Myrsinaceae: (Roto) Possibly *Myrsine cheesemanii*, an indigenous tree of undisturbed sites in the Ngaputoru group of the Cook Islands (Franklin & Merlin, n.d.).

Myrtaceae: (Lan, Roto) A family of many species of trees, shrubs and rarely climbers. The Lanoto'o taxa are likely to be one of the 15 species of *Syzygium*, such as *Syzygium samoense* and *Syzygium inophylloides*, the majority of these species being medium-sized trees common in the undisturbed montane and cloud forests of Upolu and Eastern Samoa (W.A. Whistler, pers. comm., 1980b).

Neonauclea forsteri**,** Rubiaceae: (Lan, Tem, Vh) A large timber tree widely distributed in the lowland to montane forests of Samoa. Whistler (1980b) believes that this tree may be a secondary forest species in Eastern Samoa, since it has small, wind dispersed seeds and was most frequently found in areas with some indication of previous disturbance. *Neonauclea forsteri* was recorded by Florence (1983) in Tahiti and Mo'orea, in the *Hibiscus-Ficus* forests at the mouths of large river valleys, and was also found as isolated stands in the *Metrosideros-Dodonaea* hygrophile forests sometimes up to altitudes of 1000m. The fine-grained wood is commonly used for making paddles for canoes.

Nephrolepis **sp.**, Oleandraceae: (Roto, Tem) Possibly *Nephrolepis biserrata* or *Nephrolepis hirsutula*, ferns common in the damp valleys and high mountains of Rarotonga (Wilder, 1931), and in moist depressions of the Society Islands (Papy, 1954). *N. hirsutula* is native to tropical Asia and the Pacific islands and is common to locally abundant in plantations, on fallow land, and in pastures in Samoa (Whistler, 1983), and in disturbed places and open forest in the Cook Islands.

Ophioglossaceae: (Lan) Possibly the epiphytic fern *Ophioglossum pendulum*. Wilder (1931), noted this species as being common in dark, deep valleys of between 160-300m in Rarotonga.

Palaquium **sp.**, Sapotaceae: (Lan-I) Most probably *Palaquium stehlinii* (W.A. Whistler, pers. comm.), a large tree of the foothills and montane forests in Samoa. Today this tree is commonly used in the timber industry (Whistler, 1984).

Pandanus tectorius, Pandanaceae: (Roto, Tem, Vh-I) Synonym: *Pandanus odoratissimus*. A palm-like tree up to 8m or more high, with xerophytic adaptations which allow it to withstand harsh coastal locations where it is abundantly found on rocky and sandy shores. It often forms the chief vegetation above high-water mark in many Polynesian islands, with the *Pandanus* littoral scrub being particularly well developed on Upolu between littoral shrubland and littoral forest. It has also been found growing on hills in Rarotonga to at least 275m (Cheeseman, 1903); in the high-altitude vegetation formations of Tahiti (Florence, 1983), where it adapts to all terrains and all types of soils (Papy, 1954); and in the highest crater lake basins of Upolu. *Pandanus* is second only to the coconut palm in importance in Polynesia and Micronesia generally, and on the atolls it is the principal source of food, either for its edible kernels or for the fleshy fruit base of some cultivated varieties. The spiny-edged leaves are the preferred material for thatch (which can last 10-12 years), fans, hats, mats, and baskets, and formerly for sails. The fruits are often used to make colourful and fragrant necklaces, while the male flowers can be used to scent coconut oil. The indigenous "screw-pine" was once common on the coasts and in the *makatea* forests of Mangaia and Atiu, but is now severely reduced in numbers by an introduced mealy-bug pest. Despite its pollination by birds or insects, *Pandanus* is a prolific pollen producer and may be over-represented in fossil pollen records.

Pandanus **sp.** Pandanaceae: (Lan, Vh-I) The species from both the Lanoto'o and Vaihiria sequences are likely to be varieties of *Pandanus tectorius* (as above).

Passiflora quadrangularis, Passifloraceae: (Roto) A strong climbing shrub common in woods and often cultivated. Found growing wild in all districts of Rarotonga below an altitude of 65m.

Pemphis acidula, Lythraceae: (Tem-I) A shrub, or small tree, up to 5m high found growing on rocky or sandy shores of the high islands and atolls, and sometimes forming nearly pure bands of vegetation on exposed rocky shores. It is a pioneer plant of coralline limestones (Papy, 1954) and is well adapted to salt spray and intense sunlight (Florence, 1983). It is a widespread species, ranging from Tropical East Africa to Southeastern Polynesia and Micronesia, but does not reach Hawai'i. The wood of *Pemphis* is very hard, and is one of the favourite Polynesian woods used to make small carved objects such as canoe parts, fish hooks and spears. Native name: *'A'ie.*

Peperomia leptostachya, Peperomiaceae: (Roto) Erect, fleshy herb found throughout Polynesia in moist forests, especially on rocks.

***Peperomia* sp.**, Peperomiaceae: (Tem, Vh) Possibly *Peperomia tahitensis*, a moist forest herb endemic to the Society Islands.

***Phylanthus* sp.**, Euphorbiaceae: (Roto, Tem) Possibly *Phylanthus amarus* a small annual herb common in open pastures, dry, disturbed places, and along roadways. This widely distributed weed is native to tropical America, and was first reported from Samoa in 1893 and from Tonga in 1926 (Whistler, 1983).

***Piper* sp.** Piperaceae: (Vh) Possibly *Piper methystichum* (*kava*), a dioecious shrub probably introduced when the islands were first colonized by the Polynesians. Once widely cultivated but now uncommon in cultivation or merely persisting in a few places. In former times, the root of this plant was chewed or pounded, mixed with water, and taken as an intoxicating beverage during ceremonies, but this practice was officially stamped out by the missionaries.

Piperaceae: (Lan, Roto, Tem) Possibly the endemic *Piper latifolia*, an abundant shrub in the dense woods of Rarotonga and the Society Islands (Papy, 1954), where it forms much of the forest floor cover above an altitude of 150m.

***Pipturus* sp.**, Urticaceae: (Roto, Vh-I) The species of *Pipturus* recorded in the Roto sequence is most probably *Pipturus argenteus*, a small, indigenous tree, occasional in disturbed places and *makatea* forests in the Cook Islands. The tough inner bark of this tree was used in former days to make fishing line, nets and rope (Whistler, 1990). *Pipturus vaihirianensis* is most likely to be the species found in the Lake Vaihiria sequence. This tree is endemic to the high-altitude hygrophile forests of the Society

Islands and found overhanging streams around Lake Vaihiria at an altitude of 500m (Moore, 1940).

***Pisonia* sp.**, Nyctaginaceae: (Roto, Tem-I) Both the Mo'orea and Atiu species are likely to be *Pisonia grandis*, a indigenous, medium to large tree (up to 20m), which is common to abundant in the littoral forest of atolls and high islands (Whistler, 1980a). It is a widespread species, ranging from Tropical Africa to Southeastern Polynesia and Micronesia, but not occurring in Hawai'i. *Pisonia grandis* may be dependent upon seabirds for dispersal and for soil high in nitrates and phosphates. The tree is of limited economic importance, but the timber is sometimes used in construction.

Pittosporum undulatum, Pittosporaceae: (Vh-I) Native forest tree frequently found in the *Metrosideros* forests of the Society Islands and in areas with high light penetration (Papy, 1954).

Pittosporum orohenensis, Pittosporaceae: (Vh-E) This tree reaches up to 10m in height, and is endemic to the mid- to high-altitude hygrophile forests of the Society Islands. Noted by Moore (1940) on the south side of Mount Orohena on Tahiti, at an altitude of 1600m.

***Pittosporum* sp.**, Pittosporaceae: (Lan, Roto) Atiu species could be *Pittosporum rarotongensis*, a tree found between 100 to 200m elevation on the dry interior hills of Rarotonga. Alternatively, *P. arborescens* is an indigenous tree noted by Franklin and Merlin (n.d.) on the *makatea* limestone of the Ngaputoru group of the Cook Islands. Apparently no *Pittosporum* species occur on Upolu today (W.A. Whistler, pers. comm.); however, Christophersen (1938) notes the presence of *Pittosporum samoense* in the high-altitude forests of Savai'i.

Polypodium phymatodes, Polypodiaceae: (Roto, Tem, Vh). This fern is very abundant in all soils and situations, from the high-water mark to the highest hills on Rarotonga. Found in rocky habitats on Tahiti, and common in coastal locations on Tetiaroa atoll (Papy, 1954).

Polyscias guilfoylei, Araliaceae: (Tem) Erect-growing shrub often cultivated and used for hedges.

***Portulaca* sp.**, Portulacaceae: (Lan) Possibly *Portulaca lutea*, a low, succulent, perennial herb common in open pastures, in lowlands, and coastal areas. It is one of the hardiest of littoral species, able to survive in the harshest of habitats and was noted in Christophersen (1935) as occurring in lava-cracks on Savai'i. *P. lutea* is occasionally used for food, either cooked or raw, but is otherwise of little importance in Polynesia.

Premna tahitensis, Verbenaceae: (Tem, Vh) Small tree found in the valleys of mid-altitude areas and some windward slopes of the high-altitude hygrophile forests of Tahiti and Mo'orea (Papy, 1954).

Pritchardia vuylstekeana, Palmae: (Rot E/I) Now listed as an endangered palm of the Cook Islands (Whistler, 1988) and is given the status: Indigenous or Polynesian endemic. Recorded on Miti'aro by Sykes, Whistler and Merlin in 1986 (pers. comm.), where it was growing in scattered clusters on the rugged *makatea* of the south part of the island. This fan palm, was previously thought to be endemic only to the nearby island of Makatea where it was noted by Wilder in 1932, and described as an erect tree, with a diameter at breast height of 8" (~20cm), and situated in coral rocks at 200' (~65m) elevation (Pollen from this specimen was used to identify the fossil pollen from the Lake Roto core). Florence (1983), also noted *P. vuylstekeana* in an area of Makatea island where soil and water was very scarce, and the palm was accompanied by *Alyxia scandens*, *Canthium barbatum*, *Glochidion ramiflorum* and *Tarrena sambucina.*

Procris pedunculata, Urticaceae: (Lan, Vh-I) Small succulent herb common in Rarotonga on all mountains at the base of trees and on rocks (Wilder, 1931). Also recorded in Samoa (Whistler, 1984) as an epiphytic or terrestrial herb of the coastal to montane forest, but mainly occurring in the lower to middle elevations (Christophersen, 1938), particularly in moist ravines. In Tahiti, this herb is found epiphytically on the branches of primary forest trees in the high-altitude cloud forests. Also found epiphytically on coconut trees.

***Procris* sp.**, Urticaceae: (Roto, Tem) Possibly *Procris pedunculata*, as above.

Proteacea: (Roto-R) The Proteaceae is a family of recently introduced oriental plants, commonly planted around settlements.

Psidium cattleianum, Myrtaceae: (Tem-R) The introduced strawberry guava is a small spreading tree common in all districts of Rarotonga, Tahiti and Mo'orea, and grown under cultivation for their fruit. Recorded as being introduced to the Society Islands in 1845 (Papy, 1954).

Psidium guajava, Myrtaceae: (Roto, Tem-R) The highly cultivated guava is a shrub or tree of European introduction, grown for its edible fruit. In wet forest areas it becomes a tree, up to 10m tall, but in exposed areas it is a shrub about 2m tall. It is a pantropic species (weed) native to Mexico but now naturalized in most tropical countries, and was recorded as being introduced to the Society Islands in 1815 (Papy, 1954) where it has since spread profusely in disturbed and frequently fired areas to form large expanses of impenetrable vegetation with *Gleichenia linearis*. It is occasional to common in pastures, plantations and along roadsides. The seeds of the guava are readily dispersed by birds who eat the fruit.

Psilotum nudum, Psilotaceae: (Lan, Tem-I) An indigenous, leafless fern ally, occasionally found growing in the forests of Rarotonga. Grows on the ground or in rocky crevices and can survive in both moderately dry as well as wet environments. Was seen growing as an epiphyte on the trunks of coconuts around lake Temae on Mo'orea.

Pteris tripartita., Pteridaceae: (Lan, Roto, Tem, Vh-I). Synonym: *Pteris commans.* A very large fern common on the rich alluvial soils along banks of main streams on Tahiti (at high altitude) and Rarotonga (up to 160m elevation).

Rapanea myricifolia, Myrsinaceae: (Vh-I) A small tree growing in the rainforests of the Society Islands (Papy, 1954).

Rapanea tahitensis, Myrsinaceae: (Tem, Vh-I) Native tree of upper valley slopes on Tahiti and Mo'orea (Papy, 1954).

***Rapanea* sp.**, Myrsinaceae: (Roto, Vh, Lan) Atiu species could possibly be *Rapanea cheesemani*, a small spreading tree common at altitudes between 300-400m in Rarotonga. or less frequently up to an altitude of 600m. Tahiti species may be one of two endemic species on the Society Islands: *R. orohenensis* and *R. rhomboidalis*, both of which are recorded above 1000m, south of Mount Orohena, in Tahiti. Lanoto'o species is most likely to be *R. myricifolia* noted in the coastal forest and montane scrub vegetation of Samoa (Whistler, 1984).

Reynoldsia tahitensis, Araliaceae. (Tem-I) A tree, 8-10m tall, found growing in high valleys of the cloud forests of Tahiti up to an altitude of 1800m (Florence, 1983).

Reynoldsia verrucosa, Araliaceae: (Vh-I) Large tree of the cloud forest on Tahiti.

Schizaeaceae: (Tem) Possibly *Schizaea dicotoma*, a fern common on the hilly, dry sides of the valleys and in the forests of higher elevations in Rarotonga (Wilder, 1931). Inhabits dry and unproductive soils in Samoa.

***Selaginella* sp.**, Selaginellaceae: (Lan, Roto, Vh) A wide variety of species belong to this family but are generally associated with moist and shaded slopes, of forests.

Sida rhombifolia, Malvaceae: (Roto-A) Synonym: *Sida microphylla.* Branching perennial shrub, 30-150cm in height, and commonly growing on roadsides, in plantations, and in sunny waste places, where it is often a dominant species. This pantropic species was probably an aboriginal introduction to Polynesia (Whistler, 1983), and the stout fibre and stiff branches from this plant are often made into bundles and used as brooms.

***Sida* sp.**, Malvaceae: (Roto) Possibly *Sida acuta*, synonym: *S. carpinifolia* a very troublesome weed, often covering the ground to the exclusion of everything else. Common everywhere in the Cook Islands in disturbed and cultivated areas, and also found on the coastal plains of Mo'orea and Tahiti on a substratum of coral debris and sand, where salt concentrations are high (Papy, 1954).

Sophora tomentosa, Papilionaceae: (Tem-I) An indigenous shrub or small tree, up to 3m or more high, and found on the sandy shores of high islands and atolls. It is a widespread species, distributed from India to Southeastern Polynesia, but is of little or no economic value in Polynesia.

***Stachytarpheta* sp.**, Verbenaceae: (Tem-R) Possibly *Stachytarpheta urticilifolia*, a pantropic weed native to tropical America and first reported from Samoa in 1839 and from Tonga in 1953 (Whistler, 1983). It is common in plantations, bush fallow, roadsides and particularly in pastures where it becomes a real pest (Whistler, 1983). Found to be extremely common on the roadside and as undergrowth in plantations in Mo'orea and Tahiti (Florence, 1983).

Stenochlaena palustris, Blechnaceae: (Lan, Tem, Vh) A marsh fern often associated with mangrove forest habitats.

***Styphelia* sp.**, Epacridaceae: (Tem) Probably *Styphelia pomarae* a shrub associated with relatively undisturbed shrubland or rainforests of the Society Islands (Papy, 1954). Noted by Florence (1983) in the summit scrub vegetation of Tahiti, where intense insolation, relatively low moisture and high exposure to winds prevail.

***Tarenna* sp.**, Rubiaceae: (Roto, Tem) Most probably *Tarenna sambucina*, a small tree of open habitats, noted by Florence (1983) in association with *Pritchardia vuylstekeana Alyxia scandens*, *Canthium barbatum* and *Glochidion ramiflorum* in an area of Makatea island where soil and water were very scarce.

***Tectaria* sp.** Aspidaceae: (Roto) Possibly *Tectaria decurrens*, a ground fern growing at around 300m altitude on Rarotonga (Wilder, 1931). Also found on mossy banks and cliffs, in the deep shade of Maara valley, Tahiti (Florence, 1983).

Terminalia catappa, Combretaceae: (Tem-A) A large deciduous, spreading tree, up to 30m high, common in the littoral forest of atolls and high islands, extending into coastal and lowland forests on high islands (Whistler, 1980a). It is a widespread Pacific species, ranging from Tropical Asia and Australia to Eastern Polynesia and Micronesia, although over much of the eastern part of its range it is considered to be an aboriginal introduction (Whistler, 1980a). It is an early introduction to Hawai'i where it is commonly known as "false *kamani.*" *Terminalia* is a good timber tree used for making canoes, houses and gongs, and it is also cultivated as a ornamental or shade tree, as well as for its edible seeds. The bark and leaves are sometimes used to make a black dye or ink.

Thespesia populnea, Malvaceae: (Tem-A/I) An indigenous, spreading tree up to 15m in height, commonly growing in the littoral forest areas of atolls and high islands, and rarely found far from the shore (Whistler, 1980a). It is a widespread species, ranging from Tropical Africa to Eastern Polynesia and Micronesia. It is probably an aboriginal introduction in the eastern part of its range, including Hawai'i (Whistler, 1980a). The wood of *Thespesia* is highly esteemed by the Polynesians, and is used to make bowls, paddles, and other carved objects. The fruit, when crushed, has medicinal properties and is used to treat urinary tract ailments and abdominal swellings (Whistler, 1990). Cheeseman (1903) also noted that the bruised or charred leaves were frequently used as a dressing for wounds. Native name: *Miro.*

***Timonius* sp.**, Rubiaceae: (Tem-I) Most probably *Timonius polygamus* a small, indigenous shrub, common on the coastal rock strand in the Cook Islands and Society Islands (Florence, 1983). Common in the shrub layer in coconut plantations and thickets and clearings.

Trema orientalis, Ulmaceae: (Lan, Tem, Vh) Small tree or shrub characteristic of young disturbed mid-altitude and lowland forests where forest cover is incomplete. Often occurring in sunny places.

***Trema* sp.**, Ulmaceae: (Roto) Most likely to be *Trema cannabina*, an indigenous species now very rare in the Cook Islands but common elsewhere in the region. Last collected in Mangaia around 1974 (Whistler, 1990).

Triumfetta procumbens, Tiliaceae: (Roto) Creeping herb with long trailing stems. Common on sandy beaches of atolls and high islands and found by Whistler (1983b) in the open areas of the *Ipomoea* Sand Strand of the Aleipata Islands, Samoa. A widespread species, ranging from Tropical Asia and Australia to Southeastern Polynesia and Micronesia, but does not reach Hawai'i. The plant is only of minor importance in the Pacific islands. In Rarotonga the fibre obtained from this plant was formerly used in making twine for fish nets (Whistler, 1990).

Triumfetta rhomboidea, Tiliaceae: (Lan-R) Synonyms: *T. batramia* and *T. angulata.* A pantropic weed possibly native to the Old World Tropics, and first reported from Samoa in 1905 (Whistler, 1983). It is a common weed of bush fallow, pastures, disturbed places, and roadsides.

Typha angustifolia, Typhaceae: (Lan, Roto, Tem, Vh) Emergent aquatic with buried rhizome, often forming pure stands (Papy, 1954).

Typha latifolia, Typhaceae: (Lan, Roto, Tem, Vh) Emergent aquatic reed.

***Vaccinium* sp.,** Ericaceae: (Tem, Vh) Possibly *Vaccinium cereum*, an endemic shrub of high-altitude regions on Tahiti and Mo'orea (Papy, 1954).

***Vernonia* sp.,** Compositae: (Roto-R) Possibly *Vernonia cinerea,* a small erect annual herb 15-60cm in height, and common in lawns, pastures and sunny waste places (Whistler, 1983). Native to tropical Asia this weed was first reported from Samoa in 1893 and from Tonga in 1890 (Whistler, 1983).

Vittaria elongata, Vittariaceae: (Tem) Cheeseman (1903) found this fern abundant at the roots of trees on dry declivities up to 500m on Rarotonga.

Weinmannia parviflora, Cunoniaceae: (Vh-I) One of the dominant taxa of mid- and high-altitude hygrophile forest formations in the high islands of the Societies (Florence, 1983), and recorded from 500 to 2200m in Tahiti. Also noted by Florence (1983) on the slopes protected from the wind in the cloud forest of Tahiti.

***Weinmannia* sp.,** Cunoniaceae: (Tem) Possibly *Weinmannia parviflora* (as above).

Weinmannia rarotongensis, Cunoniaceae: (Roto-E) Common forest tree growing at an altitude of 300m on Rarotonga.

***Weinmannia* affinis,** Cunoniaceae: (Lan) A small to medium sized tree rarely found below 500m in Samoa, and occurring in the constantly damp and cool cloud forest community. Also noted in Christophersen (1935) occurring at altitudes between 1300-1400m on Savai'i where it was sometimes found epiphytically growing on other trees.

Wikstroemia foetida, Thymelaeaceae: (Lan, Vh) Synonym: *Wikstroemia raiatensis.* A shrub or small tree of sunny places and commonly associated with the fernlands of Samoa (particularly at Luatuanu'u in Upolu) and Tahiti. Also noted as being common on the montane cinder cones at high elevations on Savai'i (Whistler, 1978).

APPENDIX 4

A. Radiocarbon dates from the sediments of Lakes Lanoto'o, Roto, Rotonui, Temae and Vaihiria.

Code	Lake	Depth (m)	^{14}C age (yr BP) +1Ø	Calib. yr BP	Calendar yr	^{13}C PDB o/oo
Upolu						
SRR-3716	Lanoto'o	0.88-0.94	2425±70	2461	512 BC	-18.0
SRR-3717	Lanoto'o	1.58-1.62	3575±65	3880	1931 BC	-20.8
SRR-3086	Lanoto'o	2.80-2.90	8920±80	--	--	-24.6
Atiu						
SRR-3713	Roto	1.41-1.58	385±45	479	AD 1471	-27.0
SRR-3282	Roto	2.85-2.90	540±110	543	AD 1407	-23.7
R-16071	Roto	3.52-3.53	1420±45	1310	AD 640	
[SRR-3714	Roto	5.32-5.52	3380±70	3634	1685 BC	-26.1]
SRR-3283	Roto	6.50-6.55	3100±150	3355	1406 BC	-28.8
SRR-3715	Roto	7.86-7.91	4970±55	5680	3731 BC	-29.1
SRR-3284	Roto	10.30-10.35	6730±90	7579	5630 BC	-30.0
SRR-3084	Roto	13.88-13.98	7820±70	8611	6662 BC	-29.2
Miti'aro						
SRR-3285	Rotonui	2.50-2.60	4380±100	4934	2985 BC	-8.9
SRR-3286	Rotonui	5.45-5.55	5340±110	6140	4191 BC	-11.2
SRR-3287	Rotonui	6.85-6.90	6170±120	7104	5155 BC	-15.1
SRR-3085	Rotonui	7.12-7.22	6970±70	7769	5820 BC	-25.4
Mo'orea						
SRR-3088	Temae	6.8-6.9	1210±90	1160	AD 790	-27.7
SRR-3288	Temae	11.45-11.56	1540±100	1411	AD 539	-15.9
Tahiti						
[SRR-2552	Vaihiria (a)	4.65-4.75	1290±120	1265	AD 685]	
GX-10697	Vaihiria (b)	2.46-2.50	320±200			
Beta-10100	Vaihiria (b)	5.05-5.14	540±90			

Dates in brackets [*] are believed to be contaminated with old carbon.

B. Carbon content and isotope enrichment values of sediments from Lakes Lanoto'o, Roto, Rotonui, Temae and Vaihiria.

Depth	Organic carbon	
(m)	Wt. % C	^{13}C PDB o/oo
*Radiocarbon dated samples are underlined.		
Lanoto'o, Upolu		
0.88- 0.94	39.0	-23.7
		(-18.0?)
1.58- 1.62	29.1	-23.8
		(-20.8?)
2.80- 2.90		-24.6
Roto, Atiu		
0.70- 0.79	9.8	-28.9
1.41- 1.58	-	-27.0
1.47- 1.53	8.8	-26.0
2.50- 2.53	22.8	-32.6
2.85- 2.90	-	-23.7
3.52-3.53		-33.5
3.60- 3.62	19.9	-32.2
4.46- 4.50	18.6	-28.1
5.32- 5.52	-	-26.1
5.46- 5.52	20.2	-25.0
6.50- 6.55	-	-28.8
6.82- 6.84	13.6	-28.3
7.86- 7.91	19.6	-28.9/29.1
8.94- 8.98	20.3	-23.5
9.94- 9.98	20.4	-28.9
10.30- 10.35	-	-30.0
13.88- 13.98	-	-29.2

Depth	Inorganic carbon			Organic carbon	
(m)	Wt % C	^{13}C PDB o/oo	^{18}O PDB o/oo	Wt. % C	^{13}C PDB o/oo
Temae, Mo'orea					
0.80- 0.84	(NO MEASURABLE CO$_3$ $^{2-}$ or HCO$_3$$^-$)			15.8	-26.7
1.66- 1.70	20.6	-4.1	-2.2	23.0	-18.2
2.66- 2.70	0.6	+0.8	-2.8	11.7	-19.7
3.60- 3.66	5.1	+1.6	-1.9	13.4	-21.0
4.70- 4.74	5.2	+2.7	-1.8	5.5	-19.8
5.70- 5.74	7.4	+3.2	-1.2	5.5	-19.0
6.70- 6.74	1.1	-5.2	+1.8	3.3	-26.1
6.80- 6.90	-	-	-	-	-27.7
7.80- 7.84	10.0	+3.2	-0.9	12.4	-18.0
8.72- 8.76	10.1	+2.8	-1.1	12.8	-16.9
9.74- 9.78	9.1	+2.7	-1.1	6.3	-18.7
10.48- 10.52	9.6	+2.8	-1.2	10.4	-16.9
11.30- 11.34	9.2	+2.0	-1.2	3.6	-20.0
11.45- 11.56	-	-	-	-	-15.9
Rotonui, Miti'aro					
0.88- 0.92	0.3	-3.6	-8.8	47.9	-3.9
1.80- 1.86		(NO MEASURABLE CO$_3$ $^{2-}$ or HCO$_3$$^-$)		49.6	-4.1
2.50- 2.60	-	-	-	-	-8.9
2.80- 2.86		(NO MEASURABLE CO$_3$ $^{2-}$ or HCO$_3$$^-$)		45.2	-5.6
3.80- 3.86		"		51.5	-5.4
4.80- 4.86		"		50.7	-10.7
5.45- 5.55					-11.2
5.80-5.86		"		53.3	-7.5
6.74- 6.80		"		49.3	-3.3
6.85- 6.90		-		-	-15.1
7.12- 7.22		-		-	-25.4

APPENDIX 5

PREPARATION OF GLASS DISCS FOR XRF ANALYSIS BASED ON THE FUSION METHOD OF NORRISH AND HUTTON (1969).

0.373g of the dried inorganic sample was measured into a pre-weighed, platinum-gold-rhubidium crucible using a Cahn balance. 0.027g of Sodium nitrate ($NaNO_3$) and 2.0g of spetroflux was then mixed with the sample to bring the total weight of crucible contents to 2.4g. The $NaNO_3$ was added to maintain an oxidizing environment within the sample when heated.

The crucible was heated, over the oxidizing flame of a bunsen burner, until the contents had fused together and no more gas bubbles were given off. Particular care was needed to prevent any of the sample being lost from the crucible on forceps etc. The resulting weight loss (LOI) corresponded to CO_2 and CO_3 lost from carbonates and H_2O lost from clay minerals.

The remaining residue of non-volatile, non-organic material was then reheated, to approximately, 900°C over an air assisted bunsen burner. When the sample was completely fused the molten liquid was poured onto a hotplate press and a glass disc was made. The disc was placed in the tray to settle and cool. After the removal of excess glass, the discs were placed in containers and run through the Philips PW 1212 XRF Spectrometer.

APPENDIX 6

PLATES OF FOSSIL POLLEN, SPORES, DIATOMS AND MACRO-ORGANISMS: PLUS FOSSIL GRAIN CHARACTERISTICS.

The following plates show the range of fossil pollen and spores which were found within the four Pacific cores described in this thesis and is in no way intended to be a catalogue of all Pacific taxa. The identified taxa of the fossils are followed by the core locations in which the grains were found (i.e. Lan, Roto, Tem, and Vh), with the underlined location being the source of the particular grain shown. When pollen grains and spores have been identified to species level further distinguishing characters (other than those identified in standard texts such as Erdtman, 1952, 1957, 1965 and 1971) have been included to differentiate between similar taxa known to be, or likely to have been present within the Pacific region during the Holocene. No attempt was made to review all know species within genera since this would have assumed unmanageable proportions. In practice much time was saved by excluding several species on geographical grounds. Genera recognised within the geographical units used van Balgooy (1971) for the Pacific region were considered before genera more typical of areas beyond the Pacific, with the exception of known pan-tropical genera. The general terminology of Faegri and Iversen (1991) and Moore, Webb and Collinson (1991) has been used where possible in the description of fossil grains and spores. Assistance with the identification of important pollen taxa was provided by palynologists including Donald Walker (Australian National University), the late Gerdip Singh (Australian National University), John Flenley (Massey University), Robert Morley (Robertson's Research), Keith Ferguson (Kew herbarium) and Mark Bush (Duke University). All fossil pollen and spores in these plates are at x1000 magnification except where noted otherwise and have been grouped according to the number and arrangement of visible apertures (i.e. under light microscope conditions).

Detailed descriptions of diatom morphology have been comprehensively covered in standard morphological texts and are therefore not repeated in this thesis.

Light microscope photographs.

PLATE 1.

Vesiculate grains.

1. Pinaceae/Podocarpaceae: (Roto, Tem) x500 magnification. Grains are bi-vesiculate, with coarse reticulate and semi-circular sacci. Bilaterally symmetrical. Exine is 2-2.5μm thick, tectate, with fairly distinct columellae. Slight thickening of the proximal part of the exine (crest). Slight constriction occurs between the air-sacks and the body of the grain. Colpus membrane is smooth. Grains are variable in size.

Inaperturate grains.

2-3 *Wikstroemia foetida*, Thymelaeaceae: (Lan). Grains are spherical and measure 18-25μm in diameter. Exine is 1.5-2.5μm thick, semi-tectate, with distinct but often irregularly spaced columellae. Coarse reticulate sculpturing with lumen up to 2μm diameter (greater than the width of the muri) and irregular in shape and size.

4-5. *Wikstroemia foetida* comp., Thymelaeaceae: (Vh). As above.

6. *Stachytarpheta* comp., Verbenaceae: (Tem). Grains spherical, measuring 50-51.5μm in diameter. Exine is >2μm thick, verrucate with verrucae irregularly spaced and variable in height from 0.5-3μm. Exine is transparent and smooth between verrucae. Grains frequently "dented" and as a consequence often appear to possess a colpus.

7. *Peperomia leptostachya* comp., Piperaceae: (Roto). Grains spherical to oblate and around 14-16μm in diameter. Darkly stained exine which is 1.7-2.0μm thick, reticulate (tectate) and with distinct columellae. Exine is sometimes rugulate in appearance. The grains of *Peperomia tahitensis* are consistently smaller in size with a maximum diameter of ~12μm.

8. *Piper* sim., Piperaceae: (Vh). Grains spherical, measuring 8-10μm in diameter. Exine is finely scabrate and 0.7-1.0μm thick.

9. *Stephania forsteri* sim., Menispermaceae: (Vh). Grains spherical to oblate, measuring 10-12μm in diameter (reference pollen of this species varied considerably in size). Thickened exine is variable in thickness but usually ~2-2.5μm thick. Reticulate (irregular and distinctly "lace-like" i.e. with very thin muri) with lumen diameters up to 4μm. Grains of *Stephania japonica* are typically 11-13μm in diameter, have a more compact reticulate pattern and have a visible pore in equatorial view.

Fenestrate grains.

10-11. *Elephantopus mollis*, Compositae (liguliflorae): (Roto, Tem). Grains spherical, 30-35 μm in diameter. Lophate with echinae on the borders of lacunae. Equatorial ridges are present with a single central row of echinae. Hexagonal and regularly shaped lacunae are up to 7μm in diameter, while muri measure 2-3μm in thickness. Echinae are regular and up to 1.5μm in length. Pores are not distinct.

Monocolpate grains.

12. *Cocos nucifera*, Palmae: (Lan, Roto, Tem). Grains elliptic (accuminate) in equatorial view, occasionally triangular in trichotomosulcate grains. Average length of elliptic grains are 49μm but range from 40-55μm; the average width (i.e. across the ventral plane) measures 30μm ranging from 20-37μm; average height (i.e. from ventral to distal edge) measures 32μm and ranges from 20-42μm. One apex is frequently truncated. Exine measures 1-2μm thick and is translucent with two layers clearly visible. Sculpturing appears to be coarse scabrate under the light microscope (but seen as fossulate sculpture under the scanning electron microscope, shown in Plate 15) with perforations occasionally seen in mature grains particularly between distal and ventral regions, but rarely seen around margins of colpus. Broad elliptical to sub-elliptical colpus up to 7μm wide and restricted to the distal side of grain. Margins of colpus indistinct (diffuse) with no definite margo visible.

13. *Pritchardia vuylstekeana*:, Palmae: (Roto). Grains elliptic (obtuse-accuminate) in equatorial view. Similar in general shape and structure to *Cocos* but invariably smaller in size and not truncated at apex. 32-37μm in length and 20-25μm wide. Exine is denser than *Cocos* and more regular in thickness at 1-1.3μm. Exine has a coarser scabrate sculpture which appears to grade to a finer scabrate towards the colpus. Exine layers are not visible, but columellae are fairly distinct. Colpus more distinct than *Cocos*, tapering towards apices. Pollen from the genus *Pritchardia* is also similar in appearance to the genus *Livistonia* which can normally be distinguished by its coarser reticulate sculpture, more distinct colpus margin and thinner exine. *Livistonia* pollen is invariably smaller averaging between 16-20μm.

14. Palmae: (Lan, Tem). Similar to *Pritchardia* but psilate in sculpture. Possibly an immature grain.

15. *Ascarina polystachya* comp., Chloranthaceae: (Tem, Vh). Grains spherical, 19-23μm in diameter. Two distinct exine layers are visible and the endexine is deeply stained brown by the acetolysis treatment. Thick reticulate exine (1.5-3.0μm) with very clear columellae. Colpus granulate with obscured edges. Colpus up to 7μm in width and

extending onto proximal side of the grain. Apices of colpus not tapering. Distinct margo present which is consistently 2μm in width. The denser reticulate pattern of *Ascarina diffusa* is the main distinguishing factor between these two species.

16. *Astelia nadeaudi*, Liliaceae: (Vh). Grains elliptic (accuminate), 22-27μm in length and 16-18μm wide. Exine is <1μm thick, translucent with a gemmate sculpture. Gemmae ~1μm in length and regularly spaced along linear rows but not as distinctly linear as found within the species of *Commelina* (see below). Wide, psilate colpi (4μm wide in centre to 3μm at apices) with indistinct margins. Margo absent.

17. *Commelina nudiflora* comp., Commelinaceae: (Roto). Grains elliptic (accuminate), 23-26μm in length and 16-18μm wide. Exine is >1μm thick, translucent with gemmate sculpture. Gemmae ~1μm in length and arranged in distictly linear rows parallel to colpus. Narrow colpus with distinct margins, 2μm wide in the centre tapering towards the apices. Margo absent.

18. *Colocasia esculenta*, Araceae: (Roto, Tem). Grains spherical with regularly distributed broad-based echinae (very high density). Echinae are at least 2μm in length (maximum length 3.5μm). Grain diameter measures 23-26μm. Short and indistinct colpus. Similar in general appearance to *Pandanus* species which are monoporate but often have the pore obscured by echinae.

Dicolpate-syncolpate grains.

19. *Barringtonia asiatica*, Barringtoniaceae: (Roto, Tem). Grains are elliptic (obtuse), measuring ~50μm in length and 32-35μm in width. Grains with thick (>1μm) more or less psilate exine which becomes coarsely reticulate along the thickened copi margins (exine 2-3μm thick).

Tricolpate grains.

20. *Grewia* comp. *crenata* sim., Tiliaceae: (Lan, Tem). Grains oblate in equatorial view and semi-angular in polar view (25-28μm greatest diameter). Exine is <1μm thick but thickening to 2μm around colpi which is slightly processed. Fine reticulate sculpturing with regularly spaced network. Columellae visible in exine. Short open-type colpi measuring 2μm in width. Polar area index large.

Stephanocolpate.

21. *Rapanea tahitensis* comp., Myrsinaceae: (Tem, Vh). Grains spherical to quadrangular convex (obtuse) in polar view, obtuse in equatorial view, with a maximum diameter of ~22μm. Sculpturing is psilate to very fine regular scabrate, with thin tectate

exine (0.9-1.2μm thick), columellae indistinct. Four short, straight and recessed colpi, unpatterned with slightly thickened margo constricted at equator, although no clear transverse aperture was visible. Polar area index large. The grains of *Rapanea myricifolia* are very similar except for their generally larger size, ranging in diameter from 23-25μm. No thickening of the exine was observed around the colpi of the reference pollen of *R. myricifolia*. Some of the Pacific species of the genus *Myrsine* produce grains of similar appearance but which have a micro-reticulate sculpture and frequently have colpi with "ragged" margins.

22. Myrsinaceae: (Lan , Roto, Vh). Grains quadrangular convex (obtuse) in polar view, obtuse in equatorial view, with a maximum diameter measuring ~18μm. Sculpturing psilate, with thin translucent exine (<1μm, not thickened around colpi). Four short recessed colpi. Polar area index large.

23. *Passiflora quadrangularis* comp., Passifloraceae: (Roto). Grains prolate in equatorial view and up to 40μm in length. Circular to elliptic in polar view measuring around 30-32μm in diameter. 6-7 psilate and open colpi present measuring up to 4μm wide at the equator. Apocolpium very coarsely reticulate with irregularly shaped lumen, particularly elongated in equatorial region while circular in polar region. Maximum length of lumen reach 8μm. Muri are straight or curved and raised ~1μm and are always narrower than the diameter of the lumen. Polar area index small.

PLATE 1

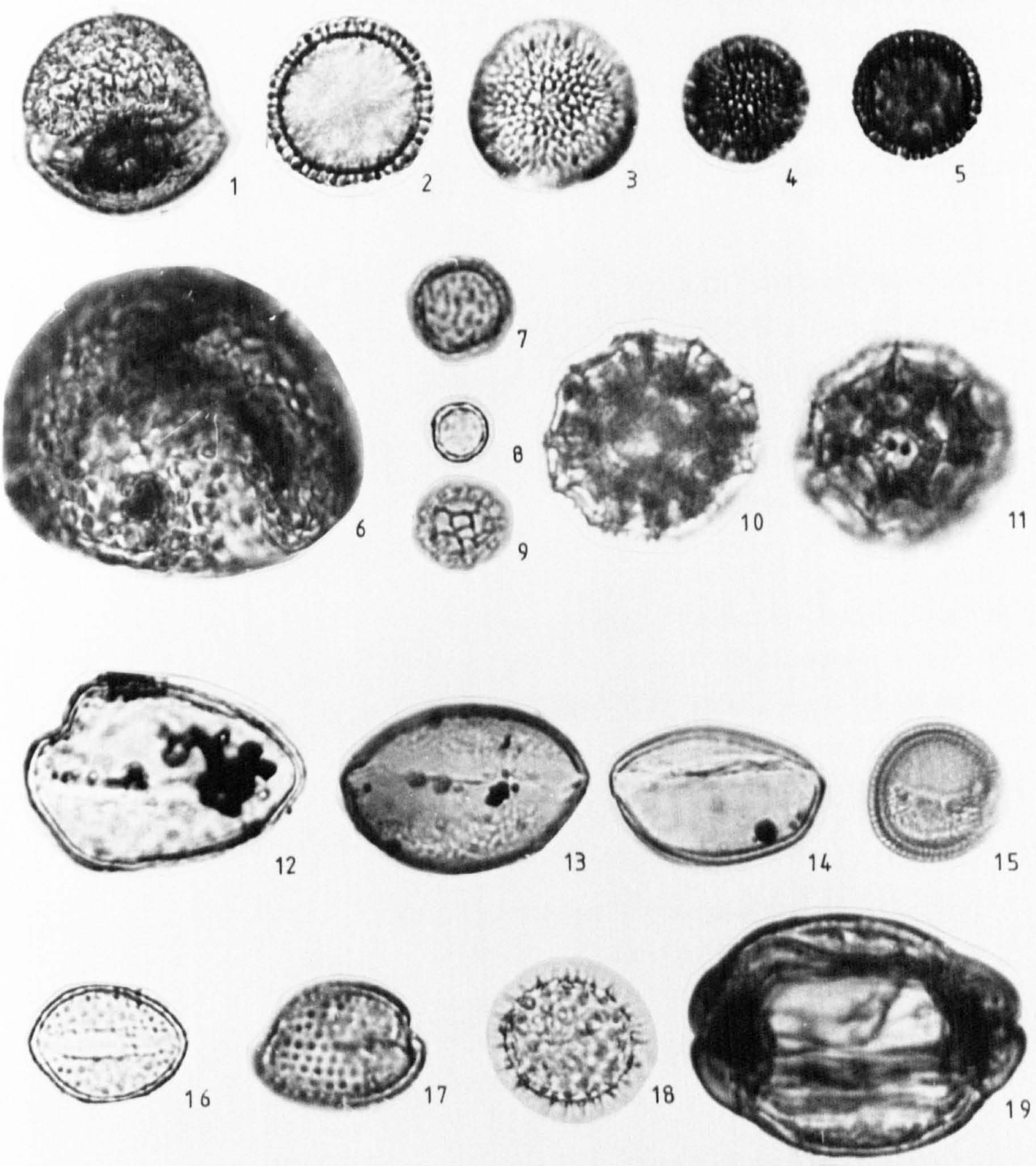


PLATE 2

Syncolpate grains.

1. *Loranthus insularum*, Loranthaceae: (Lan). Amb acute-triangular (concave), radially symmetric and with a maximum diameter of 30-32μm. Scabrate exine measures 0.8-1μm in thickness and there are no obvious thickenings of exine in the mesocolpium although several ridge-like structures are visible in polar view. The three colpi are slightly depressed and indistinct, anastomosing at both poles. Transverse colpi are short and indistinct.

2-3. *Metrosideros collina* comp., Myrtaceae: (Tem, Vh). Grains tricolporate, amb triangular-obtuse (concave) to triangular-obtuse (convex) and have a diameter measuring 15-18μm. Radially symmetrical. Scabrate exine is 1-1.2μm wide with no obvious thickenings at the pores. Colpi are narrow, anastomosing in the polar areas to form concave triangle around apocolpium. Short transverse colpi measure 1-1.3μm in length. Similar grain morphology to *Eugenia rariflora* (below) except for differing shape of the pores which are more circular in *E. rariflora.*

4. *Eugenia rariflora* comp., Myrtaceae: (Tem). Grains are tricolporate, amb triangular-obtuse (straight) to triangular-obtuse (convex) with diameters of 16-17μm. Radially symmetrical. Scabrate exine is 0.8-1μm thick increasing to 1.4μm near the pores. Polar view of pores and adjacent exine appear distinctly square-shaped. Pore diameter measures ~1μm. Colpi are narrow, anastomosing in the polar areas but becoming indistint (no apocolpium visible).

5. *Psidium gaujava*, Myrtaceae: (Roto, Tem). Grains tricolporate, amb triangular-obtuse (convex) with a diameter of 13-15μm. Radially symmetrical. Scabrate to fine reticulate exine is 0.8-1μm thick with a slight increase in thickness visible near the pores. Colpi narrow and frequently not seen to join in polar region (i.e. apocolpium present). Pore diameter measures 0.5-1μm.

6. *Eugenia* comp., Myrtaceae: (Tem). Grains tricolporate, amb triangular-obtuse (concave) to triangular-obtuse (convex), with a diameter of 12-13μm. Radially symmetrical. Psilate exine is 0.8μm thick in the area of the mesocolpium but thickening to 1μm around pores. Polar view of pores and adjacent exine appear distinctly square shaped. Colpi are wide and very distinct, anastomosing in the polar areas to form concave triangle around apocolpium. Pore diameter measures 0.6-0.8μm.

7. *Guioa rhoifolia*, Sapindaceae: (Lan). Grains tricolporate, amb triangular-acute (straight), with a diameter of 13-15μm. Radially symmetrical. Psilate to fine scabrate

exine is 1.2-1.5μm thick and has two distinct layers. Pores spherical and distinct, with a diameter of 1-1.3μm. Colpi are thin at apices, widening to 2μm half-way between apex and pole, then anastomosing in the polar areas (no apocolpium present).

Monoporate grains.

8. *Freycinetia impavida*, Pandanaceae: (Tem, Vh). Grains bilateral plano-convex to irregular pear-shaped measuring 15-18μm in length and 10-12μm in width. Fine scabrate exine measures ~1μm in thickness but thickens slightly to 1.5μm on wall opposing the single pore. Single large pore measures 4-6μm in diameter, and has a distinct outline but no anulus.

9-10. *Pandanus tectorius*, Pandanaceae: (Roto, Tem, Vh). Grains spherical-oblate with lengths ranging between 20-23μm and widths between 15 and 20μm. Single indistinct pore is present without an anulus and measuring around 4μm in diameter. Echinate exine is usually <1μm thick (excluding echinae). Echinae are regularly spaced, have a distinct bulbous base and are <1μm in length, unlike *Pandanus radula* which has irregularly spaced micro-echinae. *Pandanus radula* also has a circular pore with distinct anulus which is slightly protruding.

11. Gramineae: (Lan, Roto, Tem, Vh). Grains spherical with diameters between 25 and 30μm. Exine is psilate to scabrate. The single spherical pore measures ~3μm in diameter and has a very distinct and protruding anulus.

12. Gramineae: (Lan, Roto, Tem, Vh). Grains spherical to prolate with diameters measuring between 20 and 25μm. Exine scabrate. Spherical pore 2.5-3.0μm in diameter with distinct and protruding anulus.

13. Gramineae: (Lan, Roto, Tem, Vh). Grains spherical with diameter measuring between 40 and 45μm. Exine coarse scabrate. Spherical pore 4.0-5.0μm in diameter with distinct and protruding anulus.

14. Cyperaceae: (Lan, Roto, Tem, Vh). Heteropolar "pear shaped" grains with pseudopores. Exine is extremely thin. Grains from the Cyperaceae family are frequently crumpled and often too damaged to permit generic determination.

15-16. *Cyperus pennatus*, Cyperaceae: (Roto). Heteropolar "pear-shaped" grains slightly pointed at apex, measuring ~20-22μm at maximum diameter. Grains have perforate tectum with lacunae i.e. areas where the tectum is broken up into small frustillae, usually forming an areolar sculpturing. One lacuna forms a psuedopore (rudimentary pore) at the broad end of the grain. Lateral lacunae are variable in size and shape but are generally oblong with their length being twice as long as their breadth and more than half the length of the whole grain. Faint collumellae visible in exine which is usually >1μm in thickness. The similar grains of *Cladium mariscus* may be distinguished by the prominant narrow apex of the grain which projects out like a beak.

17. *Fimbristylis cymosa* comp., Cyperaceae: (Tem). Grains are similar in general morphology to *Cyperus pennatus* but with 4-6 lateral lacunae more or less circular in shape. The narrow end of the grain is more rounded and the overall maximum length of the grain is generally shorter, averaging around 15μm. Exine has psilate sculpture with indistinct columellae.

18. *Kyllinga* comp., Cyperaceae: (Vh). Grains ovoid with average diameter of 16μm. Lateral lacunae are more or less circular with lengths measuring around 20-35% that of the whole grain. Fine scabrate exine ~1μm thick with indistinct columellae.

19-20. *Typha angustifolia*, Typhaceae: (Lan, Roto, Tem, Vh). Grains spherical to oblate, measuring 18-23μm in diameter. Reticulate exine is 2-2.3μm thick, tectate with very distinct columellae and two layers visible. Muri sometimes duplicolumellate especially at junctions. Muri are narrower than lumina. Lumina vary in width and shape wit the largest always in the area opposing the pore. The single pore is spherical (~5μm in diameter) with an indistinct outline and without a thickened margin. The pollen of *Typha angustifolia* is very similar to *Typha latifolia* grains which are more usually found in tetrads.

Diporate grains.

21. *Lepinia* sim, Apocynaceae: (Roto). Grain damaged. Asymmetrical plano-convex grain measuring 50-55μm in length and ~30μm in width. Exine irregular verrucate sculpture with psuedopores. Two large "vestibulate" circular pores at each end of the grain ~20μm in diameter. No thickened anulus visible as found in *Alyxia* sp. (below).

22. *Fuchsia cyrtandroides*, Onagraceae: (Vh). Grain elliptic, accuminate obtuse. Equatorial view elongated, 55-60μm in length and 34-37μm in width. Exine finely scabrate, becoming roughly scabrate near the pores. Exine 1-1.5μm thick, tectate, columellae are fairly distinct. Pores are protruding, vestibulate and with a diameter of 14-16μm.

23. *Trema* comp. *orientalis* sim., Ulmaceae: (Lan, Tem, Vh). Grains circular or oval in polar view, oblate in equatorial view. Lengths measure 22-24μm and width 20-22μm. Sculpturing unevenly scabrate, with columallae visible but not particularly

distinct. Exine 1-1.3μm thick, increasing around the pore. Pores circular (3-3.5μm) with thickened protruding anulus.

24. *Trema* sp., Ulmaceae: (<u>Roto</u>). Grains similar to *Trema orientalis* (above) but significantly smaller in size (Length 15-16μm, width 14-16μm).

