THE UNIVERSITY OF HULL

THE OLIGO-MIOCENE SEDIMENTS OF THE MALTESE ISLANDS

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by

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ABSTRACT

The Oligo-Miocene Sediments of the Maltese Islands

by

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The Maltese Islands are situated at the south-western end of the Malta-Ragusa Rise, an area characterised by high gravity anomaly values and a ridge-like bathymetrical profile. The Islands lie 50-80km. south of Sicily and 282km. away from the north African coastline.

The sedimentary sequence is entirely composed of shallow water carbonates, dominantly marine, and with biohermal developments in the upper and lower exposed formations. The intermediate formations accumulated in somewhat deeper water and are characterised by planktonic foraminifera.

Subdivision of the Upper and Lower Coralline Limestone Formations into 7 new members and 11 new beds was found necessary, in order to appreciate fully the local environments represented in these shallow water units. The Globigerina Limestone and Blue Clay Formations are now considered as fairly shallow water deposits, the analysis of the associated phosphorite conglomerate beds of the former indicating that dominant transport of clasts was from the west, in an area of primary phosphorite and glauconite development. The Greensand Formation is re-defined on the basis of sedimentology, and the upper part of previous classifications is now included in the Upper Coralline Limestone Formation.

For each of the Formations a total of 15 biofacies are proposed on the basis of faunal variation. The probable depth ranges of each are used to refine conclusions drawn from the sedimentological interpretations, in order that the palaeoenvironments may be reconstructed. The study of a newly defined brachiopod marker horizon within the Upper Coralline Limestone has resulted in the prediction of the ecology of the four species involved, primarily with the aid of bryozoan growth-form studies. A new fossil fish horizon in western Malta is also discussed.

A number of tectonic structures previously referred to as "sinks" are re-defined,and a prolonged episode of Cainozoic cavern development,associated with subaerial and submarine subsidence is postulated on the basis of structural and sedimentological interpretations.

ACKNOWLEDGEMENTS

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CHAPTER 1

INTRODUCTION

(i) General

The Maltese Islands lie on the southern extremity of a submarine rise which extends southwestwards from the Ragusa region of Sicily and forms part of the divide between the eastern and western Mediterranean basins. The rise is nowhere covered by more than 260 metres of water with an average of less than 50 metres being present. The islands lie 50-80 kilometres south of Sicily, 215 Km. southeast of the volcanic island of Pantellaria and 163 km. east of the island of Lampedusa. The African coast lies 282 km. away in Tunisia and 322 km. away in Libya, (Fig.1b).

Three main islands make up the Maltese group. Gozo, the most northerly one, is approximately 14.5 km. long in an east to west direction and 6.5 km. in width. Malta, the largest island, is 27.5 km. in a north-east to south-west direction and 13 km. wide at its widest point. The island of Comino lies between the two and consists of an almost bare rock some 2.5 km. east to west and 1.6 km. north to south. Three smaller uninhabited islands surround the main ones; Cominotto, lying immediately to the west of Comino, St.Paul's Island lying immediately to the east of the Mellieha Ridge in northern Malta, and the island of Filfla which lies some 4.8 km. to the west of Torri Zurrieq, on the southern coast of Malta. The highest points on Gozo and Malta are respectively 743 ft. (226.5m.) and 758 ft. (231m.)

The island group is entirely composed of Oligocene and Miocene shallow water carbonates (Fig.2). Shallow water limestone formations both cap and underlie the exposed stratigraphic sequence. Softer limestones and marls with a dominant planktonic element make up the middle formations of the sequence. The only islands to exhibit the full stratigraphical sequence are Malta and Gozo. The smaller islands, including Comino, are entirely made up of the Upper Coralline Limestone capping sequence. Terrestrial gravels, marls and clays, now invariably calcreted, complete the geology and occur as isolated pockets or thin spreads on all formations. A lacustrine tufa deposit containing leaves is preserved around Ghemieri bridge in the Fiddien valley, 2km. west of Rabat, Malta.

All the Oligo-Miocene formations are richly fossiliferous both in macro and microfaunas. Floras are generally restricted to coralline algae and are responsible for biohermal developments in certain formations. Several macrofossils, such as Terebratula and Scutella are useful for correlation. Other fauna includes lamellibranchs, gastropods, nautilids, sepiids, corals, echinoids, bryozoans, sponges, ostracodes, foraminifera, pteropods, and crustaceans.

Late Tertiary faulting often displays northeast-southwest graben structures and has preserved younger sequences which would have otherwise been removed by erosion. Most faulting is of normal type with displacements of less than 70m. The Victoria Lines Fault of north-central Malta and the Maghlak Fault of southwestern Malta are noteable exceptions with maximum displacements of up to 132 metres.

Erosion has reduced the area of outcrop of the higher formations to the western third of Malta and to isolated buttes and mesas on Gozo. The geomorphology of the islands owes its development to the dominant fault trends, which often bring weak and incompetent strata down to sea level, thus facilitating rapid erosion of those areas. Quite recent graben development may be responsible for the inundation of the St.Paul's and Mellieha bays in Malta.

Variations in resistance to erosion within the formations reflect the degree of cementation of the sediments. The effect is to produce hard ledges where limestones occur and hollows at marl outcrops. Karst topography is the dominant weathering form in the more crystalline formations.

(ii) Previous Literature

Perhaps the earliest reference to Maltese geology was made by Xenophanes of Colophon (c.540-510 B.C.) He observed the remains of marine life high above sea level and other evidence for the former presence of the sea on what is now land. He attributed these phenomena to periodical invasions of the sea during which time man and his dwellings must have been submerged. Abella (1647) discussed certain geological aspects and Scilla (1747), an artist, sketched a few of the commoner fossils. Dolomieu (1791) was the first worker to describe the formations.

Spratt (1843) was the earliest worker to record accurately data of the geology and palaeontology of the islands and established the following stratigraphy:

Upper Limestone
Yellow Sand, Sandstone and Marl
Freestone
Lower Limestone

Spratt (1867) was also the first to publish on the Quaternary mammal remains of the islands. A map of the geology of the islands by Spratt and Earl Ducie, drawn shortly afterwards, was published with a more comprehensive report on the geology by Adams (1864). Fuchs (1874) followed this by the first significant contribution to knowledge of the Maltese faunas and from this gave quite accurate age determinations for the strata.

The most important synthesis of information to this date was made by Murray (1890) who produced a full description of the geology of the islands, including conditions of deposition of the formations. He included several maps showing the topography of the islands and their surrounding bathymetry including the geological map of the Maltese Islands which was reproduced from previous work by Spratt, Earl Ducie and Adams. A year later Gregory (1891) presented a detailed study of the Maltese echinoids and their possible uses in correlating between neighbouring European areas. Cooke (1893a), (1893b), (1894) and (1896) wrote a great deal of detailed work on the Globigerina Limestone and Blue Clay formations. He described the varied marine mammal remains from these formations and re-estimated depositional depths. Cooke concluded that much of the faulting within the islands was of recent date. The early 20th century saw little advancement of knowledge on Maltese geology, although Hobbs (1914) produced an important tectonic study of the islands and was first to comment on the origin of the puzzling circular faults of Murray's map. Roman and Roger (1939) produced a useful paper on the pectinid faunas of Malta together with a correlation chart for the Mediterranean showing the time ranges and the inter-relationships of the species.

Attention was drawn to the islands again, after a lull in publications, by Morris (1952), with a report on the water supply of Malta; this contains much borehole data. This interest in water and oil potential within the islands was continued by Cooper et al. (1952), Harrison (1954) and Durham Colleges (1955). Hyde (1955) summarised most of the data then known about Maltese geology and this remains today as the best general reference on the subject. In the same year British Petroleum Co. Ltd., produced 2 inch to the mile maps of the solid geology of the main islands. These replaced the earlier maps of Spratt and Murray which were on far too small a scale to convey anything more than general details. A BP report at this time by Russell drew together much borehole data on the islands. In 1957 R.Costain Ltd. produced a detailed private report on Malta's groundwater supply in which the Upper Coralline Limestone areas were carefully examined for reservoir potential. All faults were also carefully located and a great deal of new borehole data was obtained.

Two Ph.D. theses stand out as the most significant contributions of recent date. Wigglesworth (1964) produced a detailed study of the stratigraphy and echinoid palaeontology of Gozo including a geological map of the island, which unfortunately remains unpublished. The Durham Colleges survey (1955) had succeeded in subdividing the Globigerina Limestone for the whole of Malta and as an extension to this Wigglesworth made a similar subdivision of the Gozo sequence. The significance of the Scutella Bed as a stratigraphic marker horizon was confirmed as was the more general significance of Schizaster. The thesis of Felix (1973) is a detailed study of the stratigraphy of the Maltese rocks based on the study of their contained foraminifera. This has enabled the Oligo-Miocene succession within these isolated islands to be correlated accurately on an international basis. It was, however, found difficult to correlate parts of the lowest and highest formations present due to the difficulty of extracting suitable foraminifera, particularly in the case of the lowest formation where planktonic forms are unknown.

(iii) Outline of the Present Project

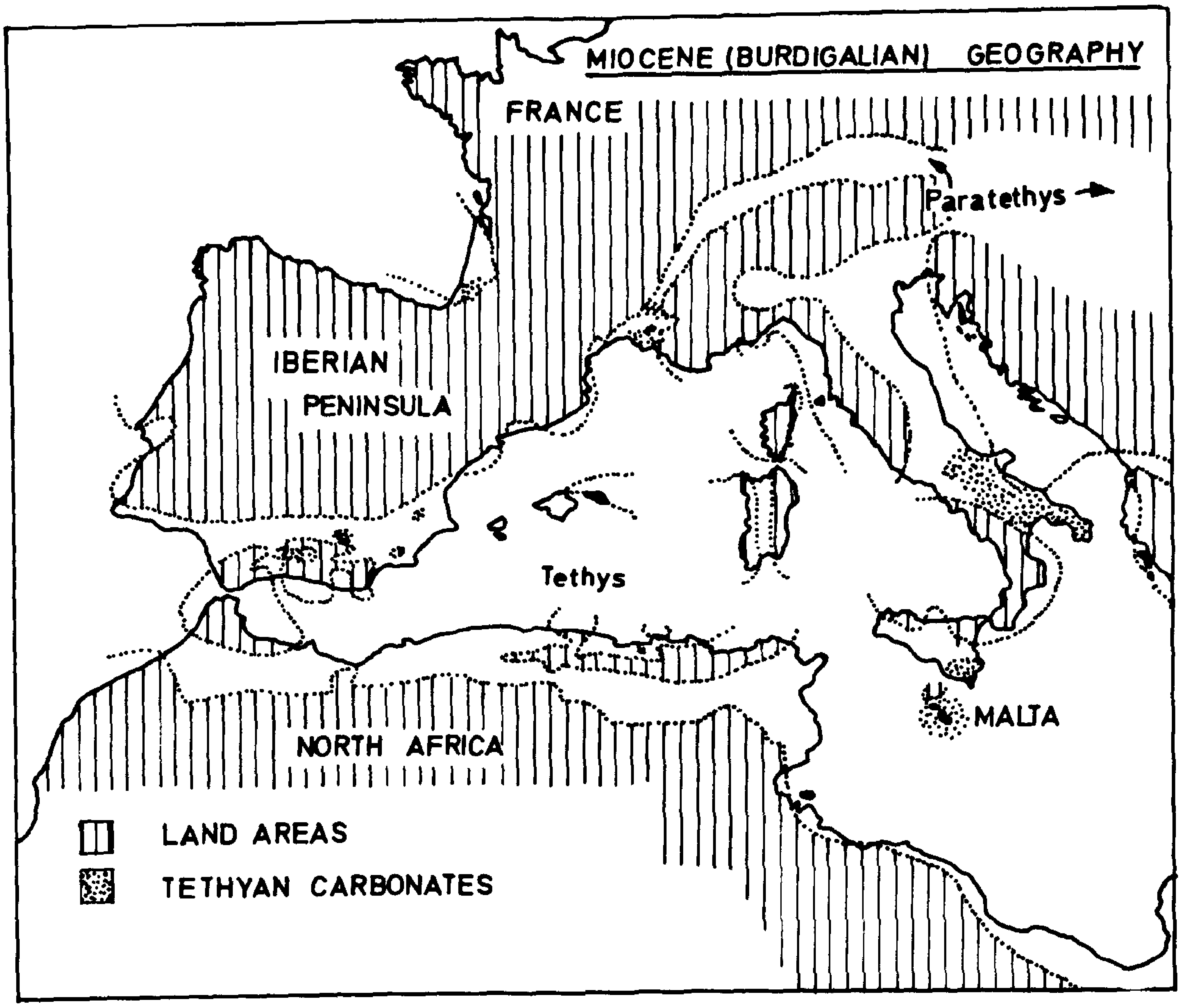
From the outset it was appreciated that a great deal of knowledge had already been obtained from all formations with regard to the faunas present and stratigraphy. The Upper and Lower Coralline Limestone formations which lie at the top and bottom of the sequence, however, had never been subdivided successfully, although there had been several attempts to do so (see Hyde 1955, p.52). It was decided that a detailed study of the two formations might result in a successful stratigraphic subdivision and hence a greater understanding of prevailing Miocene conditions of deposition. In conjunction with this a regional study and remapping of all the Upper and Lower Coralline Limestone areas of the major islands was undertaken at a scale of 6 inches to the mile in Malta and 4 inches to the mile in Gozo. This was particularly necessary, as the western third of Malta had not received attention in recent studies apart from the Costain survey (1957). This latter survey was primarily concerned with accurately locating fault traces and the base of the Upper Coralline Limestone for the purpose of water reserve estimation.

Further aims of the present work were to obtain as much field data as possible on formation thicknesses and faunal content of both the Coralline limestones and the Greensand, Blue Clay and Globigerina Limestone with a view of constructing isopachyte maps and biofacies distributions. Particular attention was paid to the phosphorite conglomerate beds and the Greensand as exotic derived clasts occur at these levels and may yield useful palaeoenvironmental data. The San Leonardo area in south-eastern Malta was examined in detail in order that the relationship between the supposed Upper Coralline Limestone outlier and the main outcrop could be ascertained. The Upper Globigerina Limestone at Delimara was also studied in an attempt to tie it in with the parent outcrops of western Malta.

Sediment distributions were studied by means of isopachyte maps which were constructed from field data and supplementary data obtained from reports in the possession of British Petroleum Ltd. and the Waterworks Department, Malta. The resurvey of the western third of Malta, together with notes on the San Leonardo, Delimara and Il Mara areas was carried out on 6 inches to the mile base maps obtained, with thanks, from the Public Works Department, Malta. These lack grid coordinates and so those present on the 1954, 2 inches to 1 mile Ordnance Survey map of the Maltese Islands, (G.S.G.S.5859. 4th edition), have been used throughout the thesis, and are inserted on to the Upper and Lower Coralline Limestone distribution map at the back of the thesis, for reference.

A detailed study of a selected horizon in the basal Upper Coralline Limestone was carried out. The purpose of this study was to examine the effects of the environment on various groups of biota. It was hoped to apply the data obtained to other formations with an aim to increasing the understanding of the palaeoenvironments present. Almost two hundred thin sections were examined in the petrological study of the formations as part of a detailed facies analysis.

The classification of the Maltese limestones posed several problems and the only suitable one found was that of Folk (1959, 1968). When applied to the Maltese rocks however it suffers from the following drawbacks: much of the cement binding the Greensand and parts of the Upper Coralline Limestone has been removed by solution and several other horizons have recrystalised to microsparite. This creates difficulties in interpreting the depositional environments by Folk's scheme. Nomenclatorial difficulties were also met with in the case of the conglomerate beds in the Globigerina Limestone and the Greensand as Folk's terminology does not cater for large volumes of derived clastics. This problem was resolved by adding the prefix "lithoclast" to the standard terminology whenever the derived component was greater than 25%.



Modified from Chevalier 1961

Fig. 1a

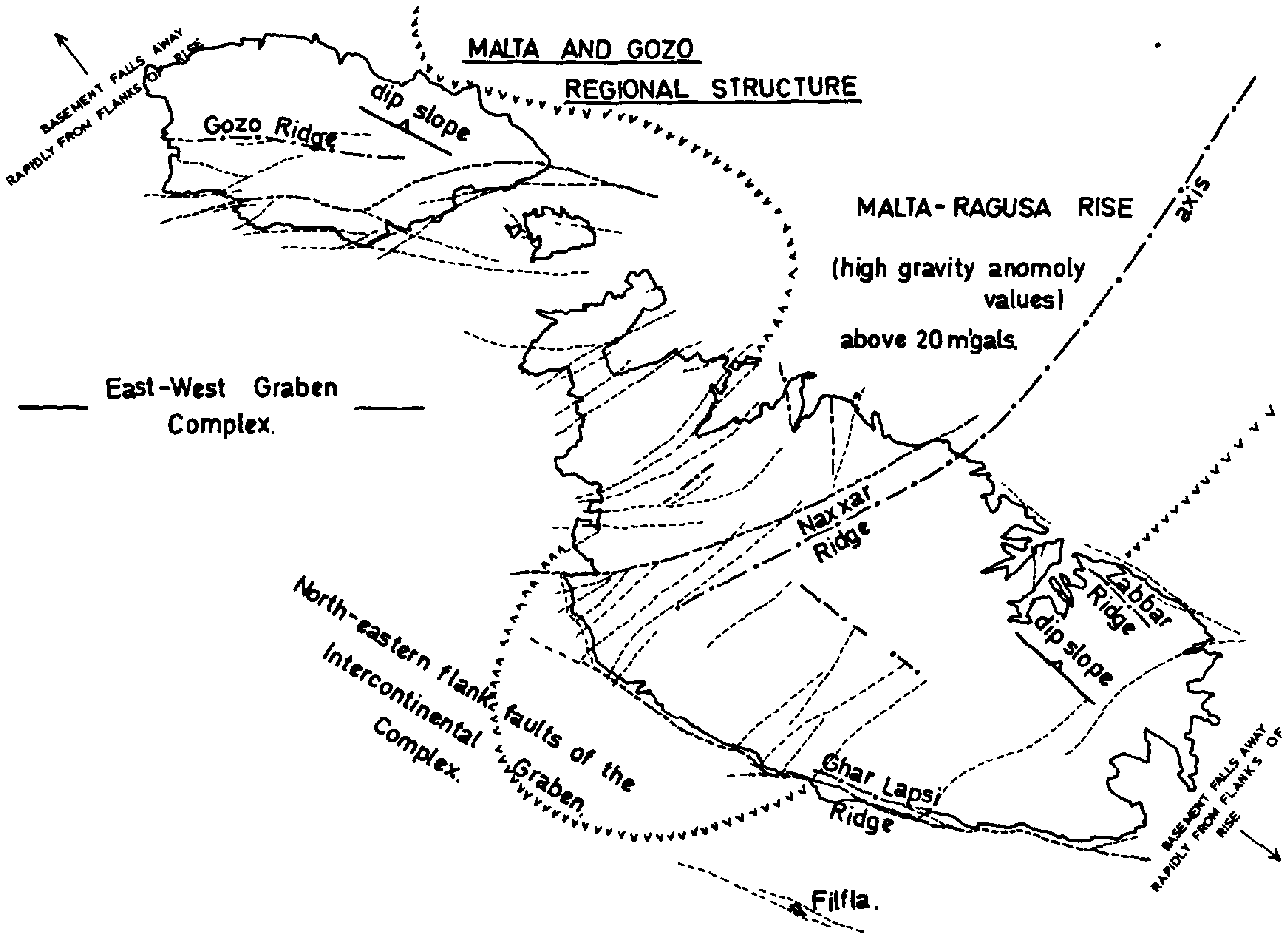
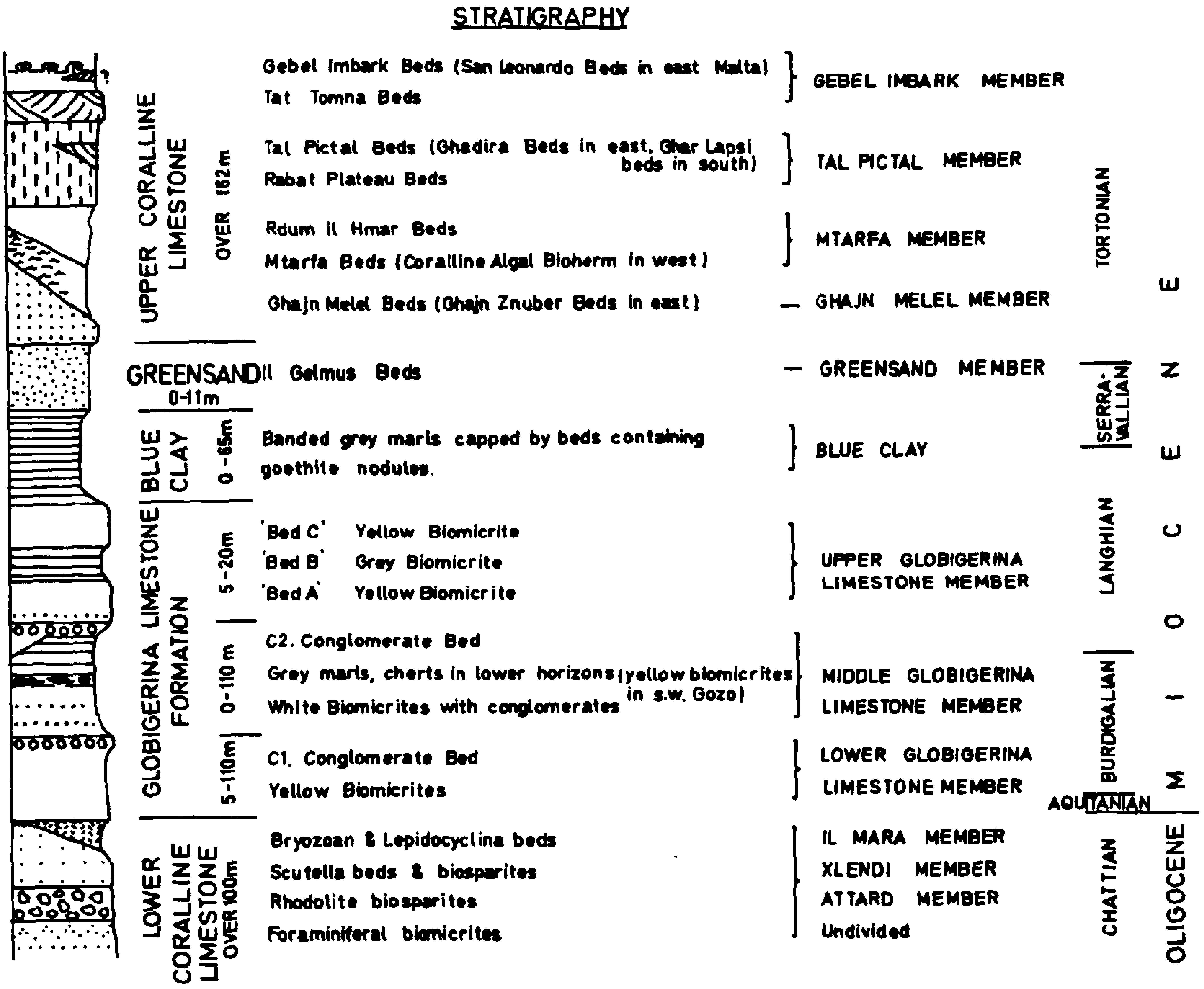


Fig. 1b



STAGE CORRELATION FROM FELIX.R.1973.

Fig. 2a

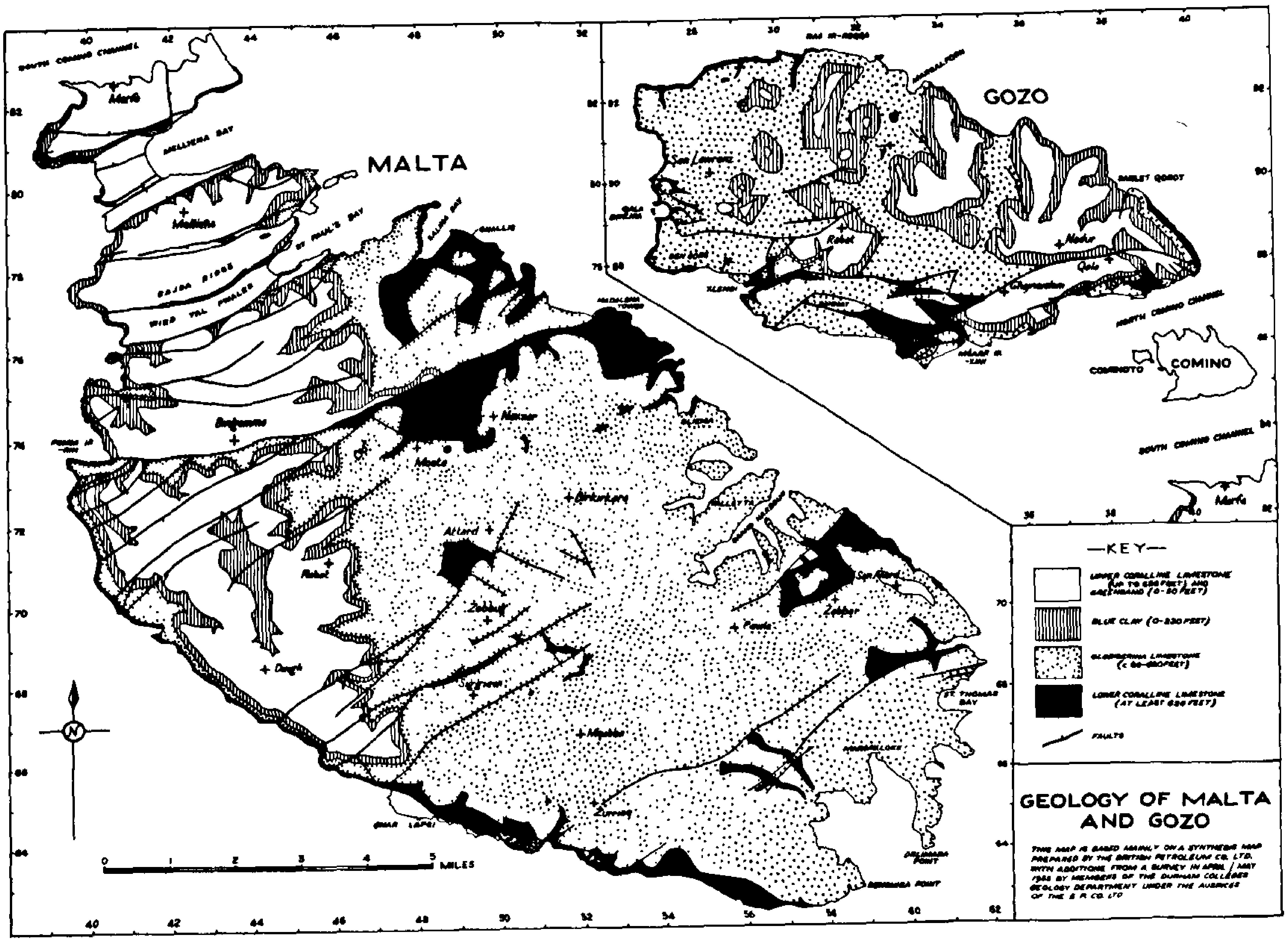


Fig. 2b Geology of Malta and Gozo.

CHAPTER 2

GENERAL

The Malta-Ragusa rise, which trends north-eastwards from the islands, is marked by a strong positive gravity anomaly of +17 to +28 milligals (Cooper et al. 1952, p.577) and contrasts strongly with values of -11 or -12 milligals obtained for the offshore areas to the south of the Maltese Islands. The general configuration of the anomalies in a northeast-southwest section, at right angles to the trend of the rise, is that of an asymmetrical triangle with its steepest face towards the northwest and its more gentle dipping face, where anomaly values fall away gradually, towards the southeast (Fig.1b). Harrison (1954, p.605) presented a more detailed free air gravity map of Malta. He recognised a high subsidiary anomaly centred on Zabbar in the south and extending north west to Naxxar. The steep drop in gravity values to the west and southwest of the islands was also confirmed. The anomaly values are interpreted as being caused by a body of denser basement material, which is closest to the surface beneath the highest values. Malta is apparently positioned quite close to the margins of the southern end of the Malta-Ragusa rise, as interpreted from this data.

Two structural contour maps of the islands of Malta (Fig.3), and Gozo (Wigglesworth 1964), (Fig.4), are presented. Both are based on the top of the Lower Coralline Limestone, which may be Xlendi Member in some area or Il Mara Member in others. Generally speaking the top of the formation is designated as the highest point at which recognisable Scutella fragments occur. In the absence of this echinoid the top of the highest beds containing abundant Lepidocyclina sp., or an interformational erosion surface occurring in south-western Malta, have been used to delineate the top of the Lower Coralline Limestone formation. This follows the use of House et al. (1961, p.26).

Much of the data used in the construction of the map of Malta comes from reports in the possession of the Waterworks Department, Malta, such as the Costain (1957) report. Other data have been obtained from British Petroleum Co.Ltd. reports; a great deal of measured section work undertaken by the author in the field finally complements the data.

The following discussion is a partly reproduced form of that appearing in a private report to the Maltese Waterworks by Pedley (1972).

2. Malta

Malta may be conveniently subdivided at the Victoria Lines Fault, (3973 to 5277) into two regions of contrasting structure.

a. Southern Malta

b. Northern Malta

a. Southern Malta

The regional dip is 2-3° towards the east-north-east and allows widespread, though isolated, Lower Coralline Limestone outcrops. Faulting is relatively simple, normal faults with displacements of up to 50 metres being typical. Two structural depressions occur in this region. The first is centred on French Creek (564710), with a low of -50 metres. The other lies in the Delimara area (6064) and falls away to more than -150 metres below sea level at Delimara point. Both structures appear to have developed throughout Globigerina Limestone times, when over 100 metres of Lower Globigerina Limestone infilled the former basin and at least twice that thickness of Middle Globigerina Limestone levelled the latter structure.

The following strong positive elements also considerably influenced sedimentation throughout the Oligo-Miocene:

(i) The Naxxar Dome (495750). This was uplifted prior to the deposition of the Il Mara Member of the Lower Coralline Limestone and caused severe local erosion of the Attard Member.

(ii) The Zabbar Dome (576712). This extends approximately parallel to the San Leonardo coastline of eastern Malta. Positive movement along this structure was responsible for several episodes of erosion during the deposition of the Lower Coralline Limestone. It remained a depositional high throughout the remaining Miocene and is responsible for the prominent unconformity of Upper Coralline Limestone rocks overlying Globigerina Limestone in this area. Both this structure and the Naxxar Dome conform approximately to the position of the high gravity anomaly values of Harrison (1954).

(iii) The Ghar Lapsi Dome (490653). This is an elongated dome lying parallel to the east coast and truncated to the south-west by the Maghlak Fault. Positive movement about this structure during Lower Coralline Limestone times is responsible for the erosional contact between the Attard and Xlendi Members and the overlying Lower Globigerina Limestone.

b. Northern Malta

Northern Malta is characterised by multiple horst and graben structures caused by parallel normal faulting. Although not so obvious, the regional dip in this area is 2° towards the north-east. The Lower Coralline Limestone is poorly exposed and consequently contours have had to be constructed with the aid of isopachyte maps, drawn up for each of the overlying units, plus borehole data on the base of the Upper Coralline Limestone. A few of the larger boreholes however, do penetrate the Lower Coralline Limestone and give some stratigraphic control. No comparable depressions to Southern Malta are seen in this area. The few culminations of this area, for example the Ghallis Dome (490653) are of low amplitude and have had no obvious effects on sedimentation.

c. Faulting

Apart from a few minor north-south faults, two fault sets are recognised with additional evidence of movements contemporaneous with deposition.

(i) East-North-East Trending Faults. This is the dominant set within the islands and is made up of normal type faults, including the Victoria Lines Fault. Fault displacements are usually achieved not by a single dislocation, but by two or more parallel fractures which progressively step down younger beds. This is particularly well seen at Fomm ir-Rih (407737), where the Victoria Lines Fault shows slices of Globigerina Limestone and Blue Clay caught up between the down thrown Upper Coralline Limestone and the Lower Coralline Limestone. The same features are also seen in the Qammieh Fault at Qammieh (401808).

Complementary synclines are developed against the Victoria Lines Fault and the Mizeip Fault (410784 and 420782) and were fully documented by Morris (1952). The present study interprets these as drag folds which have developed against the two major faults of the island. Their apparent synclinal nature may well be exaggerated as boreholes have only penetrated the Upper Coralline Limestone and it may well be that plastic flowage within the incompetent Blue Clay virtually accounts for the whole of the synclinal development. Inland the faults are difficult to follow due to soil and Quaternary cover. It has, however, been recognised that the trends of many of the major faults are marked by solution subsidence structures. This relationship is best seen in the northern area of the Rabat Plateau and will be discussed in a further chapter. Fault displacements range from a metre to over 200 metres, with the greatest displacements generally on the western side of the island.

(ii) West-North-West Trending Faults. This set is not commonly seen inland though they are present. The Ghar Lapsi area (4864), illustrates this fault-set superbly as subaerial and marine erosion have collectively combined to exhume most of the larger dislocations and fault gullies, including the Maghlak Fault, which has a normal displacement of over 230 metres. Although only exposed in the vicinity of Ghar Lapsi it is probably responsible for the entire coastal outline from Ras ir-Raheb (395737) in the north to Benghisa Point (588631) in the south. Illies

(1969, p.7) believes this to represent part of the northern limb of an intercontinental graben, extending from the Rhine Graben in Germany to the Hon Graben of Libya.

As with the previous fault-set, fractures are composite, with Blue Clay and Globigerina Limestone caught up between the fault planes. The Maghlek Fault and its subsidiary fractures affect a wide area of the upthrown side, and folds and inverts the Upper Coralline Limestone on the downthrown limb at Ras il Hamrija (492644). The intersection of both west-north-west trending faults and east-north-east forms is well seen in this area (see Fig.3), and almost total exposure allows the conclusion that both sets are contemporaneous. This is suggested by the swing of several of the east-north-east faults on the coastline south of Ras il Hamrija, to a west-south-westerly direction by the time they reach the Blue Grotto (508641).

(iii) Syndepositional Fractures. These were first recognised by Wiggleswort: (1964, p.23) between Dahlet Qorrot (3889) and Mgarr (3686), in eastern Gozo. They consist of prominent north-south joining within the Lower Globigerina Limestone, which do not penetrate the overlying Lower Main Conglomerate (C1). Small phosphatised pebbles from C1 penetrate these joints to a depth of 12 ft. (3.7 metres), forming small neptunian dykes. This fracturing is obviously related to local uplift as the overlying Globigerina Limestone is absent from this area, possibly due to a combination of non-deposition and active erosion. North-easterly trending neptunian dykes, of otherwise identical form, have been located within the Middle Globigerina Limestone of Imtahleb (418700), during the present study, where they underlie a local conglomerate band, and penetrate more than 7 metres of underlying sediment. Similar but unfilled joints, present in the Middle Globigerina Limestone but absent in the overlying Upper Main Conglomerate Bed (C2), are recognised at Qammieh in northern Malta (plate 5a). Felix (1973, p.17) also records neptunian dykes from Wied tal Qlieghi, Malta.

3. Gozo

The structure contour map of Gozo (Fig.4) is the work of Wigglesworth (1964), and only the more interesting points and general interpretations will be considered here. Regional dip values are 3-4° towards the north-east. The only structural depression of the island (3289) has had no recognisable effect on sedimentation. However, the San Lawrenz Dome (285895), the only culmination, appears to reflect a comparable structure in the pre-Miocene basement and causes significant thinning of both the Globigerina Limestone and the Blue Clay Formations of the island. Further studies have revealed that it is related to the Comino Straits High which lies between Malta and Gozo and both are considered as extensions of a more regional marginal high which existed just off the western coastlines of Malta and Gozo throughout Oligo-Miocene times.

The south-eastern side of Gozo shows the dominant east-south-east fault patterns typical of northern Malta; northern Gozo generally lacks faulting. It is considered that the island of Comino represents a partially submerged horst, the north and south Comino channels being as complementary graben structures. Several faults on Gozo (e.g. the Xlendi-Kercem Fault) show signs of transverse movement. East-north-east trending faults are not obvious, though the Sannat Fault (315869) may represent this set. The localised fault complexes of Qawra-Tal Harrax and Xlendi on the western coast of the island are of complex origin, involving large scale solution subsidence structures, which are considered elsewhere.

4. Interpretation of Regional Structures

The dominant fault systems of the islands apparently owe their origin to planes of weakness within the basement, lying at a depth of over 5km. beneath the islands. The basement, as interpreted from geophysical data, is seen as a positive feature which carries a thinning cover over the axial portions but thicker flanking deposits around its margins.

Even so, sedimentation on the top of the rise amounts to over 3000 metres of Tertiary and upper Cretaceous shallow water carbonates as shown in the BP Naxxar borehole (personal communication).

The Naxxar, Zabbar and Ghar Lapsi Domes are interpreted as minor highs along the main ridge present prior to sedimentation. If the domed areas are studied (see Fig.1b) then a discontinuous series of ridges becomes apparent. The Naxxar, Comino Straits High and Gozo ridges may represent parallel culminations of the Malta-Ragusa rise, though the former also appears to be laterally linked at depth with the Zabbar Dome. These structures conform with the east-north-east fault trends and may have imposed the regional fracture trends.

The Zabbar and Ghar Lapsi Domes conform to the west-north-west fracture systems as well as to the regional rise west of the islands. The Maghlak fault of Ghar Lapsi is believed to represent the eastern flank of a large west-north-west trending fracture system guided by the positive basement features. The island of Filfla is a small horst block caught up within the general graben structure. It is believed that this major graben is responsible for the low gravity values encountered south of the Maltese islands, (Cooper et al. 1952).

The horst and graben development between the Sannat-Qala Fault system of Gozo and the Victoria Lines Fault of central Malta is also considered to represent a subsidiary multi-graben complex trending in an easterly direction from the main fracture, and may be responsible in part for the reduction in gravity anomaly values in this area. The other north-easterly trending faults of the south Malta area are considered to represent minor fracturing on the truncated nose of the Malta rise.

5. Age of Movements

There is clear evidence from the islands that movement has been continuous from early Tertiary times. This has taken the form of solution subsidence formation, neptunian dykes and seafloor oscillations throughout Oligo-Miocene times and the development of faulting and associated folding in later Tertiary times, continuing until the present day. Rizzo (1928, p.26) records stalactites below the breakwater foundations of Valletta harbour, 3000 year old cart tracks disappear beneath the sea in St.George's Bay, and raised beach material is preserved in the cliffs at Ta'L-Imgharrqa (420816) on the Marfa Ridge.

Sedimentation on such a perminent feature as the Malta-Ragusa Rise must always have been minimal on the crestal areas and thicker on the protected flanks. A continuous rain of planktonic debris must have fallen on this mid-Tethyan ridge, thus creating the impression of deep water deposits in a known shallow water area.

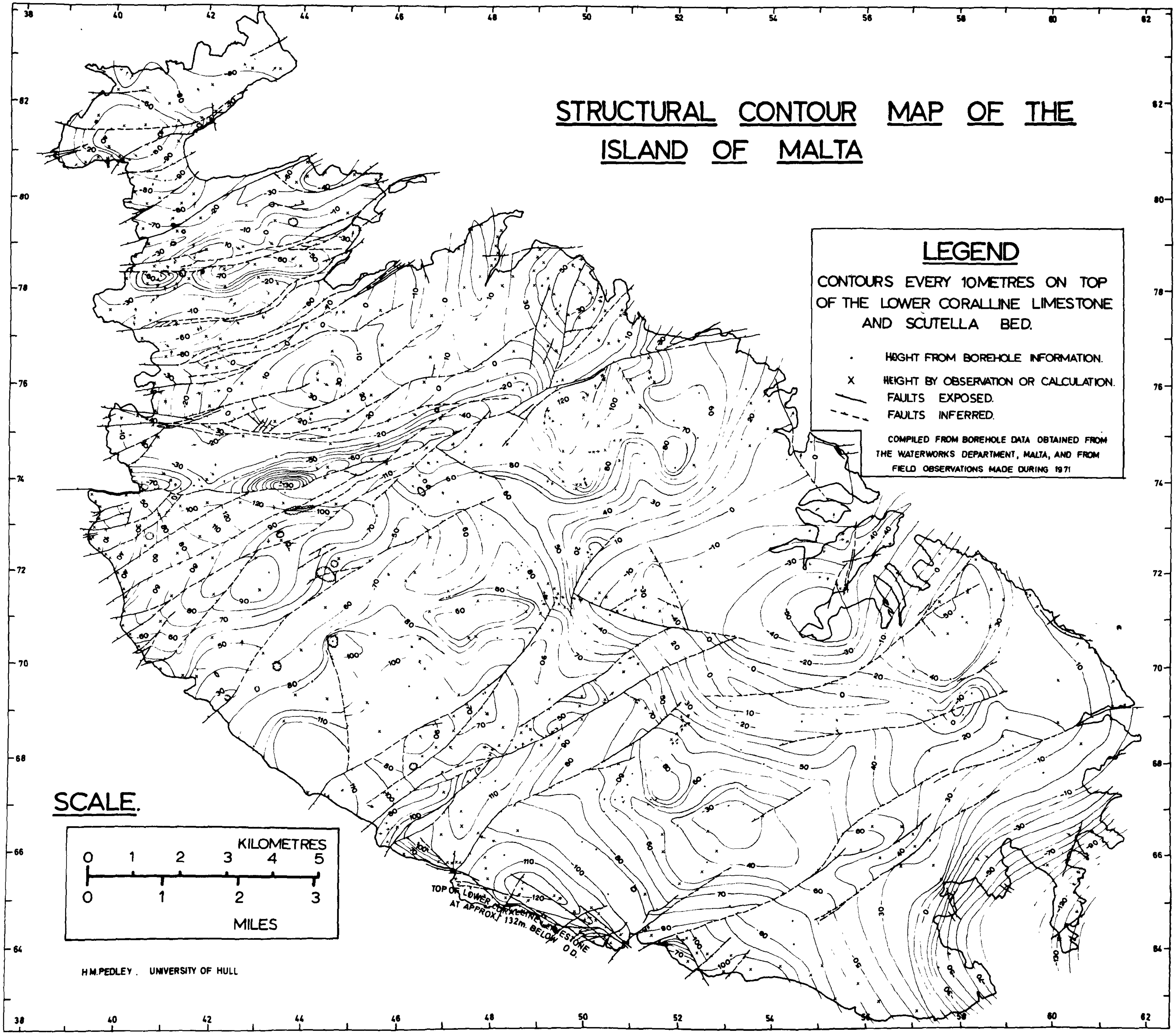


Fig. 3

The author also acknowledges work on a previous structural contour map of central Malta done under the auspices of British Petroleum Ltd., by K.C.Dunham, A.A.Wilson and M.R.House of the Durham Colleges Survey,1955.

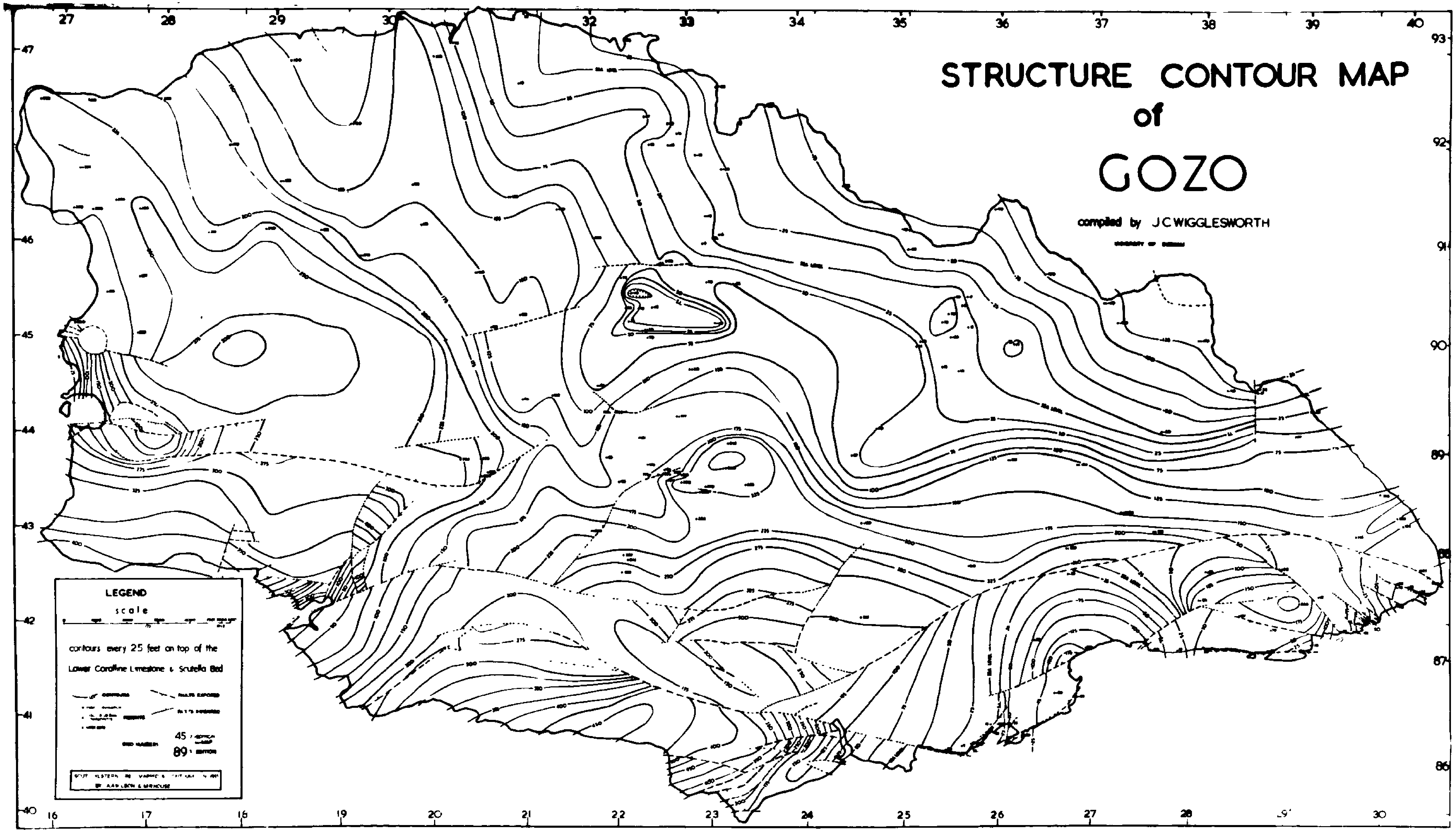

STRUCTURE CONTOUR MAP
of
GOZO
compiled by J C WIGGLESWORTH
LEGEND
scale
contours every 25 feet on top of the
Lower Coralline Limestone & Scutella Bed
45
89
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Fig. 4

CHAPTER 3

LOWER CORALLINE LIMESTONE FORMATION

1. Stratigraphy

This is the lowest exposed formation of the islands. It is infrequently exposed around the margins of both main islands, being most obvious but least accessible in Dingli Cliffs of western Malta and in the cliffs between Mgarr ix-Xini (3486) and Wardija point (2668) in Gozo (see Fig.5).

It was recognised as a distinct formation from the earliest times and is recorded by Spratt (1843), as "Semi Crystalline Limestone". The formation name in use today originates from the work of Murray (1890, p.474), when it was merely sub-divided into "Lower Non-Crystalline Limestone" and "Upper Semi-Crystalline Limestone". Sub-division has always been difficult due to the inaccessibility of the formation: The only subdivision with any coherence up to the present study was that of Trechmann (1938, p.2), who divided off the top portion of the formation under the name "Scutella bed", on the basis of the rich echinoid fauna present at various levels within this biosparite sequence. Thomas and Watson (1952) further divided the lowest part of the sequence, seen in the cliffs in the upthrown side of the Maghlak Fault of Ghar Lapsi (485651), into "Miliolid Limestones", and considered it to represent a new formation. Russell (1955,p.12) does not consider that these small exposures warrant the erection of a new formation name and prefers to look upon them as a local facies variation.

The present study considers that the formation is more appropriately sub-divided into the following sedimentological facies, in ascending order:

(d) Il Mara Member

(c) Xlendi Member

(b) Attard Member

(a) Undivided (conforms to the Miliolid Limestones)

(a) Undivided (Miliolid Limestones in part)

(i) General

The lowest exposed strata of the islands is a biomicrite rich in benthonic foraminifera. It is best seen at Attard, (495714), Victoria Lines (4975), Xlendi (301878) and Ghar Lapsi (484649). Despite Thomas' and Watson's (1952) designation they are here considered to be a facies variant of the Lower Coralline Limestone. 125 ft (38 metres) are exposed at Ghar Lapsi from which Thomas and Watson obtained Praerhapydionina sp. and Austrotrillina sp. Little else is known of this facies, as it appears to be of uniform composition wherever it crops out. Exposure is insufficient for detailed study of these beds. They are recognised in the Naxxar, Zabbar and Ghar Lapsi boreholes of British Petroleum Ltd. and appear to extend down several hundred feet with only one Clay-Limestone break.

(ii) Petrology

Thin section components are mainly entire tests of benthonic foraminifera, which make up 35 to 40% of the rock. These are set in micrite or microsparite which may also contain up to 3% echinoid fragments. Staining reveals that all sections are entirely of low ferroan calcite.

(b) Attard Member

(i) General

Type locality Attard Quarry, due east of Mount Pleasant Hospital (495714).

The upper and lower limits of this facies are well defined where they are exposed, though the basal contact is only seen along the Victoria Lines, east of Mosta (4874), Ghar Lapsi cliffs (4865) and a debatable area around Xlendi where the member is apparently missing. Thomas and Watson (1952) estimate the thickness as 110ft (33.5 metres), but this is seen to decrease to 0 metres in the cliffs between Ras il Bajjada (502646), and Wied il Bassasa (525635).

(ii) Lithology and Distribution

The typical sediment type is a white rhodolite biosparite or biosparrudite. The rhodolites are often arranged into crude bedding planes and vary in size from a few millimetres up to 95 millimetres. Attard quarry shows typical forms of the latter size, which appear as dense spheroidal colonies (Plate 1c). Salina Bay (485783), on the other hand, exhibits abraded rhodolites of 20 or 30mm diameter which show encrustation by *Calpensia* sp.

In western areas of Malta a bioherm development occurs, being particularly well seen at Wied Maghlak (488652), where corals and mollusc shell casts are abundant. This same development is also seen in the quarries at Il Hnejja (389874) Gozo. The bed is replaced by cross-bedded biospararenites and biosparrudites, identical to the Xlendi member, south of Zurrieq, Malta, and by foraminiferal micrites at Xlendi. Insufficient data has been obtained to recognise the significance of this.

Throughout the remainder of Gozo and Malta algal rhodolite limestones are prominently developed at this horizon. At Attard the lower limit to the member is arbitrarily fixed at the base of a *Kuphus* bored horizon, as rocks below this brownish-grey micrite rarely contain rhodolites and rapidly pass down into yellow foraminiferal micrites. The bored horizon possibly correlates with a comparable horizon low within the Formation at Migra Ilma (458660) recorded by Felix (1973, p.19)

(iii) Petrology

Because of the large size of many of the rhodolites, thin sections from some localities are almost entirely of one colony. More frequently, however, thin sections show areas of coralline algal growth and bioclastics. The rhodolites are referable to the genera *Lithothamnion* sp. and *Archaeolithothamnion* cf. *intermedium* Raineri, the latter being common at Attard. Coralline algal components vary from 25-80% of the slides examined and are usually accompanied by 2-11% of large benthonic foraminifera, with *Heterostegina* sp. and *Nummulites* sp. figuring dominantly.

Many species of bryozoans account for about 2.5% of the total components. Small percentages of echinoid clasts and calcitic molluscs also occur (see Fig.7). Some samples, for example from Il Mara (575626), show that damaged coralline algae were recolonised on several occasions. Throughout the entire study all thin sections were stained at one end with a solution of alizarin red S and potassium ferricyanide, as described by Dickson (1965) All limestones within the Attard Member proved to be of low ferroan calcite.

An unfortunate feature of many slides from areas within extensive biohermal developments is the fact that the coralline algae are often micritised, thus making modal analysis of these components very difficult. Aragonite solution has left many fossils within the biohermal developments as cavities.

(iv) Fauna and Flora

Recognisable fauna is rare in the rhodolite facies, although specimens of *Strombus* sp. occur in the Ghar Lapsi cliffs (4856) and are recorded elsewhere, including Attard. The algal rhodolites are dominated by *Lithothamnion* sp. but at Ras il Raheb (3973) and Attard *Archaeolithothamnion* sp. (Plate 2a) are abundant. *Corallina* sp. and *Jania* sp. also occur sporadically, usually as detached phyllodes. In addition, Eames (1952, p.4) records *Melobesia* sp. and *Mesophyllum* sp. It is commonly found that each rhodolite has a composite form, which may have been eroded and recolonised on several occasions, sometimes with different genera encrusting the outside to that in the centre of the structure. Miliolinid foraminifera, *Austrotrillina* sp. and alveolinids also occur but no planktonic foraminifera are recognised in thin section.

The biohermal developments yield the following corals, many of them housed in the corals section of the British Museum (Natural History). *Favites* sp. *Stylophora* cf. *conferia* Reun., *Colpophyllia sp. aff. vetusta* Michelin, *Acropora* sp. from the Ta Kandia quarries, Siggiewi, and *Diploastraea* sp. from Misrah Ghenck (488752). *Tarbellastraea cf. reusiana* ME & H, *Porites* sp. and *Monastrea (Heliastraea) cf. forbesi* Duncan, occur at Ix

Xaghra tal Maghlak (483649) together with an indeterminate genus, sp.a (Plate 15a). At (488652) *Meandrina* sp. and coral A occur. Associated with the corals is a fauna rich in aragonitic gastropods and lamellibranchs, and although these are now preserved as casts, the following have been identified: *Lithophaga lithophaga* Linné, *Cardita* sp., *Pholadomya* sp. and *Natica* sp.