25. *Alyxia stellata* comp., Apocynaceae: (<u>Roto</u>). Asymmetrical plano-convex grain, 45-48μm in length and 24-27μm in width. Exine 2μm thick, clearly two layered with distinct colummellae, and reticulate sculpturing. Pores "vestibulate" circular and very large (12-14μm diameter) and surrounded by thickened anulus (3μm wide and 2.3μm thick) which protrude slightly (other species of *Alyxia* have non-protruding pores and are often larger in diameter).

26. *Ficus tinctoria* comp., Moraceae: (Roto, <u>Tem</u>). Peroblate or oblate, 10-12μm in length and 6-8μm in width. Psilte exine which is relatively thick (>1μm) compared with other *Ficus* species. Simple circular pores without anulus.

27. *Procris pedunculata* comp., Urticaceae: (Lan, <u>Vh</u>). Grains are spherical, measuring 12-13μm in diameter. Fine and regularly patterned reticulate exine, <1μm thick with visible columellae. Circular pore measuring ~2μm in diameter with a thickened and protruding anulus.

28. Urticaceae/Moraceae: (Lan, Roto, <u>Tem</u>, Vh). Grains circular in polar view, oval in equatorial view with a maximum diameter of ~13μm. Psilate or scabrate exine. Pore measures 1-2μm in diameter with a slightly thickened anulus. Includes the genera *Procris* (synonym *Elatostema*), *Debregaesia*, *Laportia* and *Cypholophus* (in the Urticaceae family) and *Maclura* and *Malaisia* (in the Moraceae family).

Triporate grains.

29. *Pipturus* sp., Moraceae: (<u>Vh</u>). Grains spherical, measuring 10-13μm in diameter. Exine variable in thickness but averaging 1μm, finely reticulate with distinct columellae. Three simple and indistinct circular pores (no greater than 2μm in diameter) with thin anulus, not protruding.

30. *Allophylus vitiensis* comp., Sapindaceae: (<u>Roto</u>). Grains triangular in polar view, obtuse with straight or slightly convex sides, and with a maximum diameter measuring ~25μm. Eliptic obtuse in equatorial view. Three elongated pores/short transverse colpi at each apex 2-3μm wide. Exine fine scabrate sculpture <1μm thick with slight thickening around pores.

31. *Celtis paniculata* comp., Ulmaceae: (Roto, Tem, Vh). Sub-spheroidal in polar view, 20-24μm in diameter. Oblate in equatorial view. Exine finely scabrate, 0.8-1μm thick and visibly tectate in structure. Recessed spherical pores 3-3.5μm in diameter, with anulus ~1μm wide with costae present. Grains of *Celtis paniculata* are invariably larger than those of *Celtis orientalis* (below) but are otherwise similar in morphology.

32. *Celtis orientalis* comp., Ulmaceae: (Vh). Polar view circular, equatorial view oblate with an equatorial diameter of ~16μm. Exine fine to coarse scabrate, 1μm thick, tectate and with distinct columellae. Pores spherical with a diameter of 2.5-3μm, distinctly thickened anulus which is up to 1μm wide and slightly protruding. Costae apparently absent.

PLATE 2

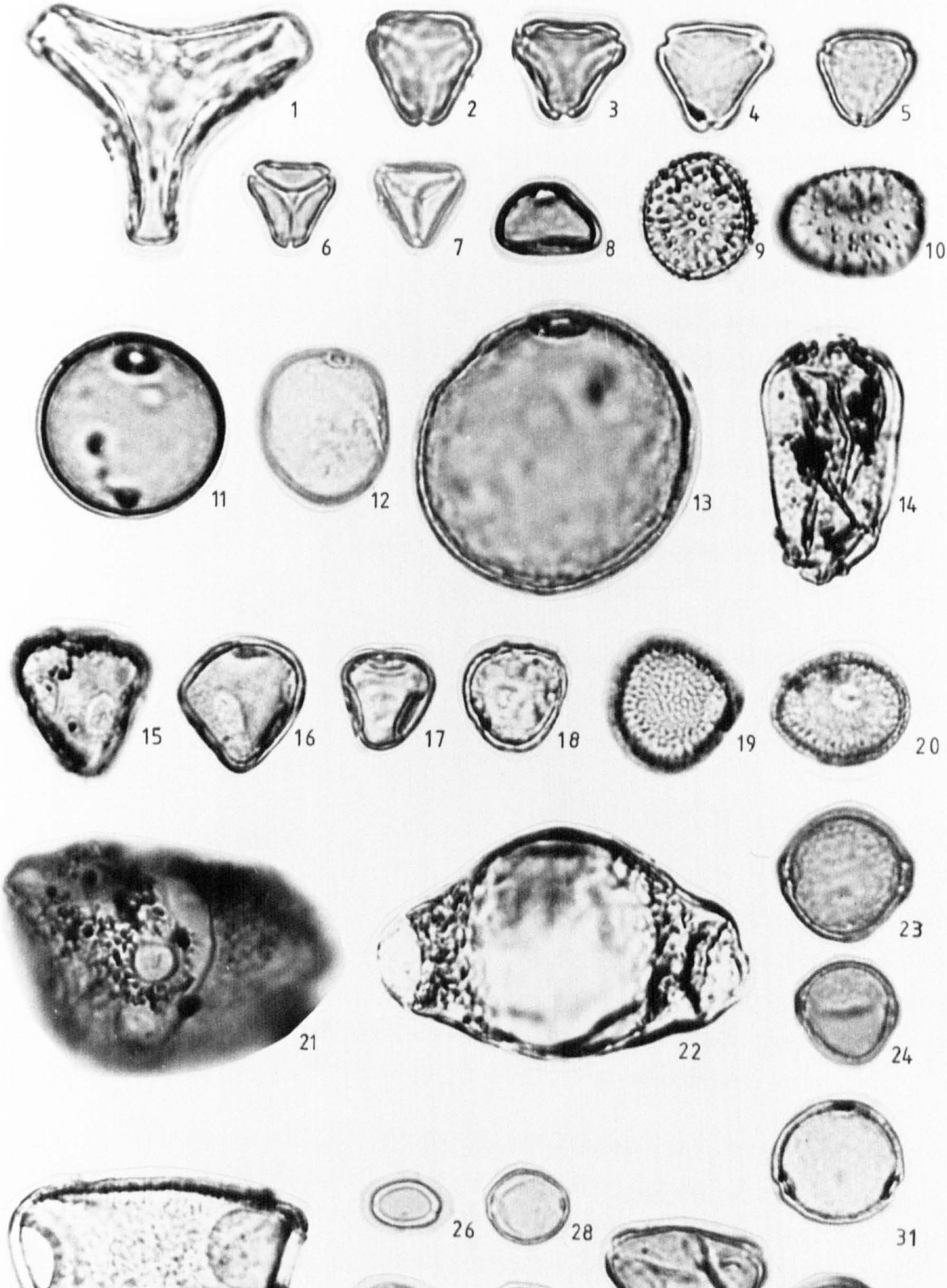

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PLATE 3.

Triporate grains (continued).

1-2. *Canthium barbatum* comp., Rubiaceae: (Roto). Grains semi-triangular to triangular in polar view, oblate to circular in equatorial view with equatorial diameter of ~35μm. Thick exine (~2μm) distinctly reticulate. Reticulate pattern, heterobrochate i.e. irregular in shape and size with the larger, often elongated, lumen found towards the centre of the apoporium (maximum length 5.5μm) and smaller lumen (~2μm diameter) found towards mesoporium. Muri up to 2μm wide but invariably less than the diameter of the lumen. Large circular to transversely elongated pores up to 8μm in diameter with thick patterned and protruding anuli up to 4μm thick. Pollen of *Canthium merrellii* has a more compact reticulum with less thickening of the exine around the pores.

3. *Casuarina equisetifolia*, Casuarinaceae: (Roto, Tem). Grains are convex (obtuse) triangular in polar view and obtuse elliptic (acuminate) in equatorial view. Maximum diameter ~30μm. Exine fine scabrate but sometimes appearing rugulate, often in excess of 2μm thickness especially around pores. Three circular and protruding pores, 3-4μm in diameter. Anulus distinct with crevassing present.

4. Proteaceae comp.: (Roto). Grains obtuse triangular concave (apices truncated) in equatorial view, with maximum diameter of ~30μm. Fine scabrate exine (1-2μm thick) but appearing almost verrucate in some areas. Three indistinct circular pores occur at the apices but no anuli visible.

Stephanoporate grains.

5-6. *Altingia* comp., Altingiaceae: (Vh). Grains spherical in shape ranging between 25 and 28μm in diameter. Coarse scabrate exine (<1μm thick) becoming granulate around the 12 to 14 pores. Pores irregularly shaped but more or less spherical with an average diameter of 4μm and slightly protruding. Pore boundary indistinct. Pollen from the genus *Albizzia* are similar in appearance but have larger dimensions.

7. *Cyathula* sp., Amaranthaceae: (Roto). Grains spherical to oblate, around 20μm in diameter and with 40-45 regularly spaced and distinct circular pores. Psilate exine <1μm thick with no variation around pores. Pore diameters average 2μm. Similar in general appearance and size to species of *Acharanthes*, especially *Acharanthes indica* and *Acharanthes aspera* but with significantly fewer pores.

8. *Acalypha* sp., Euphorbiaceae: (Lan). Grains circular to oblate, measuring 14-16μm in diameter. Exine 1-1.2μm in width with fine scabrate sculpturing. Four circular

pores (~2μm in diameter) with irregular anulus distinctly protruding in polar view. Grains also found as 3-colporate (see Plate 5).

9. *Alnus japonica* comp., Betulaceae: (Roto). Convex hexagonal shape in polar view, with maximum diameter between 20 and 22μm. Psilate exine, 1-2μm thick between pores with two layers visible. Neighbouring pores (anuli) connected with bands (arci) of nexinous thickening up to 2μm thick. Five pores distinctly vestibulate (2μm) with thickened protruding anuli.

Stephanocolporate grains.

10-11. *Pemphis acidula*, Lythraceae: (Tem). Very distinctive quadrangular (acute) shape in polar view with four distinctly recessed colpi. Equatorial diameter measures ~30μm. Grains more or less prolate in equatorial view, measuring 30-32μm in length. Exine fine scabrate to reticulate averaging 2μm thickness in the mesocolpium. Outer layer of the exine extends around colpus opening to form a type of flange/vestibulum seen to protrude out from the grain in polar view. Four equatorial pores are slightly elongated along polar axis (6-7μm long). Colpi are long and the polar area index is relatively small. Grains are darkly stained by the acetolysis process.

12-13. *Claoxylon tahitensis* comp., Euphorbiaceae: (Tem, Vh). Grains 5-colporate, spherical or oblate in equatorial view, 17-20μm in length and 17-19μm in width. Exine with feint reticulate sculpture, 1-1.8μm thick, with distinct columellae, slight exinous thickening around colpi. Two exine layers also visible. Colpi wide and medium length, slightly constricted at the equator. Transverse colpi almost aequatorialis.

14. *Myrsine affinis* comp., Myrsinaceae: (Vh, Tem). Grains tetrazonocolporate, prolate in equatorial view with a length of 13-17μm. Exine has a scabrate sculpture (~1μm thick). Colpi narrow and long and slightly constricted at the equator. Polar area index is large. Colpi often irregularly formed, with indistinct margins. Frequently grains possess 3 or 5 colpi. Possess indistinct transverse colpi which are often not visible under light microscope.

15. *Messerschmidia* comp., Boraginaceae: (Tem, Roto). Grains tetrazonocolporate, prolate in equatorial view with a length of 24-26μm and width of 20-23μm. Exine with psilate sculpture (>1μm thick), slightly thickened around transverse colpi although no distinct anulus is present. Colpi narrow and long and slightly constricted at equator. Small polar area index. Four distinct transverse colpi up to 5μm long and ~2μm wide. Similar in superficial appearance to several members of the melastomataceae e.g. *Melastoma* (No. 18 below).

16-17. *Mussaenda* sp., Rubiaceae: (Roto). Grains tetra-zonocolporate, more or less spherical in shape, with a diameter measuring 18-19μm. Exine psilate, ~1μm thick. Polar area index large, colpi short and wide but do not posess a margo. Four circular pores ~2μm in diameter, with distinct anulus. Similar in shape and size to *Glochidion* spp. (No. 21-22 below) but do not possess the reticulate sculpturing.

18. *Melastoma denticulata* comp., Melastomataceae: (Lan,Tem, Vh). ($C_3P_3+C_3$). Prolate to perprolate in equatorial view (20-22μm in length), amb circular with a diameter measuring 15μm. Exine psilate, 0.8-1μm thick. Colpi long and narrow and not constricted at equator. Polar area index small. Pore not distinct, diameter 2-4μm. Pollen is very similar to *Melastoma melabathricum* which can only be distinguished by its greater size (i.e. ~24μm in length).

19. *Astronia fraterna* comp., Melastomataceae: (Tem). ($C_3P_3+C_3$). Oblate in equatorial view, with a maximim diameter of ~10μm. Amb semi-triangular and measuring 11μm in diameter. Exine psilate, 0.8-1μm thick. Colpi short, narrow and recessed, not constricted at equator. Three pores indistinct, diameter ~1μm, anuli absent.

20. *Miconia calvescens* comp., Melastomataceae: (Tem, Vh). ($C_3P_3+C_3$). Spherical to oblate in equatorial view, amb circular and 14μm in diameter. Unlike *Astronia fraterna* *Miconia* is radially symmeric. Psilate exine 0.8-1μm thick. Colpi short, narrow and slightly recessed. Polar area index large. Three small indistinct pores 0.8-1μm in diameter.

21-22. *Glochidion* sp., Euphorbiaceae: (Lan, Roto, Tem). Grains tetra-zonocolporate, spherical to prolate in equatorial view with a length between 15 and 17μm. Exine 1.6-2μm thick (columellae distinct), with densely reticulate (uniform) sculpturing. Diameter of luminae up to 1.2μm. Polar area index large, colpi narrow, straight and recessed, with margo. Four circular pores around 1.5μm in diameter with distinct anuli. Similar types are found in some *Phyllanthus* spp. but usually with less distinct sculpturing.

23-24. *Disoxylum* sp., Meliaceae: (Lan). Grains tetra-zonocolporate, spherical with a diameter between 20 and 22μm. Exine finely scabrate, ~1μm thick (columellae indistinct). Four colpi narrow and relatively short and not recessed, polar area index large. Margo absent from colpi. Four circular pores, 3μm in diameter, with distinct, but thin, anuli (<1μm wide).

Triads.

25. *Styphelia* comp., Epacridaceae: (Tem). Tricolpate/tricolporate? Each grain is sub-triangular in outline and with a maximum diameter of 16-18μm. Grains very darkly

stained (brown) by acetolysis with thick psilate exines (>1μm thick). Only one exine layer visible. Interior walls appear thicker than exterior walls. Each grain appears to have three elongated transverse colpi.

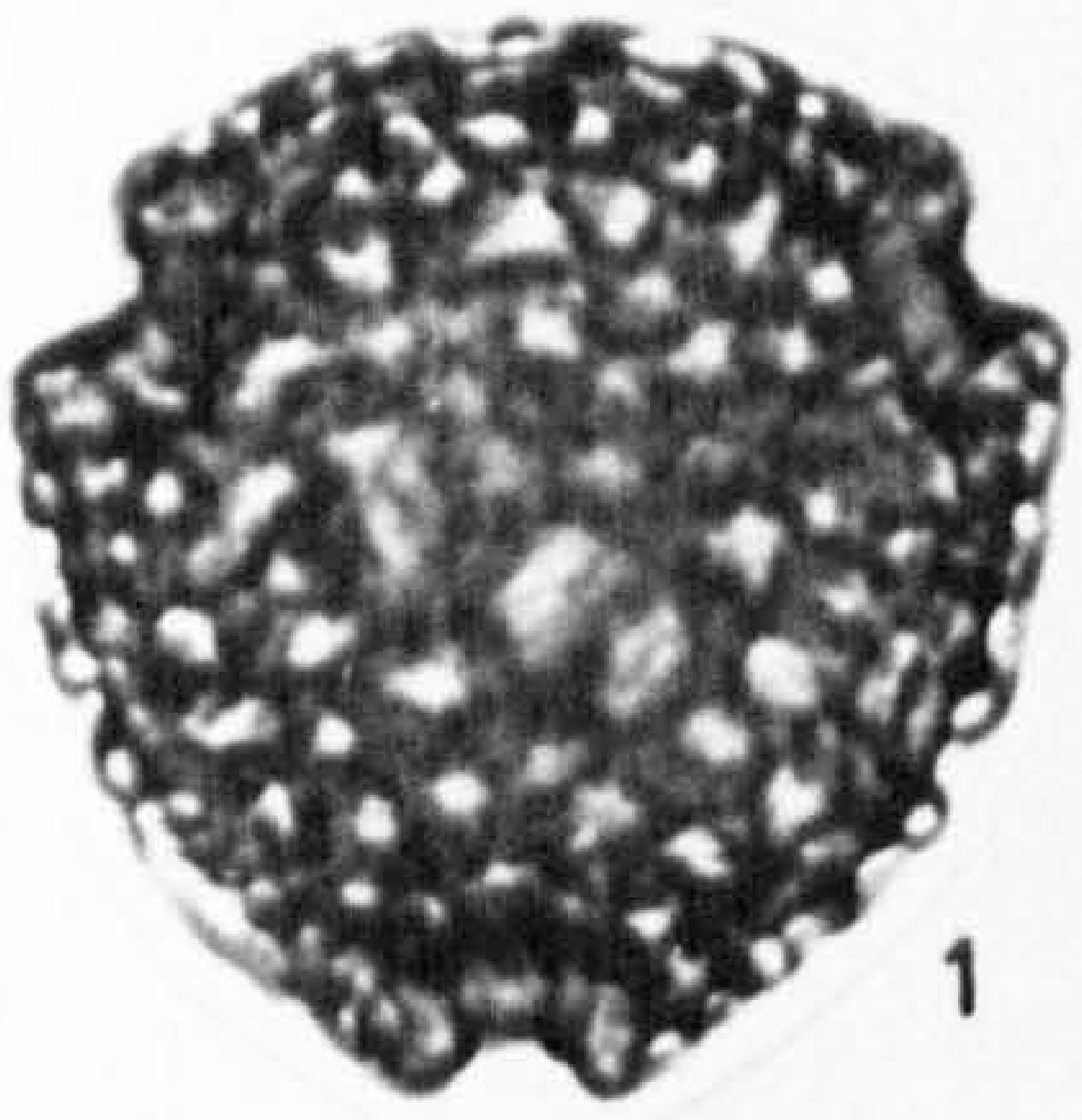
Tetrads.

26-27. *Typha latifolia* comp., Typhaceae: (Lan, Roto, Tem, Vh). Flat, loose tetrad. Exine reticulate or sometimes micro-reticulate sculpture (1-1.5μm thick). Muri often duplicolumellate, especially in the corners of the reticulum. Individual grains are sub-spherical, measure 18-20μm in diameter and have distict pores (~4μm diameter) which are roughly circular and have margins that are not sharply delimited.

28-29. *Mimosa pudica*, Papilionaceae: (Lan, Tem). Mostly found in closed tetrahedral tetrads (i.e with no gaps between the grains) and united by their proximal faces. Sometimes found as single grains (No. 28) which appear spherical and di-colpate where they were once attached to the tetrad. Individual grains average 8-9μm in diameter. Exine psilate and translucent (i.e. little stained during the acetolysis treatment). Tetrads up to 10μm diameter.

30. *Gardenia tahitensis* comp., Rubiaceae: (Tem). Four grains united in closed tetrahedral tetrad, total diameter 42-45μm. Individual grains spherical or sub-oblate, triporate with a diameter measuring ~35μm. Exine is coarse scabrate, 1-1.7μm thick. Pores are spherical (3-5μm diameter) with distinct protruding anuli (2-3μm wide). Single grains are sometimes observed.

PLATE 3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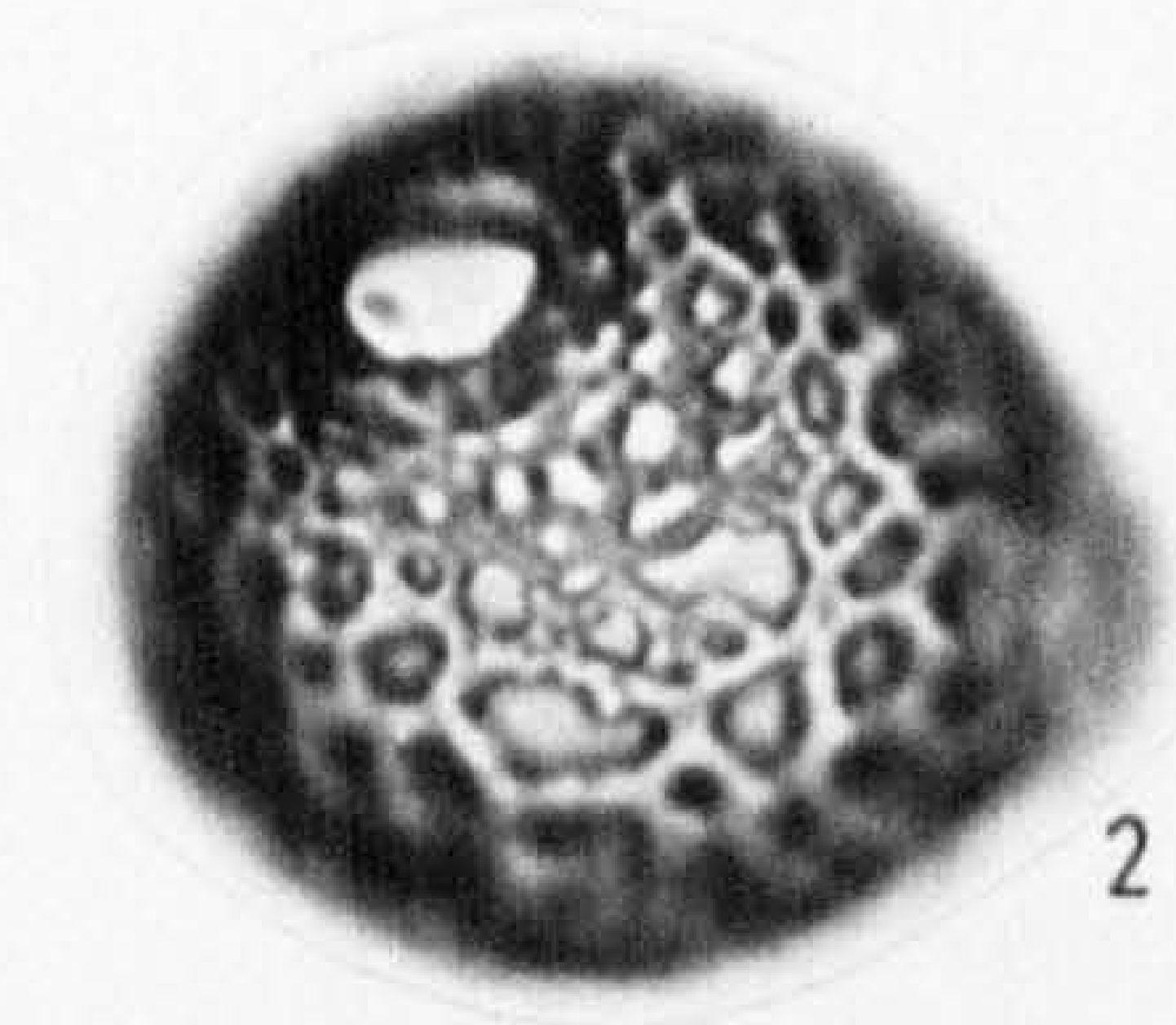
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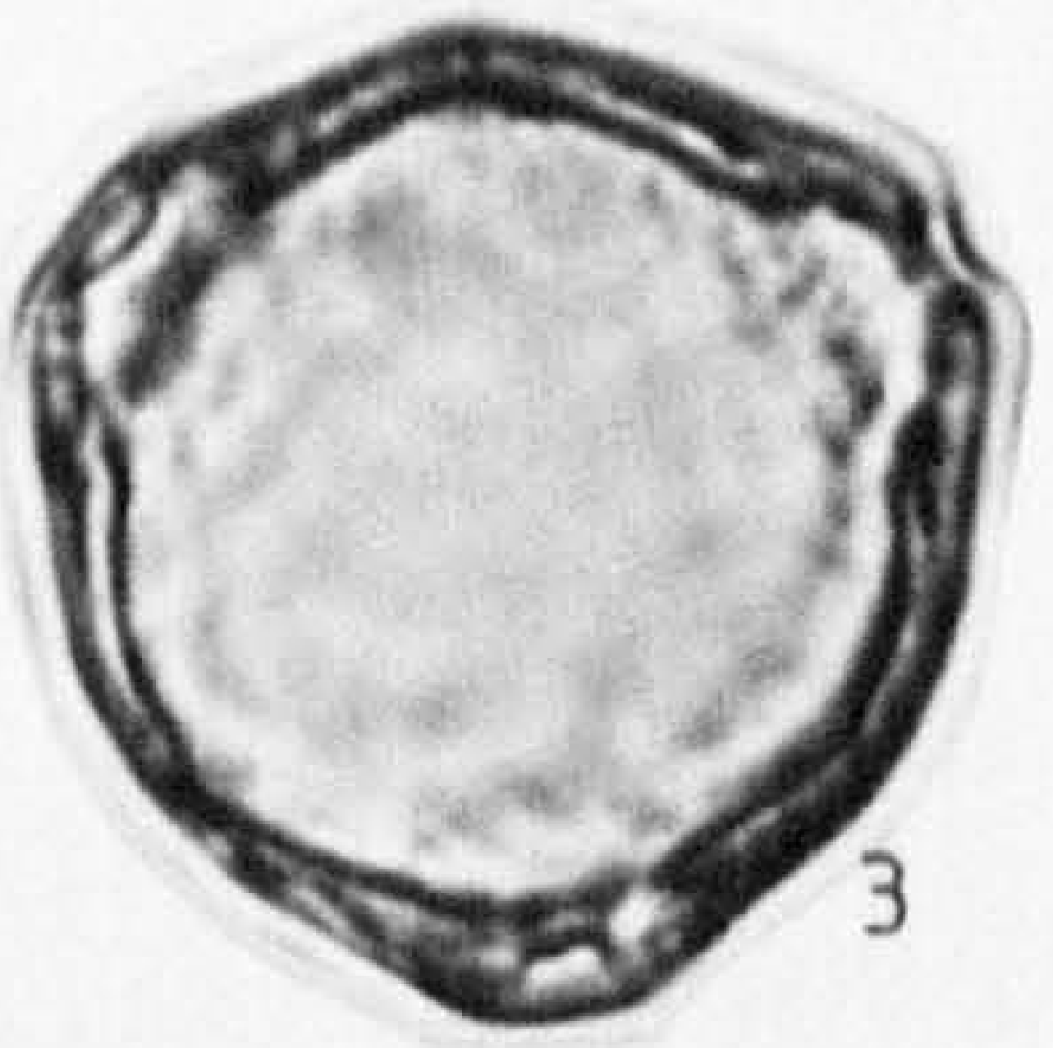
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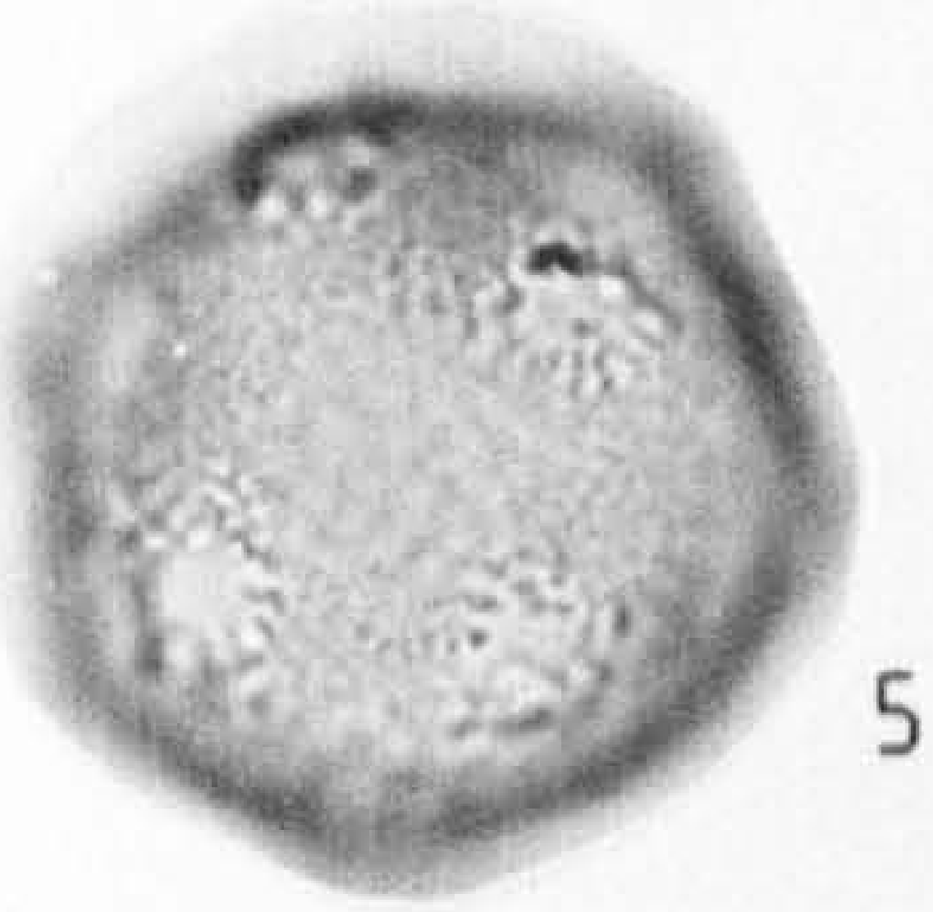
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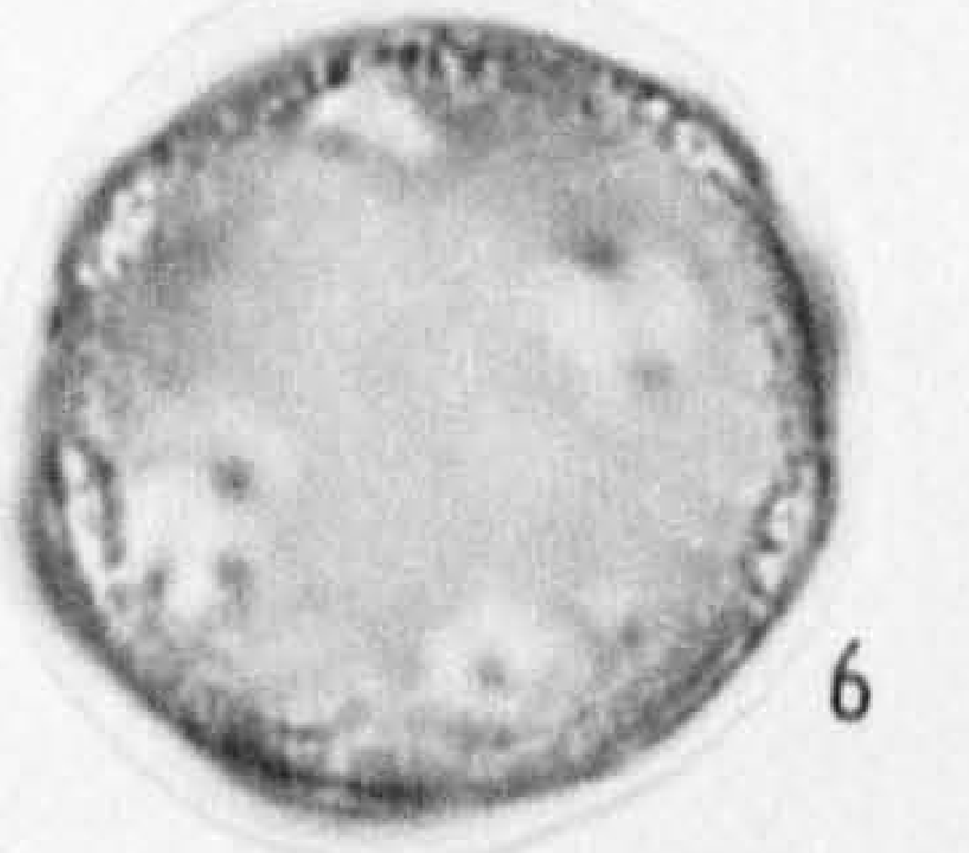
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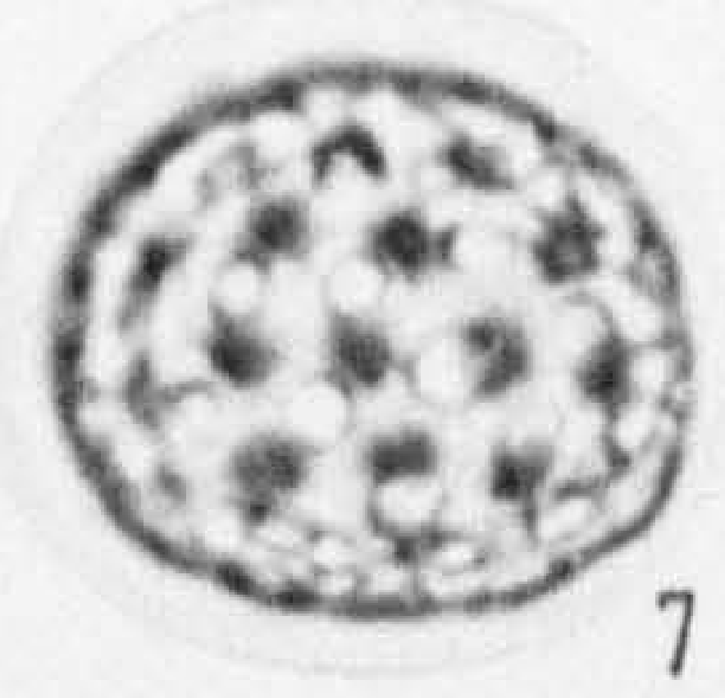
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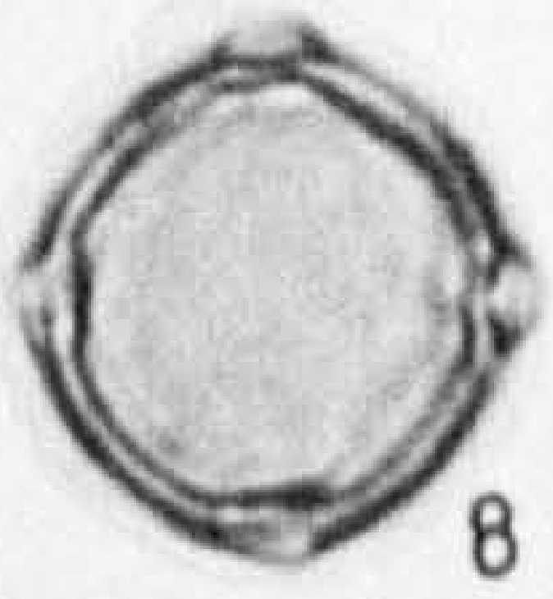
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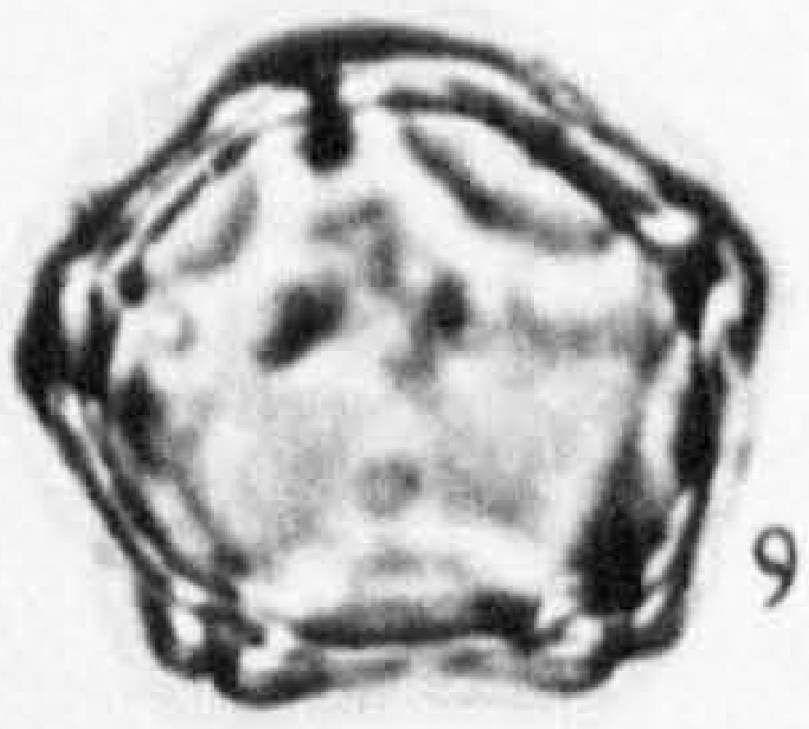
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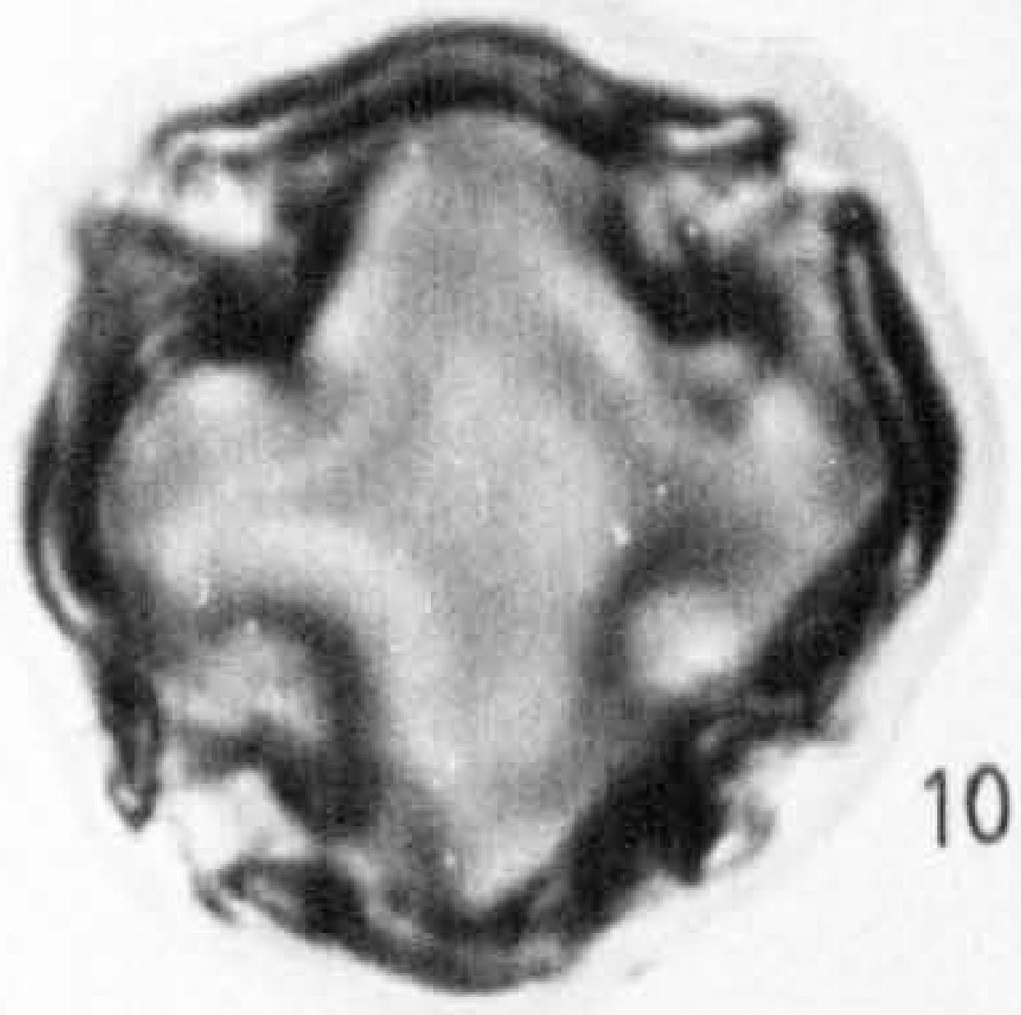
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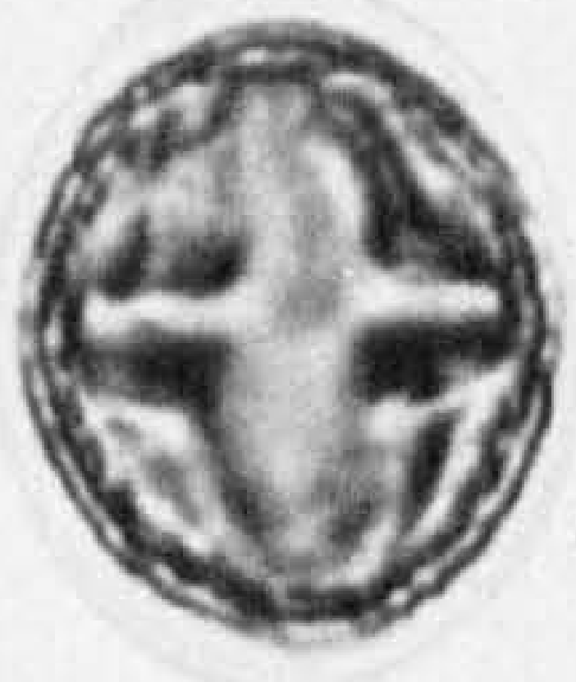
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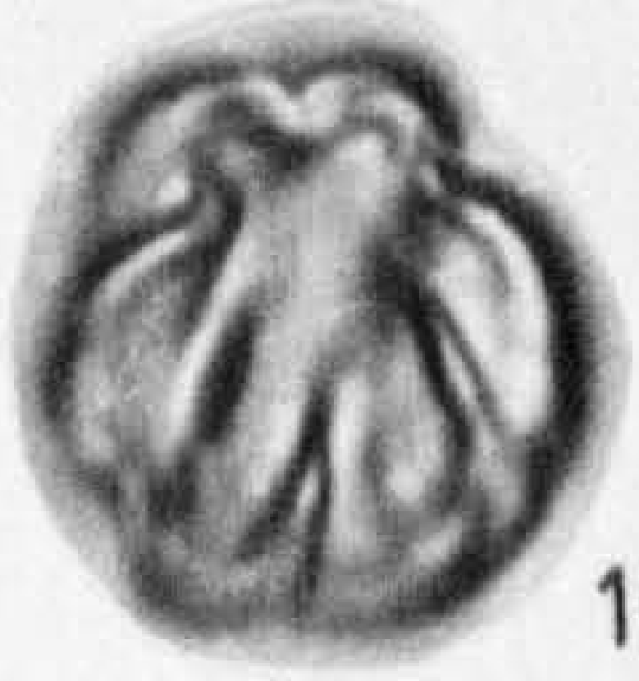
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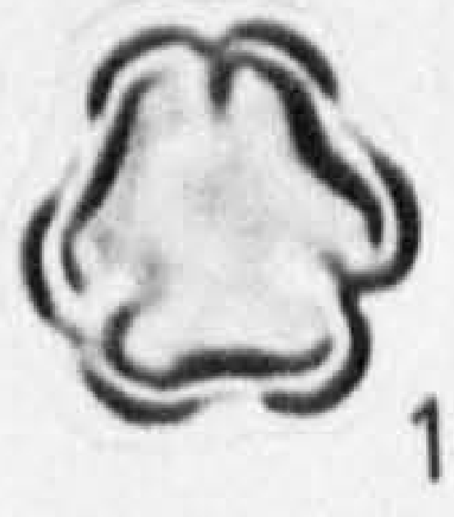
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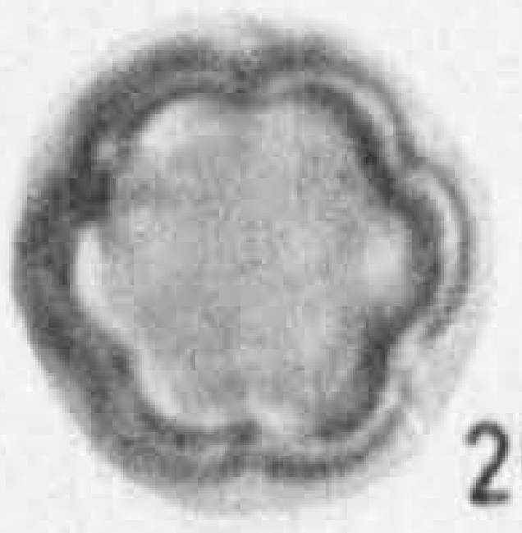
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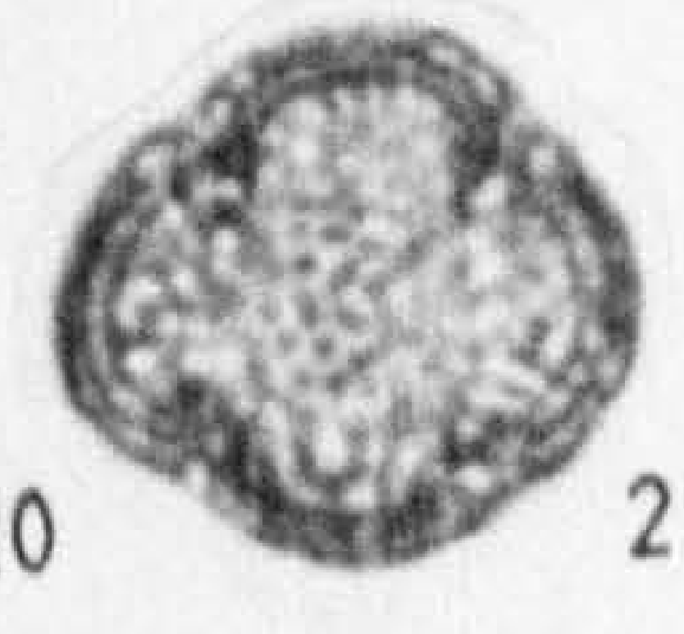
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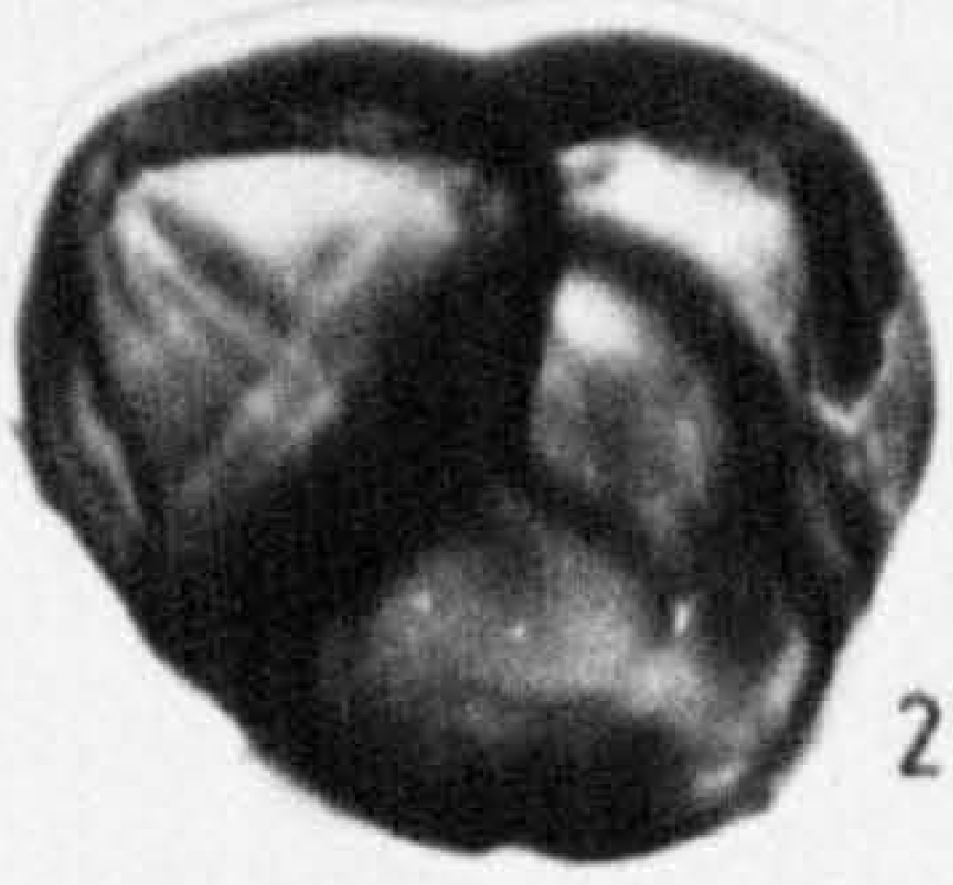
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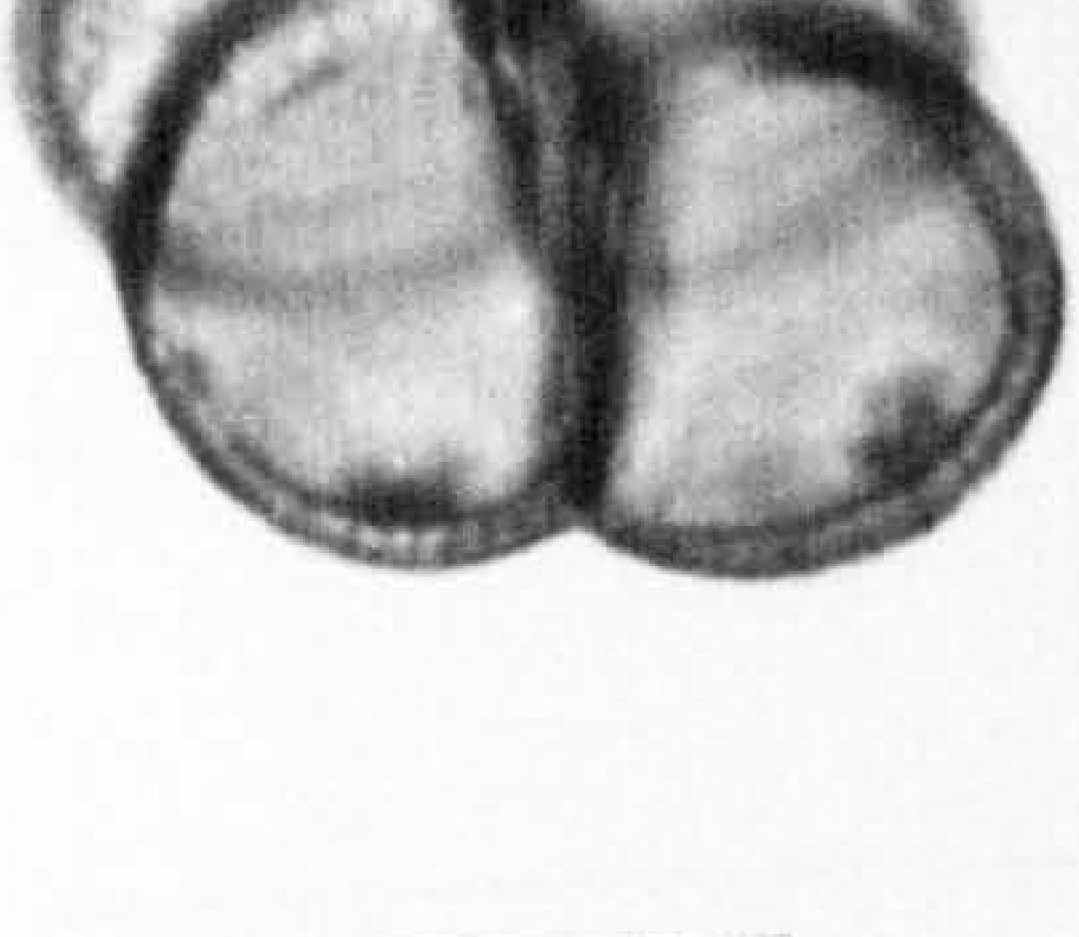
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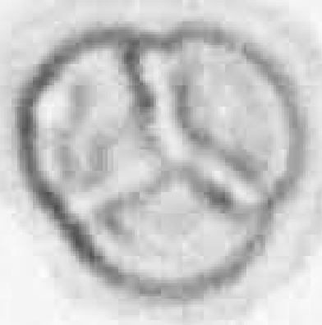
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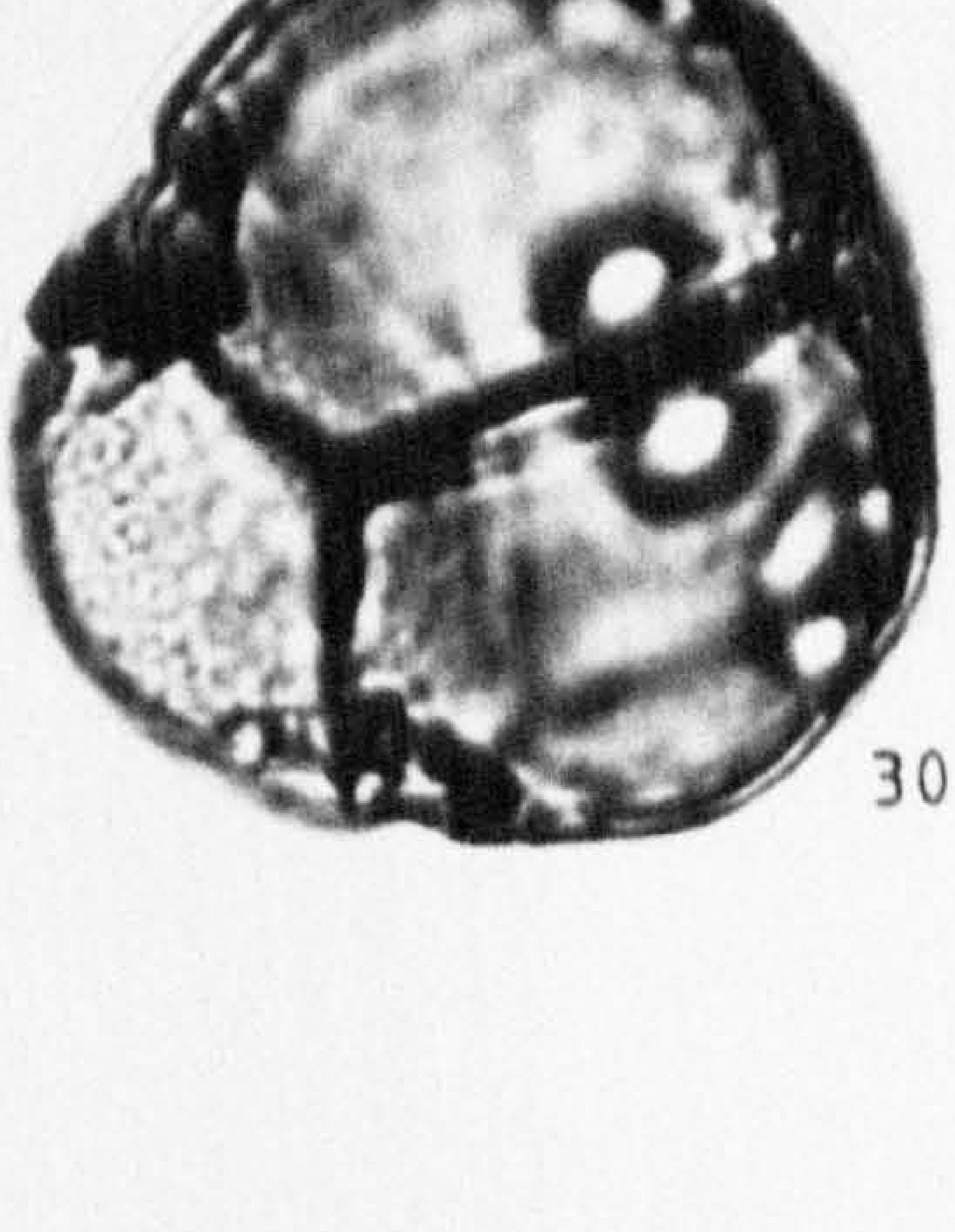
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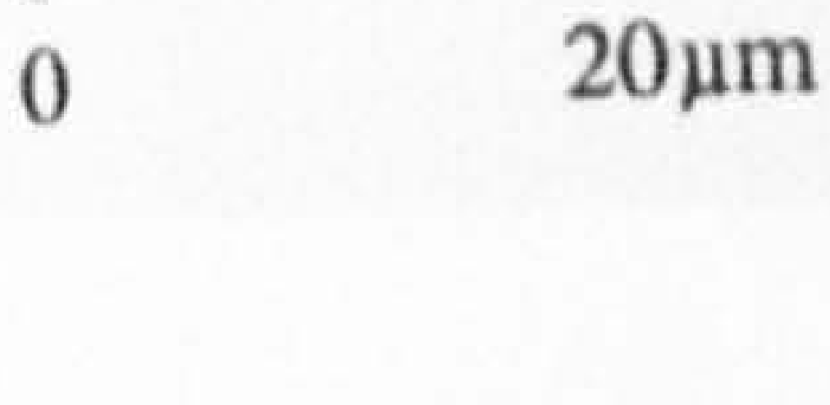


PLATE 4.