A micritic bed at the base of the Attard Member in the Attard quarries yields a caryophyllid coral, *Glycimeris deshayesi* Mayer, *Lucina* sp., *Cardita cf.Crassa* Lamarck,*Lithophagus lithophagus* Linné, *Chlamys* sp., two abherent species of *Chama* sp., *Cardium* sp. *Natica tigerina* Defrance *Cassis* sp., *Tornus* sp., *Erato* sp., *Turritella* sp., capulid gastropods, a large species of *Venus* sp., *Serpula* sp., and *Entobia* sp. The latter is represented by mud infilled burrow systems, now showing as protrubences on the internal shellcast surfaces. Directly below the micrite bed is a hard ground bored by *Kuphus polythalamid* Linné, indicating a sharp break in deposition.

C. Xlendi Member.

(i) General

Type locality Xlendi valley, below road bridge (301878).

The rocks of this locality embrace most of the variations seen within the member. The base here is transitional with the underlying white biomicrites. 9.6 metres of brown to grey biosparenite and biosparrudite are exposed and grade transitionally into the overlying soft yellow biomicrites of the Lower Globigerina Limestone Formation. This facies is characterised by the occurrence of broken and entire echinoids, largely of *Scutella subrotunda* Leske, though *Chlamys* sp. also occur. These lie in a 2.7 metre bed close to the top of the member in the type locality (See also Plate 1d), but may also occur as several beds, for example, at Ghar il-Qamh (307930), or are unrecognisable as at Qawra, Malta. (7947).

The top of the member is taken everywhere as the highest occurrence of recogniseable Scutella fragments or in the absence of these, as in the Dingli Cliffs area (4367), the upper limits are marked by an intraformational erosion surface. The formation normally rests on the Attard Member but may rest on "Miliolid Limestones", as at Xlendi.

ii) Lithology and Distribution

The most obvious field feature of the member is its cross-bedded nature. This is well seen at Ghar il-Qamh and also along the Victoria Lines of Malta. In certain areas, for example Xlendi and Rdum il-Qammieh, this feature is poorly developed, however, the member is still readily identified by its coarse grained nature and usually by the presence of recogniseable specimens of Scutella sp. Observable thicknesses range from over 22 metres at Ghar il-Qamh (306931), to 0 metres at Rdum Dikkiena (444674), though the absence at the latter locality is due to an intraformational unconformity.

The member encompasses all the strata previously grouped under the term "Scutella bed". This was given formation status by Wigglesworth (1964, p.15) but is not considered to warrant this status under the present study. The present study gives these beds Member status. A great deal of the member lacks a recognisable Scutella horizon, and often only isolated fragmentary individuals are present. Other areas exhibit several Scutella beds, thus leading to confusion. The new name also embraces beds previously considered to lie outside the "Scutella bed", such as the biosparites below the erosion surface at Rdum il-Qammieh, at which locality the "Scutella bed" is developed in a Lower Globigerina facies above a disconformity (Plate 1b).

The Xlendi Member is recognised throughout both Malta and Gozo, being thickest in the north-western part of Gozo (See Fig.6). It thins at Ta L-Ghattuq (322893) in central Gozo, but thickens further south and appears to retain this thickness throughout northern Malta. Considerable thinning occurs in central Malta, at Attard quarry (495714) and in western Malta. A few metres are present beneath the Il Mara Member at Il Mara (575626) and it is again strongly developed along the coastline north-east of Marsascala (606691).

The contact with the underlying Attard Member is usually transitional over a thickness of approximately a metre. Within this thickness algal rhodolites, dominant in the Attard Member, become fewer and often take on an abraded appearance. Membraniporiform bryozoans incrust them in some areas, as at Salina Bay (485783). The only strong disconformity within the islands at the base of the Xlendi Member is at Naxxar Gap (497757), where Attard Beds are seen folded into an eroded anticline, causing local flanking dip value of up to 30° within the Attard Member. The only location where a Scutella bed appears in direct contact with the Attard Member is at Fomm ir-Rih (402736) and is considered to represent a local condensation of the Xlendi Member.

The top of the Member usually shows a fairly sharp contact with the Lower Globigerina Limestone, though where local developments of the Il Mara Member facies occur, for example northern Malta, the beds grade upwards into that member.

(iii) Petrology

Sediments, in general, range from sparse algal or foraminifera biosparites, to sorted foraminifera biospararenites and biosparrudites. Large benthonic foraminifera, such as Amphistegina sp., Spiroclypeus sp., Austrotrillina sp., and Rotalia sp., occur in many of the sections examined. These are occasionally entire but are more often fragmentary, and make up from 50-95% of the fauna in some slides (Plate 2d). Coralline algal fragments also figure high in some slides, such as those from Wied Qirda (511690). They normally comprise up to 12% of the rock (see Fig.7), echinoid and mollusc fragments make up the minor components.

At times the modal analysis of the Xlendi Member resembles that of the Attard Member; for example, the coralline algal samples from

Wied Qirda and Ras il Bajjada (502646), which contain 40% and 60% algal material respectively. These are, however, algal fragments and not entire rhodolites or *in situ*. crustose coralline growths which are diagnostic of the Attard Member only. All the sections examined were composed of low ferroan calcite.

(iv) Fauna and Flora

This is generally sparse except for *Scutella subrotunda* Leske and benthonic foraminifera, such as *Heterostegina* sp. and *Amphistegina* sp. An unnamed *Scutella* sp. described by Wigglesworth (1964 p.60) is common in parts of Gozo and is now also recorded from the San Leonardo coast of eastern Malta (5971). *Echinolampas* sp. also occurs in the basal *Scutella* bed of eastern Malta. Bryozoans, when present, are represented by high energy forms. At Rdum il Qammieh a complex interdigitation of the Xlendi and Il Mara Members is associated with an erosional plane. The basal *Scutella* bed (980 mm), consisting mainly of fragmentary *Scutella subrotunda* Leske and branching *Cellepora* sp. colonies, is believed to be of this facies. Other faunal elements are abraided beyond recognition. Eames (1952,p.5) records *Chlamys (Aequipecten) northamptoni* Michelin, *Chlamys (Amusiopecten) burdigalensis* Lamarck, *Ditrupa* sp., *Hemiaster* sp., *Textularia* sp., *Gyroidina* sp. and *Globigerina* sp., though the planktonic foram.must be restricted to the top of the member. Both *Lithothamnion* sp., and *Archaeolithothamnion* sp.,including *A. batuense* Airoldi, are recognised. In addition,Zammit-Maempel (1972) records *Echinocyamus* sp. and *Coelopleurus melitensis* Zammit-Maempel from Qammieh.

d. Il Mara Member

(i) General

Type locality Il Mara, south-eastern Malta (575626).

The member is best developed in eastern Malta, but minor developments occur in northern Malta and southern Gozo, where the thickness is less than

5 metres. Thicknesses in south-eastern Malta vary from 32.5 metres at Il Mara to 7.5 metres at Tal Mela (537635). The last locality lies close to the Il Mara-Xlendi transition. The base of the member, when seen, rests with a fairly sharp contact on the Attard Member at Ta Mela, but with a transitional contact on the Xlendi Member elsewhere in southern Malta. The top contact is transitional with the Lower Globigerina Limestone except at San Rocco (587721), where interdigitation of the two members occurs.

(ii) Lithology and Distribution

In the field this facies is distinguished from the Xlendi Member by its prominant cross-stratification, the finer grained yellow nature of the sediments, and by the dominance at some horizons of *Lepidocyclina* sp., individuals of which attain dimensions of over 110mm. diameter and make up dense beds which appear very similar to jumbled pototo crisps (Plate 1a).

In eastern Malta the member is clearly seen to be a lateral facies development of the Xlendi Member, but extends north in time so that upper beds of the Il Mara Member also occur above the Xlendi Member. The transitional beds, well seen at Qammieh, yield the earliest recognised planktonic foraminifera of the islands, confirming that these beds grade imperceptably up into the Lower Globigerina Limestone.

(iii) Petrology

Only four thin sections were examined but it is believed that these are representative. The finer sediments from central areas of the member in eastern Malta are dominantly yellow sparse biomicrites and contain articulated brachiopods at certain horizons, which make up 5-8% of the rock. They are usually accompanied by unabraded benthonic foraminifera in about the same proportions. Echinoids are an insignificant component. The *Lepidocyclina* bed is usually dominated by entire specimens set in either a sparry or, more usually, a micritic matrix (see Fig.7). These are often accompanied by bryozoans and other giant foraminifera, the total making up 35-40% of the slide. Echinoids are again a minority component. No coralline algal fragments are recorded from the Member, though small percentages may be present in transitional areas with the Xlendi Member.

(iv) Fauna

Lepidocyclina (Eulepidina) dilatata Michelotti and probably other forms, previously regarded as *Lepidocyclina elephantae*, are the dominant faunal element of the facies. *Heterostegina* sp., *Amphistegina* sp. *Nummulites* sp., *Spiroclypeus* sp., and alveolinids are also common in these beds, particularly when beds transitional with the Xlendi Member are examined. Scattered fragments of *Scutella subrotunda* Leske occur but may well have been derived from the Xlendi facies.

In the yellow micrites of eastern Malta the brachiopod *Terebratula minor* Phillipsi forms small shell banks, and is associated with fenestrate bryozoans at Wied has Saptan (571655), and *Halimeda* sp. at San Leonardo (6007112). At both Il Mara and Wied iz-Ziju (597686) horizons containing *Echinolampas deshayesi* Desor and a fauna of aragonitic bivalves and gastropods, as casts only, occur. *Ostrea* sp. are often associated, as is *Chlamys* sp. Below this horizon, at Il Mara, *Cellepora* sp. in scroll-like growth-forms, together with asteroid ossicles, vinculariform bryozoans, referable to *Sertella* sp, cribrimorphs, erect *Membranipora* sp. and occasional *Spondylus* sp., are common in the *Lepidocyclina* beds. *Cidaris cf. melitensis* Forbes occurs as detached spines and plates in the transitional biosparites of San Rocco (587721), where it is associated with *Terebratula minor* Phillipsi and fenestrate bryozoans.

The faunas of the isolated Il Mara facies developments of southern Gozo and northern Malta usually exhibit *Lepidocyclina* sp., and bryozoans of membraniporiform, celleporiform and vinculariform habit. The top

Scutella bed of Rdum il Qammieh is of this facies. It carries an abundant fauna of *Schizaster parkinsoni* Defrance, *Scutella subrotunda* Leske, *Scutella* sp., *Hpatagus dekoninki* Wright, *Echinus tortonicus* *Gregoryaster* sp., *Pericosmus latus* Agassiz and *Chlamys* sp.

(v) Diagenesis within the Formation

An early effect of this was the dissolution of all the aragonitic fossils present within the formation. Generally speaking the resulting cavities have remained unfilled until the present, though low ferroan sparry calcite has partially infilled small cavities such as bryozoan and foraminiferal chambers and inter-sediment sites. Limonite is the main colouring agent within the rocks.

2. Palaeoenvironmental Interpretation

The Lithofacies of the Lower Coralline Limestone may be further subdivided into the following biofacies :

a) Biofacies A Miliolid Foraminifera Biofacies
b) Biofacies B Rhodolite Biofacies (Attard Member)
c) Biofacies C Biolithite/Mollusc Biofacies
d) Biofacies D Clypeastrina Biofacies (Xlendi Member)
e) Biofacies E Giant Foraminifera Biofacies (Il Mara Member)
f) Biofacies F Reteporiform Bryozoan/Pectinid Biofacies

a) Biofacies A. Miliolid Foraminifera Biofacies

Felix (1963) would place this poorly exposed facies in his *Austrotrillina*/*Peneroplis* zone. Planktonic foraminifera appear to be absent. Sedimentation appears to have been in very sheltered water in which the micrites accumulated. Felix (1973, p.82) considers deposition to have taken place in a "shallow gulf type area". This is substantiated by Bandy and Arnal (1957, p.2047), who consider that a dominant miliolinid assemblage reflects a depth range of the order of 0-150 ft. (0-47 metres).

b) Biofacies B. Rhodolite Biofacies

A fairly rapid change occurred at the top of the Miliolid Limestones. They initially coarsened and shortly afterwards spheroidal colonies of coralline algae developed. At first these rhodolites were small and irregular in form and show no indication of movement. Towards the top of the sequence, best seen in the Attard Quarries (Plate 1c), the rhodolites increase in size to 95mm, become very spheroidal, and show obvious signs of periodical movement on the seabed. The matrix of the rock becomes coarser from the base of the facies upwards. Some of the rolled rhodolites, for example at Il Mara and Attard, show signs of recolonisation after severe abrasion. Johnson (1962, p.24) states that *Lithothamnion* grows best in conditions of fairly high energy water circulation, in warm seas of normal salinity, and with a depth range (Johnson 1965, pp.16-17) of between 12-25 metres. Johnson (1965, p.25) also states that nodular development is common in very strong currents. The average depth of *Archaeolithothamnion* according to Johnson (1963, p.188) is 12-60 metres. These appear to reflect depositional depths of less than 25 metres.

c) Biofacies C. Biolithite/Mollusc Biofacies

In western areas of Malta biohermal coralline algal development with abundant hexacorals further indicates subtropical temperatures with clear shallow sea water of normal salinity. It appears that these bioherms developed as low positive structures in the shallowest areas of the Rhodolite biofacies. The initial unstable substrate was first colonised by crustose coralline algae but was soon followed by an abundant coral, mollusc and gastropod fauna dominated by a high proportion of carnivores such as *Turritella* and *Erato*, infaunal filter feeders such as *Glycimeris* and *Cardita* and epifaunal suspension feeders such as the pectinids. Although the basal micrite bed at Attard quarry provides most of the species listed here and probably represents a sheltered depression in the sea bed, the biohermal developments also yield a less frequent fauna of the same species. The corals are infrequently bored by Lithophaga, a tropical and Mediterraenean species of the present day. Biofacies C is considered to be a subdevelopment of the Rhodolite biofacies, as the sediments surrounding the bioherms are identical to the latter and contain a similar fauna. Strombus sp. is a prominent element of this and is recorded from Attard and Ghar Lapsi. The inter bioherm areas are again typified by rhodolites, which delineate both biofacies.

Jointly the two biofacies reflect a depositional environment of increasing energy, possibly produced by the removal of one of the flanks of the "Miliolid Limestone gulf" by submergence. This probably allowed access of marine currents into the gulf and an open shoal environment developed, subjected to moderate turbulence and typified by rhodolites.

d) Biofacies D. Clypeastrina Biofacies.

This biofacies corresponds to the Xlendi Member and is characterised by echinoids of the sub-order Clypeastrina. These thick shelled echinoids appear to be the only ones able to withstand this rigorous environment. Scutella subrotunda, the dominant species here, is invariably abraided and fragmentary. Spine bearing specimens have never been located, hence it is difficult to postulate their life environment. Less damaged specimens, however, occur in the planar bedded areas (see Fig.6), where turbulence was apparently less and it is considered that this is a likely life environment for them. Kier and Grant (1965, p.1) record Encope Michelina Agassiz in areas of deep sand, into which they burrow to a depth of a few centimetres. Hedgepeth (1957, p.1191) records Scutella as a shallow water dweller, where they crawl along the bottom partially covered in sand. The flat disc-like form is, therefore, one best suited to lying just below the sediment/water interface under turbulent conditions. Perhaps colonies of these were periodically excavated by the strong currents and transported varying distances after death. Scutella is also associated with Echinolampas, a shallow burrower, in eastern Malta. Heterostegina and Nummulites also indicate shallow conditions.

Although the sedimentary composition of the Member is very similar to the Attard Member, the macroscopic appearance could not be less so. Tabular cross-bedding is the dominant bedform, though foreset studies give no preferred orientation, except at Ghar il Qamh (306931), Gozo, where a south-easterly current direction is indicated. The sets are dominantly made up of low angle, concave, foresets (7-14° in Malta, 4-18° in Gozo), and averaging 10° for both islands. Each set varies from 100mm. to 2.5 metres in height. McKee (1964, p.286) indicates that this form of low angle bedding is indicative of emerging offshore bars. Swinchatt (1967, p.113) and Jopling (1965, p.782) confirm this view and suggest that low angle concave foresets are to be expected where velocity/depth ratios increase. Areas of calmer deposition, such as the transitional areas between this Member and the Il Mara Member, are dominated by planar bedding or even massive lithologies. These, as previously stated, probably reflect lower energy conditions in sheltered or deeper areas.

The abundance of abraded coralline algal clasts within the Xlendi Member leads to the conclusion that there may well be some degree of contemporaneity between this and the Attard Member. Intense erosion of the top of the Attard Member at Naxxar Gap, however, together with localised anticlinal development, points to significant lithification of the Attard rhodolite beds prior to the development of the Xlendi Member, with subsequent reworking of sediments. Both conclusions may, therefore, be true.

It appears that the offshore bar and shifting sandwave environment developed in response to the increasing turbulence within the environment. There appears to have been a turbulence threshold beyond which regeneration of damaged rhodolites ceased. Once this was reached the seafloor stability which these growths imparted was removed, and the remaining bioclastic debris was permitted to move more freely. At Salina Bay membraniporiform bryozoans colonise the dead rhodolites at the top of the Attard Member but were soon overcome by the shifting bioclastics. These deposits show evidence of accumulation in a shallow environment. The absence of land derived material and obvious channelling, indicate that land was some distance away at that time.

e) Biofacies E. Giant Foraminifera Biofacies

There is a transitional change between this biofacies and the Xlendi Member in a lateral direction, and between it and the Lower Globigerina Limestone in a vertical sense. The biofacies is dominated by the giant benthonic foraminifera Lepidocyclina and Heterostegina, but also with an abundance of other benthonic foraminifera, none of which are abraded. Together these forms make up extensive banks, particularly in the thickest areas of deposition. Vaughn and Cole (1941, p.21) record both as being warm (20-30°C), shoal water forms with a maximum depth tolerance of 50 metres in Trinidad. Carpenter (1862, p.288) indicates that these forms are also abundant in Australian and Philippine waters of the present day.

f) Biofacies F. Reteporiform Bryozoan/Pectinid Biofacies

This is a further subdivision of the Il Mara Member and is dominated by Sertella sp.(reteporiform), with abundant Cellopora (celleporiform) and erect Membranipora (membraniporiform) bryozoans. Vinculariform bryozoans are of minor significance. These subdivisions are based on those originated by Stach (1936) and will be discussed in more detail in the Terebratula-Aphelesia Bed, Chapter 10. The Biofacies F bryozoans are usually in large unabraded sections and the pectinids are often articulated. Collectively the bryozoans suggest gentle to moderate current velocities, with slow sedimentation in normal salinity seawater, varying in depth between 10 and 90 metres (Lagaaij and Gautier 1965, p.51). It would also appear that a firm seabed was also present, though the presence of erect membraniporiform bryozoa does not preclude the presence of marine grasses. In some areas the Member is thought to have been deposited in moderately deep water, the lack of coralline algal fragments indicating that the micrites were also far away from such source areas.

In marginal areas of the facies, such as the San Leonardo coastline of southern Malta, *Scutella* sp. and *Echinolampas* are associated with *Lepidocyclina* in a mixing of biofacies D, E and F. *Cidaris* is also common in this mixed biofacies at San Rocco and confirms the generally higher energy of the transitional parts (see Fig.6). Possibly the finest developments of this facies are at Il Mara.

Interspersed with these beds, but generally with a low bryozoan component, are the sporadic bioherms of articulated *Terebratula minor* (Fig.6.). These are usually in the finest micrite areas towards the top of the Il Mara Member, possibly where sheltered conditions occurred. *Thecidium adamsi* also appears to be from similar horizons (Adams 1864, p.10). Specimens in the British Museum of Natural History (B.M.N.H.10728) suggest that they were attached to crinoid-like material during life. The pectinids were probably abundant in the previous two biofacies but are only well preserved here due to the overall calmer conditions.

3. General Details

The preceding biofacies are usually very distinct, although in several areas a clear transition between them is well seen. At Qammieh in northern Malta there is a rapid change from the Clypeasterina biofacies to the succeeding Lower Globigerina Limestone. It is, however, considered that the intermediate beds are related to the upper parts of biofacies F. Here on a wave-cut platform hundreds of moderately perfect *Scutella* sp. occur in a yellow biosparite, which grades imperceptibly upwards into Globigerina Limestone. No significant orientation is recognised other than a general parallelism with the bedding. They are considered to represent a reworked life assemblage. None show spines and most were fractured after death. Two specimens showed premortal damage but this merely amounted to minor crescentic and 'V' shaped clefts being removed from the periphery of the tests. These could have been caused by crustacean or cidarid predation and fragments of both are associated in the same beds.

4. Geological History of the Lower Coralline Limestone Formation

In summary, it may be stated that the Il Mara Member and its biofacies variations reflect deposition in a moderately deep environment which first established itself in the east, but gradually moved northwestwards with time. The shallower shoal areas, biofacies E, were dominated by giant forams, and the deeper, more sheltered areas by bryozoans. This Member is transitional with both the underlying Mlendi Member and the overlying Globigerina Limestone. A positive change from a closed environment, the Miliolid Limestones, through a shallowing but more open marine episode, Attard and Mlendi Members, to a regional submergence, Il Mara Member, is recognised. This progressive change from a reefal environment (Attard Member), through Lepidocyclina bearing deeper beds, ultimately to Globigerina Limestone formation appears to be very similar to the Cretaceous and Tertiary reef formations and flanking sediments of the Middle East (Henson 1950).

TABLE 1

FAUNAL AND FLORAL LIST FOR THE LOWER CORALLINE LIMESTONE

In compiling this list the following references have been consulted: Wright (1855), Duncan (1865), Fuchs (1874), Murray (1890), Gregory (1929), Roman and Roger (1939), and specimens housed in the British Museum (Natural History). Genera and species of known horizon and those collected during the present study are noted in the text. The authorships of all species are listed, where known.

Echinodermata

Cidaris adamsi Wright.
Cidaris oligocenus Gregory.
Cidaris avenionensis Desmant.
Cidaris tongremanus Wright.
Cidaris melitensis Forbes.
Echinus tortonicus.
Psammechinus duciei Wright.
Brissus cylindricus Agassiz.
Brissopsis grateloupi Sismonda.
Hemiaster scillae Wright.
Hemiaster cotteaui Wright.
Schizaster parkinsoni Defrance.
Scutella subrotunda Leske.
Scutella sp.
Clypeaster latirostris Agassiz.
Pericosmus latus Agassiz.
Breynella equizonata Gregory.
Eupatagus dekoninki Wright.
Echinolampas posteriolatus Gregory.
Echinolampas deshayesi Desor.
Gregoryaster sp.
Echinocyamus sp.
Collopleurus melitensis Zammit-Maempel.
Asteroid dermal denticles.

Gastropoda

Turritella cathedralis Brongniart.
Turritella incisa.
Turritella sp.
Cassis elegans.
Conus deperditus.
Natica tigerina Defrance.
Natica sp.
Ova sp.?
Voluta modesta.
Fusus lugensis.
Fusus elongatus.
Bassilissa sp.
Amaurellina sp.
Pyrula cf. condita (Klien) Brongniart.
Murex cf. asper.
Tritonium sp.
Pleurotomaria sp.
Panopea sp.
Erato sp.?

TABLE 1 (continued)

Lamellibranchiata

Pectan malvinae Dubois.
Pecten haveri.
Pecten deletus.
Pecten arcuatus.?
Pecten sp.
Flabellipecten pasinii Meneghini.
Flabellipecten fraterculus Sowerby.
Chlamys (Amusiopecten) burdigalensis Lamark.
Chlamys (Aequipecten) northamptoni Michelin.
Ostrea edulis var. boblayei Linné.
Ostrea sp.
Pholadomya sp.
Venus aglaurea.
Venus lugensis.
Tellina cf.biangulata.
Cardita laurae.
Cardita crassa Lamark.
Cardium tenuicostatum.
Cardium cf. porulosum.
Cardium sp.
Chama sp.
Lithophaga lithophaga Linné.
Kuphus polithalamid Linné.
Crassatella cf. neglecta.
Crassatella sp.
Glycimeris sp.
Arca sp.
Arca grumensis.
Cudilacea sp.
Spondylus cf. cisalphinus.
Spondylus sp.

Decapoda

Cancer spp.

Brachiopoda

Thecidium adamsi Macdonald.
Terebratula minor Phillipi.

Bryozoa

Cellepora sp.
Sertella sp.
Vinculariform forms.
Membraniporiform forms

Anthozoa

Astraea (Heliastraea) ellisia Defrance.
Astraea (Heliastraea) forbesi Duncan.
Stylopora cf. confera Reun.
Tabellastraea cf. reusiana ME and H.
Porites sp.
Monastraea sp.
Meandrina sp.
Collpophyllia sp. aff. vetusta Michelin.
Caryophyllid.
Coral genus A sp.a.

TABLE 1 (continued)

Miscellaneous

Entobia sp.
Serpula sp.

Foraminifera

Lepidocyclina (Eulepidina) dilatata Michelotti.
Spiroloculina sp.
Miliolina sp.
Neoalviolina melo Fichtell and Moll.
Textularia trochus d'Orbigny.
Claviculina communis d'Orbigny.
Carpentera utricularis Carter.
Gypsina sp.
Cycloclypeus sp.
Heterostegina sp.
Rotalia soldanii d'Orbigny.
Nummulites sp.
Praerhapydionina sp.
Austrotrillina sp.
Amphistegina sp.
Spiroclypeus sp.
Globigerina sp.

Coralline Algae

Lithothamnion miocenum Samsonoff.
Lithothamnion intermedium Kjellman.
Lithothamnion sp.
Lithophyllum destefanii Samsonoff.
Achaeolithothamnion intermedium Rainier.
Corallina sp.
Jania sp.
Melobesia sp.
Mesophyllum sp.

Unless specifically noted in the text the precise horizons from which this fauna and flora were collected is not known beyond what has been stated. Field evidence suggests that most of the molluscan element present has been collected from the Attard Member and the echinoids from the Scutella beds and transitional facies of the Il Mara Member. The scope of this work does not include a detailed study of the foraminifera, and detailed faunal lists of this and all the formations to be studied are to be found in Felix (1973).

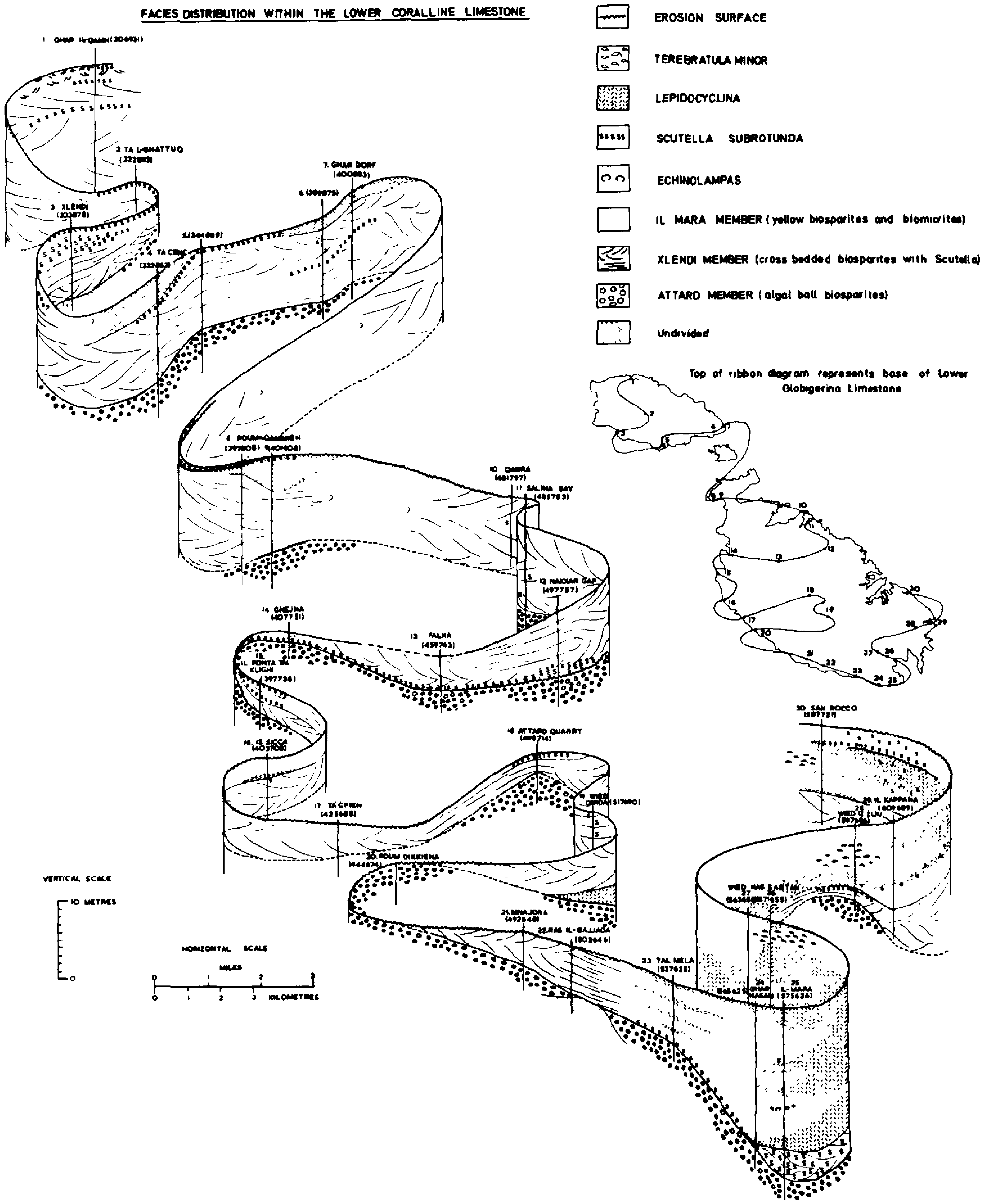

FACIES DISTRIBUTION WITHIN THE LOWER CORALLINE LIMESTONE
EROSION SURFACE
TEREBRATULA MINOR
LEPIDOCYCLINA
SCUTELLA SUBROTUNDA
ECHINOLAMPAS
IL MARA MEMBER (yellow biosparites and biomicrites)
XLENDI MEMBER (cross bedded biosparites with Scutella)
ATTARD MEMBER (algal ball biosparites)
Undivided
Top of ribbon diagram represents base of Lower Globigerina Limestone
1 GHAR IL-QAMH (304931)
2 TA L-GHATTUQ (332883)
3 XLENDI (303878)
4 TA CENC (332862)
5 (344869)
6 (388875)
7 GHAR DORF (400883)
8 RDUM-QAMMIEH (399808)
9 (409808)
10 QAWRA (481797)
11 SALINA BAY (485783)
12 NAXXAR GAP (497757)
13 FALKA (459743)
14 GNEJNA (407751)
15 IL PONTA TAL KLIGH (397736)
16 IS SICCA (403708)
17 TA CPIEN (425688)
18 ATTARD QUARRY (495714)
19 WIED QIRDA (517690)
20 RDUM DIKKIENA (444674)
21 MNAJDRA (492648)
22 RAS IL-BALLIADA (502646)
23 TAL MELA (537635)
24 GHAR HASAN (546625)
25 IL-MARA (575626)
26
27 WIED HAS SABTAN (543658) (571655)
28 WIED Z ZLIU (597688)
29 IL KAPPARA (609689)
30 SAN ROCCO (587721)
VERTICAL SCALE
10 METRES
0
HORIZONTAL SCALE
MILES
0 1 2 3
0 1 2 3 KILOMETRES

Fig. 6

MODAL ANALYSES OF LOWER CORALLINE LST.

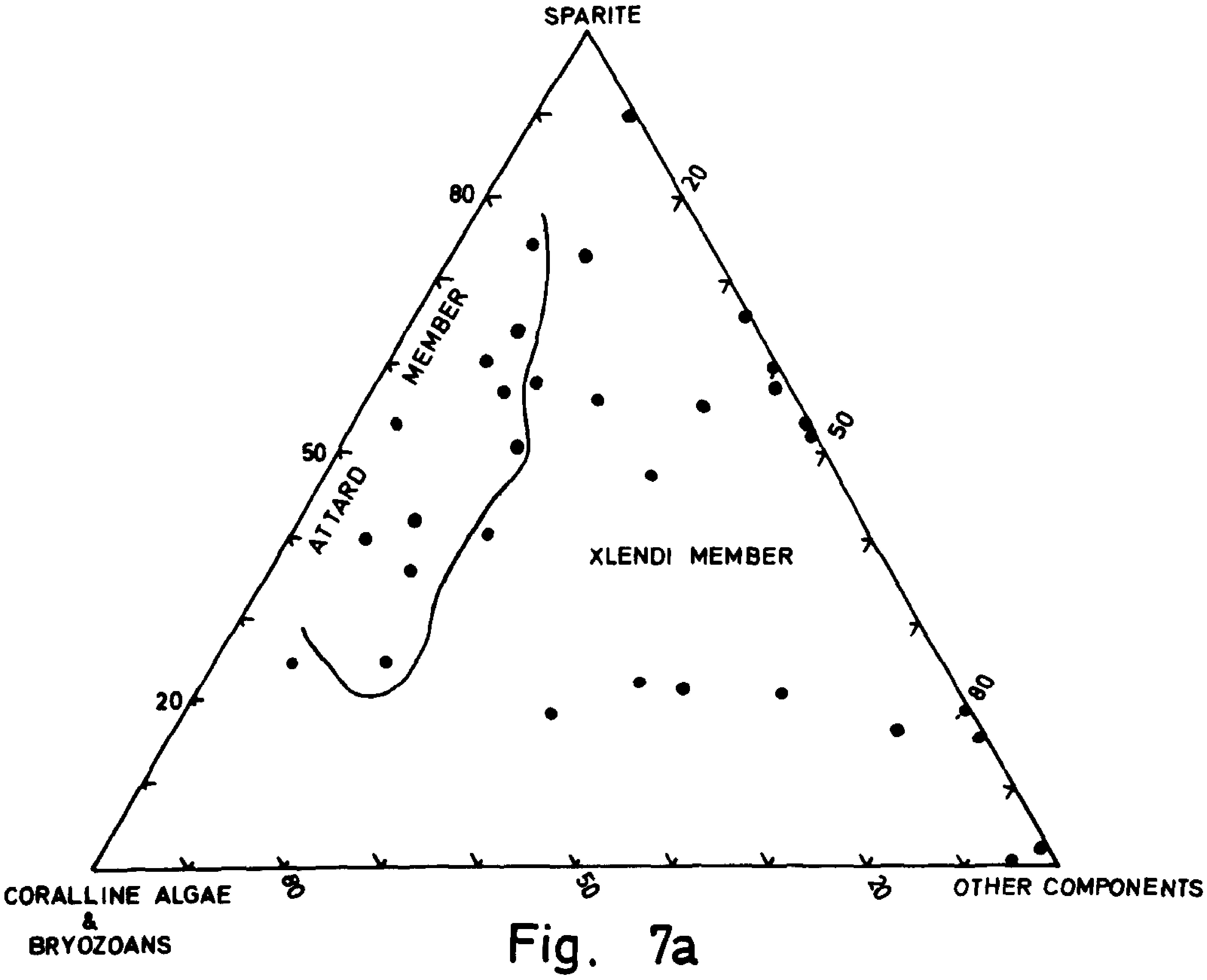


Fig. 7a

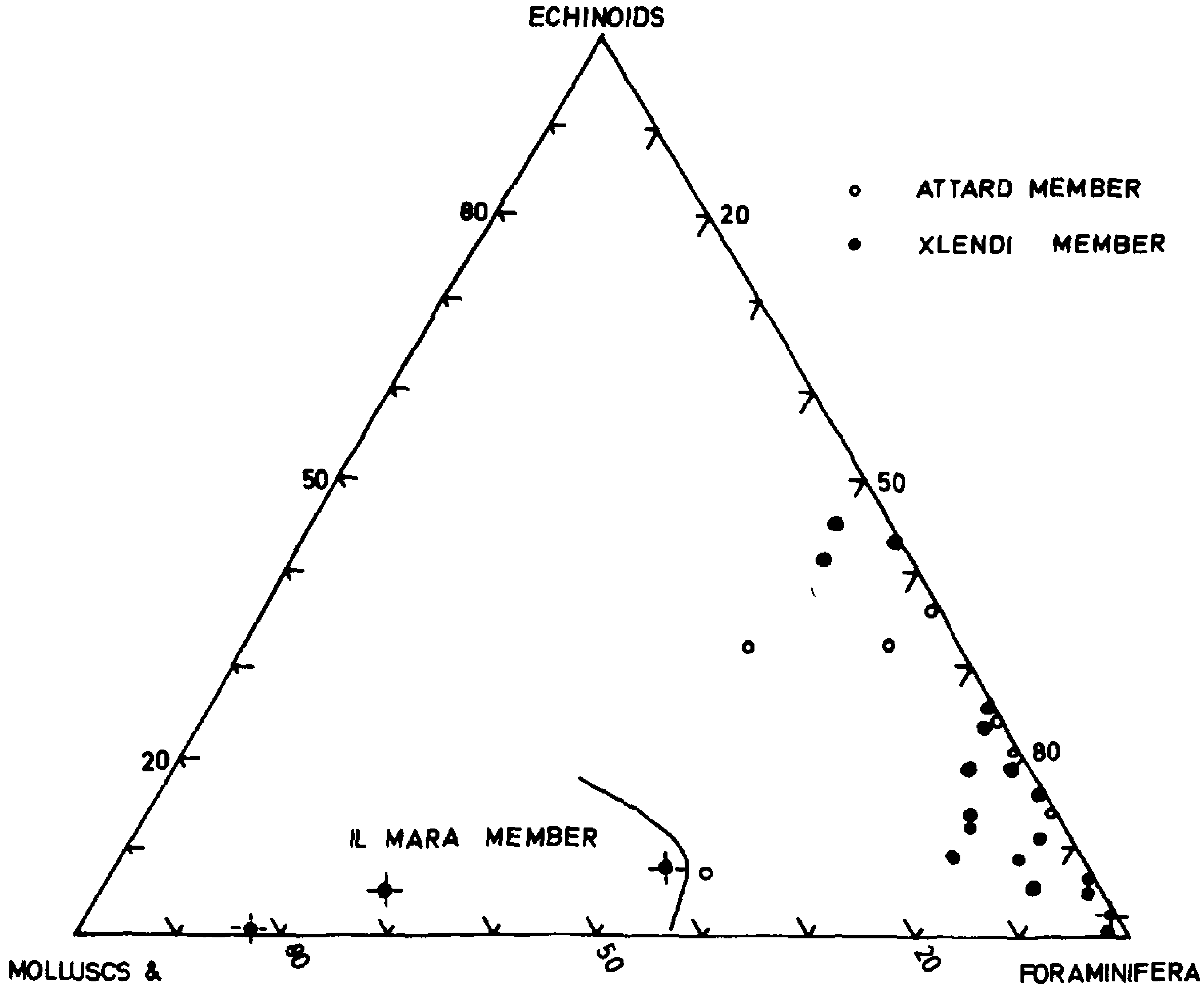


Fig. 7b

CHAPTER 4

THE GLOBIGERINA LIMESTONE

1. Stratigraphy

This formation is exposed over about 65% of the islands, though the upper members are restricted to areas closely adjacent to the Blue Clay and Upper Coralline Limestone. Most of Eastern Malta is covered by pale yellow biomicrites of the Lower Globigerina Limestone. Spratt (1843), first named this formation the "Calcareous Sandstone" but this was later changed to Globigerina Limestone by Murray (1890, p. 470), due to the abundance of the planktonic foraminifer Globigerina sp. Various subdivisions have been erected on the basis of either rock colour (an unreliable criterion), or the presence of phosphorite beds which extend over wide areas of the islands. These latter beds, however, have to be treated with caution, due to their possible bifurcating nature.

Morris (1952, p. 55-56), later confirmed by House et al. (1961, p.27-28) presented the best subdivision of the Formation and this is adhered to in the present work, with minor nomenclatorial changes (see Fig. 2).

3 Upper Globigerina Limestone	c.	Bed C
	b.	Bed B
	a.	Bed A
2 Middle Globigerina Limestone	b.	C2 Phosphorite Conglomerate Bed
	a.	White biomicrites, Grey marls with chert
1 Lower Globigerina Limestone	b.	C1 Phosphate Conglomerate Bed
	a.	Yellow biomicrites

1. Lower Globigerina Limestone

(i) General

This subdivision includes all the strata between the top of the Lower

Coralline Limestone and the base of the Middle Globigerina Limestone, including the C1 Phosphorite Conglomerate Bed.

(a) Yellow Biomicrites

(i) Lithology and Distribution

The typical rock consists of a pale yellow Globigerina biomicrite, characterised by honeycomb weathering, especially in eastern Malta. Towards the west the bioclastic components increase at the expense of the planktonic foraminifera. The pale yellow colour appears to be due to oxidation of iron compounds as, when seen in fresh exposures such as in the Msida Valley (5272), the rock is pale grey.

From a maximum development of over 100 metres around French Creek (565712), the formation thins rapidly westwards to less than 1 metre in the Rdum Dikkiana area (4566), (See Fig. 9a,). In Gozo, (Fig. 9b) thicknesses are less variable and range from 5 metres in the Sannat area (315890) in south-eastern Gozo, up to over 40 metres near Wied ir-Raheb (272922) in the northwest. The C1 Bed is included in these descriptions as its contribution to total thickness is insignificant. The dominant features of the isopachyte maps (see Figs. 9 and 10), are the pronounced thinning in a westerly and north-westerly direction in Malta and the southerly thinning in Gozo. A significant aspect of the beds is the development of neptunian dykes between Dahlet Qorrot and Mgarr in Gozo. These beds grade imperceptibly down into the Il Mara Member of the Lower Coralline Limestone at Qammieh, Malta (3980) and in western Gozo, but in many other cases, however, they rest disconformably on the Lower Coralline Limestone, at the junction of which a phosphorite conglomerate bed is poorly developed, particularly at Qawra, Malta (79 80).

The strata below the C1 Phosphorite Conglomerate Bed at Fomm ir-Rih and Gnejna, Malta (407751), **are** of uncertain age as the lithology is similar to parts of the Il Mara Member but lacks the diagnostic Lepidocyclina sp. and Scutella sp. **They are** here considered to represent a transitional facies of Lower Globigerina Limestone age which was developed in the Gnejna area during most of Lower Globigerina Limestone times.

(ii) Petrology

In thin section the typical rock is seen to be a sparse to packed yellow biomicrite or foraminifera biomicrite. The foraminiferal content is dominated by *Globigerina* sp. but this is low in westerly outcrops, rising to over 50% in both easterly samples, and stratigraphically higher horizons (see Fig. 10b). The apparently low foraminiferal counts are due to the fact that point counting takes into consideration the intralocular sediments of the foraminifera, thus reducing the apparent dominance of forminifera within the samples. Bryozoans dominate thin sections from the west. Colson's analysis of the limestone (in Murray 1890, p. 469) indicates that 70-80% of the rock is made up of $CaCo_3$, but with up to 3.5% $Ca2PO_4$, 1.6% $MgCo_3$ and traces if iron and aluminium oxides. The insoluble content would appear to be 12-17% and to consist mainly of iron and alumina. A little glauconite and phosphorite pebbles (under 10mm diam.) occur with the unit in Dingli Cliffs and Rdumi Qammich, west Malta but this is derived in origin. Murray (1890, p. 470) also records quartz splinters, zircon, tourmaline, rutile, feldspar augite and hornblende from the formation as a whole, though the latter three are not confirmed in analyses carried out during this study.

All the carbonate rocks examined are composed of low ferrean calcite though a few bryozoans from Fomm ir-Rih are composed of ferroan calcite .

(iii) Fauna

Murray recognised foraminifera, ostracodes and echinoid spines in thin sections made from various horizons within the formation. *Coccolithus*, coccospheres and rhabdoliths are also abundant in some beds, as are the pen-shaped pteropod *Hyalea* sp. and *Cavolina cookie* Simonelli which are characteristic of the Lower Globigerina Limestone. The macrofauna is dominated by pectinids and irregular echinoids, though these are usually very localised in occurrence and thick sequences of the micrites are often apparently devoid of macrofossils. *Schizaster parkinsoni* Defrance and *Hemiaster cottreaui* Wright occur intermittantly throughout the beds as do infrequent horizons of *Thalassinoides* sp., especially at Qammieh, and below San Leonardo in Malta (Plate 3c.). Articulated specimens of *Asesma miocenica* Simonelli are present beneath the C1 Conglomerate Bed at Rdum Qammieh (397807), and undamaged and frequently articulated *Chlamys (Aequipecten) praescabriusculus* Fontannes and *Flabellipecten pasinii* Menighini are also common in western Malta at the same horizon. This fauna is associated with an ectoproct bryozoan fauna of vinculariform types and is dominated by reteporiforms and *Cellepora* cf. *parasitica.* These are best seen directly underlying the C1 Bed at Ras il Bajjada (502641), where additional common forms include *Spatangus ocellatus* Defrance, *Eupatagus konincki* Wright and aragonitic mollusc casts. In other parts of the island discontinuous bands of *Pecten* (*Amusiopecten*) *burdigalensis* Lamarck occur and have also previously been recorded at comparable horizons in Gozo by Wigglesworth (1964).

Nautilus occurs infrequently, occasional groups of individuals being recorded; for example 26 or more individuals from the Msida tunnel Malta have been noted (Zammit-Maempel, personal communication). Many of the fine fossil fish collected in the past from Luqa quarries are from these beds, as are the teeth and vertebrae of *Stereodus melitensis* from St. Julians. The deposits in eastern Malta are most fossiliferous and are believed to be partially condensed in nature. It is in these beds that the strongest development of *Thalassinoides* sp. occurs below the C1 Bed (Plate 3c).

b. C1 Phosphorite Conglomerate Bed

(i) General

This was originally named the "first nodule seam" by workers, including Spratt (1843). Subsequently it was realised that this bed could be traced throughout the Maltese Islands, occurring between the Lower and Middle Globigerina Limestone sub-formations. The bed was then given the formal name of "N1 Nodule Bed" by House et al. (1961, p.27), but is now considered to be a true conglomerate bed (Felix 1973, p. 24) and is here designated as C1 Conglomerate Bed.

(ii) Lithology and Distribution

The present study recognises the interpretation of Adams (1870, p. 127), that the nodules are really pebbles, but further considers the bed to be composite in origin, as secondary impregnation of the host rock, by phosphate solutions, around the pebbles has resulted in the development of a coherent and apparently nodular texture, thus creating confusion in nomenclature (See Plate 3a,b). The bed varies from about 200mm. in thickness to over 750mm. and is characterised by an irregular base and a planar top (Plate 3b). The contained pebbles are very amoeboid in form and vary in size from a few millimetres up to 160 metres. Their brown colour becomes paler with exposure and permits better examination of the mollusc and bryozoan borings which are common. No definite area of primary nodule development is recognised though there is a general increase in pebble size westwards, suggesting proximity to a source area. Throughout the islands the bed is entirely made up of reworked rock clasts and fossil casts, the latter often with phosphatised matrix still adhering to them.

(iii) Petrology

The C1 pebbles are cemented together with biomicrites similar to the Lower Globigerina Limestone. The dark brown of this matrix material is the direct result of impregnation by secondary phosphorite solutions, presumably derived from the associated pebbles. The pebbles themselves are dominantly packed Globigerina biomicrites, not dissimilar to the Lower Globigerina Limestone, though containing significantly smaller Globigerina tests. Occasional pebbles contain rounded glauconite pellets and a few show primary glauconite infilling foraminifera tests. Loose detrital glauconite pellets also occur in the C1 Bed. Finally, a few lithoclasts are themselves made up of a conglomeration of smaller phosphorite pebbles. An analysis by Cooke (1896), showed that the bed contained 51.2% $CaCo_3$, 31.66 CaP04, 10.55% Al., 3.83% Si, and 1.97% sulphate of lime.

(iv) Fauna

Faunal lists are misleading, for although this bed represents a condensed deposit, only the unphosphatised pectinids, occasional *Nautilus* casts and echinoids, all of Lower Globigerina Limestone type, may be considered as contemporaneous. The dominent pectinid form is *Chlamys northamptoni* Michelin, which usually occurs in a fragmentary or disarticulated state. The echinoids are dominated by *Spatangus* sp. and *Eupatagus* sp. Added to the list of contemporaneous fossils must be the occasional *Balanus* sp. which is found encrusting pebbles in western Gozo (329909) and *Hemiaster* sp.

Most of the derived fauna consists of bone and teeth fragments, dominated by the sharks *Carcharodon megalodon* Agassiz, *Isurus oxyrhinchus* Rafinesque, *Isurus cuspidata* Agassiz, *Odontaspis contortidens* Agassiz, *Hemerrestes serra* Agassiz, *Balistes* cf. *charcarias*. *Carcharias (Priondon) lamna* Risso, and *Lamna* sp. Waterworn bones and tusks of aquatic mammalia, including *Halitherium* sp. are also common, though often difficult to recognise. Other phosphatised casts and fossils include *Spatangus* sp. *Eupatagus* sp. *Cidaris* and spines, *Balanophyllia* sp. and *Flabellum* sp. Cooke (1896) also recorded *Conus dubius*, *Conus missigeria*, *Arca* sp., and *Cavolina cookei* Simonelli, presumably from this horizon.

2. Middle Globigerina Limestone

The white biomicrites and grey marls will be dealt with together, as precise separation of the two is difficult. The cherts, which form the only natural division, are restricted in distribution to westerly areas of Malta.

a. White Micrites and Grey Marls with Chert

(i) General

The apparently monotonous nature of the Middle Globigerina Limestone on first examination is misleading. Cooke (1893a, p. 158) described these beds and showed that the Globigerina Limestone could be divided into a tripartite division, the Middle Globigerina Limestone being "Bed B". The present study considers the sub-formation to be made up of all the beds between the top of the C1 Conglomerate Bed and the top of the C2 Conglomerate Bed. This follows the usage of House et al. (1961, p. 28).

(ii) Distribution

The isopachyte maps of the islands (Figs. 11a, b and 13) , show the same general configuration as those for the Lower Globigerina Limestone, except that the depositional high between the islands has now moved to eastern Gozo, in which area the C1 and C2 Conglomerate Beds converge and become indistinguishable (see also Wigglesworth 1964, Text Fig. 3). The thickness of the limestone varies from 0 metres to 110m, the latter figure being recorded from the Delimara area, Malta (5965).

In general,outcrops are restricted to peripheral areas of the Upper Coralline Limestone plateaux,but important outliers occur south of Birkirkara, Malta, in addition to Delimara. In Gozo,outcrops are generally restricted to Wied valleys and cliff sections.

(iii) Lithology

The white colour of the rocks reflects their general lack of iron minerals. The sequence is complex and commences with yellow biomicrites in western areas of Malta, but this rapidly changes to white limestone. In western Gozo an additional facies of yellow limestones, wedging out eastwards, was recognised by Wigglesworth (1964, p. 27) at the top of the sequence. The lower white biomicrites of both islands exhibits up to five minor phosphorite conglomerate beds, which appear in Malta to gradually converge in a westerly direction. At Tal Blata, Malta (396727) one of these is associated with deep channelling,orientated in an east-westerly direction. At Imtahleb (417700), the same bed is associated with north-east orientated neptunian dykes which are a few centimetres wide and are infilled with small phosphorite pebbles to a depth of as much as 7 metres (Plate 3d). Lateral burrow systems are also recognised, and extend out horizontally from the sides of several of the dykes.

At the top of the white biomicrites of Malta the strata is a medium grey colour and contains nodular chert horizons. This extends from Fomm ir-Rih to Siggiewi in the south. The grey chert appears to be secondary in origin and forms around burrow systems within the rock. Hyde (1955, p. 38) considers the less pure variety of this deposite to be "phtanite, an impure calcareous variety of flint". Russell (1955, p. 17), also records the occurrence of chert in the area east of Fungus Rock, Gozo (270894). This latter deposit is now recognised as being restricted to the Tal Harrax structure. It is dark khaki in colour, contains abundant macro-fossils and is well bedded.

The grey marls which commenced at the chert horizon in Malta extend to the base of the C2 Conglomerate Bed in western and eastern Malta and generally contain fewer phosphorite pebbles than the underlying beds. At Gebel Imbark, Malta (401808), strong north-easterly orientated jointing is present beneath the C2 Conglomerate Bed but does not penetrate it (Plate 5a).

(iv) Petrology

Petrologically the Middle Globigerina Limestone plots as a *Globigerina* biomicrite, similar to the Lower Globigerina Limestone,but with a generally lower benthonic foraminiferal count in the white beds (Plate 4a). A higher percentage of terriginous material occurs in the grey beds,with contents up to 10% or more in certain samples. Horizons with chert (Plate 4c) are characterised by small delicate *Globigerina* sp. which rarely comprise more than 10% of the rock. (See Plate 4c and Fig. 10b). The carbonate in all examined sections is low ferroan calcite.

(v) Fauna

The white biomicrites carry a sparse fauna of crushed Schizaster eurynotus Agassiz and Pecten burdigalensis Lamark. Schizaster parkinsoni Defrance appears to die out by the base of the Middle Globigerina Limestone, as pointed out by Wigglesworth (1964). Of special interest is the occurrence of Tomistoma champsoides Hulke, apparently from just above the C1 Conglomerate Trionyx melitensis Lydekker and Phoca rugosidens Owen, all found in the old quarries at Siggiewi, Malta.

The only fauna from the pebble beds within the white biomicrites are corals of the same genera as the C1 horizon. The cherts of Malta contain planktonic microfauna only, but the khaki cherts of western Gozo carry a rich fauna of foraminifera, Terebratula cf. minor Phillipsi and chert infilled Capsa sp. from the base of the beds. Abundant shell fragments also occur within the cherts. Associated biosparites contain abundant fragments of Cidaris avenionensis Desm.

Thalassinoides sp. is common and Lockeia sp. (Bromley 1974 personal communication) occurs at Fomm ir-Rih.

b. C2 Phosphorite Conglomerate Bed

(i) General

This is the second major phosphorite conglomerate horizon. The new name corresponds to that of "N2 Nodule Bed" in House et al. (1961, p. 27).

(ii) Distribution

This bed caps the Middle Globigerina Limestone in all areas and varies in thickness from 100mm to 500mm. It is best exposed at Fomm ir-Rih, Malta (402738) and in the cliffs south of here. There is a general thickening of the bed in a westerly direction in both islands, though thickness variations in northern Malta may reflect an advance of the source area onto the flanks of the Malta ridge, (see Fig. 12a,b). It is assumed throughout that bed thickness is a function of distance from source area. This interpretation is supported by the mean pebble size study (Fig. 12b). In this study the ten largest pebbles from a 1 metre length of bed were extracted. The longest and shortest axes for each pebble were measured and a mean axial length was obtained. The resultant ten mean axial length values were then added together and divided by the total pebble count, to give the mean pebble length for the entire sample. The method was found most satisfactory as phosphorite pebbles are usually very irregular or amoeboidal in form, often resembling English flints from the south coast. The resulting pebble study (Fig. 12b) shows the same trends in Gozo as for the bed thickness analysis but, in addition, shows an in situ development of phosphorite in western Gozo. The bed becomes broken up to the east of this area and the resultant mean pebble sizes diminish rapidly eastwards until they are under 10mm diameter at the centre of the depositional areas.

Malta does not show quite such a good fit between Figures 12a and 12b but sufficient agreement is present to state that mean pebble sizes diminish towards the centre of the island and also in a south-easterly direction at Delimara. Although the bed generally shows no sedimentary structures other than normal grading, dune development is recognised at (333915), near Marsalform, Gozo (Plate 3e) and breakup of in situ phosphorite to form breccia and conglomerate is visible in north western Gozo.

(ii) Lithology

At outcrop (Plate 5a), the bed is characterised by smaller pebbles than the C1 Conglomerate Bed and by the lack of secondary inter-pebble cementation. The individual pebbles, especially the larger ones, are amoeboidal in form and are frequently bored. Derived phosphatised fossils also make up significant proportions of the bed, these being dominantly gastropods, shark teeth and solitary corals, which often show attrition and surface varnish effects. Surface striations are common on all the derived material.

The top of the Middle Globigerina Limestone shows signs of erosion and burrowing, the abandoned burrow systems being later infilled by small phosphorite pebbles. These burrows are never as large or extensive as those below the C1 Bed. The top of the C2 Bed exhibits a transitional change between dense conglomerate and typical Upper Globigerina Limestone, with pebbles becoming fewer and smaller away from the base of the C2 Bed. The matrix of the C2 Bed in most areas is yellow Globigerina biomicrite,but at Bugibba, Malta (467785) it is white and the pebbles are dark grey, brown or green. This possibly indicates the primary state of the bed prior to oxidation of the iron compounds present.

(iii) Petrology

Detailed examination in this section reveals the existence of several distinct rock types. Most are dark brown in colour, but others are occasionally green in unweathered samples. The dominant pebble type is pale brown foraminifera biomicrite (Plate 4b) containing Globigerina sp., occasionally with intralocculär infills of glauconite. Dark brown micrites,rich in goethite (?) also occur. Other pebbles include oösparite, cherty pebbles and glauconite. The derived fossil casts are preserved in a pale brown phosphatised biomicrite. An X-ray diffraction powder analysis on one of the derived phosphatised coral casts, confirmed Murray's analysis that the rock was impregnated by collophane (francolite), this being a hydrated calcium phosphate.

The matrix between the pebbles is clearly related to normal sedimentation and is identical to the Upper Globigerina Limestone for the most part, though microspar formation has coarsened the matrix in some sections. Fragments of echinoid tests and pectinid valves complete the components,though these are never more than 2-3% of the rock.

(iv) Fauna

The contents of this bed differ only in number of species from that present in the C1 Bed. The reworked fossils are invariably abraded, carry bryozoan, sponge and small mollusc borings,and often an adherent matrix. The transported phosphatised fauna includes *Conus* sp., *Xenophoria* sp., *Flabbellun foecundum* Sesmonda, *Coenocyathus* sp., *Caryophyllia* sp., *Stephanophyllia* sp., and *Trococyathus* sp., together with *Vaginella* sp., and the tests of *Hemiaster scillae* Wright. Shark teeth are frequently abraded and phosphatised, often with encrusting *Ostrea* sp. and serpulids, now also phosphatised. The more frequent forms include *Carcharodon megalodon* Agassiz, *Lamna* sp., *Odontaspis contortidons* Agassiz, *Odontaspis cuspidata* Agassiz, *Balistes* sp., *Isurus oxyrhynchus* Rafinesque, *Hemepristes serra* Agassiz and *Carcharias* sp. Tusks of marine Mammalia and fragments of rib are also frequently found, as are the teeth of *Mastodon angustidens* Cuvier from Marsalforn.

The *insitu* fauna is dominated by the thin shelled *Chlamys burdigalensis* Lamarck and allied forms, which occur in a disarticulated and often fragmentary condition,intermixed with the yellow biomicrite matrix. Echinoids, including *Hemiaster scillae* Wright and *Echinolampas wrightі* Gregory,frequently occur in an entire state. In the areas,following the *insitu* phosphorite development of western Gozo, *Balanus* sp., and serpulids are frequently found encrusting the phosphorite pebbles . *Aturia aturi* Basterot and *Terebratula terebratula* Linné, occur in the bed below Ghajn Abdul, Gozo. The bed itself is intensely bioturbated and indeterminate unlined burrow systems penetrate up to 200mm. into the underlying Middle Globigerina Limestone. The Qawra subsidence infill,which may be approximately of this age,contains articulated *Megerlia* sp. in outcrops at the southern end of the structure.

3. Upper Globigerina Limestone

(i) General

At the top of the C2 Conglomerate Bed the Globigerina biomicrites show an immediate return to a yellow colour and exhibit a marked reduction in clay mineral content. Cooke (1896) first recognised that the beds could be split into a tripartite subdivision,but Morris (1952, p . 55-56) was first to apply this and called the beds from bottom to top, Beds A, B and C. Wigglesworth (1964, p. 31-32) applied this subdivision to Gozo but found that it failed in western and northern areas. The present study has recognised the tripartite division throughout the island of Malta,except for the western end of the Marfa Ridge (3980), Tal Bajjada (475563), and Wied L-Arhata (258466), (see Figs. 14, 15 and 16).

(ii) Lithology and Distribution

In Malta these beds are distributed around the periphery of the Upper Coralline Limestone plateaux on the western side of the islands. An important outlier exists at Delimara in eastern Malta where, it is believed, most of the subdivision is present. In Gozo the beds are exposed along the cliff sections surrounding the islands,but inland they are restricted to the Wied valleys and low land between the Blue Clay and Upper Coralline mesas and buttes. Honeycomb weathering is typical of beds A and C.

The general isopachyte map of the islands (Fig. 16b) clearly indicates the same general configuration as that for the Lower Globigerina Limestone, with thinner successions in westerly areas and around the Comino Straits. In addition, however, the beds are also seen to thin southwards in western Malta and northwards in the Delimara region. Little data has been accumulated on these beds and hence they are briefly dealt with.

a. Bed A

(i) General

This is the lowest division and varies in thickness from under 5 metres to over 8 metres (Fig. 15a), with deposition centred on north-western Malta and central Gozo. The bed is lithologically similar to the Lower Globigerina Limestone,but in addition contains scattered goethite and limonite concretions. A thin phosphorite conglomerate (C2b) is developed 0.2m to 2.5m above the base of the bed and,though it is present throughout western Malta, it is most apparent in the coastal sections between Imtahleb (417704) and Il Kullana (457663). This bed is absent from Delimara, and the Upper Globigerina Limestone base here is associated with sub-centimetre sized phosphorite pebbles (C2). All three subdivisions of the Upper Globigerina Limestone are present at Delimara, with Bed A being best developed (Plate 4d). The lithology of these is different to other areas and consists of ribs of well cemented rock alternating with softer beds. Several hardgrounds are developed within the bed.

b. Bed B

(i) General

These sediments mark a return to grey marl sedimentation,typical of the top of the Middle Globigerina Limestone. The isopachyte map for this bed indicates the same general configuration as for Bed A, and with thickness ranges of the same order (Fig. 15b). In western Gozo the bed appears to be unrepresented and Bed C rests disconformably on Bed A,with scour and fill channels at the contact (Plate 5b). At Wied L'Arhata in Malta brown marls make up Bed B and apparently extend to the top of the Globigerina Limestone Formation. The bed is 2.5 metres thick at Delimara.

c. Bed C

(i) General

This bed marks a final return to the yellow Globigerina Limestone deposition before the onset of Blue Clay conditions (Fig. 16a). The bed is typified by honeycombe weathering and an abundance of goethite concretions particularly towards the top of the Bed. The areas of maximum deposition shifted slightly at this time to a north-south belt, extending down the western side of Malta, where up to 8 metres of sediments accumulated. The area of thickest sedimentation is Delimara but it is likely that the beds were originally thicker here prior to the post-Miocene erosion.

(ii) Combined Petrology

Murray (1890, p. 479) recorded quartz splinters, feldspar, tourmaline, zircon, rutile augite and hornblende from the sub-formation. Thin section studies show that these components are in insignificant quantities and that the rock is typically a sparse to packed *Globigerina* biomicrite (10b). Although Murray (1890, p. 470) indicates that the $CaCo_3$ content may approach 95% for the purest sample, it was found that samples from western Gozo, where the beds are thinnest, were nearer 60% $CaCo_3$, the rest being clay particles.

(iii) Combined Fauna

The fauna of these beds is rather sparse, though the pteropod *Vaginella* sp. does appear to be characteristic of the yellow biomicrites. Wigglesworth (1964. p. 32) records conoclypeid echinoids and pectens from eastern Gozo. The Delimara Bed A contains scattered *Schizaster eurynotus* Agassiz and *Chlamys burdigalensis* Lamark, *Ostrea* sp. and *Thalassinoides* sp. are also present in the area. Cooke (1896) records abundant lignite in Bed B at Qammieh in northern Malta and this was confirmed during the present study. The thin phosphorite conglomerate bed above C2 yields an abundance of eschariform bryozoans possibly *Escharia monilifera* Mich, which are identical to (B.M.N.H. D9404). Scattered throughout beds A and C are the thick shells of *Epitonium meletensis* (Fuchs). Cooke (1896) also records *Pecten koheni* Fuchs, *Pecten denudetus* Reus, *Dolichostoma catapracta* *Aturia* sp., and *Nuculana* sp. Withers (1953) records the barnacles *Scalpellum mollinianum* and *S. lovisatoi* from the Lower Globigerina Limestone and *Scalpellum mollinianum*, *S. lavisatoi* and *Trilasmis melitense* for the Upper Globigerina Limestone. The crabs *Calappa heberti*, *Necronectes schaffen*, *Neptunus* granulatus and Ranina (Ranina) cf. brevispina also occur at this level. Backfilled echinoid burrows are frequent in the Lower Globigerina Limestone of Mellieha Point west of Mgarr, Gozo.

4. Diagenesis within the Formation

Several lines of evidence suggest that early penecontemporaneous diagenesis was important within the formation. The main evidence is: the formation of neptunian dykes within the partly lithified sediments previously mentioned; the development of phosphatised pebbles from lithified Globigerina Limestone sediments, and the occasional occurrence of marly white limestone clasts within the C2 Phosphorite Bed in Malta (Felix 1973, p. 25) and also in eastern Gozo. These are considered to be the result of erosion of the Middle Globigerina Limestone. It would appear that subsequent to the development of Thalassinoides burrow systems into the top of the lower Globigerina Limestone lithification occurred and the burrows were abandoned, ultimately to be infilled by phosphorite pebbles and bioclastics. This hardground remained uncovered for a considerable time and corrosion and attrition within the shallow water environment was responsible for widening the apertures to these burrows and produced the characteristically fretted karstic appearance to the surface. It is considered that secondary phosphorite diagenesis of this fretted surface and the inter-pebble matrix was the direct result of impregnation of that surface by descending phosphate charged pore solutions (D'Anglejan 1967, p. 86), from the closely associated and overlying phosphorite pebbles, though Felix (1973, p. 27) considers that the base of some solution pits are unphosphatised. The secondary phosphatisation of the Lower Globigerina Limestone resulted in only a partial replacement of the pre-existing carbonate, and earlier ferroan calcite replacement of various bryozoan fragments resited this phosphatisation. Some foraminifera within the derived phosphorite pebbles also resisted phosphatisation.

The horizons of Middle Globigerina chert formation show that small 0.1mm dolomite rhombs formed prior to silicification in a manor similar to that noted by Larsen and Chillinger (1967, p. 332). In Malta the chert has often selectively replaced the matrix without affecting the calcite foraminiferal tests, which are,however,frequently seen to enclose radiating quartz fibres. The macrofossils within the Gozo chert have also resisted silicification even though the matrix is completely replaced. It is clear, therefore,that the chert is diagenetic in origin. It is considered that the cherts of Malta formed from low temperature, saturated pore solutions of low pH. in a manner comparable to that suggested by Blatt et al. (1972, p. 468). The cherts of the Tal Harrax outlier of Gozo are bedded,rather than concretionary,in nature and are associated with a benthonic fauna. It is uncertain whether these are of the same origin as the Malta examples, or whether they formed on the seabed within this syndepositional solution subsidence structure more or less penecontemporaneously with carbonate deposition,in a manor comparable to the formation of bedded cherts (Blatt et al. 1972, p. 537; Rasmussen 1971, p. 213),though Blatt's postulated depths of 120-183 metres must be considered as absolute maximum in this case and depths of about 50 metres would be more acceptable.

The presence of infilled Entobia borings within derived phosphatised shell casts from the C2 Phosphorite Conclomerate suggests that these lithoclasts entered the Maltese area as aragonitic shells,which were subsequently removed by dissolution at some time after arrival. The darker rims to C1 phosphorite pebbles and the yellowish brown haloes within the matrix immediately surrounding pebbles from higher horizons is an effect of outward migration and concentration of ferrous solutions from within the pebbles. The origin of this iron is probably to be found in the breakdown of glauconite clasts and infills within the pebbles,but may also originate from iron oxides which are occasionally seen to infill foraminifera tests.

Late stage diagenesis is probably related to the final subaerial history of the islands and consists of the development of secondary cementation at selected sites within the rock, causing the development of hard ribs alternating with softer layers. Selective cementation of sediments within poorly defined burrow systems is responsible for the development of the characteristic honeycomb weathering.

5. Palaeoenvironmental Interpretation

The lithofacies of the Globigerina Limestone Formation described above possess a remarkably constant biofacies make up, which is as follows:

a. Biofacies F Reteporiform Bryozoan/Pectinid Biofacies
b. Biofacies G Pectinid/Spatangoid Biofacies
c. Biofacies H *Chlamys*/*Hemiaster* Biofacies
d. Biofacies I Solitary Coral/Mollusc Biofacies
e. Biofacies J Eschariform Bryozoan Biofacies

a. Biofacies F Reteporiform Bryozoan/Pectinid Biofacies

This is identical to the previously described biofacies F of the Lower Coralline Limestone and is considered to represent the area of shallowest deposition within the Lower Globigerina Limestone sea, which had retreated north-westwards throughout Lower Coralline Limestone times to the Fomm ir-Rih area. The bryozoan assemblage, dominated by reteporiform and large celleporiform types, is considered to be characteristic of depths in the order of 50 to 60 metres, with moderate to gentle current action and little or no sedimentation.

The pectinid fauna is frequently articulated and is little damaged, further supporting the interpretation. The final diagnostic feature of the facies is the general lack of planktonic foraminifera, suggesting that the environment was cut off from normal marine circulation.

b. Biofacies G Pectinid/Spatangoid Biofacies

The most widely developed biofacies within the islands falls into this category and includes all the Lower Globigerina Limestone, Middle and Upper Globigerina Limestones;with the exception of F above. Throughout the islands the biofacies is typified by a dominant planktonic foraminiferal microfauna and a macrofauna of disarticulate pectinids and entire,but spineless tests of Schizaster sp., and other spatangoid echinoids. In spite of the apparently unreworked nature of the sediments,the disarticulation of the pectinids and the lack of spines on the echinoids is taken to indicate intense bioturbation,and possibly even periodic reworking of the sediments by current action in some areas.

Depths of less than 200 metres are envisaged for the accumulation of this biofacies,and not the 1000 fathoms postulated by Murray (1890, p. 474). The former estimate is based on a comparison with the Miocene Globigerina Limestones of the English Channel (Funnel 1967, p. 334), in which the limestones have a comparable Globigerina percentage. Felix (1973, p. 56) considers a depth of 40 to 100m for the Lower the Middle Globigerina Limestone, though the benthonic foraminifera faunas of parts of the Upper Globigerina Limestone of buliminids suggests depths up to 150 metres. The accumulation of such a high planktonic foraminiferal content on a comparatively shallow shelf area is explained by the Miocene position of Malta on a mid Tethyan submarine rise. Drifting open sea planktonic elements including pteropods, cephalopods and foraminifera would be brought into the shallow intra-rise basins, such as the Maltese area, by water or wind currents. Upon death these components would rain down from the water into the shallow basins, thus creating the misleading effect of a deep water deposit in an otherwise shallow basin. The abundance of deep sea pteropods within this biofacies need not indicate depths in excess of 200 metres,as Avnimelich (1966, p. 310) pointed out in his study of the Miocene pteropod facies in Israel. The reason for the general low faunal content, apart from that mentioned above, is not apparent unless these deposits accumulated more rapidly than expected, thus creating the effect of heavy sedimentation. The marl beds of the Middle and Upper Globigerina Limestone need not indicate shallower water but merely periodic influx of Blue Clay type clay suspensions entering from outside the region. The presence of abundant horizons of Thalassinoides sp . points to a "Cruziana Ichnofacies" (Seilacher 1967) depth which is also consistent with other evidence. Bromley 1974 (personal communication) considers very shallow conditions to have prevailed in western areas of the islands,on the basis of contained trace fossils.

c. Biofacies H Chlamys/Hemiaster Biofacies

This biofacies conforms to the in situ fauna of both C1 and C2 Phosphorite Conglomerate Beds of the Globigerina Limestone Formation. The fauna is very similar to that of Biofacies G except that the apparently moderately deep burrowing Hemiaster sp. is the only common echinoid met with in the beds. Chlamys northamptoni, the main pectinid is a thick shelled and strongly ornamented species and these points,together with its generally disarticulate or even fragmentary condition,indicate fairly high energy conditions. Conditions may have been gentler on the C2 Bed as the dominant pectinid here is Chlamys burdigalensis, a thin shelled, low ribbed form,although disarticulation is the rule in this bed also. In western Gozo both C1 and C2 Beds are occasionally encrusted with Balanus,further indicatihg conditions of strong turbulance,as does the dune development of the C2 Bed in the Victoria road south of Marsalforn, Gozo (Plate 3e). It is obvious that this biofacies is one of high turbulence and low sedimentation in an extremely shallow environment. Perhaps the best guide to depth is obtained from the phosphorite pebbles themselves,as it is difficult to envisage transport of such large blocks as some of these in depths possibly in excess of 50 metres.

d. Biofacies I Solitary Coral/Mollusc Biofacies

This biofacies is not native to the islands at these horizons and is represented by the transported pebbles, casts and fossils of the phosphorite conglomerate beds, which are believed to have been transported into the area from the west. The solitary corals are most abundant,but unfortunately they give little information regarding depth as many are wide ranging forms; for example Flabellum, deeper than 40 metres or Balanophyllia 130-520 metres. Most are, however, indicative of sub-tropical seas such as those around Australia at the present day. The Molluscan fauna is entirely of shallow water aragonitic types which are generally not found below 200 metres. The occasional occurrence of Entobia may reduce the depth estimates considerably as these borers are most prevalent in sub-littoral conditions. Adherent matrix to both corals and mollusca indicate that the two derived component types are not polygenetic in origin. Marlowe (1971, p. 811) gives phosphatisation depths of 620-750 metres in the Caribbean. This must be considered as a maximum depth. McKelvey et al. (1959) considers the Phosphoria and Park Formations to have formed in less than 40 metres of depth but Kazkov (1937) would prefer depths of 50-200 metres for phosphorite development. In view of all data at hand it is considered that the Maltese phosphorites formed at depths of not more than 75-100 metres.

e. Biofacies J Eschariform Bryozoan Biofacies

The eschariform bryozoans associated with the C2b Phosphorite Conglomerate Bed fall into this biofacies. They are most in evidence in west coast outcrops of the bed and take the form of broken sections of bilaminate stems, often showing branching. Stach (1936 p. 62) and other workers consider that a dominance of this form represents a sublittoral environment but with depths not less than 20 metres. This confirms the depth interpretation of the C1 and C2 Beds and it is quite likely that this bryozoan growthform commonly occurs in these beds also,but has been missed during the present study in virtually all examined exposures.

f. Geological History of the Globigerina Limestone

Throughout Lower Globigerina Limestone deposition the sea floor around the Maltese islands deepened and the shallower Il Mara Member facies retreated to the western side of Malta. Thick accumulations of *Globigerina* biomicrites accumulated in water depths of 150-200 metres in most areas.

The shallowest areas of deposition throughout the Globigerina Limestone episode were close to the western margins of the Malta-Regusa rise (Fig. 8b), which possibly lay at the most a few kilometres away from the western and northern margins of the Maltese Islands. In these areas phosphatisation of the newly deposited limestones appears to have occurred, probably resulting from upwelling cold Tethyan currents from the west which were rich in phosphates. These phosphates were possibly precipitated in the shallow warm waters where organic production was high. Bromley (1967, p. 504), D'Anglijan (1967, p . 18) and Gulbrandsen (1969) all agree that these deposits develop best in warm climates where sedimentation is minimal. The general lack of detritals at this time may have further aided phosphorite development and further suggests the existence of an arid climate at this time.

Lower Globigerina Limestone deposition was brought to a close by the onset of severe erosive conditions which were felt most strongly in western Malta and Gozo. It is considered that erosion was intense enough in the areas of primary phosphorite development to cause breakup of the beds and transportation of them eastwards into the area of the Maltese islands. This ultimately resulted in the smallest pebbles travelling the greatest distance. Little sedimentation occurred for some time after the deposition of the conglomerate in this shallow water and it appears that the C1 Bed remained uncovered for sufficient length of time to become cemented with secondary phosphate pore solution precipitates leached from the associated pebbles, in the manner postulated by Twenhofel (1950, p. 523). This caused the development of a rigid upper crust to the bed, which resisted further erosion though tabular planation of the surface did occur before the onset of Middle Globigerina Limestone deposition.

After renewed downwarping of the seafloor at the close of C1 times the pure white Middle Globigerina Limestone was deposited in depths comparable to that of the preceding subformation. The absence of beds between C1 and C2 in eastern Gozo (Wigglesworth 1964, p. 29) may be due in part to erosion as well as non-deposition (white biomicrite clasts within C2 here support this theory). The greatest subsidence was in the north-west and south-east, occasional layers of phosphorite pebbles indicating that further erosion of the phosphorite beds west of the islands occurred periodically. The possibility that land areas may have been present nearby is indicated by the occurrence of the crocodilian genus Tomistoma. The present day species of this living Malayan genus do not venture far from land, though they do frequent river deltas and shallow marine environments.

The grey marl development of western areas may represent deposition in a more proximal source area, though the widespread distribution of marls and clays, within the Tethys at this time, due to the Alpine orogeny, renders the interpretation suspect. The sparse faunas of the grey marls may also be a reflection of increased sedimentation in an area with a stable population density.

A further major uplift of the area to the west of the islands, with possible additional uplift in the east, occurred at the close of the Middle Globigerina Limestone deposition and similar deposition to those described for the C1 Bed resulted. Either uplift was not as severe as in C1 times or the source area was further away at this time, for bed thickness and pebble sizes are generally less in the C2 Conglomerate Bed. The sub-conglomerate burrow systems of the C2 Bed are also less developed, suggesting that the period of uplift was of less duration. The constancy of pebble type between C1 and C2 is taken to indicate phosphatisation was continuing uninterruptedly throughout Globigerina Limestone times in the source areas, particularly to the west.

The presence of Mastodon teeth in the phosphorite conglomerate beds of Marsalforn, Adams (1879), is considered to indicate that northern Gozo lay in close proximity to a northern land area as it is believed that a floating carcass would hot drift far from land. The associated waterworn bones of Halitherium sp. in the C2 Bed may also indicate close proximity to land as Adams and Ager (1967, p. 265) indicates that river estuaries are the chief areas frequented by their modern counterparts. The abundant shark teeth of the C2 Bed are believed to be partly reworked and partly the result of reduction in overall sedimentation rates at this time.

Upper Globigerina Limestone sedimentation commenced gradually with a gentle episode of subsidence during which time turbulence within the environment was reduced. This resulted in transport of only the smallest phosphorite pebbles into the area ,creating a normal upward grading to the C2 Bed which finally grades imperceptibly upwards into the Upper Globigerina Limestone. In northern Gozo (332913) higher energy conditions continued for a time and phosphorite pebbles were heaped up into 0.5 metre high megaripples orientated at 124° (Fig. 8a) suggesting that the prevailing current was from the west or south west.

The detailed isopachyte maps previously discussed indicate that the Maltese Islands occupied two or more basins of deposition at this time in which an alternation of yellow and grey biomicrites and marls accumulated. The amalgamation of these divisions of the Globigerina Limestone beds in western Gozo, eastern Malta and western Malta is believed to indicate that the margins of the sedimentary basins most closely approached the islands at these points. Channelling in the sediments in this area is extensive and is consistent with an extremely shallow water environment.

TABLE 2

FLORA + FAUNA OF THE GLOBIGERINA LIMESTONE

In compiling this list the following references have been consulted: Wright (1855, 1864), Adams (1879), Murray (1890), Gregory (1890-91), Cotteau (1914), Reed (1949), Romam and Roger (1939), Withers (1953), The British Museum (Natural History) and material collected during the present study.

Vertebrata.

Trionyx melitensis Lyddecker.
Tomistoma champsoides Hulke.
Tomistoma gaudense Hulke.
Halitherium schinzi Kaup.
Phoca rugosidens Owen.
Delphinus sp.
Scaldicetus sp.
Squalodon sp.
Stereodus melitensis Owen.
Lamna eligans.
Lamna sp.
Carcharodon megalodon Agassiz.
Balistes cf. carcharias.
Isurus oxyrhynchus Rafinesque.
Isurus hastilis Agassiz.
Isurus cuspidata Agassiz.
Mylobatis sp.
Odontaspis contortidens Agassiz.
Hemiprestes serra Agassiz.

Echinodermata.

Cidaris adamsi Wright.
Cidaris avenionensis Desm.
Cidaris scillae Wright.
Leiocidaris sismondai Mayer.
Anapesus hungaricus Lamarck.
Echinocyamus studeri Sismonda.
Echinocyamus stellatus Caped.
Echinonius sp.
Tristomanthus vassali Wright.
Breynella equizonata Gregory.
Studeria spratti Wright.
Lithnia subglobosa Lamarck.
Perecosmus latus Agassiz.
Gregoryaster (Pericosmus) coranguinum Gregory.
Hemiaster scillae Wright.
Hemiaster cottreau Wright.

Table 2 continued ....

Echinodermata cont...

Opiaster vadosus Gregory.
Holcopneustes lorioli Stephanini.
Schizaster eurynotus Agassiz.
Schizaster parkinsoni Defrance.
Brissus tuberculatus.
Brissopsis grateloupi Sismonda.
Brissopsis cresenticus Wright.
Brissopsis duciei Wright.
Iteterspissus extentricus Wright.
Eupatagus konincki Wright.
Spatangus marriorae Desor.
Spatangus pustulosus Wright.
Spatangus delphinus Defrance.
Spatangus oscellatus Defrance.
Lovenia anteroalta Gregory.
Echinolampas scutiformis Leske.
Echinolampas laurilardi Agassiz.
Echinolampas wrighti Gregory.
Echinolampas manzoni Gregory.
Metalia melitensis Gregory.
Trachyaster cottreaui?
"Pentacrinus" gastaldi.

Gastropoda.

Conus misingeri.
Conus sp.
Conus dubius Gulia.
Natica sp.
Epitonium melitensis (Fuchs)
Epitonium retusta.
Cassis sp.
Aporrhais pes-pelicani (Linné)

Lamellibranchiata.

Pecten koheni. Fuchs.
Pecten cristatus Fuchs.
Pecten denudatus Reuss.
Flabellipecten pasinii Meneghini.
Chlamys (Aequipecten) northamptoni Michelin.
Chlamys (Amusiopecten) burdigalensis Lamarck.
Chlamys praescabriuscula Fontannes.
Asesma miocenica Sismonda.
Arca sp.
Cardium sp.
Capsa sp.
Nuculana sp.
Maginella deshayesi.

Table 2 continued ....

Cephalopoda.

Aturia aturi Basterot.
Nautilus sp.
Sepia sp.

Crustacea.

Calappa heberti.
Necronectes schafferi.
Neptunus granulatus.
Ranina (Ranina) cf. brevispina.

Cirrepeda.

Scalpellum mollianum Segvenza.
Scalpellum lovisatoi.
Trilasmis (Poecilasma) melitensis Withers.
Balanus sp.

Brachiopoda.

Terebratula cf. sinuosa Brocchi.
Terebratula minor Phillipi.

Bryozoa.

Retipora sp.
Cellepora cf. parasitica Mich.
Isis peloritana Seg.
Escharia cf. monilifera Mich.
Vinculariform bryozoan growth-forms.

Pteropoda.

Hyalea cf. tauneusis Sismonda.
Cavolina cookei Simonelli.
Vaginella sp.

Anthozoa

Ceratocyathus sp.
Ceratotrochus sp.
Flabellum avicula Michelin.
Flabellum foecundum Sesmonda.
Caryophyllia sp.
Balanophyllia sp.
Stephanophyllia imperialis Michelin.
Trochocyathus latero-cristatus Ed. W. and H.

Table 2 continued ....

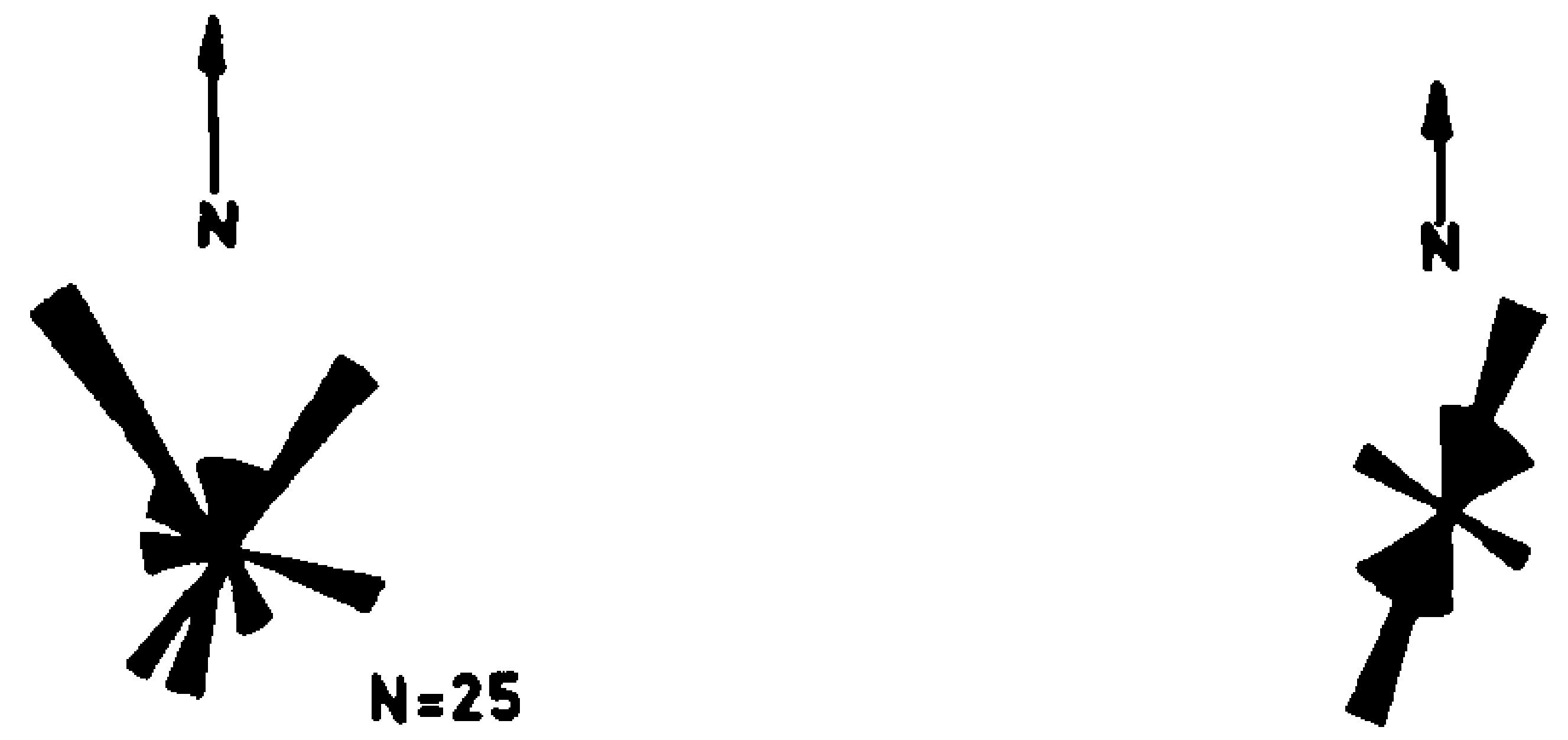
Miscellaneous.

Amber.
Coccolithus sp.
Coccospheres.
Rhabdoliths.
Thalassinoides sp.
Ophiomorpha sp.
Teichichnus sp.
Lockeia sp.

Foraminifera.

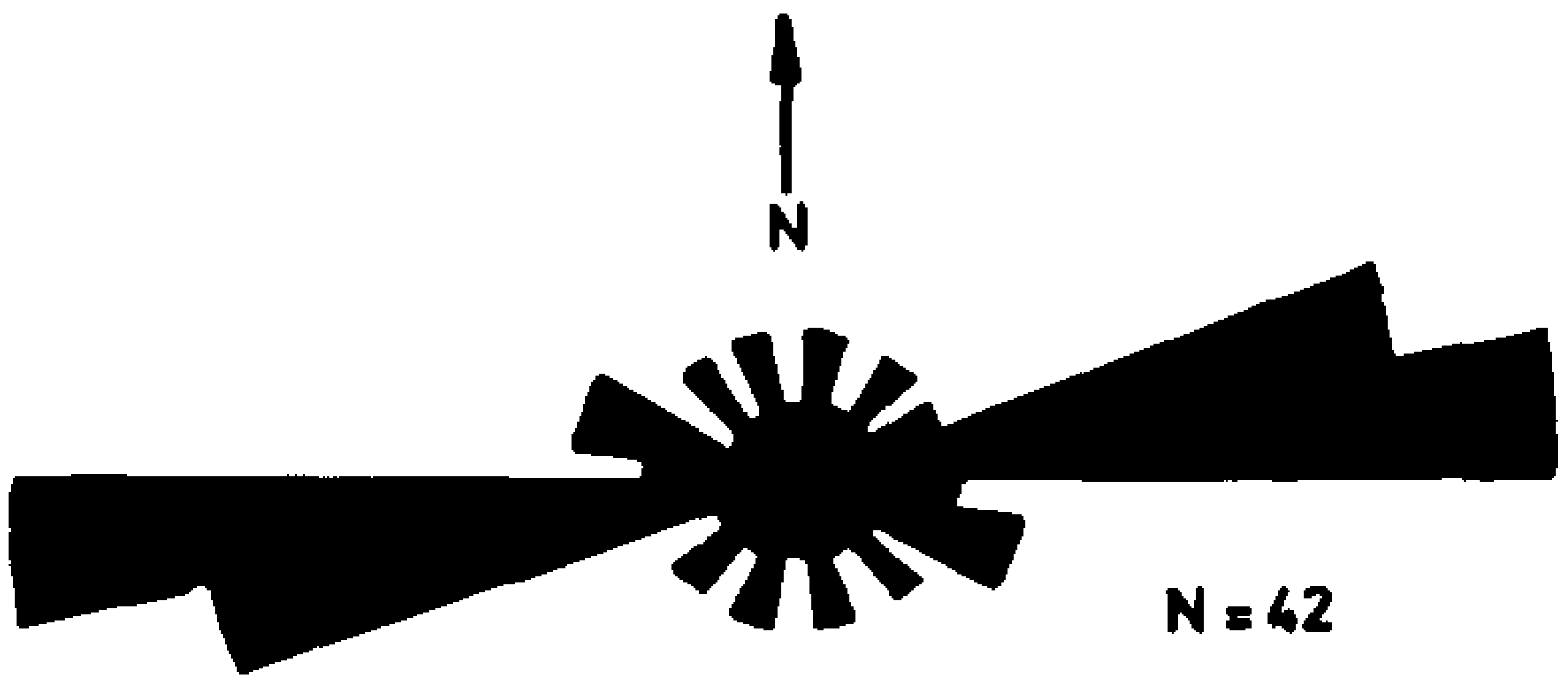
Haplophragmium sp.
Textularia sp.
Gaudryina sp.
Clavulina sp.
Bulimina sp.
Bolivina sp.
Cassidulina sp.
Ehrenbergina sp.
Legena sp.
Nodosaria sp.
Rotalia sp.
Rhabdogonium sp.
Vaginulina sp.
Robulus sp.
Uvigerina sp.
Globigerina sp.
Orbulina sp.
Pullenia sp.
Sphaeroidina sp.
Discorbis sp.
Truncatulina sp.
Anomolina sp.
Pulvinulina sp.
Nonionia sp.

It is believed that most of the unlocated echinoids were probably collected from the richly fossiliferous Lower Globigerina Limestone. Other common fossils from the Formation are planktonic foraminifera, *Rotalia* sp., *Truncatulina* sp., *Pulvinulina* sp,, and pteropods.



FORESET DATA
XLENDI MEMBER

SCOUR AND FILL &
SAND WAVE ORIENTATION
DATA GLOBIGERINA LST.



CIDARID SPINE ORIENTATION IN IL MARA MEMBER
SAN ROCCO MALTA

DIRECTIONAL DATA FROM THE LOWER CORALLINE AND GLOBIGERINA LIMESTONE FORMATIONS.

Fig. 8a

SYNTHESIS OF CONDITIONS PREVAILING DURING GLOBIGERINA LIMESTONE DEPOSITION

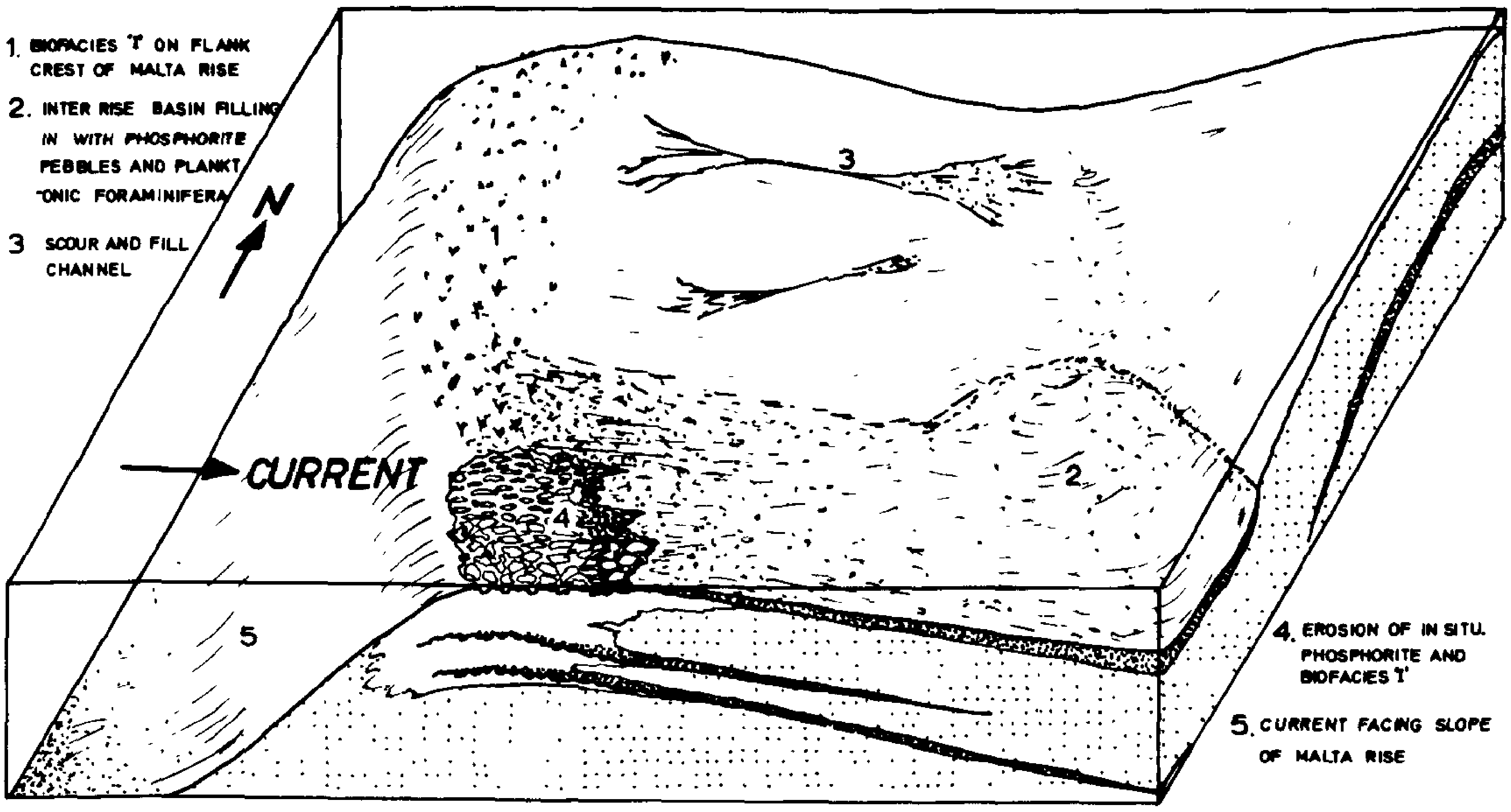


Fig. 8b

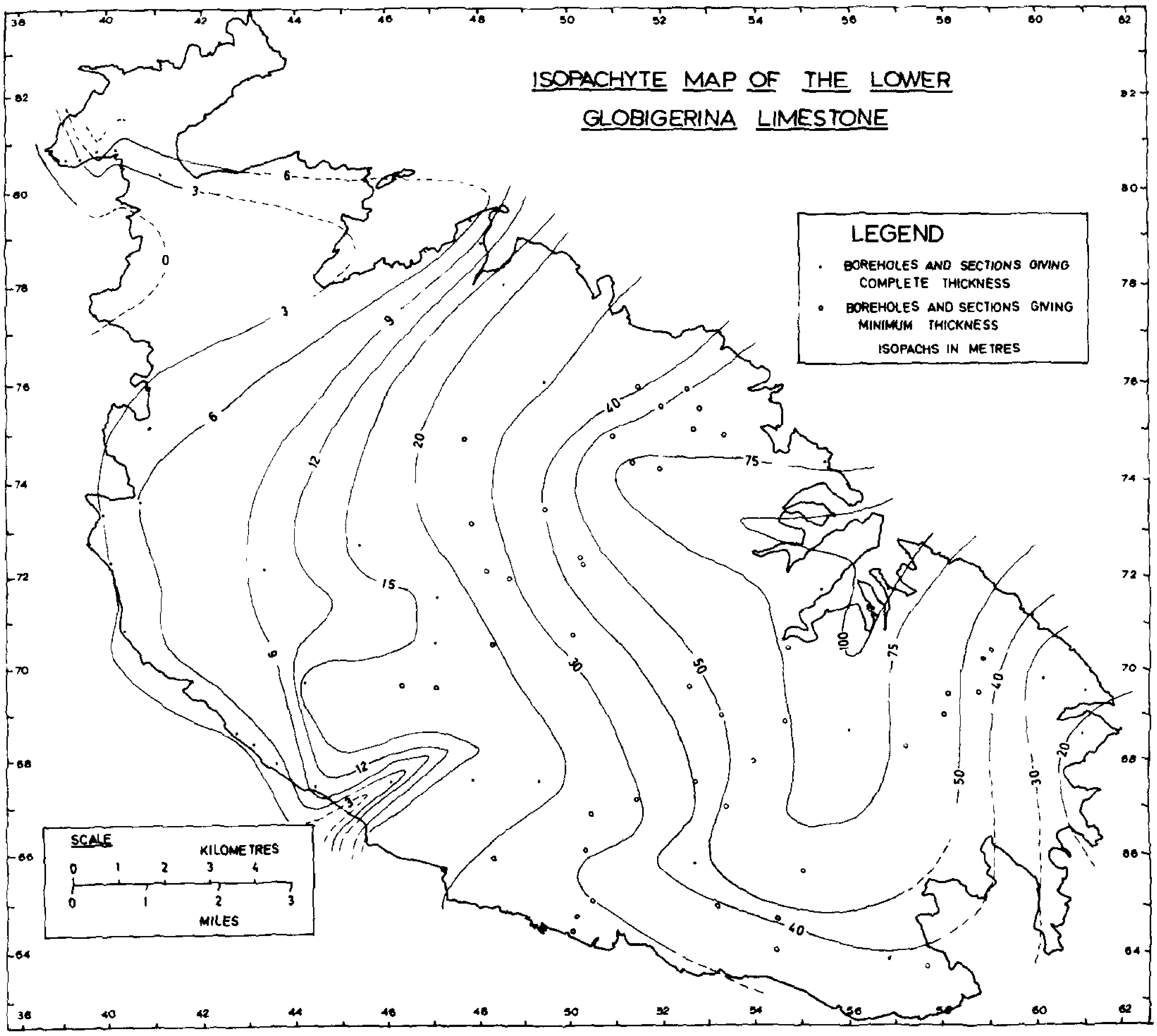

ISOPACHYTE MAP OF THE LOWER GLOBIGERINA LIMESTONE
LEGEND
· BOREHOLES AND SECTIONS GIVING COMPLETE THICKNESS
○ BOREHOLES AND SECTIONS GIVING MINIMUM THICKNESS
ISOPACHS IN METRES
SCALE
KILOMETRES
0 1 2 3 4
0 1 2 3
MILES
0
3
6
9
12
15
20
30
40
50
75
100
38 40 42 44 46 48 50 52 54 56 58 60 62
82 80 78 76 74 72 70 68 66 64

Fig. 9a

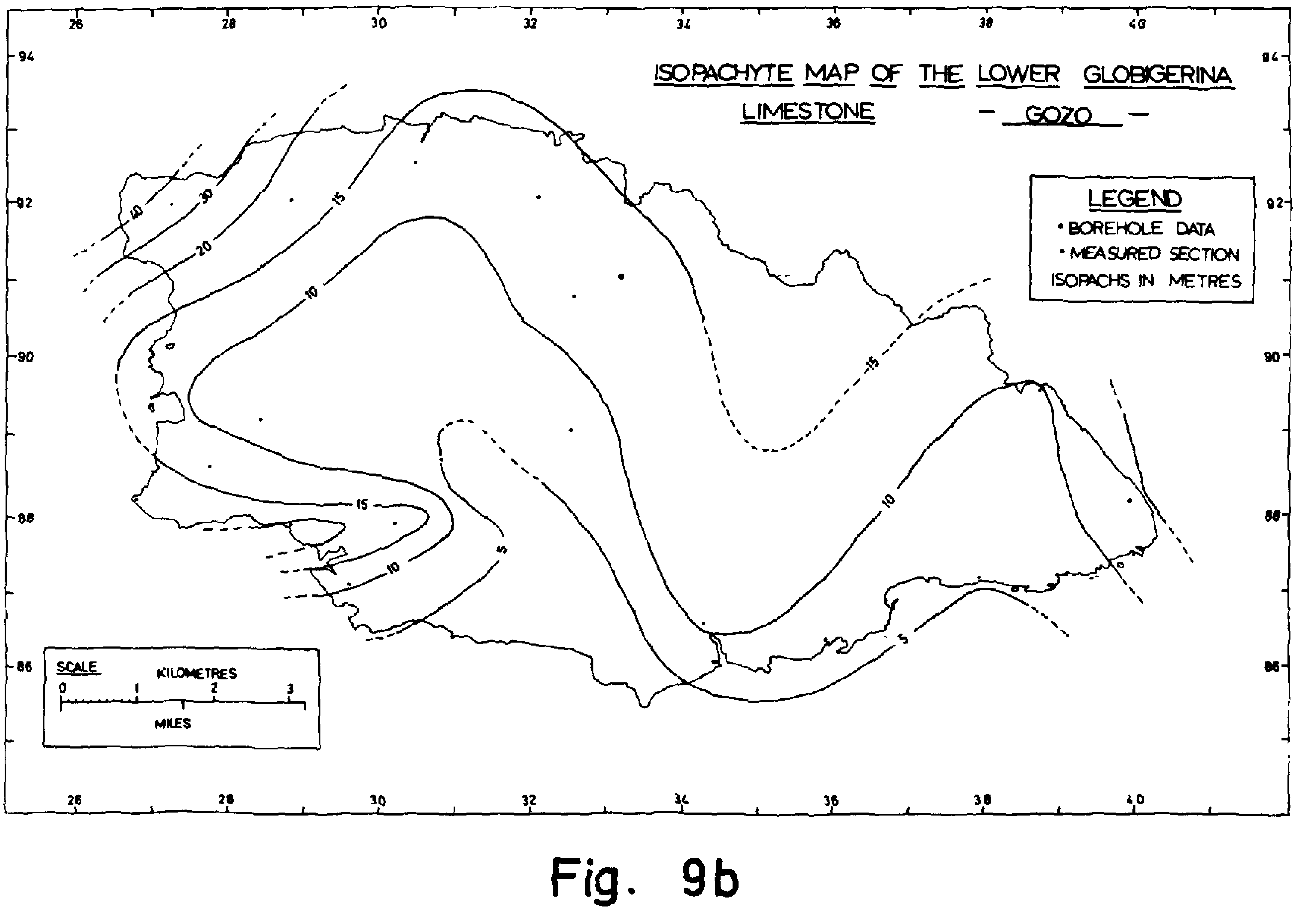

ISOPACHYTE MAP OF THE LOWER GLOBIGERINA LIMESTONE - GOZO -
LEGEND
• BOREHOLE DATA
· MEASURED SECTION
ISOPACHS IN METRES
SCALE
KILOMETRES
0 1 2 3
MILES
40
30
20
15
10
5
0
26 28 30 32 34 36 38 40
94 92 90 88 86

Fig. 9b

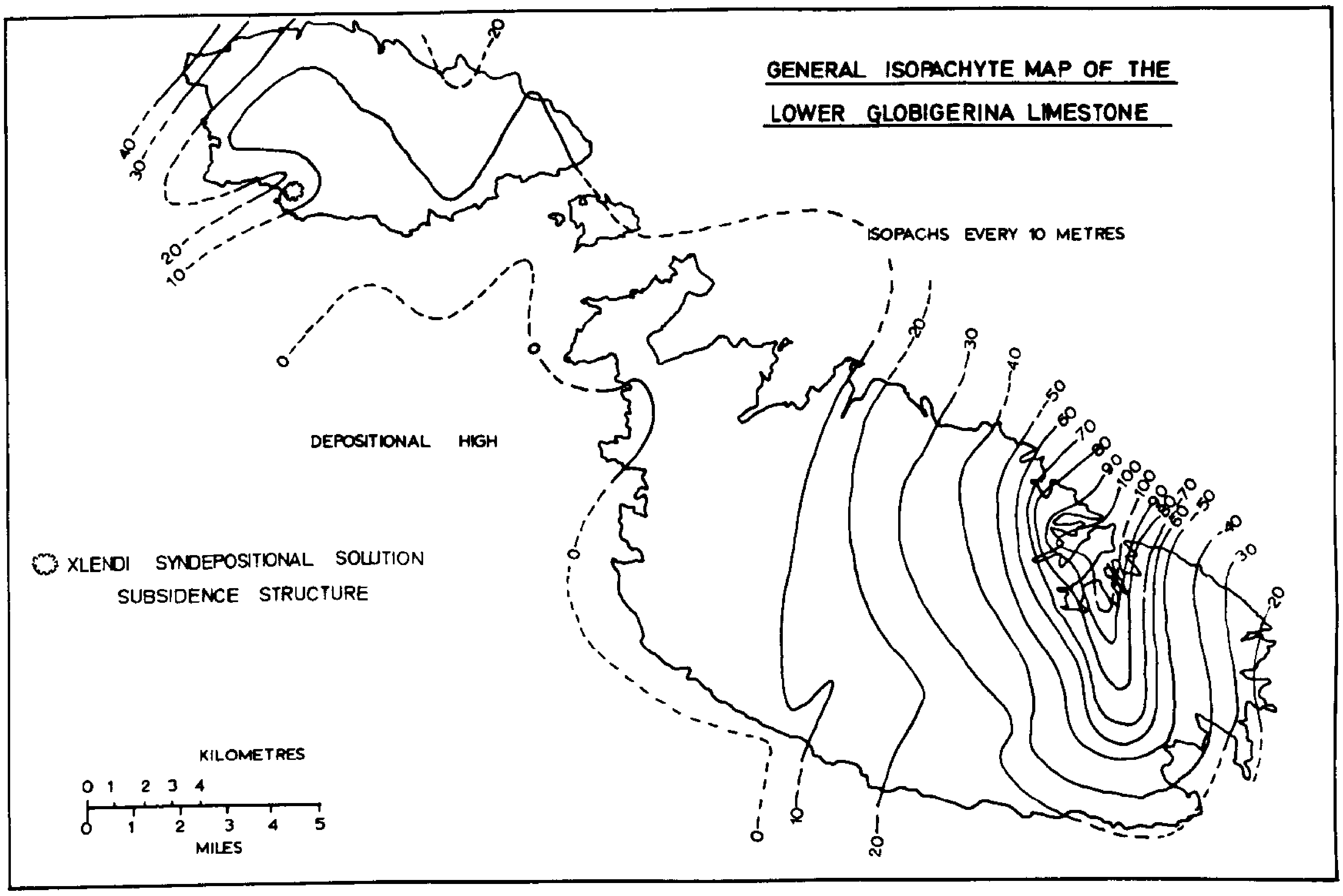


Fig. 10a

MODAL ANALYSIS OF GLOBIGERINA LST.