Echinate grains.

1. *Ipomoea batatas* comp., Malvaceae: (Roto). Grains are spheroidal with a diameter of 100μm (excluding echinae). Sculpture scabrate to fine reticulate in areas between the echinae. Periporate, with approximately 130 distinct pores that are more or less circular, 5μm in diameter and with no anulus. Exine 2-3μm thick between echinae. Echinae 5-11μm long, 5-8μm across at base tapering abruptly to a sharp tip. Echinae aspidote i.e. placed on circular areas protruding as rounded domes (3-4μm high) from the general surface.

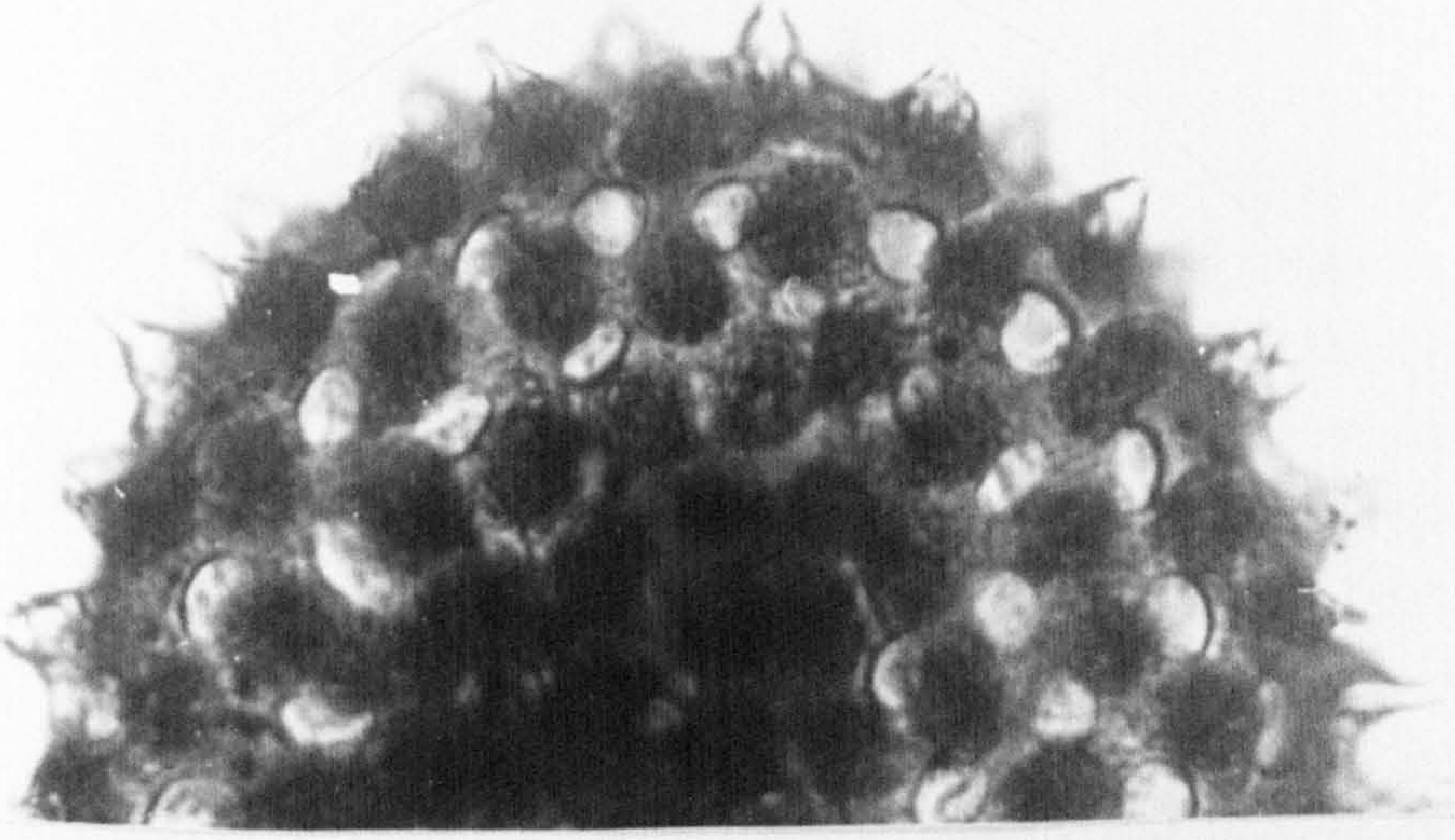
2. *Hibiscus tileaceus*, Malvaceae: (Roto, Tem). Grain spheroidal, diameter 120μm (excluding echinae). Sculpture reticulate in areas between the echinae. Periporate, with approximately 130 distinct pores that are more or less circular, 6-7μm in diameter, with anuli up to 3μm in thickness. Exine 2-3μm thick between echinae. Conical shaped echinae 20-30μm long, 6-10μm across at base tapering into sharp tips. Echinae aspidote (domes up to 4μm high).

3. *Sida rhombifolia*, Malvaceae: (Roto). Grain spheroidal with a diameter of 55-60μm (excluding echinae). Sculpture scabrate to verrucate in areas between the echinae. Periporate, with approximately 55-60 indistinct pores that are more or less circular, 4μm in diameter with thin anuli. Exine ~1μm thick between echinae. Blunt echinae (verrucae?) 3-6μm long, 5μm across at base. Not obviously aspidote.

4. *Sida* sp., Malvaceae: (Roto). Grain spheroidal with a diameter of 60-65μm (excluding echinae). Sculpture scabrate to fine reticulate in areas between the echinae. Grains periporate but the pores are indistinct. Exine ~1μm thick between echinae. Thin echinae are 8-11μm long and distinctly curled with sharp tips, 5-6μm across at bulbous base. Echinae aspidote (domes up to 3-4μm high).

5. *Thespesia populnea*, Malvaceae: (Tem). Grain spheroidal with a diameter of 55μm (excluding echinae). Sculpture psilate to scabrate in areas between the echinae. Grains periporate but the pores are indistinct. Exine 1-2μm thick between echinae. Echinae up to 14μm long but their length is variable, 6-7μm across at base abruptly tapering into sharp tips which are invariably curved. Echinae aspidote (domes up to 1-2μm high).

PLATE 4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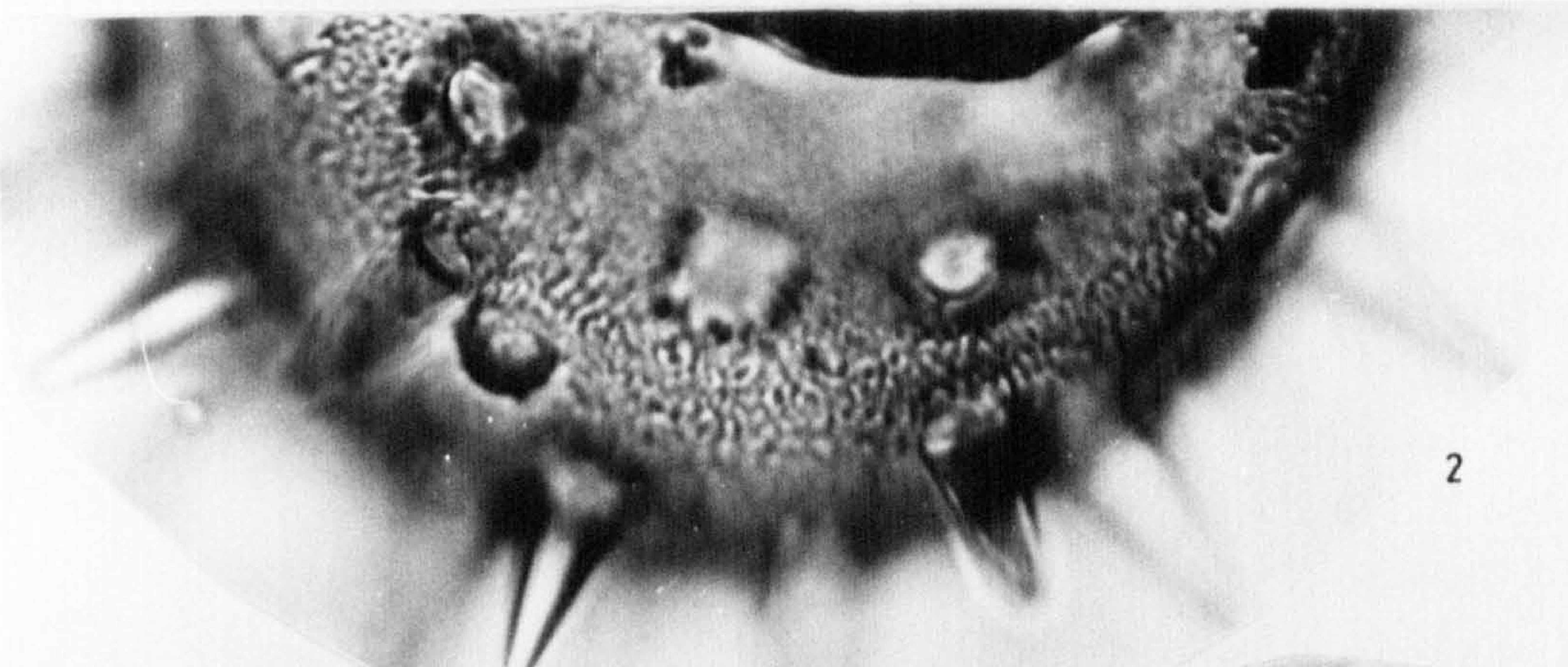
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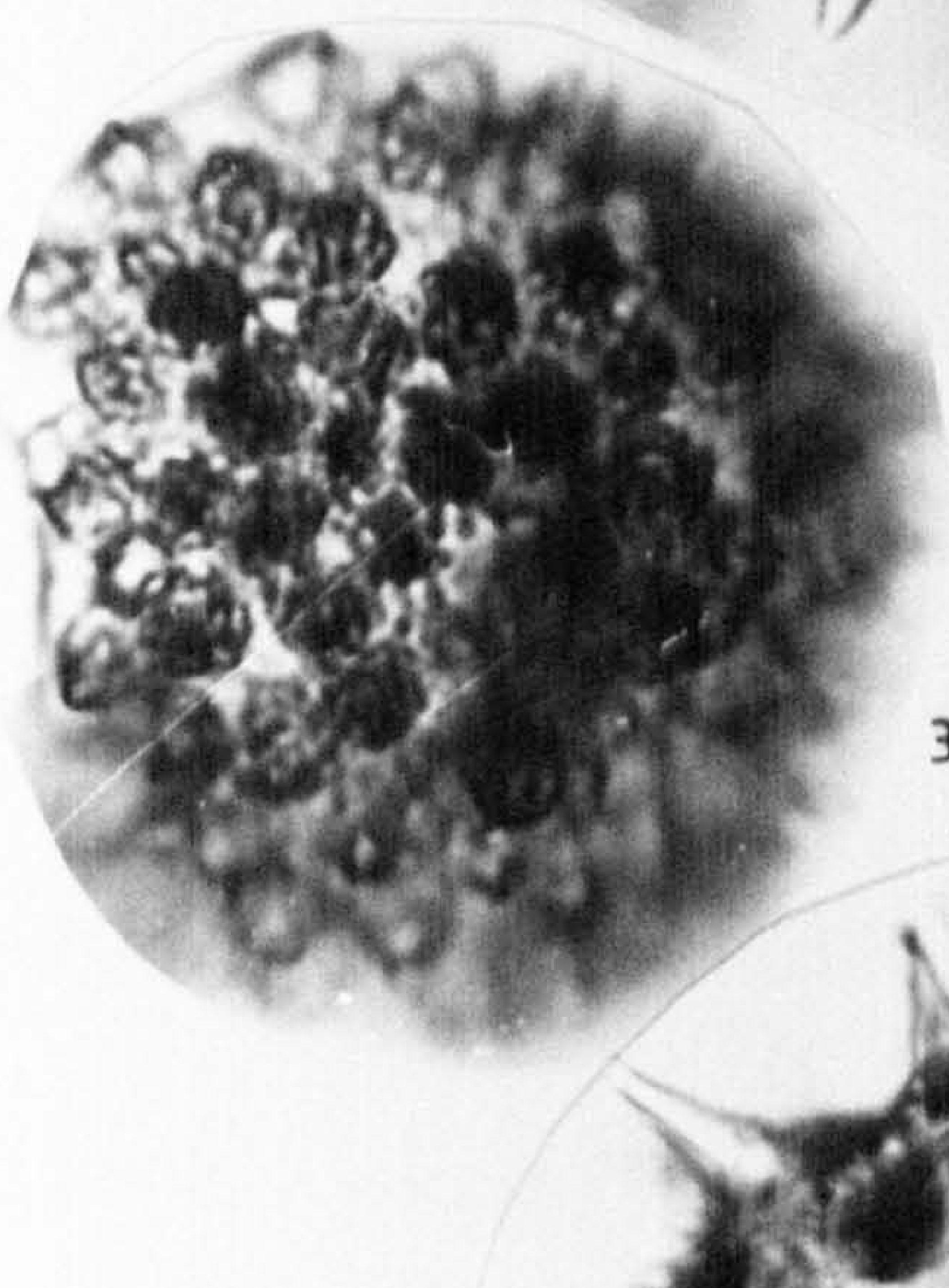
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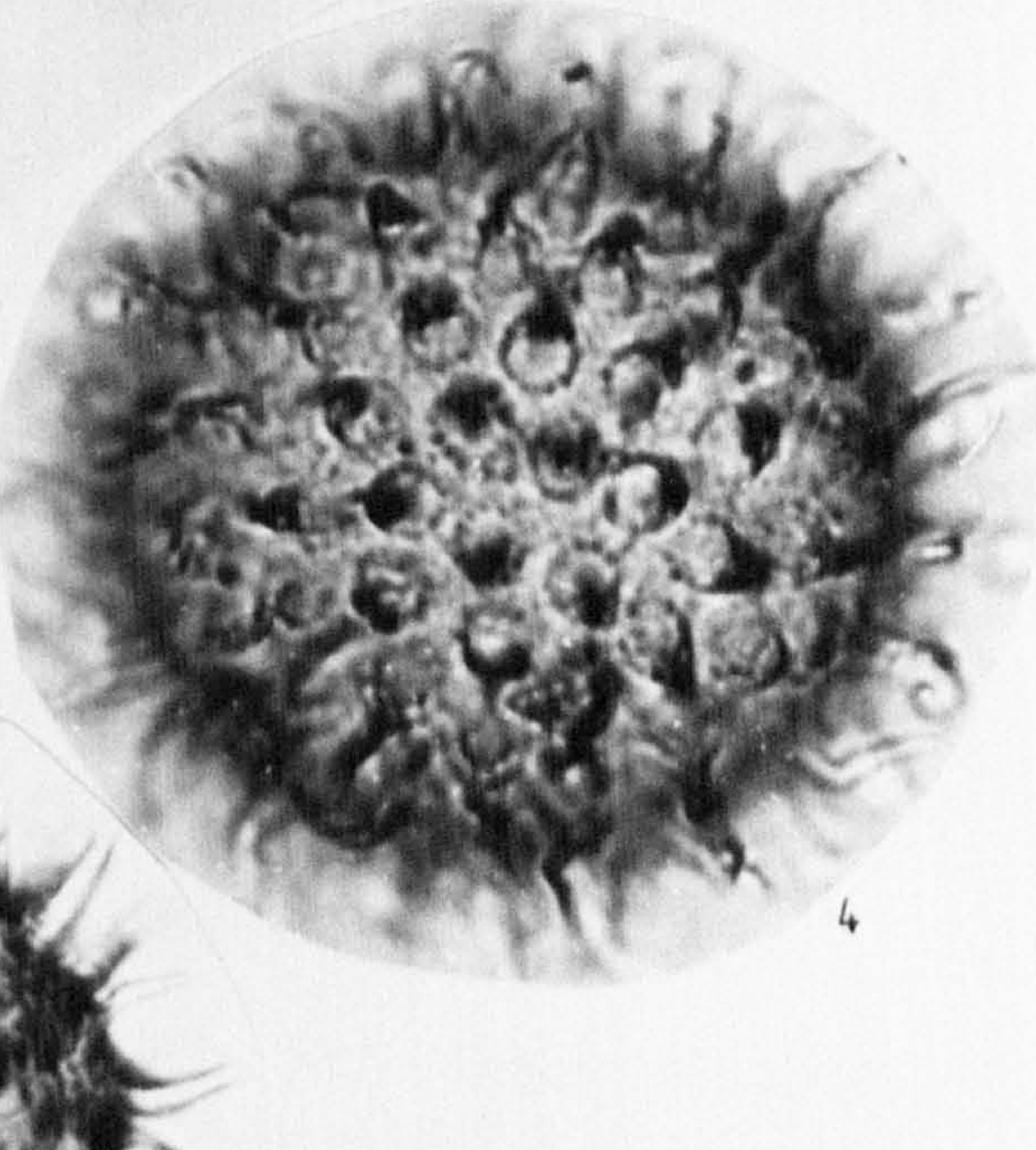
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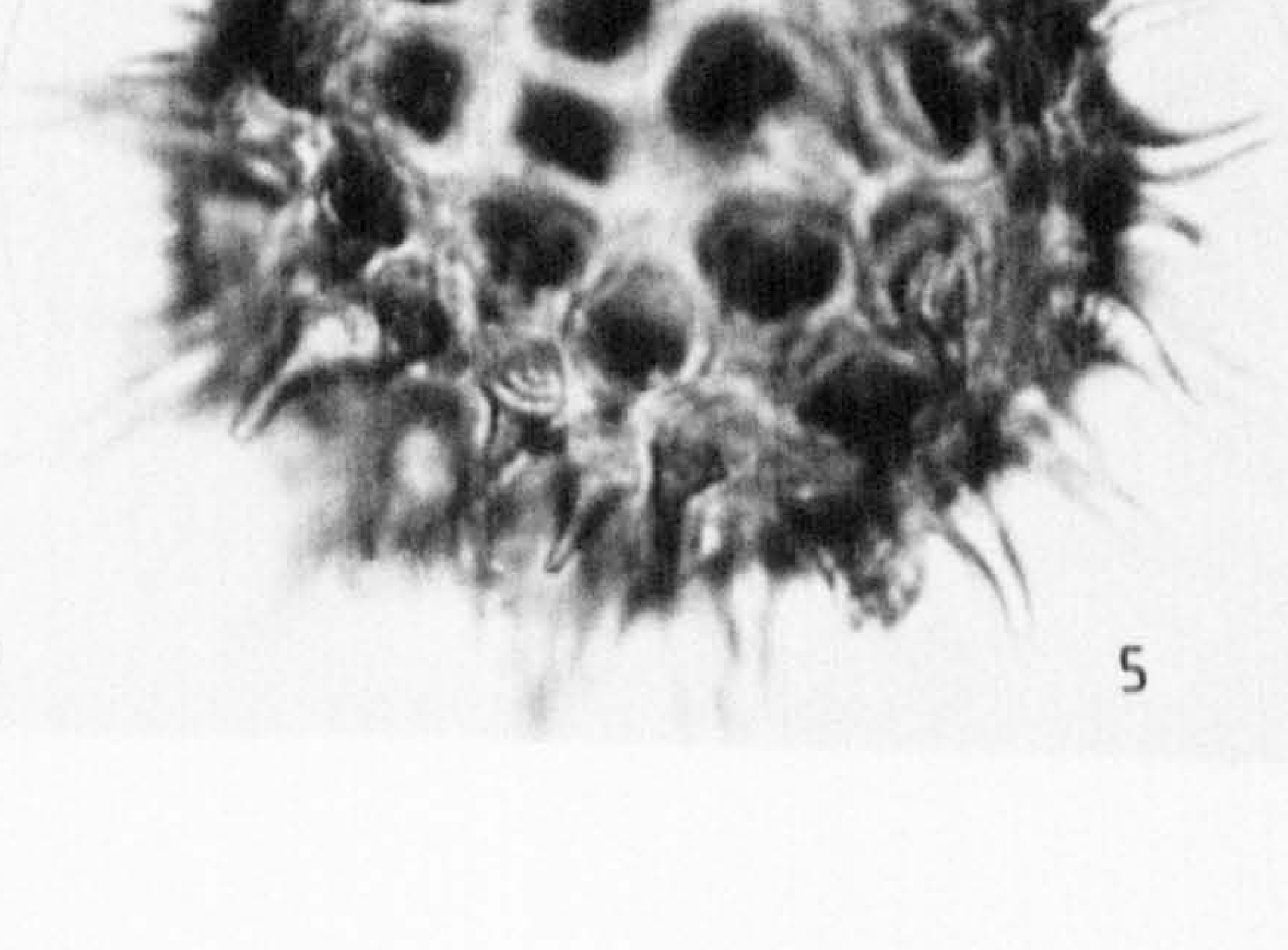
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PLATE 5.

Tricolporate grains.

1-2. *Coprosma tahitensis*, Rubiaceae: (Tem, Vh). Grains obtuse (convex) triangular to circular in polar view, with a diameter measuring 24-26μm. Oblate in equatorial view. Exine finely reticulate, 1.5μm thick with slight thickening around transverse colpi. Three thin and short colpi distinctly recessed. Polar area index large. Three distinct transverse colpi which are up to 5μm wide i.e. considerably wider than meridional copli. Transverse colpi approximately 12μm long but not aequatorialis. Pollen grain similar to those of *Coprosma laevigata* which differs mainly by its larger size and longer transverse colpi (see below). *Coprosma rapensis* pollen is also similar to these species but may be distinguished by its coarser reticulate sculpture.

3-4. *Coprosma laevigata*, Rubiaceae: (Roto). Grains between obtuse (convex) triangular and circular in polar view, oblate in equatorial view, 26-28μm in diameter. Exine coarse scabrate to fine reticulate, 1.5μm thick with distinct thickening around transverse colpi. Three thin and short colpi. Polar area index large. Three distinct transverse colpi which are up to 6μm wide and approximately 17μm long but not aequatorialis.

5 + 11. *Ixora bracteata*, Rubiaceae: (Roto, Tem). Grains oblate in equatorial view and obtuse-convex triangular in polar view with a maximum diameter of ~25μm. Colpi are crassimarginate and scabrate. Polar area index is small. Pores are elongated along polar axis and are distinctly protruding. Exine is 1-2μm thick and finely reticulate in the mesocolpium with lumen measuring <1μm in diameter.

6-7. *Morinda* comp., Rubiaceae: (Lan). Grains spherical or oblate, with a diameter measuring 30-33μm. Exine is coarsely reticulate, 2.5-3μm thick (slight exinous thickening around colpi). Average diameter of the lumen is 1μm but can be variable and are always greater than the thickness of the muri. Columellae clearly visible. Colpi are psilate and up to 4μm wide. Pores are circular to eliptical in shape (slightly elongated along polar axis) and have a distinctly protruding reticulate anuli. Pores are up to 5μm in diameter, anuli are 2-4μm wide and distinctly thicker on equatorial side of pores.

8-9. *Neonauclea forsteri*, Rubiaceae: (Lan, Tem, Vh). Grains are oblate or speroidal, with a diameter measuring 13-15μm. Exine is finely reticulate but fossil grains often appear psilate when in a deteriorated condition. Meridional colpi are distinct, narrow and have thickened margo. Circular pores (1.5-2μm diameter) have distinct anuli (1-1.2μm thick). Polar index is small. This pollen type is also found in the genus

Nauclea; however, pollen grains of *Nauclea* spp. tend to be much larger and have a more pronounced sculpturing than that of *Neonauclea.*

10. *Tarenna* comp., Rubiaceae: (Roto, Tem). Grains are oblate or spheroidal, with a diameter measuring 13-15μm. Exine is scabrate and ~1μm thick. The thin meridional colpi almost join in polar area. Indistinct circular pores (1.5μm diameter) have no visible anuli. Polar index is small. Grains tends to stain deeply which often obscurs the finer sculpture details.

12. *Meryta* comp., Araliaceae: (Tem). Grains are sub-triangular in polar view, measuring ~18-20μm in diameter. Oblate in equatorial view, measuring ~18μm along the polar axis. Exine is ~1μm thick and finely reticulate with lumen slightly increasing in size to ~1μm in polar areas. The slight exinous thickening around the three long and slightly intruding meridional colpi form a distinct psilate margo. Greatest thickening is found in the equatorial area. Polar area index is very small. Distinct rectangular shaped transverse colpi which are almost aequatorialis and measure 1μm in width.

13. *Polyscias* comp. *guilfoylei* sim., Araliaceae: (Tem). Grains are more or less spherical in polar view, prolate in equatorial view with lengths of around 18-20μm and widths of 18-19μm. Exine is finely reticulate with lumen measuring <1μm in diameter and regularly spaced. Two layers are clearly visible in exine as are the columellae which usually distinguishes this species from others. Long colpi with distinct margo which is particularly thickened in equatorial region. Polar area index is small. Transverse colpi are thin but measure up to 6μm in length and are not aequatorialis.

14. Araliaceae comp.: (Lan). Similar in characteristics to *Meryta* comp., Araliaceae (above) but significantly larger in size, up to 27μm in length.

15-16. *Reynoldsia verrucosa* comp., Araliaceae: (Vh). Grains are semi-triangular (obtuse-convex) in polar view and measure ~30μm in diameter. Oblate in equatorial view, measuring ~24-26μm along polar axis. Exine is >1μm thick and irregular with coarse rugulate sculpture (semitectate). Rugulate pattern becomes noticeably more coarse towards equatorial region. Three short and slightly intruding colpi are 10-12μm in length and have a distinct thickening of rugulate exine layer around the grove. Indistinct circular pores (2-3μm diameter) have feint anuli. Polar area index is large.

17-18. (Tricolpate?) *Ilex cymosa* comp., Aquifoliaceae: (Vh). Grains are inter-subangular to semiangular in polar view, oblate or spherical in equatorial view and measure around 19-23μm in diameter. Exine is gemmate to baculate (intectate), 2-3μm thick. Gemmae are often of considerable size range over the whole grain averaging ~1-1.5μm in diameter but are elongated in polar areas where they are up to 3μm long. Colpi are scabrate, up to 8μm wide and are distinctly recessed. Polar area index is small. No pores are visible under the light microscope.

19. (Tricolpate?) *Ilex anomala* comp., Aquifoliaceae: (Vh). Grains are inter-subangular to semi-angular in polar view, prolate in equatorial view and 24-27μm in length (excluding sculpture). Exine pilate and clavate (intectate), 1-2μm thick, with the tops of clavae/pilae reaching 1-2μm in diameter, but distinctly decreasing in size towards the colpi. Colpi long and up to 4μm in width, polar area index small. A small circular porus is sometimes visible within the colpus.

20-21. (Tricolpate?) *Ilex tahitensis* comp., Aquifoliaceae: (Vh). Grain are more or less spherical in polar and equatorial view with a diameter of 20-23μm (excluding sculpture). Exine is 0.7-1μm thick, baculate and clavate (intectate) with the tops of clavae measuring 0.5-1.5μm in diameter. There is no distinct size variation in sculpture near colpi. Colpi are up to 5μm wide. Polar area index is small. No pores are visible.

22. *Euphorbia* comp., Euphorbiaceae: (Lan). Grains are prolate in equatorial view and inter-semi-lobate in polar view, measuring 28-30μm in length and 22-25μm in width. Scabrate exine is ~1.5μm thick, columellae are visible but are not distinct. There is a thickening of exine around transversally elongated pores.

23. *Euphorbia* comp., Euphorbiaceae: (Tem). Grains are prolate in equatorial view and inter-semi-lobate in polar view, measuring 23-25μm in length and 17-19μm in width. Coarse scabrate to micro-reticulate exine is thick, up to 3μm, with very distinct columellae. Exine becomes thinner around the psilate colpus area. Rectangular to oval transverse colpi measure up to 5μm in length.

24. *Euphorbia hirta*, Euphorbiaceae: (Lan). Grains prolate in equatorial view, inter-semi-lobate in polar view, measuring 16-18μm in length and 13-14μm width. Coarse scabrate to micro-reticulate exine is thick, up to 2μm, with distinct columellae. Exine becomes thinner around the psilate colpus area. Rectangular transverse colpi are 3-4μm in length. Similar pollen characteristics are found in *Euphorbia atoto* which has a diameter range between 20-22μm.

25. *Acalypha* sp., Euphorbiaceae: (Lan, Roto, Tem). Grains are oblate in equatorial view and obtuse-convex triangular in polar view, 14-16μm in diameter. Exine is 1-1.2μm in width with fine scabrate sculpturing. Colpi are very short and often indistinct. Four circular pores (~2μm in diameter) with irregular anulus are distinctly protruding in polar view. Grains are also found as 4-colporate (see Plate 3).

26. *Macaranga tahitensis*, Euphorbiaceae: (Tem, Vh). Grains are oblate in equatorial view and obtuse-convex triangular in polar view, 12-13μm in diameter. Exine is scabrate to micro-reticulate, often darkly stained brown. Transverse colpi (slit-like) measure ~4μm in length and appear patterned in surface focus only. Exine measures ≤1μm in width, and appears slightly thickened around colpi in polar view. Polar area index is large. Colpi are short and narrow and slightly recessed.

27. *Homolanthus* comp. *moerenhoutianus* sim., Euphorbiaceae: (Tem, Vh). Grains are prolate in equatorial view and inter-semi-lobate in polar view, measuring 25-27μm in length and ~20μm in width. Exine is 2-2.5μm thick, with distinct columellae. Fine reticulate sculpturing with lumen measuring ≤1μm in diameter. Exine becomes thinner around the psilate-scabrate colpus area. Rectangular to oval transverse colpi are up to 5-6μm in length. Similar in characteristics to *Euphorbia* spp. but invariably larger in dimensions and with a distinct reticulate sculpture.

28. *Dodonea viscosa*, Sapindaceae: (Tem, Vh). Grains are prolate to spheroidal in equatorial view and sub-spheroidal in polar view, measuring between 22-24μm in length and 20-22μm in width. Exine is psilate to fine scabrate, 1.5-2μm thick, tectate, columellae are very short and indistinct. Colpi are long, closed type and thin. Polar area index is small. Poroid areas are large and usually ruptured, circular to oval in shape, laterally elongated (4-6μm in diameter), and protruding. Anuli not as distinct as other species. Exine darkly stained by acetolysis.

29-30. *Pittosporum* comp. *undulatum/orohenensis* sim., Pittosporaceae: (Vh). Grains are sub-triangular in polar view, 19-21μm in diameter and with open type colpi. Oblate in equatorial view with a length of 18μm along polar axis. Exine is ~1μm thick, finely reticulate but columellae are not distinct. Relatively short and indistinct colpi have large irregular shapped pores (often irregular diamond shaped and ruptured) slightly elongated along equatorial axis. Average diameter of pores is around 4μm. Unable to distinguish between the grains of these two species under the light microscope.

31-32. Caesalpiniaceae: (Tem). Grains are oblate in equatorial view and obtuse-convex triangular to circular in polar view. Equatorial diameter measures 30-34μm. Exine is ~2μm thick and regularly reticulate with lumen measuring ~1μm in diameter. Distinct columellae and two layers often visible. Colpi are crassimarginate and finely scabrate, up to 15μm wide at equator with a psilate margo. Polar area index is very small. Large pores (4-5μm in diameter) are slightly elongated along the polar axis and have distinct anuli.

PLATE 5

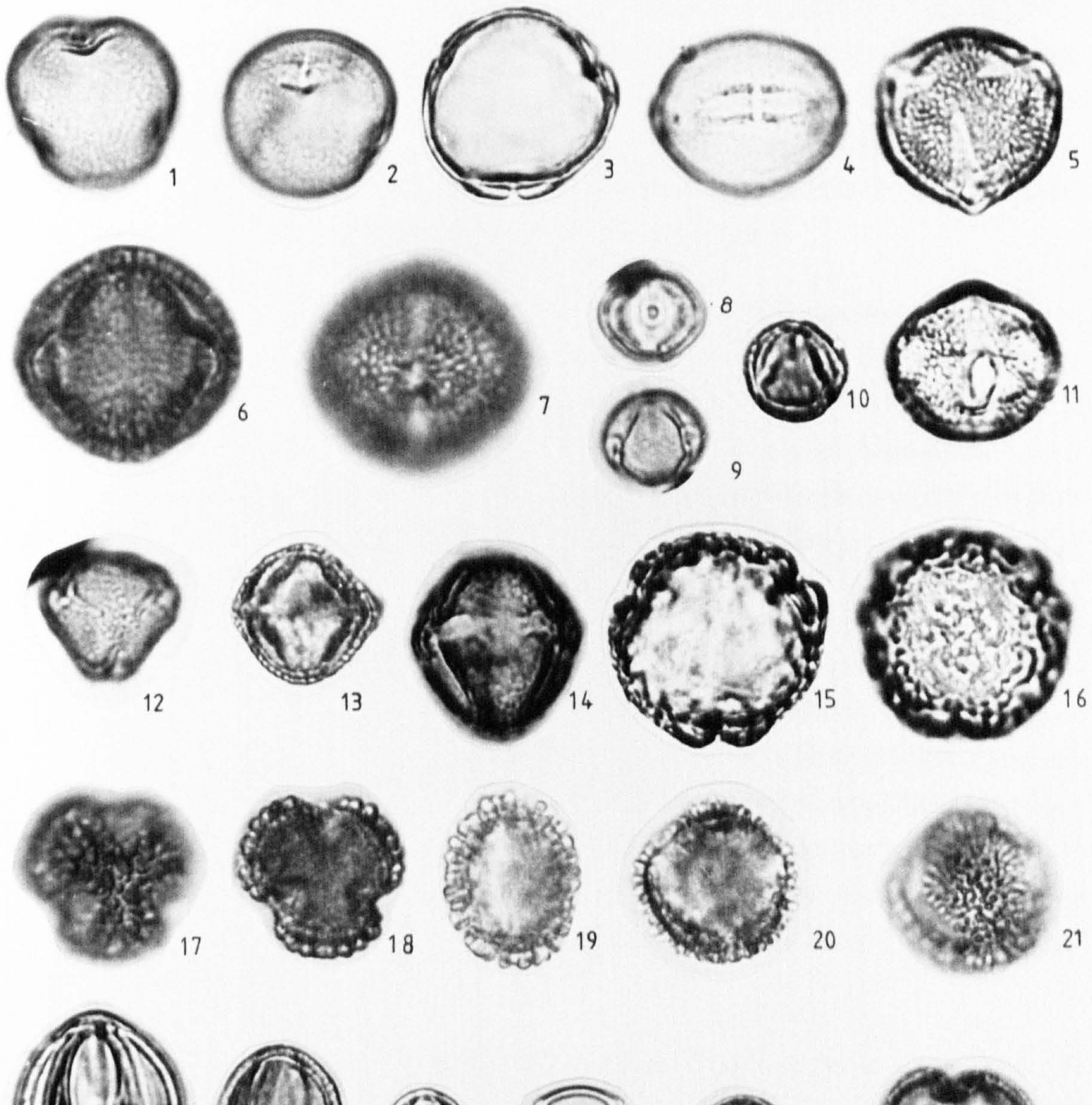
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PLATE 6.

Tricolporate grains (continued).

1. *Triumfetta procumbens*, Tiliaceae: (Roto). Grains are inter-semi-lobate in polar view with a maximum diameter of 30μm. Prolate in equatorial view, typically 42-44μm in length. Exine is 2-2.5μm thick, reticulate, often distinctly 2-layered and columellae are distinct and evenly distributed (similar to genus *Trichospermum* but less uniform reticulum and of smaller scale). Greatest diameter of lumen measures 1μm, decreasing in size towards colpi. Pore oval and equatorially elongated, up to 8μm in length and 5-6μm wide. Colpi are long and have a thin margo. Polar axis is small.

2. *Grewia* sim., Tiliaceae: (Lan). Grains are more or less circular in polar view, prolate in equatorial view, 30-32μm in length and 17-20μm in width. Exine is reticulate and columellae are quite distinct but are slightly unevenly distributed. Largest diameter of lumen is 1.3μm, generally uniform in size. Exine is 1-1.5μm thick. Meridional colpus is clearly interrupted by transverse aperture, rectangular to oval and equatorially elongated (may be patterned in surface focus) and up to 7μm in length, and ~4μm wide. Colpi long, polar axis small.

3. *Calophyllum inophyllum*, Guttiferae: (Tem). Grains are more or less circular in polar view, with a diameter of ~30μm. Spherical to oblate in equatorial view with a pole to pole length of ~25μm. Exine is >1μm thick and has an irregular reticulate pattern. Two exine layers are visible. Lumen have ~1μm diameters on average but noticeably increase in size in the two polar areas. Colpi are long and open and the polar area index is small. Transverse colpi are long (10μm long and 1.5μm wide) but are not aequatorialis. Edges of transverse colpi are very distinct. Grains are always deeply stained during acetolysis treatment.

4. *Lantana camara* comp., Verbenaceae: (Lan). Grains more or less circular in polar view, with a diameter measuring between 30-33μm. Oblate in equatorial view with a pole to pole length of ~30μm. Exine is >1μm thick and has an scabrate pattern. Only one exine layer is visible. Colpi are medium length, scabrate and have indistinct edges. Transverse colpi are long (but not aequatorialis) and rectangular in shape (up to 14μm long and 4μm wide) and are distinctly protruding. Edges of transverse colpi are thickened.

5. *Justicia* sim., Acanthaceae: (Tem). Grains are more or less circular to square in polar view, with greatest diameter at equator measuring between 18-22μm. Prolate to compressed oval shape in equatorial view with a pole to pole length of 35-37μm. Exine

is ≤1μm thick in mesocolpium and has an indistinct reticulate pattern appearing slightly striate (along polar axis) in equatorial view. Colpi are long with indistinct edges. Pores are spherical to oval in shape and around 3-4μm in diameter and distinctly protruding. Edges of pores are distinctly thickened to form protruding anuli which measure around 2μm wide (exine up to 4μm thick).

6. Solanaceae sim.: (Roto). Grains are sub-triangular in polar view, 20-22μm in diameter. Oblate (apiculate) in equatorial view, 15-16μm along polar axis. Psilate to fine scabrate exine >1μm thick, thickened around the three long, intruding colpi to form a distinct psilate margo. Greatest thickening found in equatorial area. Polar area index is very small. The indistinct spherical shaped pores (~2μm diameter) distinguish this pollen type from species from the family Araliaceae (such as *Meryta*) which have a superficial resemblance.

7-8. *Premna tahitensis* comp., Verbenaceae: (Vh). Grains are inter-semi-lobate in polar view with maximum diameter of 18μm. Prolate in equatorial view, typically 20-22μm in length. Exine is 1.5-2μm thick, fine reticulate, distinctly 2-layered and with very clearly defined columellae. Diameter of lumen is ≤1μm and regular in appearance. Small spherical pores are often not visible under light microscope conditions. Colpi are long with thick psilate margo. Polar area index is small.

9. *Alstonia costata* comp., Apocynaceae: (Tem). Grains are inter-hexagonal with flat colpi in polar view, 20-22μm in diameter. Oblate (compressed oval) in equatorial view, 15-17μm along polar axis. Fine scabrate exine is ≥1μm thick, but not thickened around the long and thin colpi. Polar area index is very small. Oval pores are indistinct and elongated along equatorial axis (~3-4μm in length).

10. Sapindaceae: (Lan). Grains are sub-triangular in polar view, 14-15μm in diameter. Oblate (apiculate) in equatorial view, 10-11μm along polar axis. Fine scabrate exine is of very irregular thickness but generally <1μm thick. Exine is extended around the long and open type colpi to form a flange structure either side (equatorial bridge). Polar area index is medium. Oval to rectangular pores are elongated along equatorial axis and measure ~2μm in length.

11. *Palaquium* sp., Sapotaceae: (Lan). Grains are circular in polar view, prolate in equatorial view (slightly apiculate). 24-27μm in length and 18-21μm at maximum width around equator. Sculpturing evenly scabrate or faintly micro-reticulate. Feint columellae visible in exine. Transverse colpus are oval in shape and equatorially elongated (~4μm in length). This type resembles a large proportion of grains from the genus *Palaquium* but differs from the genus *Planchonella* (Sapotaceae) only in the sculpturing pattern (i.e.

Planchonella has no pattern), and transverse colpi morphology (i.e. protruding and mainly circular).

12. *Sophora tomentosa* comp., Papilionaceae: (Tem). Grains are circular to semi-triangular in polar view, with diameters between 15-17μm. Oblate (apiculate) in equatorial view and measuring 13-15μm in length. Fine scabrate exine generally <1μm thick but distinctly thicker around pores and colpi which are protruding. Two layers not visible in the exine. Long and open type colpi containing clearly defined operculate pores. Polar area index is medium.

13-14. *Weinmannia parviflora* comp., Cunoniaceae: (Vh). Grains are circular to semi-angular in polar view and 13-14μm in diameter. Prolate in equatorial view with lengths between 14-16μm. Reticulate exine (lumen consistently 1μm in diameter), 0.8- 1.2μm thick, tectate, columellae very clearly defined but two exine layers not often visible. Open type colpi of medium length, slightly constricted at equator. Polar area index is medium. Pores are fairly distinct and spherical to oval in shape (1-1.2μm in diameter). Slight thickening of exine around pore but there is no clear margo.

15-16. *Weinmannia rarotongensis*, Cunoniaceae: (Roto). Grains are circular to semi-angular in polar view, diameter 9-10μm in diameter. Prolate in equatorial view with lengths between 10-11μm. Exine ≤1μm thick, micro-reticulate but often appearing psilate, 0.6-0.8μm thick, columellae are indistinct. Colpi are medium length and narrow, sometimes slightly constricted at equator and are indistinct in the polar region. Pores feint (~0.4μm in diameter).

17-18. *Weinmannia vescoi* comp., Cunoniaceae: (Tem, Vh). Grains are inter-semi-lobate in polar view, 7-9μm in diameter. Prolate in equatorial view with lengths between 10-11μm. Micro-reticulate exine is 0.6-0.7μm thick, columellae are indistinct. Colpi are long and narrow and slightly constricted at equator. Pore are indistinct (0.5μm in diameter).

19-20. *Elaeocarpus tonganus*, Elaeocarpaceae: (Lan, Roto). Grains circular to inter-semilobate in polar view, diameter 10-12μm in diameter. Prolate in equatorial view with lengths between 12-13μm. Exine is psilate, 0.8-1μm thick. Colpi long and medium in width with faint transverse colpi ~2μm in length and 0.5μm wide.

21-22. Elaeocarpaceae: (Tem). Grains are circular to inter-semilobate in polar view, diameter 12-15μm in diameter. Prolate in equatorial view with lengths between 10-16μm but usually less than 14μm. Exine psilate, possessing only one visible layer. Polar index is small in larger grains, but in grains less than 12μm in length the index is variable. Colpi possess equatorial constrictions but there are no transverse colpi visible.

23-24. *Bidens pilosa* comp., Compositae: (Roto, Tem, Vh). (tubuliflorae): Grains are circular to sub-triangular convex in polar view, spherical in equatorial view, with diameters measuring between 18-20μm excluding sculpture. Exine is echinate (aspidote) with approximately 80 slender and uniformly distributed echinae, measuring 1.7-2.2μm at their base (slightly bulbous) and 4-5μm in length, tapering to sharp point. Tip of echinae are often slightly curved. Exine has psilate pattern between echinae. Three short open type colpi with indistinct equatorial pores.

25-26. *Bidens paniculata* comp., Compositae: (Vh). (tubuliflorae): Grains are circular to sub-triangular convex in polar view, sperical in equatorial view with a diameter between 18-20μm excluding sculpture. Exine is echinate (aspidote) with approximately 45 echinae, measuring 2-3μm at their base (not bulbous) and 4.5μm in length, tapering to sharp point. Tip of echinae often slightly curved. Exine has psilate pattern between echinae. Three short open type colpi with equatorial pores which are more distinct than those found in *B. pilosa* (above). Main difference betweeen *B. pilosa* and *B. paniculata* is the number of echinae and variation in the echinae base.

27-28. *Fitchia* sp., Compositae: (Vh). (tubuliflorae): Grains are circular to sub-triangular convex in polar view, spherical in equatorial view and have a diameter of 50-54μm excluding sculpture. Exine is echinate with approximately 70 echinae, measuring 4-5μm in length, significantly wider at base (up to 5μm) with a relatively blunt apex. Echinae either side of colpi are larger with broader base (aspidote) as distinct from the narrower echinae found on the mesocolpium. Exine has a coarse scabrate pattern between echinae. Three long open type colpi have clearly defined margos (1-1.5μm wide) and contain feint equatorial pores.

29-30. *Ageratum conyzoides*, Compositae: (Roto, Tem, Vh). Grains are sub-triangular convex to inter-semilobate in polar view, spherical in equatorial view and have a diameter of 14-15μm. Exine is echinate with approximately 80 echinae (not aspidote), regularly spaced over exine surface and measuring 1-1.2μm at base, 1-2μm in length, tapering to sharp point. Exine has psilate pattern between echinae. Three medium length open type colpi have no margo. Equatorial pores are indistinct.

PLATE 6

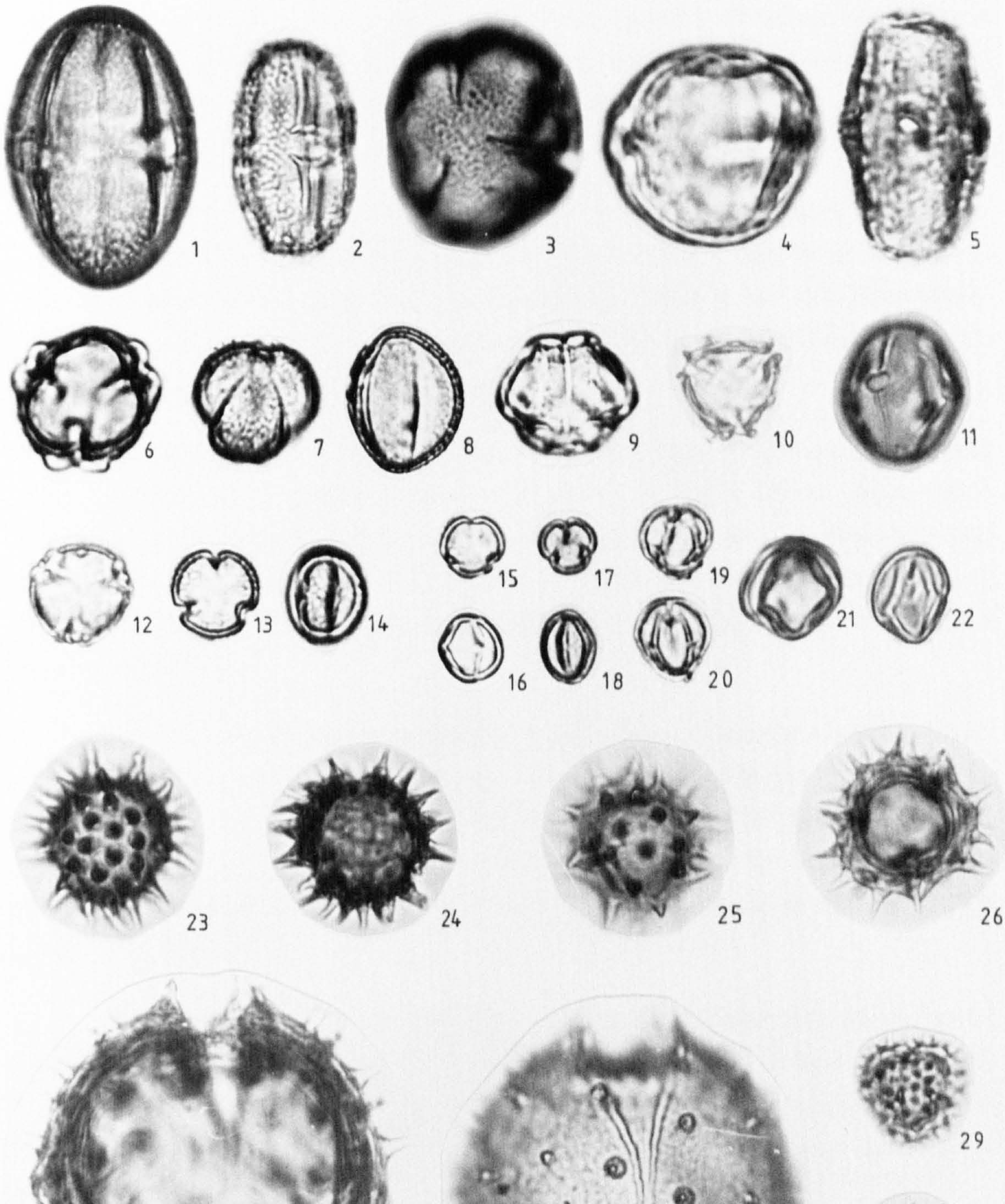
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PLATE 7.

Monolete spores.

1. *Polypodium phymatodes* comp., Polypodiaceae: (Roto, Tem, Vh). Spores are plano-convex in shape. Spore length (+gemmae) measure 57-62μm, spore height (+gemmae) 35-40μm, spore wall is 3-4μm thick. Sclerine (endosporium) is finely verrucate-gemmate. Gemmae 1-2μm in diameter. Exosporium is absent. Laesurae are 1/2 - 3/4 the length of spore.

2. *Polypodium pelucidum* comp., Polypodiaceae: (Tem, Vh). Spores are concavo-convex. Length 40-45μm and height 23-26μm. Spore wall is 2-4μm thick. Sclerine is verrucate (large verrucae are 3-5μm in diameter and regular in size and distribution). Exosporium is absent and a margo is also absent. Laesurae are 1/3 the length of spore and do not widen towards the middle of spore.

3. *Davallia solida/elata* comp., Davalliaceae: (Tem, Vh). Grains concavo-convex to plano-convex. Spore length measures 35-38 μm and height 17-20μm. Spore wall is 1-2μm thick. Sclerine is verrucate (large discrete and rounded verrucae are up to 3-5μm in diameter). The larger verrucae are usually on the distal polar face. Exosporium is absent. Laesurae are 1/2 the length of spore. Margo is 1-2μm thick and widens towards the middle of spore.

4. *Nephrolepis exaltata* comp., Oleandraceae: (Tem). Concavo-convex to plano-convex. Spore length measures 33-36μm (+gemmae), spore height (+gemmae) 23-25μm, spore wall 1-2μm thick. Sculpturing elements of the sclerine vary from gemmate to verrucate. Large gemmae measuring 3-4μm in diameter are often seen at the angles and on the distal polar face. Exosporium is absent. Laesurae are 1/2 to 2/3 the length of spore. Margo absent.

5. *Hypolepis* comp., Dennstaedtiaceae: (Vh). Concavo-convex to plano-convex. Sclerine is densely echinate (slender echinae measure up to 3-5μm in length). Exosporium is absent. Spore length is 37-39 μm (+echinae), spore height is 23-25μm (+echinae), spore wall is 1-2μm thick. Laesurae are 2/3 to full length of spore and are not opened. Margo absent.

6. *Asplenium nidus*, Aspleniaceae: (Roto, Vh). Concavo-convex. Endosporium is minutely echinate. Exosporium is present and folded into irregular anastomosing ridges with fimbriate membranous crests (echinate). 5-8 endospore echinae are present between adjacent ridges. Spore length 28-31μm, spore height 15-17μm, endospore wall 1-1.5μm thick. Ridges of exospore are up to 4μm thick. Laesurae are 2/3 the length of

spore. Spores similar in morphological character to *Asplenium caudatum* which has an average length of 50μm.

7. *Cyclosorus* comp., Thelypteridaceae: (Vh). Plano-convex. Sclerine is irregularly verrucate and rugulate (few scattered short echinae which are no greater than 1.5μm in length). Exosporium is absent. Spore length 27-29μm, spore height 13-16μm, endospore wall 1μm thick. Laesurae extends the full length of the spore and has no margo.

8-9. *Christella dentata* sim., Thelypteridaceae: (Vh). Concavo-convex to plano-convex. Endospore is psilate to fine scabrate. Close fitting verrucate exospore. Verrucae are no greater than 1μm in diameter and are often denser in region of scar. Spore length 28-31μm, spore height 15-17μm, endospore wall 1-1.5μm thick. Exospore 2-4μm thick (thickest around scar). Laesurae are 2/3 to the full length of the spore.

10. Marratiaceae: (Lan). Plano-convex. Sclerine is finely verrucate and sparsely echinate (on distal polar face). Exospore is absent. Spore length 15-17μm, spore height 9-12μm, spore wall 0.8-1μm thick. Laesurae is 1/2 length of spore, thin margo present.

11. *Marratia* sim., Marratiaceae: (Vh). Concavo-convex to plano convex. Sclerine is gemmate. Exosporium is absent. Spore length (+gemmae) 18-20μm, spore height (+gemmae) 11-13μm, spore wall 1-1.1μm thick, gemmae 0.8-1μm in diameter. Laesurae extend full length of spore but with no visible margo.

12. *Psilotum nudum*, Psilotaceae: (Tem). Concavo-convex. Sclerine is psilate, exosporium is verrucate to scabrate. Spores often occur without exospore Spore length 50-53μm, spore height 16-18μm, endospore wall 1-1.5μm thick, exospore 2-3μm thick. Laesurae extend 3/4 length of spore with margo up to 4μm thick.

13. *Stenochlaena palustris*, Blechnaceae: (Lan, Tem, Vh). Concavo-convex. Sculpturing elements are variable from gemmate and baculate. Spore is transparent and colourless even after being subjected to prolonged acelolysis. Spore length (+gemmae and baculae) measures 32-37μm, spore height (+gem. and bac.) 17-20μm, baculae up to 4μm high and mainly occuring on distal polar face, gemmae up to 2.5μm diameter. Laesurae extend 2/3 to full length of spore, with margo 1-1.3μm thick. *Stenochlaena palustris* spores are similar to those of *Stenochlaena areolaris* but the latter are frequently larger with dimensions of 80μm x 40μm. Echinae are also tapered unlike *Stenochlaena palustris*. *Stenoclaena laurifolia* spores also have a superficial resemblance to *Stenochlaena palustris* spores but have verrucae aligned in ridges more or less parallel to the equatorial axis.

14. Monolete unidentified: (Roto, Tem, Vh). Plano-convex. Sclerine is psilate, without endosporium. Spore length 45-55μm, spore height 30-38μm, spore wall 1-2μm thick. Laesurae extend 3/4 to full length of spore. This group consists chiefly of spores of a wide range of taxonomic groups which have lost their exosporium due to fossilisation or acetolysis. Several different morphological forms were distinguished but no attempt was made to identify them. Some species from the following genera have been observed to possess uncharacteristic monolete psilate spores:-

Spores psilate in a fresh state: *Aglaomorpha, Dipteris, Gleichenia, Leptochilus, Lindsaya, Microsorium, Polypodium, Schizaea, Sphenomeris.*

Spores psilate or scabrate on losing exosporium: *Asplenium, Athyrium, Blechnum, Bolbitis, Crypsinus, Cyclosorus, Diplazium, Drynaria, Drymoglossum, Dryopteris, Elaphoglossum, Hypolepis, Lepisorus, Leptochilus, Lindsaya, Microsorium, Nephrolepis, Phymatodes, Polypodium, Polystichum, Pyrrosia, Selliguea, Sphenomeris, Tectaria, Tapeinidium, Woodwardia.*

This list is by no means exhaustive.

Trilete spores.

15. *Acrostichum aureum*, Pteridaceae: (Lan, Roto, Tem). Equatorial limb is sub-triangular to sub-triangular-concave, not radially symmetric. Equatorial diameter measures 55-60μm. Perine is 2μm thick and very sparsely verrucate on a generally coarse scabrate surface. Verrucae are up to 1.5μm thick and are irregularly spaced. Laesurae are short and do not reach the apices and are slightly curved. Laesure have distinct margo which is 4-5μm thick half way along the scar but tapers off at apices. Spores of this taxa are always darkly stained by the acetolysis process.

16-17. *Gleichenia linearis*, Gleicheniaceae: (Lan, Roto, Tem, Vh). Equatorial limb is subtriangular-concave and radially symmetric. Equatorial diameter measures 22-32μm. Straight, raised and thickened laesurae extend 3/4 to equator and bifurcate at apices. Perine is finely scabrate, 1-2μm thick. Genera easily identified by presence of arci parallel to the spore margins on the proximal face.

18. *Lygodium scandens* comp., Schizaeaceae: (Tem). Equatorial limb is sub-triangular to sub-triangular-convex with an equatorial diameter (+verrucae) measuring 40-45μm. Perine coarsly verrucate-areolate and 4-5μm thick. Verrucae (up to 2μm thick) regular on distal face, becoming elongated on proximal face. Laesurae slightly wavy and almost reaching equator. Spores of this species were frequently found damaged in the fossil state. The spores of *Lygodium reticulatum* are similar in superficial appearance to

Lygodium scandens but have a much larger equatorial diameter (50-60μm) and have a reticulate sculpture.

PLATE 7


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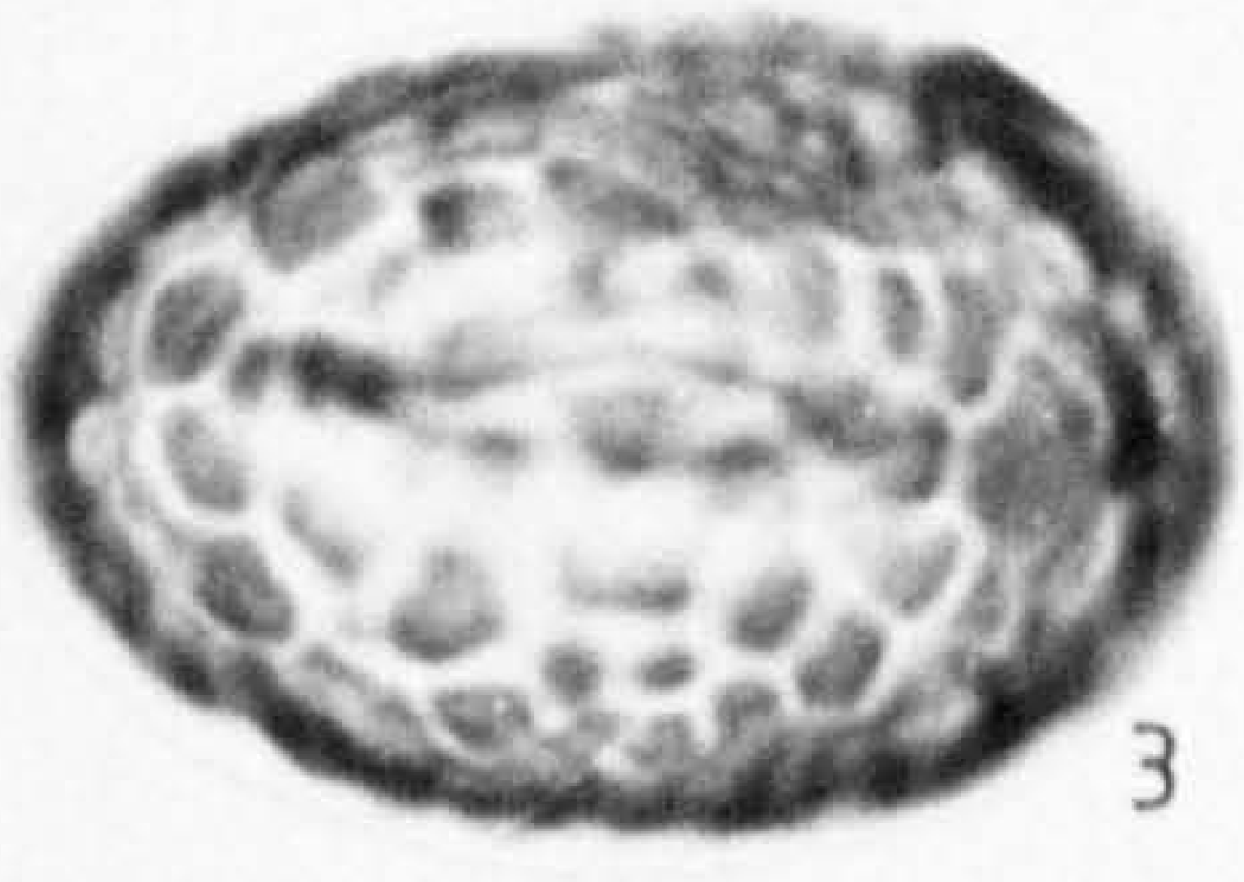
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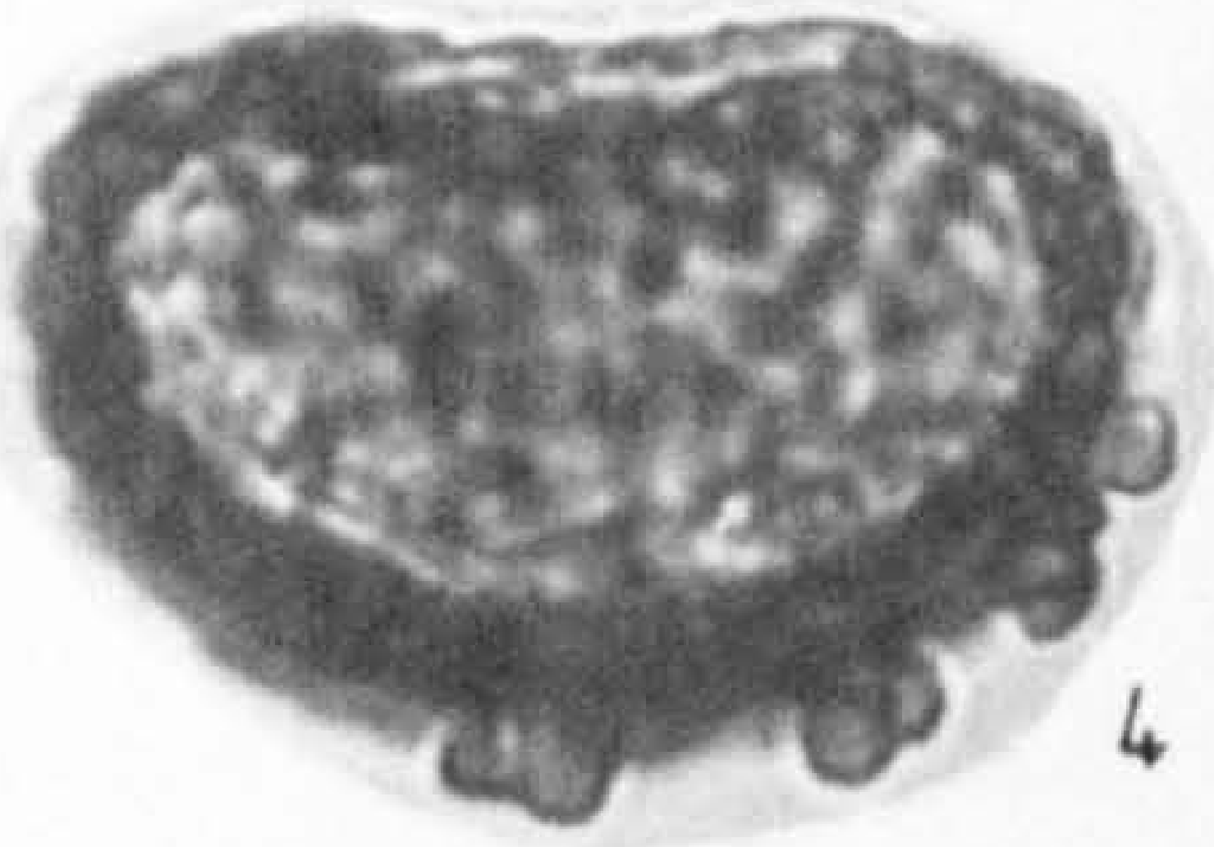
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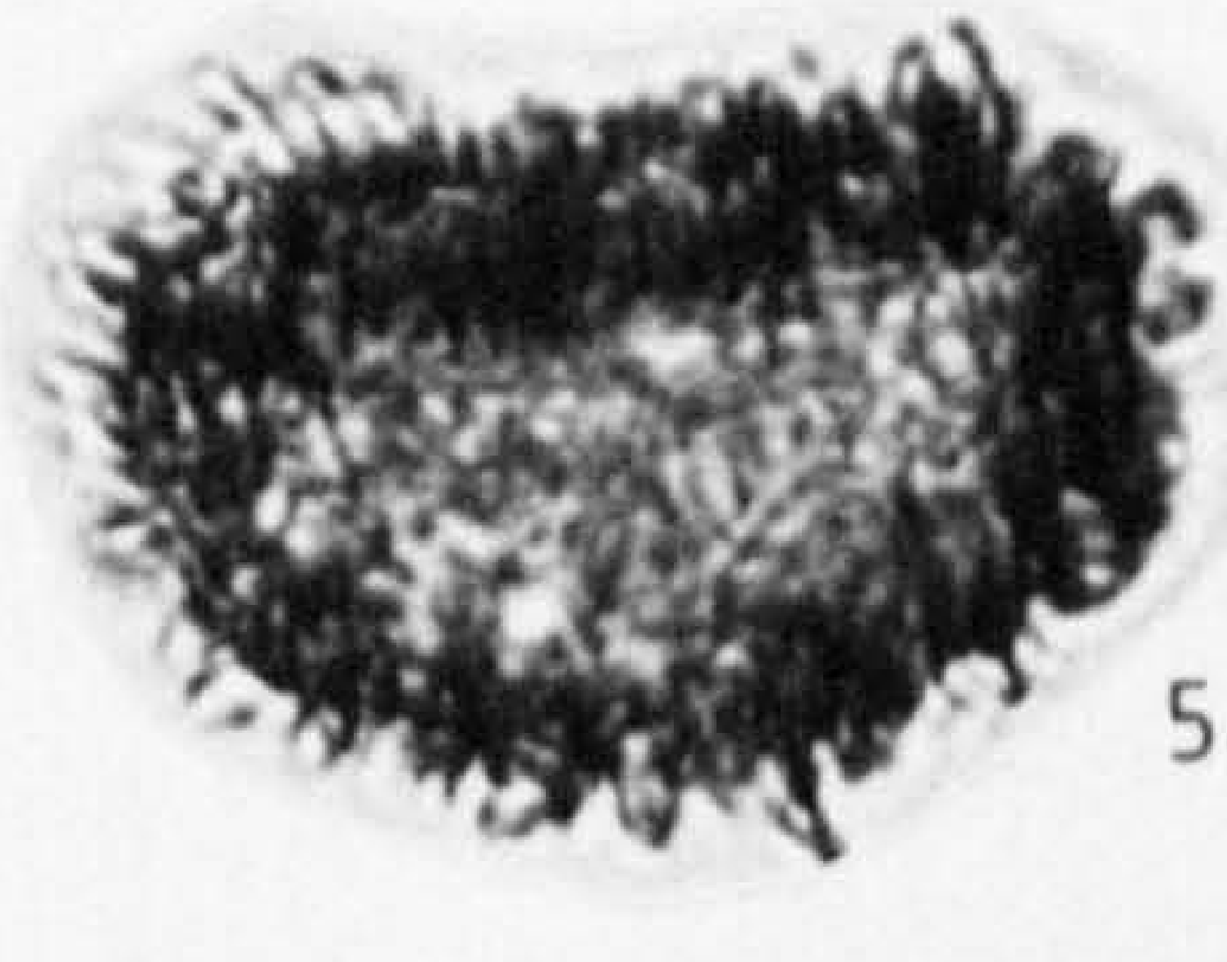
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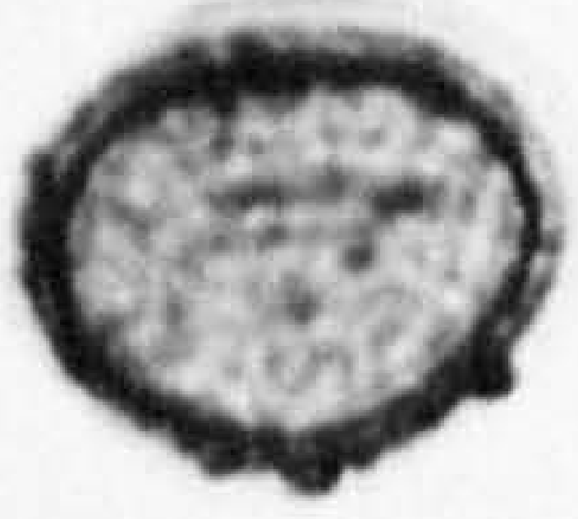
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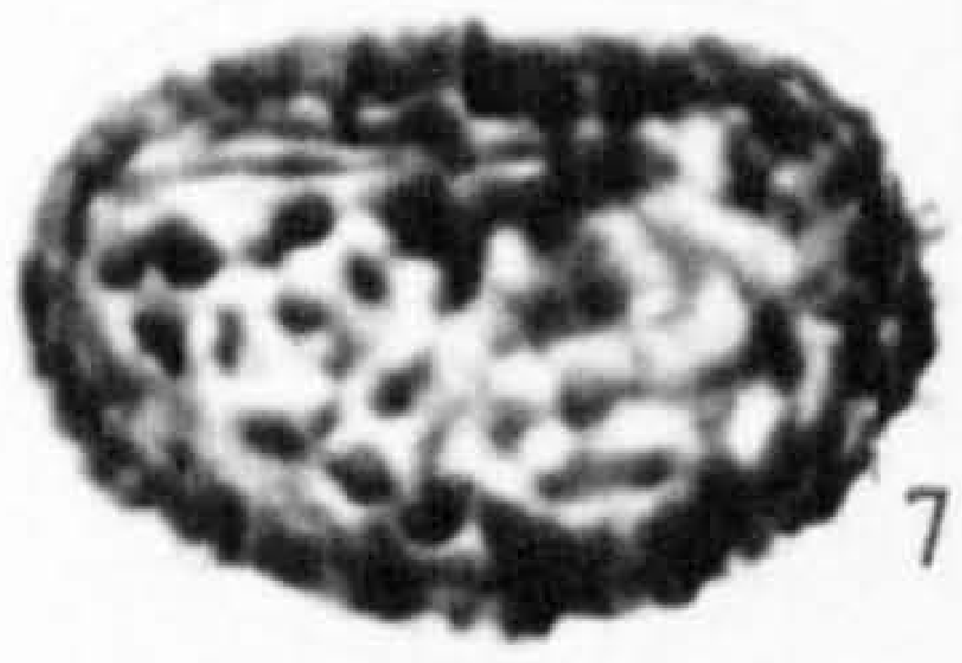
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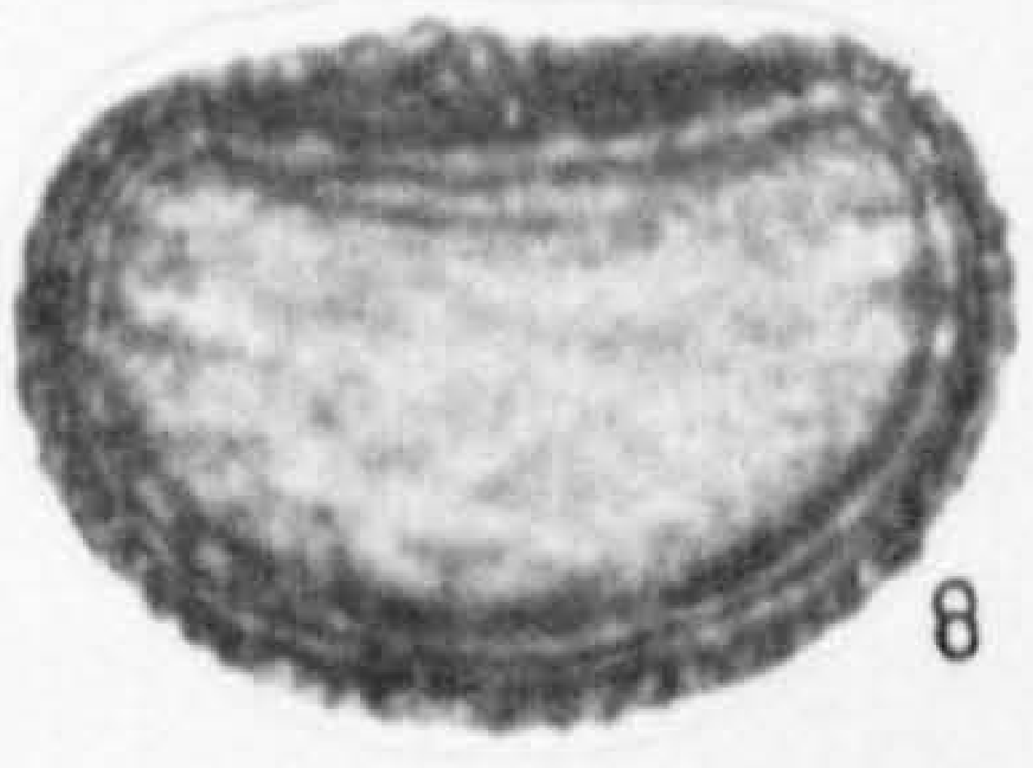
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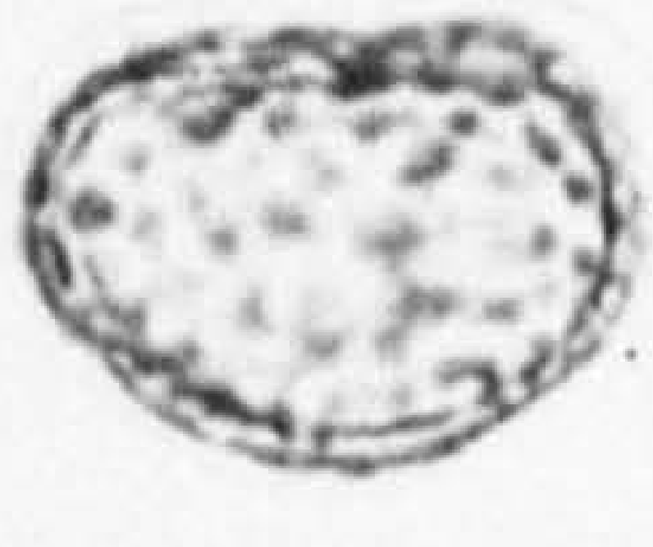
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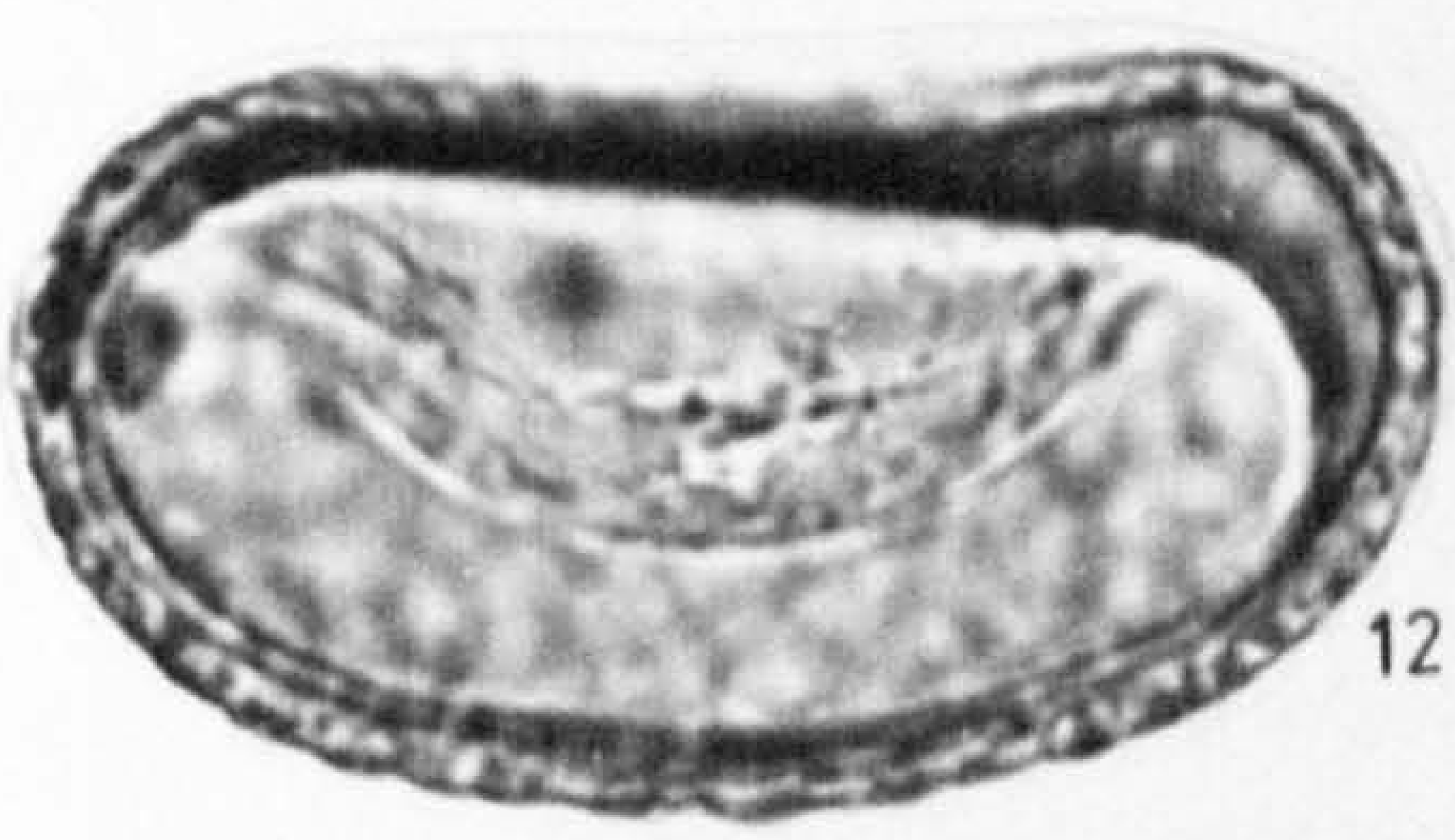
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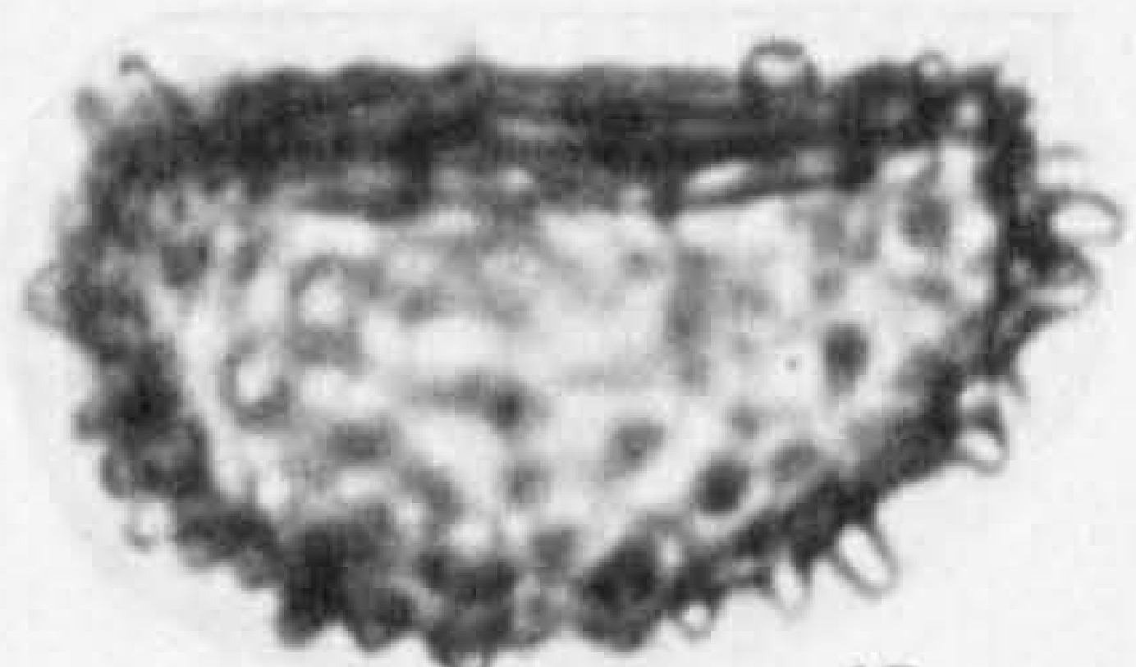
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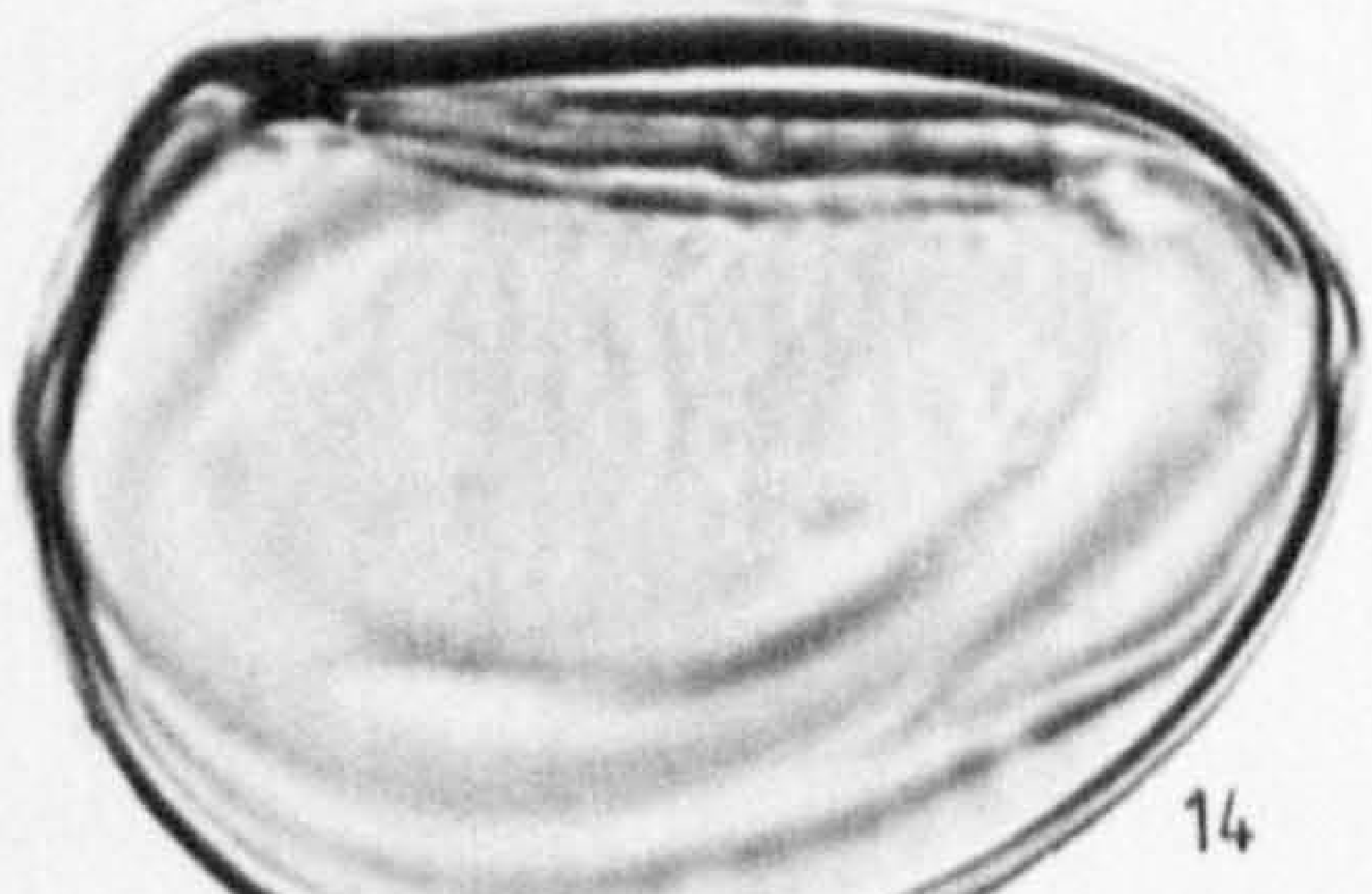
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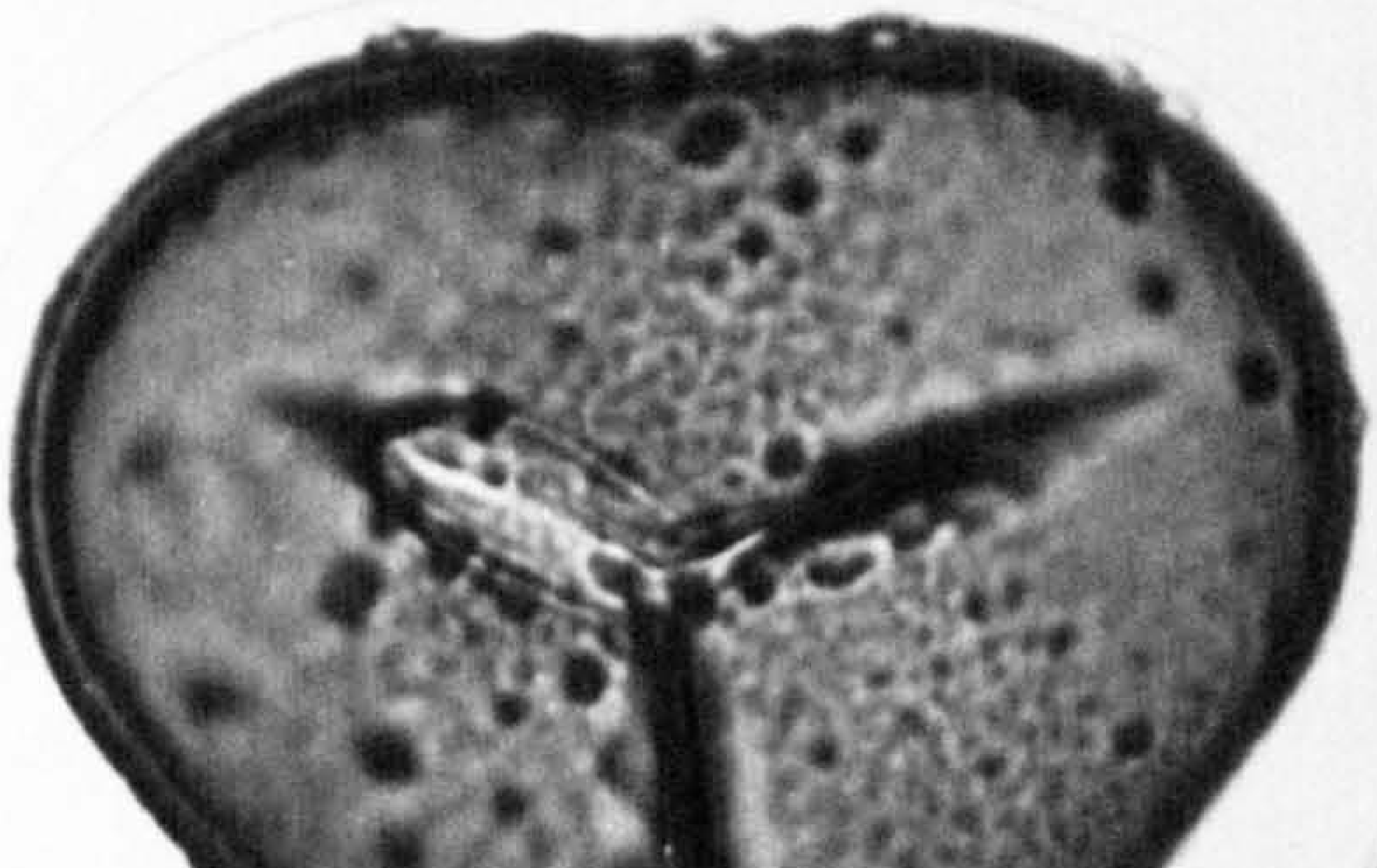
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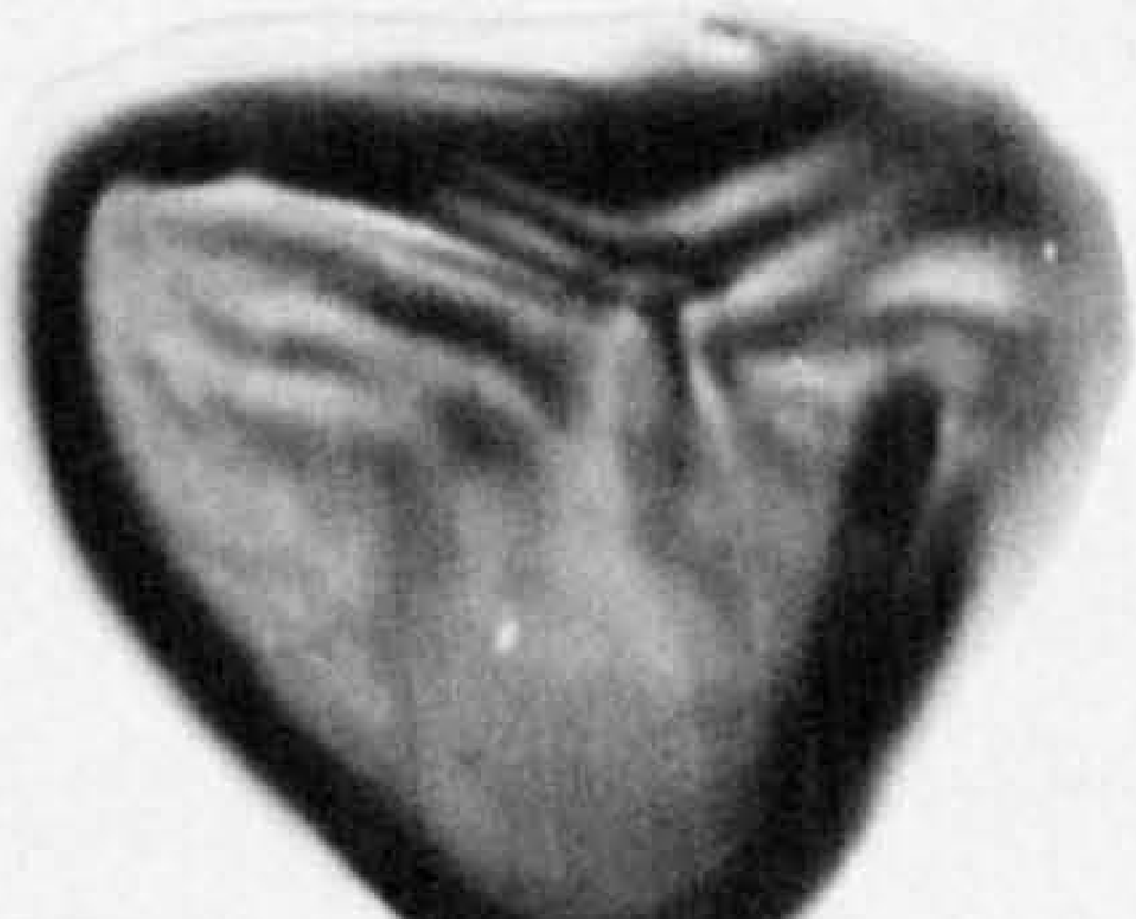
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PLATE 8.

Trilete spores (continued).

1-2. *Pteris tripartita/commans*, Pteridaceae: (Lan, Roto, Tem, Vh). Equatorial limb is sub-triangular to sub-triangular-concave (corners distinctly rounded). Laesurae extend almost to equator, boardered by darker brown margo about 2.5μm thick (thinning to 2-2.2μm around apical region). Perine not observed. Sclerine has large verrucate pattern, especially on distal face, distinctly thickened along equator forming a cingulum which is more or less psilate. Spore diameter measures 34-38μm; sclerine (distally) 1-3μm; sclerine (along equator) 4-6μm thick.

3. *Pteris* sim., Pteridaceae: (Tem). Equatorial limb is subtriangular convex. Laesurae extend to equator, boardered by darker brown margo about 1.5μm thick (thinning to 1μm around apical region). Perine not observed. Sclerine coarse rugulate pattern, especially on distal face, distinctly thickened along equator forming a cingulum, which is more or less psilate. Spore diameter measure 25-27μm; sclerine (distally) 1-1.5μm; cingulum distinctly undulating and variable in thickness.

4. *Pteris* comp. Pteridaceae: (Tem). Equatorial limb is subtriangular convex. Laesurae extend almost to equator, no distinct margo. Perine not observed. Sclerine is verrucate to rugulate pattern, especially on distal face, distinctly thickened along equator forming a cingulum, which is more or less psilate and undulating. Spore diameter measure 32-34μm; sclerine (distally) 1-1.5μm; sclerine (along equator) variable between 4-6μm.

5. *Cyathea affinis*, Cyatheaceae: (Roto, Tem, Vh). Equatorial limb is sub-triangular-concave with an equatorial diameter of 23-26μm (corners rounded). Undulating laesurae extend almost to equator with indistinct margo 1.5-2μm thick. Endospore is psilate, 1-1.3μm thick, slightly radially thickened. Exospore frequently present, psilate and interadially thickened (0.2-2μm thick).