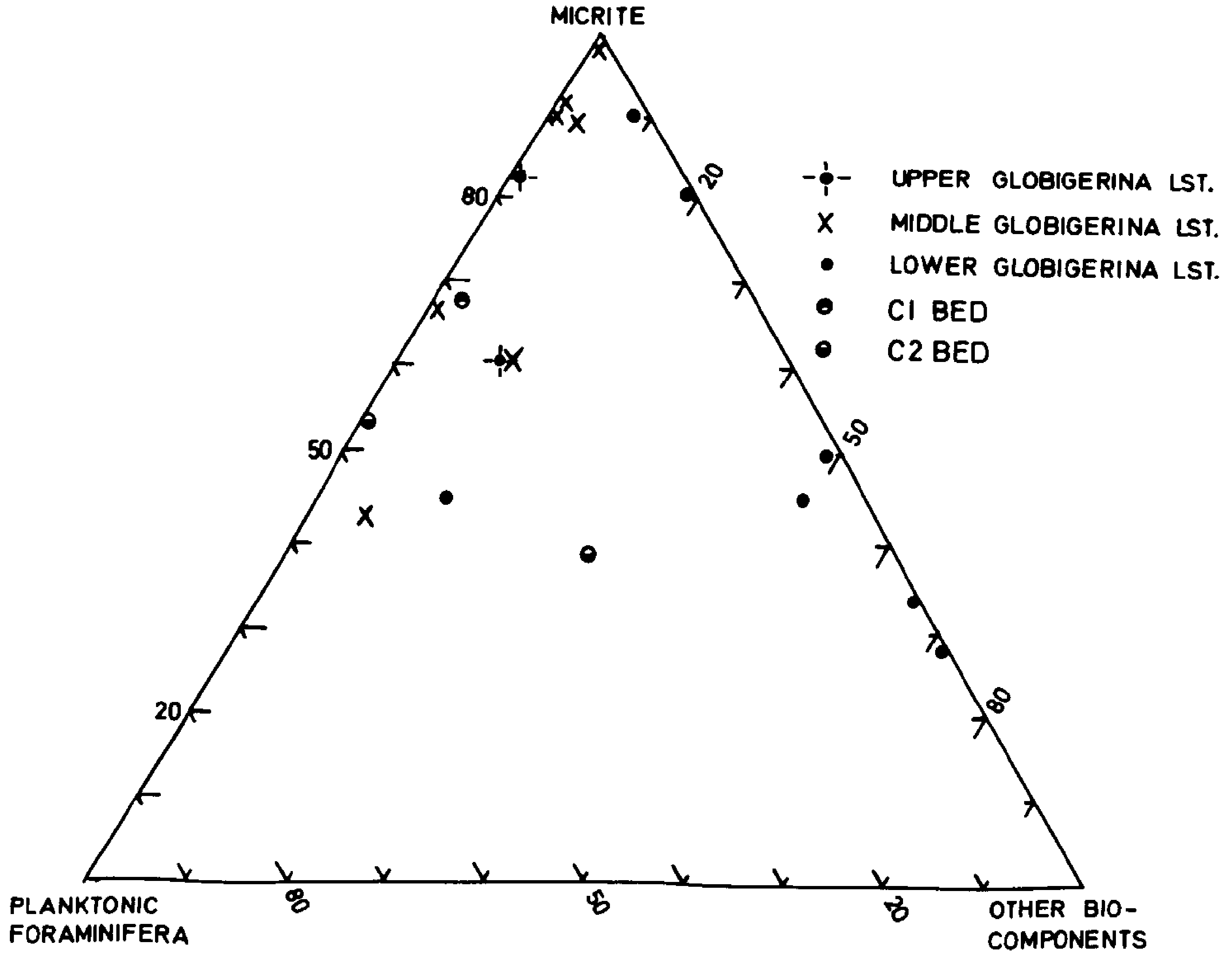


Fig. 10b

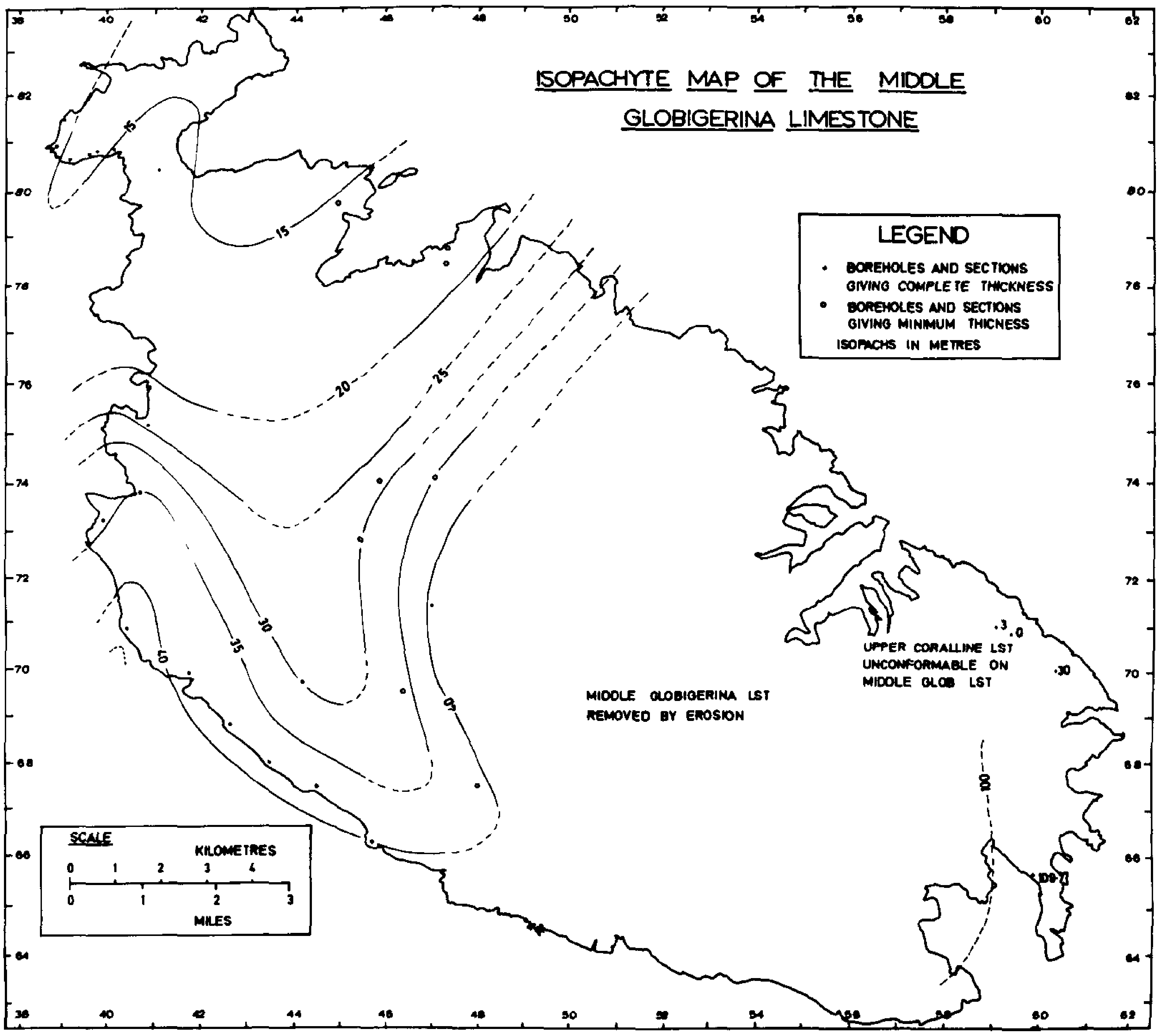


Fig. 11a

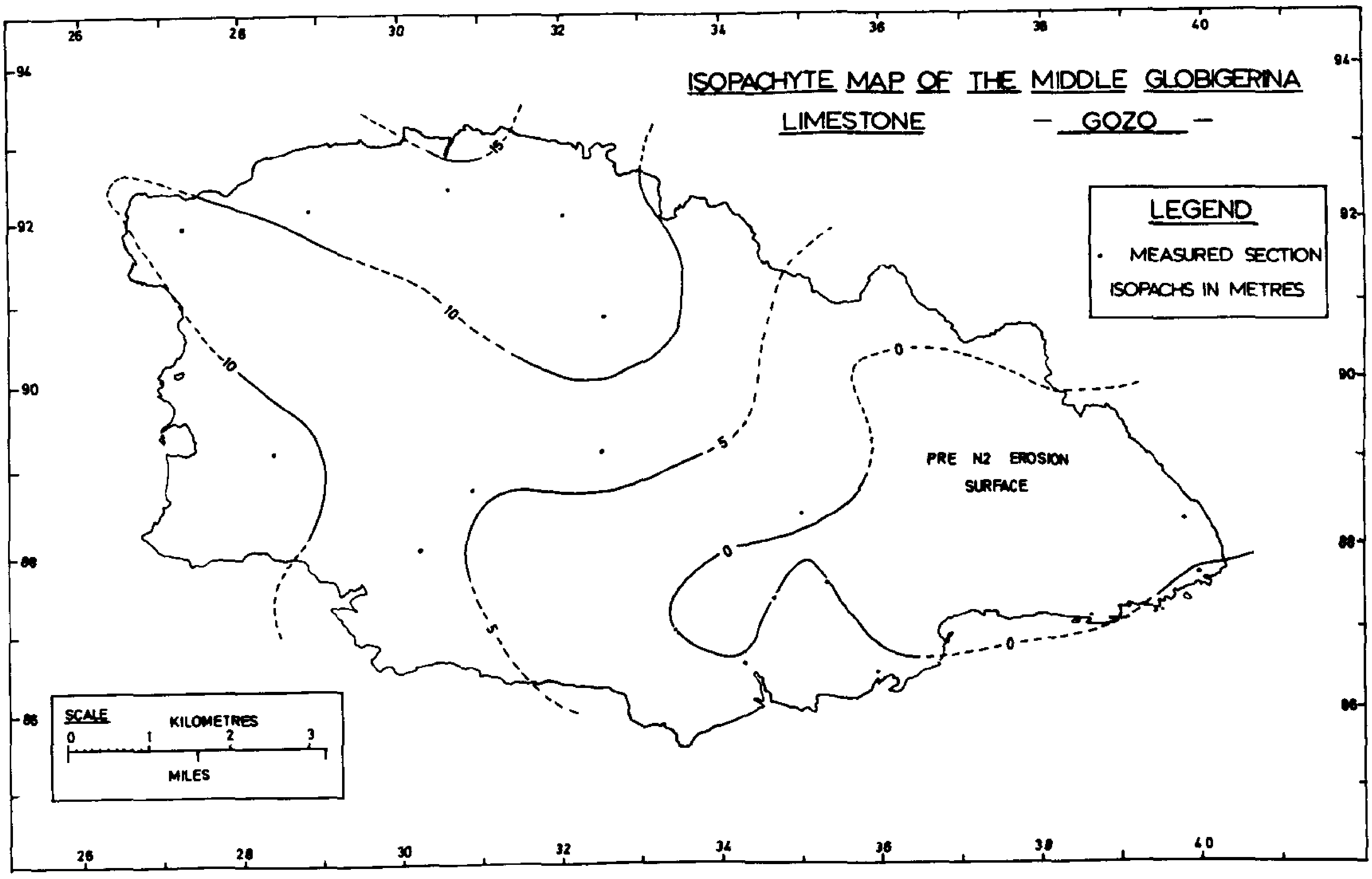


Fig. 11b

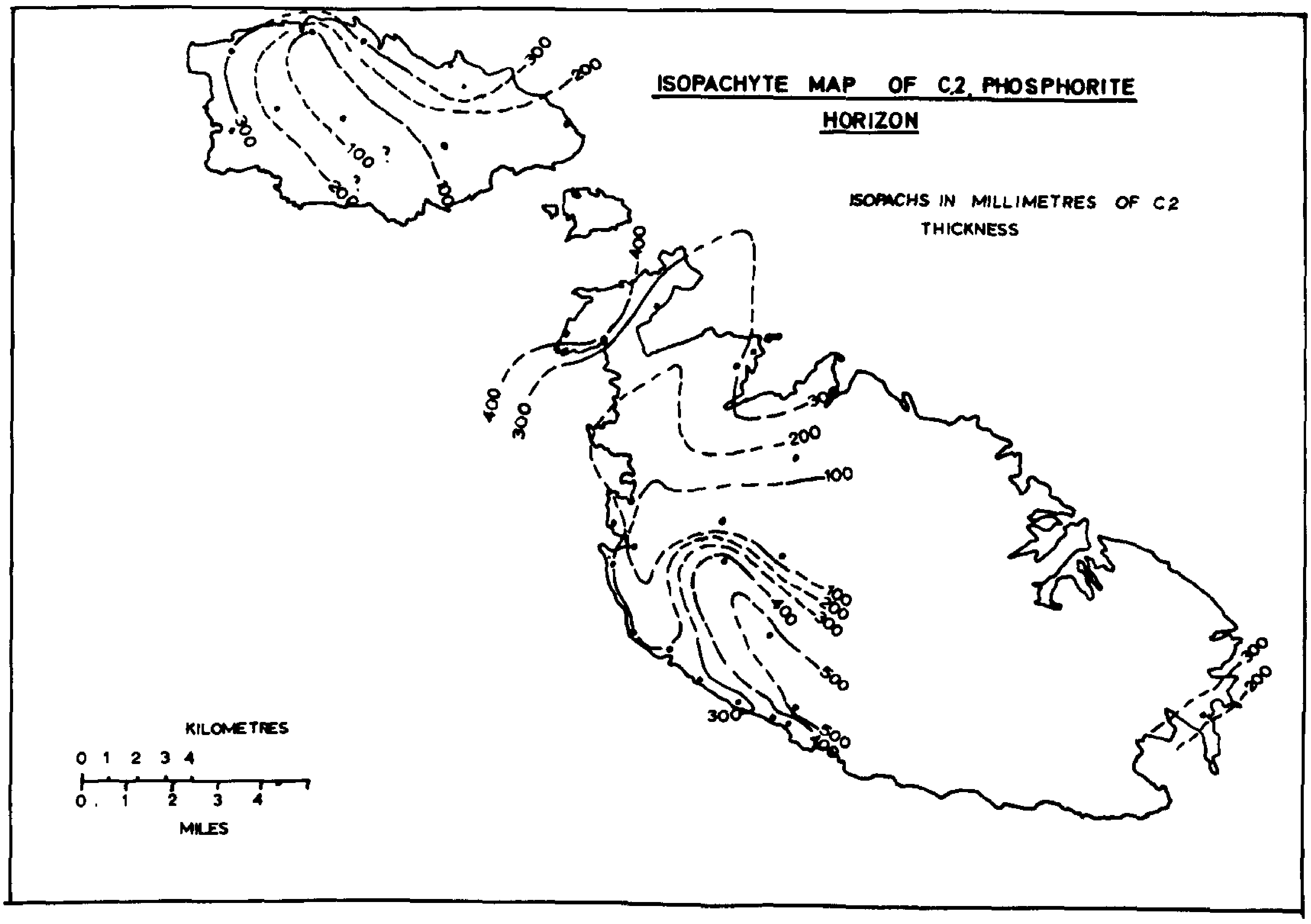


Fig. 12a

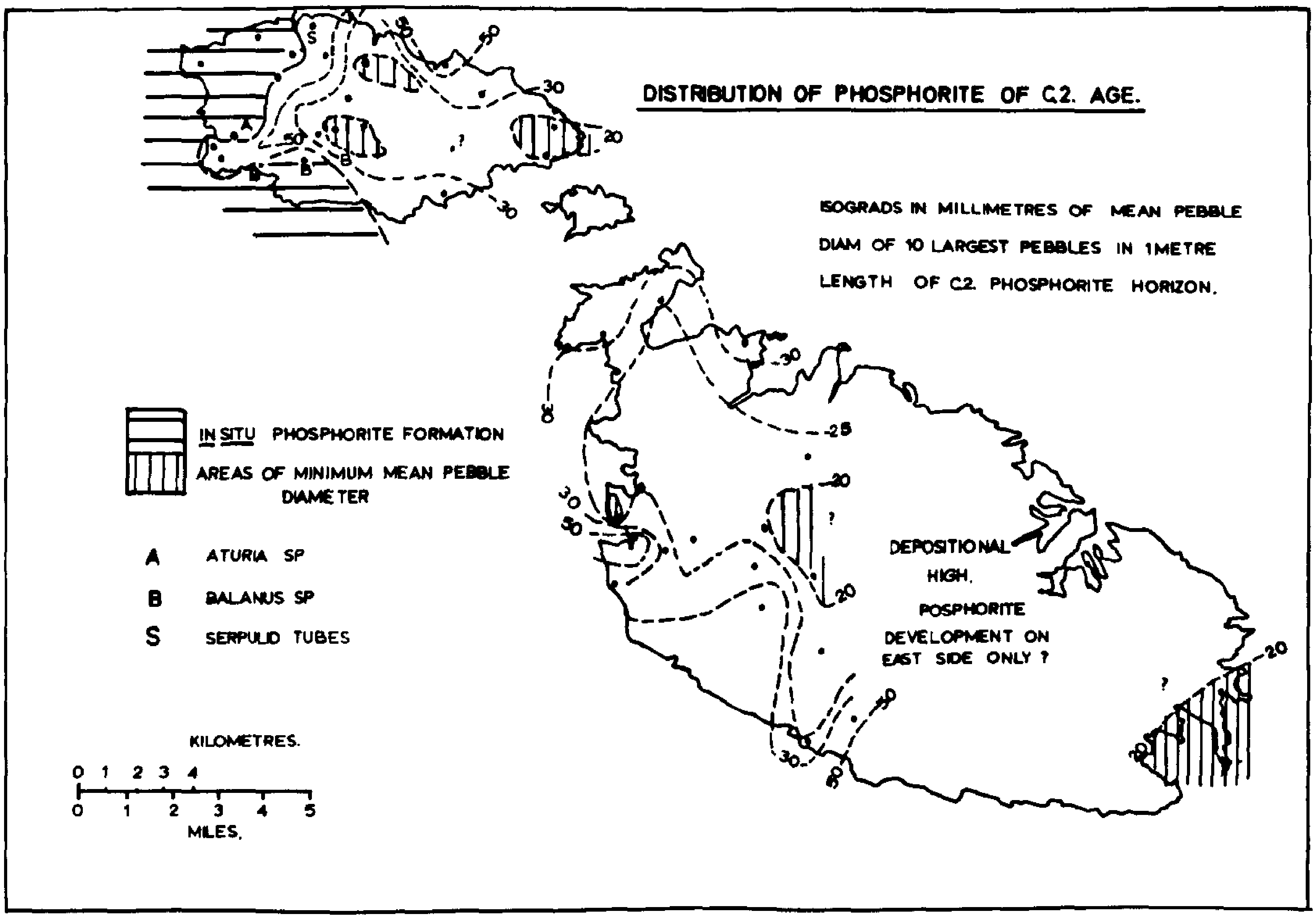


Fig. 12b

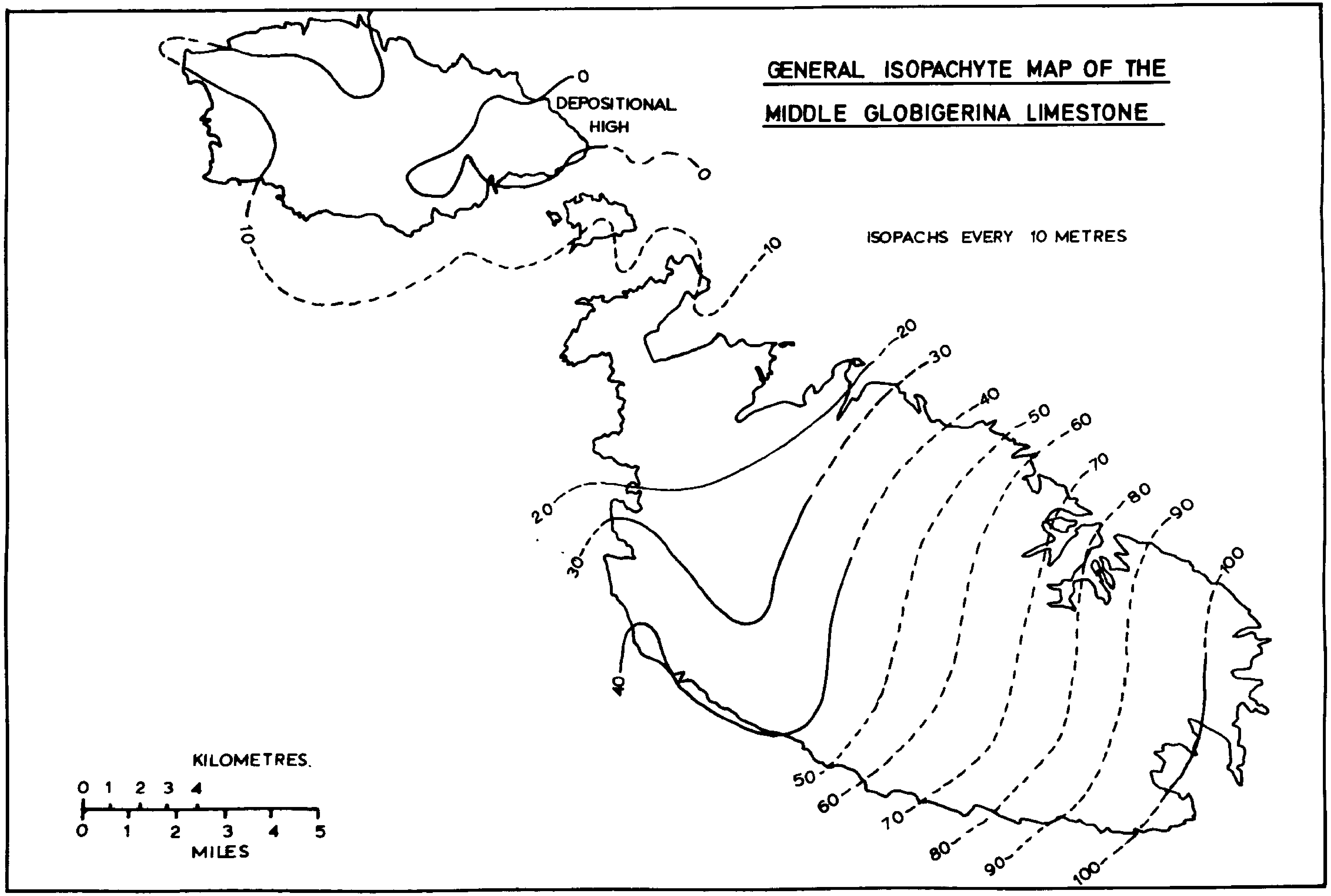

GENERAL ISOPACHYTE MAP OF THE
MIDDLE GLOBIGERINA LIMESTONE
ISOPACHS EVERY 10 METRES
DEPOSITIONAL HIGH
0
0
10
10
20
20
30
30
40
40
50
50
60
60
70
70
80
80
90
90
100
100
KILOMETRES.
0 1 2 3 4
0 1 2 3 4 5
MILES

Fig. 13

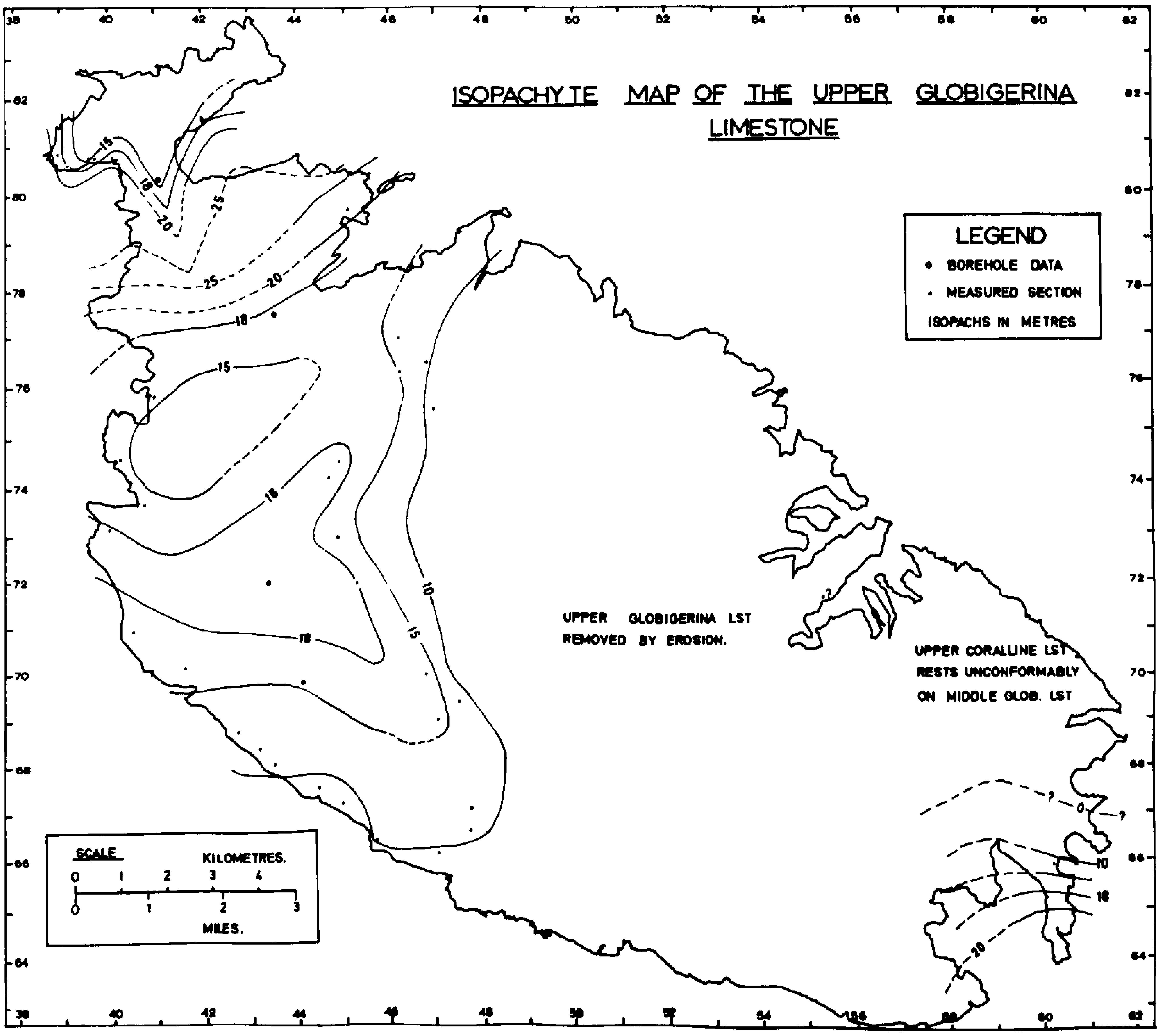


Fig. 14a

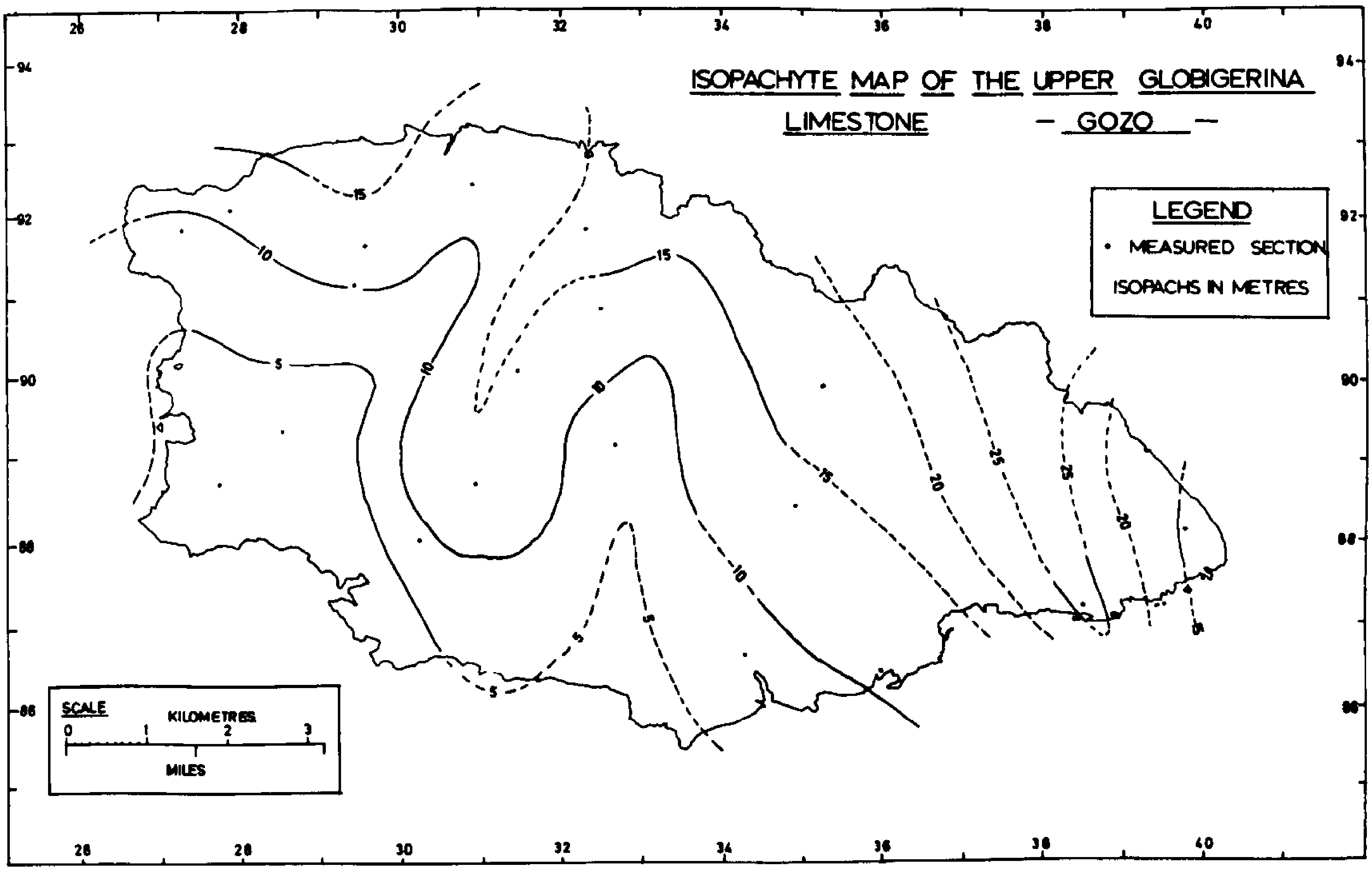


Fig. 14b

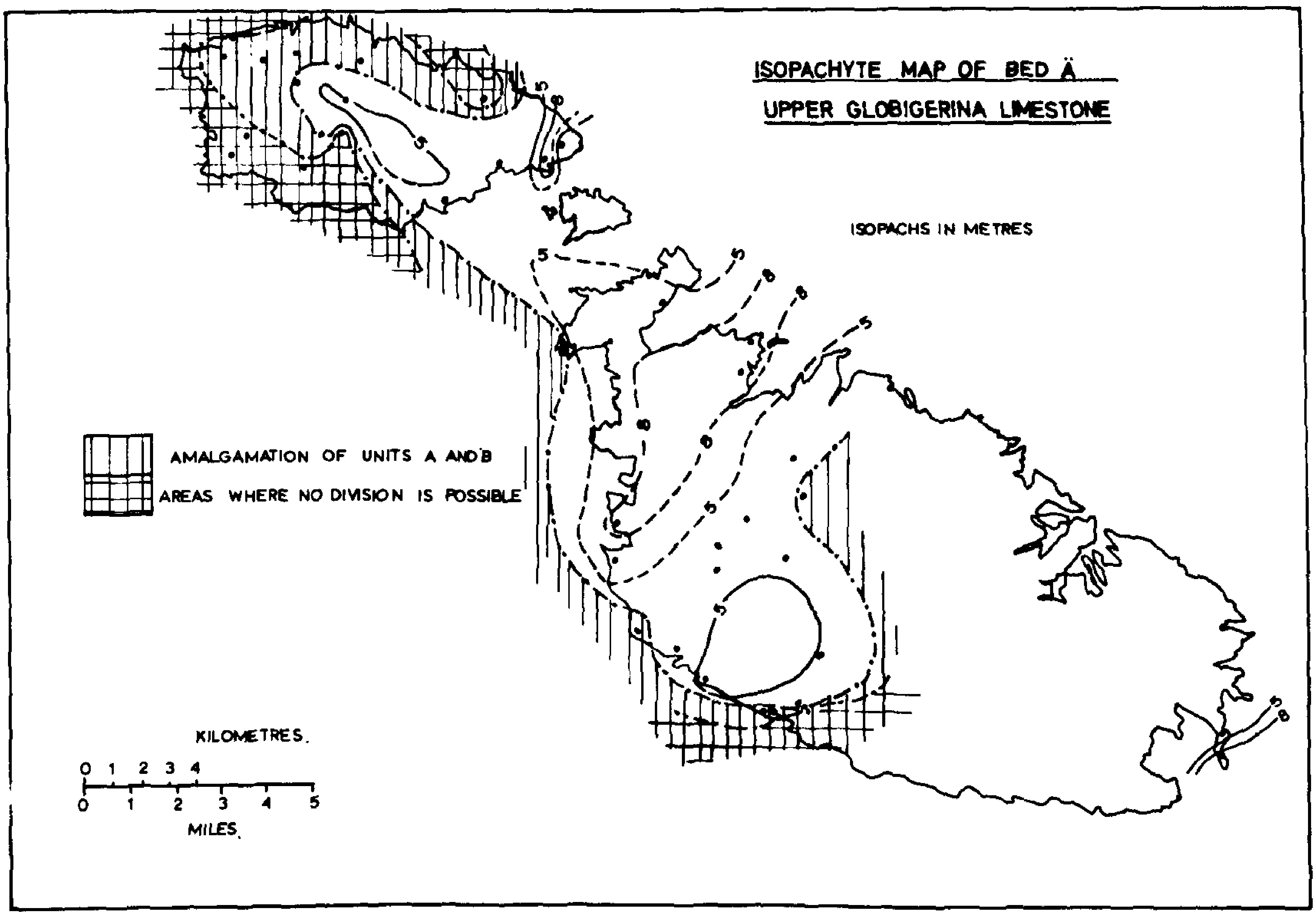


Fig. 15a

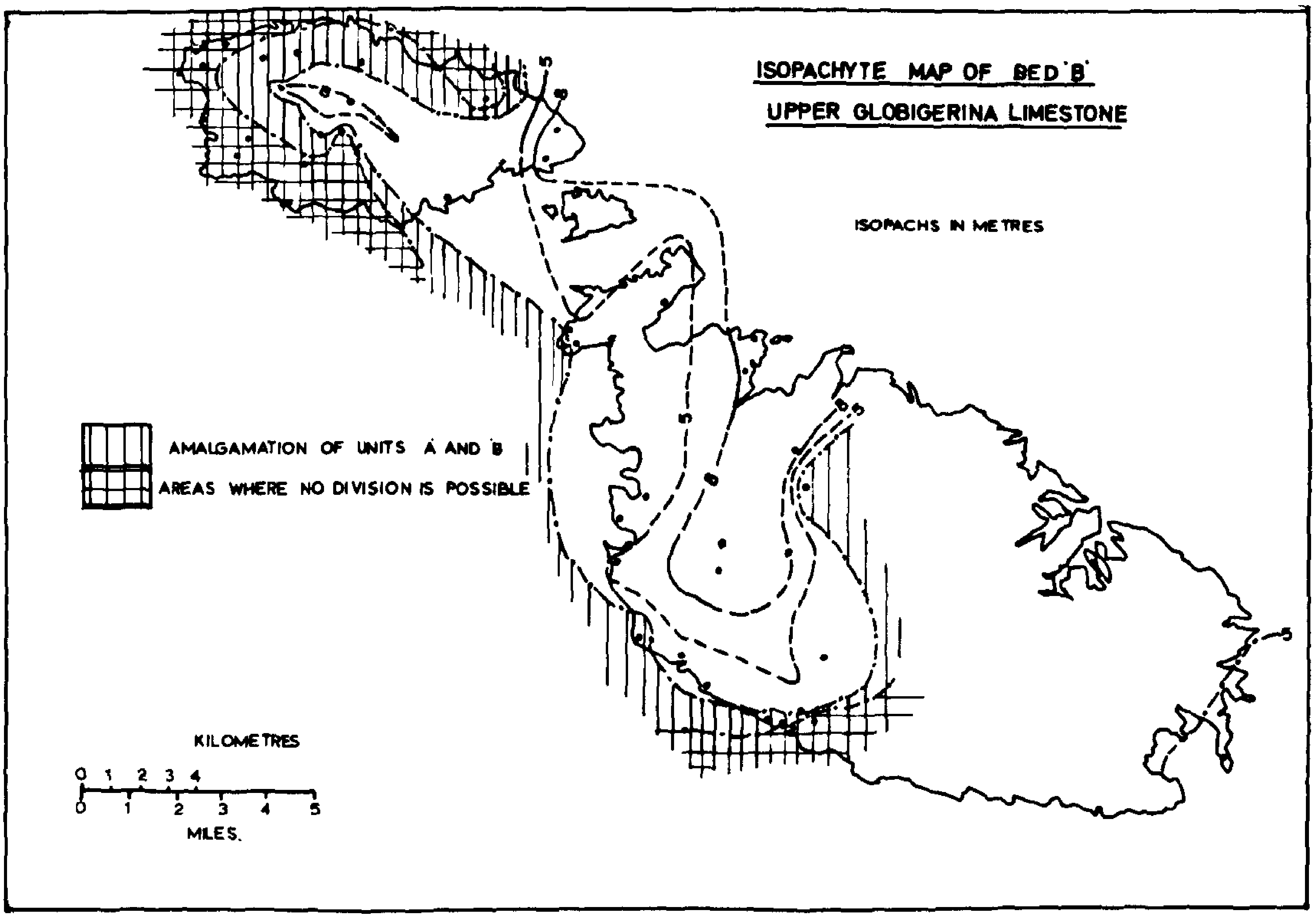


Fig. 15b

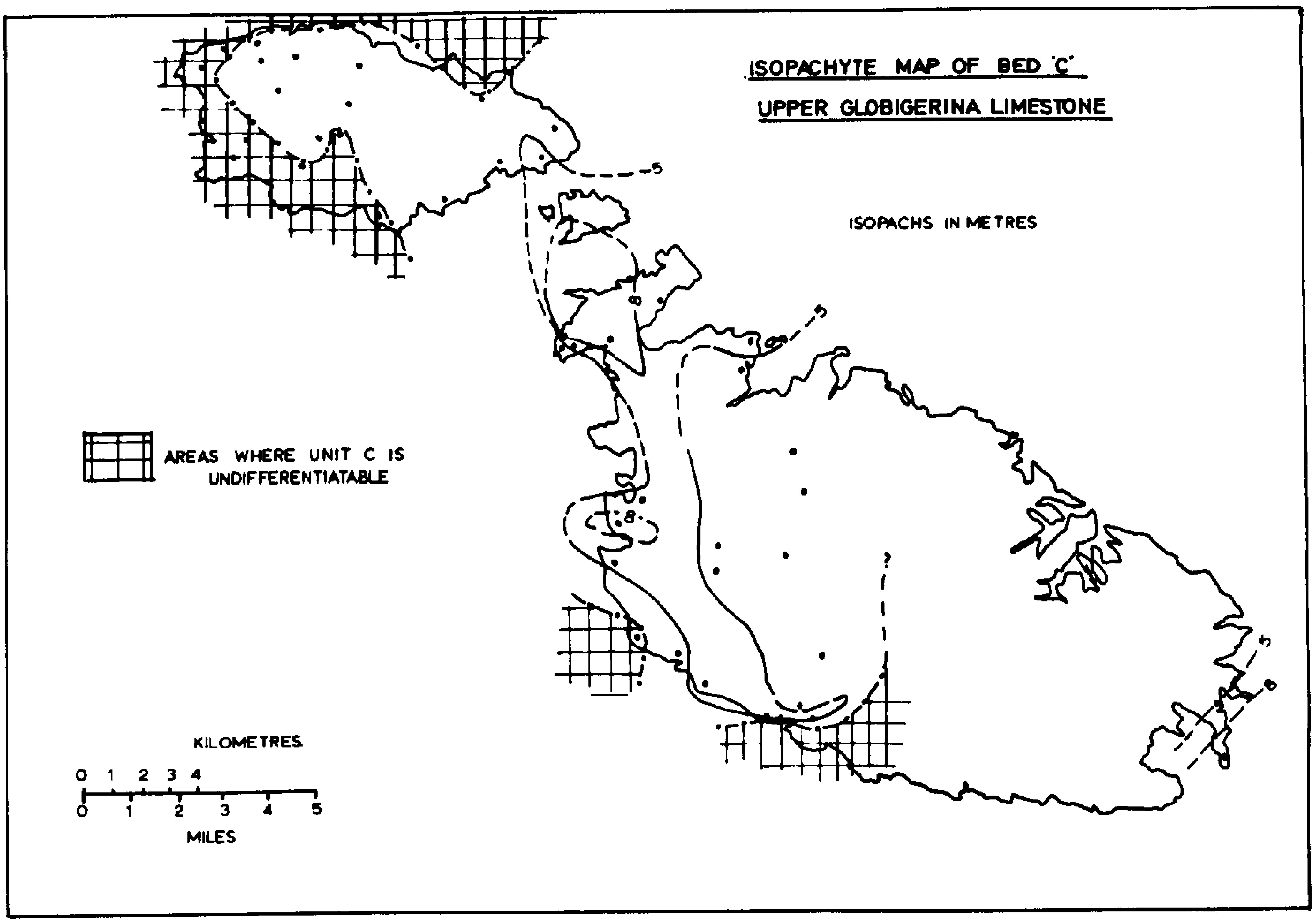


Fig. 16a

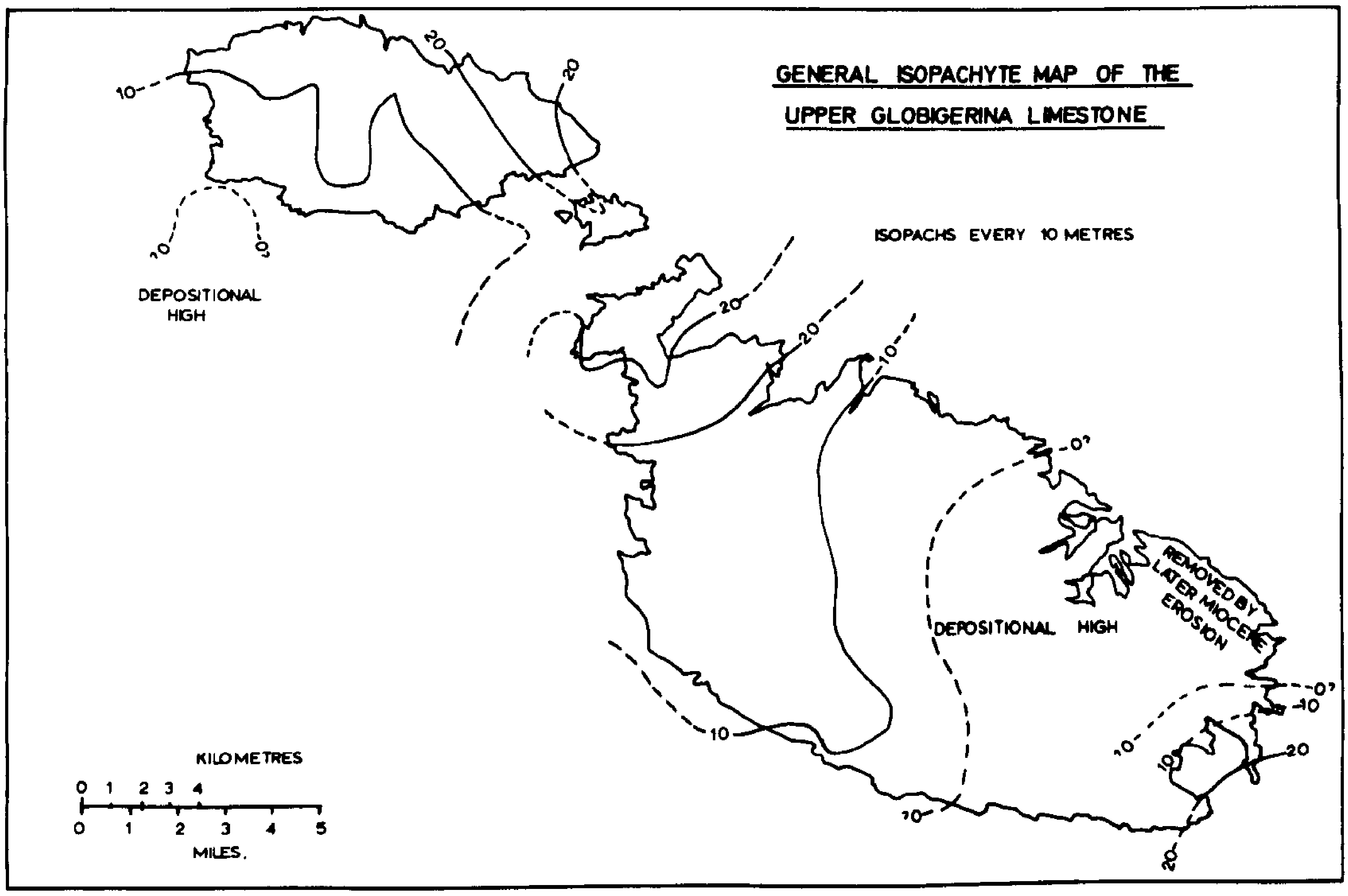


Fig. 16b

CHAPTER 5

BLUE CLAY FORMATION

1. Stratigraphy.

(i) General

The name "Marl Bed", applied in 1843 by Spratt, has unfortunately been abandoned for the less accurate term Blue Clay, which was substituted by Murray (1890, p.468). Present outcrops form rampart-like slopes adjacent to the Upper Coralline Limestone areas of both main islands, though well exposed material is only seen around the coast, such as at Gnejna Bay and Qammieh in Malta. Dabrani, in northern Gozo, is perhaps the finest inland exposure. It is believed that the top of the formation occurs above sea level, on the southern flank of the island of Filfla, off south-western Malta, and springs and water seeps have been recorded from this scree hidden contact in the past.

Past workers have been inclined to regard the formation as of minor importance, Spratt (1843), including it with the "Yellow and Black Sands" of the Greensand Formation. Cooke (1893b, p.45) considered it an argillaceous division of the Globigerina Limestone and stated that the formation thickness was generally less than 10ft. (3 metres). Russell (1955, p.18) was the first worker to appreciate the true thickness of the Blue Clay and estimated a maximum thickness of over 230 ft, which was subsequently confirmed by House <u>et al</u>. (1961).

No attempt is made here to subdivide the formation, though it is recognised that the dark and light banding is absent from the top 6-8 metres in north-western Malta and southern Gozo. These uniformly grey upper beds are characterised by goethite and limonite concretions.

a. Lithology and Distribution

The formation varies in thickness from a maximum of 65 metres in northern Gozo and north-western areas of Malta, down to 18-23 metres in the areas peripheral to the Comino Straits and eastern Malta (see Figs. 17 and 18). The beds are characterised by alternations of pale grey and darker grey banding. Attempts to correlate these bands between outcrops in the Ta'Lippija (408753) and Ghajn Znuber (407790) areas of Malta during the present study indicate that the thicker bands are laterally persistent, although the thinner beds do die out away from areas of maximum formation thickness. The formation is entirely made up of marls, except for a thin reworked glauconite pellet horizon, recognised 3.5 to 5.5 metres below the top of the formation, at Ta'Lippija and L'Isla, (491645), Malta, and at Kemuna Tower (354881), Gozo. Above this horizon and at the top of the succession, in areas flanking the Comino Straits, the strata are characterised by a uniform dark brown to dark grey marl which lacks banding and contains abundant goethite and limonitic concretions. Dolomite concretions occur at this horizon in the outliers of western Gozo.

The lower contact of the beds with the underlying Upper Globigerina Limestone is always of a transitional nature, the pale grey upper Globigerina Limestone passing imperceptibly upwards into the darker grey Blue Clay Formation. The upper contact to the formation with the Greensand is usually sharp, and may show hardground development, as at Karraba (406760), Malta, or erosion, as at Ghajn Barrani, Gozo. The only apparent transitional contact is at Il Gelmus (310894) Gozo. At Qawra (270900), Gozo, the top of the formation grades into a packed foraminiferal biosparite, possibly a local development formed at the close of Blue Clay sedimentation.

b. Petrology

Thin sectioning is impractical in these soft sediments, though the relative volumes of the various components can readily be determined, either by breaking the samples down in a pan of water over a bunsen flame and subsequently sieving the breakdown products, or by taking thick acetate peels of smoothed specimen faces which results in the pulling off of a thin veneer of clay. Cooke (1893b, p.45) stated that the colour banding in the Blue Clay was a direct result of the amount of $CaCO_3$ present, the darker bands being the product of low carbonate content. This statement was found to be generally correct, as indicated by the following hydrochloric acid insoluble residue determinations, guaged against the rock colour chart values of Goddard et al. (1963).

Locality	Sample	Carbonate Content
Ta'Lippija	Dark grey (5Y7/2) top of Clay	0%
As above	Pale grey (5GY6/1) base of Clay	10.3%

It was also found that weathered samples with a high iron content are a yellowish-brown colour, resulting in an apparent darker colour than would be anticipated from their carbonate content especially when wet, for example:

Locality	Sample	Carbonate Content
Rdum (401809)	Medium grey (5GY6/1)	15.5%
As above	Yellowish grey (10YR7/4)	23.0%

Finally, Murray (1890) suggested that the base of the Blue Clay was best taken as the basal clay horizon below which carbonate content increased above 30%. This was tested for the following locality:

Locality	Sample	Carbonate Content
Tal Blata (452804)	Upper Globigerina Lst. (5Y7/2)	68.3%
As above	Intermediate sample (5Y7/2)	64.5%
As above	Blue Clay (10YR7/4)	22.2%

The present study also found that there was a general decrease in the carbonate content from the base of the formation to the top.

X-ray diffraction powder analyses for several Blue Clay samples from Ta'Lippija, Halk it Taffel (491646) and Rdum (401809), Malta, indicated that the clay component content of these marls is remarkably constant, being dominantly kaolinite, but with minor indeterminate mica clay mineral components and a little quartz. Goethite and pyrite are recorded in several traces and it was found that X.R.D. traces for the concretions at the top of the Blue Clay indicated that goethite is the major constituent, though this appears to be a secondary oxidation product.

Sieved fractions from washed Blue Clay samples yielded an abundance of foraminifera, dominated by planktonic forms. Sieved samples taken from the glauconite bed in the upper part of the formation clearly indicated that the glauconite grains are rounded detrital constituents associated with highly abraded foraminifera fragments, brown glauconite biomicrite clasts and rare books of biotite mica. Other minor detritals components identified include topaz, gypsum, rutile and tormaline. Murray (1890) also records quartz, feldspar and augite.

c. Fauna

The upper horizons, characterised by goethite concretions, yield the most prolific faunas, though the banded lower beds produce crushed specimens of diminutive gastropods, *Tellina* sp., *Chlamys* sp., and *Corbula* sp. These are associated with *Flabellipecten koheni* Fuchs and *Chlamys burdigalensis* Lamark, both of which also occur in the Greensand Formation. *Flabellipecten larteti* Tournour accompanies them in the top part of the formation. Fish remains are uncommon, teeth of *Carcharodon megalodon* Agassiz and *Odontaspis* sp., being collected during the present study. Other vertebrate material occurring throughout the formation consists of the vertebrae, ribs and teeth of *Phoca* sp., Cetacea and cranial fragments, and seven consecutive vertebrae of *Hyperoodon* sp., the latter collected from the upper part of the Blue Clay at Iz-Zewwieqa

(374872), Gozo.

The strata associated with the goethite concretions at Ghajn Znuber, Rdum il Qammieh and Tal Blata in northern Malta yield an abundance of goethite replaced fossils, including the gastropods: *Conus* sp., *Murex* sp., *Cassis* sp., *Xenophora* sp., *Turritella* sp., *Turricula* sp.?, *Pisania* sp.?, *Mitra* sp., *Strombus* sp., and *Pyrula* cf. *burdigalensis* Michelotti. The following bivalves and cephalopods were also collected: *Lucina* sp., *Arca turonica* Dujardine, *Cardita* cf. *partschi* Golds., *Venus* sp., *Cardium* sp., *Aturia aturi* Basterot, *Sepia sepulta* Michelotti, and *Nautilus* sp.

Solitary corals occur in abundance, including *Flabellum foecundum* Sesmonda, *Stephanophyllia imperialis* Michelin, *Balanophyllia* sp., *Ceratotrochus* sp., *Aplocyathus pyramidalis* Michelin, *Acanthocyathus* sp. and *Trochocyathus* sp. These are often accompanied by *Schizaster eurynotus* Agassiz, which frequently carries spines (Plate 16a,b.), and the pteropod *Vaginella* sp. is also commonly found. *Ostrea navicularis* occurs, associated with the glauconite bed at Halk it-Taffel, Malta, and *Ostrea edulis var. boblayei* Deshayes is frequently met with at the top of the formation. Rounded driftwood fragments which have been bored are also occasionally found at Rdum il Hmar, Malta. Most of these fossils were found loose on the surface and so it is difficult to locate their precise horizon. They do, however, appear to be restricted to the Upper 8 metres of sediment in the localities listed. The only areas of Gozo to yield fossils from this horizon are Fort Chambrey (365865), where Wigglesworth records gastropods, Ta Xiep (396874), where occasional *Aturia* sp. occur, and Dabrani, where solitary corals occur. Throughout the rest of the islands concretionary fossils are rare, though occasional *Schizaster* sp. is found. Fine burrow systems up to 1mm. diameter ramify throughout the formation at all levels.