6-8. *Cyathea (Hemetelia) horrida*, Cyatheaceae: (Tem, Vh). Amb is triangular-concave to triangular-convex with an equatorial diameter of 25-30μm. Laesurae extend almost to equator, no margo. Psilate sclerine radially 1-1.3μm thick, inter-radially thickened to 4-6μm. Three large circular-oval pores (alveolae) in the wall of the inter-radial thickening have a diameter of 4-5μm. Sclerine shows extra thickening in that area. Further smaller perforations are frequently found all over spore. Perine not observed.

9. *Alsophila* sp., Cyatheaceae: (Lan). Amb is triangular-concave with an equatorial diameter of 30-34μm (excluding cingulum). Laesurae are thin and extend

almost to equator. Thin and slightly raised margo. Sclerine has an indistinct reticulate pattern, especially on distal face. Sclerine distinctly thickened along equator forming an incomplete cingulum which is more or less psilate and often darkly stained (maximum width in inter-radial areas up to 6μm). Perine not observed although two layers are often seen in the sclerine.

10. *Alsophila* sim., Cyatheaceae: (Roto, Vh). Equatorial limb is sub-triangular-concave with an equatorial diameter of 25-27μm (corners rounded). Straight laesurae extend almost to equator with indistinct margo. Endospore 1-1.3μm thick and slightly thickened radially. Coarse reticulate sculpture with irregular shaped and sized lumen (<1-2.5μm in diameter). Three to four large lumen (2.5μm in diameter) often observed in the reticulum on the distal surface. Exospore absent.

11. *Cyathea(Hemetelia)* sp., Cyatheaceae: (Vh). Equatorial limb is sub-triangular-concave with an equatorial diameter of 20-22μm (corners rounded). Slightly undulating laesurae extend almost to equator with distinct darkened margo consistently 1.5-2μm thick. Endospore striate with lines adjacent to the three scars. Endospore 1-1.5μm thick and thickened radially up to 2μm. Exospore absent. Grains usually darkly stained by acetolysis treatment.

12. *Cyathea* sp., Cyatheaceae: (Vh). Equatorial limb is sub-triangular-concave with rounded corners. Equatorial diameter of 20-22μm. Straight laesurae, slightly parted and extending 2/3 the distance to the equator. Margo thin and indistinct. Endospore psilate, 1-1.3μm thick, slightly inter-radially thickened. Exospore frequently present, psilate and interadially thickened (0.2-2μm thick).

13. *Cyathea* sp., Cyatheaceae: (Vh). Equatorial limb is sub-triangular-concave with an equatorial diameter of 38-40μm. Slightly undulating laesurae extend almost to equator with thin margo <1μm thick. Endospore is psilate, 1-1.5μm thick, slightly radially thickened. Exospore is absent.

14. *Angiopteris evecta*, Angiopteridaceae: (Lan, Roto, Tem, Vh). Equatorial limb is circular to nearly circular. Distinctly raised but thin laesurae (not open) extend 3/4 to equator. Not bifurcating at apices. Margo not observed. Sclerine has coarse scabrate uniform pattern, 1-2μm thick. Perine not observed.

15. *Lycopodium phlegmaria*, Lycopodiaceae: (Lan, Roto, Tem, Vh). Amb is triangular convex, radially symmetric, equatorial diameter 34-36μm. Straight laesurae extend 2/3 to equator with indistinct margo. Endospore is regularly 1-1.3μm thick (no radial or inter-radial thickenings) with a foveolate sculpture on the distal surface.

Exospore is absent. Spores of *Lycopodium squarrosum* are similar in appearance but are reticulate in sculpture.

16-17. *Lycopodium cernuum*, Lycopodiaceae: (Lan, Roto, Tem, Vh). Amb obtuse triangular convex, radially symmetric, equatorial diameter 28-31μm. Raised, slightly undulating, laesurae extend 2/3 or almost to the equator, margo 2-3μm wide. Sclerine radially ~1μm thick, inter-radially 3-5μm thick forming interadial thickenings. Rugulate to fossulate. Sclerine also thickened in distal part where fossulae are coarser. Proximal face sometimes psilate. Perine not observed.

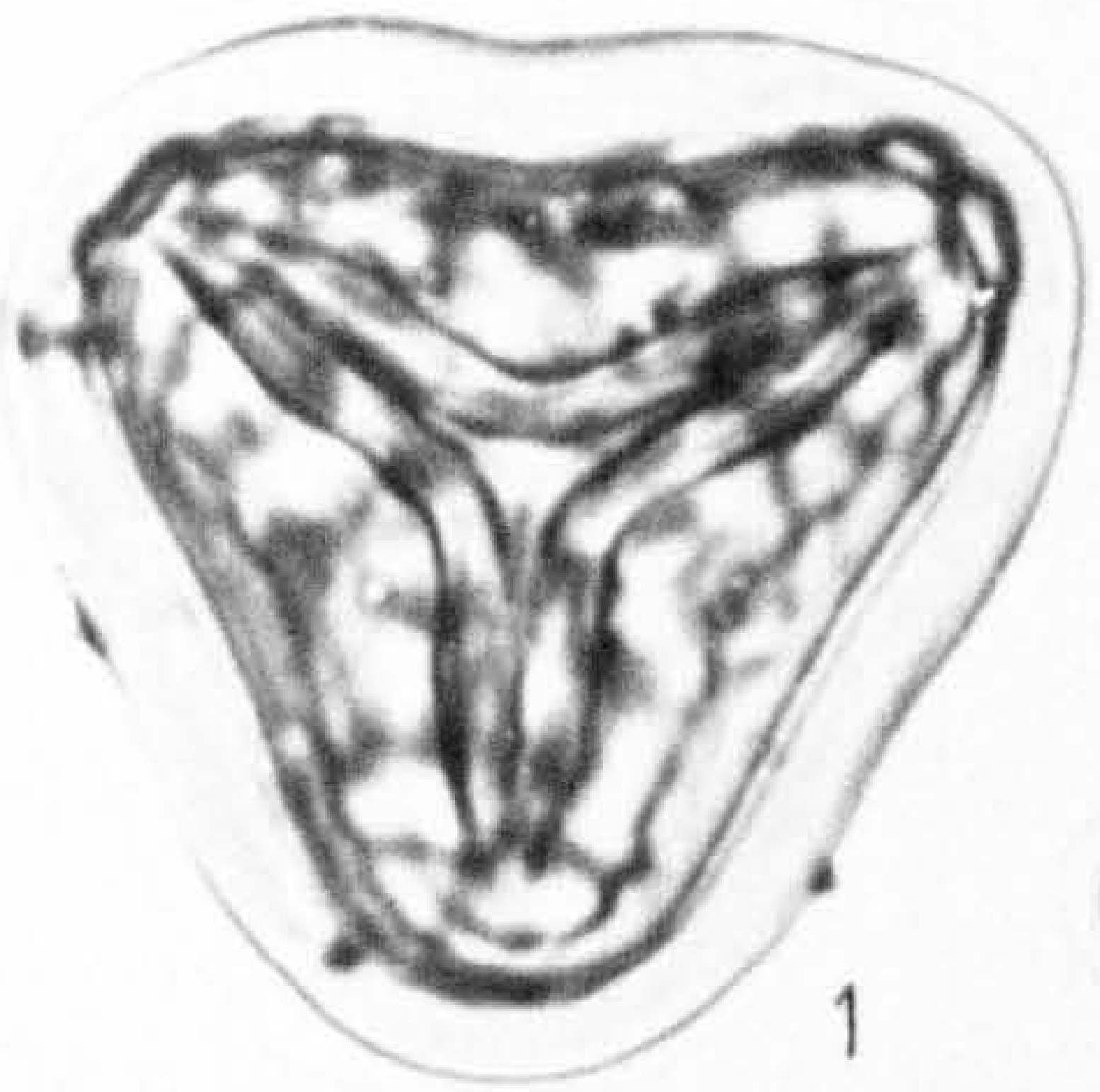
18. *Jamesonia* comp., Hemionitidaceae: (Vh). Amb subtriangular-concave with a diameter of 25-27μm. Undulating laesura arms extending almost to equator where they are seen to bifurcate. Raised margo 1.5-2μm thick. Endospore is scabrate, 1-1.3μm thick, slight inter-radial thickenings. Distinct thickened lines run perpendicular to the three radial scars on the distal surface. Exospore sometimes present, psilate and interadially thickened.

19. *Jamesonia* comp., Hemionitidaceae: (Tem). (probably same as 18 above but with straight laesurae and flattened corners of the triangular amb).

20. *Onychium* sim., Adiantaceae: (Vh). Amb is circular with an equatorial diameter of 29-36μm. Laesurae possibly extending to equator and bordered by coarse ridges and sclerine thickenings. Sclerine is verrucate and 2-4μm thick with ~6 nearly parallel and slightly undulating ring-shaped ridges (psilate, 1μm wide and 2-3μm thick) surrounding the equator.

21. *Selaginella* comp., Selaginellaceae: (Lan, Roto, Vh). Amb is circular to subtriangular convex with an equatorial diameter (+ echinae) of 26-28μm. Laesurae extend almost to equator. Undulating margo ~1μm wide is provided with echinae. Sclerine is 1-2μm thick and ornamented with 1-2μm long irregularly spaced echinae (bulbous at base and curved towards tips).

PLATE 8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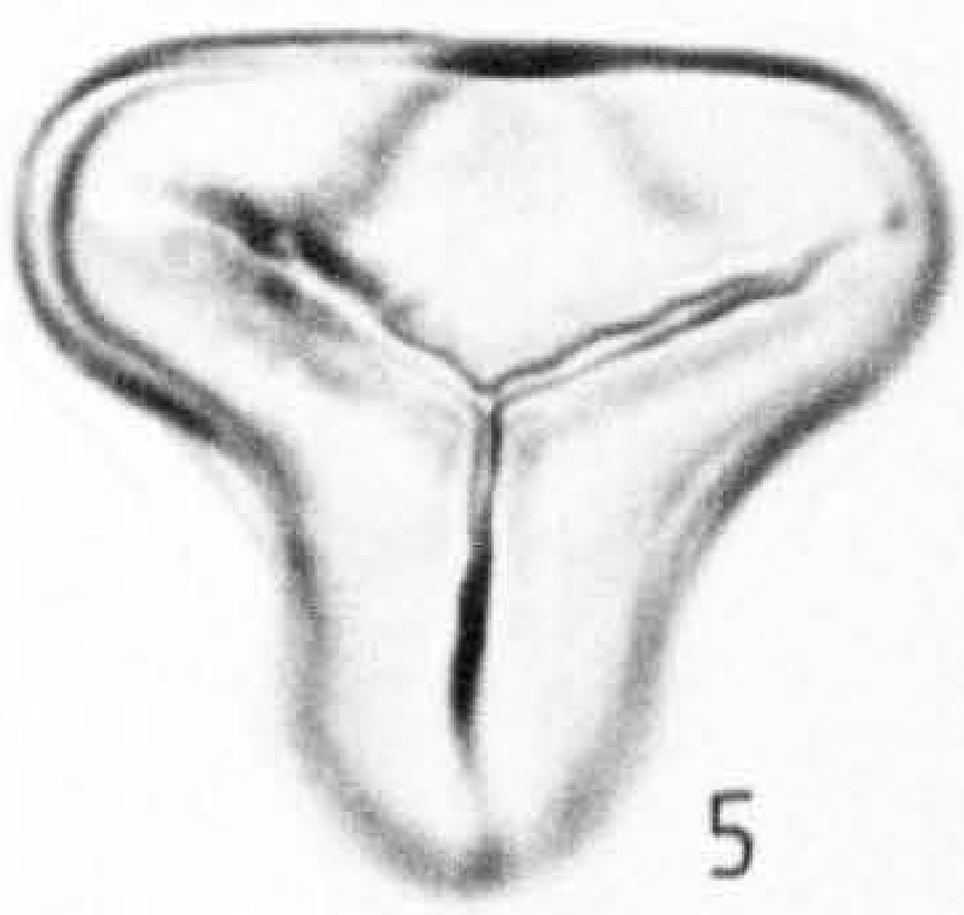
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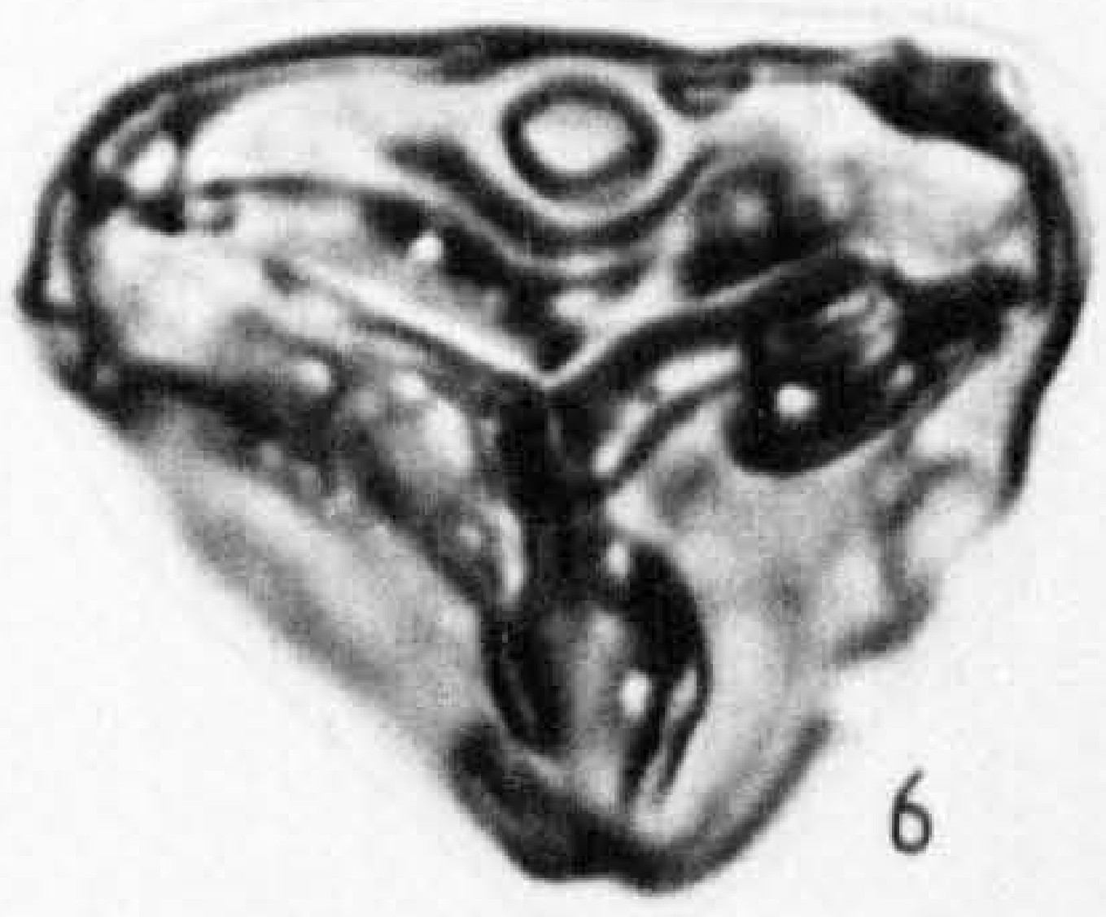
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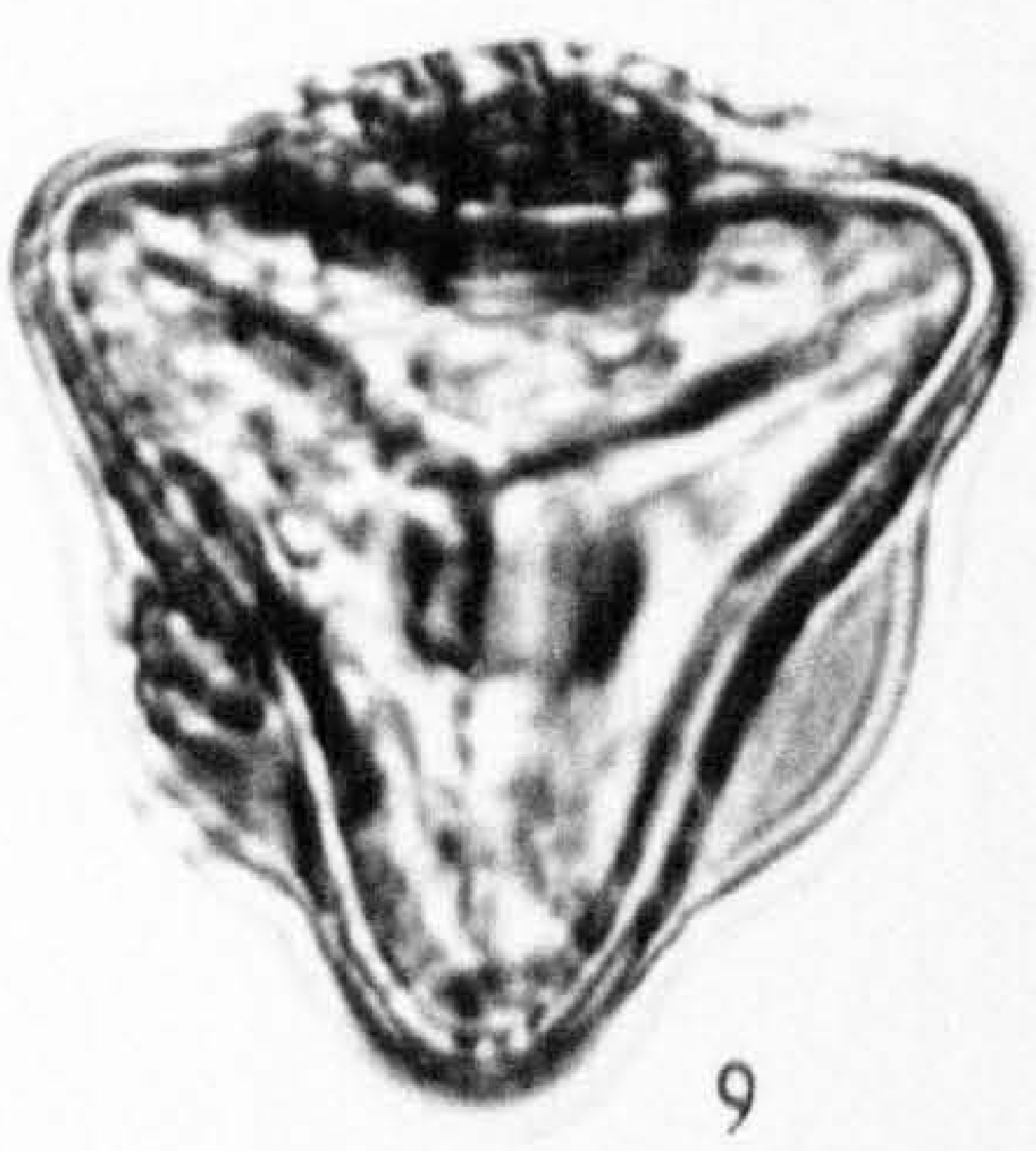
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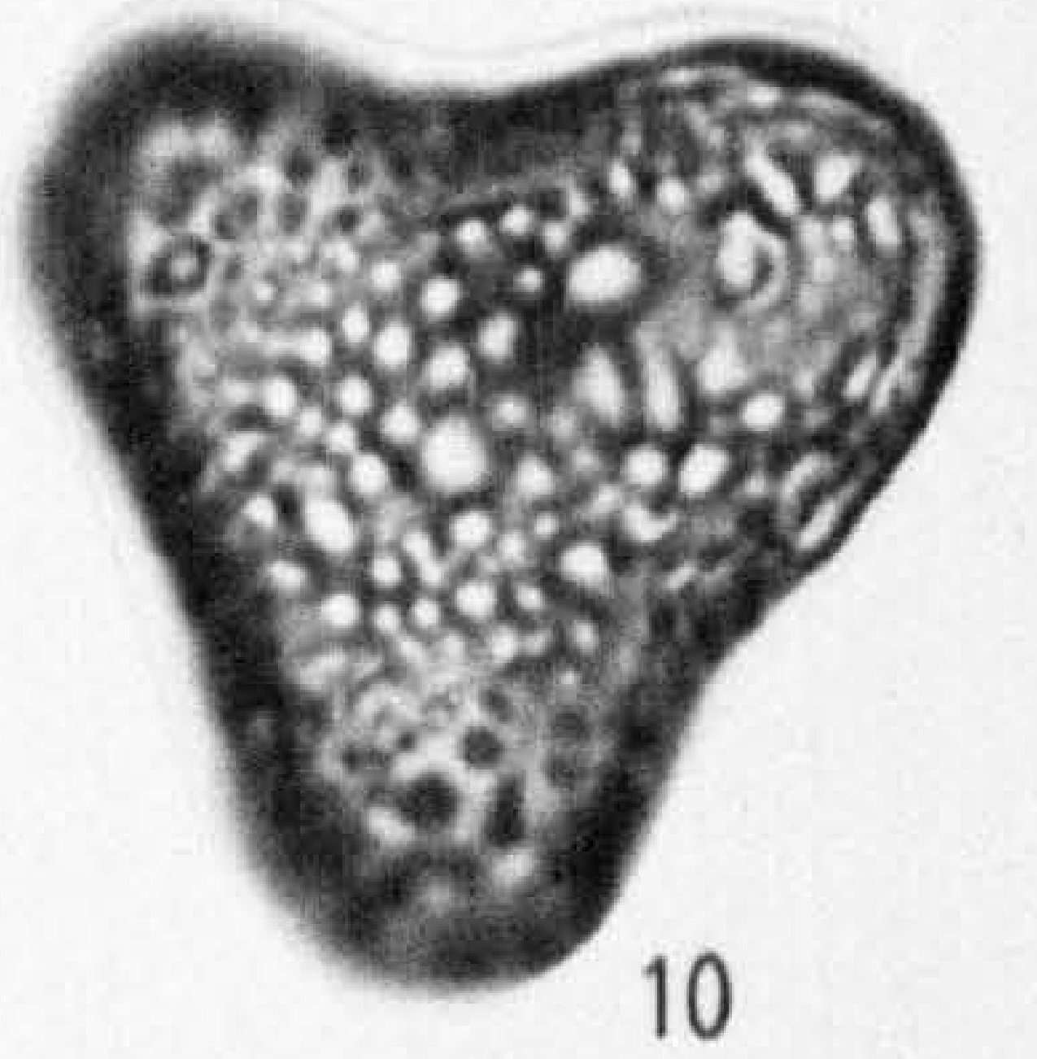
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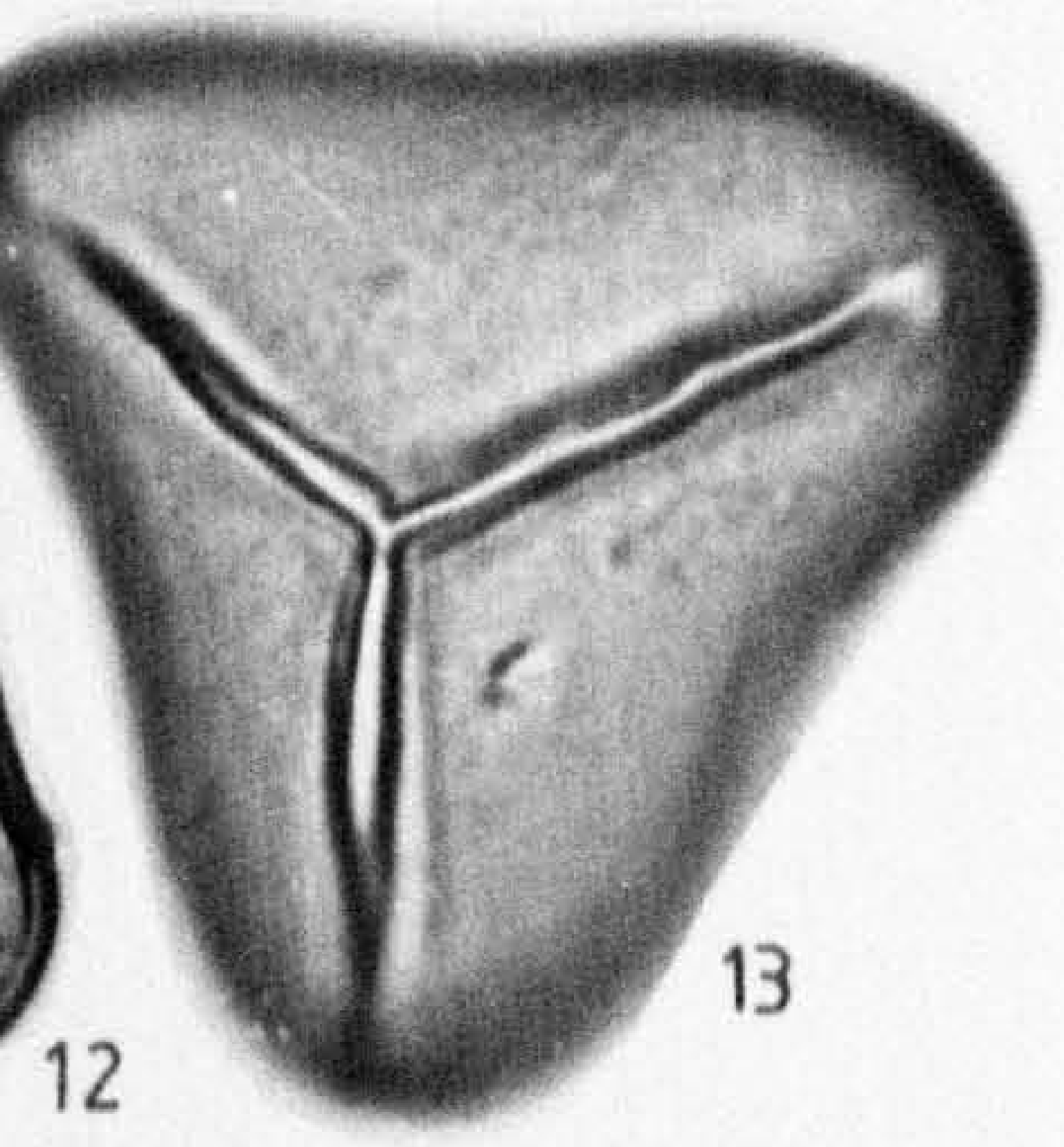
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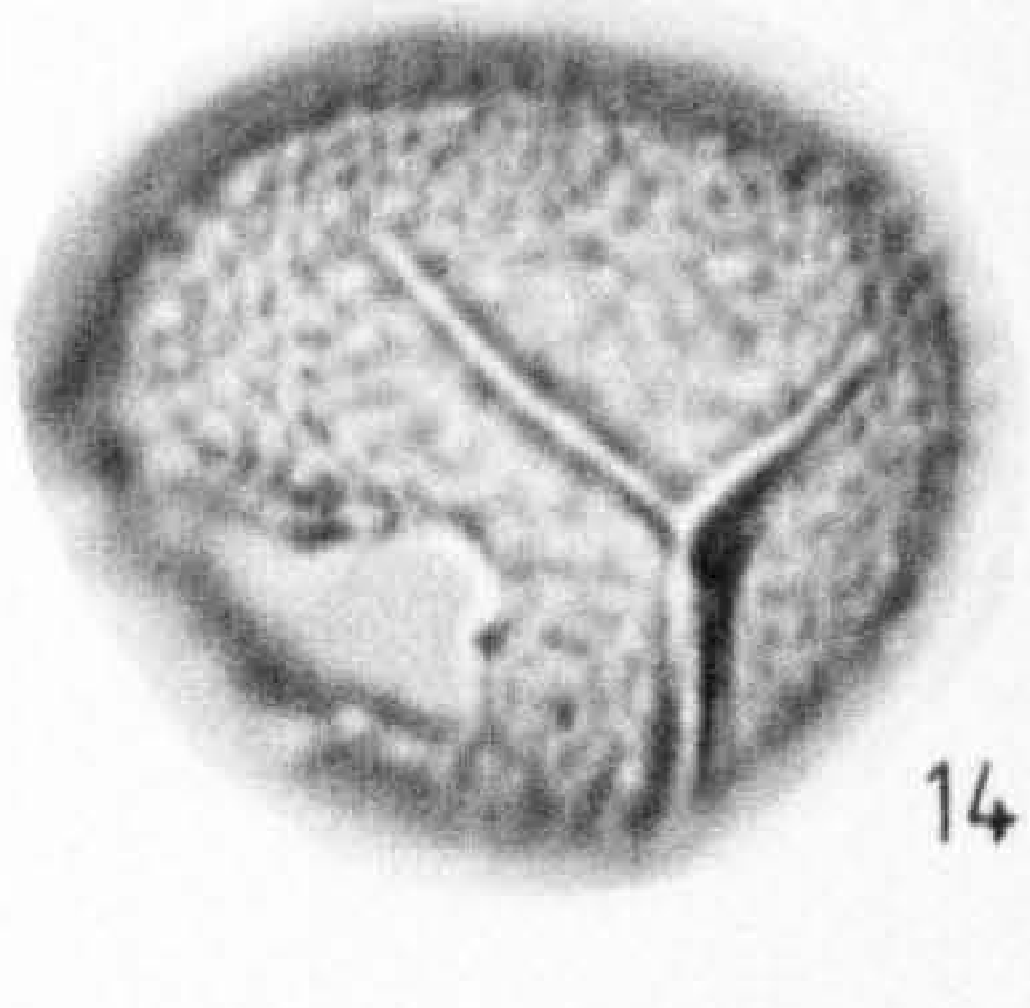
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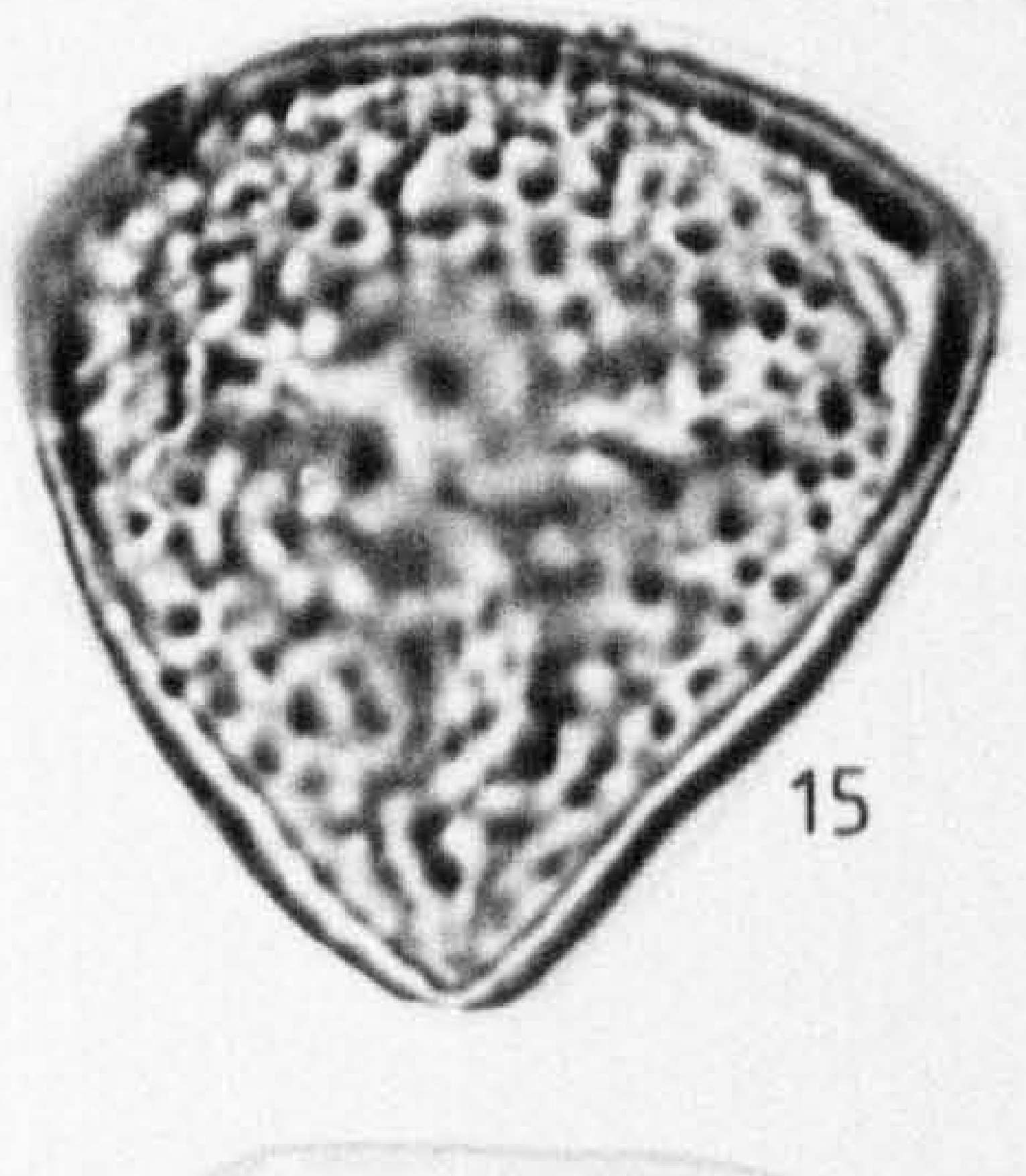
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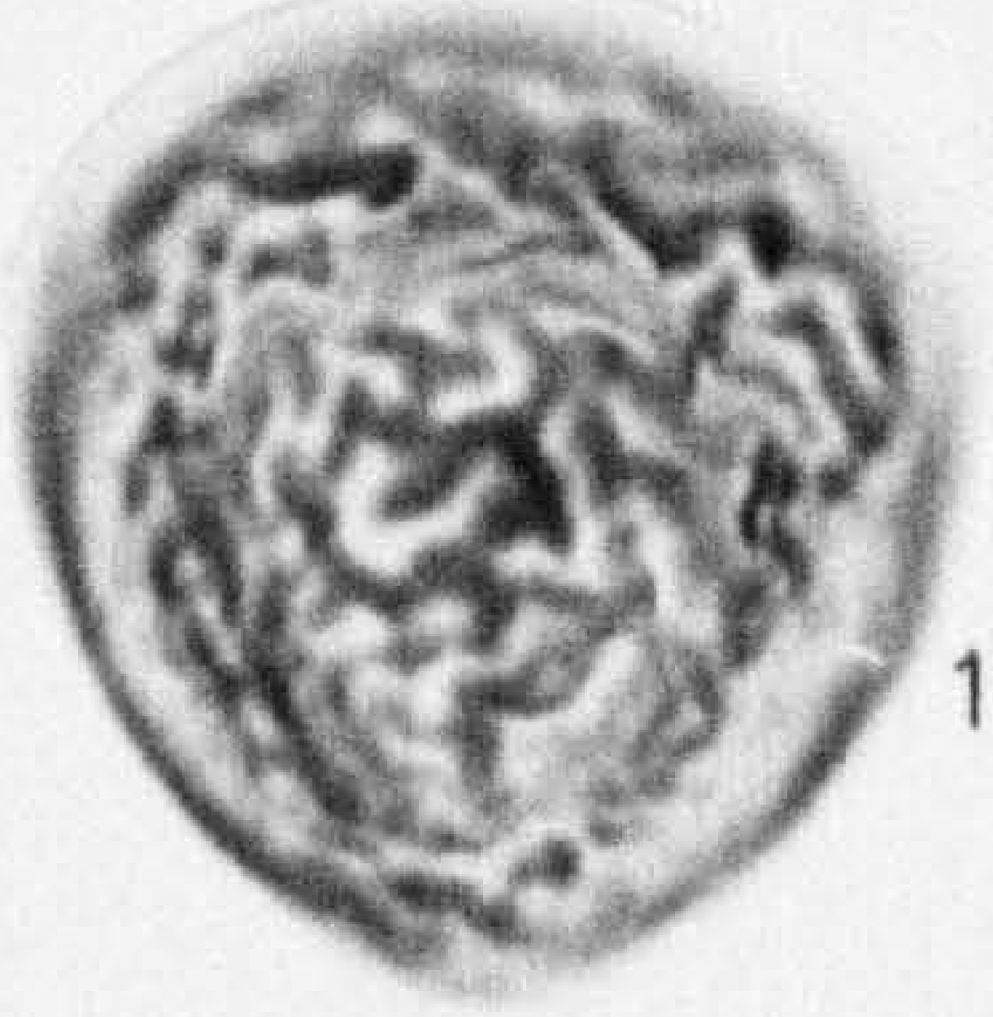
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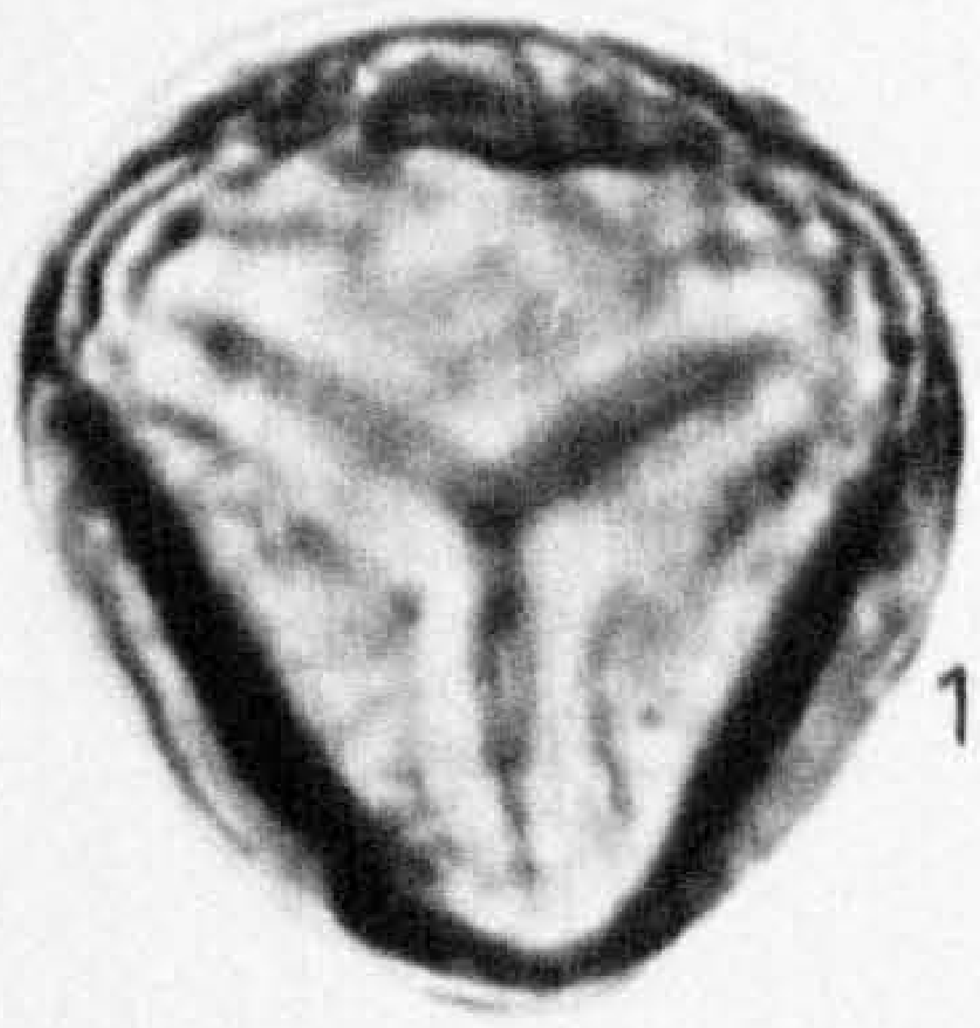
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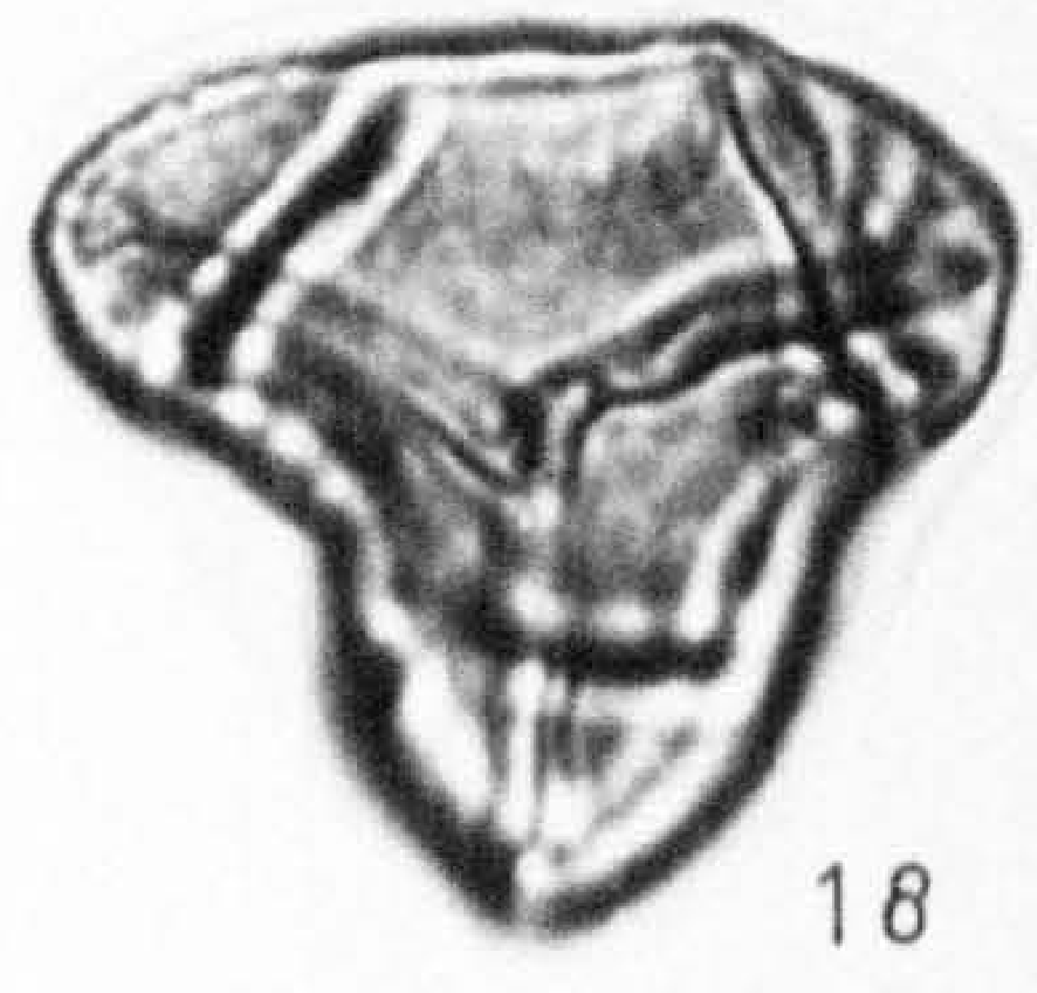
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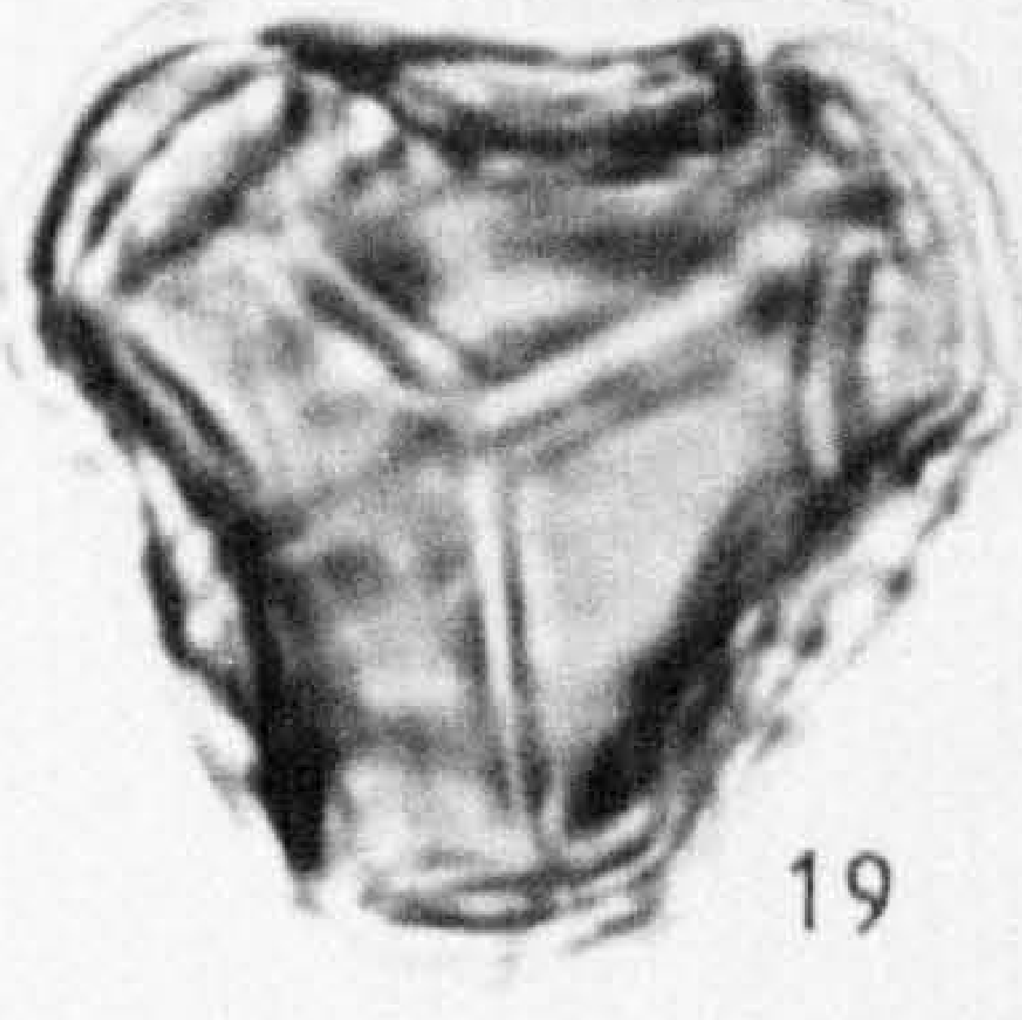
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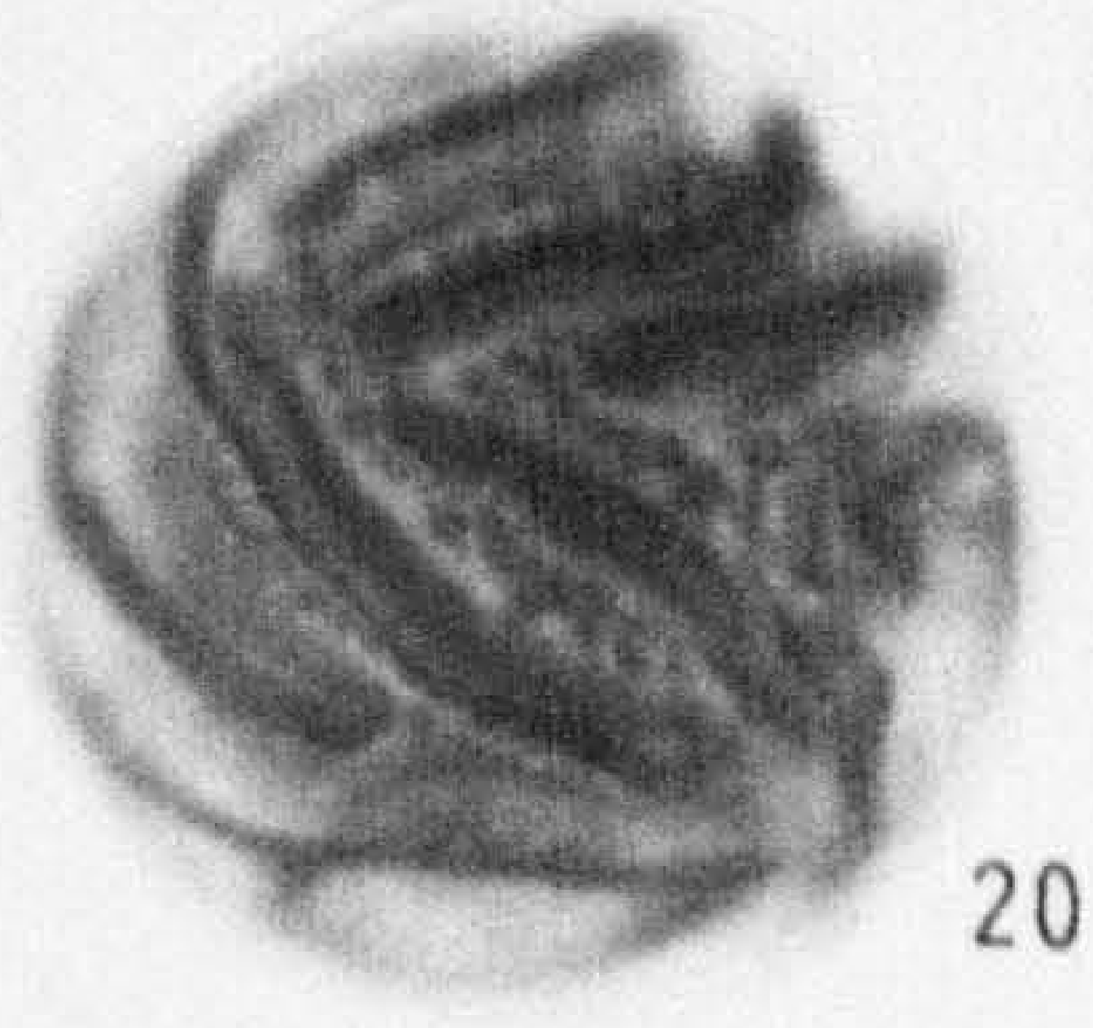
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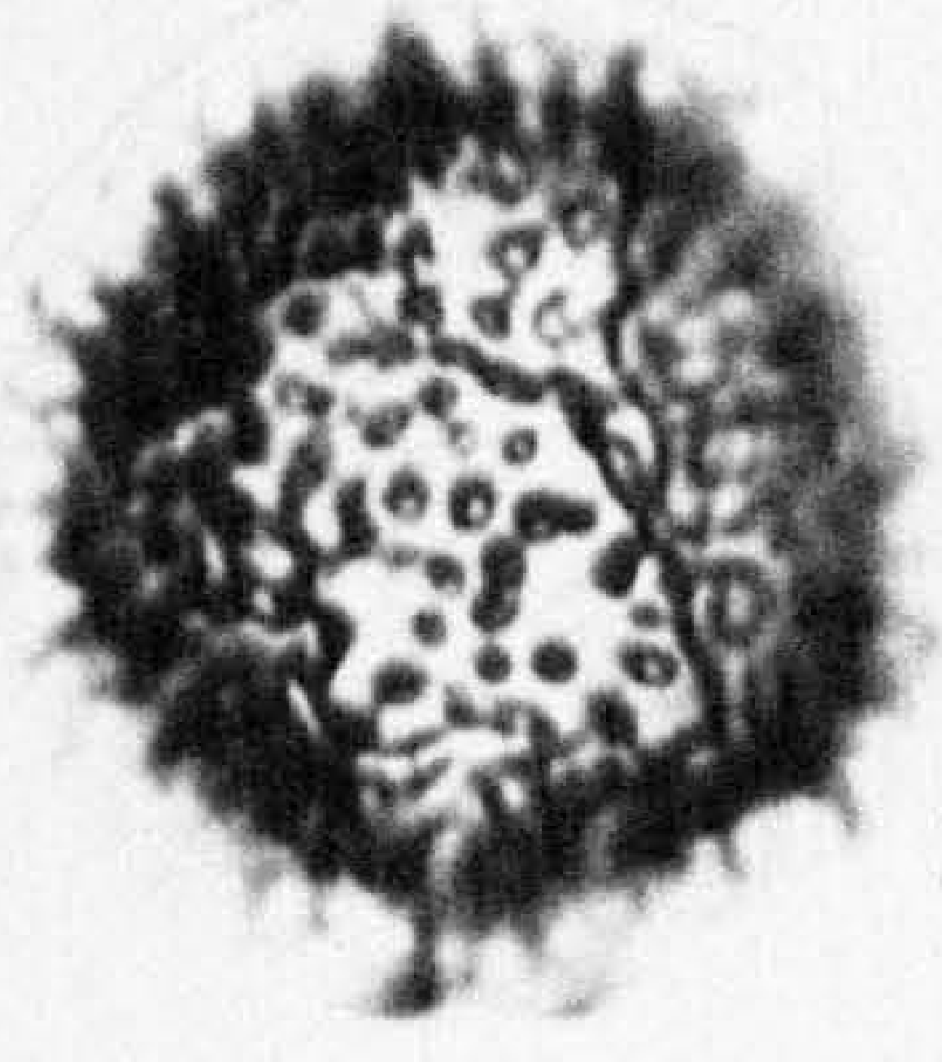
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0 20μm

PLATE 9.

Dinoflagellates.

1-2. Dinoflagellate type 1: (Tem).

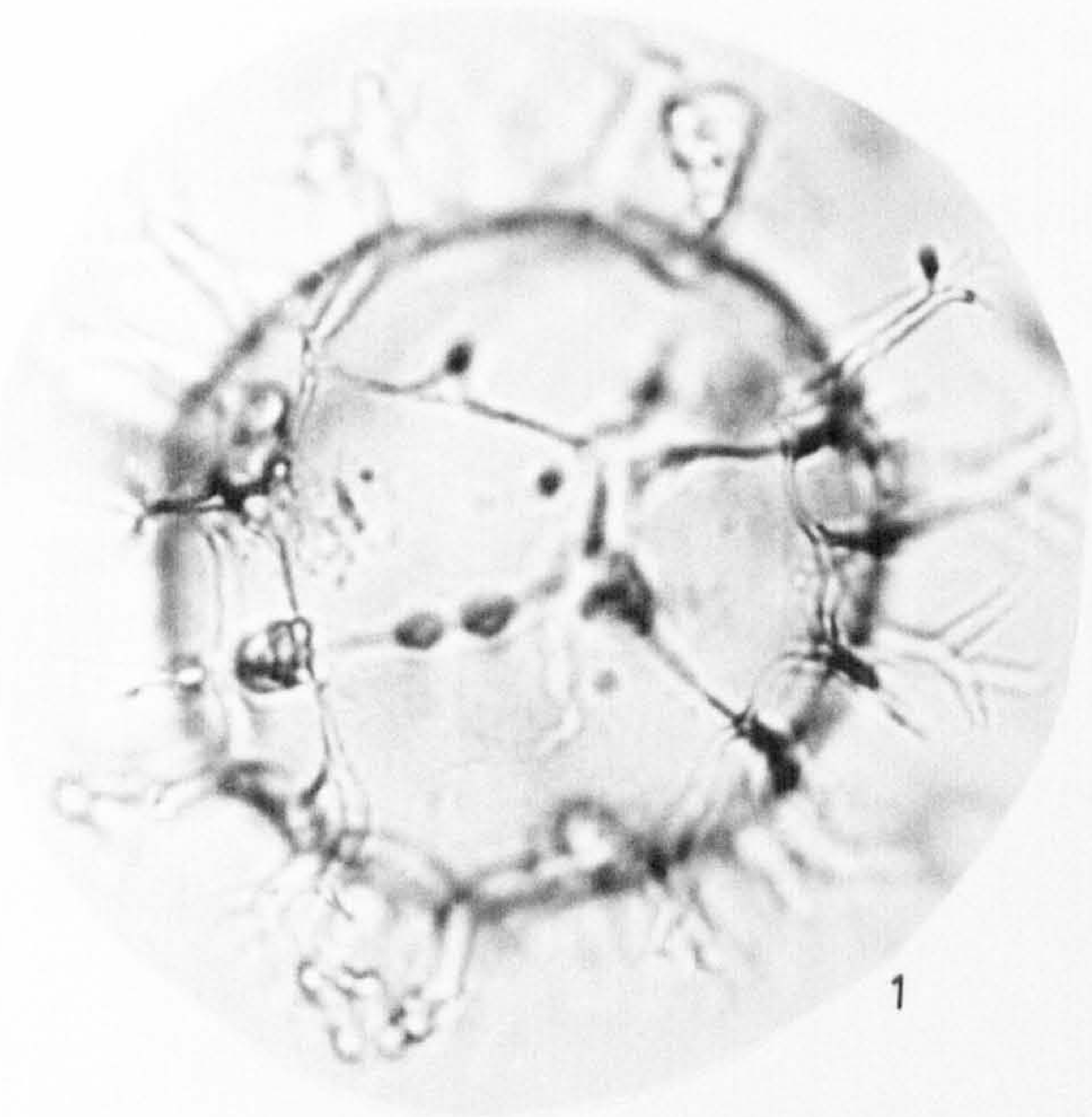
3-4. Dinoflagellate type 2: (Tem).

5. Dinoflagellate type 3: (Tem).

6. Dinoflagellate type 4: (Tem).

7. Dinoflagellate type 1, (*Hysterix* comp.): (Roto).

PLATE 9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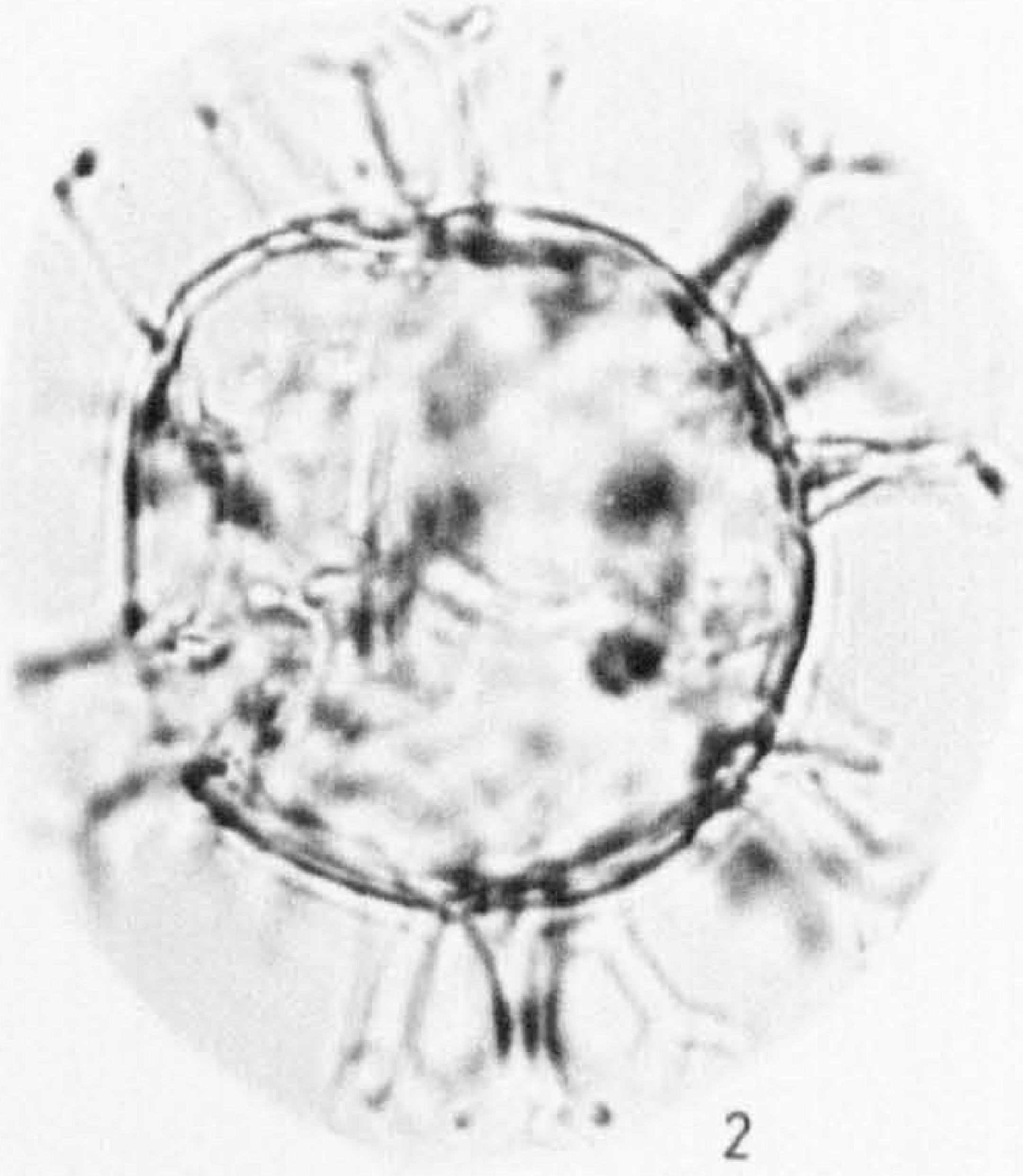
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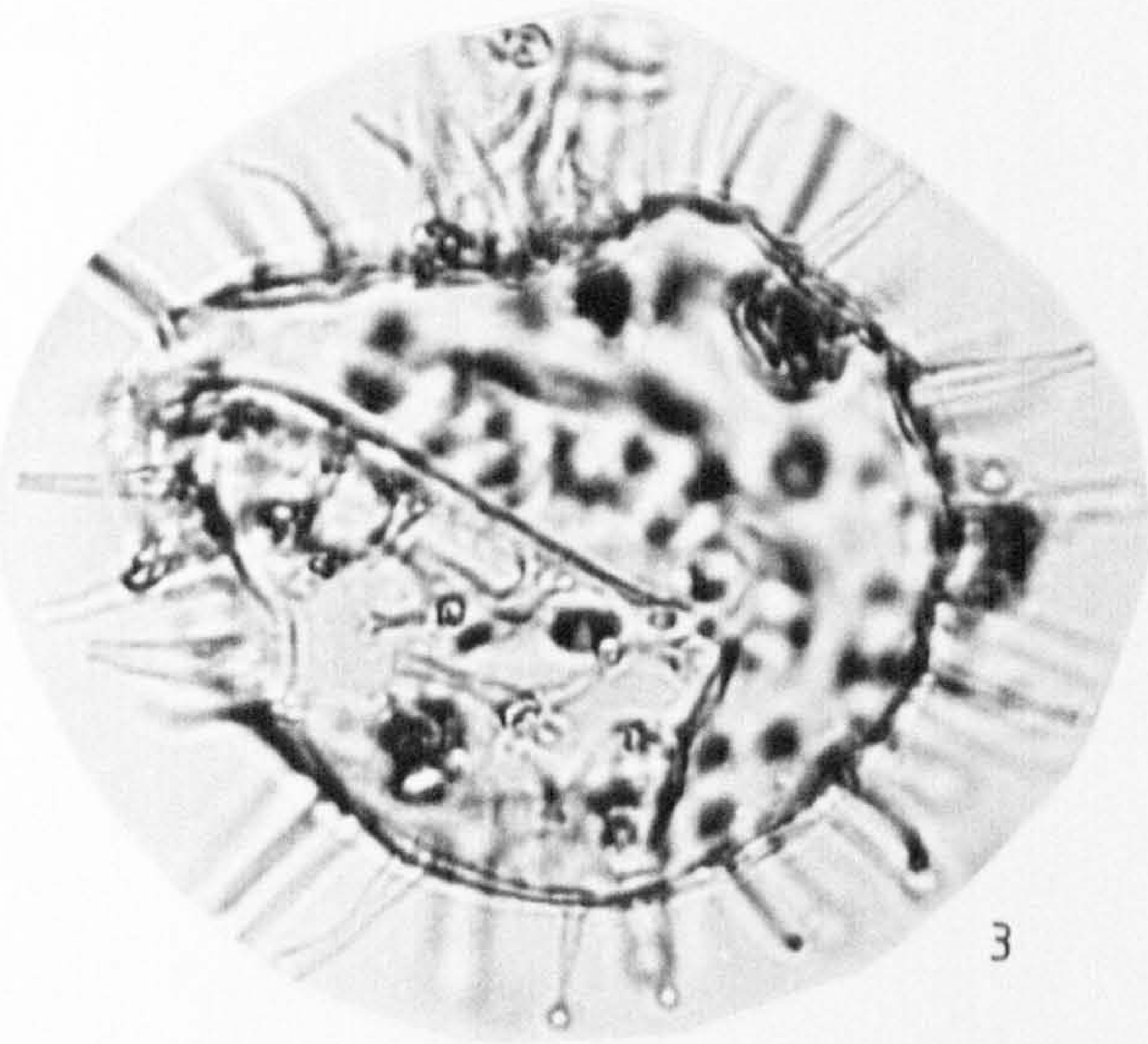
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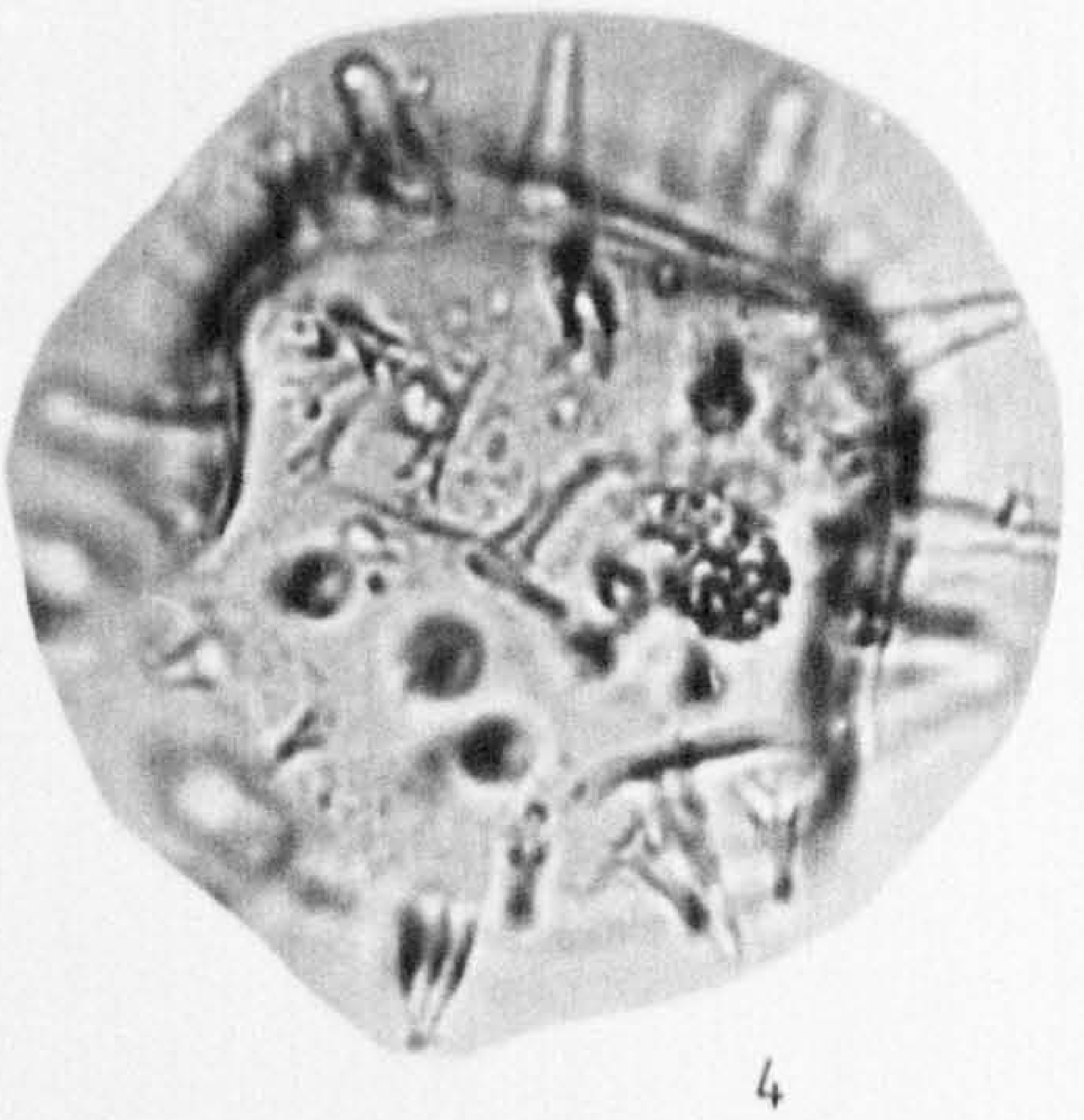
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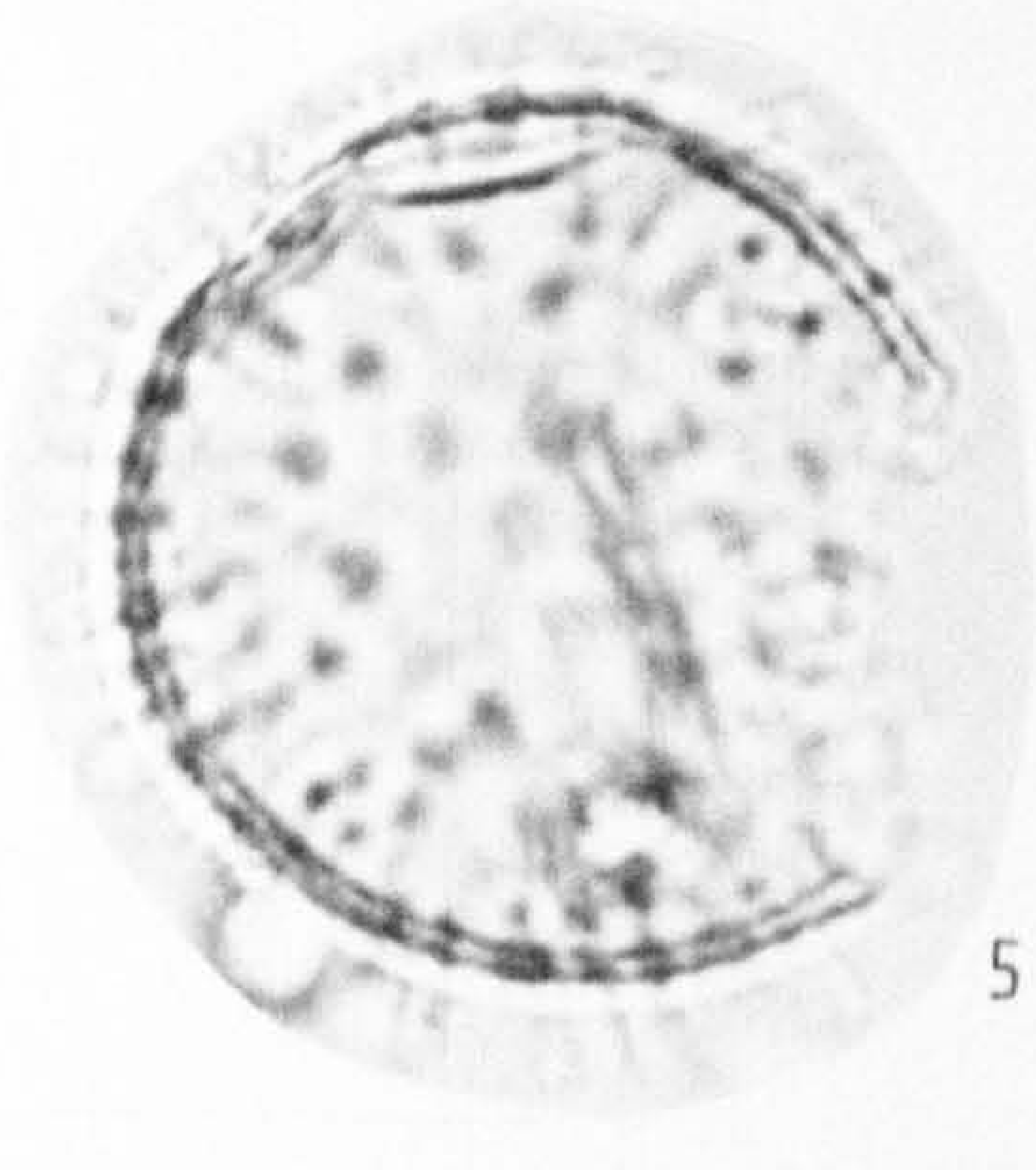
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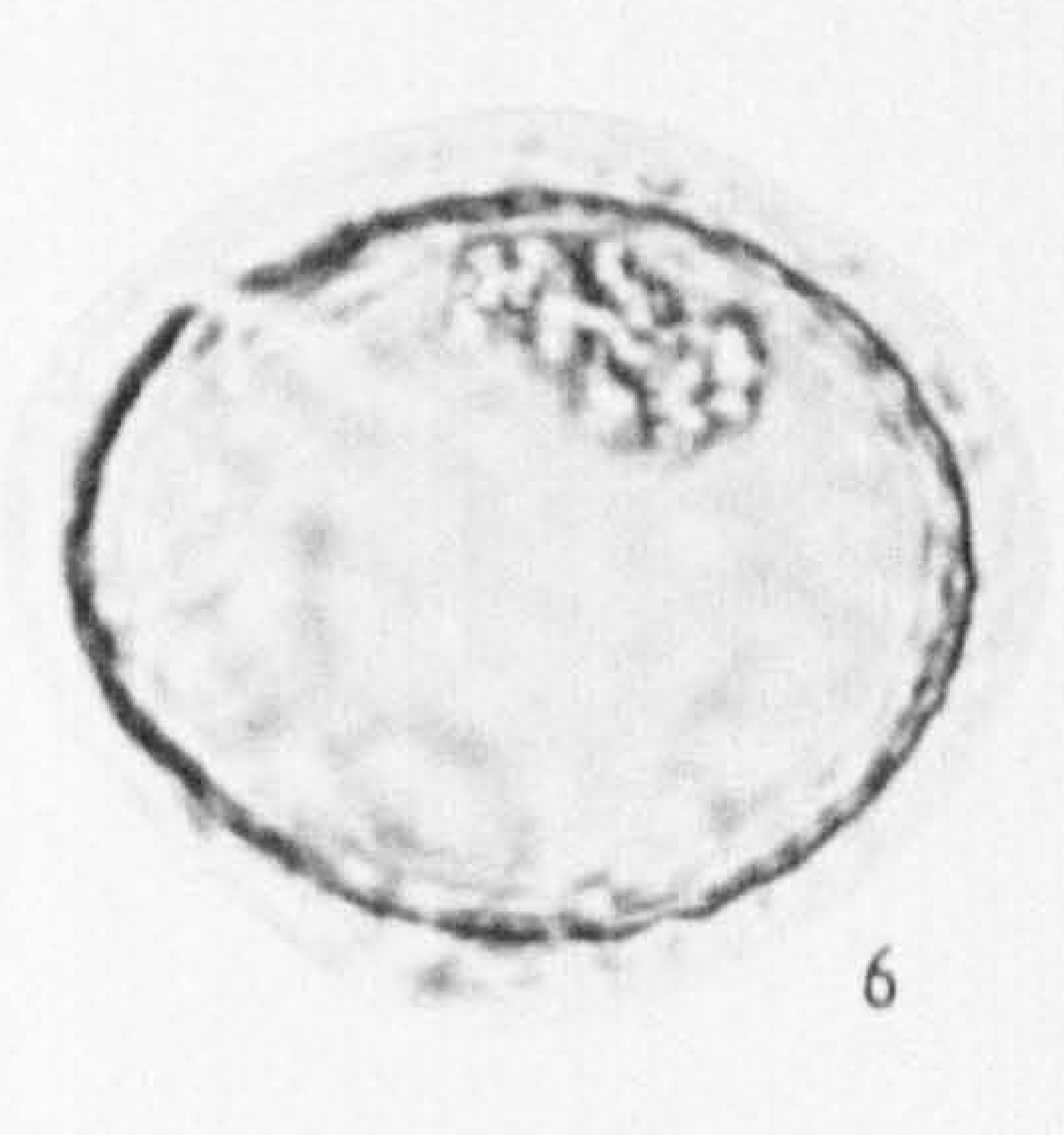
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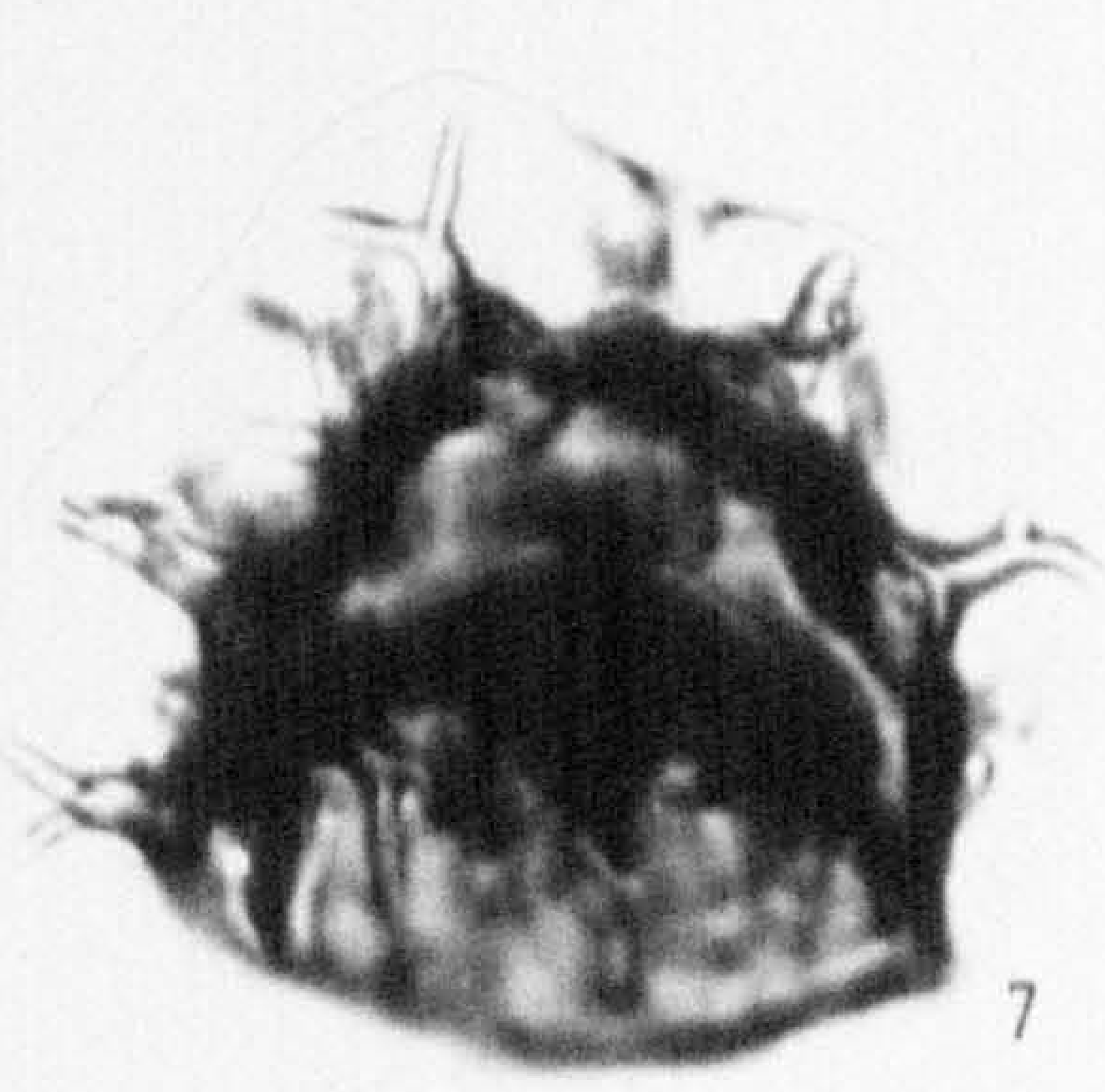
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0 20μm

PLATE 10.

Diatoms from the Lake Roto sediment sequence.

Descriptions of diatom morphology have been comprehensively covered in the standard morphological texts (e.g. Hustedt, 1930-1966; Patrick & Reimer, 1966, 1975; Kramer & Lange-Bertelot, 1986) and are therefore not repeated here.

Centric diatoms.

1-2. *Thalassiosira weissflogii.*

3. Unidentified.

4. Unidentified.

Resting spores.

5-6. *Chaetoceros* sp.

Pennate diatoms.

7. *Diploneis smithii.*

8. *Diploneis smithii.*

9. *Diploneis* sp.

10. *Pinnularia subcapitata/gibba.*

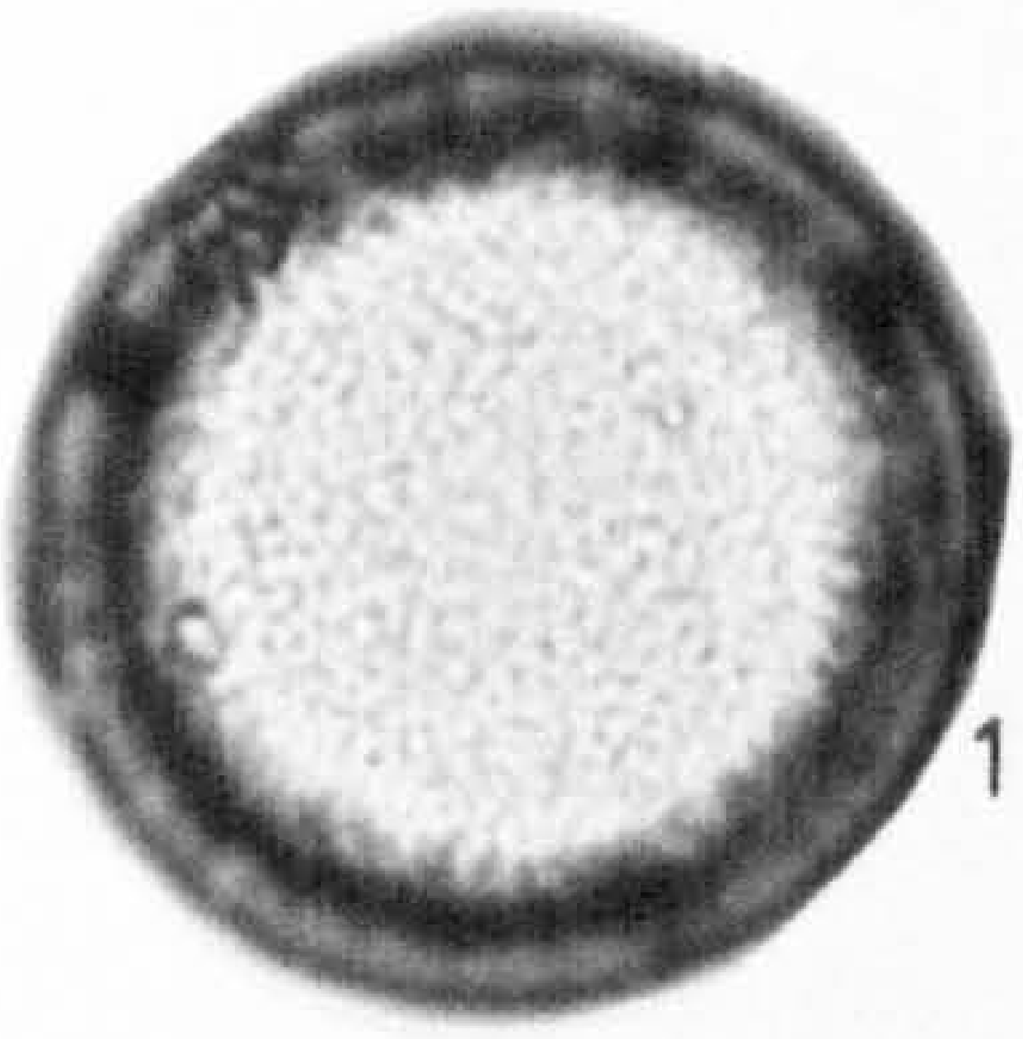
11. *Pinnularia subcapitata/gibba.*

12-13. *Achnanthes coarctata.*

14-15. *Achnanthes inflata.*

16. *Achnanthes exigua.*

PLATE 10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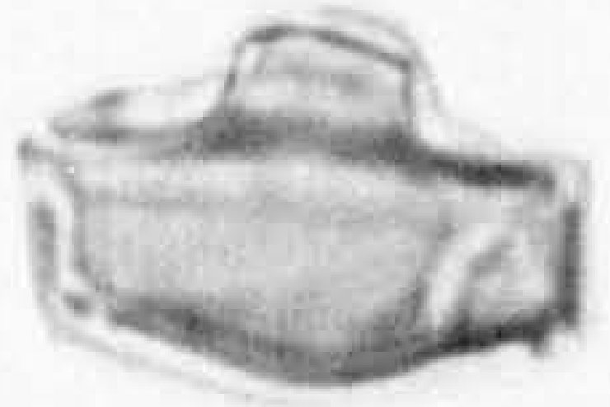
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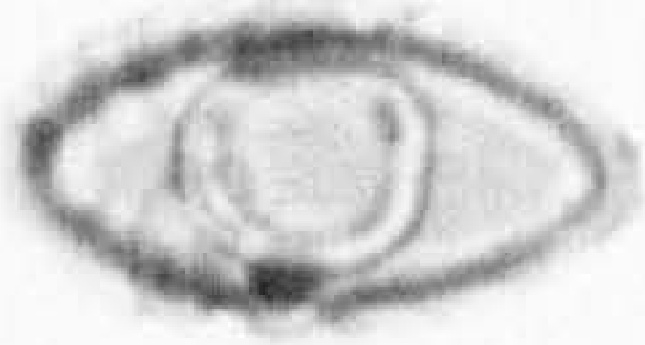
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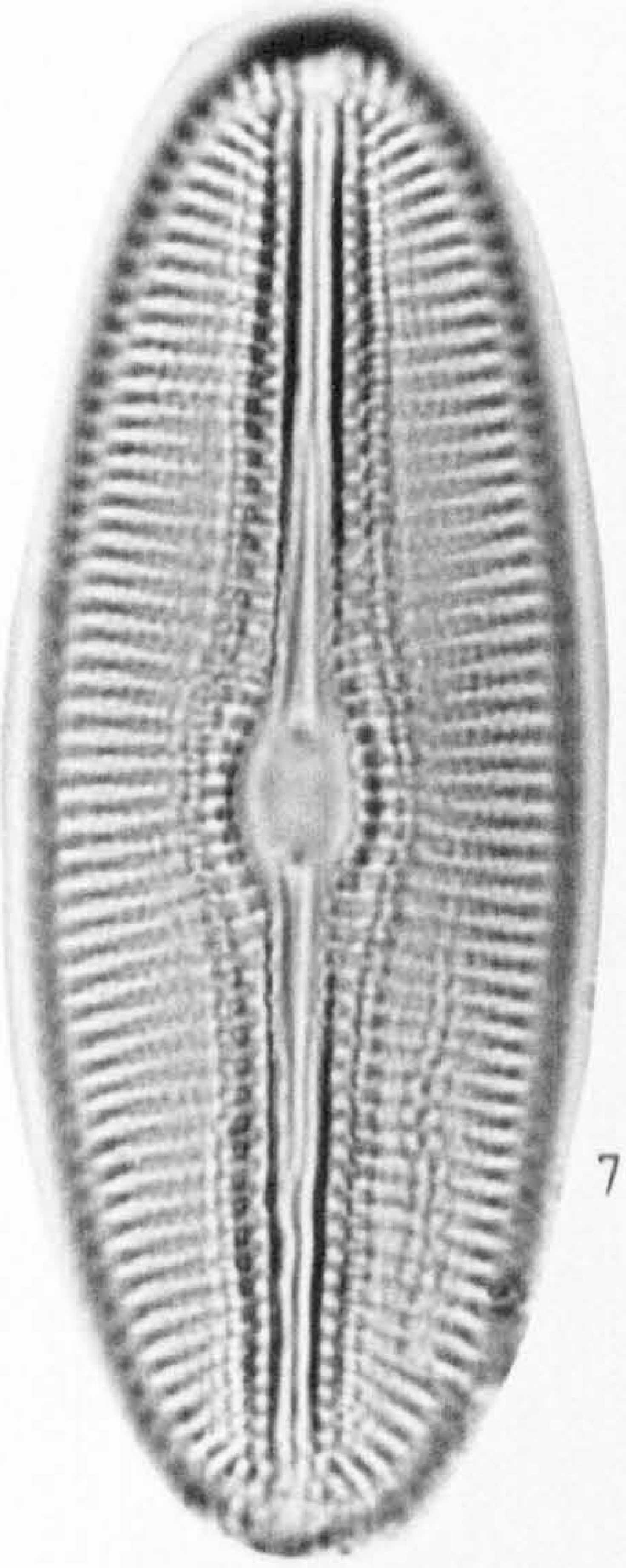
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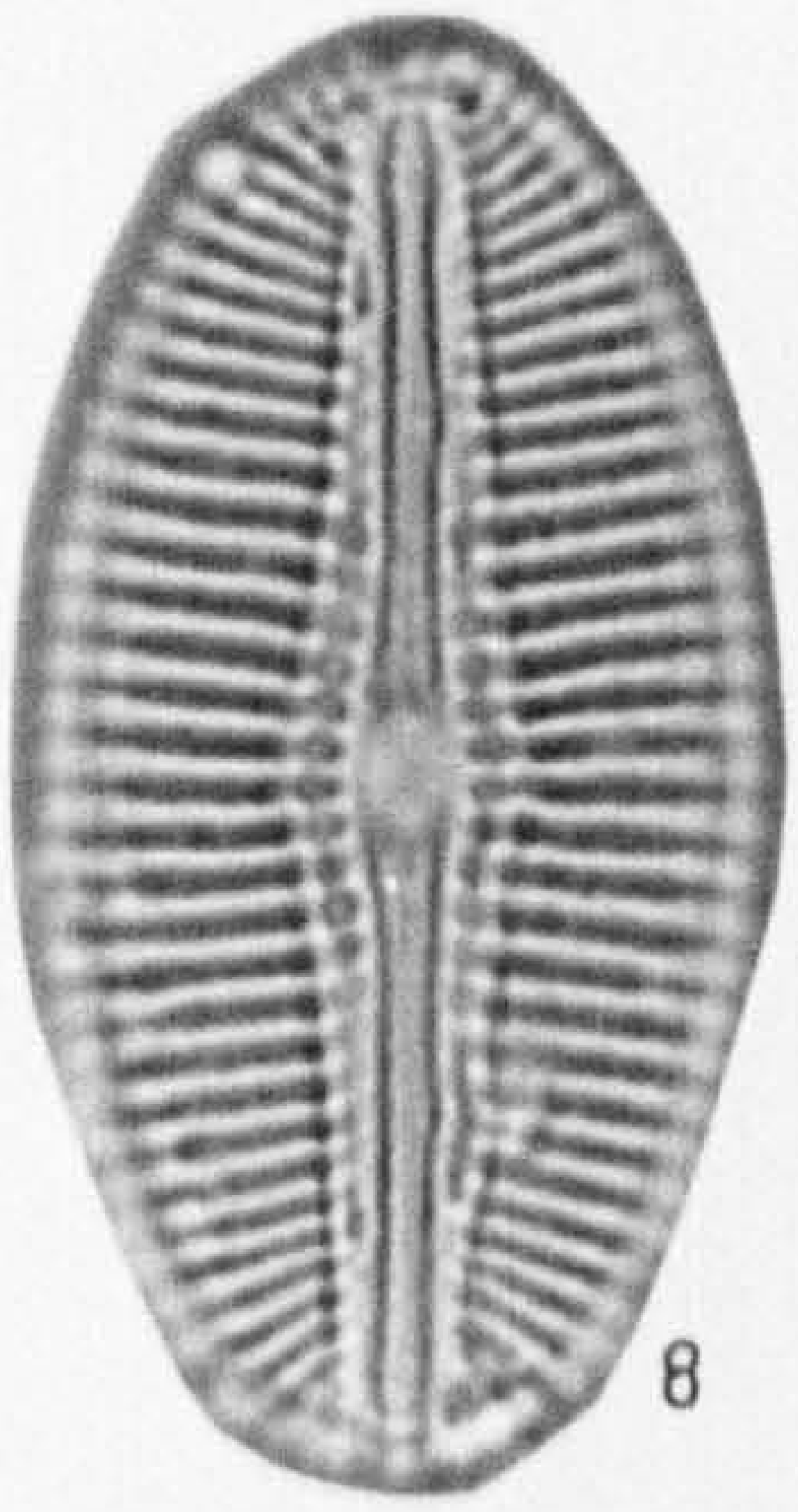
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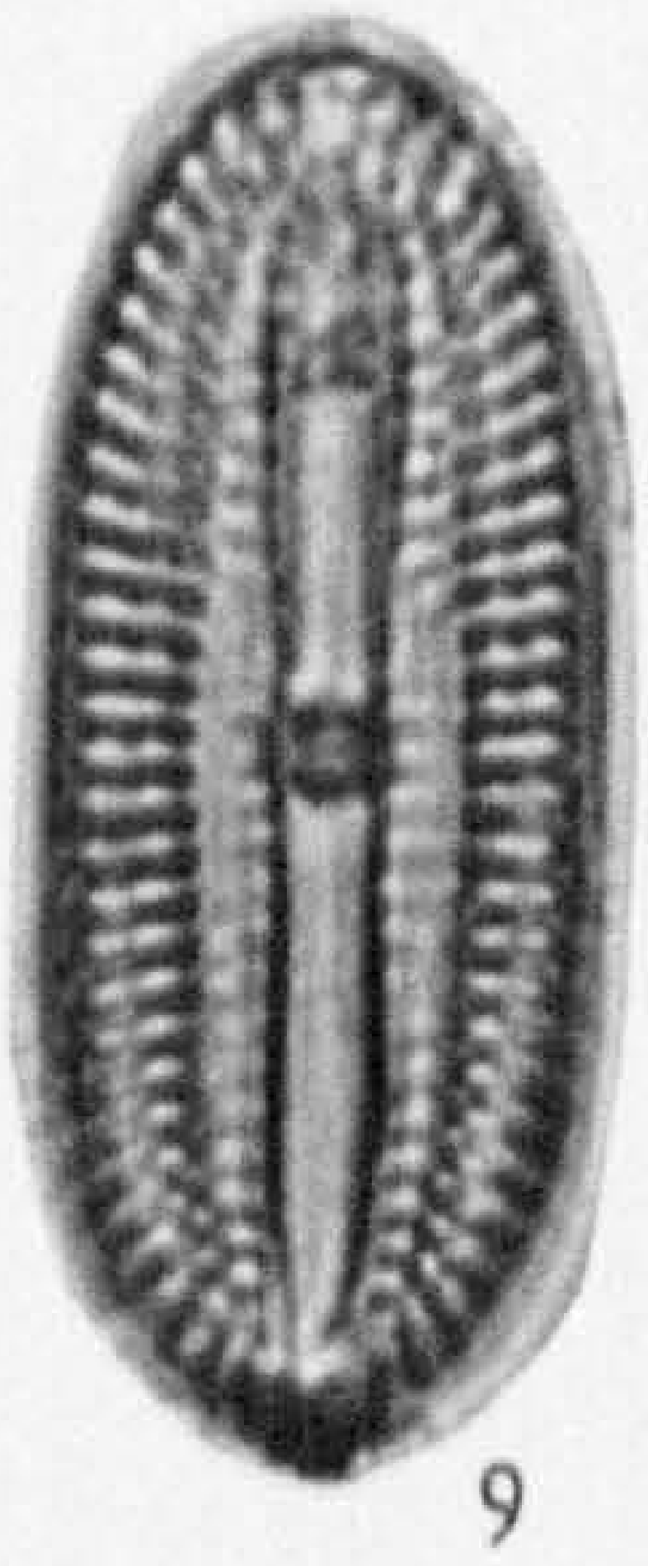
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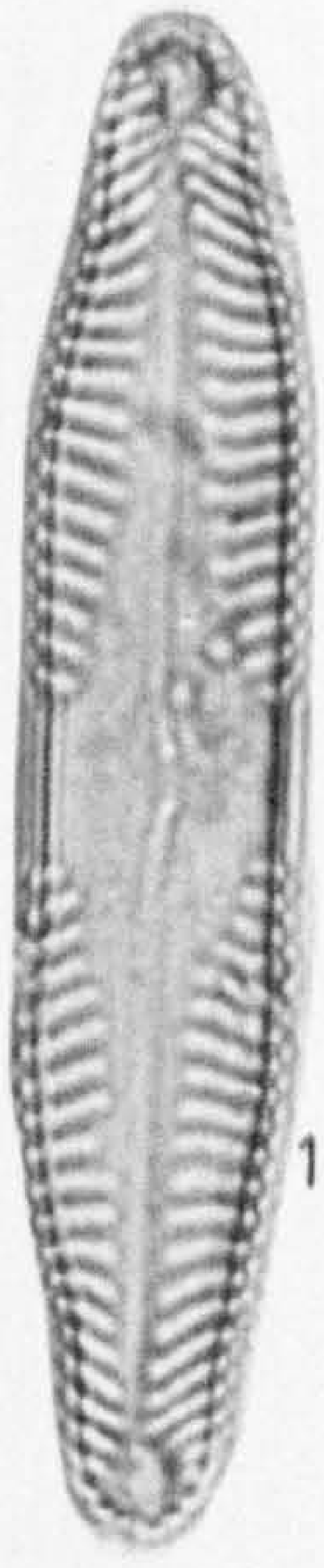
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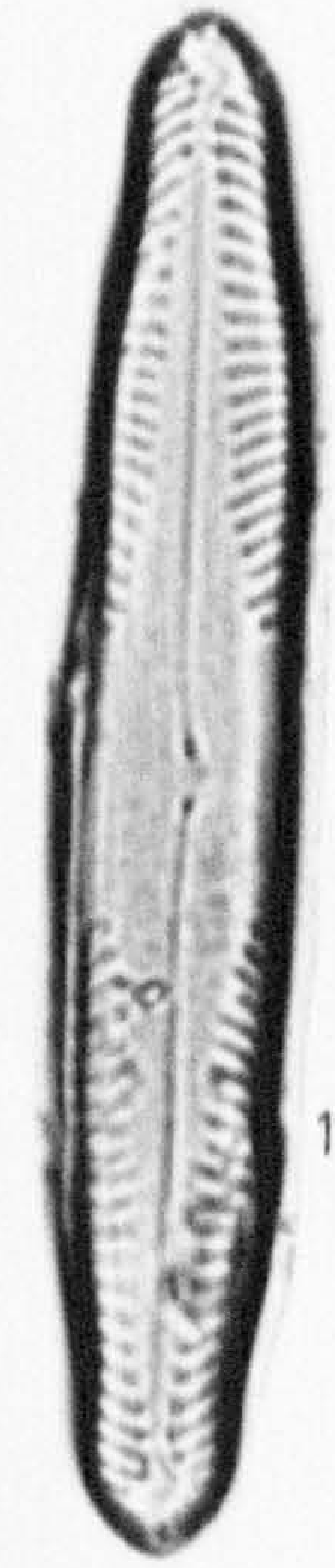
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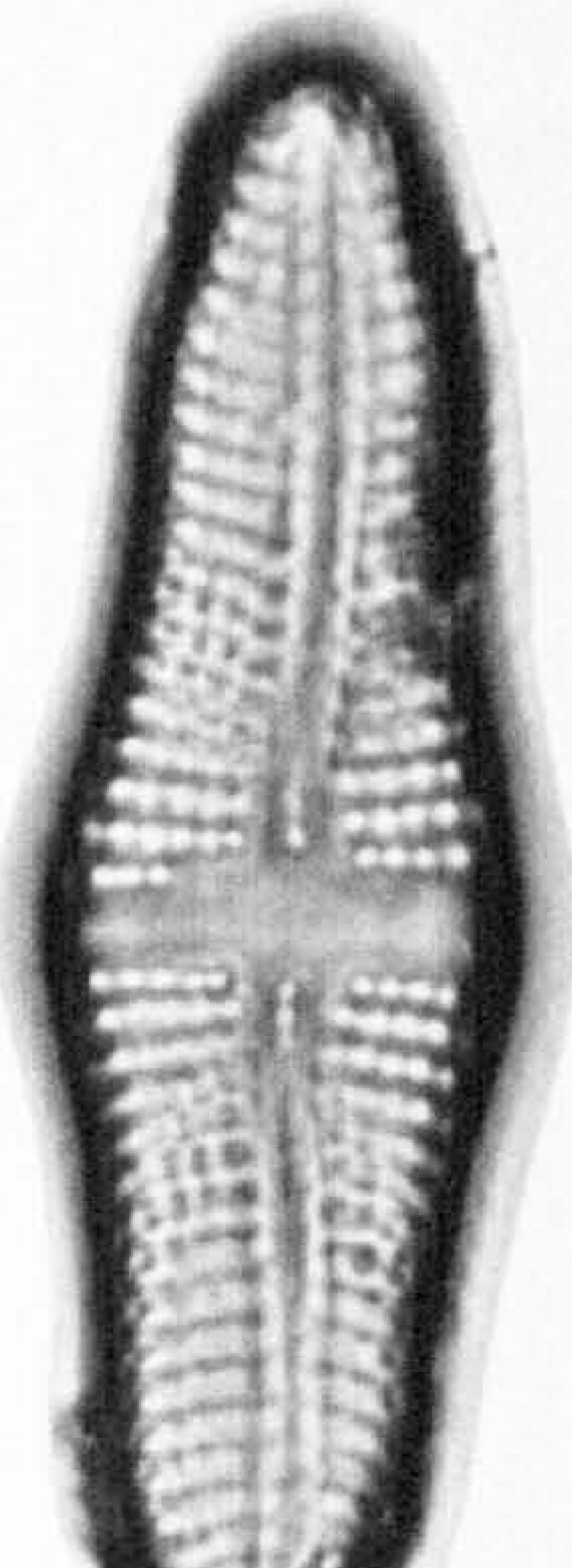
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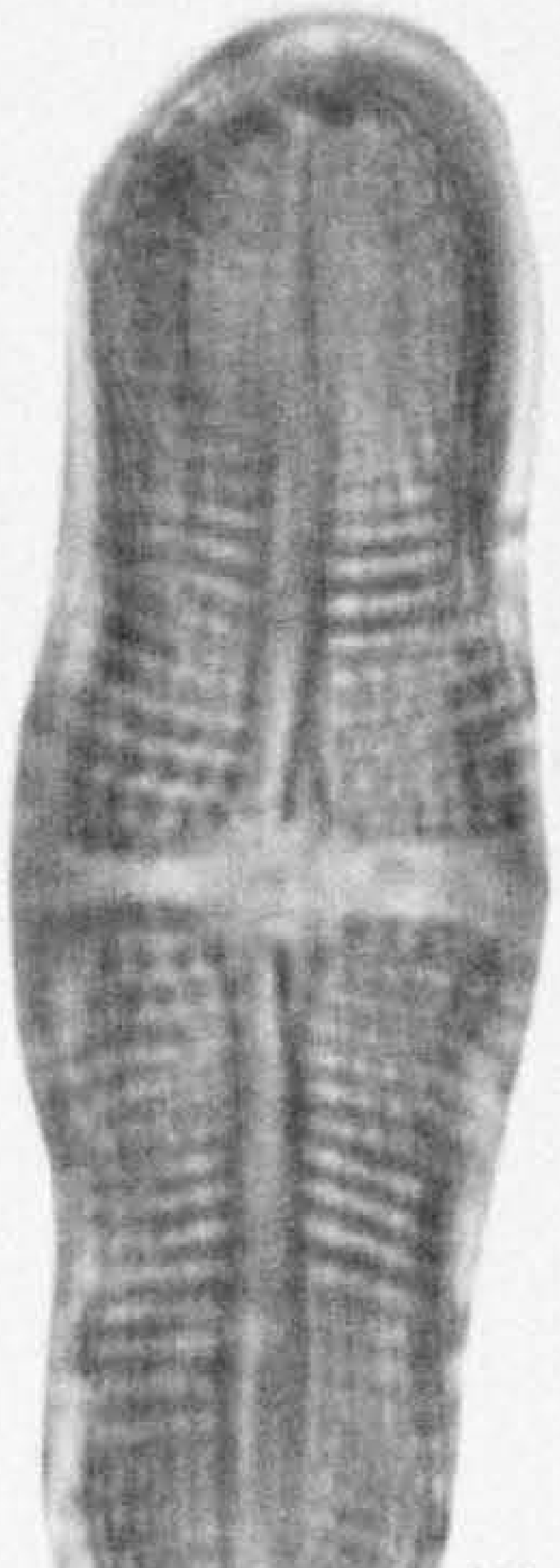
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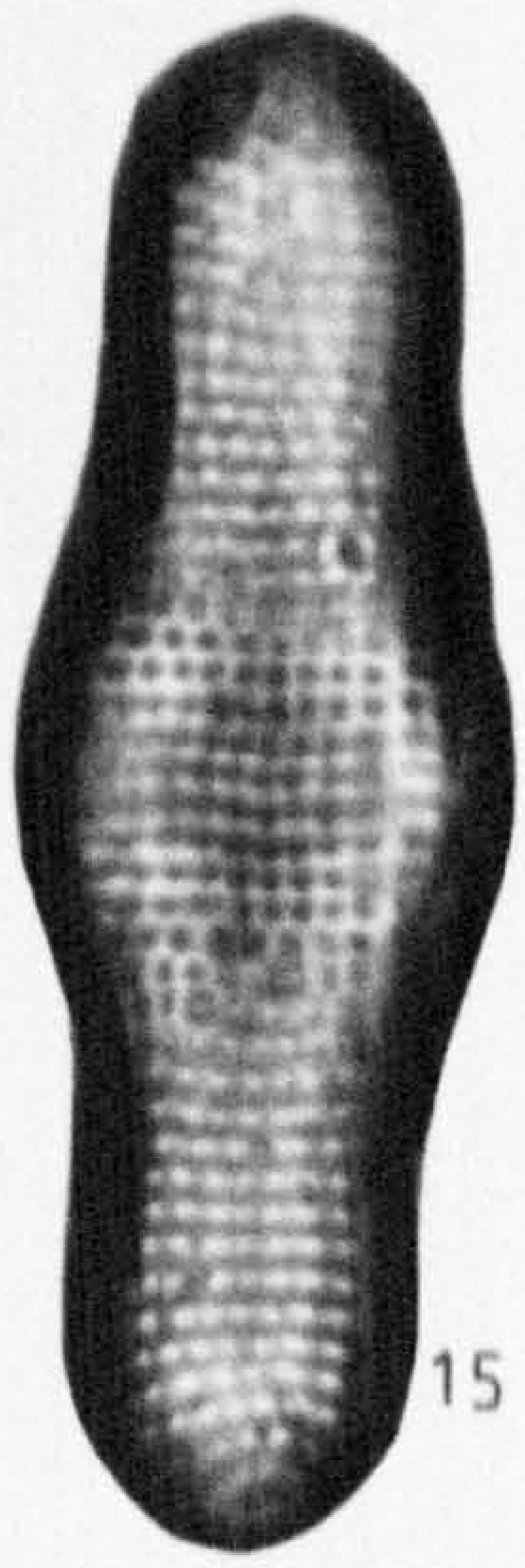
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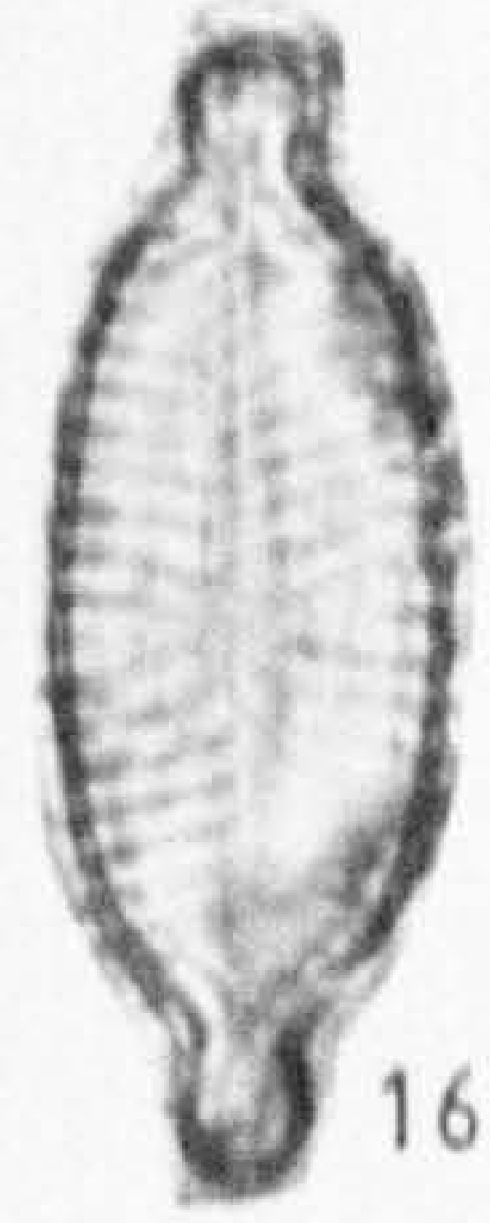