Murray's list of microfossils includes 122 species and 33 genera. The present study has indicated that the dominant forms are Globigerina sp. and Orbulina sp. However, samples from Ta'Lippija, Malta also contain high counts of Uvigerina sp., and other common forms found in samples include Siphonina sp., Eponides sp. and occasional Nodosaria sp. Schizaster spines also frequently occur. Felix (1973) presents the most comprehensive foraminifera lists.

A brief search for pollen grains within samples from both the Blue Clay at Gnejna Bay and the 1 metre marl associated with the San Leonardo Beds (600706) gave very low yields, primarily consisting of monolete and trilete pteridophyte spores and pollen from Gramineae. Further attempts were abandoned, as it is believed that the advanced state of oxidation within these rocks has resulted in the destruction of all pollen grains except those with resistant exines. No environmental conclusions can be drawn from this data as both spores and grass pollen may be blown many miles from source.

2. Diagenesis within the Formation

Within the Blue Clay Formation in general the first stages of diagenesis are marked by minor compaction effects which have crushed many of the smaller macrofossils, which appear to have subsequently remained unreplaced. The goethitic beds at the top of the formation in north-western Malta yield detailed information on diagenesis and the following sequence has been recognised during the present study:

a) Early impregnation of all cavities within the micro-and macrofossils and all burrow systems with pyrite, often in the form of discrete octahedral crystals.

b) Dissolution of all aragonitic shell material (and cellulose tissues in fossil wood), ultimately resulting in the formation of shell casts. In western Malta, pseudomorphism of aragonite by pyrite or

c) Oxidisation of pyrite to goethite at a later date with the concomitant production of gypsum, which formed crystals within some shell cast cavities and twinned crystals within the Blue Clay matrix.

d) Further oxidisation of the goethite to yellow or redish ochreous material but still of goethitic composition.

At Tal Blata (452804) samples from low in the Blue Clay sequence (Plate 13a) indicate that, subsequent to the breakdown of pyrite to botryoidal goethite, a second generation of pyrite octahedra was developed, suggesting that reducing conditions must have occurred at least in some areas at a late stage in the diagenetic history of the formation. Although development of a radiating botryoidal structure is the commonest form of goethite, especially around concretions within the Blue Clay, it is frequently found that the goethite directly replaces the pyrite and pseudomorphs the original octahedral form (Plate 13d). This is especially so along the linings of shell cast cavities.

The Blue Clay is significant in that it is the only formation to contain replaced aragonitic fossils. In all other formations these fossils are merely represented by shell casts. This original replacement, discussed under b.) above, faithfully reproduces all the shell microstructure of lamellibranchs and preserves the chamber and cell form of the Cephalopoda and wood remains. It is thought that the initial mineralisation of these fossils was originally by pyrite, as weathered samples show pyrite infills to foraminifera, and the centres of goethite concretions and fossils are also frequently formed of pyrite. The fact that many fossils have been crushed subsequent to mineralisation indicates that pyrite replacement occurred before compaction and general lithification. The contorted and fractured nature of the septa of many of the Cephalopoda is believed to be a late stage effect of the original pyrite infill, which underwent a volume change upon oxidation to goethite. Gypsum, produced as a biproduct, infilled some of the remaining cavities.

The only other diagenetic effects recognised are the large light brown sandy textured concretions, up to 1.3 metres long, occurring within the solution subsidence structures of western Gozo. Upon staining, these concretions are seen to be composed of ferroan dolomite with a rhombic texture. The centre of each crystal frequently includes a limonitic inclusion, suggesting that the dolomite is a very late stage event, which developed after oxidation of the iron compounds to limonite. Occasional glauconite grains are scattered through the rock. It is believed that the concretions are probably of early origin but have subsequently undergone dolomitisation from an original calcite form. There is no evidence that they have grown in situ. at the expense of the surrounding Blue Clay Formation.

3 Palaeoenvironmental Interpretation

Two distinct biofacies occur within the Blue Clay Formation and are as follows:

a. Biofacies G Pectinid/Spatangoid Echinoid Biofacies

b. Biofacies I Solitary Coral/Mollusc Biofacies

a. Biofacies G. Pectinid/Spatangoid Echinoid Biofacies

This biofacies embraces the Blue Clay Formation below the beds containing goethite concretions. These beds are characterised by Flabellipecten koheni and Chlamys burdigalensis, though these forms are always disarticulated. Schizaster eurynotus is the dominant echinoid, though it is never as large in these beds as in the Globigerina Limestone Formation. The abundance of infaunal elements in the biota indicate that stable conditions prevailed throughout deposition, with no reworking of the bottom sediments. The partial absence of filter feeders in this part of the formation may be due to the turbid conditions prevailing, as clay particles would tend to choke the filtering apparatus of these forms. Felix (1973, p.57) considers that a muddy open marine environment of up to 150 metres depth is suggested by the foraminifera fauna, which is dominated by buliminid species.

b. Biofacies I Solitary Coral/Mollusc Biofacies

The 8 metres of beds containing goethite concretions in north-western Malta and southern Gozo are placed into this biofacies. The comparable, though small, faunas of these beds relate them to the derived phosphatised sediments of the Globigerina Limestone phosphorite horizons. It is considered that clay sedimentation may have slackened off at certain times to permit colonisation of the area by filter feeders. The corals are today represented in Australian waters (Doust, 1968), by forms ranging from 40 metres down to 520 metres and so are of little value in fixing depths. The bivalves, however, are more characteristic of depth ranges of 1 metre to 200 metres, hence the probable depth of deposition for these beds must lie between 40 and 200 metres. Considering the close proximation of these beds with the shallow water Greensand it is here believed that the upper part of the Blue Clay Formation was possibly deposited in depths less than 75 metres.

c. Geological History of the Blue Clay Formation

At the close of Globigerina Limestone deposition, deposition was centred on two basins, one in Gozo and the other in central northern Malta, and also an indistinct area around Delimara. The isopachyte maps of the Blue Clay Formation indicate that the Comino Straits High had retreated partially towards the west and that deposition in the Delimara region had possibly been terminated. This alteration of the location of the areas of minimum sedimentation resulted in the evolution of an elongated north-south depression centred on eastern Gozo and western Malta, and also a poorly defined area in north-western Gozo in which thicknesses increased rapidly, possibly reflecting sedimentation on the flanks of the Malta Rise.

Sedimentation continued uninterruptedly throughout Blue Clay deposition, periods of low clay influx producing the paler bands and periods of higher influx the darker bands. Towards the close of deposition areas to the west of the islands again became uplifted temporarily and strong westerly currents scoured the area, sweeping glauconite pellets, rock clasts and foraminiferal debris into the western parts of Malta and also Gozo. Finally, as the depositional depth decreased and sedimentation possibly waned the sparse infaunal element was supplemented by a dominant epifaunal and semi-epifaunal element, composed primarily of filter feeders and scavengers, but also with a high predatory gastropod assemblage. Into this environment drifted nektonic faunas such as the cephalopods. Many of the marine vertebrates must also have drifted into the area as decaying carcases in a manner postulated by Schäfer (1972, Chap.1). The occurrence of isolated vertebrae and also occasional collections of articulated vertebrae is consistent with Schäfer's conclusions that such animals, once dead, would float about shedding cephalic, cervical bones and caudal vertebrae in a random fashion before ultimately sinking to the seabed or totally disintegrating.

A significant point in this upper Blue Clay fauna is the apparent zonal arrangement of the faunas associated with the goethitic concretion horizons about the Comino Straits High. Diverse molluscan, coral and echinoid faunas occur closest to the High in north-western Malta but with impoverished faunas of gastropods and corals further away, especially in central Gozo. Furthest away from the High the concretions are unfossiliferous or are associated with rare echinoids. No definite cause can be attributed to this, though the shallow area about the Comino Straits may have acted as a baffle, protecting the waters of that area from a westerly or south-westerly direction, which is consistent with current directional data obtained from other formations. Another alternative explanation is that much of the clay sediment within the Blue Clay entered from the south by means of aeolian transport from north Africa, as is the case today in the southern area of the east Mediterranean Basin (Venkatarathnan in Stanley 1972, p.467). This, of course, would not prevent redistribution by marine currents subsequent to initial deposition.

TABLE 3

FLORAL + FAUNAL LIST OF THE BLUE CLAY FORMATION

The list has been constructed from the following sources: Spratt (1843), Wright (1855), Fuchs (1874), Gregory (1890-91), Murray (1890), Roman and Roger (1939), Reed (1949), and material collected during the present study.

Vertebrata

Phoca rugosidens Owen.
Hyperoodon sp.?
Other Cetacea.
Dugong.
Isurus hastilis Agassiz.
Carcharodon sp.
Odontaspis contortidens Agassiz.
Aeobatis sp.
Diodon sp.
Myliobatis sp.
Chrysophrys sp.

Echinodermata

Cidaris sp.
Schizaster eurynotus Agassiz.
Echinolampas hayesianus Desor.
Echinolampas laurillardi Agassiz.
Eupatagus dekonincki Wright.
"Pentacrinus" gastaldi.

Gastropoda

Strombus sp.
Conus sp.
Cassis sp.
Axinus angulatus.
Natica helica Brocchi.
Apporhais pes-pelicani (Linné).
Murex vaginatus.
Murex sp.
Xenophoria sp.
Turritella sp.
Turricula sp.
Pisania sp.
Mitra sp.
Pyrula cf. burdigalensis Sowerby.
Nucula sp.
Rostellaria sp.
Columbella sp.
Pleurotoma ramosa.
Fusus sp.
Epitonium melitensis (Fuchs).
Buccinum sp.

Lamellibranchiata

Pecten cristatum Fontannes.
Pecten spinulosus Münster.
Pecten denudatus.
Pecten vigolenensis Simonelli.

TABLE 3 (continued)

Chlamys (Amusiopecten) burdigalensis Lamark.
Aequipecten destefani Ug.
Flabellipecten koheni Fuchs.
Flabellipecten larteti Tournour.
Ostea edulis var. boblayei Deshayes.
Ostrea navicularis.
Cardita sp.
Cardita partschi Gold.
Cardium sp.
Arca turonica Dujardine.
Lucina sp.
Tellina sp.
Corbula sp.

Cephalopoda

Aturia aturi Basterot.
Nautilus sp.
Sepia sepulta Michelotti.
Sepia sp.

Pteropoda

Vaginella sp.

Anthozoa

Stephanophyllia imperialis Michelin.
Flabellum foecundum Sesmonda.
Balanophyllia sp.
Ceratocyathus sp.
Aplocyathus pyramidalis Michelin.
Acanthocyathus sp.
Trochocyathus sp.

Conifera

Araucarioxylon sp.

Foraminifera

Spiroloculina spp.
Miliolina spp.
Planispirena sp.
Haplophragmium sp.
Gaudryina sp.
Textularia spp.
Clavulina spp.
Bulimina spp.
Virgulina sp.
Bolivina spp.
Cassidulina spp.
Ehrenbergina sp.
Lagena spp.
Nodosaria spp.
Frondicularia sp.
Rotalia spp.
Rhabdogonium sp.
Vaginulina sp.
Polymorphina spp.

TABLE 3 (continued)

Uvigerina spp.
Sagina sp.
Globigerina spp.
Orbulina sp.
Pullenia spp.
Sphaeroidea sp.
Discorbis sp.?
Truncatulina spp.
Anomolina sp.
Eponides spp.
Nonionina sp.
Amphistegina sp.

The greater part of this fauna has probably been collected from the goethitic beds at the top of the formation, particularly in north-western Malta but also to a lesser extent in southern Gozo.

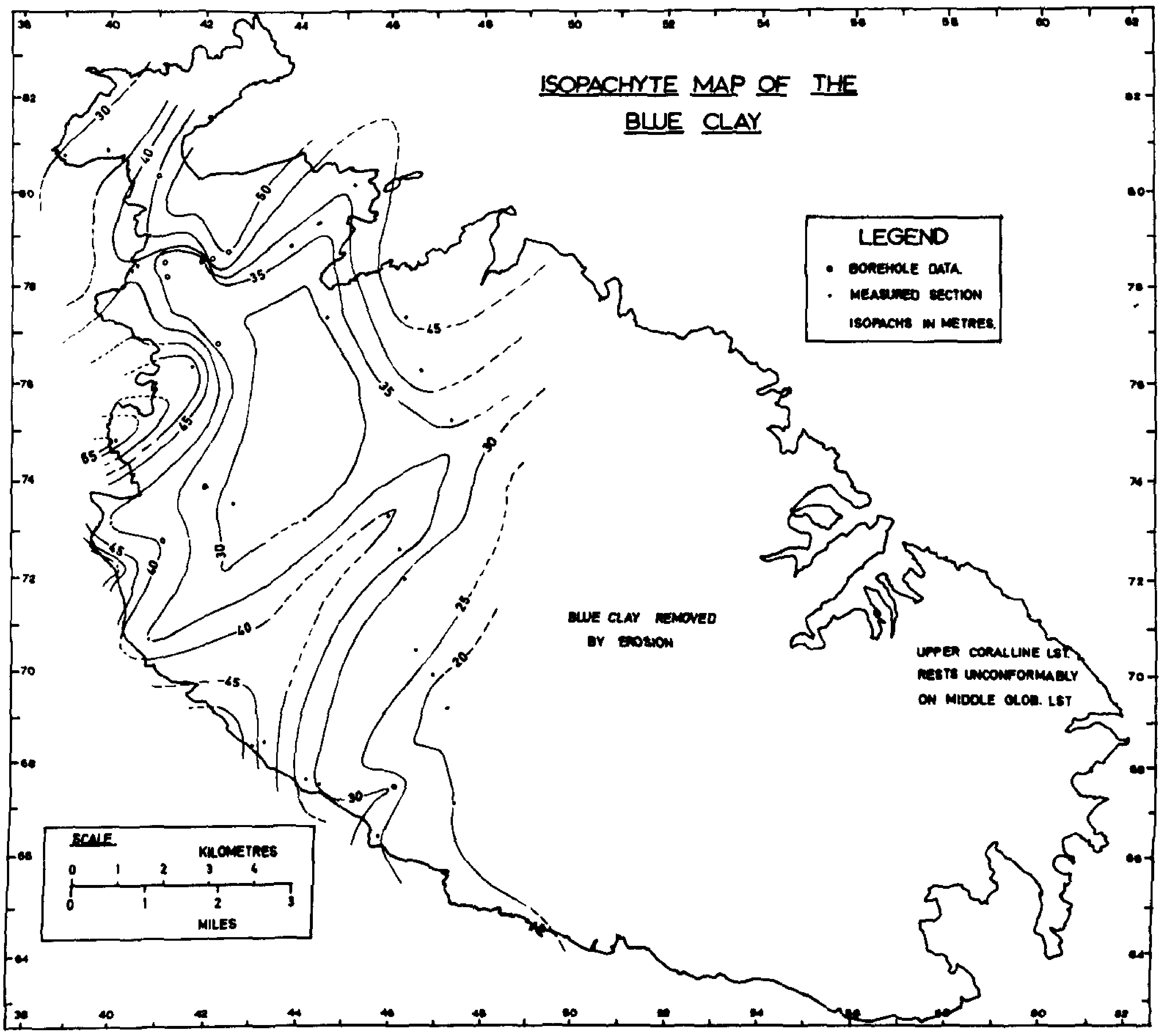


Fig. 17a

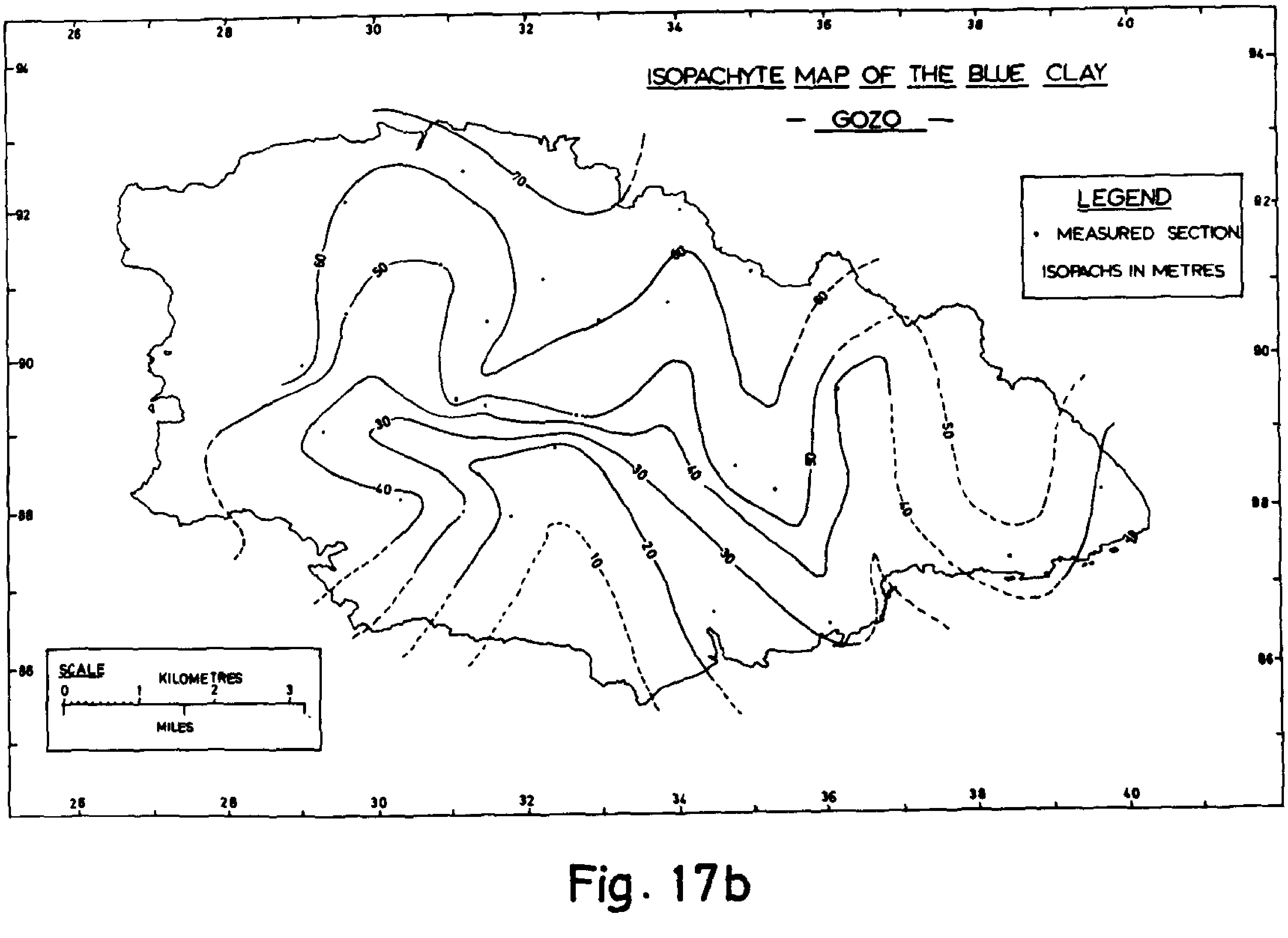


Fig. 17b

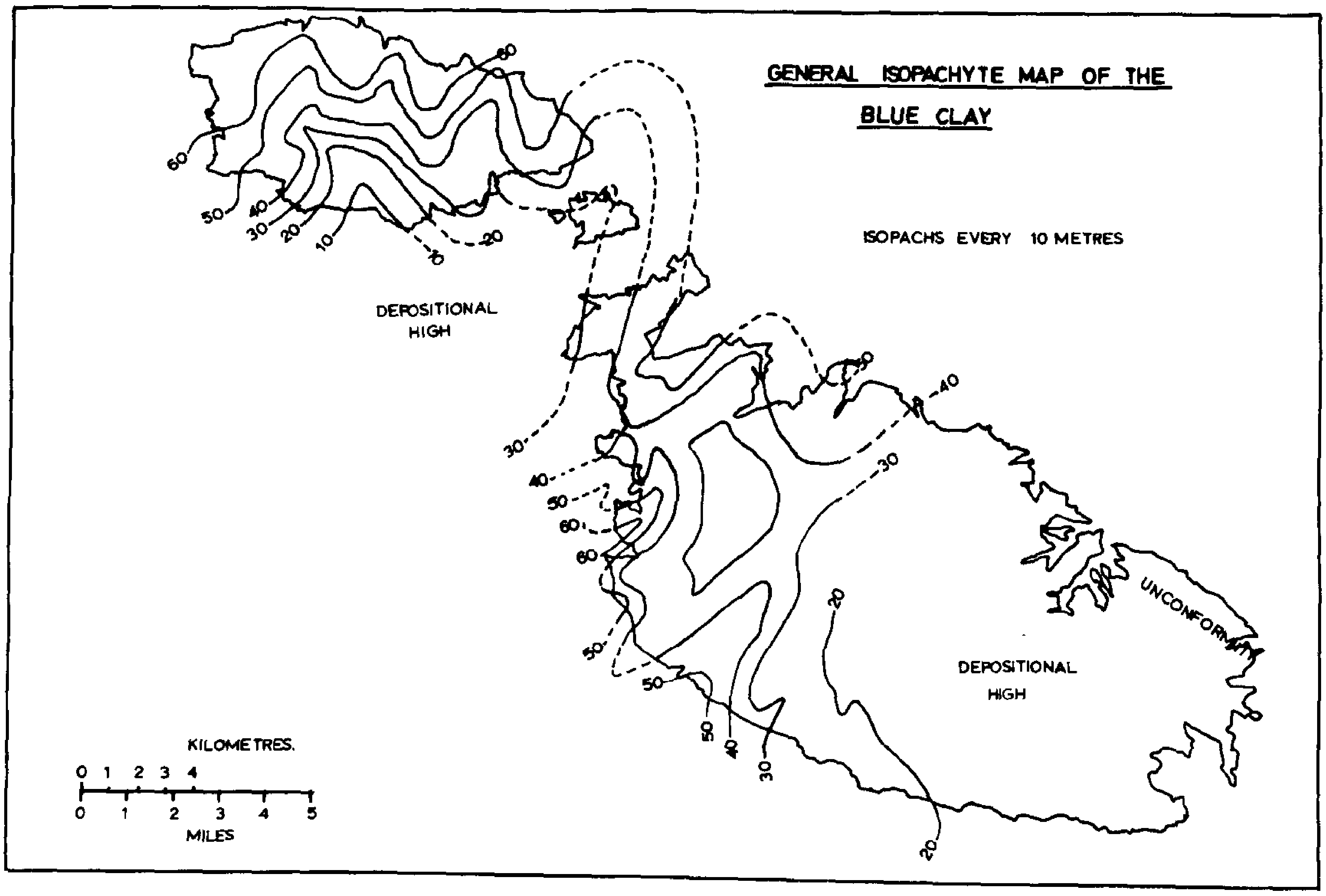


Fig. 18a

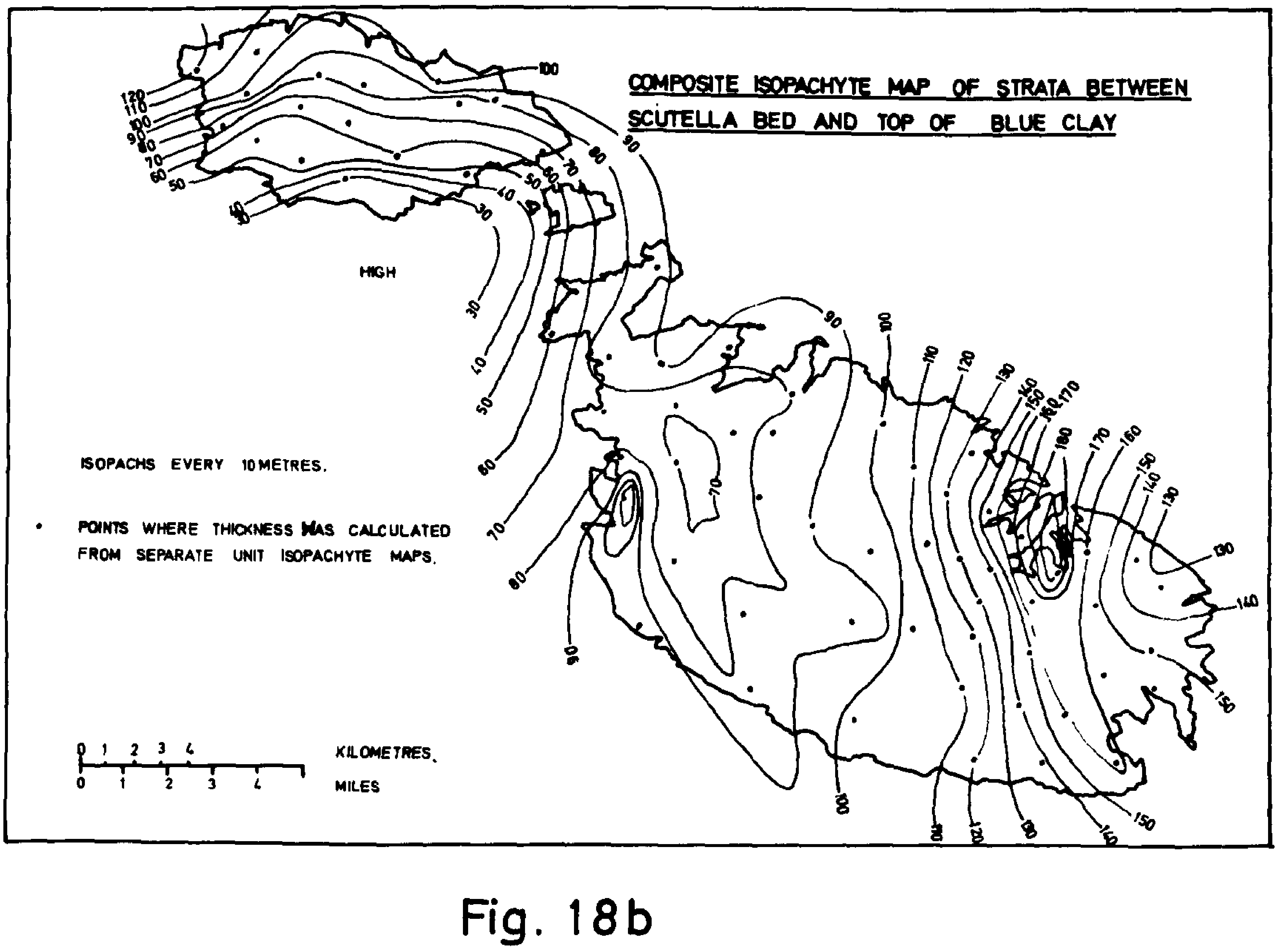


Fig. 18b

CHAPTER 6

GREENSAND FORMATION

1. Stratigraphy

For many years the Greensand was regarded as a subdivision of the Blue Clay (Spratt 1843). Murray (1890, p.463) proposed the term Greensand. From this time onwards both glauconitic sands and overlying light brown biosparites were included within the formation (see Wigglesworth 1964, pp.41-44). The present study retains the formation status of the Greensand, though it only recognises those beds of friable dark-green sediment containing significant quantities of detrital glauconite as making up the formation. The overlying brown biosparites are now considered to be basal Upper Coralline Limestone.

a. Il Gelmus Member

(i) General

Type locality Il Gelmus, Gozo (310894)

At the type locality a transitional sequence is recognised between the base and the underlying Blue Clay Formation. Within the fairly sharp transition the dominantly planktonic foraminiferal Blue Clay marl becomes glauconitic, though it is recognised that the glauconite grains are well rounded and detrital in nature. The member is characterised by massive bedding and is frequently burrowed. At Il Gelmus the top of the beds are marked by a sharp contact.

(ii) Lithology and Distribution

Outcrops in other areas of Gozo indicate that thicknesses vary from a maximum of 11 metres at Il Gelmus to nothing. Throughout Malta the member is less than 1 metre thick and has been subsequently reworked and assimilated into Upper Coralline Limestone sediments. In Gozo isopachyte studies reveal that the main area of deposition was in two interconnected north-south orientated basins, one centred on Il Gelmus and the other on Gordon (296921, Fig.5), with up to 7 metres being recognised at the latter locality. A third 2 metre thick pocket (Plate 6c), originally believed to have been continuous with the main basins but subsequently detached by interformational erosion (see Fig.20), occurs at Ghar Ilma (292892). Basal contacts, when seen away from the Gozo basins, are sharp or even erosional, as at (351865) in southern Gozo. The top of the member is, invariably, sharply terminated in localities west of a line from Gordon to Il Gelmus, but to the east of this the contact is more transitional. Here the Upper contact is often marked by a rapid facies change from friable greenish-grey lithoclast biosparite to a well cemented brownish biosparite. Some areas, such as Baroganni Rock (380876), merely show isolated pockets of black glauconite containing derived mollusc casts and with sharp upper and lower contacts.

(iii) Petrology

For petrological study it was found that disaggregation of the samples by either hydrochloric acid or washing soda was the most succesful method. The sediments are best described as clayey or micritic, lithoclast biosparites. The dominant co ponent is well rounded, allogenic glauconite originally of freeform habit, much of which shows alteration along cracks to a pale brown mineral. X-ray diffraction confirms that the fresh green grains are glauconite showing disordered structure, as defined by Burst (1958, pp.312-13), but the alteration product is goethite. Detrital gypsum grains (Plate 6b) are also common in the washed fractions. They are usually tabular cleavage flakes but bear rounded corners due to attrition during transport. A third component consisting of rounded lithoclasts of brown glauconite micrite occurs in the samples, although usually in sub-1mm. clasts (Plate 6e). It may compose larger clasts bearing the internal moulds of molluscs. Collectively these derived components make up 68% of the rock at Gordon and 77% at Ghar Ilma, although this is reduced to approximately 50% in the Malta Greensand. These are associated with clay minerals, powdery goethite clasts, occasional books of biotite and bioclastics. Grain size analyses of washed samples show that most of the components are less than 2.50, though hydrochloric acid insolubles average 1.5-2.50. Quartz, topaz and zircon grains also occur frequently.

The biogenic components are difficult to identify, but appear to consist of foraminiferal debris with occasional pectinid and echinoid clasts, all in a highly abraded. condition. At the top of the formation, in parts of Gozo and Halk it Taffel, Malta, chalky white concretions are abundant, which prove on examination to be entirely made up of micro-crystalline non-ferroan calcite.

(iv) Fauna

Generally speaking the fauna is sparse. At the type locality Schizaster eurynotus Agassiz is prominent and frequently bears attached spines. It is associated with scroll-like Cellepora polythele Reus. and Chlamys multistriatus Poli. A large number of articulated casts of Glycimeris cf. deshayesi (Mayer)are also abundant and fragments of Echinolampas sp. occur. Heterostegina depressa d'Orbigny is common to all Greensand localities in Gozo, though it is rarely present in large numbers. Indeterminate vertical burrows of up to 200mm. in length and of circular cross section are common. Fuchs (1874, p.97) gives a further impressive list of bivalves, many from the type locality.

At Gordon a similar, but sparser, fauna dominates, and at Ghar Ilma additional echinoids such as Clypeaster altus Lamark and Clypeaster marginatus Lamark occur, though the former is usually highly abraded, bored by marine biota and encrusted by serpulids and bryozoans.

In Malta, where the typical facies is not developed, for example at Il Fawwara (456664), the rock is composed of abraded and disarticulated adult *Terebratula terebratula*, Linné associated with *Dentalium* sp., cellariform bryozoans, and pectinid fragments of such forms as *Chlamys scrabella*, Lamark, and also *Ostrea edulis* var. *boblayei* Deshayes. The Greensand at the latter locality is capped by 0.8 metres of white micrite containing an abundant fish fauna dominated by *Bregmaceros albyi* Sauvage. Fragmentary and waterworn fragments of the vertebral column and cranium of Cetacea, *Phoca* sp. and *Halitherium* sp. are common in the Greensand, together with the teeth of *Carcharodon megalodon* Agassiz and *Isurus* sp. At Dabrani, Gozo, the following derived casts were collected: *Conus* sp.; *Xenophoria* sp.; fish vertebrae; *Cardita* sp.; *Pleuromya* sp.; and also *Ostrea navicularis*. Associated with this derived fauna in eastern Gozo is an *in situ*. fauna of *Tapes salomaciensis* Fischer and occasional *Thracea pubescens* Pulteney, and occasional *Ostrea lamellosa* Brocchi.

2. Diagenesis within the Formation

The most remarkable effect within these beds is the apparent shortage of calcite cement to bind this coarse deposit together. This appears to have always been the case, as no corrosion textures to the calcitic fossils present have been recognised, though derived shell casts indicate that the original cement may have been micrite in part. There has, however, been an early stage of aragonite solution within the formation and subsequent minor cementation by sparry calcite. Much of the glauconite present is in a state of partial oxidation, and the limonitic compounds released frequently coat the bioclasts present and impart a brown colour to the rock in general. Goethitic and limonitic minerals are present within the pseudopod pores of some foraminifera and the release of these upon weathering also causes brown or yellowish surface colouration in the rock.

3. Palaeoenvironmental Interpretation

On the basis of the biota the lithofacies may be divided into the following biofacies:

a. Biofacies K Schizaster/Lamellibranch Biofacies
b. Biofacies L Cellariform Bryozoan/Dentalium Biofacies
c. Biofacies E Giant Benthonic Foraminifera Biofacies

a. Biofacies K Schizaster/Lamellibranch Biofacies

This conforms to the facies occurring within the two laterally linked basins of Gozo. The presence of spine bearing Schizaster eurynotus and articulated shallow infaunal burrowers such as Glycimeris deshayesi points to extremely stable bottom conditions with only minimal reworking by burrowers after initial deposition. The large abraded Clypeaster altus at Ghar Ilma may well have been rolled into the margins of the basin by strong current activity from areas to the west. Purser (1973, p.48) found Glycimeris in protected muddy areas of the Persian Gulf, indicating that even this normally high energy environment dweller can occur in sheltered conditions. It is believed that although vast volumes of sediment were entering the basins of Gozo, quieter conditions prevailed within them which made the environment suited to deep burrowing echinoids and other infaunal feeders. The vertical burrows present (Bromley 1974, personal communication) suggest depths of accumulation in the order of 10 metres for Il Gelmus, though deeper episodes may also have occurred.

b. Biofacies L Cellariform Bryozoan/Dentalium Biofacies

This biofacies is represented by all the Greensand areas outside the double basin of Gozo, but particularly Malta east of a line from Qammieh (401809) to Il Fawwara (456664), and is dominated by the two components listed, together with Terebratula terebratula. Stach (1936, p.63) suggested that the cellariform growth-form was adapted for life in the littoral zone, where the effects of wave action were compensated by the internodal articulation which made the colony flexible. This will be discussed in a later chapter. Evidence indicates that some of the fossils present have been highly bored by Entobia sp. and have suffered a great deal of abrasion, suggesting that these thin Greensand deposits of Malta represent continuously reworked material which accumulated slowly over a considerable period in an extremely shallow environment.

The Greensand west of the Qammieh-Fawwara line still shows obvious signs of reworking but does not contain Terebratula. This brachiopod is only found in a narrow bed at higher horizons within this area, suggesting that much of the eastern fauna is of younger date than the sediments containing them. It is, therefore, difficult to postulate the original depositional depths during Greensand deposition in these areas, though they must have been extremely shallow and may even have been comparable to those for a. (biofacies K) above.

c. Biofacies E Giant Benthonic Foraminifera Biofacies

The only remaining area included within this biofacies is that within the solution subsidence structures of Qolla S-Safra, Gozo (330922), and Tas Salvatur, Gozo (328915). The fauna in these yellow biomicrites is dominated by Heterostegina, although infrequent specimens of Chlamys (Macroclamis) latissima also occur. The rock rests conformably on the Greensand Biofacies K, which is sparsely fossiliferous here. The upper contact with the Ghajn Melel Beds is marked by a deepening of colour and a strongly burrowed and bioturbated horizon, best seen close to the top of Qolla S-Safra. Present day Heterostegina lives at depths less than 50 metres and thus provides a maximum depth range for these beds.

d. Geological History of the Greensand

Blue Clay sedimentation was abruptly drawn to a close by renewed uplift of the region. This commenced in the west and extended with time eastwards, until the whole of the Maltese islands became a shallow area of non-deposition. The appearance of foraminifera, diagnostic of coastal conditions at this time (Felix 1973, p.57), is here taken to indicate close proximity to land. Within the Gozo area two interconnecting basins developed soon after uplift and received a thick accumulation of derived glauconite pellets, brown glauconite micrite clasts and detrital gypsum grains, the latter possibly associated with the erosion of Blue Glay areas lying to the west of the islands. The basins offered a more sheltered environment than other areas of the region, where intense reworking occurred, and a stable bottom community of echinoids and molluscs flourished, together with a few species of benthonic foraminifera. In Malta and eastern Gozo few animals succeeded in colonising the shifting substrate, apart from oysters and the occasional deep burrower. Most of the fauna of Biofacies L is the result of inmixing of later faunas by means of intense bioturbation.

The youngest beds of this formation occur in the Qolla S-Safra and Tas Salvatur outliers and represent finer grained beds, transitional with Ghajn Melel Beds, which developed at the close of the Greensand episode, but which were subsequently removed by interformational erosion from all other areas. In both cases, however, there is evidence that contemporaneous solution subsidence (considered in detail in a later chapter) was responsible for the preservation of these beds (see Fig.20).

It appears that Greensand sedimentation was brought to a close by a reduction in the velocity of the prevailing westerly currents, thus allowing for the development of Biofacies E in Gozo. Subsequently, most of the Greensand was removed from western Gozo by erosion, in part contemporaneous with the overlying Ghajn Melel Beds. This resulted in the removal of the western sides of the interconnected Gozo basins, leaving the Ghar Ilma Greensand, representing the western extremity of the southern Gozo basin, as an outlier prior to the development of the

Coralline Algal Bioherm, which is locally developed here. It is considered likely that the lowest horizons of the Ghajn Melel Beds may be in part contemporaneous with parts of the Greensand, as there is some indication of lateral transition in western Gozo.

TABLE 4

FAUNAL LIST FROM THE GREENSAND

In compiling the faunal list the following references have been consulted: Forbes (in Spratt 1843); Fuchs (1874); Adams (1879); Gregory (1890-91); Reed (1949), and material collected during the present study.

Vertebrata

Halitherium cf. schinzi Kaup.
Phoca sp.
Cetacea.
Oxyrhina sp.
Odontaspis sp.
Carcharodon megalodon Agassiz.
Indet. vertebrae.

Echinodermata

Clypeaster altus Lamarck.
Clypeaster marginatus Lamarck.
Echinolampas pignatarii Airaghi.
Echinolampas wrighti Gregory.
Schizaster eurynotus Agassiz.
Spatangus sp.

Gastropoda

Turritella cathedralis Brongniart.
Xenophoria sp.
Epitonium melitensis (Fuchs.).
Conus sp.
Natica sp.
Dentalium sp.
Strombus sp.

Lamellibranchiata

Pecten tournali.
Pecten cristatum Fontannes.
Pecten substriatus.
Chlamys (Amusiopecten) burdigalensis Lamarck.
Chlamys multistriatus Poli.
Chlamys scrabella Lamarck.
Chlamys solarium Lamarck.
Ostrea virleti Deshayes.
Ostrea digitalia Eichw.
Ostrea lamellosa Brocchi.
Ostrea frondosa DeSerres.
Ostrea edulis var. boblayei Deshayes.
Spondylus crassicosta Deshayes.
Arca fichtelii Deshayes.
Isocardia sp.
Thracea pubescens Pulteney.
Tapes vetusta.
Cytherea pedemontana.
Venus umbonara.
Venus multilamella.
Lutraria oblonga.
Tellina planata.

TABLE 4 (continued)

Cardium hians Brocchi.
Cardium multicostatum.
Loripes incrassata (Dubois).
Lucina haidingeri.
Glycimeris deshayesi (Mayer.).
Pleuromya sp.

Brachiopoda

Terebratula terebratula Linné.

Bryozoa

Cellepora sp.
Cellepora cf. polythele Reus.
Cellaria sp.
Canda sp.
Crisia sp.
Scrupocellaria sp.
Membraniporiform types.

Crustacea

Necronectes schaferi.

Ostracoda

Aurila sp.
Bairdia sp.

Miscellaneous

Serpula sp.
Entobia sp.
Crustacean burrows.

Foraminifera

Globigerina sp.
Orbulina sp.
Elphidium sp.
Heterostegina depressa d'Orbigny.
Textularia sp.
Eponides sp.
Nodosaria sp.

CHAPTER 7

UPPER CORALLINE LIMESTONE FORMATION

Stratigraphy

This formation was originally designated as the "Upper Limestone" by Spratt (1843, p.225) and was subdivided into the following four divisions,which were estimated to total 250ft. in thickness.

White rubbly sandstone
Coarse grained sandstone
White or grey-brown bed
Red coralline stratum (base)

Ultimately, the formation was renamed Upper Coralline Limestone by Murray (1890, p.461), probably on account of the abundant coralline algae which occur in the lower horizons. Later attempts to subdivide the formation by Russell (1955, p.25) and by the Costain Survey (1957) created arbitrary subdivisions based on the more obvious lithologies. Some of these, however, are the result of secondary solution and recrystallisation in the middle and upper beds and are not absolutely governed by stratigraphical subdivisions, hence, the proposed subdivisions are unsatisfactory. A number of the less altered basal members were,however,appreciated, though their interrelationships and regional extent were never recognised until the present study. The following stratigraphic succession with a thickness totalling approximately 150 metres is based on the author's work.

4 Gebel Imbark Member	(c.San Leonardo Beds in east (b.Gebel Imbark Beds (a.Tat Tomna Beds
3 Tal Pictal Member	(d.Ghar Lapsi Beds in south (c.Ghadira Beds in east (b.Tal Pictal Beds in west (a.Rabat Plateau Beds at base
2 Mtarfa Member	(c.Rdum il Hmar Beds (b.Mtarfa Beds (a.Coralline Algal Bioherm in west
1 Ghajn Melel Member	(b.Ghajn Melel Beds in west (a.Ghajn Znuber Beds in east

As the study of this formation and its ultimate subdivision has occupied the greater part of research involved in this project it will be dealt with in considerable detail in this and the succeeding two chapters. Throughout these chapters it will be necessary to refer to figure 5.

1. Ghajn Melel Member

Type locality Ghajn Melel, Gozo (317926)

Until the present study these strata were included within the Greensand, though the reason for this is far from being obvious. In the field the strata vary from a pale orange-brown colour, typical of the Ghajn Melel Beds, to a dark brown colour, more characteristic of the Ghajn Znuber Beds. Figures 19 and 20 illustrate the distribution of the member and show its proposed relationship with other beds, including the fact that it is laterally equivalent in age to the Coralline Algal Bioherm and Mtarfa Beds. From Fig.5 it is seen that the member is restricted in distribution, being most in evidence in north-western Gozo and in the Dingli area of Malta. The member is subdivided on the basis of grain size and biocomponents into the following beds:

b. Ghajn Znuber Beds

a. Ghajn Melel Beds

a. Ghajn Melel Beds

(i) General

At the type locality a complex interfingering, dominantly of Ghajn Melel Beds, but also including Ghajn Znuber Beds, occurs and forms the thickest development of this member within the islands. It is 16.5m. thick at this locality. In Malta, however, the Ghajn Melel Beds are poorly represented, being not more than a few millimetres in thickness in western areas. The Ghajn Melel Beds appear to interfinger laterally with the Ghajn Znuber Beds, there being a gradational lateral contact between the two.

The basal contact of the Ghajn Melel Beds in western Gozo is always disconfor~~m~~mable (see Fig.20) and may be on Greensand, or on eroded Blue Clay, as at Ghajn Barrani (342916), where angular blocks of Blue Clay occur up to 500 mm long. Frequently the basal contact with the Greensand is bioturbated, giving the false impression of a gradational change. The top of the Member is impossible to fix accurately in many areas of western Gozo as later erosion has removed the upper horizons of the member. However, White Tal Pictal Member limestones cap some outcrops, especially around Zebbuge, and outcrops further east are capped by coralline algal Bioherm of the Mtarfa Member.

(ii) Lithology and Distribution

The general appearance at outcrop is of a rubbly pale orange-brown rock which is often so recrystallised that all traces of primary structures and fossils have disappeared. The beds appear to increase in thickness towards the centre of the basinal area in which the Greensand Formation accumulated. Thick lensoidal accumulations of Heterostegina sp. are characteristic of the Ghajn Melel Beds. The fossils are invariably unabraded and are either orientated parallel to the bedding direction, or are stacked into burrows, where they frequently line the walls of these structures. For the most part the beds are of uniform lithology, though highly recrystallised areas often show a rubbly or pseudobrecciated appearance. The strong basal erosion surface recognised at Il Gelmus and Gordon (Fig.20) appears to be connected with similar erosion planes within the lowest beds of the Ghajn Melel Beds, indicating that these lowest strata of the beds may in part be laterally equivalent in age to parts of the Greensand which was being deposited to the west. The occurrence of glauconite grains associated with the lower horizons of the Ghajn Melel Beds supports this conclusion.

(iii) Petrology

The dominant rock type in thin section is a foraminifera microsparite, although it is apparent that the microspar was originally micrite which has coarsened upon subsequent recrystallisation. Towards the margins of the area, particularly in the east, the unabraded Heterostegina sp., which occur almost to the exclusion of other foraminifera, are associated with limonitic impregnated and fragmentary specimens, for example at Kemuna Tower, Gozo (357889). These beds are transitional with the Ghajn Znuber Beds. Within the central areas of deposition, as at Il Gelmus (311895) and south-east Victoria (323887), the microsparites are almost devoid of fauna and consist of rhombs of calcite with limonitic nuclei (Plate 8c). These beds obviously conform to those described by Murray (1890, p.464) as marking the top of what was then considered as Greensand, but which is now recognised as basal Upper Coralline Limestone. It is the limonite present within the strata which gives the rock its characteristic brownish colour. As this is generally only abundant within the chambers and pseudopod pores of the reworked foraminifera present around peripheral areas of the depositional basin, it is found that the more typical biomicrites from the central areas of deposition exhibit a paler brown to orange colour. The composition of these beds is illustrated in Figs.21a, b, and 22a.

(iv) Fauna

In central areas of deposition no fauna is recognised for considerable thicknesses of strata, although at certain horizons (Fig.20) large developments of the benthonic foraminifera Heterostegina cf. depressa d'Orbigny (Lenticulites complanatus Defrance of Wright, 1855) occur in an unabraded form, and Clypeaster marginatus Lamark and vinculariform bryozoans are occasionally found. In marginal areas of the basin isolated Clypeaster altus Lamark together with Clypeaster marginatus Lamark occur. A significant form seen in these beds and apparently restricted in vertical range is the large Chlamys (Macrochlamis) latissima Brocchi. These are considered to be approximately equivalent in age to the Terebratula - Aphelesia Bed, to be discussed later in the chapter. They occur as isolated, though frequently articulated individuals, usually towards the base of the Ghajn Melel Beds.

There is a marked absence of planktonic foraminifera from these beds. Vertical and inclined single burrow systems of circular cross section are common in these beds. They vary in diameter from 10mm. to 21mm. and appear to conform to similar structures in Libya, described as *Alukichnus* sp. by Doust (1968).

b. Ghajn Znuber Beds

(i) General

Type locality Ghajn Znuber, Malta (408790)

These beds occur principally in south-eastern Gozo, around Ghajn Znuber in north-eastern Malta, and as a northerly trending tongue from the Dingli Cliffs area inland (Fig.19). The type locality exhibits a particularly coarse development of these beds, amounting to 5.1 metres in thickness. They are stained dark brown and directly underly the Coralline Algal Bioherm with apparent conformity. A similar form of contact is seen in the south-eastern coast of Gozo, west of Mgarr. In south-western outcrops the basal Upper Coralline Limestone erosion surface, previously referred to, appears to separate these beds from the bioherm. The basal contact is also generally sharp and may rest on Blue Clay or Greensand. Glauconitic pellets are frequently intermixed with the beds, being most in evidence in the lowest horizons. Alternatively, the base may consist of a loosely bound biosparite containing reworked fossils and casts, as at the type locality.

(ii) Lithology and Distribution

At outcrop the rock strongly contrasts with all other beds on the islands due to its dark brown colour, coarse grainsize and abundance of large fossils (Plate 6d). In Dingli Cliffs the rock, although finer grained, is capable of forming vertical cliffs over 13 metres high. Throughout the outcrop these beds contain large internal casts of molluscs, and occasional bones and teeth of marine mammals and sharks. In Malta the beds vary in thickness between 2 and 13 metres, though the beds are unrepresented in many areas.

The general distribution of these beds in Gozo is difficult to appreciate from Fig.19, though the main outcrop trends in a north-easterly direction from Fort Chambray (3686) to the area just north-west of Nadur (3788). This structure, forming a lens-like distribution, has been previously recognised by Newberry (1958,p.3). In Gozo the beds attain a maximum thickness along the Mgarr coast of just over 4 metres.

The general lack of Ghajn Melel Beds in Malta prevents an accurate assessment of the interrelationship between the Ghajn Melel and Ghajn Znuber Beds. However, the more extensive exposures of both groups of beds in Gozo indicates that they are at least in part laterally equivalent, the Ghajn Melel Beds occurring primarily in the west and the Ghajn Znuber Beds interfingering from the east. The presence of coarse beds interfingering with the Ghajn Melel Beds in northern Gozo, and including the type locality, further indicates that the Ghajn Znuber Beds may extend around the northern periphery of Gozo as well as around the eastern part of the island. In Malta the extension of the <u>Terebratula-Aphelesia</u> Bed, discussed in Chapter 10, into the Ghajn Znuber Beds of the Dingli Area indicates that, although the Coralline Algal Bioherm overlies the Ghajn Znuber Beds in most areas, the facies persisted in western Malta and for a time was laterally contemporaneous with the Coralline Algal Bioherm.

(iii) Petrology

Reference to Figs. 21a, b and 22a, indicates that the main features are the low echinoid counts and the high proportions of benthonic foraminifera, which may be over 90% in some samples. Initially it was found difficult to establish an accurate boundary line between the Ghajn Znuber and Ghajn Melel Beds as in the field only the colour and macrofaunal content appears different. Modal analysis, however, clearly indicates the fact that the Ghajn Znuber Beds contain a high proportion of lithoclasts of two types. The first consists of powdery yellow limonite clasts. These often wash out of the rock, either during weathering, or during thin sectioning, but when examined appear to originally have been angular to rounded goethite lithoclasts varying in size from 0.5mm. up to 18mm. in extreme cases, such as at Tal Lippija, Malta. The second derived component consists of the previously mentioned

Heterostegina fragments which have obviously been impregnated by goethite prior to being fragmented. Plate 8b illustrates both *in situ* foraminifera and derived clasts. Glauconite occurs as scattered derived grains. When percentages of these various components are ultimately plotted out (Fig. 22a) there is a clear distinction observable between the two beds, the Ghajn Melel Beds with less than 20% lithoclasts, and the Ghajn Znuber Beds with up to 70% derived material. Grain counts suggest that the derived component increases from less than 10% at Kemuna Tower to a maximum around the cliffs east of Mgarr, Gozo. Isograd studies of derived components show trend in a north-easterly direction and outline the division between the Ghajn Melel and Ghajn Znuber Beds. The Ghajn Znuber Beds generally conform to an unsorted lithoclast *Heterostegina* biosparrudite. Most thin sections were found to be cemented by a sparry low-ferroan calcite.

(iv) Fauna

The finest fauna from these beds comes from the Mgarr coastline of south-eastern Gozo. In the cliffs here there is an abundance of *Clypeaster marginatus* Lamark, *Clypeaster altus* Lamark and *Clypeaster altus* var. *pyramidalis* Michelin, the latter, on examination, being restricted in occurrence to this locality. Associated with these are disarticulated valves of the large oyster *Ostrea virleti* Deshayes, *Chlamys* (*Macroclamis*) *latissima* Brocchi, and large hemispherical masses of *Cellepora mammalata* Busk in normal growth position. Other common pectinids at this horizon are *Chlamys scrabella* Lamark, occasional *Pecten solarium* Lamark, and *Pecten senensis* Tournour. This fauna is associated in all areas with fragmentary *Heterostegina depressa* d'Orbigny. The fauna at the Ghajn Znuber outcrops is identical in all respects, except for the lack of *C. altus* var. *pyramidalis* and, as with the previous locality, small spheroidal rhodolites come in at the top of the beds (Plate 6a). The earliest coralline algal colonies, occurring towards the top of the Ghajn Znuber Beds, encrust the *Cellepora* colonies but ultimately, as the sediments become finer, true rhodolites develop. The basal beds, which are best seen in this area, but which also occur as a thin veneer beneath the Coralline Algal Bioherm of the Tal Lippija area, contain an abundance of derived phosphatised mollusc casts which are often encrusted by membraniporiform bryozoans, particularly at Hmar (412747).

The rocks of the Tal Lippija and Dingli areas are generally finer grained than their northern counterparts and contain different faunal elements. *Clypeaster altus* Lamark and *Clypeaster marginatus* Lamark are both present in inland exposures of the Dingli outlier, but *Echinolampas pignatarii* Airaghi is the dominant form encountered in coastal exposures at Dingli. *Cellepora mammalata* Busk is also present as hemispherical masses up to 90mm. diameter. *Terebratula terebratula* Linné, *Spondylus crassicosta* Lamark, *Chlamys* (*Macrochlamis*) *latissima* Brocchi and *Chlamys multistriatus* Poli, *Chlamys scrabella* Lamark and *Turritella* sp. complete the fauna from the inland areas of Dingli.

The Tal Lippija fauna is markedly dissimilar from the remainder of the member. The rock is paler in colour and is largely made up of *insitu* casts and moulds of *Glycimeris deshayesi* Mayer, *Cardium* sp., *Lucina* sp., and other indeterminate mollusc fragments, together with infrequent *Clypeaster altus*, Lamark and *Echinolampas pignatarii* Airaghi.

Derived fossils occur sporadically throughout the beds and include *Arca* sp., *Cardium* sp., *Glycimeris* sp., *Conus* sp., teeth of *Carcharodon megalodon* Agassiz, *Odontaspis* sp., and waterworn bones of Cetacea. A waterworn rib of *Halitherium* sp. was also found at Ghajn Barrani, Gozo, lying within a contemporaneous solution subsidence infill. Bromley (personal communication) has noted abundant vertical foraminiferal walled burrow systems, 30-40mm. in diameter and 0.5m. long, penetrating these sediments at Ramla Bay, Gozo.

2. Mtarfa Member

This newly erected member is considered to be the lateral equivalent of the Ghajn Melel Member and occurs in eastern areas of Malta and Gozo. The member is conveniently split into three subdivisions on the basis of colour and biological content as follows:

c. Rdum il Hmar Beds
b. Mtarfa Beds
a. Coralline Algal Bioherm

a. Coralline Algal Bioherm

(i) General

Type locality Tal Mas, western Malta (402725)

At this locality the bed thickness is almost 16 metres and consists of cream micrite with abundant Lithophyllum rhodolites which are orientated with their long axes parallel to the bedding. The basal 1.16m of the sequence is pale grey, contains laminated crustose coralline algae and rests with a moderately sharp contact on Blue Clay. Frequently, however, a thin glauconite layer separates the two. The top contact is not seen at this locality. The subdivision is distinguished from the laterally equivalent Mtarfa Beds, lying to the east, mainly on the basis of rhodolite content, which is absent from the latter beds (Plate 7a).

(ii) Lithology and Distribution

The Lithophyllum rhodolites usually occur as elliptical to spheroidal colonies showing a dendritic branching habit. The majority of the rhodolites are between 50 and 160mm. in diameter and each appears to have existed, at least initially, as a separate entity. They are now enclosed in yellow micrite. In a few cases, however, lateral growth has tended to link these colonies together, imparting a ridged framework to the rock. The typical bioherm rock consists of alternating layers of rhodolite rich and micritic rich horizons. In some areas, for example at Tas Santi (422729), a great deal of detrital Lithophyllum occurs, though this appears to have been transported live, as growth was clearly re-established upon arrival, producing vertical laminar growth points. Differential weathering causes the more resistant rhodolites to weather out prominently in relief from the softer powdery micrites.

These beds are best exposed at the base of cliff sections in eastern Gozo and western Malta. In western Gozo the beds rest with a transitional to sharp contact on the Ghajn Melel Member. In eastern Gozo they overlie Greensand. It would, therefore, appear that the beds die out westwards, from a maximum in eastern Gozo and western Malta, and are replaced laterally by the Ghajn Melel Member.

The upper contact is difficult to recognise, as recrystallisation in the overlying Tal Pictal Member often penetrates down into the top of the Coralline Algal Bioherm. In the extreme east of Gozo the beds pass transitionally upwards into the Rdum il Hmar Beds (see Fig.5). In Malta the same general relationships are seen, although inland outcrops are often obscured by soil or Quaternary material, making interpretation difficult. At the top of the bioherm the strata becomes progressively whiter. This seems to have regional significance and appears to equate with the change from yellow Mtarfa Beds to white Rdum il Hmar Beds further east, suggesting that there may be lateral correlation of the topmost Coralline Algal Bioherm with the Rdum il Hmar Beds, even though the lower part of the bioherm clearly equates with the Mtarfa Beds on the basis of the Terebratula-Aphelesia Bed (see Chapter 10).

The thickness variations and maximum extent of these beds of algal rhodolites is displayed in Fig.23. Typical lithological variations are displayed in Fig.24b.

(iii) Petrology

Most examined thin sections were for the purpose of identification of the coralline algal component. Samsonoff (1917b, p.612) records the dominant species of alga from the Upper Coralline Limestone as Lithophyllum destefanii Samsonoff. However, the type description fails to give cell and oogonium parameters. A detailed examination of the Coralline Algal Bioherm indicates that one major species of Lithophyllum is present.

Lithophyllum in Coralline Algal Bioherm

Oogonium 525 (630) µm x 170 (189) µm

Perithallus 16 µm x 14 µm

Hypothallus 21 µm x 21 µm

These parameters, primarily the large size of the oogonium, are typical of the Maltese species. Johnson (1965) records L.destefanii but does not provide cell parameters. However, none of the other recorded Miocene species fits the values found for these specimens in the Coralline Algal Bioherm. Therefore, it is very likely that this species is L.destefanii of Samsonoff (Plate 8d).

Further thin section study indicates that besides being made up of over 40% Lithophyllum rhodolites, the micrites contain less than 10% pectinid fragments and minor amounts of echinoid debris. When sectioned the rhodolites themselves occasionally provide evidence of movement during formation. The nuclei of most rhodolites consist of a planar section of that species which, in its early stages, appears to have been overturned on several occasions. Upon each overturning episode, growth continued on the resulting upper surface. In the late stages, however, most growth occurred on one side, indicating that the larger forms rarely moved.

The grey basal beds to the bioherm contain lichen-like crustose coralline algal growthforms, apparently of the same species as the Lithophyllum rhodolites (Plate 19d). These usually occur as detached fragments in a grey marl matrix. X-ray diffraction powder analysis of the grey basal marl shows that the clay component is indistinguishable from that occurring in the Blue Clay Formation, being dominantly kaolinite, but with minor percentages of quartz, mica clay minerals and possible muscovite.

(iv) Fauna and Flora

As previously stated, the dominant algal species is probably Lithophyllum destefanii Samsonoff, although Mesophyllum sp. also occurs, together with rarer Archaeolithothamnion sp. Within this framework the most dominant feature is a prominent bed containing Terebratula terebratula Linné (Plate 7c). This occurs as a single band of frequently articulated shells, throughout the Coralline Algal Bioherm, except in north-eastern Gozo, (Fig.22b). Associated with this bed is Aphelesia bipartita (Brocchi). Other brachiopods associated with the lowest horizons of the bioherm, but not restricted to the Terebratula-Aphelesia Bed, are Megathiris sp., Argyrotheca sp., Megerlia sp. and Terebratulina caput-serpentis Linné.

Areas of the bioherm closely associated with the Ghajn Znuber Beds in the Dingli area of Malta carry additional faunas to the main body of the bioherm and these are more characteristic of the Ghajn Znuber Beds. These include Clypeaster altus Lamark, Clypeaster marginatus Lamark, small hemispherical Cellepora sp., and Ostrea virleti Deshayes. It is in these areas that the fauna is frequently highly abraded and bored by molluscs, Entobia sp. and bryozoans, and also heavily encrusted by Serpula sp. and membraniporiform brozoans. Turritella sp. also occurs together with Chlamys (Macrochlamis) latissima Brocchi. Nodular developments of Calpensia impressa Moll. are common in the beds as a whole, but are especially abundant at Il Qortin, Gozo (377899) and in the St.Catherine's Chapel area, Malta (445697). Spondylus crassicosta Lamark is a common form in this facies and often occurs in an articulated condition. An abundance of indeterminate crustacean fragments including Harpactocaranus sp. and Scylla sp. occur in these beds. Brissus oblongus Wright, Cidaris melitensis Wright, Echinus duciei Wright, Schizaster eurynotus Agassiz and Strombus sp. are also occasionally found. Corals are generally absent, though Tarbellastraea sp. was collected at Ghajn Znuber from a planar colony within the upper part of the beds. A more complete faunal list is given for the Terebratula-Aphelesia Bed in Fig.34. Balanus sp. occurs within the bioherm on the Tas Salvatur outlier in north-eastern Gozo.

b. Mtarfa Beds

(i) General

Type locality, Mtarfa, Malta (456717)

These are the type beds of the Member, which are moderately well exposed beneath the crystalline capping sequences of the Maltese Islands, but especially so around Mtarfa. At the type locality the beds have an intensely bioturbated base. This bioturbation resulted in the assimilation of glauconite grains into the basal beds from the underlying Greensand Formation. This particular feature of the contact between the Greensand and Mtarfa Beds is commonly seen in eastern areas of Malta. However, the true relationship is seen when the intermixed unabraded Greensand fossils are examined, as they still contain typical Greensand sediment. The succeeding beds consist of about 7 metres of yellow biomicrites with a generally low macrofaunal content.

(ii) Lithology and Distribution

These beds are typified by their pale yellow or cream colour, their fine grained nature, lack of algal rhodolites, and a low allochemical content. In Gozo, the Mtarfa Beds are poorly represented (see Fig.5), being restricted to the eastern extremity of the island. Here the beds are often less than 2 metres thick and lie directly on Greensand. In Malta, the beds are well developed and extend as a broad belt from the eastern Marfa Ridge southwards throughout the entire outcrop to Gebel Ciantar, at the southern end of the Upper Coralline Limestone plateau. They are again recognised in the Ghar Lapsi outlier to the south. Throughout the whole area the beds lie, with bioturbated contact, on the Greensand, and gradually pass upwards as yellow biomicrites into the overlying Rdum il Hmar Beds. In all areas the Mtarfa Beds are well bedded but with occasional horizons of a more massive nature. In such cases bioturbation and fossil horizons are the only means of observing the horizontality of these beds. A report by Hyde (1955, p.110) of tectonically disturbed beds near Mtarfa is now recognised as a secondary effect, involving calcite cementation in the vadose zone, particularly at sites in close contact with the water table. Although not examined, it is anticipated that the basal Upper Coralline Limestone of the island of Filfla is also composed of the Mtarfa Beds. This extrapolation is based on facies trends in Fig.23.

(iii) Petrology

The typical rock is either a fossiliferous micrite or, more commonly seen towards the base of the beds, a sparse biomicrite. A significant feature of this bed is its general lack of planktonic foraminifera, a feature which it shares with the Ghajn Melel beds and the Coralline Algal Bioherm. Usually, planktonic foraminifera account for less than 1% total rock volume. Benthonic foraminifera are also uncommon in most areas, although 12% are recorded from beds at Fort Mosta, Malta (483754). This is, however, unusual and the general colour in the field and this low foraminiferal count are the two major means of distinguishing these beds from the Ghajn Melel Member. (See Fig.21a). Fragments of spatangoid echinoids and pectinids occur in minor proportions, but mollusc moulds (Plate 8a and Fig.21b) are further characteristic. Microsparite development is common in some samples but it is believed that the original matrix was micrite.

(iv) Fauna

The most outstanding feature of the fauna is the dominance of spatangoid echinoids such as Schizaster eurynotus Agassiz, which may attain a length of up to 110mm., as at Il Fawwara, Malta (456664), (see Plate 7b). Echinolampas wrighti Gregory is occasionally encountered, as is Spatangus pustulosus Wright. These beds are coarsest towards the base, at which horizons the fauna is most prolific. Aragonitic mollusc casts and moulds abound and include forms such as Cardium hians Brocchi, Thracea pubescens Pulteney, Arca turonica Dujardine, Lutraria lutraria Linné, Arca sp., lucinids including Loripes incrassata Dubois, together with Turritella sp. and Genota sp. Pectinids are common, and Chlamys scrabella Lamarck is the commonest, frequently being articulated. Pecten vigolenensis Simonelli and occasional Chlamys multistriatus Poli also occur. The most prolific faunas occur at Fawwara, Malta. To the west of San Pawl il-Bahar on Gebel Wardija, (4677) and also in the coastal outlier west of the town, crustacean remains are abundant and include Callianassa sp., and the remains of spider crabs, which frequently occur in a semi-articulated condition. Crustacean remains are also common throughout the beds of other areas but are invariably fragmentary. In western Gozo this facies is thin but exhibits large Terebratula terebratula Linné and articulated Tapes sallomocensis Fischer, Thracea pubescens Pultency and Pleuromya sp. Towards the top of the beds there is a colour change from yellow to cream and the macrofauna becomes sparse. Echinus duciei Wright is occasionally found, as are encrusting serpulids.

c. Rdum il Hmar Beds

(i) General

Type locality Rdumn il Hmar, Malta (427823).

On first examination of the type locality the beds appear to be devoid of fossils and superficially resemble the soft Cretaceous chalks of Europe in texture. About 12 metres of this rock is visible at the type locality, resting with transitional contact on the Mtarfa Beds. The top of the beds is not preserved at this outcrop (Plate 9a).

(ii) Lithology and Distribution

Throughout outcrop these beds are massive in nature and fossils are patchily distributed, being casts and moulds for the most part. In some cases, for example at the type locality, the better cemented burrow systems weather out in relief, producing a nodular effect at certain horizons. The beds are divided into 1-1.5 metre thick units in the area south of Rabat, where they dip eastwards at up to 12°. This may reflect a primary dip direction as adjacent strata are almost horizontal. In all areas of both islands the beds show a transitional contact with both the underlying Mtarfa Beds and the overlying Rabat Plateau Beds. In the south-western area of Malta the beds pass up gradually into the Ghar Lapsi Beds (see Fig.5) and when followed westwards the beds show a lateral change into the Rabat Plateau Beds. This suggests that there was a retreat eastwards by the Rdum il Hmar Beds as time progressed.

In Gozo the beds are poorly developed and are restricted to the areas to the east of Qala (3888), with one possible exception 1km.north of Mgarr, where thinly laminated white micrites occur within a complex faulted area. On Comino the Santa Marija Bay outcrops (403860) are believed to fall into this group, though poor surface exposure makes correlation with major outcrops uncertain.

On Malta, thicknesses are always difficult to estimate, due to the transitional nature of both upper and lower contacts. This is particularly true of the eastern side of the outcrops, south of San Pawl il-Bahar, where the boundary between the yellow Mtarfa Beds and the White Rdum il Hmar Beds is affected by leaching and surface recrystallisation. Despite this the beds are recognised throughout eastern Malta as far south as Gebel Ciantar and also in the Ghar Lapsi outlier. At this latter area about 10 metres of sparsely fossiliferous white micrite occurs.

(iii) Petrology

The friable nature of these rocks makes thin sectinning difficult. However,scanning electron microscope examination (Plate 13b) reveals that the rock has been diagenetically altered to micrite, showing the crystal forms of rhomb and dodecohedra. At the type locality fossils are sparse and usually only moulds and casts survive. Some pectinids exhibit good preservation. In the Rabat Plateau, samples from higher in the beds show a dominance of clotted texture to the micrite matrix with an occurrence of upto 84% faecal pellets. The macro-fauna of this area, and particularly the Ta' Raba area, is prolific.

(iv) Fauna and Flora

Although there is difficulty in recognising the base of the beds, except in the type section, a bed of articulated Pinna sp. in growth position is recognised at Rdum il Hmar, San Pawl il Bahar, Il Qolla (457764) and Ghajn il Kbir (464679). It is associated with a prominent vertically burrowed horizon. Both these occur close to the base of the Rdum il Hmar Beds and provide a useful correlation horizon throughout Malta. At the type locality the only apparent macrofossil is the occasional *Schizaster eurynotus* Agassiz; *Cardium* sp. and *Thracea pubescens* Pulteney occur in a fauna dominated by *Lucina collumbella* Lamark. This fauna is well developed throughout the whole of the outcrop, though *Thracea* is more prominent and *Lucina* less so in the more southerly outcrops. Added to the faunal and floral list is the prolific fauna found at the Ta' Raba quarries (461679) in strata towards the western and upper part of the facies. Included here are rare *Lithophyllum* rhodolites, *Lucina columbella* Lamark, *Cardium hians* Brocchi, *Thracea pubescens* Pulteney, *Glycimeris deshayes* Mayer, *Pecten vigolenensis* Simonelli, *Lima* sp., low spired gastropods, a tooth of *Isurus* sp., abundant *Thalassinoides* and *Ophiomorpha*, some with the burrow systems lined in part with membraniporiform bryozoans. Most of the molluscan fauna is represented by casts and moulds, many of which contain casts of *Entobia* sp., which originally had burrowed into the aragonitic shells.

3. Diagenesis within the Members

Few additional points remain to be noted, though staining reveals the following:

a. Ghajn Melel Member

Most of the Ghajn Melel Member is composed of low-ferroan calcite, even though the general colour suggests a more ferruginous composition. The only ferroan calcite recorded occurs in the shells of some of the benthonic foraminifera. This is particularly well seen in foraminiferal fragments in the Ghajn Znuber Beds. The cement of this member is blocky sparite, frequently developing syntaxial rims around echinoid fragments. In central Gozo at Xaghra, (350897) and Il Qolla S-Safra (328923), rhomboidal low-ferroan calcite is present around glauconite casts and limonite cores, though the reasons for this are not evident. All pectinid fragments are of non-ferroan calcite and all aragonite has been removed by solution. The goethite infill to many of the Heterostegina fragments is proved to be earlier than the aragonite solution as it does not infill cavities produced by this solution. Hence, this further supports the conclusion that the foraminiferal bioclasts within the Ghajn Znuber Beds were mineralised prior to incorporation within this sediment.

b. Mtarfa Member

The Mtarfa and Rdum il Hmar Beds are all entirely composed of low-ferroan calcite, though early solution has removed all aragonitic fossils, leaving cavities which have subsequently remained unfilled. The Rdum il Hmar Beds are seen on close examination (Plate 13b) to have recrystallised to calcite rhombs and occasional scalenohedra. The Coralline Algal Bioherm, as with the rest of the member, is also dominated by low ferroan calcite and lack of aragonitic material. It appears that the carbonate released from the aragonitic shells was merely redistributed and precipitated locally in the form of cement. At Ghajn Tuffieha (412762) a little ferroan calcite occurs towards the base of the Coralline Algal Bioherm, mainly within the coralline algal colonies.

4. Palaeoenvironmental Interpretation

The Ghajn Melel and Mtarfa Members, when considered together, form a natural subdivision within the formation and are approximately time equivalent. They may be further subdivided into the following biofacies:

a. Biofacies E Giant Benthonic Foraminifera Biofacies
b. Biofacies D Clypeastrina/Celleporiform Bryozoan Biofacies
c. Biofacies I Rhodolite/Encrusting Bryozoan Biofacies
d. Biofacies K Schizaster/Lamellibranch Biofacies
e. Biofacies M Lamellibranch Biofacies

a. Biofacies E Giant Benthonic Foraminifera Biofacies

This biofacies conforms to the Ghajn Melel Beds of western Gozo. As with its counterpart, the Il Mara Member of the Lower Coralline Limestone, these beds contain varying amounts of unabraded benthonic foraminifera which form lensoidal accumulations at certain horizons (compare Figs. 6 and 20). In this case, however, *Heterostegina* is the only foraminifera present in any quantity. Even these are rare or absent from areas of accumulation around central Gozo. The planar bedded, micritic nature of the deposits suggests calm conditions. The *in situ* foraminifera *Heterostegina* is typical of modern shallow subtropical seas from Australia to the West Indies (Carpenter 1862, p.292). Vaughan and Cole (1941, p.30) recognise the depth range of the species to be less than 50 metres, thus suggesting that the Ghajn Melel Beds accumulated in a protected basinal area. The sediments are characterised by the shallow burrower *Clypeaster marginatus*, which appears to prefer fine sediments. It appears that the Ghajn Melel Beds (Biofacies E) were centred on central Gozo and were surrounded to the north and east by the higher energy Ghajn Znuber Beds (Biofacies D).

b. Biofacies D Clypeastrina/Celleporiform Bryozoan Biofacies

This biofacies conforms to that of the Ghajn Znuber Beds both in Gozo and in Malta. *Clypeaster altus* and *Clypeaster altus* var. *pyramidalis* are the typical echinoids encountered and *Cellepora mammalata* is the dominant bryozoan. The high energy of this laterally equivalent facies to the Ghajn Melel Beds is illustrated by the fragmentary nature of the allochems, the sparry calcite cement, and by the abraded nature of many of the contained macrofossils. Many of the Clypeasters are overturned and none bear spines. The contained pectinids and oysters are also invariably disarticulated. The only data on depth and current velocity come indirectly from burrows and bryozoans. In some areas, such as Ramla Bay, abundant vertical burrows occur in what Bromley (personal communication) considers to be depths not greater than 5 metres. The bryozoans which occur are hemispherical masses, usually in growth position. Celleporiform bryozoans, according to Lagaaij and Gautier (1965, p.52), are mainly littoral and sub-littoral, typical of areas of low sand transport. They were discussing the small sub-centimeter colonies, whereas the forms under consideration may be up to 100mm. in diameter. It is, therefore, tentatively concluded that the large Maltese forms are adapted to sub-littoral environments with extensive sediment reworking and a moderate to high velocity current. This is consistent with the lithoclast content of the Beds, which display mass transport of large foraminiferal fragments and also occasional transport of casts of fossils up to 30mm. diamter. This environment developed around the northern and eastern flanks of the protected Ghajn Melel basin and appears to have taken the form of shallow shoals.

c. Biofacies I Rhodolite/Encrusting Bryozoan Biofacies

This is an alternative designation for the Coralline Algal Bioherm of the Mtarfa Member. The fauna is dominated by encrusting bryozoans dominated by membraniporiform types, but also with abundant celleporiform types (see Chapter 10). Stack (1936), Lagaaij and Gautier (1965) and Schopf (1969) all agree that these forms are strongly developed in littoral and sub-littoral environments of high energy.

The large sinus bearing brachiopod Terebratula terebratula may also indicate high energy conditions, as Boucot (1953, p.146) suggests that sharply biplicate brachiopods occur in the shallowest water. Finally, the algal rhodolites give evidence relating to the energy and depth of the environment. Johnson (1965,p.16-17) lists most recent species of Lithophyllum as living in water depths less than 25 metres but with some species going down to 45 metres. Lithophyllum became the dominant crustose coralline algal genus in the Miocene to the detriment of Lithothamnion. It is most characteristic of sub-tropical seas. In view of this evidence and general field relationships it is considered that the biofacies is representative of clear water conditions with moderate to high energy and depths of between about 15 and

60 metres, the latter figure being based on the occurrence of two brachiopod genera of the diminutive Megathirididae (Chapter 10).

The frequent occurrence of small encrusting bryozoans bearing blade-like slots or attachment areas strongly indicates the presence of eel grass or similar forms allied to *Thalassia* sp. within the environment. Although it is considered that the algal rhodolites could have provided sufficient shelter on their leeward margins to permit the accumulation of micrite, it is also believed that the marine grass within the facies was also responsible for trapping large volumes of sediment, either by binding it together with roots or by causing the leaves to act as current baffles. This may account for the alternations of rhodolite horizons and micrite layers within the bioherm, the micrite being deposited as a result of the sediment trapping vegetation. In areas where marine grasses were established, calmer seabed conditions would prevail which would not be so favourable to algal rhodolites, hence there would be a corresponding reduction in rhodolite numbers during these intervals.

d. Biofacies K *Schizaster*/Lamellibranch Biofacies

This biofacies corresponds to the Mtarfa Beds. The faunal elements remain remarkably constant throughout the islands. *Schizaster eurynotus* the dominant echinoid is an irregular form, probably adapted to burrowing at depths down to half a metre or so. The spatulate spines are a common fossil within the micritic samples, though they are never found attached to the tests. This relationship has probably been caused by bioturbation. Other echinoids present are invariably irregular burrowing scavengers . This presence of occasional specimens encrusted with serpulids indicates that empty tests frequently lay on the surface of the sediment and were used by other biota as attachment points and colonisation.

The remainder of the fauna is dominated by burrowing lamellibranchs, a few being detritus feeders, but the majority being suspension feeders. This would indicate stable bottom conditions and little or no sedimentation.

Depositional depths are difficult to estimate, though the occurrence of lucinids and Cardium indicates a shallow environment with moderate water circulation. Gastropods are not common in the main body of the beds and so the environment cannot be positively identified as a lagoon except in its lowest horizons, where they are more prolific. The environment is more characteristic of a fairly open shallow shelf environment.

c. Biofacies K Lamellibranch Biofacies

This biofacies differs slightly from the preceding one and characterises the Rdum il Hmar Beds. Echinoids are far less abundant, although Schizaster eurynotus still occurs occasionally. Lamellibranchs, however, are the dominant forms and many of them, such as Cardium and Glycimeris, may indicate stronger currents within the upper beds of this biofacies. This is partly borne out by the coarsening of sediments in the west and also towards the top of the biofacies. The presence of Ophiomorpha, Lockeia and Teichichnus (Bromley, personal communication) within the Rdum il Hmar Beds suggests relatively shallow water, and possibly of less than 100 metres depth. Towards the west, where the facies in part merges with the Rabat Plateau Beds and underlying Coralline Algal Bioherm, gastropods become abundant, suggesting that this dominantly shallow shelf facies may approach a lagoonal situation in small areas of Malta.

5. Il Fawwara Fish Bed

a. General

This bed consists of a thinly laminated 0.8 metre thick, pale grey micritic horizon, occurring between the Greensand below and the Mtarfa Beds above. The outcrop is restricted to a single locality, Il Fawwara (456664), and appears to be lensoidal in cross section as the beds are absent in cliff exposures both to the north and east of the outcrop.

b. Petrology

The micrite bed is characterised by alternating layers of pale grey and cream laminae, each pair varying from approximately 1.0mm. to 6.7mm. in total thickness. Detailed examination shows that most laminae pairs are the product of one depositional episode and it is seen that the lower pale grey portions pass transitionally upwards into the thinner cream to yellow laminae. Occasionally, however, thicker orange to cream coarser bands containing bioclastics and glauconite grains intervene with the normal sequence. The basal contact of many lamina is erosional and frequently cuts down into the cream upper layers of the previous lamina. Bulk sample breakdown reveals that the rock consists of 23% fossils by weight, together with a small percentage of clay. The rest of the samples appear to consist of micritic sediment, forming the matrix to the rock.

c. Fauna

The bulk sample analysis, achieved by boiling the sample in water and subsequently sieving, yielded the following microfossils: *Anomalina* sp.; *Nodosaria* sp.; *Austrotrillina* sp.?; occasional *Globigerina* sp.; the ostracodes *Bairdia* sp. and occasional *Cithereis* sp.; Schizaster spines, juvenile *Chlamys* fragments; scales, vertebrae and otoliths of *Bregmaceros* sp.; and a great deal of indeterminate material.

Further samples were examined by splitting the fissile micrite along laminations, the rock always parting along the cream laminae. Although many of these planes proved to be unfossiliferous, several exhibited small disarticulate aragonitic mollusc casts such as *Lucina* sp., *Arca turonica* Dujardine and rare *Haliotis* sp. Occasional *Cellaria* sp. bryozoans also occur. Infrequent (0.5mm diameter) annelid burrows occur within the cream laminae, and one lamina about 0.3 metres above the base yielded an abundance of fragmentary and disarticulate molluscs, lunulitiform bryozoan colonies, and blades of what appears to be seaweed of unknown affinity (Plate 14d). These are encrusted by membraniporiform 'A' type bryozoans (see Chapter 10). On this and all other laminae, bioturbation is absent apart from rare annelids, which cause little detectable sediment disturbance.

The fossil fish contained within these beds are quite abundant, over 32 complete and fragmentary specimens of Bregmaceros being obtained (Plate 14a), but with only fragmentary remains of other species. All the specimens discovered appear to have been lying at the lamina tops and show some dismemberment in most specimens. There has, however, been little transportation of resulting fragments so that frequently all fragments lie within a few millimetres of the main body of the specimen. The following fish have been identified:

(i) Bregmaceros albyi Sauvage

(ii) Syngnathus sp.

(iii) Serranus sp.

(iv) Indeterminate genus of Zenidae?

(i) Bregmaceros albyi Sauvage

Detailed comparison between descriptions by Danilchenko (1967 translation p.50), Thompson (1840, p.443), Munro (1950) and Leonardi (1959) indicate that the commonest fish remains are referrable to Bregmaceros albyi Sauvage. This species is associated with many coprolites containing scales and otoliths referable to the genus Bregmaceros (Plate 14b). One specimen exhibits well preserved fossil stomach contents, consisting of fish scales, fins and other fish fragments. The collection is dominated by adults, only 9 individuals being under 40mm.in length with the largest being 69mm.

(ii) Syngnathus sp.

One fragmentary specimen exhibiting 80mm.of trunk region, together with a few isolated hexagonal shields was collected. The domed shields are ornamented by tubercle bearing carinae, each shield averaging 10-11mm.in length.

(iii) Serranus sp.

One partially complete specimen is believed to belong to this genus, but the lack of major areas of the anterior of the specimen and other damage make this identification uncertain. The specimen is, however, definitely referable to the Serranidae. A further collection of fin rays and scales indicates that other members of the Percoidea are present.

(iv) Indeterminate genus of Zenidae?

One anterior portion of a deep bodied specimen bears a certain degree of resemblance to Xenopsis sp., although this is a very tentative identification.

d. Palaeoenvironmental Interpretation

The Il Fawwara Fish Bed is believed to be contemporaneous with the final stages of Greensand reworking, during a time of low turbulance, but before the initiation of widespread Mtarfa Bed development. It is believed that a localised depression developed within the Greensand covered seabed shortly after the development of the Terebratula-Aphelesia Bed, which directly underlies the fish bed at Il Fawwara. At a distance of 1 kilometre to the west the Coralline Algal Bioherm was developing, but was only donating sediments to the east of the structure at intermittant periods, when either the dominant eastward moving current became temporarily stronger or when storm activity caused agitation on the bioherm crest. The resulting effect of either possibility was for the prevailing current to pick up and carry fine bioherm derived sediment, juvenile molluscs, echinoid spines, bryozoa and seaweed in an easterly direction. It would subsequently settle out of suspension or traction in the quietest water, such as the Fawwara basinal depression.

The erosive basal contacts and oxidised tops to each lamina strongly suggest that much of this sediment was transported from the Coralline Algal Bioherm in the form of a turbidity current, in a similar manner to that postulated for the Solenhofen Limestone by Van Straaten (1971, p.4). Upon arriving at the Fawwara basin the sediment traction currents would carry the sediment across the previous deposits, causing scouring and minor erosion, before the sediments finally settled out of the current to form the next lamina in the succession. The low velocity of this density current, once within the basin, is testified by the small amount of disarticulation suffered by the fossil fish, which apparently lay on the upper surface of the previous laminae. The partially graded nature of some laminae further supports the conclusion that each of the laminae are the product of a single episode of sedimentation from suspension. Finally, the presence of high energy biota such as Haliotis and Arca in this tranquil environment and high energy bryozoan growth-forms such as Cellaria, (see Chapter 10 for environmental prerequisites), further supports the conclusion that much of the fauna has been transported into the environment. The indiginous fauna appears to be dominated by lunulitiform bryozoans and the fossil fish.

The remarkable lack of burrowers within the sediment is difficult to explain as it is considered that the periodic influxes of worms by the turbidity currents would have been sufficient to retain colonisation of the substrate. Perhaps most life was dead upon arrival, being choked in the fine micritic suspension in which it was being carried, as suggested for the Solenhofen Limestone by Van Straaten (1971). This is preferred to the theory of Hulseman and Emery (1961), who postulate an anaerobic environment for an apparently similar, but larger environment, affecting recent sedimentation in the Santa Barbara Basin, California. Here oxygen influx was restricted to small amounts, brought into the basin by successive turbidity flows.

The episodes between successive Maltese flows appear to have been tranquil within the basin. Colonisation by lunulitiform bryozoans occurred and rare annelids burrowed short distances into the sediments. The fossil fish are believed to have sunk, upon death, to the seabed and subsequently remained there in an intact condition until they became covered by the next sediment influx.

(i) Depth of Accumulation

The depth of accumulation of these sediments must be deeper than the shallowest bioherm areas (20 metres) from which most of the sediment was obtained. Lagaaij (1963) states that modern lunulitiform bryozoans inhabit depths of 2-300 fathoms (down to 550 metres, but with a normal maximum depth of 80 metres.) They prefer normal salinity, a stable seabed of small particle size and a location below wavebase. They are best suited to temperatures of 12-31°C. It is concluded that the beds accumulated in water depths of approximately 60 metres.

(ii) Ecology of Bregmaceros

The present day ecology of Bregmaceros (David 1946, p.62) is open sea (90-300 fathoms), extending to the margins of the neritic zone (20-40 fathoms, 37-73 metres). Syngnathus sp. today inhabits rocky or grassy areas of the neritic zone, frequently being nocturnal in habit. The concluded depth of the environment is still considered to be a reasonable estimate, in view of these further details.

It is now necessary to consider the abundant coprolites, most of which contain otoliths of Bregmaceros albyi. The stomach contents of one of the collected specimens of Bregmaceros indicate that the species, at least occasionally, fed on fish. Clancy (1956, p.258) further lists fish remains, together with chaetagnaths, siphonophores and algal filaments within the stomachs of modern species. He does, however, state that the main food is copepods. Nevertheless it is a possibility that B. albyi was at times cannibalistic and this would account for the large numbers of coprolites. However, as up to 7 otoliths are recorded in some coprolites, it is felt that many may represent the excrement of a much larger predator.

Bregmaceros appears to have evolved in the Persian area during the Oligocene (Jonet, 1949) and reached Sicily and Algeria by the Upper Miocene. This is consistent with the horizon in which it is found in Malta, which is considered to be Tortonian in age.

The Fawwara Fish Bed is overlain by highly fossiliferous Mtarfa Beds which contain abundant articulated Loripes incrassata (Dubois) and Cardium hians, Brocchi. Many burrows originating at this level pass down to the base of the fish bed and are infilled by later sediments.

6. Geological History of the basal Upper Coralline Limestone

A general outline of the history is presented here, although precise details on the Terebratula-Aphelesia Bed will be examined in Chapter 10. Several of the resulting conclusions from Chapter 10 will be included here in order to give a complete picture.

The shallow water Greensand episode drew to a close with the quieter water Qolla S-Safra Beds of northern Gozo (Fig.20), which were subsequently removed from other areas of outcrop by a prolonged erosional episode, represented by the basal Upper Coralline Limestone erosion surface. This had greatest effect in western Gozo, but minor halts in sedimentation are also recognised in marginal areas of the Coralline Algal Bioherm. Large volumes of Greensand and other contemporaneous sediments were removed from western Gozo and areas further west, eventually causing a truncation of the underlying sequences of western Gozo. Ultimately, uplift in areas to the west of the islands became sufficient to shelter the Maltese area and a north-south orientated basin developed in Gozo and extended down the extreme western side of Malta (Fig.24a). The western side of the basin was flanked by areas subject to marine erosion, whereas the eastern flank was bounded by a local extension of the shallow water carbonate platform which, although initially of lagoonal aspect, was to develop into the shelf seas environment characteristic of the Rdum il Hmar Beds.

The earliest sediments to develop within this depression are coarse lithoclast biosparites rich in limonitic lithoclasts, glauconite and reworked Heterostegina fragments. Most of this sediment is probably derived from areas to the west of the islands and was transported eastwards by the dominant westerly current. This sediment is represented by the Ghajn Znuber Beds.

Gradually, as the basin developed, the deeper areas became sheltered from the effects of the dominant current, at least in western Gozo, and biomicrites and pure micrites accumulated in the central areas of the "biocalcarenite" basin of Fig.24b. These are the Ghajn Melel Beds. They are not obviously developed in Malta, indicating that the basinal development was not as well formed there. By this time the Ghajn Melel Beds were accumulating in western Gozo, and the Ghajn Znuber Beds, although still developing, were restricted to the higher energy eastern rim of the longitudinal basin. Within this latter an extremely shallow water shoal area, there was large scale transport of fossil debris and lithoclasts. The abundance of lithoclasts within the beds along the Mgarr coast of Gozo and in Maltese outcrops is possibly due to the continued supply of material from western sources until much later times than in central Gozo.

Within the Ghajn Znuber Beds of Gozo an ideal niche developed for the hemispherical *Cellepora* bryozoans, which colonised the surface of the high energy substrate, and the *Clypeaster altus*-*Echinolampas pignatarii* groups that made shallow burrows within the sediments. *Clypeaster altus* var. *pyramidalis* preferred the higher energy conditions of Mgarr, Gozo, possibly because a form with high test inflation could burrow deeper into the sediment, whilst still exposing the apical system, and hence would be less susceptible to excavation and overturning by turbulence.

It is more difficult to account for the stability of the *Cellepora* colonies. The initial points of attachment were seaweed fronds or similar objects, but as the colonies grew they settled onto the substrate and constructed multilayered hemispherical structures, similar to mushroom heads in cross section. These frequently bear an underturned flange. This apparently enabled the colonies to remain upright in a very turbulent environment. Because of their semi-permanent nature on the shifting seafloor they were themselves encrusted by other bryozoans and oyster spat.

In comparable beds in Malta a change is seen from the Ghajn Znuber sections, which are similar to those of Gozo, to the apparently calmer conditions of the Dingli area. At Ghajn Znuber the high energy conditions are illustrated by the high disarticulation seen in the pectinids.

The Dingli deposits appear to be more closely related to the Coralline Algal Bioherm than those previously discussed. They are penecontemporaneous with the bioherm and probably represent a narrow north-south orientated channel at the foot of the Coralline Algal Bioherm. These sediments are generally finer grained than the other areas of the Ghajn Znuber Member and contain a somewhat different fauna, including Clypeaster marginatus and Echinolampas pignatarii. Cellepora colonies are less common and may indicate lower energy conditions than at Ghajn Znuber, as do the pectinids, which are frequently articulated.

Towards the close of Ghajn Znuber Bed deposition conditions appear to have become calmer. Although this is primarily reflected in the diminishing grain-size within the rocks at Ghajn Znuber, it is also indicated by great faunal changes. Within isolated pockets or patches on the eastern flanking rim of the north-south orientated basin, crustose coralline algal development commenced. Initially these biohermal areas appear to have been isolated from each other, but subsequent colonisation filled in the gaps, producing a north-south belt along the highest energy area of the eastern rim of the basin (see Figs.22b and 23). The changes which brought about this biofacies are not clear, although the sections at Ghajn Znuber are instructive. Initial colonisation by Lithophyllum in this area was by rhodolitic colonies less than 30mm. diameter. These were, however, rapidly smothered by Cellepora incrustations. Within the finer grained higher horizons of the Ghajn Znuber Beds further rhodolite development by larger colonies was more successful until ultimately, at the base of the Coralline Algal Bioherm, the Lithophyllum rhodolites, again only 30mm. diameter, occur almost to the exclusion of Cellepora colonies, and the associated fauna becomes similar to the immediately overlying Coralline Algal Bioherm.

The area of bioherm development is clearly related to the aerial distribution of the Ghajn Znuber Beds, which underly them in many areas (compare Figs.19 and 23). This is particularly so in the Dingli area of Malta. In many areas off the peak energy shoals of Ghajn Znuber Beds initial

Lithophyllum colonisation took the form of thin veneers of crustose coralline algae associated with grey marl. These areas are considered to lie below the zone of turbulence, possibly in small basins subject to clay influx, in part winnowed from remaining areas of Ghajn Znuber Bed development but, particularly in western Malta, derived directly from erosion of Blue Clay or similar deposits on the western side of the basin. This material settled into the calmer areas and was trapped by the laminae of the Lithophyllum colonies. These grey horizons with coralline algal laminae invariably pass upwards into typical yellow micrites containing well formed algal rhodolites. This was a direct response to the increasing energy within the environment as the small isolated pocket-like biohermal depressions became infilled and were subsequently brought into the zone of strong turbulence. This favoured the rhodolite growth-form in preference to the laminar growth-form and the pockets rapidly amalgamated into one entire north-south bioherm, with biocalcarenites and biomicrites of the Ghajn Melel Beds developing to the west and yellow biomicrites and micrites of the Mtarfa Beds developing to the east (see Fig.22b and Fig.40).

The Mtarfa Beds were initially developed as a narrow tract immediately to the east of the Coralline Algal Bioherm. This side of the Bioherm provided shelter from the strong easterly moving water currents and provided an environment into which fine micritic suspensions could settle. Either the platform area east of the bioherm began to subside, or the Coralline Bioherm built up a strong positive feature subsequent to this, as the yellow Mtarfa Beds extended their distribution throughout eastern Malta and eastern Gozo. This calm sheltered environment proved to be ideal to burrowing and filter-feeding mollusca, echinoderms and crustacea, and to those forms preferring sandy seabeds in sheltered settings such as Pecten sp. Correlation of the upper beds of the Coralline Algal Bioherm with the Ghajn Melel Beds is difficult. However, a marked colour change from brown or yellow to pale grey or white, at the top of the latter beds and several metres below the top of the former, is taken to indicate a regional change in iron content of particles entering the area. This change is also witnessed at the top of the Mtarfa Beds, which are succeeded by the white chalky Rdum il Hmar Beds. This provides a tentative means of correlation in the absence of faunal evidence.

The Rdum il Hmar Beds are partially contemporaneous with the upper part of the Coralline Algal Bioherm and, initially at least, must have developed under identical conditions to the Mtarfa environment. Conditions, however, were gradually changing and the lagoonal environment, most typical of the lowest part of the Mtarfa Beds, was gradually giving way to a more open shallow platform area. This was presumably protected from the westerly currents initially by the Coralline Algal Bioherm, but later by the Rabat Plateau Beds. These are contemporaneous with the upper horizons of the Rdum il Hmar Beds and formed large shallow water shoal areas down the western sides of the islands. The Rdum il Hmar deposits became more lagoonal in aspect in the south-western area of outcrop and the upper beds pass laterally into the Ghar Lapsi Beds. These are discussed in Chapter 8 and are considered to represent sub-littoral deposits close to the southern margins of the depositional basin.

SPEC. No.	LENGTH	DORSAL FIN	ANAL FIN	BODY / HEAD	BODY / DEPTH	HEAD / EYE	EYE / SNOUT	HEAD / PECT'L	HEAD / MAXILLA	NUCHAL APP. / HEAD	HEAD / ANAL FIN RAY	BODY / VENT. FIN RAY
12	53·5	13-10-13	13-9-13	4·9	6·7	3·8	1·0	2·3	2·1		0·7	2·5
17	38·1	13-?-?	13-9-15	5·5	7·5	3·3	0·9	2·0	2·0	1·04	0·74	2·1
7	30·0	10-9-17	13-9-12	5·2	7·0						0·96	2·7
6	44·1	11-9-15	12-6-20	5·1						1·3	1·1	2·7

Fig. 19a. Size parameters for four specimens of Bregmaceros from the Il Fawwara Fish Bed, Malta.

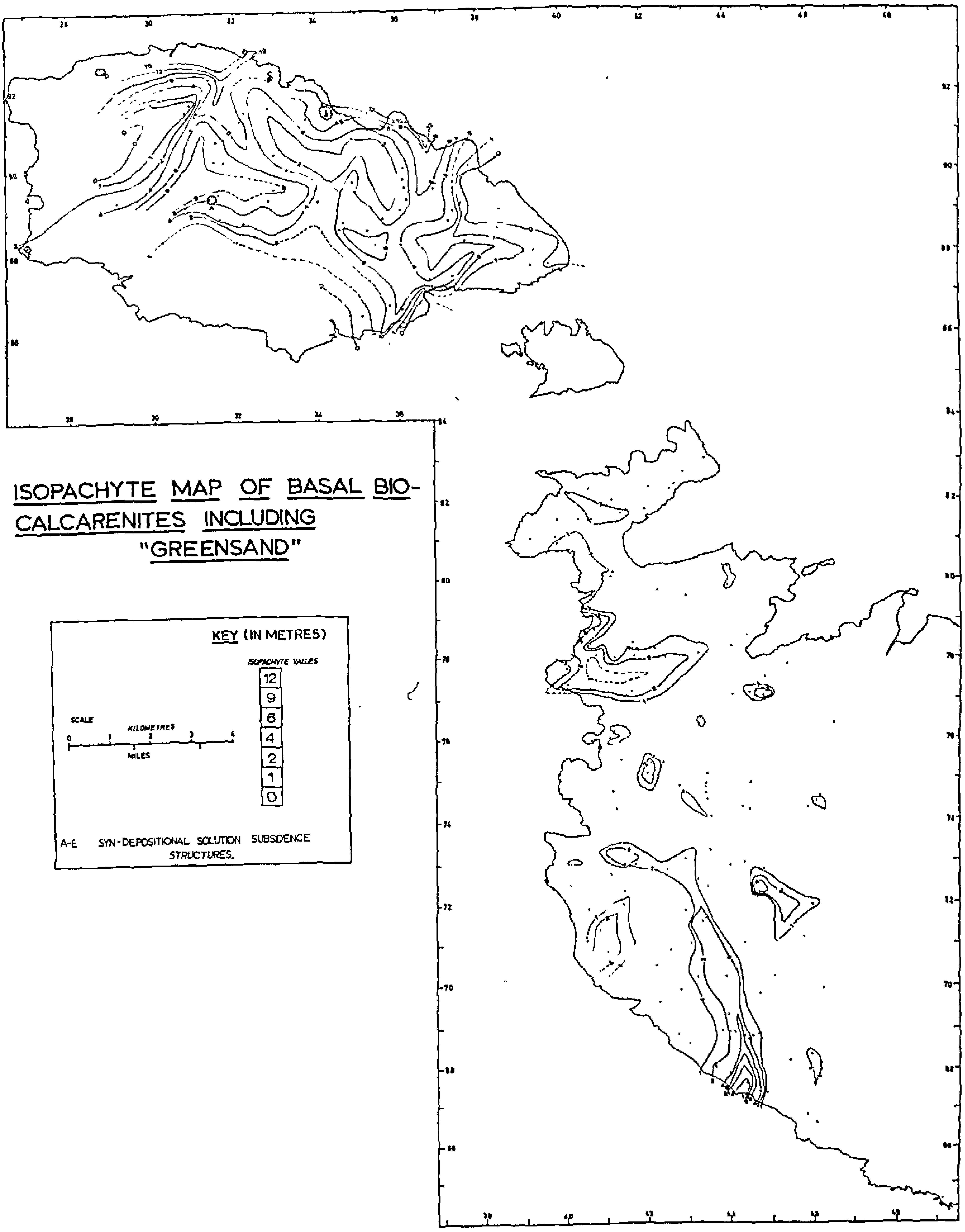
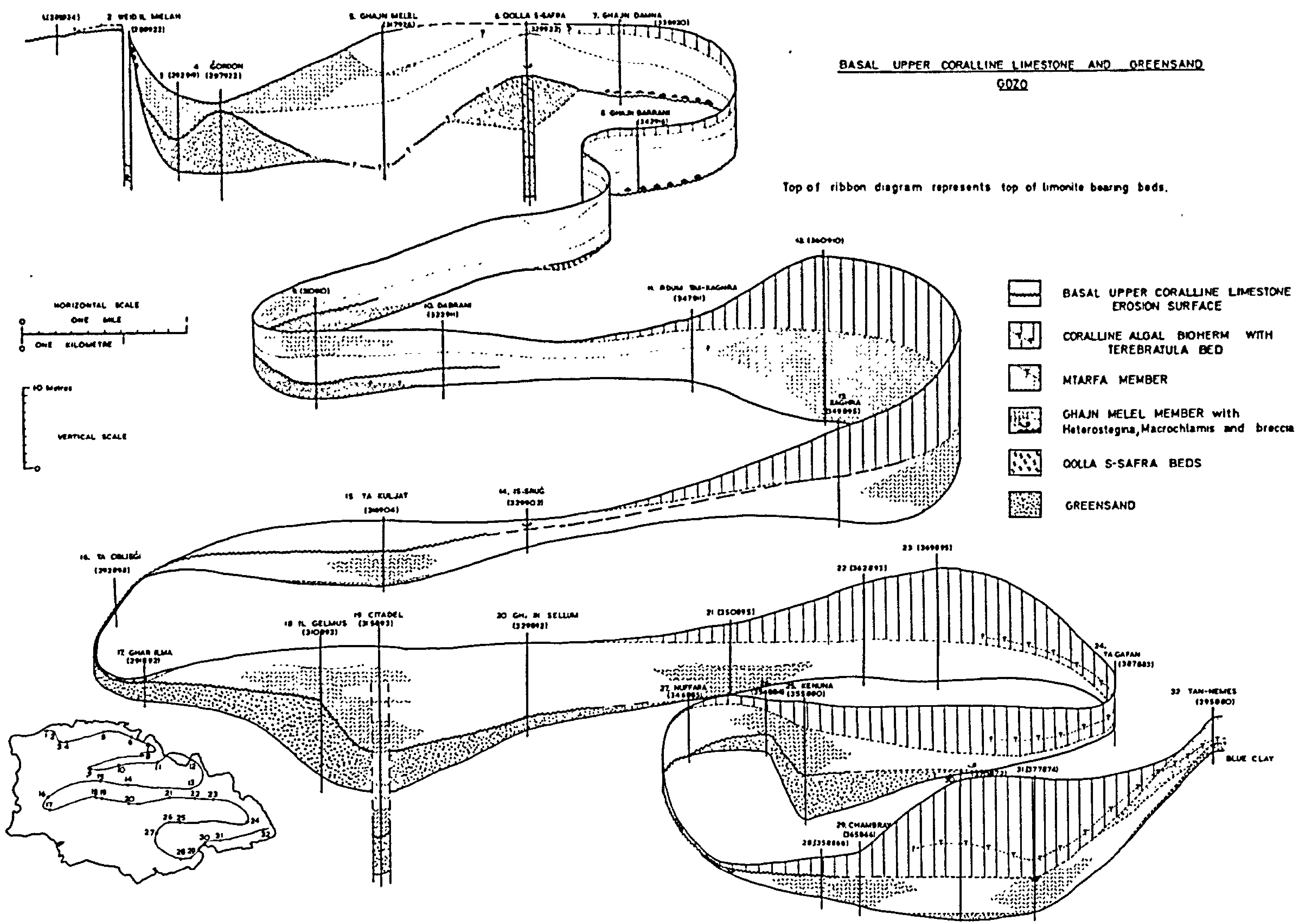

ISOPACHYTE MAP OF BASAL BIO-CALCARENITES INCLUDING "GREENSAND"
KEY (IN METRES)
ISOPACHYTE VALUES
12
9
6
4
2
1
0
SCALE
KILOMETRES
0
1
2
3
4
MILES
A-E SYN-DEPOSITIONAL SOLUTION SUBSIDENCE STRUCTURES.

Fig .19b


BASAL UPPER CORALLINE LIMESTONE AND GREENSAND
GOZO

Top of ribbon diagram represents top of limonite bearing beds.