16

0 14μm

PLATE 11.

Pennate diatoms (continued).

1. *Stauroneis phoenicenteron.*
2. *Nitzschia* sp.
3. *Nitzschia* sp.
4. *Nitzschia* sp.
5. *Amphora coffeaeformis.*
6. *Eunotia* sp.
7. *Caloneis* sp.
8. *Fragilaria brevistriata.*
9. *Fragilaria brevistriata.*
10. *Navicula pupula.*
11. *Navicula* sp.
12. *Gomphonema gracile*/var. *affine.*
13. *Gomphonema affine* var. *insigne.*

PLATE 11

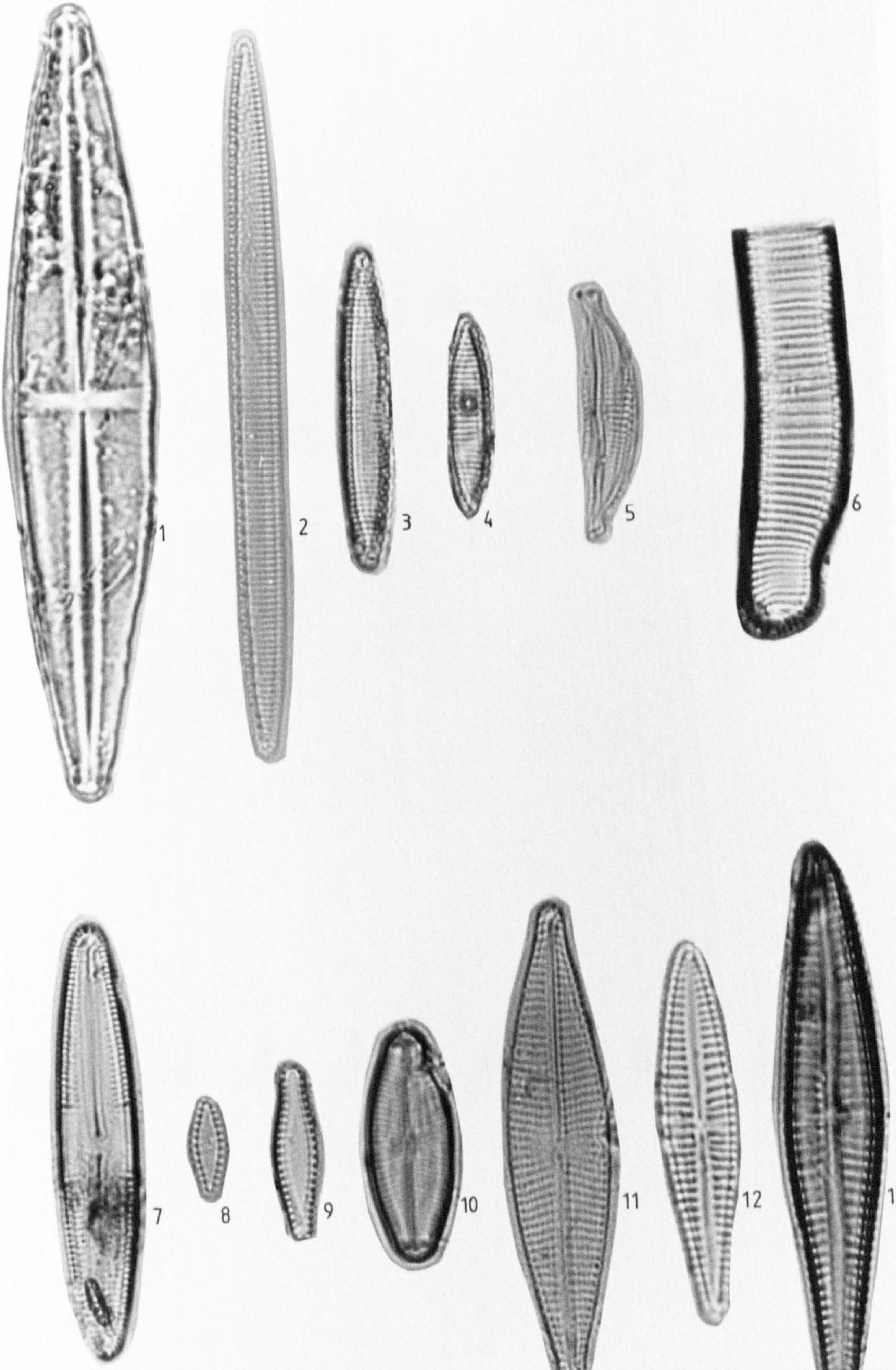


PLATE 12.

Scanning electron micrographs.

Diatoms and clay laminations from Lake Roto, Atiu.

1. Concentration of *Thalassiosira weissflogii* associated with clay laminations at 3.10m.

2. Clay lamination showing chlorite minerals and high concentrations of diatoms, including *Diploneis* sp., *Nitzschia* spp. and *Thalassiosira*.

3-4. *Thalassiosira weissflogii*.

PLATE 13.

1-2. Marine resting spore, *Chaetoceros* sp., characteristic of the Lake Roto sediments, between 9.50 and 4.0m.

3. Lamination within the Lake Roto sediment sequence showing the clay mineral, chlorite, surrounding a species of *Navicula*.

4. Valve of *Pinnularia acrosphaeria*, common in the sediment of Lake Roto above 3.05m.

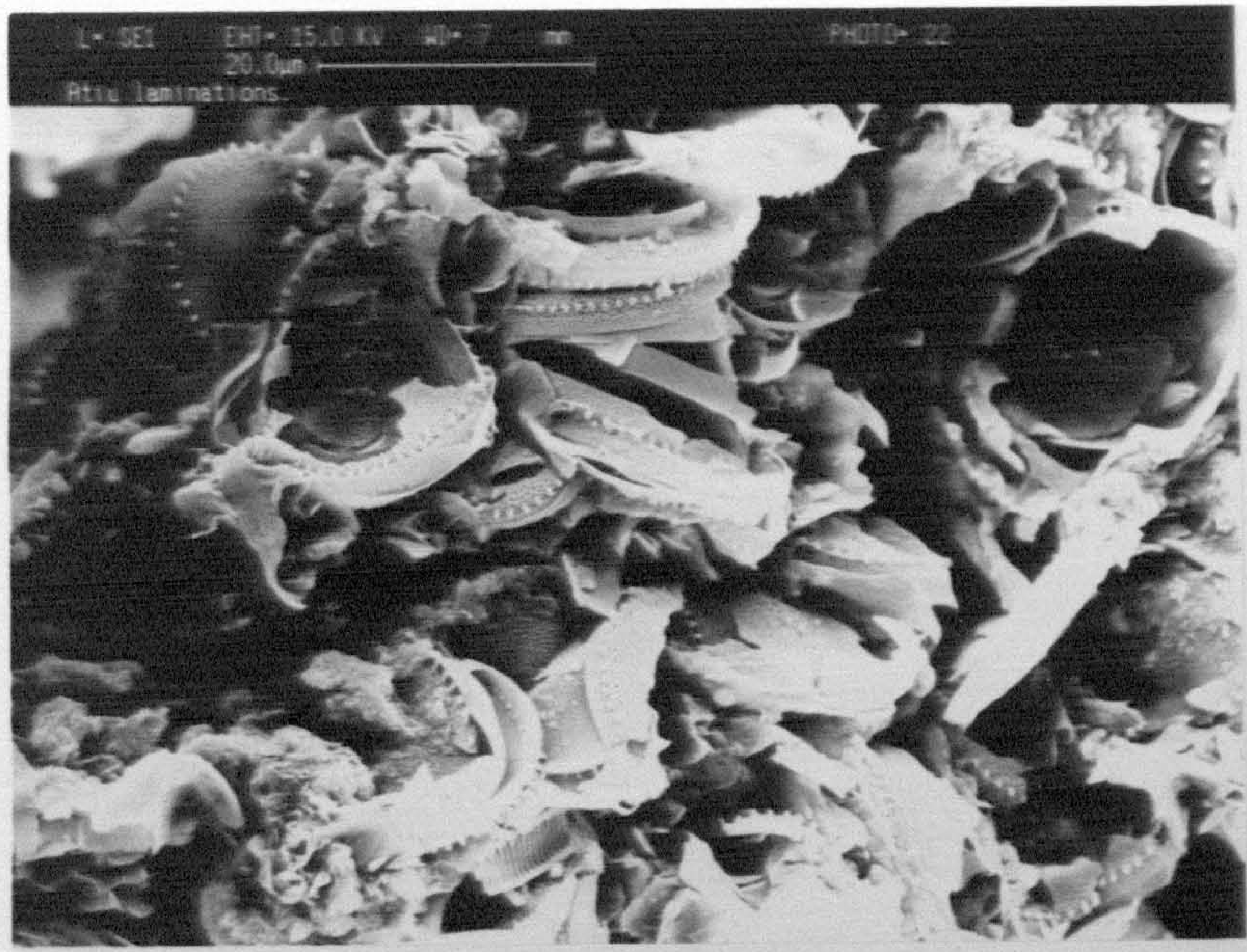
PLATE 14.

1. *Stauroneis phoenicenteron*, common in the sediment of Lake Roto above 3.30m.

2-3. *Nitzschia* sp., common throughout the Lake Roto sequence.

4. *Navicula* sp., common throughout the Lake Roto sequence.

PLATE 12



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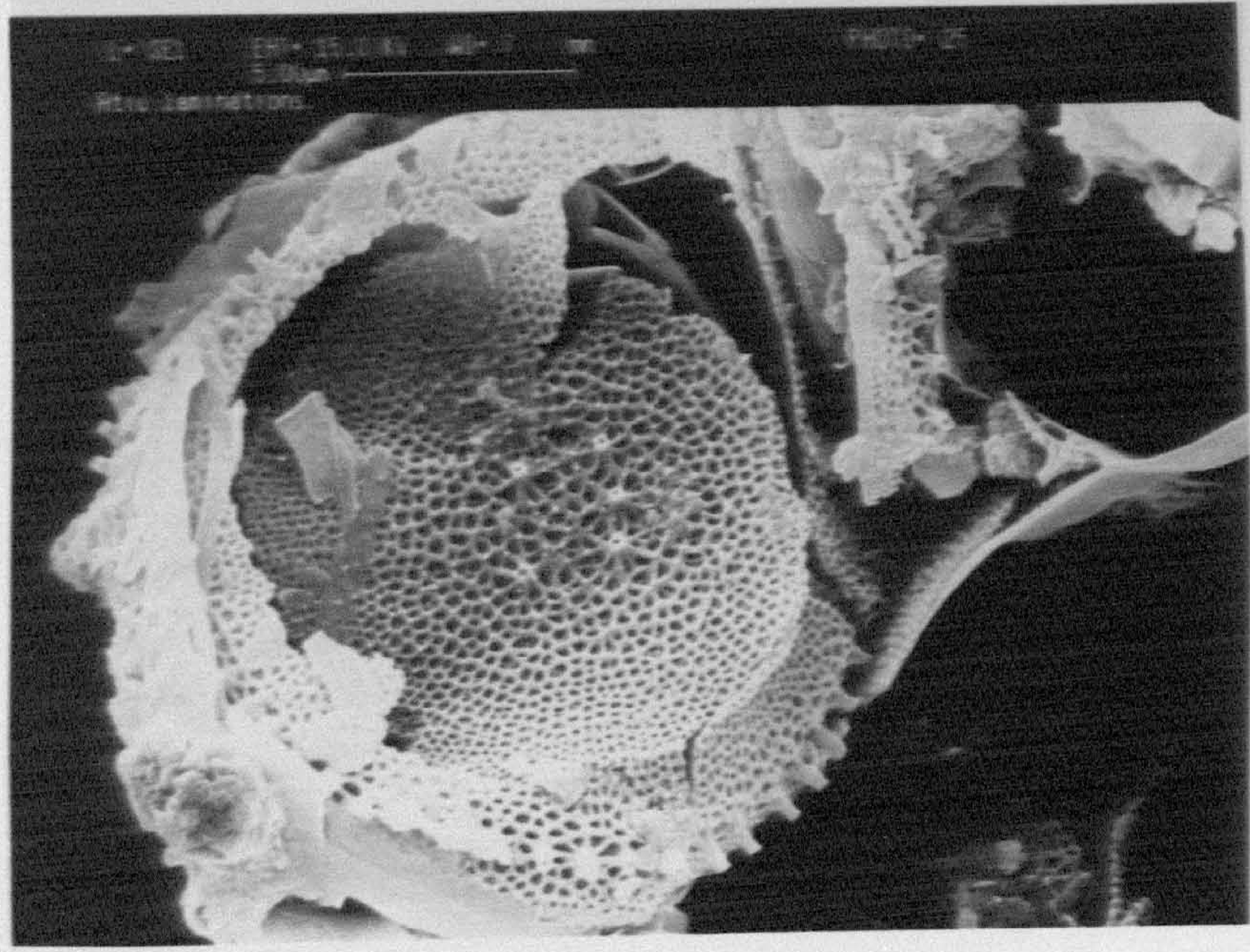

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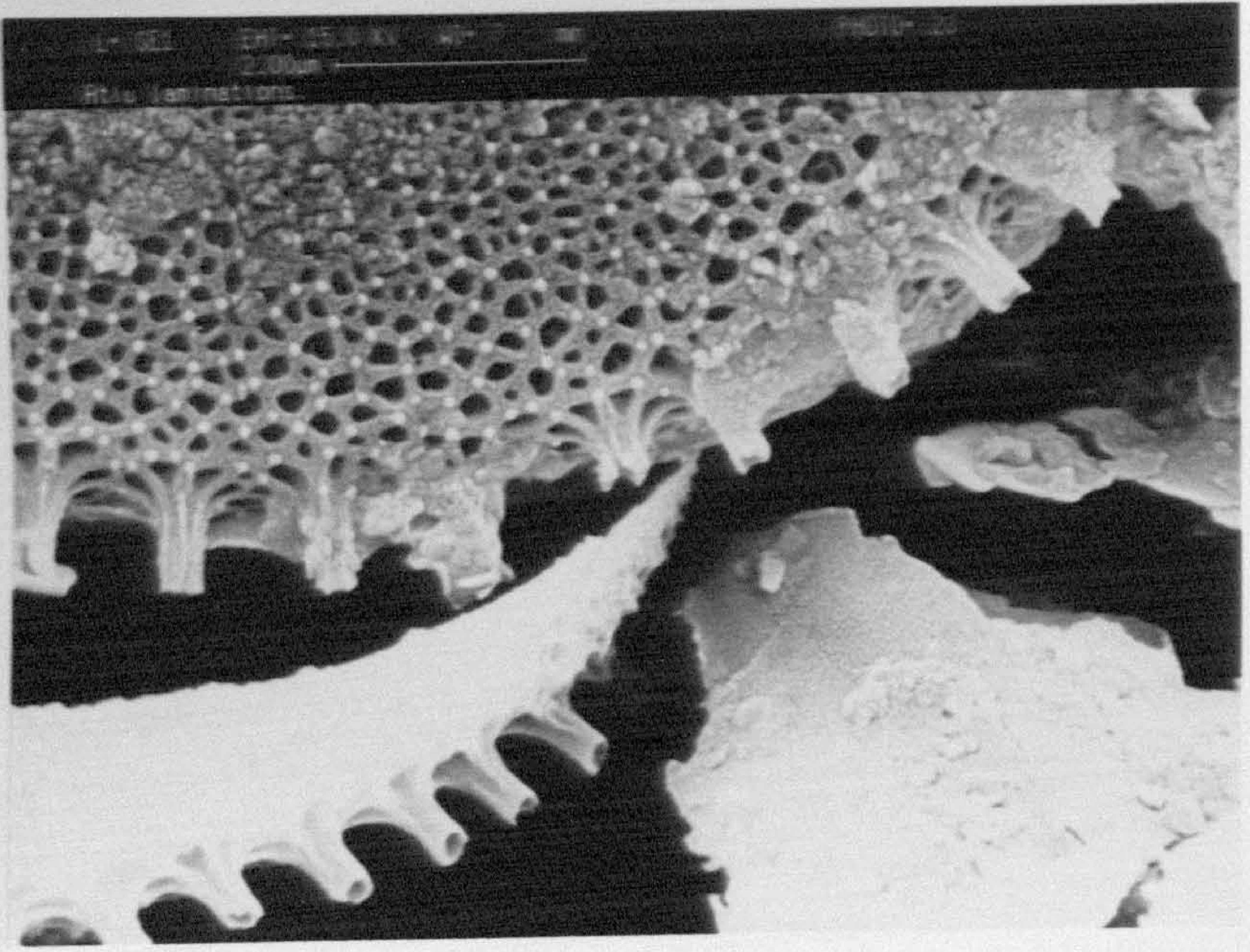

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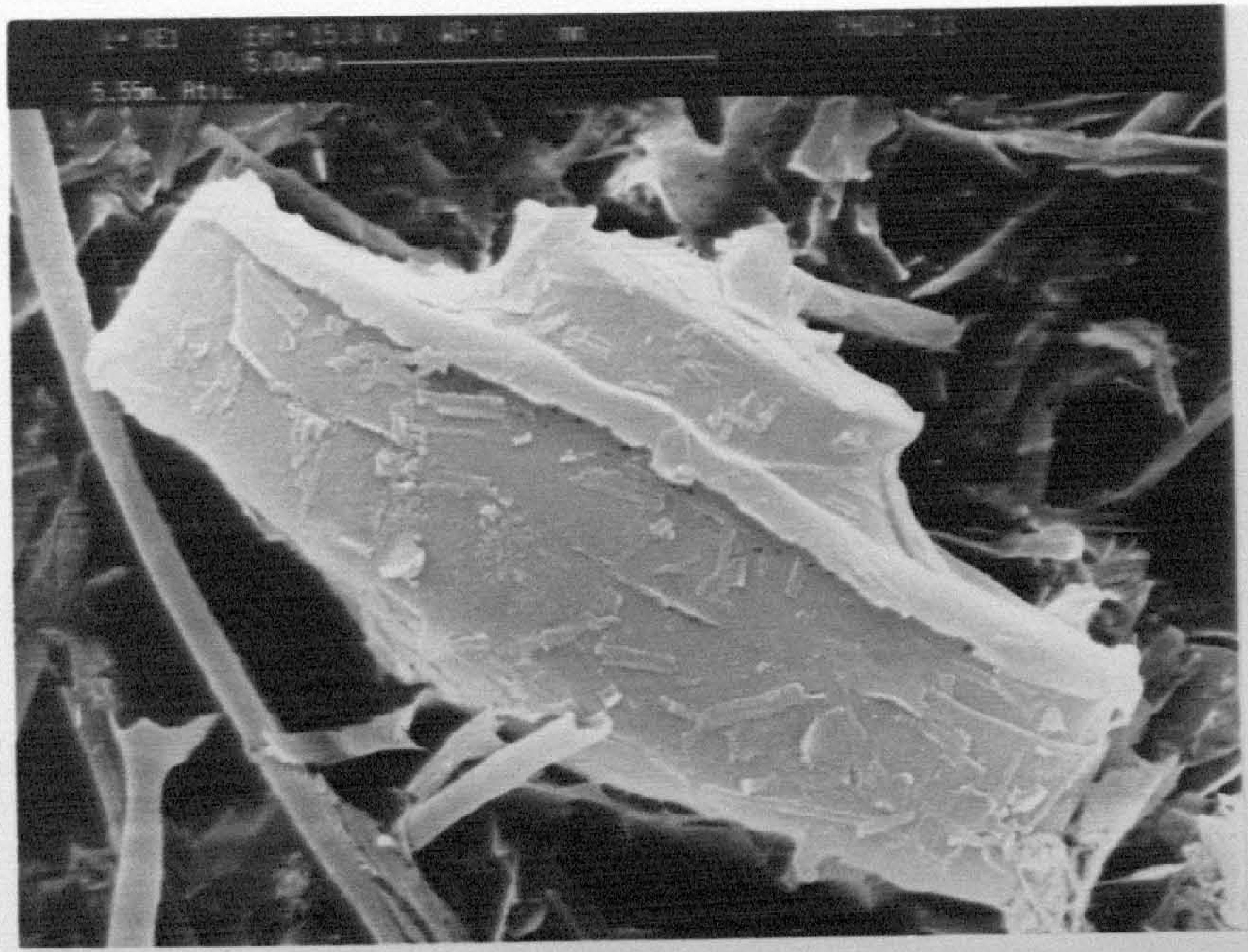
PLATE 13



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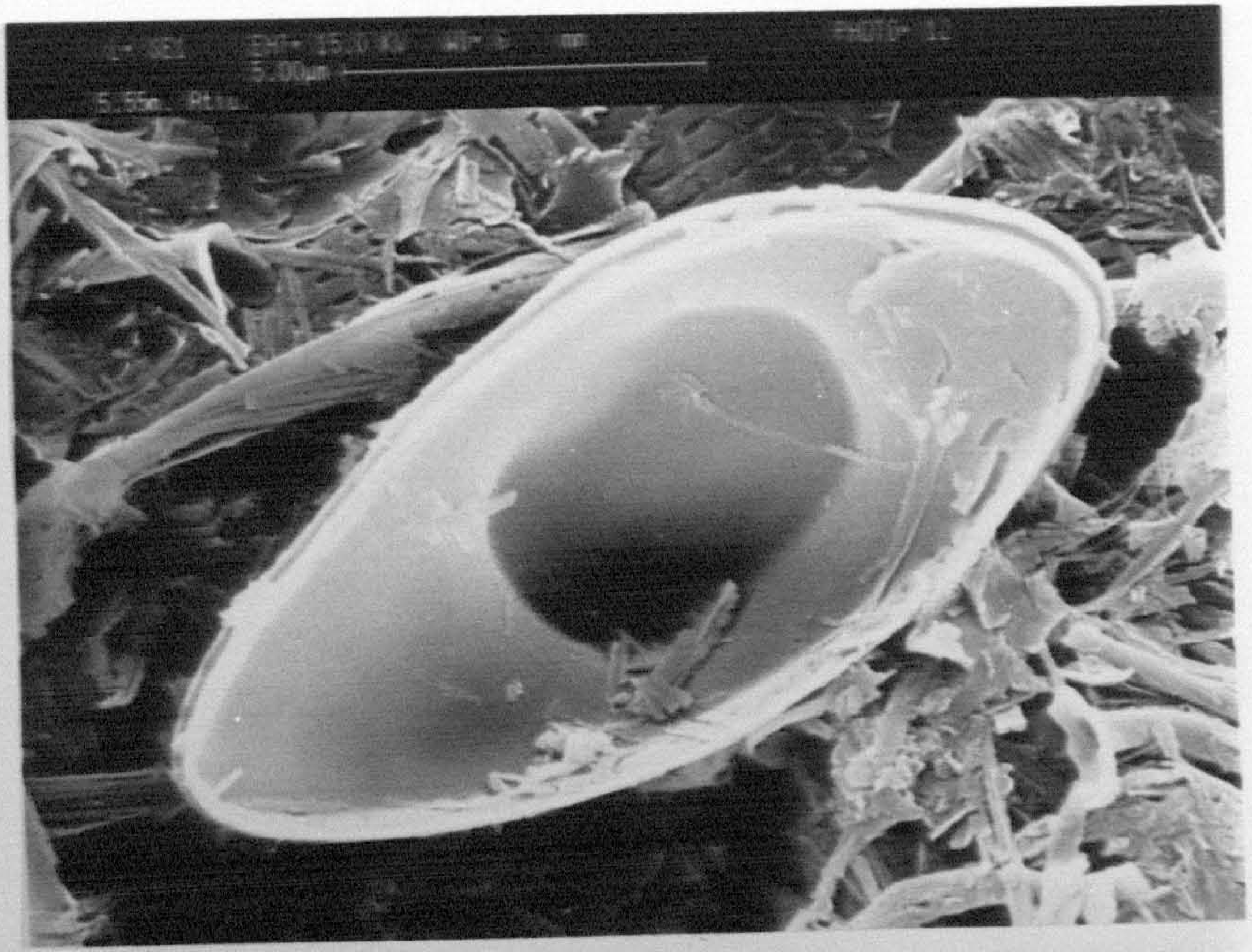

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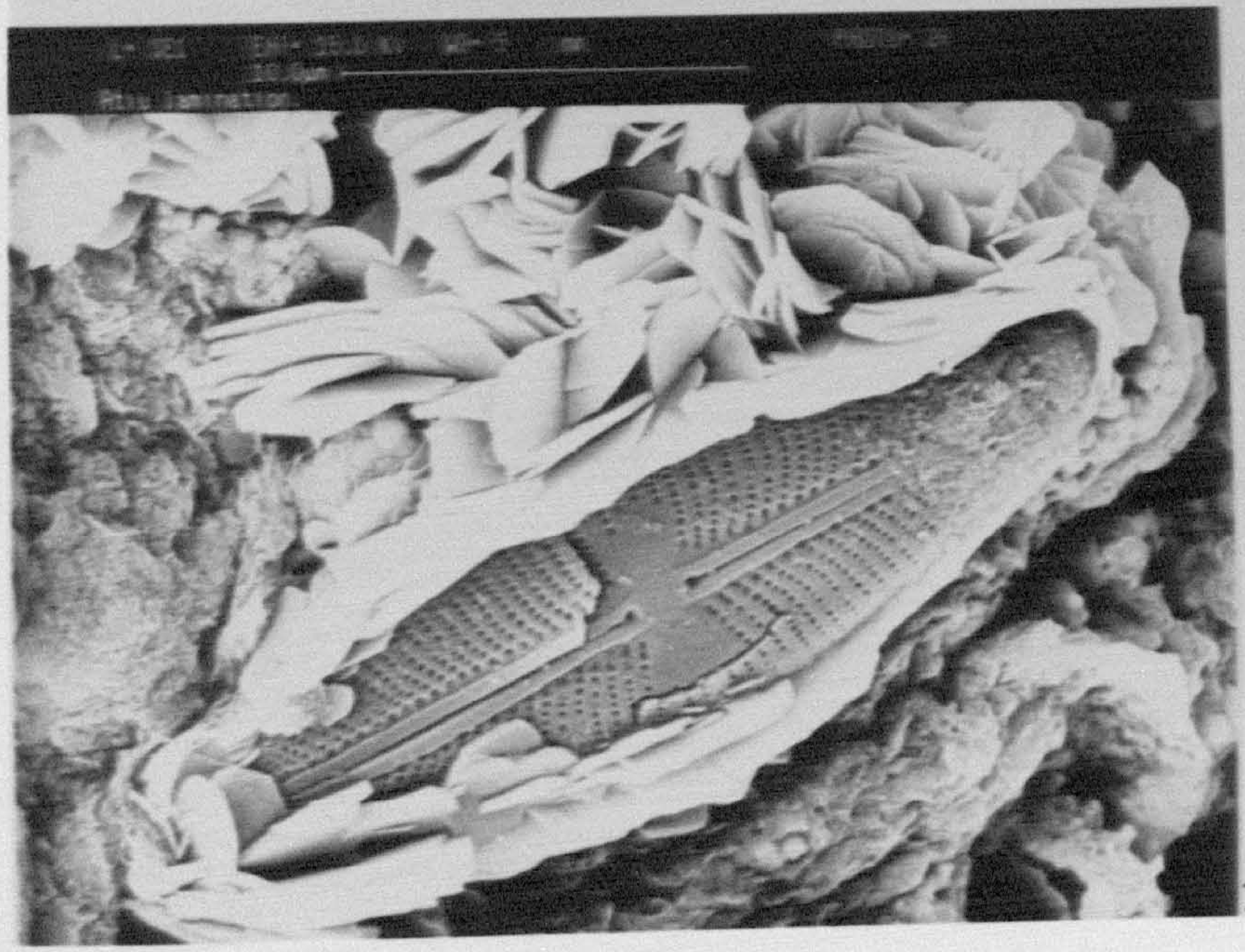

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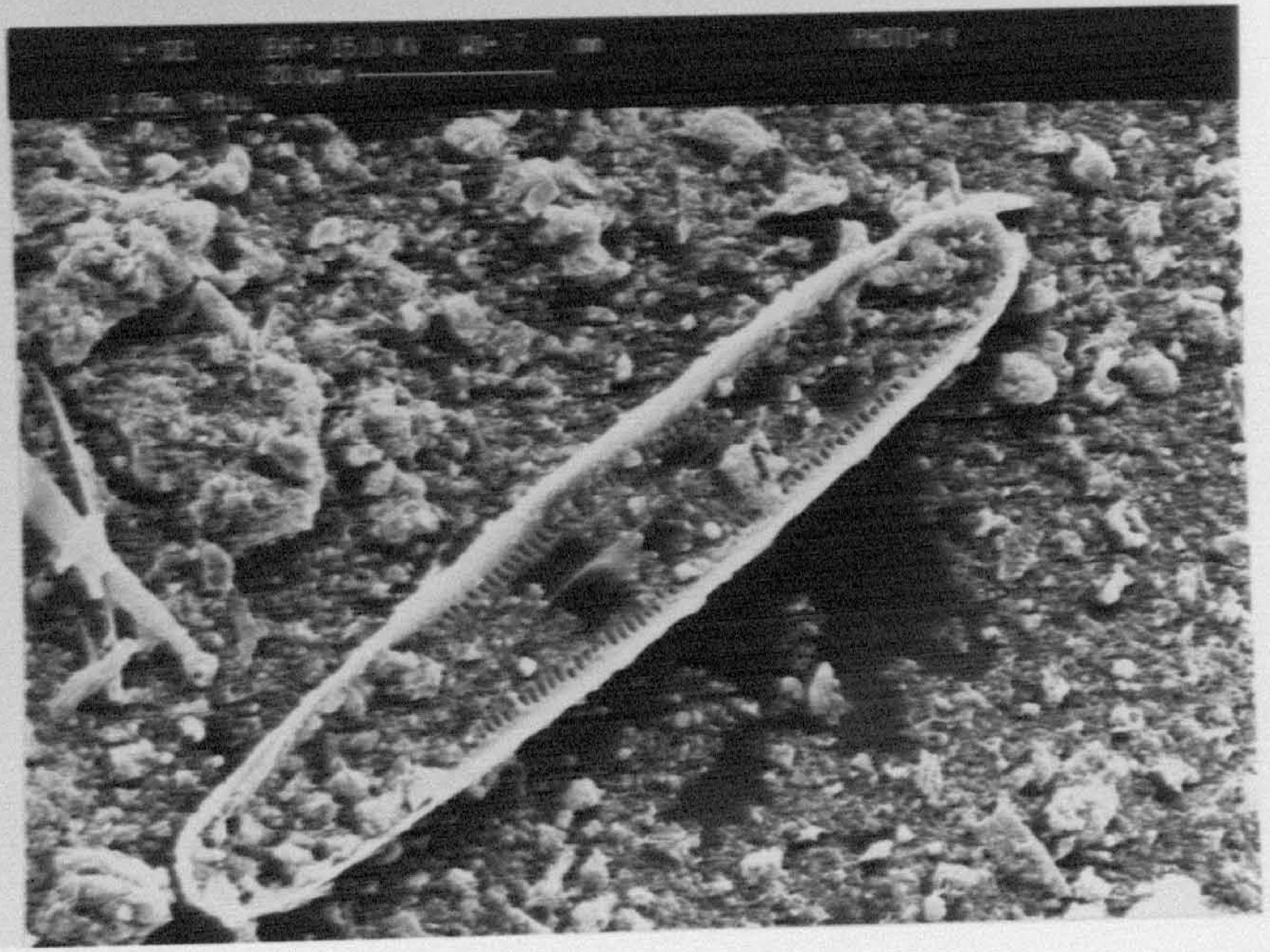

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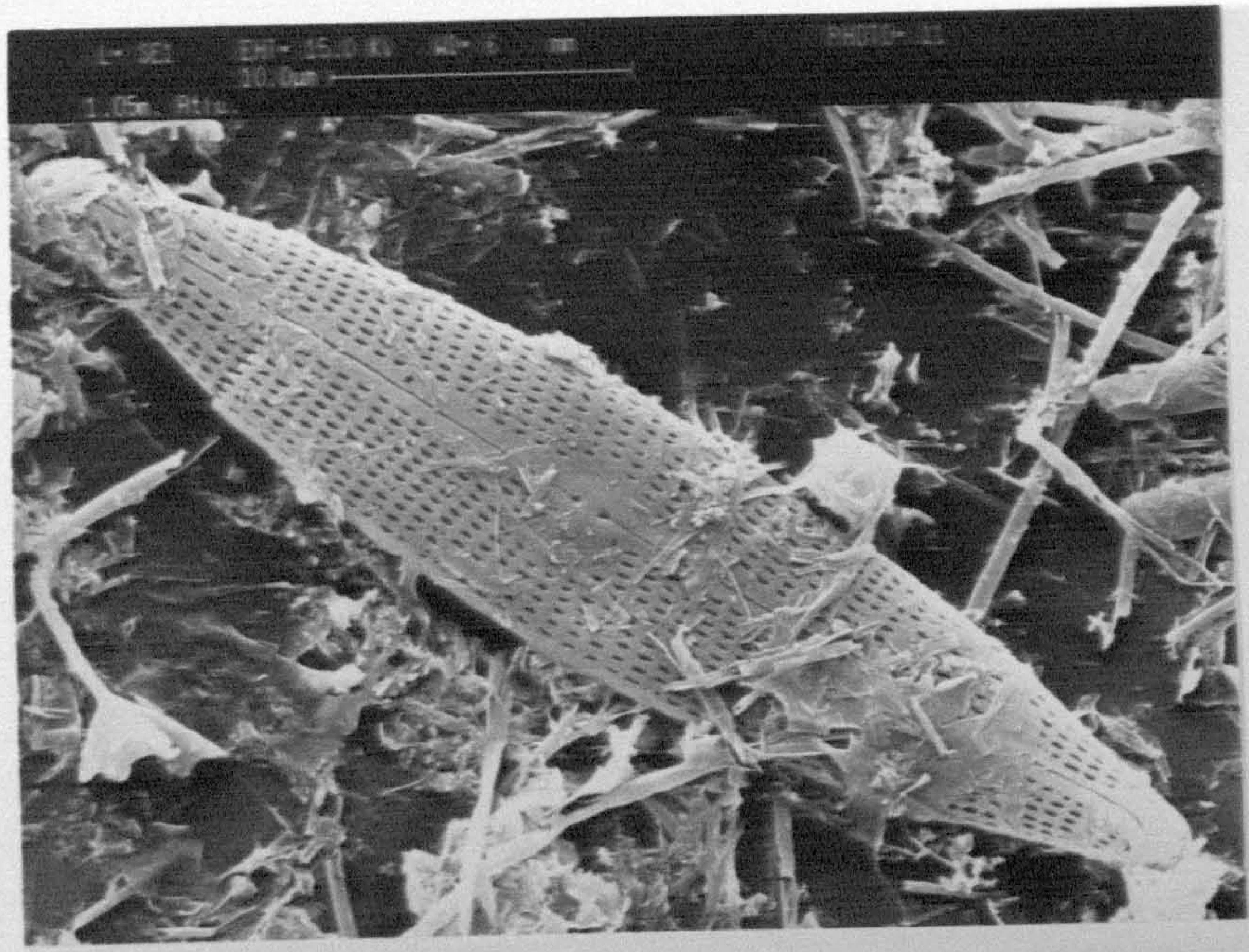
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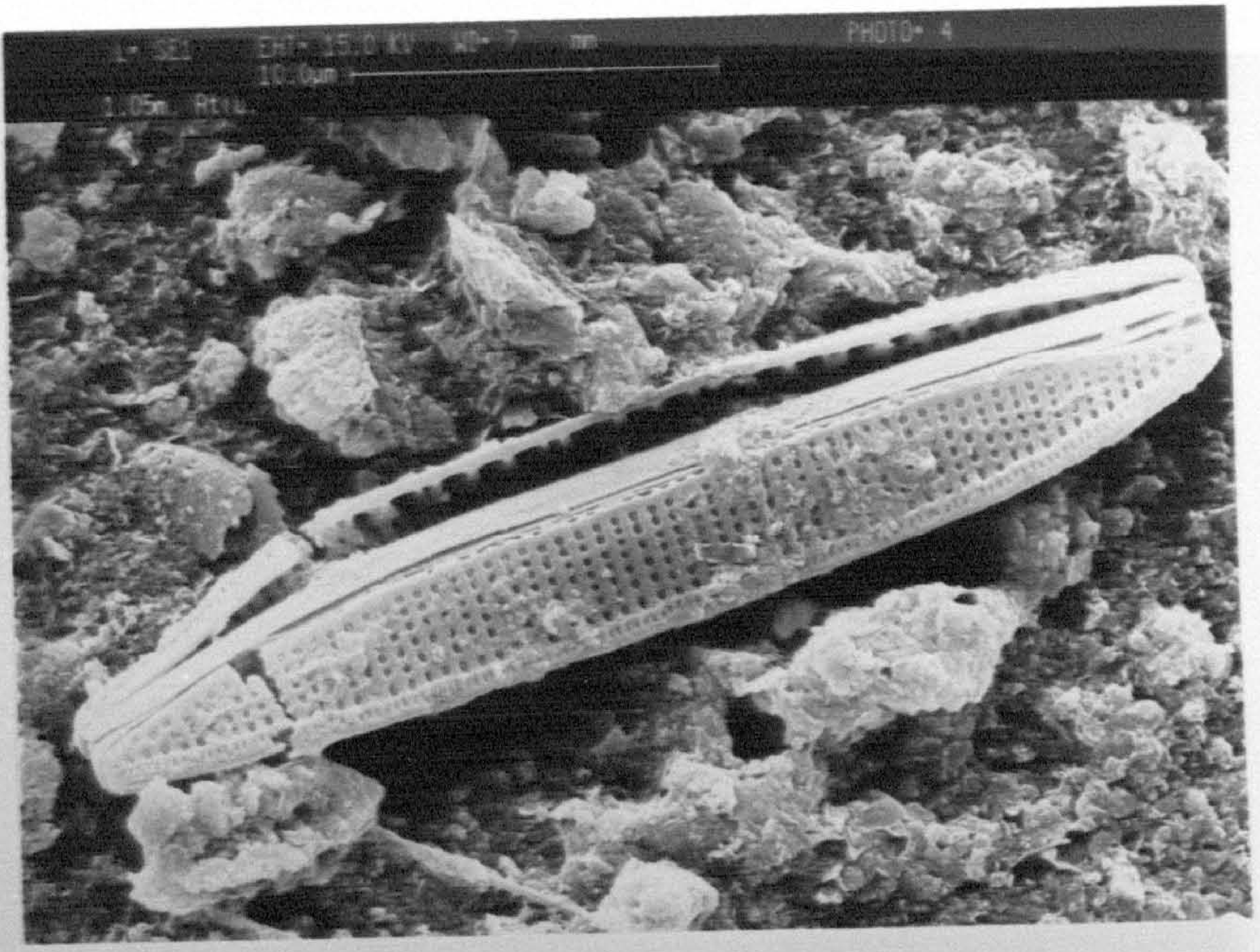

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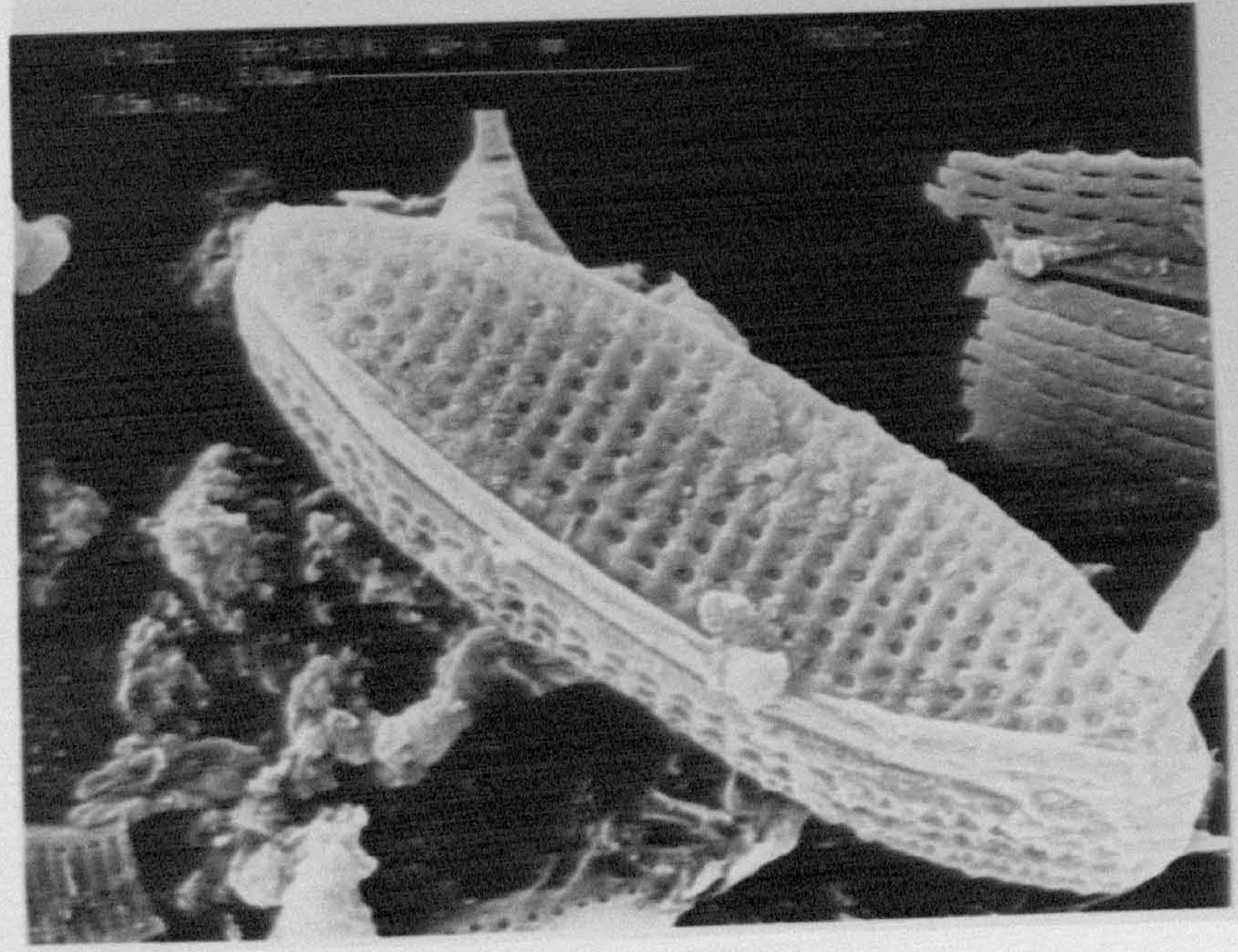
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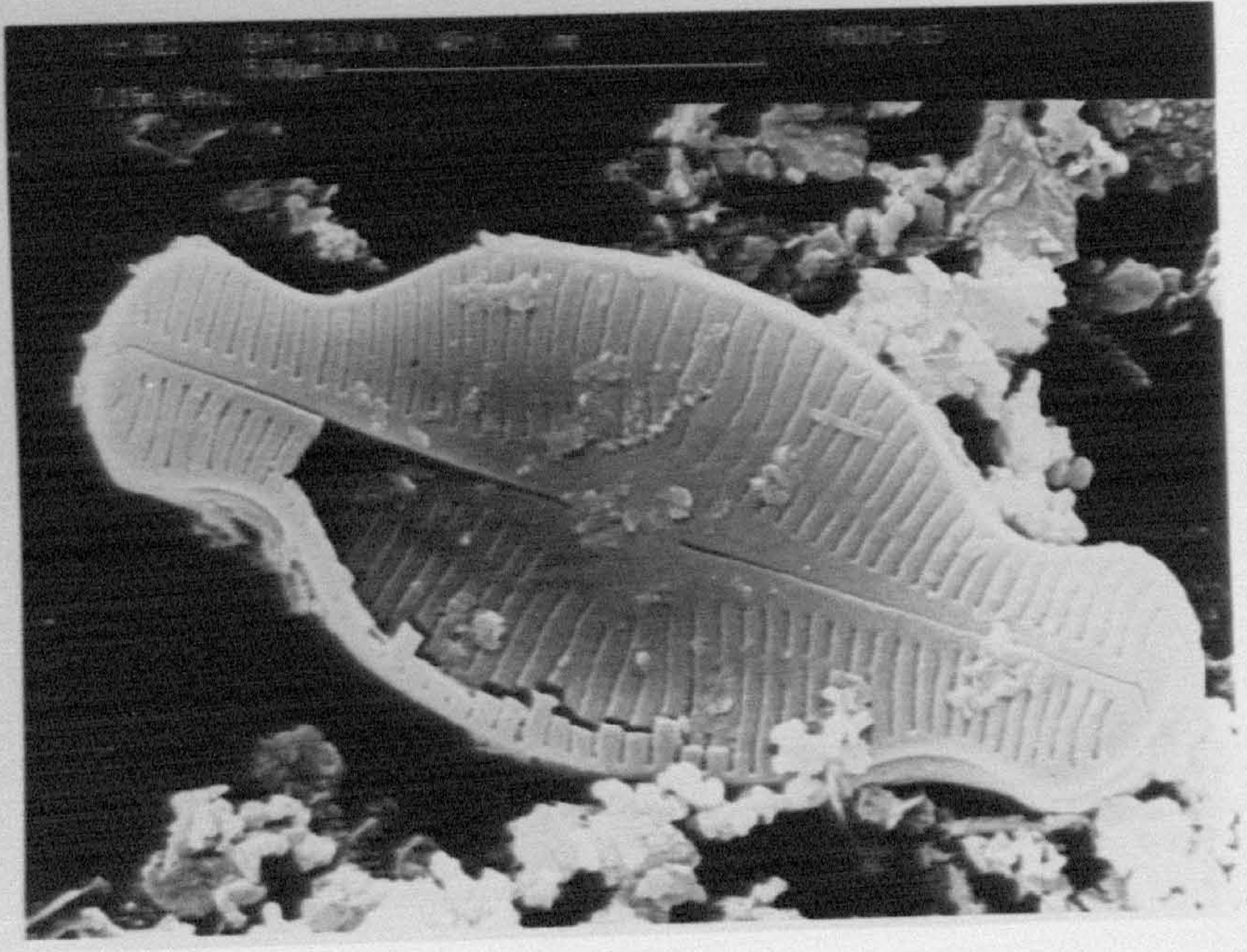
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PLATE 15.