Fig. 20

MODAL ANALYSES OF GHAJN MELEL & MTARFA MEMBERS

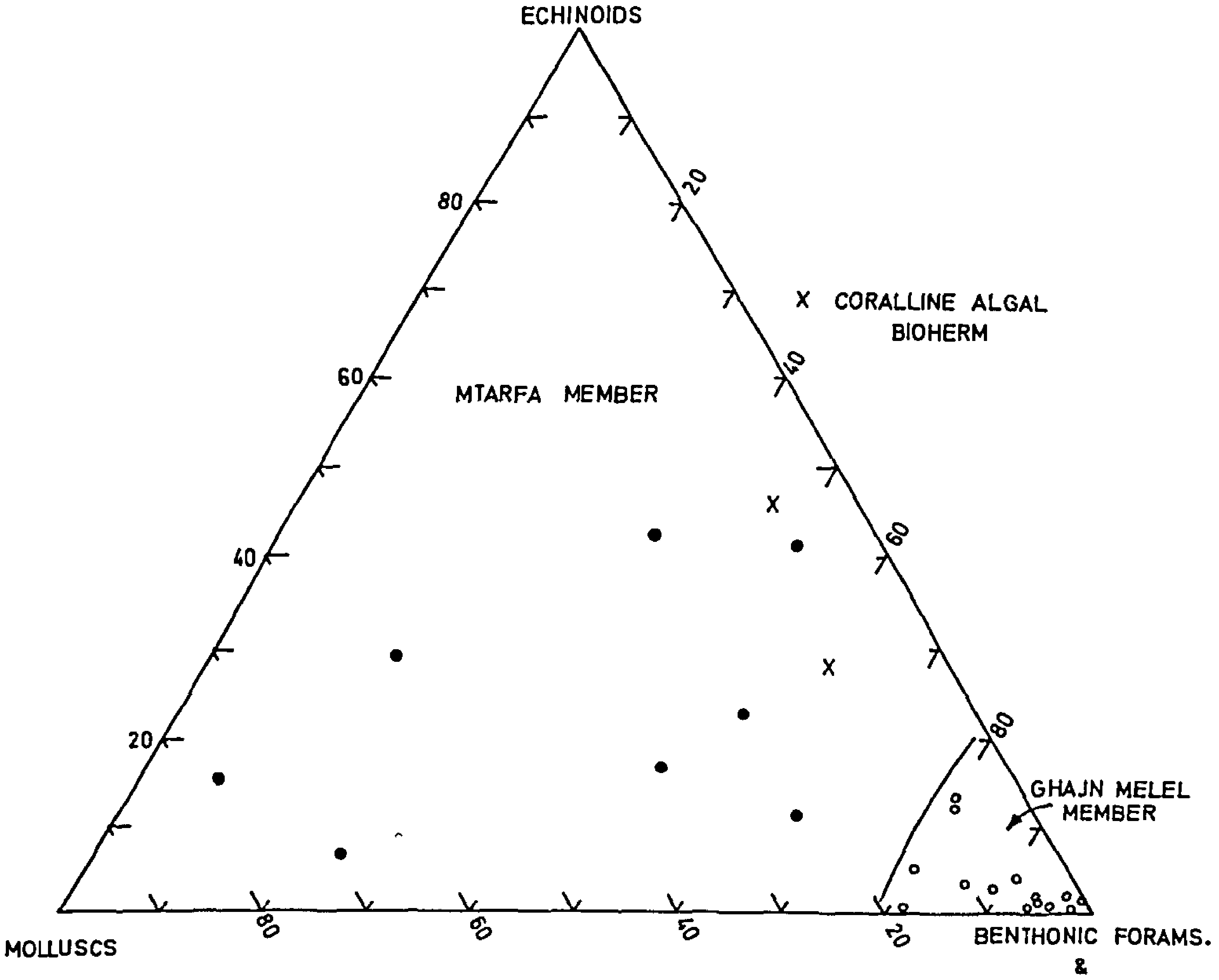


Fig. 21a

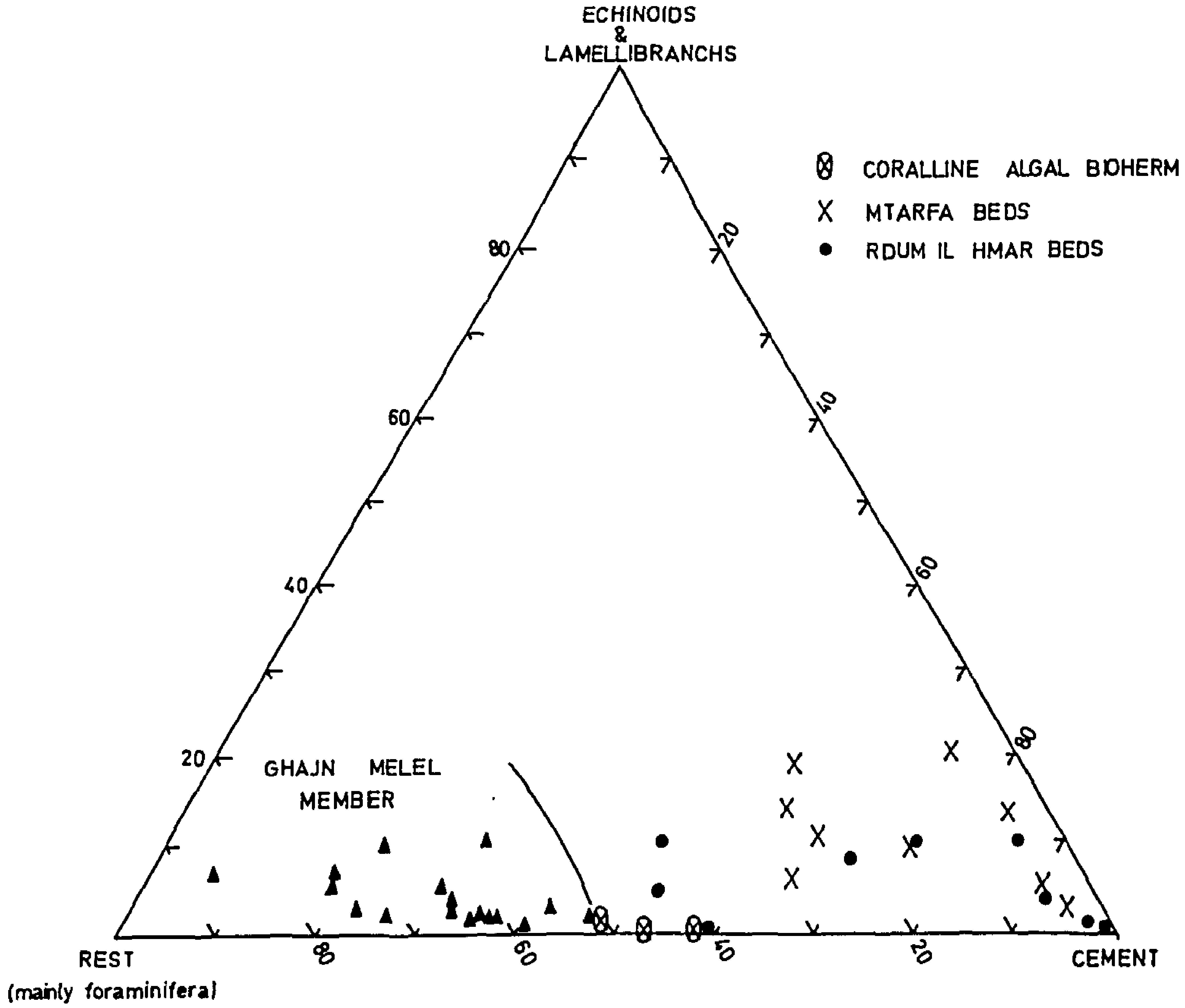


Fig. 21b

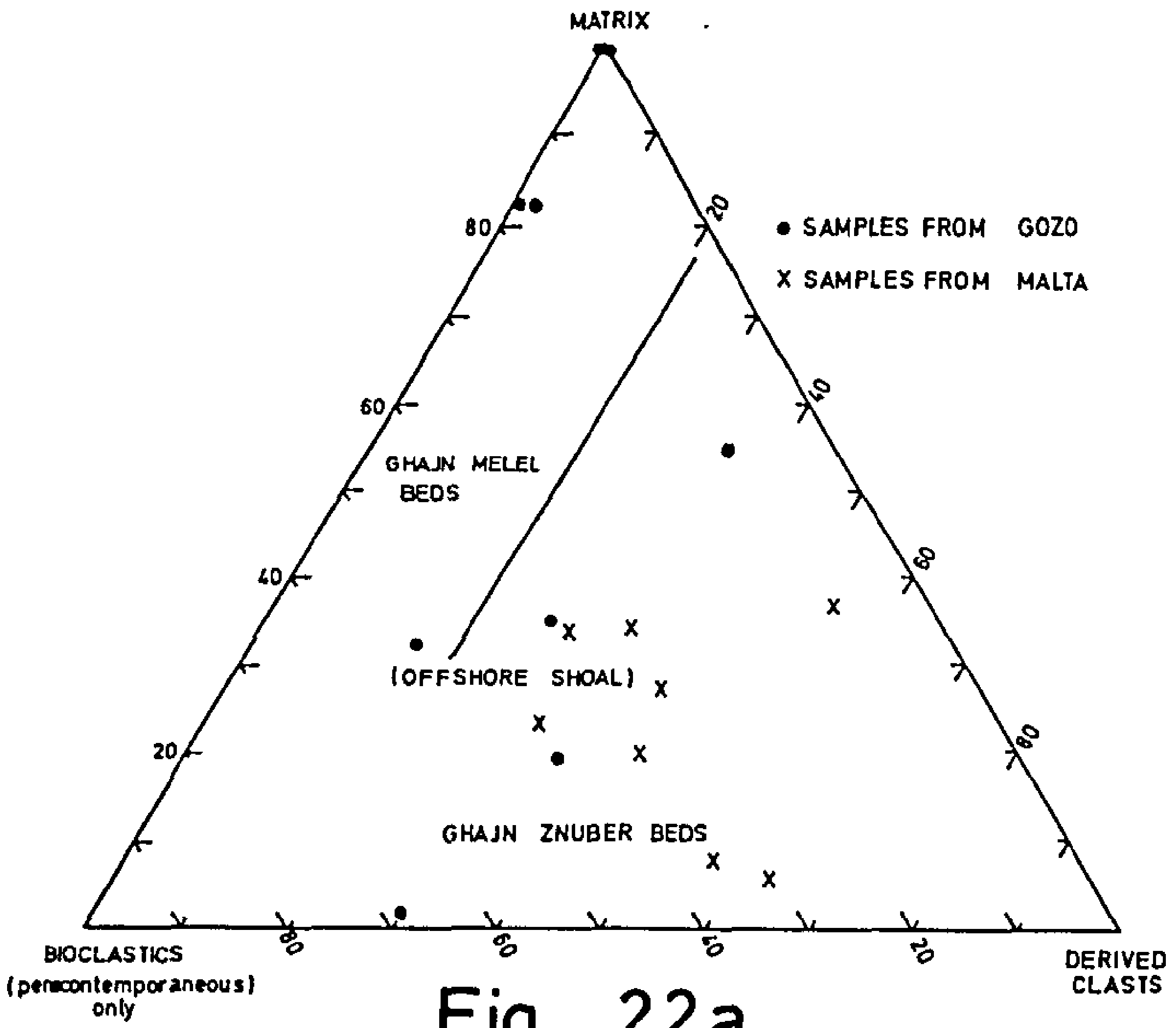


Fig. 22a

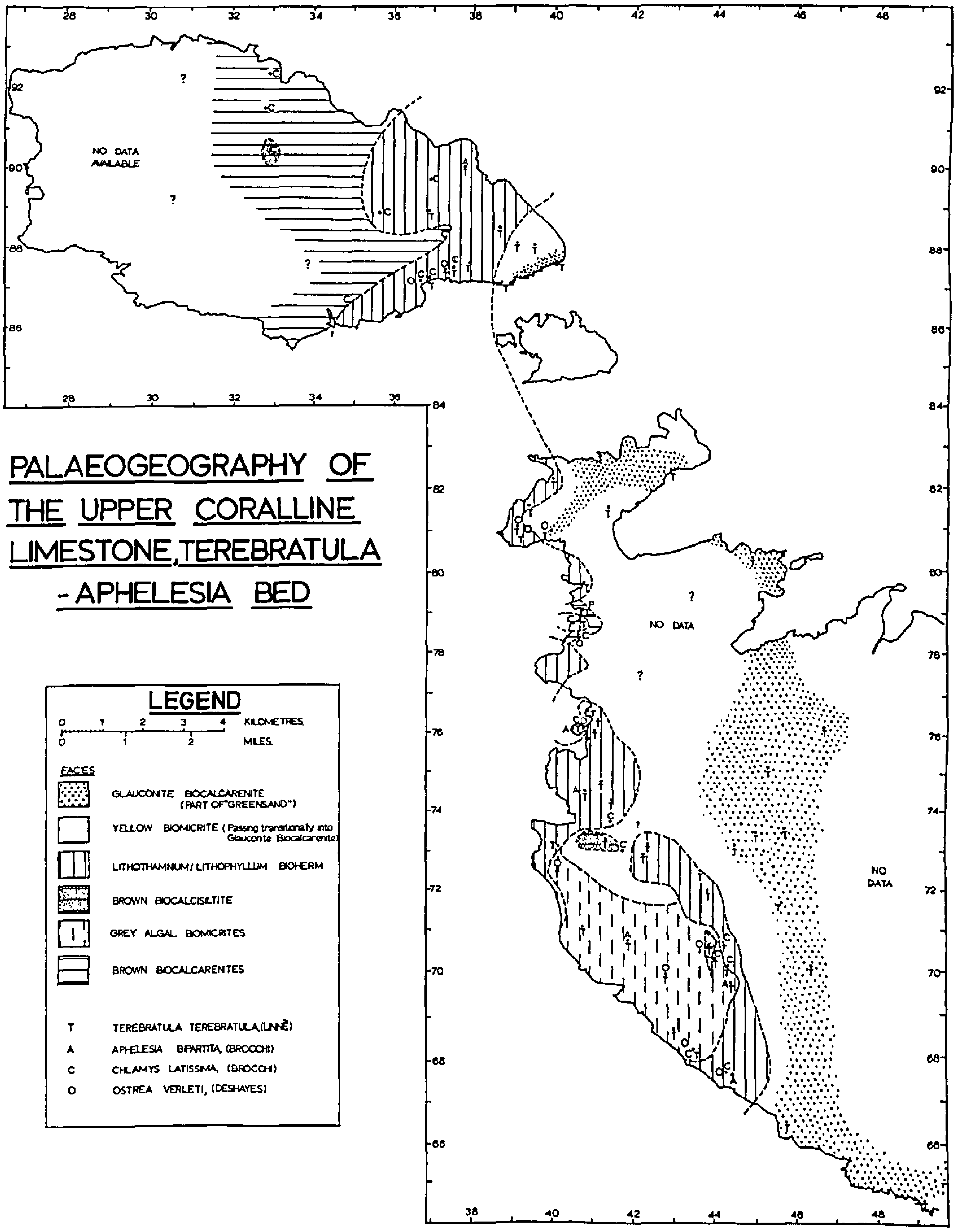


Fig. 22b

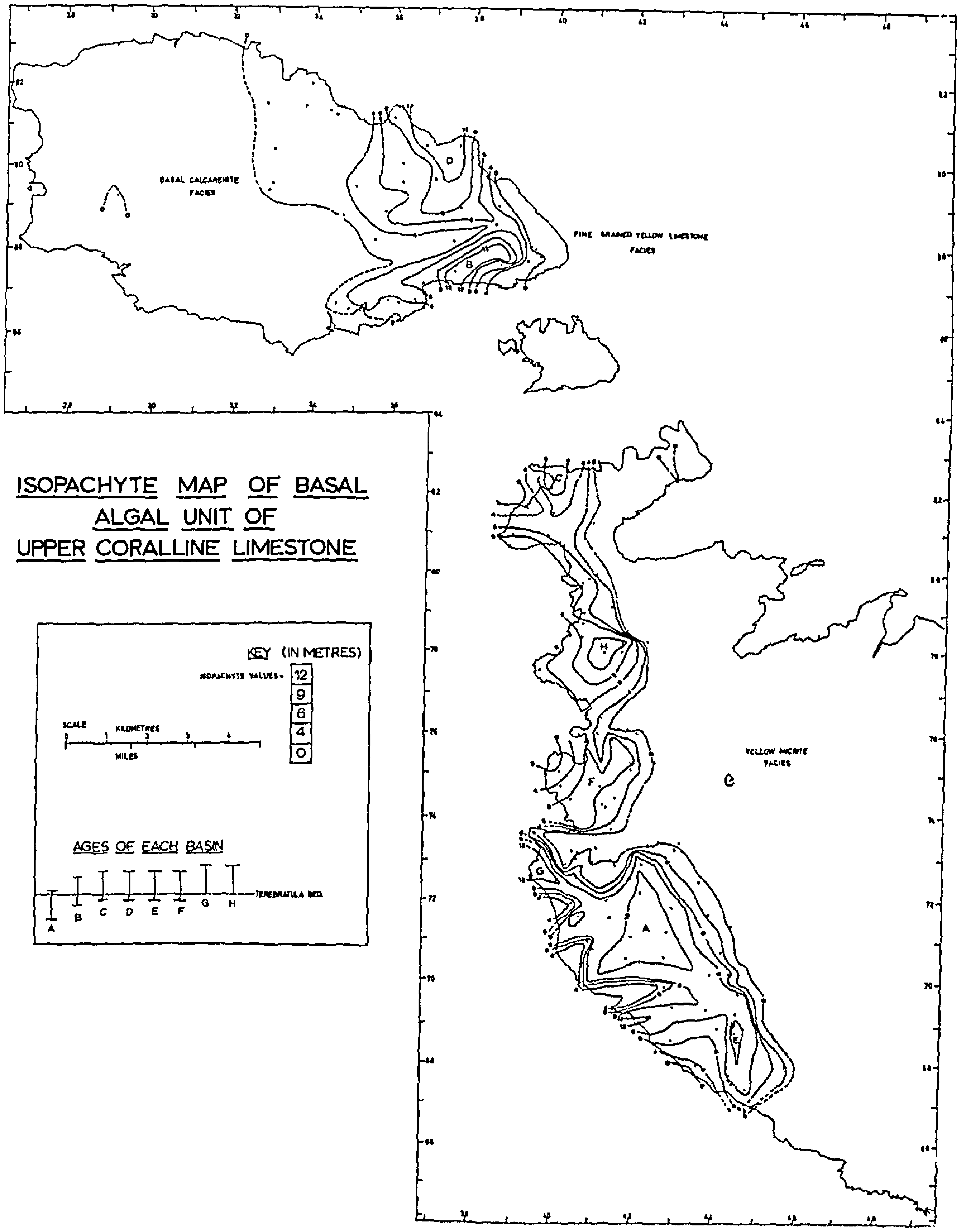

ISOPACHYTE MAP OF BASAL ALGAL UNIT OF UPPER CORALLINE LIMESTONE
KEY (IN METRES)
ISOPACHYTE VALUES
12
9
6
4
0
SCALE
KILOMETRES
0 1 2 3 4
MILES
AGES OF EACH BASIN
TEREBRATULA BED
A
B
C
D
E
F
G
H
BASAL CALCARENITE FACIES
FINE GRAINED YELLOW LIMESTONE FACIES
YELLOW MICRITE FACIES

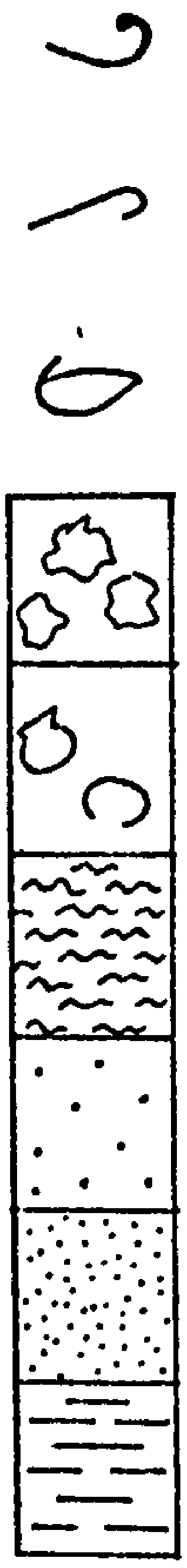
Fig. 23

FIGURE 24b

Legend

Localities

23	(401725)	Karraba, Malta.
193	(401730)	Qleighi, Malta.
192	(414730)	Tal Qortin, Malta.
191	(411733)	Concezione, Malta.
189	(422729)	Ta Santi, Malta.
79	(430733)	Lands Nadur, Malta.
188	(435724)	Ta Magistra, Malta.



Ostrea virleti

Chlamys (Macrochlamis) latissima

Terebratula-Aphelesia Bed

Rabat Plateau Beds

Mtarfa Beds with pectinids and echinoids

Coralline Algal Bioherm

Ghajn Znuber Beds

Greensand

Blue Clay

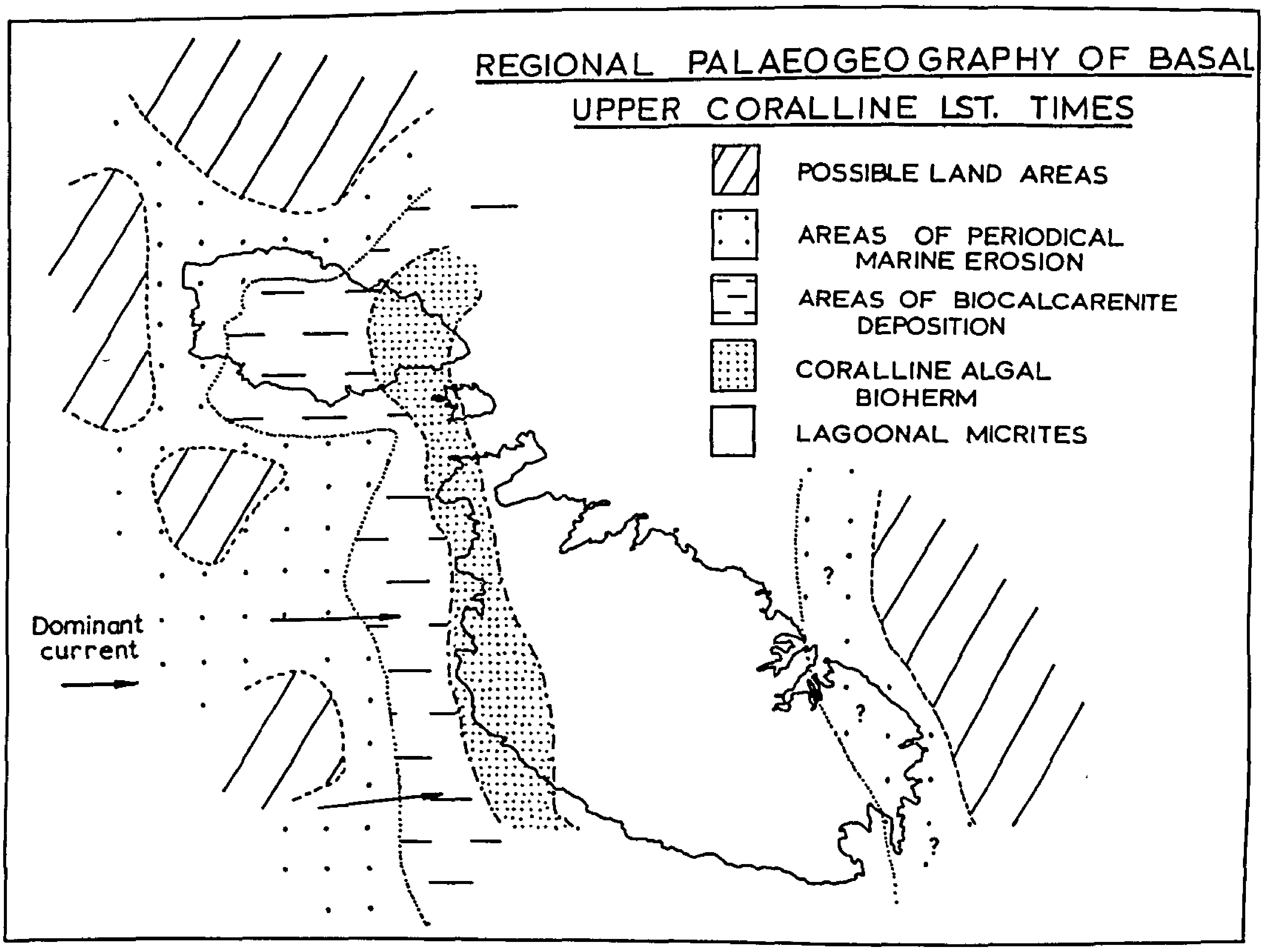


Fig. 24a

SECTIONS ILLUSTRATING THE GENERAL FORM AND CORRELATION OF THE VARIOUS FACIES PRESENT IN THE BASAL UPPER CORALLINE LIMESTONE DEPOSITS

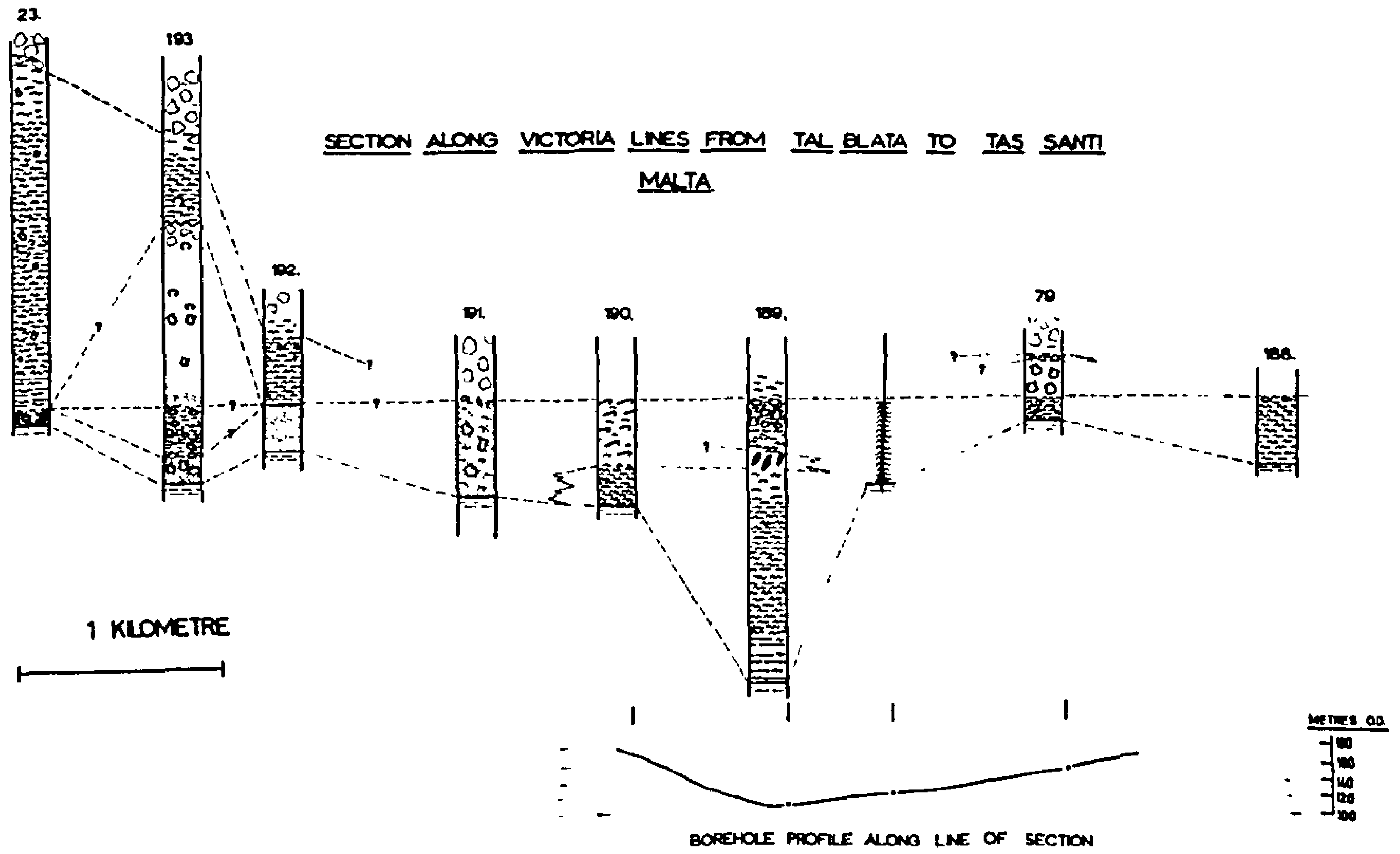


Fig. 24b

CHAPTER 8

UPPER CORALLINE LIMESTONE

1. Tal Pictal Member

Type locality. Tal Pictal, Malta (434685)

The present study recognises this new member throughout both Gozo and Malta where it generally occupies the highest ground on the Upper Coralline Limestone plateaux and buttes. The member is divided as follows:

d. Ghar Lapsi Beds
c. Ghadira Beds
b. Tal Pictal Beds
a. Rabat Plateau Beds

a. Rabat Plateau Beds

(i) General

These beds are only clearly distinguished in the Rabat Plateau, where a variable thickness of partially or entirely recrystallised rhodolitic biosparite is preserved. Their lower contact is almost certainly transitional with the underlying Coralline Algal Bioherm, although it appears as an unconformity, due to the extensive recrystallisation of the total bed thickness (Plate 9c). Recrystallisation was apparently prevented from penetrating into lower horizons by the finer micritic nature of the underlying Coralline Algal Bioherm, which has a low porosity. The top of these beds is taken as that horizon at which carbonate mound development of the Tal Pictal Beds commences and is recognised throughout the major islands. At the type locality carbonate mound structures are well developed, their micritic composition strongly contrasting with the biosparitic nature of the flanking intermound sediments and the adjacent Rabat Plateau Beds.

(ii) Lithology and Distribution

Towards the top of the Coralline Algal Bioherm in all areas there is a coarsening of sediments and a reduction in the number of rhodolites present. This is frequently masked by secondary recrystallisation, as previously stated, which forms a sharp base to the Rabat Plateau Beds and can be traced throughout the outcrop from Ghar Lapsi in south-western Malta to northern Gozo. These rocks are characterised by a pale grey colour and sparsity of macrofossils. The beds are thickest on the Rabat Plateau, north of the Victoria Lines Fault and in south-eastern Gozo where a marl bed occurs at (351865). They appear to pass laterally westwards in Gozo into Tal Pictal Beds. In easterly areas this lithofacies is difficult to distinguish from the coarser top of the Rdum il Hmar Beds, which are believed to be penecontemporaneous in part with the Rabat Plateau Beds. This correlation is based on the occurrence of coralline algal fragments and occasional rhodolites which are present within the top chalky beds of the Rdum il Hmar Beds and are considered to reflect progressive easterly migration into the area of the Rabat Plateau Beds. The capping sequence to the Upper Coralline Limestone at Ghar Lapsi is also considered to represent part of the Rabat Plateau Beds as it consists of typical oobiosparite and coralline algal biosparite similar to the latter and does not apparently contain carbonate mound developments. A marl band occurs towards the top of the sequence in this outlier. A similar marl band occurs at (348865) west of Fort Chambrey, Gozo though these beds are not obviously correlateable.

(iii) Petrology

In this section these rocks are particularly difficult to interpret as recrystallisation has frequently obliterated all evidence of allochems and macrofossils, hence the rock appears as a mass of sparite bearing a shadowy texture, possibly representing ghosts of the original fossils.

Frequently the hand specimen gives a more precise idea of the content as the ghosts of the various components still retain subtle shade contrasts. Identification of the bioclastic components is rarely possible beyond the genera or even family level (Plate 11a), although modal analysis does indicate that about 20-30% of the rock is either of coralline algal fragments or rhodolites but with additional infrequently scattered pectinid and echinoid fragments. All thin sections examined are of non-ferroan calcite.

(iv) Fauna and Flora

Lithophyllum rhodolites are the dominant floral component with minor occurrences of Corallina sp. and Jania sp. Pectinids occur uncommonly. Clypeaster altus, Lamarck is occasionally found, especially along the cliffs of western Marfa Ridge, Malta. At Ghajn Selum, Gozo (328894) and Ta'Zuta, Malta (456668) vertical and inclined multibranching tubular networks 0.5mm. to 10 mm.diameter occur. These bear hair-like side branches and though specifically resembling the description of Caëgichnus (Doust 1968, p. 131) are considered to be root systems of indeterminate marine or intertidal vegetation (Plate 16e).

b. Tal Pictal Beds

(i) General

These beds give their name to the Member and are recognised in both Malta and Gozo. At the type locality small carbonate mounds are developed in sediments not too dissimilar to the underlying Rabat Plateau Beds.

(ii) Lithology and Distribution

The rocks are distinguished from the Rabat Plateau Beds by the extensive development of carbonate mound bioherms. At outcrop the sediments surrounding the bioherms are indistinguishable from the Rabat Plateau Beds, though they have not suffered the same degree of recrystallisation. The carbonate mounds on the other hand are significantly different, being lensoidal in the lower beds and apparently orientated in an east-west direction (Plate 9d). These lenses are frequently oolitic in the lowest horizons, such as in the Dingli Cliffs where they are 3-5 metres wide and 1 metre thick, but higher in the sequence, such as west of Mellieha, Malta, the bioherms may be over 32 metres in width and 2-3 metres thick. These latter mounds are dominantly micritic, though this may partially reflect recrystallisation of coralline algae and coral which make up the main framework of the mounds. Disarticulate mollusc shells also figure highly in these structures.

In Malta the beds transitionally succeed the Rabat Plateau Beds and are best developed in western areas of the island. A lateral facies change occurs eastwards and the beds pass into Rabat Plateau Beds (Fig. 5). In Comino the same lateral relationship is seen with Tal Pictal Beds passing eastwards into Rabat Plateau Beds. Although Gozo is dominated by Rabat Plateau Beds in the east, these give way westwards into Tal Pictal Beds, particularly around Victoria. These outcrops are now restricted to isolated buttes but are sufficiently well exposed to prove conclusively that the Tal Pictal Beds rest directly on Ghajn Melel Member and it would appear that the Rabat Plateau Beds are undeveloped in most areas of western Gozo.

Throughout the islands the beds are capped by Tat Tomna Beds of the Gebel Imbark Member. At this contact carbonate mound development abruptly ceases and the strata is succeeded by a minor erosion surface in western Malta. Above this, and elsewhere in the islands, Tat Tomna Beds cross-bedded oopelsparites succeed the mounds .

(iii) Petrology

Despite the initial field evidence of gross dissimilarity between the country rock of these beds and the carbonate mounds, modal analysis indicates that the two are closely related (Fig. 25b), although the carbonate mounds have a higher molluscan content. Figure 26a further shows that unlike the interbank sediments, the carbonate mounds also contain a high coralline algae and compound coral component, both of which are generally found in situ within the mounds. Several of the lower carbonate mounds from the Rabat Plateau have a high oolitic content and a low fauna, but usually it is the interbank sediments which actually contain the highest oolith content. This may reach 60% in some samples. Several of the higher carbonate bioherms show internal solution and penecontemporaneous infill (Plate 11d).

(iv) Fauna and Flora

The interbank sediments contain occasional Clypeaster altus Lamark and similar foraminiferal and coralline algal fragments to the Rabat Plateau Beds. In addition Halimeda sp. is common in the higher horizons. Within the carbonate mound or banks environment Lithophyllum sp., Mesophyllum sp., Lithoporella sp. Dermatolithon cf. nitida Johnson, Lithothamnion sp., and rare Archaeolithothamnion sp. form the binding and framework, together with occasional colonial corals such as Tarbellastraea cf. reussiana ME+JH, Diploastraea ravlini Ed & H., Favites sp., Acropora sp., and an indeterminate compound seleractinian coral (Plate 15c). Abundant encrusting bryozoans and foraminifera also occur, together with occasional vermetid gastropods. Within this framework occur a mass of disarticulate lamellibranchs (Plate 9d) and gastropods including Venus sp., Cardium sp., Gastrena (Capsa) lacunosa Chemnitz, Tapes sp?, Schilderia, sp., Arca turonica, Dujardine, Tellina sp., Chama pseudounicornis Sacco, Ostrea sp., Gastrochaena squamulosa Desio, Lithophaga lithophaga Linné, Gibbula sp., Lucina senensis, L. incrassata, (Dubois) Glycimeris deshayesi, (Mayer) Ostrea digitalina Eichw., Lima sp., Pecten vigolenensis Simonelli, Strombus sp., Conus sp., Turritella sp., Haliotis sp., Erata sp., Pleurotoma sp., capulid gastropods and small indeterminate low spire gastropods. All this carbonate mound material is preserved as shell casts which have frequently been highly bored by Entobia sp., and bryozoans which now stand out as casts within the shell cavities. 0.3 metres diameter cushion shaped seballariid mounds occur at Qassam Barrani, Malta and are made up of individual tubes of Protula sp., the apertures of which converge towards the mound centres.

C. Detailed Study on Selected Carbonate Mound Developments

Three localities have been studied in order to appreciate fully the origins, structure and ecology of these carbonate bodies.

(iii) Qassam Barrani Area (405792)
(ii) Tat Tomna (417788) - Mellieha Area
(i) Tal Pictal Area (432685)

(i) Tal Pictal Area (432685)

These are the earliest carbonate mounds developed, are lensoidal in form, and are 3-32 metres wide and 1-4 metres high. The majority of carbonate lenses are cemented by sparite, but there is evidence to indicate that in situ coralline algal development has been responsible for binding parts of some of the structures, although in many specimens examined this has been subsequently micritised. Although the rest of the biota of these structures is sparse an indeterminate colonial scleractinian coral, often forming dome shaped colonies up to 300 mm. diameter and 150 mm. high, is particularly characteristic of these carbonate mounds of the Tal Pictal Beds (Plate 15c). This coral is uncommon in the early mounds but becomes increasingly more important higher in the beds.

Oosparite and oobiosparite make up the intra-mound sediment and are clearly distinguishable from the unsorted biosparites surrounding the mounds. The latter are less well cemented and are banked up against the mound flanks, suggesting that the more highly fossiliferous mounds at least acted as positive lithified seabed structures. All appear to be orientated in a crude east-west direction, resulting in a lensoidal cross sectional appearance along the studied cliff sections.

(ii) Tat Tomna (417788) - Mellieha Area

These mounds occur at the top of the Tal Pictal Beds and represent the largest structures to be found within these beds (Plate 15d). The carbonate mounds of this area are more accessible and a three dimensional interpretation is possible.

The mounds are of varying size and are less lensoidal in nature than the earlier structures discussed above. Many are 3 metres high and over 30 metres in length with an approximate east-west orientation of their long axes. However, the latter may be more apparent than real as all the quarry sections are orientated in this direction. At the above co-ordinate an abandoned quarry exhibits a north-south orientated section through two adjacent carbonate mound lobes.

Internally the mound is characterised by an abundance of clionid bored molluscs, occasional vermetid gastropods and the indeterminate compound coral previously referred to. Within this mound area these corals are prolific (Plate 15c), the ones in the lower part of the mound in this plate being orientated to former stands of the developing carbonate mound front. In places the coral may comprise up to 20% of the mound structure. It is clearly an allied form to that occurring in similar carbonate mounds within the Attard Member of the Lower Coralline Limestone (Plate 15a, b). The flanking position of this coral genus in relationship to the mounds may indicate a preference of the colony for a fairly high energy location. Large areas of micrite enclose the biota of the mound and both these areas and the corals are frequently bored by Lithophaga lithophaga , some of which can be clearly seen to bore vertically upwards into the underside of loblets of the mound (Plate 10b) suggesting that the mounds were positive framework structures bearing overhangs.

On the microscopic scale the mounds are seen to have been initially cemented by micrite and bound together with coralline algae but were subsequently affected by cavity formation. Within these solution hollows and cavities, "gloomy cavity" colonisation has occurred (Garrett, et al, 1971, p. 665), consisting mainly of serpulids, membraniporiform bryozoans and encrusting foraminifera (Plate 11cii) all of which have added to the framework. Other cavities appear to have formed by solution, possibly deeper within the lithified mound, and have been subsequently infilled by silt, micrite and other penecontemporarneous sediments, occasionally forming geopetal structures (Plate 11d). Most of the aragonitic shell casts from within the carbonate mounds are disarticulated but the dense concentration of these in comparison to their virtual absence outside these structures strongly implies that they were bound into place shortly after the death of these animals, possibly by rapid coralline algal growth. This is confirmed by laminar micritic structures, mainly recognised in thin section, which occur abundantly within the mounds. Occasionally these micritised areas are seen to have a cellular structure, with oogonia (Plate 11ci) and are considered to be an indeterminate genus of crustose coralline algae.

The sediments surrounding the mound are clearly seen to be banked up against them and consist of unsorted biosparites and biosparrudites. These are clearly seen between the two mound lobes at Tat Tomna quarry, where they are banked up against the vertical carbonate mound sides. Halimeda sp.

figures high in these sediments as does Spondylus sp., Ostrea sp. and a wedging horizon of nodule-like domichnia of an indeterminate crustacean. Rare talus from the mound is also present at the foot of the lobes. Identical Halimeda rich biosparites are banked up against similar positive carbonate mounds at (417788) west of Mellieha, Malta. Associated with these are frequent wedges of shell debris including Glycimeris. Most of the above structures have also been confirmed in western Gozo, where mound boundaries are, however, more difficult to define.

(iii) Qassam Barrani Area (405792)

This problematic area is tentatively referred to the top of the Tal Pictal Beds on the basis of its contained patch reefs and its location on top of a cross bedded (Ghadira Beds?) sequence. This has been partly confirmed from aerial photography of the area.

The carbonate mounds are lensoidal in section and occur in a fine grained laminated oobiosparite, associated with possible dessication polygons. Several of these structures consist of 1.5 metre diameter by 0.3 metre thick lenses of sabellariid worm reef composed of a genus similar to Protula sp. Comparable samples from mounds high in the Upper Coralline Limestone at Tas Salvatur, Gozo (329915) have also been collected. The sequence at Qassam Barrani is succeeded by foraminiferal biosparites and micrites, which are very similar in aspect to later Gebel Imbark Beds.

d. Ghadira Beds

Type locality Ghadira, Malta (406803), (Plate 9b)

(i) General

These beds are restricted to Malta north of the Victoria Lines Fault and the island of Comino, occurring at the latter in the westerly facing vertical cliffs below Comino Tower. In western areas they appear to be contained within the Tal Pictal Beds, which both under and overly them, but in the eastern area of outcrop (see Fig. 5) they may be both underlain or overlain by Rabat Plateau Beds.

At the type locality the beds consist of coarse grained biospararenites and biosparrudites. These form a thick succession of easterly dipping foresets, each being 1-1.5 metres in thickness with a dip of about 22° and a foreset amplitude of 18 metres (see Fig. 26b).

(ii) Lithology and Distribution

The beds attain maximum development in western areas of outcrop and can be recognised at Ghadira, Comino, Ghajn Tuffieha, Bajda and Qassam Barrani. At the former three outcrops large sections exist parallel to the easterly dipping foreset direction, but at the latter two localities beds believed to be equivalent to topsets and bottomsets are exposed, suggesting that the beds are lensoidal in an east-west direction. Although usually only the upper and best developed set is exposed in the islands, at Ic - Ċumnija in the sea cliffs, low angle tangential, southerly dipping foresets (lower vector group in Fig. 26b) are seen. These are considered to represent the earliest sets developed in the area. The Qassam Barrani outcrop is comprised of scour and fill channelling, and low angle cross laminated beds dominantly made up of oobiosparites, and is less than 6 metres in thickness. It is considered to extend eastwards into a more typical area of easterly dipping foresets, primarily recognised from aerial photography. The foresets conform to the "Alpha-cross stratification" of Allen (1963, p. 101), although the Qassam Barrani outcrop exhibits the "Nu cross-stratification of Allen (1963, p. 101) and is similar to the Tal Tomna Beds of eastern Gozo.

(iii) Petrology

The most common rock type of these beds is a packed oosparite or biosparite, which is not dissimilar to the Tal Pictal Beds (See Fig. 25b). The biosparite horizons are dominantly made up of coralline algal and foraminiferal fragments. The oolitic samples generally contain up to 60% ooliths, though this is frequently at the expense of the bioclastics, which are absent in some samples. Faecal pellets (20-40%) figure in rocks from Qassam Barrani.

Individual megaforesets were sampled at intervals along their length at Ghadira, Ghajn Tuffieha and Bajda Ridge, in order to compare the relationships between the Ghadira Beds and the remainder of the adjacent Tal Pictal Member.

At Ghadira (408806) 8 samples from a 1.4 metre thick foreset showed a general reduction in the percentage of ooliths from the top of the foreset down towards the base of the foreset, a distance of about 150 metres.

At Ghajn Tuffieha (422757) a comparable foreset, 200 metres long, was sampled at 7 points along its length and showed no apparent trend.

At Bajda Ridge (422775) Ghadira Bed foresets, again plunging eastwards at 18°, were sampled at 3 points and indicated that these foresets contained under 2% ooliths, although recrystallisation prevented further interpretation. Finally at this locality, beds immediately capping the Ghadira Beds between (416775) and (435780), a distance of almost 2 kms., were sampled regularly at 6 points in order to appreciate the relationships between the Tal Pictal, Rabat Plateau and Ghadira Beds. Modal analysis of these samples indicated that beds at the western end of the transect were associated with carbonate mound deposits, whereas those in the east were more micritic in composition. These latter also contained significantly fewer ooliths and a higher percentage of benthonic foraminifera. In addition, the eastern samples were indistinguishable petrologically from beds transitional between the Rdum il Hmar Beds and the Rabat Plateau Beds.

In conclusion, it may be stated that throughout these beds the foresets are consistent with beds produced by a moderate to low velocity current with low suspension transport, entering a fairly deep depression (Jopling 1965, p. 782 and Swinchatt 1967, p. 111). Modal analysis shows the gross similarity between the Rabat Plateau Beds and the Tal Pictal Beds, but further indicates the close relationship between these two and the Ghadira Beds. It is finally concluded that one of the main access points for coarse sediments entering the Rdum il Hmar area to the east, from the shallower western area dominated by the Tal Pictal Beds, was via the Ghadira foresets (see Fig. 27 and 40). It is difficult, however, to prove conclusively the possibility that the inter-bank channels, associated with the reticulate mudbank development low in the Tal Pictal Beds, may have aided in the funnelling of shallow water carbonates into the Ghadira Bed foresets.

e. Ghar Lapsi Beds

(i) General

Type locality Ghar Lapsi outlier at In Neffiet (492645).

This thinly bedded facies appears to be a lateral equivalent of the basal Rabat Plateau Beds, or possibly the top of the Rdum il Hmar Beds.

(ii) Lithology and Distribution

These beds, now totally recrystallised, are entirely restricted to the extreme southern end of the Rabat Plateau and the Ghar Lapsi area of Malta. They consist of thinly laminated, sparsely fossiliferous white or pale grey sparites. Their close proximity to the Maghlak Fault in the Ghar Lapsi outlier has resulted in the overfolding of these beds, though dips decrease westwards (see Plate 10d). The thickness of the beds is probably about 20-30 metres. Rdum il Hmar Beds lie conformably below with

Rabat Plateau Beds above.

In the Fawwara and St. Lawrence area of the southern Rabat Plateau these beds are recognised as developing laterally from beds transitional between the Rdum il Hmar Beds and the Rabat Plateau Beds. At the former locality beds become less massive until at (470679), to the south-west of St. Lawrence church, the Ghar Lapsi Beds become more obviously layered into 1 metre beds. It is believed that this increasingly thinly laminated tendency ultimately results in the 20-30mm. laminae seen at the type locality. Ripple lamination is recognised at Fawwara, otherwise no macro-structures are recognised. This conforms to the "Nu-cross stratification" of Allen (1963).

(iii) Petrology

Outcrops on the Rabat Plateau are highly recrystallised and yield little information of value, as is also the case at the type locality. Samples taken from the type locality show that alternating laminae of micrite and biomicrite occur. Thin sections from In Neffiet illustrate micro-scale scour and fill structures associated with the beds. These are just visible in the hand specimen. Being entirely recrystallised and partially dolomitised the components of the laminae are difficult to recognise.

(iv) Fauna

Benthonic foraminifera similar to Rotalia occur as ghosts within the laminated micrites and rare pectinid fragments are also occasionally present.

2. Diagenesis within the Member

The entire sequence is characterised by recrystallisation. This varies from minor pore solution and subsequent sparry cement development, to large scale recrystallisation, best seen in the Rabat Plateau and Tal Pictal Beds. Vast interconnecting cavernous networks have developed within these beds by the action of percolating groundwater, and frequently a pseudonodular appearance has been developed on solution surfaces. On closer examination these 'nodules' are seen to be solution resistant Lithophyllum rhodolites which have become exhumed by solution of the surrounding coarser biocalcerenite matrix. Occasionally solution has gone further, such as along the Tal Merlah cliffline (408708), where a breccia appears to have developed as a result of collapse of the netlike solution horizons under the weight of the overlying strata. Much of this must have occurred at a late stage in the history of the rock, though the final stage, well seen along the Dingli Cliffs, consists of non-ferroan stalactite formation within the solution cavities. Smaller dendritic calcite growths within some cavities superficially resemble coralline algal rhodolities, although thin sectioning reveals them to be made up of either a stalactite growth or sparry calcite.

Frequently along the Dingli Cliffs there is a sharp contact between the totally recrystallised vügh filled Rabat Plateau Beds and the comparatively unaltered underlying Coralline Algal Bioherm.

Although the dominant carbonate is low-ferroan calcite the top Tal Pictal Beds West of Mellieha (4279) have been partially dolomitised and this also appears to have affected the Rabat Plateau Beds at Ghar Lapsi. The underlying Ghar Lapsi Beds in this area are partly altered to low-ferroan dolomite. This dolomitisation is earlier than the stalactite formation, as non-ferroan calcite frequently infills the cavities within the dolomitised rock.

All the aragonite fossils within the member are now represented by shell cast cavities, and it is believed that aragonite solution was one of the earliest effects of diagenesis, as it was in all previous members.

In some carbonate mounds of the Tal Pictal Beds cavities have been infilled by blocky non-ferroan calcite.

3. Palaeoenvironmental Interpretation

General

Biofacies for the Ghar Lapsi Beds and the Ghadira Beds have not been erected, because of the lack of fauna. However, the following biofacies have been recognised within this subdivision of the formation.

a. Biofacies B   Rhodolite Biofacies

b. Biofacies C   Biolithite/Mollusc Biofacies

a. Biofacies B   Rhodolite Biofacies

This facies is directly analogous to Biofacies B in the Lower Coralline Limestone. It is here made up of both the Rabat Plateau Beds and those areas of the Tal Pictal Beds surrounding the carbonate mounds. The rhodolites are well formed spheroidal colonies intimately associated with the coarse biosparite matrix, indicating that moderate energy conditions prevailed. The normal rhodolite component is *Lithophyllum*, which is today characteristic of depths of from 12-25 metres (Johnson 1965, p. 16-17), and with greatest development in tropical seas. Within the biosparites *Corallina* and *Jania* occur. Recent species (Johnson 1954, p. 46) are most typical of areas of clear water and high tidal range. In summary, it would appear that this biofacies is characteristic of moderate to strong energy areas in warm shallow seas with little or no silt and mud sedimentation. This conclusion is supported by the coarse biosparitic nature of the sediments which are typical of a high energy regime.

b. Biofacies C   Biolithite/Mollusc Biofacies

This biofacies is characteristic of the areas of carbonate mound development associated with the Tal Pictal Beds, and is directly analogous to the comparable developments within the Attard Member of the Lower Coralline Limestone. The prolific coralline algal and molluscan populations are typical of shallow depth, and the presence of abundant borers indicates that the mounds formed positive lithified structures during sedimentation. Molluscs within this biofacies have been extensively bored by Entobia sp., Bromley (1970, p. 70) in a study of borings as trace fossils, considered that clionid borings were most common in the first 25 metres of the sub-littoral zone. This suggests that the biofacies under consideration also accumulated under comparable depths. This is further supported by the abundance of Halimeda sp. in the inter-mound sediments, as this genus prefers a shallow water lagoonal environment (Garret 1971, et al. p. 666 and Chapman 1906, p. 702).

The overall structure and biotal content of the younger carbonate mounds is remarkably similar to that of the algal cup reefs of Bermuda (Ginsburg and Schroeder 1973), which are 10-30 metres in diameter, 8-12 metres high, and form lithified carbonate structures just below sea level. On the basis of this it is believed that the Maltese examples are closely comparable, and formed under similar environmental conditions, to those of Bermuda. It appears likely that the Halimeda developed in the protected embayments between adjacent mound lobes, where calmer conditions possibly prevailed.

The micritic and oolitic carbonate mounds of the lowest horizons, seen in cross section at Tal Pictal, are more difficult to account for. The oolitic structures are frequently cross-bedded and may represent sand waves in channel deposits of carbonate material, which was being funnelled eastwards from areas outside the islands. The micritic mounds with corals and coralline algae are undoubtedly carbonate mound structures where finer sediments were bound together by crustose coralline algae and coral and, though no confirmatory evidence is seen, marine grass may have further aided in trapping sediments to produce a positive structure. They are considered to represent a reticulate mudbank development occurring in somewhat deeper water to the later mounds, which lay to the east of the shallowest mound area (see Fig. 27). They are comparable, although on a much smaller scale, to the mudbank developments encountered off the east coast of Florida (Ginsburg 1956). The faunal content of the Maltese examples is comparable to those of Florida, except for the generally lower coral and Halimeda content, though no conclusions are drawn from this. Both carbonate mound types appear to have accumulated in comparable water depths of not more than 25 metres. Perhaps the reticulate mounds developed in response to the dominant easterly migrating current, whereas the larger later mounds developed in response to a more open environment subject to wave action.

The Qassam Barrani sabellariid mounds appear to reflect an intertidal development, possibly in a localised area of uplift. They are comparable to, although smaller than, structures recognised by Multer (1970, p. 12) at Key Biscayne, Florida.

c. Geological History of the Tal Pictal Member

Micritic sedimentation within the Rdum il Hmar Beds was gradually terminated by the influx of bioclastic sediments entering the north-south depression from shallower areas to the west of it. To the south the Ghar Lapsi Beds developed in an intertidal and shallow water environment which developed at this time. The intertidal San Leonardo Beds (to be discussed later) may possibly belong to this phase, though no positive evidence is available. If they are contemporaneous, then they may represent sediments deposited on the eastern periphery of the Rdum il Hmar basin (6 in Fig. 27). To the west, shallow marine conditions prevailed and a rhodolite biosparite facies, the Rabat Plateau Beds, evolved, and subsequently migrated eastwards with time under the possible influence of a dominant westerly current. Within this area small emergent shoals developed and supported a restricted vegetation, now represented by rootlet cavities at some localities.

The resulting shallow conditions produced soon became favourable to the development of a reticulate mud bank environment between which, oolitic rich sediments were swept eastwards to aid in the infilling of the relict Rdum il Hmar depression. These are the lowest horizons of the Tal Pictal Beds.

As time proceeded, the vast volumes of derived bioclastics and ooliths produced in the shallow water environments to the west of Malta, were sufficient for the development of localised deltas, the Ghadira Beds. Sediments were channelled into the head regions of these structures, which lay in embayments between easterly migrating lobes of the Tal Pictal Beds, and foresets were built out eastwards. The amplitude of the foresets in these beds may give a minimal indication of the water depths within the rapidly filling eastern depression at this time.

In time, the relict north-south orientated eastern depression was ultimately infilled, primarily by Ghadira Beds, but also by Rabat Plateau Beds. The resulting shallow environment, which by this time extended throughout central and western areas of the islands and may even have extended into the east, was colonised by crustose coralline algae, corals, molluscs and other framebuilders, and comparable structures to the Bermudah algal cup reefs developed along the southern shores of that island.

The flanking sediments to the Maltese structures are also comparable to Bermudan counterparts, as are the multigeneration void formation and infillings within the reefs.

Sudden uplift abruptly terminated reef development and brought to a close the Tal Pictal episode. This was associated with erosion in western areas of Malta.

Although precise thickness variations within the member have not been obtained, it is apparent that the beds attain their greatest development in Comino, and Malta north of the Victoria Lines Fault. In Gozo a very thin development of Rabat Plateau Beds separates the Gebel Imbark Member from the Mtarfa Member and the Ghadira Beds are absent (see Fig. 5). A comparable thin succession of Tal Pictal Member separates Coralline Algal Bioherm from Gebel Imbark Member, and again the Ghadira Beds are absent. Between these two areas of thin development lies the island of Comino, where Ghadira Beds are thickly developed, and northern Malta, also with a thick Ghadira Bed development. The easterly convergence of the Tat Tomna Beds (Gebel Imbark Member) and Rdum il Hmar Beds (Mtarfa Member) is well displayed from Ghadira and west Marfa Ridge, where great thicknesses of Tal Pictal Beds separate the two; through the Rdum il Hmar area, where thin Rabat Plateau Beds separate them; finally to eastern Gozo, where the two lie even closer together. This relationship is inferred to exist across the Victoria Lines area of Malta, but is either removed or obscured by Quaternary deposits in this area.

The conclusion is that the Tal Pictal Member is primarily a sediment accumulation centred on western Malta, north of the Victoria Lines Fault, and Comino, which developed in response to a regional tectonic down-warp in this area. This was possibly related to the earlier north-south orientated structures of the Blue Clay Formation, Ghajn Melel and Mtarfa Members.