1. Fossil grain of *Cocos nucifera* from the Lake Roto sequence at a depth of 8.40m. Coconut was found in the sequence above 14m.

The exine of *Cocos nucifera* pollen appeared to be scabrate under the light microscope, however, the higher magnification afforded by the scanning electron microscope shows that the detailed pattern of exine actually consists of fine perforations mainly fused into fossules (sometimes with a rugulate appearance). The exine pattern becomes notably less distinct towards the ventral edge of the grain as well as on either side of the colpi and often appears more areolate than fossulate. Perforations are less prominent in these areas. Raised white spots (shown in detail in the right of the split photograph) are apparent on the surface of mature grains and are irregularly spaced. They occur both on the tops of the ridges and within the depresions, but there is a notable decrease in the density of these spots towards the ventral region and around the colpus. Grains are infrequently found in trichotomosulcate forms.

2. *Cocos nucifera* reference pollen from the island of Mangaia, Southern Cook Islands. Immature grain. White spots are notably absent.

Distinguising features of other several monocolpate genera which were compared with the fossil *Cocos nucifera* grains (light microscope and SEM).

Jubaea chilensis : Grains are plano-convex in equatorial view, flat-oval in polar view. Measure 70-90μm in length, 45-55μm in width and 35-40μm in height. Exine faintly reticulate with reticulum becoming more distinct with distance from the colpus. Colpus same length as grain, edges diffuse and occasionally folded.

Pritchardia spp. (including *P. vuylstekeana*, *P. pacifica*, *P. gaudichaudii*): Grains elliptic (obtuse-accuminate) in equatorial view, oval in polar view. 32-37μm in length and 20-25μm wide. Exine regular in thickness with a coarse scabrate sculpture which grades to a finer scabrate towards the colpus. This is particularly noticeable in *P. vuylstekeana*. Exine layers are not visible, but columellae are fairly distinct. Colpus distinct and tapering towards apices. Colpi of *P. pacifica* less distinct.

Oncosperma: spp. (including *O. horridum*, *O. fasciculatum* and *O. tigillarium*): Plano-convex in equatorial view, oval in polar view. Length 20-25μm. Exine baculate with baculi evenly distributed over surface. Colpus same length as grain, narrow or wide with clearly defined edges.

Caryota spp. (including *C. cumingii*, *C. majestica*, *C. urens*, *C. mitis* and *C. rumphiana*): Plano-convex in equatorial view, oval in polar view. Length 15-20μm. Exine faintly reticulate, brochi measure 1μm across. Exine thickened towards proximal pole, two layers visible under light microscope. Colpus same length as grain with diffuse edges.

Pinanga spp. (including *P. limosa*, *P. rigida*, *P. barnesii*, *P. gracilis* and *P. densiflora*): Plano-convex in equatorial view, oval in polar view. Length measuring ~20μm. Exine of regular thickness, coarse reticulate sculpture with brochi measuring >1μm across. Colpus edges diffuse. *P. wrayii*: has fine reticulate exine, colpus edge distinct and measures 48-54μm in length. *P. rigida* is smaller and measures 38-45μm in length.

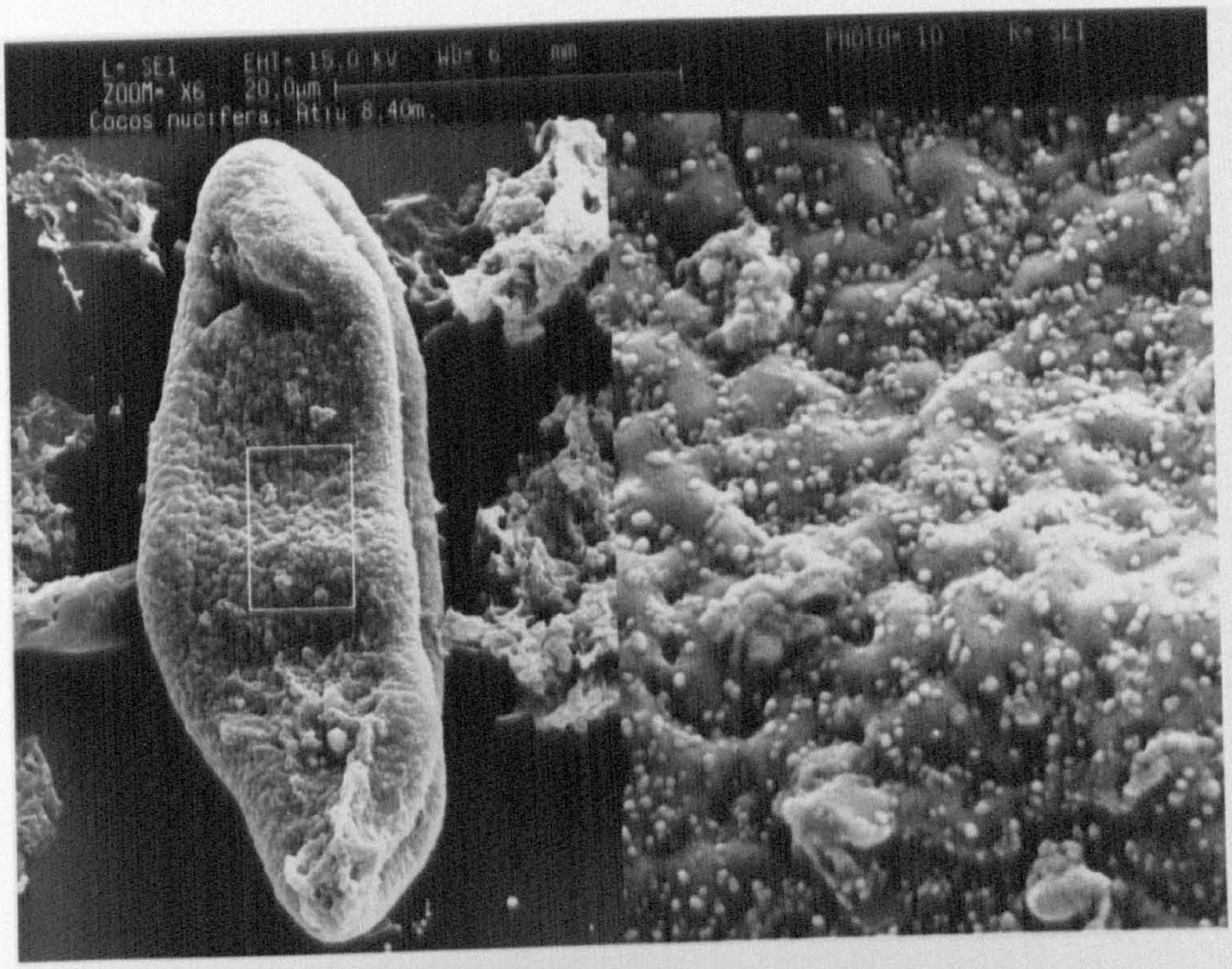
Livistonia spp. (including *L. kingiana*): Plano-convex in equatorial view and in polar view. Length 16-20μm. Exine thin, fine to coarse reticulate, brochi 1μm across. Colpus edges distinct.

Korthalsia spp. Plano-convex in equatorial view, circular in polar view. Length 20-25μm. Exine baculate, baculi scattered irregularly over exine surface. Colpus edges distinct, copus ends pointed.

Arenga spp. (including *A. caudata* and *A. pinnata*): Plano-convex in equatorial view, oval in polar view. Length 18-26μm. Exine echinate, becoming smaller and more closely packed towards colpus. Exine swollen slightly at the base of the spines. Colpus narrow, edges folded inwards.

Xyris spp. (including *X. capensis*): Plano-convex in equatorial view, oval-elongate in polar view. Exine finely reticulate, brochi 1μm across. Colpus extending around one side and both ends of grain.

PLATE 15


L= SE1 EHT= 15.0 KV WD= 6 mm
ZOOM= X6 20.0µm
Cocos nucifera. Atiu 8.40m.
PHOTO= 10 R= SE1

1


L= SE1 EHT= 15.0 KV WD= 7 mm
20.0µm
Cocos nucifera. Mangaia
PHOTO= 19

2

PLATE 16.

Macro-organisms from the Lake Temae sequence.

(Identified by J. Taylor of the British Museum of Natural History)

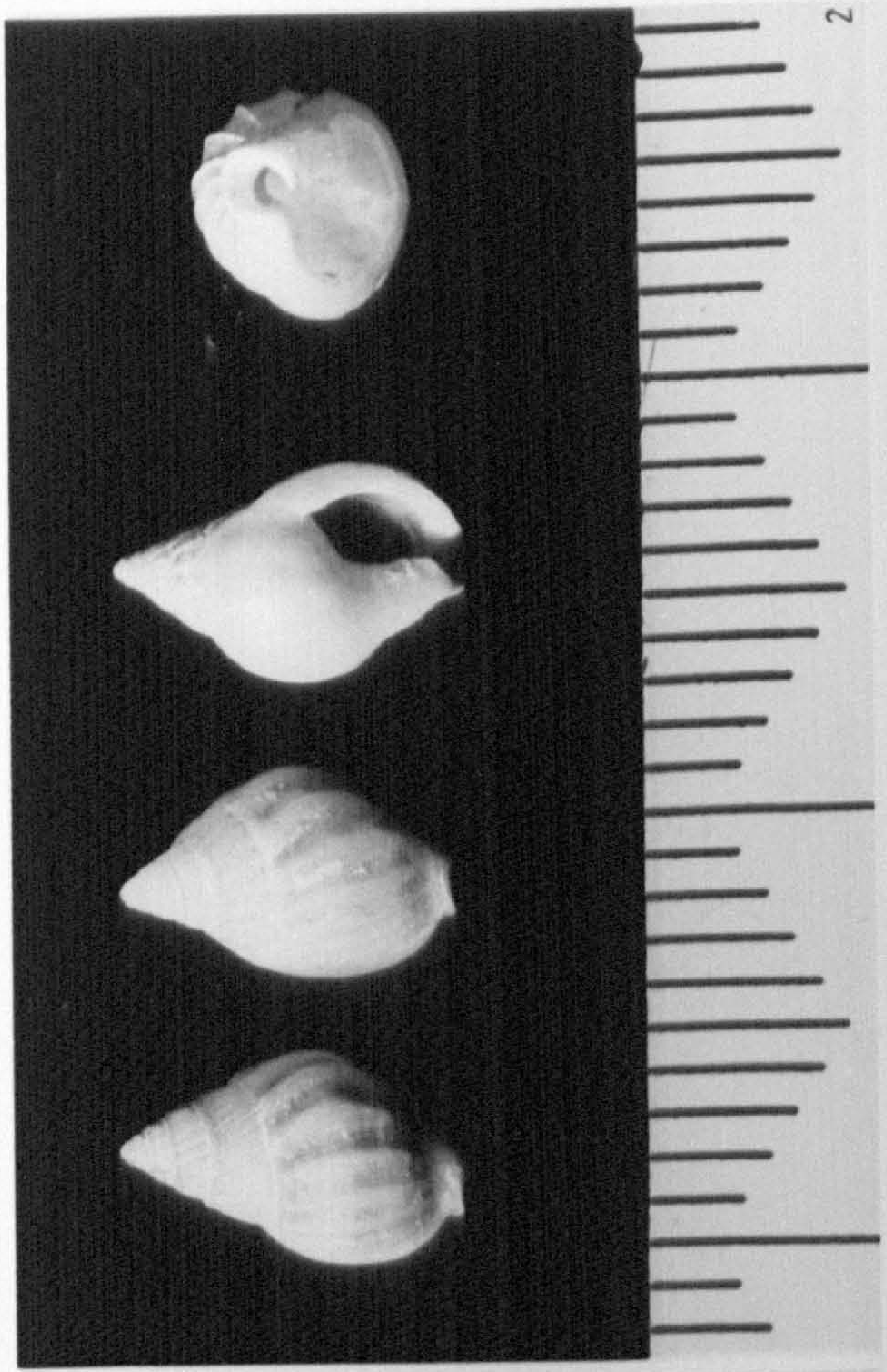
1. *Melania incisa* Reeve, a freshwater snail found in the Lake Temae sequence above 1.80m.

2. *Nassarius fraudulentus* (Marrat), marine gastropods found in the Temae sequence below 7.10m.

3. The case of *Neopomatus uschakovi* Pillai, tube worm of brackish waters, found below 7.10m.

4. Marine barnacle, found below 7.10m.

PLATE 16



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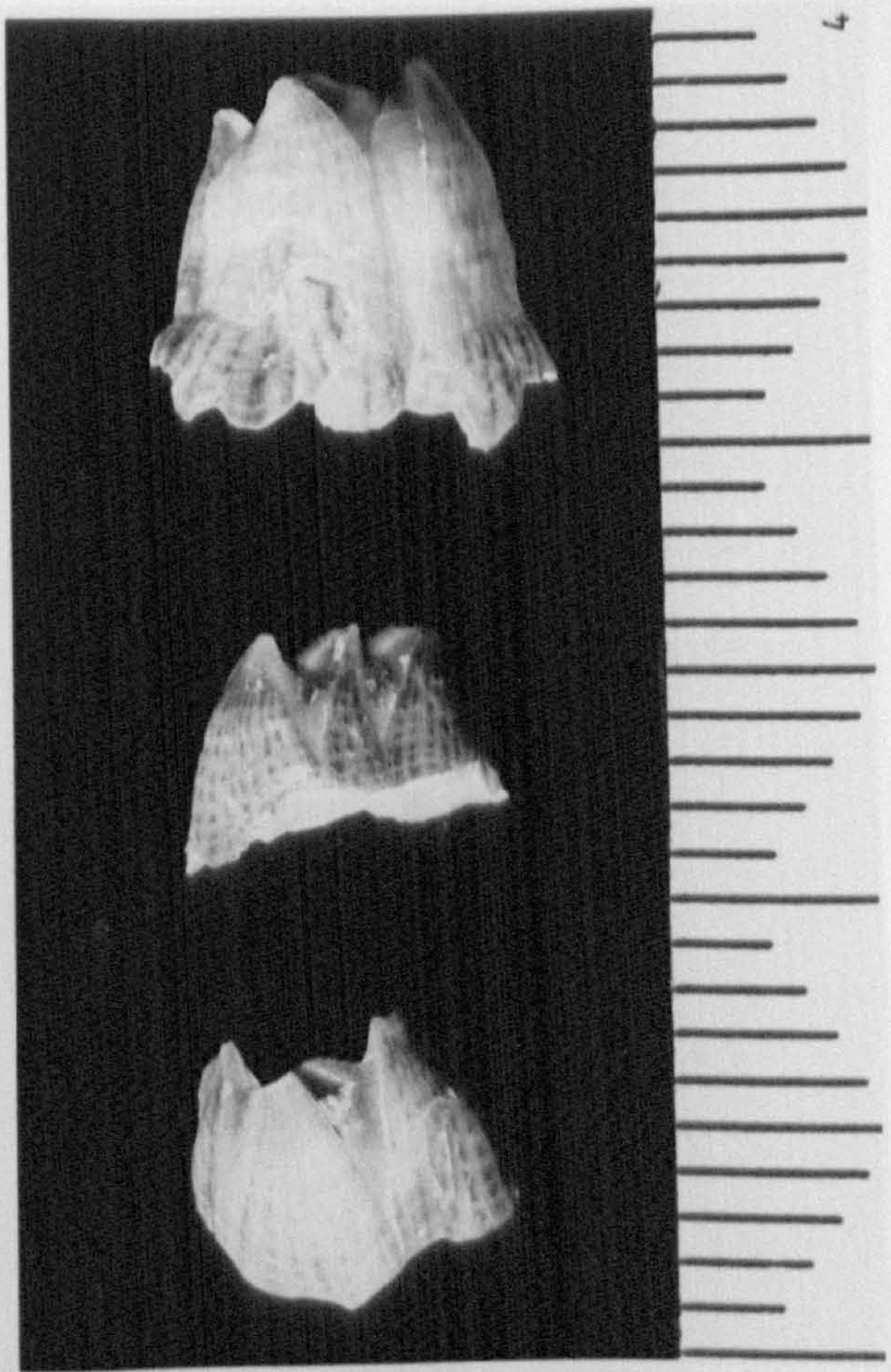
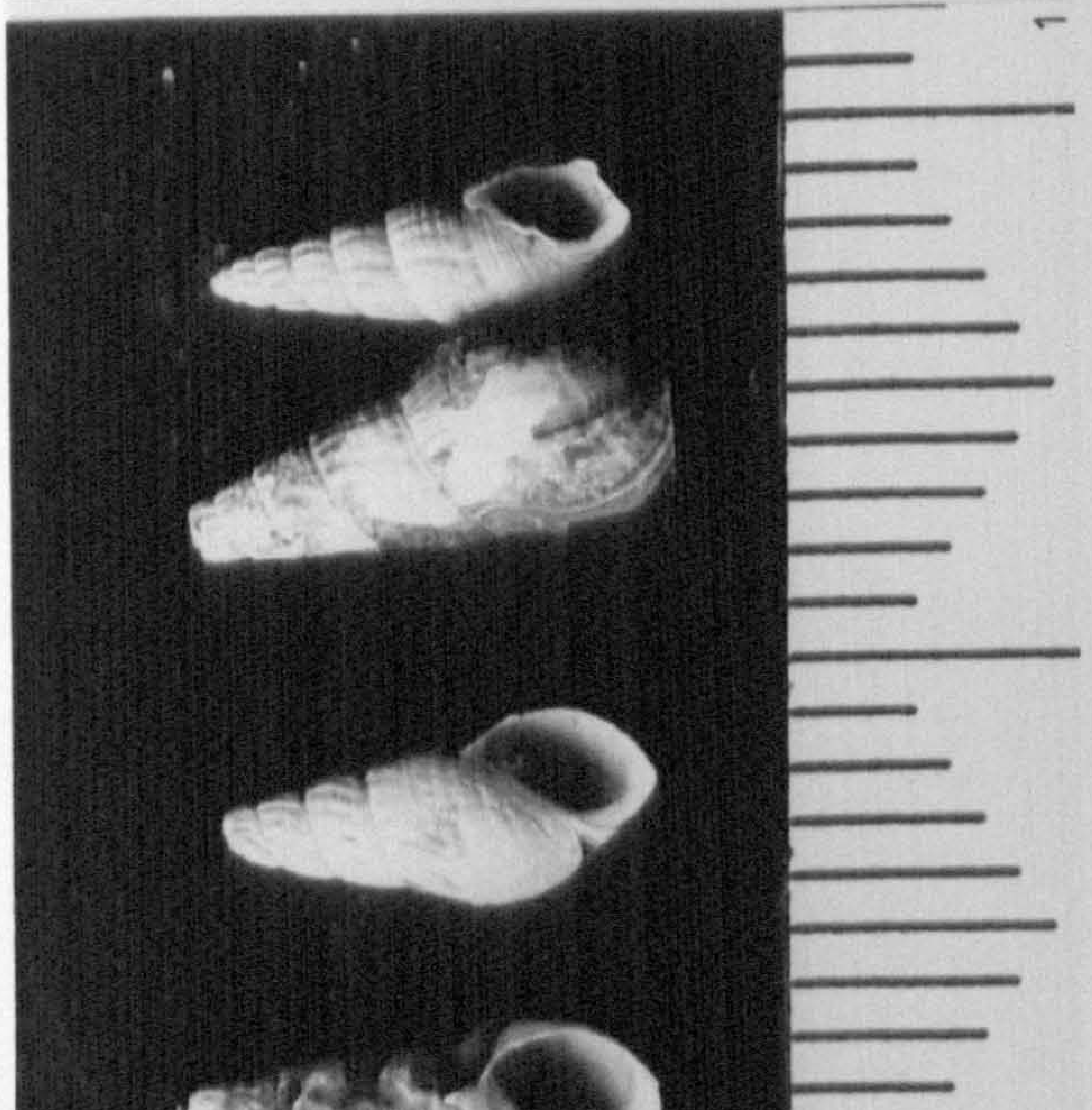
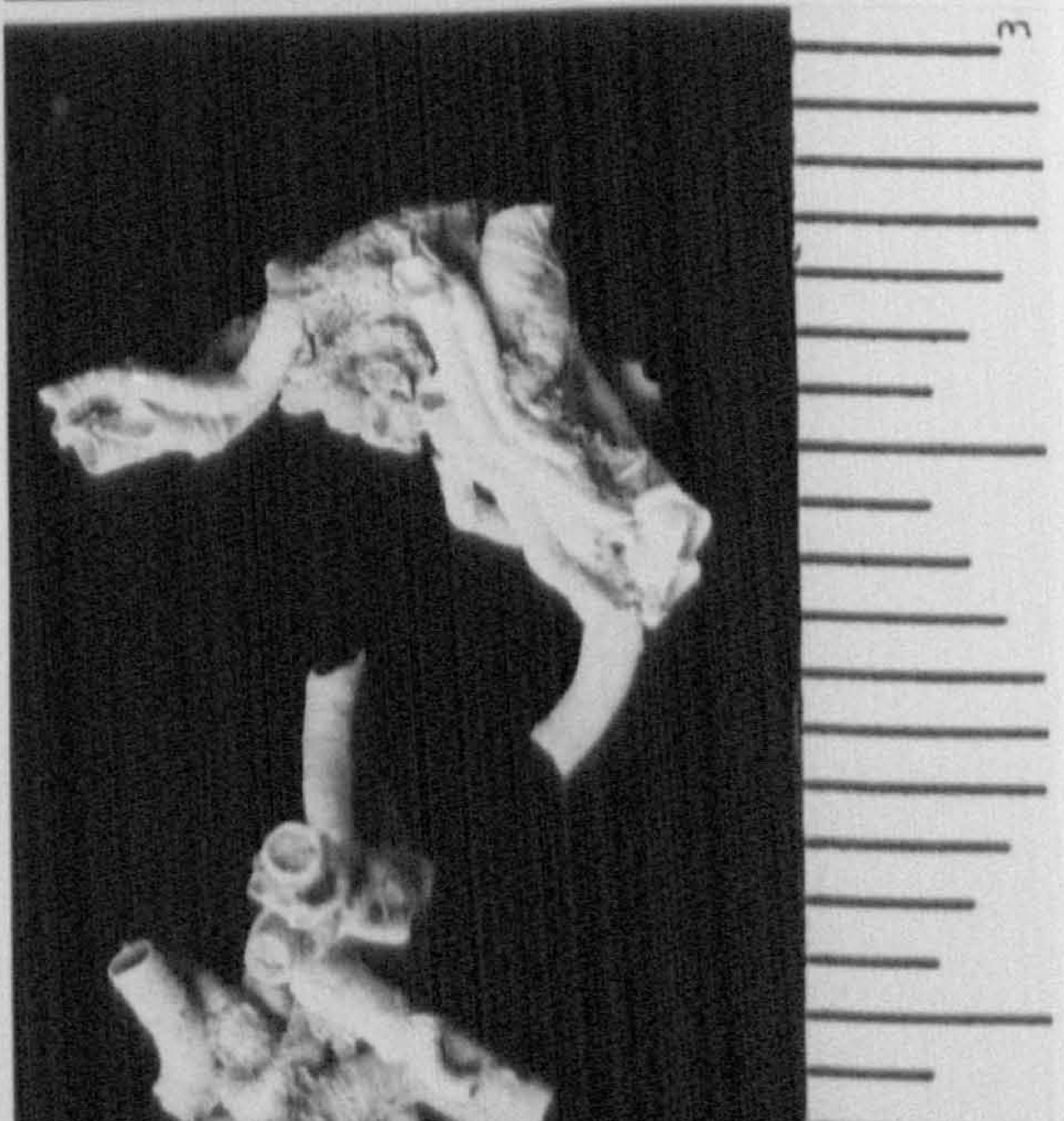


4



1



3

APPENDIX 7

STRATIGRAPHY OF THE LAKE ROTO CORE-2, ATIU

For site and borehole location see Fig.5.1.
Water depth: 6.8m from the top sediments to lake water surface.

Depth (m)	General description (Nig:Strat:Elast:Sic:Comp).
0.00-0.85	Black organic gyttja. High water content. Freshwater mollusc at 0.83m. (4:0:0:0:Ld$_2$ Sh$_2$).
0.85-1.05	Grey laminated mineral clay. (2:2:0:1:Ag$_4$).
1.05-1.30	Grey-brown clay and gyttja mix. Freshwater molluscs at 1.15m and 1.21m. (2:1:0:2:Ag$_3$ Ld$_1$).
1.30-2.00	Dark brown gyttja with black coarse fragments. Freshwater molluscs at 1.87m. (3:2:1:2:Ld$_2$ Sh$_2$).
2.00-2.18	As above but containing many clay laminations. Freshwater molluscs at 2.07m. (3:2:1:2:Ld$_2$ Sh$_2$, Ag+).
2.18-3.52	Highly laminated clay with some gyttja. Major clay horizons at 2.18-20m, 2.36-38m, and 2.45-52m. Molluscs at 3.11m, 3.13m, and 3.30m. Basalt pebble rich in quartz at 3.47m. (2:3:1:2:Ag$_2$ Ld$_1$ Sh$_1$).
3.52-4.00	Brown gyttja with some fine clay laminations. Some coarse black material at 4.00m. (3:2:1:2:Ld$_2$ Sh$_2$).
4.00-9.00	Brown gyttja with clay fraction. Highly laminated. Distinct clay laminations at 4.60-70, 7.40-60, 8.50-60m. Wood fragments at 4.10 and 6.20m. Limestone pebble at 4.95m. (3:4:1:2:Ld$_2$ Sh$_2$, Ag+).
9.00-10.23	Brown gyttja and peat. Distinct clay bands at 9.50m and 9.55m. (3:3:1:2:Ld$_2$ Sh$_1$Th$_1$).
10.23-10.80	Brown peat with small amount of gyttja. (3:2:3:2:Th$_3$ Sh$_1$).
10.80-11.05	Grey clay with peat fraction. (3:2:2:2:Ag$_3$ Th$_1$).
11.05-11.50	Brown peat. (3:2:3:2:Th$_3$ Sh$_1$).
11.50-11.60	Clay. (2:2:1:2:Ag$_4$).
11.60-12.00	Brown peat. (3:2:3:2:Th$_3$ Sh$_1$).
12.00-12.10	Clay with peat fraction. (2:2:1:2:Ag$_3$ Th$_1$).
12.10-12.80	Brown peat. (3:2:3:2:Th$_3$ Sh$_1$).
12.80-13.13	Clay with peat fraction. (2:2:1:2:Ag$_3$ Th$_1$).

13.13-13.42	Highly decomposed peat with clay fraction. Wood fragments at 13.40-42m. (3:2:3:2:Th_1 Sh_2 Ag_1).
13.42-13.52	Clay with humified peat. (3:2:2:2:Ag_2 Th_1 Sh_1).
13.52-14.00	Humified peat with clay laminations. (3:2:3:2:Th_2 Sh_1 Ag_1).
14.00-14.15	Dark brown organic gyttja. (3:2:2:2:Ld_2 Sh_2).
14.15-14.45	Grey clay/gyttja transition. (2:2:1:2:Ag_2 Ld_1 Sh_1).
14.45-15.00	Grey clay and silt. Iron staining throughout. (1:2:1:2:Ag_3 Ga_1).
15.00-16.00	Grey clay, silt and sand. Coarse sandy layer at 15.30m. Iron staining throughout. (1:2:1:2:Ag_2 Ga_1 Gs_1).

APPENDIX 8

STRATIGRAPHY OF THE LAKE TEMAE CORE-1, MO'OREA

For site and borehole location see Fig.6.9.
Water depth: 11.30m from the top sediments to lake water surface.
Coral-sand bands either major (c/s+) or medium (c/s). Fine bands not included.

Depth (m)	General description (Nig:Strat:Elast:Sic:Comp).
0.00-2.70	Dark brown fine-grained mineral mud with gyttja. (3:1:2:1:Ag_3 Ld_1)
2.70-2.80	Dark 'oily' material (probably decomposed algae).
2.80-2.97	Abrupt transition between brown mud above to light buff coloured neckron mud below. Distinct algal laminations. (2:3:3:2:Ld_2 Sh_2).
2.97-3.93	Light grey calcareous mud with red, yellow and black algal laminations. Major algal band from 3.37-38m. c/s 3.68m. Uppermost major coral sand deposit, c/s+ 3.70-74m. c/s 3.76m. (2:3:3:2:Lc_3 Sh_1).
3.93-4.00	Major coral-sand band containing plant material, forming transition with firmer calcareous mud below. (2:1:1:1:Lc_3 Gs_1).
4.00-6.35	Firm light buff calcareous mud with few algal laminations between 4.38-40 and 4.63-67. c/s 4.16m, c/s+ 4.50-63, c/s 5.05-12 plus detritus. c/s 5.25m, 5.29m, 5.32-34m, 5.38m, 5.47m, 5.51-53m, 5.64-65m plus detritus, 5.94m, 6.12m, 6.26m, 6.29m. (1:2:1:1:Lc_3 Gs_1).
6.35-6.40	Transition zone between calcareous mud above and dark brown mineral mud below. (1:2:0:2:Lc_2 Ag_2).
6.40-6.92	Dark brown fine-grained mineral mud. (3:1:2:1:Ag_3 Ld_1).
6.92-7.05	Sharp transition to coarse brown mineral mud plus much fine detrital material. (3:1:2:1:Ag_1 Ld_1Gs_1 Dh_1).

7.05-9.85	Sharp transition to pale grey calcareous mud containing many coral-sand bands. c/s 7.14m, 7.26m, 7.43m, c/s+ 7.51-55m, c/s 7.75m containing marine molluscs and barnacles, c/s at 7.89m, c/s+ 8.0-05m, c/s 8.09m, 8.11m, 8.12m, 8.20m, 8.36m, 8.51m, 8.54-55m (containing organic material and coral fragments), 8.72m, 8.79m, 8.80m, 8.85m, 8.93m, 8.97m, 9.22m, 9.27m, 9.29m, 9.30m, 9.32m, 9.44m, 9.49m, 9.51m, 9.59m, 9.69-70m, 9.74m. Occassional marine molluscs and barnacles throughout. (1:2:1:1:Lc_3 Gs_1).
[9.00-9.22	Lost.]
9.85-9.91	Brown mineral mud plus calcareous sand with marine molluscs, barnacles, coral fragments, tubeworm casts, leaf fragments and fern stems throughout. (2:1:2:2:Lc_2 Ag_1 Gs_1).
9.91-11.02	Pale grey calcareous mud with coral-sand bands throughout, plus barnacles, tube worms and marine molluscs. c/s+ at 9.91-93m. c/s 10.03m, 10.05m, 10.07m, 10.13m, 10.24m, 10.31m, 10.37m, 10.40m, 10.61m, 10.72m, 10.74-76m. (1:2:1:1:Lc_3 Gs_1).
11.02-11.18	Major coral-sand band plus leaf fragments (Gs_3 Lc_1).
11.18-11.25	Transition to dark brown mineral and calcareous mud below. (2:2:1:1:Ag_2 Lc_1 Gs_1).
11.25-11.60	Dark brown mineral and calcareous mud with coral-sand and detrital material (3:1:2:1:Ag_2 Lc_1 Gs_1).
11.60-14.50	Abrupt transition above. Pale grey calcareous mud with barnacles and coral-sand bands (without detrital material). c/s at 11.72m, 11.86m, 12.16m, 12.19m, c/s+ 12.24-29, c/s 12.31-32m, 12.85m, 12.87m, 12.92-95 (pure white sand), 13.15m, 13.56m, 13.78m, 13.95-14.00m, 14.05-07m, 14.13m, 14.20-23m, 14.27m. (1:2:1:1:Lc_3 Gs_1).

14.5m sediment core from Lake Temae showing abrupt colour changes through the sequence.

APPENDIX 9

AUTHORITIES OF MAIN PLANT SPECIES MENTIONED IN THE TEXT

Acalypha hispida Burmann f., Euphorbiaceae.
Acalypha indica Linnaeus, Euphorbiaceae.
Achyranthes aspera Linnaeus, Amaranthaceae.
Acrostichum aureum Linnaeus, Pteridaceae.
Ageratum conyzoides Linnaeus, Compositae.
Allophylus timorensis Bl., Sapindaceae.
Allophylus vitiensis Radlkofer, Sapindaceae.
Alphitonia zizyphoides (Spreng.) A. Gray, Rhamnaceae.
Alsophila decurrens Hooker, Cyatheaceae.
Alstonia costata Brown, Apocynaceae.
Alyxia stellata (Forster) Roemer & Schultes, Apocynaceae.
Angiopteris evecta (Forster f.) Hoffman, Angiopteridaceae.
Angiopteris longifolia Greville & Hooker, Angiopteridaceae.
Antrophyum plantagineum (Cavanilles) Kaulfuss, Vittariaceae.
Artocarpus incisa Linnaeus, Moraceae.
Ascarina polystachya Forster, Chloranthaceae.
Ascarina diffusa, A.C. Smith, Chloranthaceae.
Ascarina lanceolata Hooker f., Chloranthaceae.
Asplenium nidus Linnaeus, Aspleniaceae.
Astelia naudeaudi Drake, Liliaceae.
Astronia fraterna Gr., Melastomataceae.
Barringtonia asiatica (Linnaeus) Kurz, Barringtoniaceae.
Bidens paniculata Hooker & Arnott, Compositae.
Bidens pilosa Linnaeus, Compositae.
Bidens societatis Moore, Compositae.
Bischofia javanica Blume, Bischofiaceae.
Caesalpinia bonduc (Linnaeus) Roxburgh, Caesalpiniaceae.
Caesalpinia crista Linnaeus, Caesalpiniaceae.
Caesalpinia jayabo Maza, Caesalpiniaceae.
Calophyllum inophyllum Linnaeus, Guttiferae.
Cananga oderata (Lamarck) Hooker f. & Thoms., Annonaceae.
Canthium barbatum (Forster) Seemann, Rubiaceae.
Canthium merrillii (Setchell) Christensen, Rubiaceae.
Casuarina equisetifolia Linnaeus, Casuarinaceae.
Celtis pacifica Pl., Ulmaceae.

Celtis paniculata Pl., Ulmaceae.
Christella dentata (Forsk), Thelypteridaceae.
Cladium jamaicense Crantz, Cyperaceae.
Cocos nucifera Linnaeus, Palmae.
Colocasia esculenta (Linnaeus) Schott, Araceae.
Commelina diffusa Burmann f., Commelinaceae.
Commelina nudiflora Linnaeus, Commelinaceae.
Coprosma laevigata Cheeseman, Rubiaceae.
Coprosma tahitensis Gr., Rubiaceae.
Cordyline fruticosa (Linnaeus) Chev., Agavaceae.
Cordyline terminalis (Linnaeus) Kunth, Agavaceae.
Cyathea affinis (Forster) Swartz, Cyatheaceae.
Cyathea decurrens (Hooker) Copeland, Cyatheaceae.
Cyathea horrida (Presl.) C. Chr., Cyatheaceae.
Cyathea parksiae Copeland, Cyatheaceae.
Cyathula prostrata (Linnaeus) Bl., Amaranthaceae.
Cyclosorus dentatus (Forsk.) Ching., Thelypteridaceae.
Cyperus brevifolius (Rottboell) Hassk., Cyperaceae.
Cyperus pennatus Lamarck, Cyperaceae.
Cyperus javanicus Houtt., Cyperaceae.
Davallia elata (Forster) Spreng., Davalliaceae.
Davallia solida (Forster f.) Spreng., Davalliaceae.
Dicranopteris linearis (Burmann), Gleicheniaceae.
Dodonaea viscosa (Linnaeus), Sapindaceae.
Dryopteris nymphalis (Forster. f.) Copeland, Thelypteridaceae.
Dysoxylum samoense A. Gray, Meliaceae.
Dysoxylum maota Reinecke, Meliaceae.
Dysoxylum huntii Merrill, Meliaceae.
Elaeocarpus tonganus Burkill, Elaeocarpaceae.
Elaeocarpus rarotongensis Hemsley, Elaeocarpaceae.
Elephantopus mollis Humboldt, Bonpland & Kunth, Compositae.
Eugenia rariflora Bentham, Myrtaceae.
Euphorbia hirta Linnaeus, Euphorbiaceae.
Euphorbia pilulifera Linnaeus, Euphorbiaceae.
Eupritchardia vuylstekeana (Wendland) Kunth, Palmae.
Fagraea berteriana A. Gray, Potaliaceae.
Ficus obliqua Forster f., Moraceae.
Ficus prolixa Forster f., Moraceae.
Ficus rarotongensis Summerhayes, Species nova, Moraceae.

Ficus tinctoria Forster f., Moraceae.
Fimbristylis cymosa Brown, Cyperaceae.
Fitchia nutans Hooker, Compositae.
Fitchia speciosa Cheeseman, Compositae.
Fitchia tahitensis Nadeaudi., Compositae.
Freycinetia arborea (Gaudichaud), Pandanaceae.
Freycinetia samoensis Warburg, Pandanaceae.
Fuchsia cyrtandroides Moore, Onagraceae.
Gardenia tahitensis De Candolle, Rubiaceae.
Gleichenia linearis (Burmann) Clark, Gleicheniaceae.
Glochidion ramiflorum J.R. & G. Forster, Euphorbiaceae.
Grewia crenata (Forster) Schinz & Guillaumin., Tileaceae.
Grewia mallococca Linnaeus, Tileaceae.
Guettarda speciosa Linnaeus, Rubiaceae.
Guioa rhoifolia A. Gray, Sapindaceae.
Heliotropium anomalum Hooker & Arnott, Boraginaceae.
Hibiscus tiliaceus Linnaeus, Malvaceae.
Homalanthus moerenhoutianus (Meuller), Euphorbiaceae.
Inocarpus fagifer, (Parkinson) Fosberg, Papillionaceae.
Ipomoea batatas (Linnaeus) Lamarck, Convolvulaceae.
Ixora amplifolia A. Gray, Rubiaceae.
Ixora bracteata Cheeseman, Rubiaceae.
Ixora samoensis A. Gray, Rubiaceae.
Jasminium didymum Forster f., Oleaceae.
Jussiaea suffruticosa Linnaeus, Onagraceae.
Kyllinga brevifolia Rottboell, Cyperaceae.
Lantana camara Linnaeus, Verbenaceae.
Lindsaya decomposita Willdenow, Polypodiaceae.
Loranthus forsteri Schul., Loranthaceae.
Loranthus insularum A.Gray, Loranthaceae.
Ludwigia octovalvis (Jacquinot) Raven, Onagraceae.
Lycopodium cernuum Linnaeus, Lycopodiaceae.
Lycopodium phlegmaria Linnaeus, Lycopodiaceae.
Macaranga harveyana (Mueller-Argau) Mueller-Argau, Euphorbiaceae.
Macaranga tahitensis Mueller, Euphorbiaceae.
Macropiper latifolium (Linnaeus) Miq., Piperaceae.
Malvastrum coromandelianum (Linnaeus) Garcke, Malvaceae.
Malvastrum tricuspidatum A. Gray, Malvaceae.
Marattia salicina Smith, Marattiaceae.

Mariscus javanicus (Houtt.) Merrill & Metcalfe, Cyperaceae.
Mariscus pennatus (Lamarck) Merrill, Cyperaceae.
Melastoma denticulata Labillardiere, Melastomataceae.
Meryta macrophylla (Rich) Seemann, Araliaceae.
Meryta pauciflora Hemsley, Araliaceae.
Meryta salicifolia Species nova, Araliaceae.
Messerschmidia argentea (Linnaeus f.) Johnston, Boraginaceae.
Metrosideros collina (Forster) A. Gray, Myrtaceae.
Miconia calvescens De Candolle, Melastomataceae.
Mikania micrantha Humboldt, Bonpland & Kunth, Compositae.
Mikania scandens Linnaeus, Compositae.
Mimosa pudica Linnaeus, Papilionaceae.
Morinda citrifolia Linnaeus, Rubiaceae.
Musa paradisiaca Linnaeus, Musaceae.
Mussaenda frondosa Linnaeus, Rubiaceae.
Myrsine cheesemanii (Mez) Fosberg & Sachet, Myrsinaceae.
Neonauclea forsteri (Seemann) Merrill, Rubiaceae.
Nephrolepis biserrata (Swartz) Schott, Oleandraceae.
Nephrolepis exaltata Schott, Oleandraceae.
Nephrolepis hirsutula (Forster f.) Presl., Oleandraceae.
Ophioglossum pendulum Linnaeus, Ophioglossaceae.
Palaquium stehlinii Christensen, Sapotaceae.
Pandanus odoratissimus Linnaeus, Pandanaceae.
Pandanus tectorius Parkinson, Pandanaceae.
Passiflora quadrangularis Linnaeus, Passifloraceae.
Pemphis acidula Forster, Lythraceae.
Peperomia leptostachya Hooker & Arnott, Peperomiaceae.
Peperomia tahitensis Yunker, Peperomiaceae.
Phylanthus amarus Sch. & Thon., Euphorbiaceae.
Piper latifolia Forster, Piperaceae.
Piper methystichum Forster f., Piperaceae.
Pipturus argenteus (Forster f.) Weddell, Urticaceae.
Pipturus vaihirianensis Species nova, Urticaceae.
Pisonia grandis R. Brown, Nyctaginaceae.
Pisonia umbellifera (J.R. & G. Forster) Seemann, Nyctaginaceae.
Pittosporum arborescens A. Gray, Pittosporaceae.
Pittosporum orohenensis Moore, Pittosporaceae.
Pittosporum rarotongensis Cheeseman, Pittosporaceae.
Pittosporum samoense Species nova, Pittosporaceae.

Polypodium phymatodes (Linnaeus), Polypodiaceae.
Polyscias guilfoylei (Bulliard) Bailey, Araliaceae.
Portulaca lutea Forster f., Portulacaceae.
Portulaca oleracea Linnaeus, Portulacaceae.
Premna tahitensis Schauer, Verbenaceae.
Pritchardia vuylstekeana Wendland, Palmae.
Procris pedunculata (Forster) Weddell, Urticaceae.
Psidium cattleianum Sabine, Myrtaceae.
Psidium guajava (Linnaeus), Myrtaceae.
Psilotum nudum (Linnaeus) Griseb., Psilotaceae.
Pteris commans Forster, Pteridaceae.
Pteris tripartita Swartz, Pteridaceae.
Rapanea cheesemani Hemsley, Myrsinaceae.
Rapanea myricifolia (A. Gray) Mez, Myrsinaceae.
Rapanea orohenensis Species nova, Myrsinaceae.
Rapanea rhomboidalis Species nova, Myrsinaceae.
Rapanea samoensis Lauterbach, Myrsinaceae.
Rapanea tahitensis (Gr.) Mez., Myrsinaceae.
Schizaea dicotoma (Linnaeus) Smith, Schizaeaceae.
Sida acuta Burmann f., Malvaceae.
Sida carpinifolia Linnaeus, Malvaceae.
Sida rhombifolia Linnaeus, Malvaceae.
Sida microphylla Linnaeus, Malvaceae.
Sophora tomentosa Linnaeus, Papilionaceae.
Stachytarpheta urticilifolia Sims, Verbenaceae.
Stenochlaena palustris (Burmann) Bedd., Blechnaceae.
Stephania forsteri (De Candolle) A. Gray, Menispermaceae.
Styphelia pomarae (A. Gray) Moore, Epacridaceae.
Syzygium brevifolium (A. Gray) C. Mueller, Myrtaceae.
Syzygium inophylloides (A. Gray) C.Mueller, Myrtaceae.
Syzygium samoense (Burkill) Whistler, Myrtaceae.
Tarenna sambucina (Forster f.) Durand, Rubiaceae.
Tectaria decurrens (Presl.) Copeland, Aspidaceae.
Terminalia catappa Linnaeus, Combretaceae.
Thespesia populnea (Linnaeus) Solander, Malvaceae.
Timonius polygamus (Forster f.) Seemann, Rubiaceae.
Tournefortia argentea Linnaeus, Boraginaceae.
Trema cannabina Loureiro, Ulmaceae.
Trema orientalis (Linnaeus) Bl., Ulmaceae.

Triumfetta angulata Lamarck., Tiliaceae.
Triumfetta batramia Linnaeus, Tiliaceae.
Triumfetta procumbens Forster f., Tiliaceae.
Triumfetta rhomboidea Jacquinot, Tiliaceae.
Triumfetta semitrilobata Jacquinot, Tiliaceae.
Vernonia cinerea (Linnaeus) Lessing, Compositae.
Vittaria elongata Swartz, Vittariaceae.
Weinmannia affinis A. Gray, Cunoniaceae.
Weinmannia parviflora Forster, Cunoniaceae.
Wikstroemia foetida (Linnaeus f.) A. Gray, Thymelaeaceae.
Wikstroemia raiatensis Moore, Thymelaeaceae.
Xylosma suaveolens Forster, Flacourtiaceae.