MODAL ANALYSES OF THE TAL PICTAL MEMBER

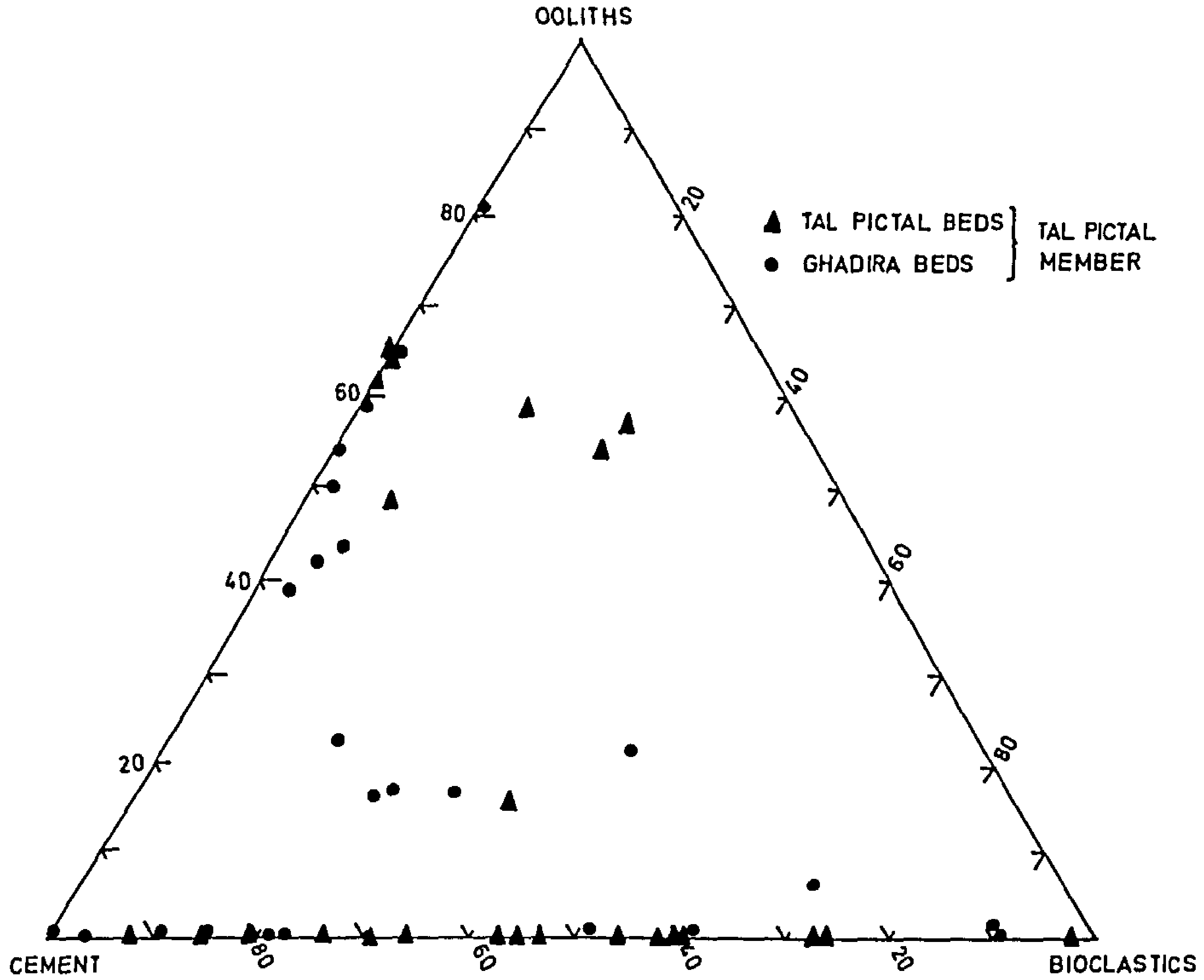


Fig. 25a

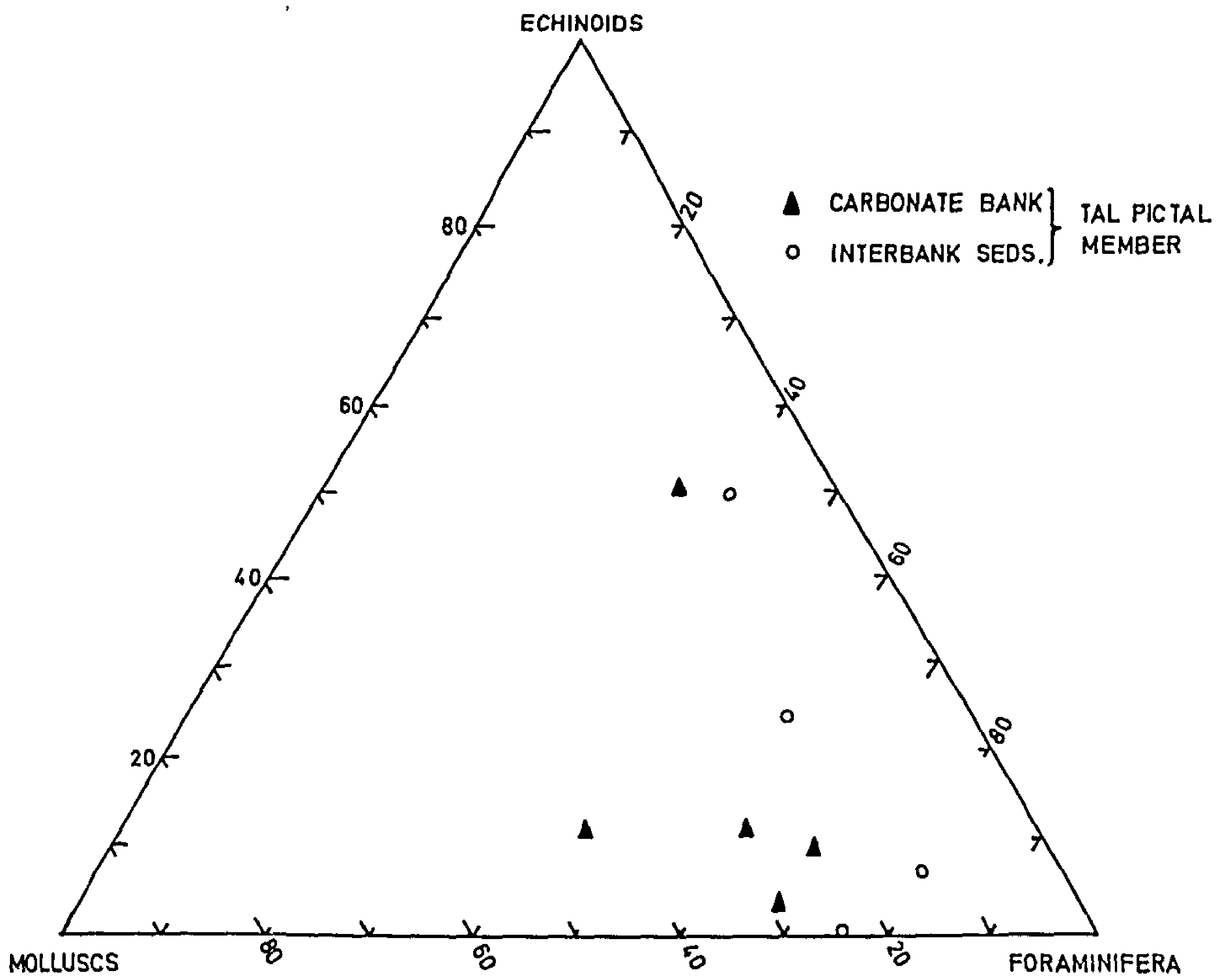


Fig. 25b

CHAPTER 9

UPPER CORALLINE LIMESTONE FORMATION

1. Gebel Imbark Member

Type locality Gebel Imbark, Malta (401807).

This is the highest subdivision of the Upper Coralline Limestone recognised in the present study and is restricted to small isolated outliers in eastern Gozo and western Malta. The Member is further subdivided into the following:

c. San Leonardo Beds
b. Gebel Imbark Beds
a. Tat Tomna Beds

a. Tat Tomna Beds

(i) General

Type locality Tat Tomna (421799), east of Mellieha (Plate 10c), where the beds attain their most typical development. Their lower contact at this locality is sharp, due to the occurrence of a basal erosion surface separating them from the underlying Tal Pictal Member in north-western extremities of Malta. This contact is even more apparent west of the type section. The typical cross-laminated oopelsparites of the Beds show a transitional upper contact with the overlying Gebel Imbark Beds, where these are preserved. More commonly, however, the Tat Tomna Beds occur on isolated outliers.

(ii) Lithology and Distribution

Pale grey, fine grained limestones exhibiting low angle cross-lamination of tabular type generally occur in western Malta. Palaeocurrent analysis shows a slight preference to a dominantly north-eastern orientational maxima (Fig.26b). Sets of cross-bedding are composed of dominant foresets, with occasional bottomsets, individual sets averaging 100-200mm. in amplitude.

At the type locality the beds are over 2.3 metres in thickness. This appears to be a maximum value and more frequently less than 1.5 metres is preserved. Outliers near Tal Pictal, Malta exhibit small scale scour and fill and tabular foresets suggesting very shallow conditions, and small scale ripple development. This contrasts with the "Mu cross-stratification" of Allen (1963, p.107) at the type locality, and the trough cross-bedding of eastern Gozo outcrops, which conform to the "Nu cross-stratification" of Allen (1963, p.101).

The beds at outcrop are variable in composition, individual laminae alternating between micritic rich and oolith rich types.

(iii) Petrology

Most samples from these beds are classified as oobiosparite or oopelmicrite, though benthonic foraminifera are often abundant in some samples. Frequently, however, these foraminifera are fragmentary and form the nuclei of the ooliths (see Fig.26a and Plate 12a). The individual pellets within the more micritic laminae are frequently aggregated into grapestone, varying in size from 0.15-0.2mm. in diameter. The ooliths range from 0.6-1mm. in diameter. The ooliths frequently contain micritic cores, possibly representing original pellet nuclei. Oosparites are the more typical rock type in eastern Gozo associated with the low amplitude festoon cross-lamination.

(iv) Fauna

The fauna of the Tat Tomna Beds is sparse, Rotalia sp. and other fragmentary benthonic foraminiferal allochems are present, usually in the form of oolith nuclei. Occasional casts of small, indeterminate gastropods are found scattered throughout the beds.

b. Gebel Imbark Beds

(i) General

Type locality Gebel Imbark, Malta (401807)

The isolated nature of the occurrence of these beds makes correlation difficult, particularly between the outcrops on Malta and Gozo.

(ii) Lithology and Distribution

Two regions with distinct lithologies can be recognised. The first is characterised by the Gebel Imbark and Tal L'Abattija outliers of Malta. Although in the field these rocks are often so recrystallised that original depositional textures have been obliterated, massive grey micrites appear to be the dominant rock type. Towards the top of the Gebel Imbark section a thin stromatolite horizon occurs, and can be traced the length of the outlier (see Fig.5). This is believed to correlate with a similar horizon closely overlying the Tat Tomna Beds at Tal L'Abattija, and another recognised in loose blocks and local walls at the eastern end of the Bingemma outlier further to the east. The strata above this horizon appears to be massive and micritic in nature.

In eastern Gozo the Tat Tomna Beds are overlaid by strata not dissimilar to the Tal Pictal Beds. Little of the beds is preserved here so the presence or absence of the stromatolite horizon cannot be ascertained. The sediments are coarsest in the northerly outliers but contain much micritic material in outliers further south. Scattered rhodolites are present in the coarser beds.

(iii) Petrology

Thin sections of the Malta material merely show massive recrystallised grey limestone which was possibly once micritic. Thin sections from the stromatolite horizon at Gebel Imbark reveal that a large quantity of gypsum is present between successive algal laminae. These grains average less than 0.1mm. in length and are considered to have grown within the algal mat soon after formation. Oomicrites occur in the lowest few metres of these beds at Gebel Imbark, although diagenesis has generally obliterated other primary structures which may once have been present.

c. San Leonardo Beds

(i) General

Type locality San Leonardo, eastern Malta, (6070). Here they form a capping sequence to the hill and rest unconformably on top of the eroded Globigerina Limestone Formation. A total thickness of 9-10 metres of sediment is preserved.

(ii) Lithology and Distribution

Two distinct beds of pale grey biosparite are recognised throughout the two kilometre long outcrop and these are separated by a bed of grey marl. This marl at its thickest is 1 metre thick where seen around the old quarries east of the fort, but becomes thinner at the south side of the moat surrounding the fort. The basal contact of San Leonardo Beds with Globigerina Limestone (see Plate 12c) is sharp, the eroded Middle Globigerina Limestone presenting an irregular upper surface, possibly produced by submarine erosion. The section visible in Plate 12c shows coarse San Leonardo Beds sediments containing lithoclasts of sparite in a biosparite matrix. At most other exposed basal contacts scattered glauconite grains, sub-1mm sized phosphorite pebbles and rare oysters are present. This horizon is possibly 5 metres in thickness and is succeeded by the marl bed, which is now greatly altered by caliche development. It has sharp basal and upper contacts. Finally the marl bed is succeeded by a further 3 metres of biosparite.

Primary structures are abundant in the two biosparite beds (see Plate 12b). The lowest biosparite shows an extensive development of scour and fill channels up to 4 metres wide and 0.7 metres deep. Many of these show evidence of lateral migration, and frequently show marly laminae within the infill, resembling typical flaser bedding. In the upper biosparite similar developments of channelling are seen, but these are on a somewhat larger scale with individual channels, such as the one visible in the south facing moat wall to the fort, being approximately 1 metre deep and 6-7 metres wide.

The largest channel infilling within these beds is seen within the two old quarries a few metres to the north of the fort. Here approximately 2 metres of coarse bioclastic and lithoclastic channel infill is preserved at the top of the sequence,and can be recognised at least 1 km. north as loose wall blocks. The bioclastics consist of coarse molluscan shell fragments and the lithoclasts of biosparite and biomicrite pebbles of up to 70mm. diameter. These undoubtedly represent a channel base lag conglomerate. Measurements indicate that most channels have axes orientated in a north-south direction (see Fig.26b),and scour and prod marks seen on the sole of some laminae support this. Where the beds are not channelled they consist of level but thinly bedded alternations of coarser and finer biosparites,frequently with whispy intercalations of darker grey marl.

(iii) Petrology

Samples from the basal contact around the north-eastern side of the outlier indicate that a thin pelmicrite was initially deposited,containing micritic rock clasts, fragments of phosphorite,and reworked glauconite grains. Higher in the beds thin micritic layers persist and are interlayered with coarser detritus. Some samples,although recrystallised, show much molluscan debris in what was once a biosparite (Plate 12d). Samples towards the top of the lower biosparite contain up to 21% echinoderm debris, with occasional bivalve, ostracode and foraminiferal fragments making up the remainder of the bioclastic component.

The 1 metre grey to dark brown marl bed above the lower biosparite is of particular interest,as samples from the middle and top of it yield a sparse fauna of ostracodes, foraminifera, small gastropods and gyrogonites of Charophyta. Occasional flakes of biotite and tourmaline are also recorded.

The upper biosparite is associated with the previously described channel infill,consisting of shell debris and limestone conglomerate,in a quarry at (600706). Sectioning shows that the well rounded elliptical pebbles, averaging 6-70mm. in length, are invariably altered to microsparite. They are, however, considered to have originally been micritic. Grey, mollusc bored biomicrite pebbles are most abundant and contain over 50% Globigerina sp., with additional echinoid debris. Well rounded brown goethite pebbles are second in abundance and occasional black micritic pebbles also occur. These latter two types rarely attain lengths in excess of 10mm. Aragonite solution has removed all aragonitic shell material and some of the goethite pebbles have been oxidised to limonitic powder. Some thin sections contain up to 40% pebbles and rounded shell fragments, though it is difficult to draw conclusions from the rounded nature of these regarding transport distances.

(iv) Fauna

The only fossils recorded in the lower biosparite are Ostrea sp. from the basal unconformity to the north-west of the old convent. Within the overlying marl bed four charophyte gyrogonite groups were identified, though the absence of the apical systems prevented identification down to organgenera. These are associated with ostracodes, including Bairdia sp., a few citherellids and trachyleberids. Amnicola sp. (Plate 16d), the dominant gastropod recorded within the samples, was further associated with the foraminifera Elphidium sp., Cidicides like forms, Rotalia sp., Bulimininae, and rare vinculariform bryozoan fragments. Occasional Schizaster spines and asteroid ossicles also occur.

The upper biosparite yields an abundance of broken and disarticulate mollusc shell casts, especially from the channel infills. These include Arca sp., Cardium sp., Glycimeris sp., lucinids, pectinids and Conus sp. Casts of Entobia sp. are also present within the shell moulds of several of the lamellibranchs. A number of lithoclasts have been bored by molluscs producing crypts similar in outline to Aspidopholas sp.

2. Diagenesis within the Member

The effects of diagenesis within the member are very similar to the preceding one in that only non-ferroan calcite acts as the cementing agent. This is likely to have resulted partially from aragonite solution, which is considered to have occurred early on in the diagenetic history.

All thin sections from the Tat Tomna Beds show that the concentric coatings to the ooids have survived solution and that the rock is now cemented by secondary blocky sparite. The San Leonardo Beds have been cemented by blocky sparite, which has also infilled some of the original shell moulds, producing structureless sparry areas in the rock where aragonitic shells once lay. Some shell moulds have been less perfectly infilled and exhibit a drusy rind around the cavity margins.

In western Gozo the Ghajn Abdul outlier occurs.This cannot be directly correlated with any other beds on the island, though the capping sequence suggests a correlation with shallow to intertidal biosparites and oolites, possibly of the Tat Tomna Beds. For this reason it is discussed here. Towards the top of the solution subsidence infill (discussed in Chapter 12) 40mm-120mm. diameter interconnecting nodules occur, and are enclosed in a white powdery micrite matrix (Plate 10e). Upon staining, both the nodules and the matrix are seen to be made up of non-ferroan calcite. The micrite is structureless, but the nodules contain ghosts of fossils and clearly indicate that the nodular development post-dated deposition. It appears that preferential cementation of selected parts of the strata, coupled by micritisation of the rest, has resulted in this development, which is considered to be closely related to the previously described pseudonodule developments examined in the Tal Pictal Member. As percolating vadose waters are invoked as causing these effects it is concluded that these structures are very late stage effects, and may be as late as Quaternary in age, resulting from the effects of ground water in a more temperate climatic regime.

3. Palaeoenvironmental Interpretation

Because of the general lack of information on this member, biofacies are only presented for the San Leonardo Beds. Palaeoenvironmental interpretations based on sedimentological characteristics are, however, presented on the remainder of the member.

a. Biofacies N Charophyte/Amnicola Biofacies

b. Biofacies O Mollusc Debris Biofacies

a. Biofacies N. Charophyte/Amnicola Biofacies

This biofacies conforms to the marl bed within the San Leonardo succession. The even texture and fine grained nature of this bed clearly indicates a calm environment for accumulation. The lens-like outcrop pattern further supports a possible fluviatile channel environment. Supporting this conclusion is a scanty marine fauna, few in species and numbers; and a brackish to freshwater fauna, dominated by four organ-genera of Charophyta; and abundant specimens of the brackish gastropod Amnicola sp. These are considered to have entered the area from the margins of a nearby lowland area, by means of a sluggish northerly current, and were possibly deposited at no great distance from the shoreline (Fig.27).

b. Biofacies O. Mollusc Debris Biofacies

This biofacies is represented by the two biosparite beds associated with the marl bed. Channelling is common within both beds, and the channel infills are consistent with a high intertidal to subtidal setting, with laterally migrating creeks or channels superimposed on this. Some of the low angle cross-bedding associated with this sediment and the flaser-like whisps of marl are also diagnostic of shallow water sediments similar to those described by Jopling (1965, p.782) and may represent ripple development. The thick accumulation of mollusc shell debris and well rounded pebbles, seen in north-eastern areas of the outlier, appear to be consistent with channel infill deposits, the whole sequence resembling sediments now accumulating low on the shore or just subtidally in the "lower sandflats" of the wash (Evans 1965, p.223).

c. Tat Tomna Beds

The fauna of the Tat Tomna Beds is very sparse, although the depositional environment may be readily deduced from the sedimentology. The beds are primarily composed of oolites, which are indicative of extremely shallow waters (Bathurst 1967 and Blatt et al. 1972, p.420). The low angle cross laminae and wedging sets also support this interpretation. Foreset orientation studies (Fig.26b) are not indicative of a dominant current direction for the beds as a whole, though the Mu cross-stratification at Tat Tomna suggests trains of migrating straight crested ripples. Opposing directions of foresets within this quarry also suggest an intertidal development comparable to those envisaged by Imbrie and Buchanan (1965, p.159), in the Bahamas. The Nu cross-stratification of Gozo outcrops is typical of small scale asymmetrical linguoid ripples. In conclusion it is believed that the Tat Tomna Beds represent an extremely shallow water to intertidal environment of migrating shoals.

d. Gebel Imbark Beds

The Gebel Imbark Beds are poorly represented in the islands due to erosion. Benthonic foraminifera occur sparingly in these beds and a stromatolite bed is recognised. The growth-form of this stromatolite is consistent with the "Mode S - type a" structures in the classification of Logan et al. (1964, p.68), in that spaced lateral linked hemispheres are most typical. This growth-form is consistent with a low intertidal carbonate mudflat environment where sheltered conditions prevail. The micritic nature of the surrounding sediments supports the conclusions of calm environment, though it is recognised that ooliths and pellets occur in the lowest horizons of the Gebel Imbark Beds, indicating that the high energy intertidal conditions of the Tat Tomna Beds were gradually reduced.

e. Correlation of the San Leonardo Beds

Correlation of this isolated outlier is difficult. For the present the beds are included in the Gebel Imbark Member, due to their intertidal nature, which is characteristic of that member. The low iron content in these beds suggests that they formed later than the Mtarfa Member, though nothing more precise can be stated. The presence of glauconite and phosphorite along the basal contact may point to the erosion of Greensand areas.

An alternative correlation with the Ghar Lapsi Beds has been earlier proposed on account of their similar characteristics (see Fig.27) but this has not been confirmed. Considerable effort was made during the present study to correlate precisely the San Leonardo Beds with other beds in the main outcrop bearing marl bands. These are generally restricted to the Tal Pictal Member and it was hoped that they could be correlated with the San Leonardo marl bed. Samples were taken from marl beds at Qassam Barrani (405792), Il Prayet (406796), Mieizbiet (358876), Il Gzira (473652) and Ta Brieghen (359865). Significant faunas were not obtained from any of these marl beds, although Qassam Barrani samples yielded rare planktonic foraminifera and benthonics, such as <u>Elphidium</u> sp., <u>Aurila</u> sp., rare trachyleberids; and small marine gastropods were also found. All these marl beds are associated with marine strata and it is therefore considered that they represent sheltered inter-shoal areas, rather than fluviatile or intertidal channels, as is the case with the San Leonardo marl bed.

4. Geological History of the Gebel Imbark Member

By the close of Tal Pictal Member times the area covered by the Maltese islands was a region of shallow seas, with carbonate mounds and patch reefs. Intense shallowing in western areas produced a submarine erosion surface upon which the oolite rich Tat Tomna Beds formed. It is considered that this extremely shallow environment was ideally suited to ooid growth in a tidal setting and gradually throughout the area oolite and pelletal shoals developed. Some, such as that in the Tat Tomna area, were controlled by ebb and flow wave effects, whereas others, possibly in slightly deeper water in eastern Gozo, were the product of transport by linguoid ripples.

The Tat Tomna Beds were drawn to a close by the development of large quantities of micrite, indicating that the Maltese area had been cut off from the influence of wave action, possibly by further uplift in the west. Within this new environment a thick sequence of micritic sediments developed in Malta and include a prominent stromatolite horizon. This appears to indicate that ultimately the micrite lagoon was brought into a supratidal environment, marking the closing stages of marine sedimentation in Malta. In Gozo, beds considered to belong to the Gebel Imbark Member show that a more vigorous environment still persisted there and algal rhodolites developed in the shallow seas. Only a few metres of sediment are preserved in these outliers and so the final stages of marine sedimentation are not seen.

If the San Leonardo Beds are related to this episode of deposition then they must represent the eastern margins of the depositional area. They may, however, correlate with a similar location during the deposition of the Ghar Lapsi Beds.

TABLE 5

Faunal and Floral List for the Upper Coralline Limestone

In compiling this list the following references have been consulted: Spratt (1843); Davidson (in Adams 1864); Wright (1855 and 1864); Duncan (1865); Fuchs (1874); Gregory (1890-91); Murray (1890); Roman and Roger (1939); Samsonoff (1917); Reed (1949); Withers (1953); and specimens housed in the British Museum (Natural History). All other data has been obtained during the present study.

Vertebrata

Bregmaceros albyi Sauvage.
Syngnathus sp.
Serranus sp.
Indet. Percoidea.
Indet. member of the Zeidae.
Carcarodon megalodon Agassiz.
Odontaspis sp.
Isurus sp.
Sparus sp.
Lamna sp.
Myliobatis sp.
Halitherium sp.
Cetacea vertebrae.

Echinodermata

Cidaris melitensis Wright.
Psammechinus duciei Wright.
Psammechinus scillae Wright.
Echinus tortonicus, Gregory.
Clypeaster altus Lamarck.
Clypeaster altus var. alto-costatus Lamarck.
Clypeaster marginatus Lamarck.
Clypeaster tauricus Desor.
Clypeaster reidi Wright.
Echinolampas hemisphaericus Gregory.
Echinolampas pignatarii Airaghi.
Echinolampas subpentagonalis Gregory.
Prenaster exentricus Wright.
Amblypygus melitensis Wright.
Spatangus delphinus Defrance.
Brissus depressus Defrance.
Brissus cylindricus Agassiz.
Brissus tuberculatus Wright.
Brissus latus Wright.
Brissus imbricatus Wright.
Brissus oblongus Wright.
Brissopsis duciei Wright.
Asteroidean dermal ossicles.

Gastropoda

Conus ventricosus.
Conus mercati.
Conus sp.
Ancillaria glandiformis.
Strombus coronatus. Defrance.
Fusus virgineus.
Fusus valenciennesi.
Murex trunculus.
Murex brandaris.

TABLE 5 (continued)

Pseudoliva brugadina.
Nassa prismaticum Brocchi.
Buccinum costulatum.
Buccinum phillipi.
Buccinum dujardini.
Terebra acuminata.
Pleurotoma granulato cincta.
Cerithium vulgatum.
Cerithium cf. varicosum.
Cerithium bronni.
Cerithium minutum.
Erato sp.?
Haliotis volhynica Eichwald.
Schilderia sp.?
Turritella vermicularis Brocchi.
Turritella riepelli.
Turritella turris Basterot.
Turritella sp.
Trochus patulus.
Trochus fanulum.
Bulla lignaria.
Natica millipunctata Lamarck.
Natica josephina.
Crepidula cochlearis.
Xenophoria sp.
Amnicola sp.
Indet. Capulid gastropods.
Indet. high spired gastropods.

Lamellibranchiata

Pecten beaudanti Bist.
Pecten senensis Tournour.
Pecten pandora Deshayes.
Pecten squamulos.
Pecten vigolenensis Simonelli.
Pecten solarium Lamarck.
Pecten varius Lamarck.
Pecten tournali.
Pecten besseri.
Pecten eligans.
Pecten substriatus.
Pecten reusii.
Pecten revolutus Michelotti.
Flabellipecten larteti Tournour.
Flabellipecten fraterculus Sowerby.
Aequipecten cristatum mut. badense Fontannes.
Chlamys (macrochlamis) latissima, Brocchi.
Chlamys scrabella Lamarck.
Chlamys (Amusiopecten) burdigalensis Lamarck.
Chlamys multistriatus Poli.
Ostrea edulis var. boblayei Linné.
Ostrea virleti Deshayes.
Ostrea plicatella.
Ostrea digitalina Eichwald.
Spondylus crassicosta Lamarck.
Spondylus quinquicostatus Deshayes.
Lima squamata Lamarck.
Lima sp.
Pinna sp.
Arca turonica Dujardine.

TABLE 5 (continued)

Arca fichtelii Deshayes.
Arca noe Pontlevoy.
Arca sp.
Glycimeris pilosus.
Glycimeris deshayesi (Mayer.)
Glycimeris obtusatus.
Gastrochaena squamulosa Desio.
Lithophaga lithophaga Linné.
Clavagella sp.
Venus multilamella.
Venus plicata.
Venus clathrata.
Tapes sallomacensis Fischer.
Tapes vetula, Basterot.
Lutraria lutraria Linné.
Lutraria oblonga.
Thracea pubescens Pulteney.
Panopea sp.
Cardita crassicosta Lamark.
Cardita scabricosta.
Cardita jouanneti.
Cardita partschi.
Cardita calyculata.
Chama gryphoides.
Chama pseudounicornis Sacco.
Tellina planata.
Tellina strohmayeri.
Capsa lacunosa Chemnitz.
Cardium hians Brocchi.
Cardium pectinatum.
Cardium multicostatum Brocchi.
Cardium turonicum.
Cardium moeschanum.
Cardium andreae Dujardine.
Lucina globulosa.
Lucina collumbella Lamark.
Lucina transversa.
Lucina haidingeri.
Lucina multilamellata Deshayes.
Loripes incrassata (Dubois.)

Decapoda

Callianassa sp.
Indet. Brachyura.
Necronectes schafferi.
Harpactocaranus cf.quadrilobatus Desmarest.
Scylla cf. serrata.

Cirripeda

Creusia cf. rangi.
Balanus sp.

Brachiopoda

Terebratula terebratula, Linné.
Aphelesia bipartita (Brocchi.)
Megathiris sp.
Argyrotheca sp.
Terebratulina caput-serpentis Linné.
Megerlia sp.

TABLE 5 (continued)

Ostracoda

Aurila sp.
Bairdia sp.
Cithereis sp.
trachyleberids.

Bryozoa

Rectorychocella sp.
Berinicea sp.
Cellaria sp.
Eschara monilifera.
Cellepora mammalata Busk.
Cellepora polythele Reus.
Cellepora parasitica Mich.
Cellepora sp.
Calpensia impressa Moll.
Calpensia sp.
Corymbopora sp.?
Vibracellina sp.
Hornera sp.
Membranipora sp.
Escharina sp.
Batipora sp.
Lichenopora spp.
Bicupularia sp.?
Escharoides sp.
Membraniporella sp.
Crisia spp.
Canda sp.
Retepora sp.
Idmonia sp.
Scrupocellaria sp.
Entalopora sp.
Cribrilina sp.
Tubucellaria sp.
Sertella sp.
Cribrilaria sp.
Porella sp.
Lunulitoform sp.

Anthozoa

Stylocoenia lobatorotunda Michelin.
Dendrophyllia irregularis. Blainville.
Porites incrustans Defrance.
Astraea (Heliastraea) sp.
Stylastraea sp.
Tabellastraea cf.reussiana ME.and H.
Coral genus A, sp. b.
Heliastraea raulini ME.and H.

Miscellaneous

Entobia cf. cretacea Portlock.
Entobia sp.
Serpula sp.
Creusia rangii Desmoulins.
Calcareous sponge triads.
Protula sp.
Caegichnus?
Alukichnus?

TABLE 5 (continued)

pteridophyte spores
grass pollen.

Foraminifera

Biloculina sp.
Spiroloculina spp.
Miliolina sp.
Alveolina sp.
Textularia sp.
Verneiulina sp.
Tritaxia sp.?
Bolivina sp.?
Pulvinulina spp.
Nonionina spp.
Polystomella spp.
Amphistegina sp.?
Caluvulina sp.?
Lagena sp.?
Nodosaria sp.
Polymorphina spp.
Globigerina spp.
Discorbina spp.
Planorbulina spp.
Truncatulina spp.
Rotalia sp.?
Elphidium sp.
Cibicides sp.
Heterostegina depressa d'Orbigny.
Anomalina sp.
Neoalveolina melo Fichtell and Moll.
Pyrgo sp.

Coralline Algae

Lithophyllum destefanii Samsonoff.
Lithophyllum sp.
Mesophyllum sp.
Lithoporella sp.
Lithothamnion sp.
Archaeolithothamnion sp.
Jania sp.
Corallina sp.
Halimeda sp.
Gyrogonites of Charophyta.

Other Algae

Stromatolites.

Of all the unlocated specimens in the list by far the greater part are most likely to have been collected from the richly fossiliferous Tal Pictal Beds. A large number of the pectinids are probably from the Ghajn Melel Member.

MODAL ANALYSIS OF TAL PICTAL & TAT TOMNA BEDS

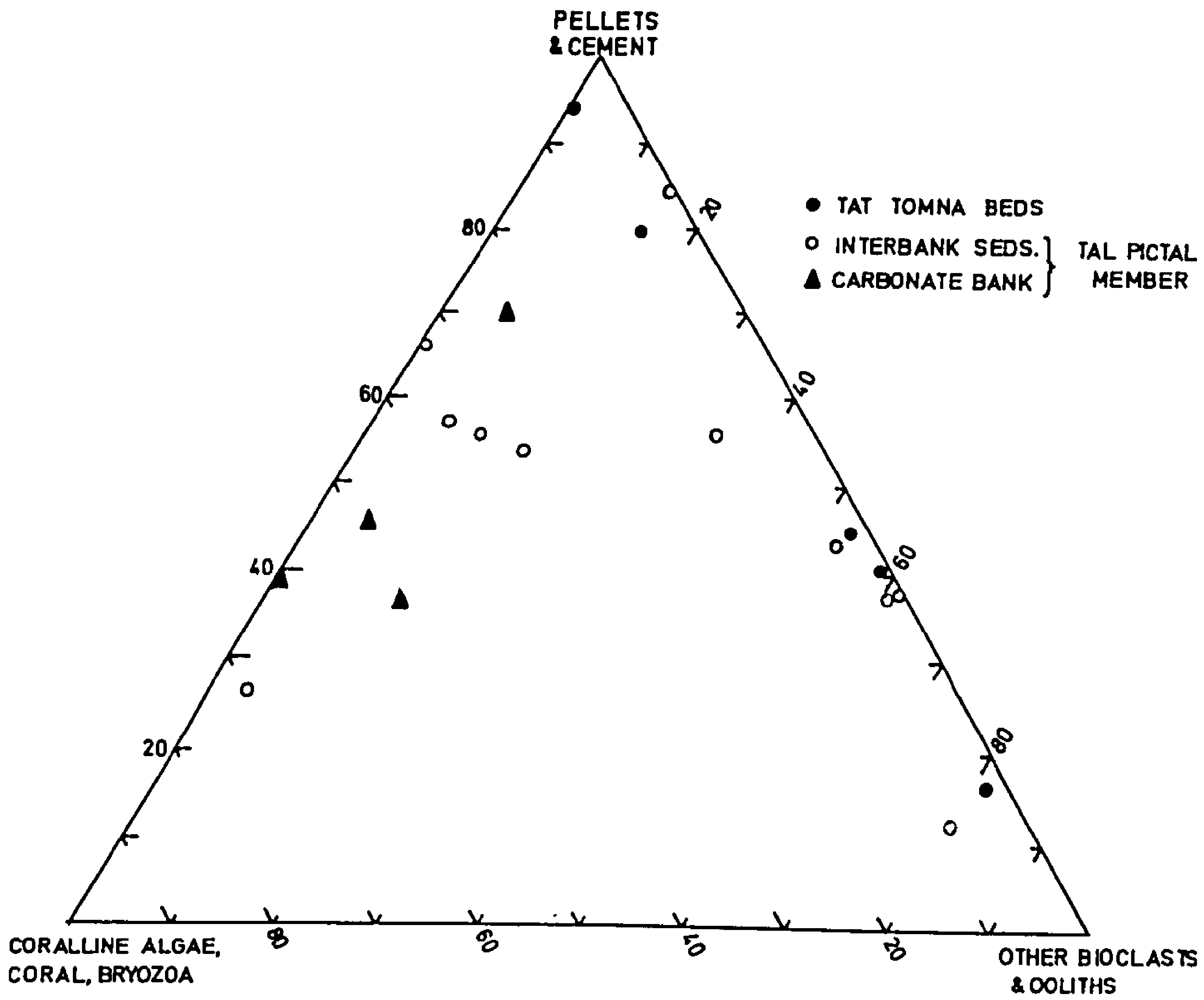
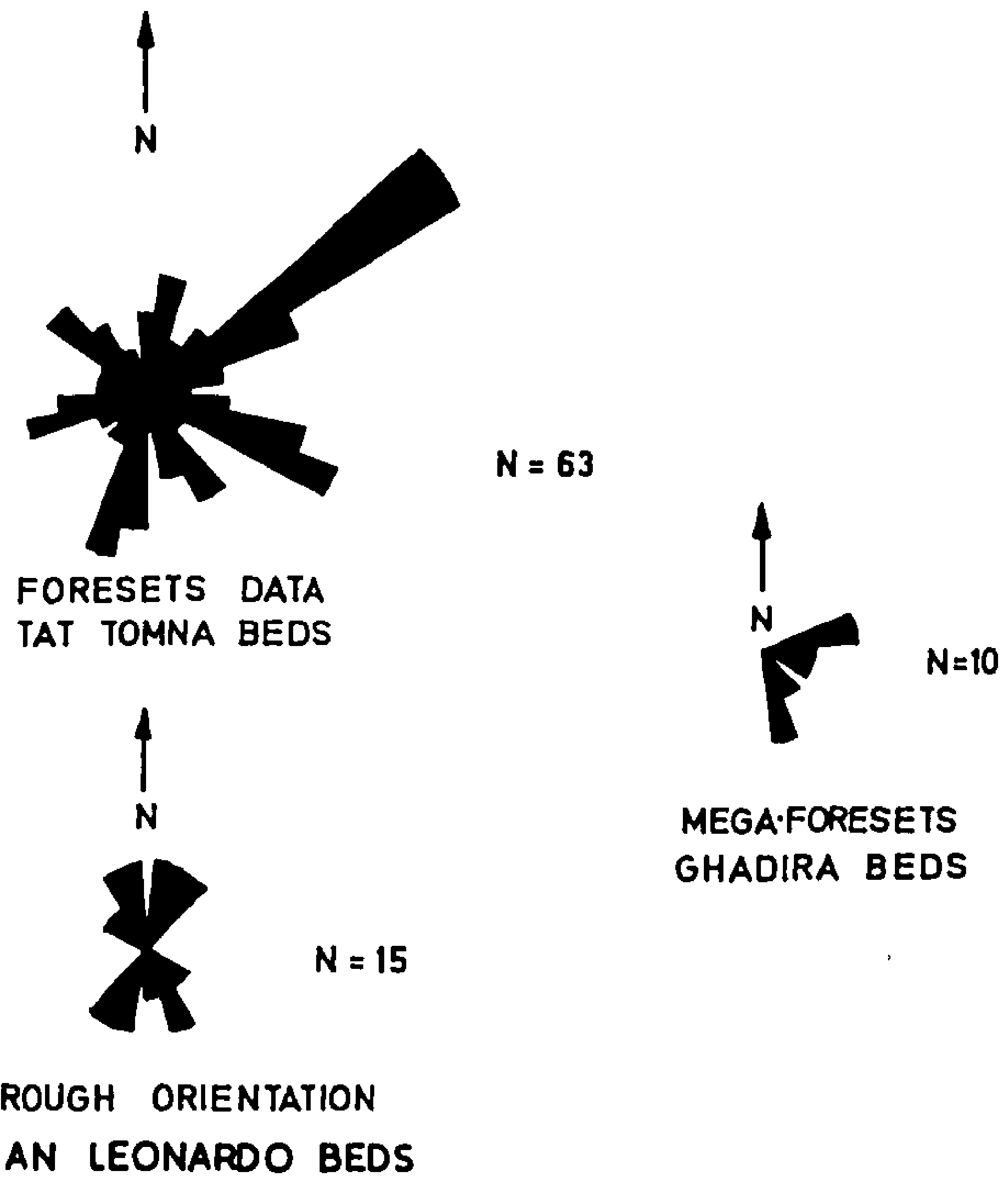


Fig. 26a



FORESETS DATA
TAT TOMNA BEDS

MEGA-FORESETS
GHADIRA BEDS

TROUGH ORIENTATION
SAN LEONARDO BEDS

DIRECTIONAL DATA FROM THE UPPER CORALLINE LIMESTONE FORMATION

Fig. 26b

SYNTHESIS OF ENVIRONMENTS OF THE TOP UPPER CORALLINE LST.

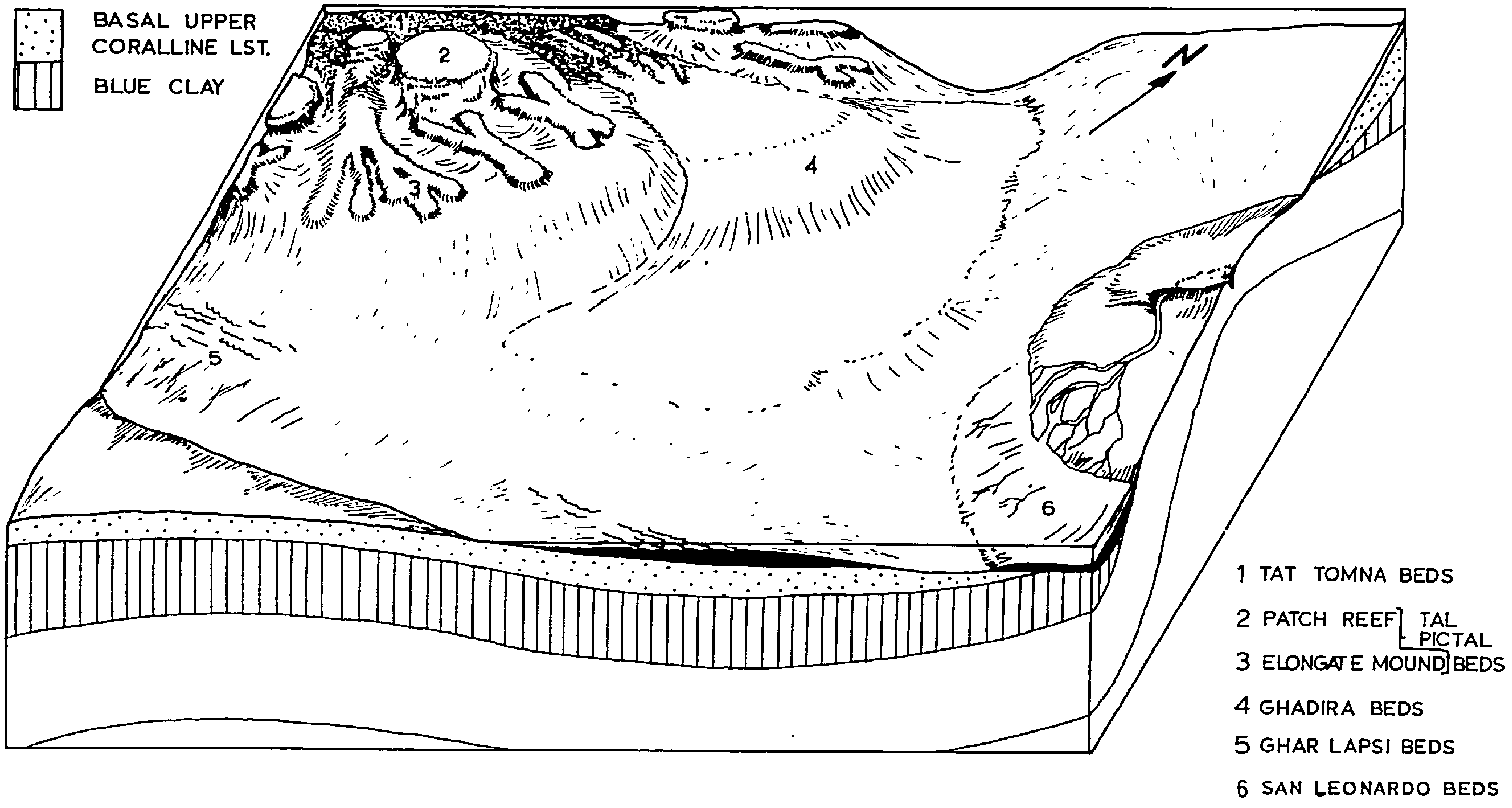


Fig. 27

CHAPTER 10

ANALYSIS OF THE TEREBRATULA-APHELESIA BED

(a) General

Within the basal Upper Coralline Limestone of both Malta and Gozo a prominent shell bed occurs (See Chapter 7). This bed, varies in thickness from 0.2 metre to 3 metres and contains the brachiopods Terebratula terebratula Linné and Aphelesia bipartita (Brocchi). The brachiopods had both been recorded previously under the names Terebratula sinuosa and Rhynchonella bipartita by Davidson (1864), but the regional distribution of the bed had never before been appreciated. The bed generally occurs in soft, marly, algal limestones in western Malta and eastern Gozo, but may also be in "Greensand" or yellow micrite (Chapter 7). In western Gozo, beds believed to be of comparable age to the brachiopod bed are represented in the Ghajn Melel Beds by biosparites containing Chlamys (Macroclamis) latissima Brocchi, which occurs in a restricted vertical range within these beds. This correlation is based on the restricted range of C. latissima in western areas of the Coralline Algal bioherm, where it occurs in association with Ostrea virleti Deshayes, either within the brachiopod bed or not more than 2 metres above that bed. These relationships are depicted in Figs. 22b and 24b.

The friable condition of the sediments, together with their highly fossiliferous nature, particularly in the case of bryozoans, facilitated detailed biotal analysis of this bed. The bed was sampled at 39 localities throughout the islands with a further 10 samples being taken for stratigraphic control purposes. Each 0.5 kilogram sample was boiled in sodium hydroxide and sieved in 5, 10, 20, 40 and 60 mesh sieves, and fines were examined. All brachiopods from each sample were collected and counts of bryozoan growth-forms were made from each sieve size. The relative abundance of all other fossil fragments was also assessed.

Generally speaking, the samples broke down relatively quickly, though prolonged boiling in well cemented samples caused some damage to components.

It was found difficult to record accurately the number of shell casts of the once aragonitic bivalves, although attempts were made to estimate these components prior to boiling. The reason for counting material from all sieve mesh sizes was that cellariform bryozoan form in particular tended to separate out in the 60 mesh, whereas encrusters were generally collected in the 10 and 20 mesh sizes. An additional sieve of 5 mesh grade was used to collect all undegraded material, mainly rhodolites and entrapped sediment. This was weighed and subsequently taken into consideration when the total numbers of specimens per locality were obtained.

b. Bryozoan Growthform Study

(i) General

Although initially the Terebratula-Aphelesia Bed study involved brachiopods only, it was extended to bryozoan growth-forms once the significance of these as environmental indicators was realised. Stach (1936) was the first to appreciate that bryozoa could be divided into a number of different growth-forms, each of which was constant and diagnostic of a particular range of conditions. This work was conducted on the Miocene strata in the Geelong district of Victoria, Australia. These growth-forms and their inter-relationships with set environments were further verified by Laagaij and Gautier (1965) in their study of the bryozoan assemblages of the marine sediments of the Rhone Delta, France. Since this time further work by Askern (1968), Schopf (1969), Cheetham (1971), and Annoscia and Fierro (1973) has clearly shown that growth-form studies are applicable to all suitable samples at least from the Cretaceous to the present day.

In the present study the emphasis has been placed on the encrusters, as they are not only diagnostic of shallow conditions, but show least tendency to be transported subsequent to death, unlike the vinculariform and cellariform groups which are readily transported upon death. All other major forms, however, have been accurately studied and conclusions drawn from this bed have been freely applied to all the Oligo-Miocene formations of the Maltese Islands.

For each sample the total numbers of each growth-form were recorded and were converted to percentages of the total bryozoans per sample. The major genera were also identified (see faunal list in Chapter 7). The growth-forms are subdivided into the following types:

a. Membraniporiform A
b. Celleporiform
c. Vinculariform
d. Cellariform

a. Membraniporiform A Growth-form

(i) General

This is an encrusting membraniporiform bryozoa typified by a calcified dorsal wall (Plate 18d). It is most characteristic of areas where disposition is slow or absent, but is adapted for life in the littoral and sublittoral zones (Stach 1936, p.61), and generally encrusts non-flexible substrates. It is typical of depths less than 40 metres (Lagaaij and Gautier 1965, p.51).

(ii) Distribution

Figure 28a indicates the percentage distribution of this growth-form. If this figure is compared with the biofacies map (Fig.22b) then it is seen that the Coralline Algal Bioherm supports the highest percentages, particularly the eastern margins of the bioherm in Malta, and with values falling away rapidly both east and west of the bioherm. There is a marked absence of species from the Ghajn Melel Member and from the Mtarfa Beds.

b. Celleporiform Growth-form

(i) General

This is the second type of encrusting bryozoa present and is typified by irregularly heaped individuals, frequently forming multilamellar masses (Plate 18f). Lagaaij and Gautier (1965, p.52) consider this form to be typical of littoral and sub-littoral conditions where no active transport is taking place. They frequently encrust flexible substrates.

(ii) Distribution

Fig.28b illustrates the percentage distribution. Again it is noted that the highest densities are located on the Coralline Algal Bioherm and at about the same situations as for the membraniporiform A group. Because of the close relationship between these two growth-form types, together with their comparable optimum habitat requirements, it has been decided to place them together into one group entitled "encrusters" (Fig.29a). This figure clearly indicates the close relationship between the bryozoa and the Coralline Algal Bioherm, even to the extent of a reduction in the number of encrusters associated with the break in continuity of the bioherm in central western Malta (Compare with Fig.22b). It is noted that, besides the previously recorded areas of low colonisation, the area of grey marly algal biomicrites, comprising the western side of the bioherm in central-western Malta, is characterised by under 25% of encrusters. The western boundary of the distribution in Gozo is apparently affected by the tongue-like extention into the Coralline Algal bioherm, of the Ghajn Melel Member, the latter of which in this area of Gozo contains a dominant eschariform bryozoan development which is typical of shallow water conditions.

c. Vinculariform Growth-form

(i) General

These bryozoans consist of erect dichotomously branched, sub-cylindrical growth-forms attached by a calcareous base to a solid stratum (Plate 18e). Stach (1936, p.62) observed that this group was "adapted for life in deep and sheltered waters where wave action is absent and currents scarcely active. This group typifies growth in quiet water." The depth range is 40-90 metres (Lagaaij and Gautier 1965, p.51).

(ii) Distribution

Although the distribution of this group (Fig.29b) appears to be similar to the encrusters, careful examination shows that the vinculariform growth habit is concentrated on the eastern side of the Coralline Algal Bioherm. It reaches the highest densities just off the bioherm on its eastern side, diminishing away rapidly to zero in eastern Malta. The group is also well represented in the grey marly algal biomicrite area to the west of the Coralline Algal Bioherm in western Malta. As a growth-form this group is poorly represented and rarely forms more than 25% of the sample.

d. Cellariform Growth-form

(i) General

This term was also first applied by Stach (1936, p.63) to designate erect flexible jointed colonies of cylindrical calcareous bryozoans attached to the substrate by means of rootlets. According to Stach (1936, p.63) "This type is adapted for life in the littoral zone where algae usually form the basis for attachment and the effect of wave action is overcome by the articulation of the long narrow internodes" (Plate 18c). "Occasionally this form extends to greater depths." Lagaaij and Gautier (1965, p.56) further pointed out that the ability of the articulated internodes passively to shake off settling clay particles probably enables this group to colonise turbid waters. Today (Gautier, 1961, p.352) this form is most typical of moderate depths on a variety of substrates.

(ii) Distribution

Examination of Fig.30a reveals that the distribution of this growth-form is diametrically opposed to that of the encrusters, being dominant in the eastern areas of Malta and to a lesser extent eastern Gozo. Samples from western Gozo yield no individuals, as is the case with the crestal area of the Coralline Algal Bioherm in central western Malta. In fact, comparison of Figs.30a and 29a clearly show the opposing distribution, together with the fact that the grey marly algal biomicrite area of Fig.22b supports up to 75% cellariform growth-form bryozoans by total count. In eastern Malta up to 100% of the sample is composed of this group, though it must be stated that in these samples very few fragments are recorded anyway.

e. Correlation of Growth-form with Environment

If the total number of bryozoan species (Fig.30b), exclusive of rare specimens occurring less than twice per sample, is plotted then a bryozoan species distribution results which in many ways further reflects the overall form of the Coralline Algal Bioherm. The highest numbers of species occur on the rhodolite areas of the bioherm,such as in north-eastern Gozo and west central Malta. The glauconitic beds of eastern Malta (Fig.22b) contain a fauna of basal Mtarfa Bed age, and exhibit less than five species per sample, as do the biosparites and lithoclast biosparites of western Gozo. There is also a significant reduction in species numbers in the southern part of the marly grey algal biomicrite area to the west of the bioherm in Malta.

On the basis of bryozoan growth-form distributions the Terebratula-Aphelesia Bed can be divided into four biofacies which are, east to west:

(i) Cellariform biofacies (1 of Fig.31)
(ii) Vinculariform biofacies (2)
(iii) Encrusters biofacies (3)
(iv) Cellariform and Vinculariform Biofacies (4)

(i) Cellariform biofacies

This biofacies occupies eastern Malta and the eastern tip of Gozo (Fig.31a) and is typified by Cellaria sp. and Crisia sp. The sediments in which these fossils occur are extensively reworked glauconite biomicrites, typical of moderately high energy conditions. The bryozoans also indicate high turbulence conditions in the sub-littoral zone. It is therefore concluded that this biofacies is one of extremely shallow turbulent water, possibly less than 20 metres in depth.

(ii) Vinculariform biofacies

Although rarely more than 25% of the growth-forms present within this environment are vinculariform types the comparatively low counts of encrusters, when compared with the bioherm, suggests that quieter conditions prevailed on the eastern side of the bioherm. These sediments frequently show isolated rhodolites set in an abundance of yellow micrite and are transitional with the Mtarfa Beds. It has been established previously that there was a dominant westerly current affecting the Maltese area throughout Miocene times and it is suggested that this current was operative at this time also. The vinculariform biofacies represents a narrow sheltered belt situated immediately to the east of the bioherm, in which fine sediments were able to periodically settle and a sheltered environment was provided for the vinculariform bryozoans. A depth range of 20-45 metres is considered reasonable. The biofacies encroaches onto the bioherm above the '2' in Fig.31a, with the development of a sub-facies of encrusters and vinculariform bryozoan growth-forms. It is considered to be a slightly lower energy sub-facies than the bioherm crest. This is supported by a similar interpretation by Annoscia and Fierro (1973, p.59) in their study of living bryozoans in the Golfo dell' Asinari, Sardinia.

(iii) Encrusters biofacies

This biofacies extends from south-eastern Gozo through the western extremeties of Malta and extends inland about the crestal bioherm area, possibly with an extention in the Ghar Lapsi area. The dominant fauna consists of Membraniporiform A growth-forms with celleporiform types to a lesser extent. Together these growth-forms comprise up to 80% of the samples from these areas. This is also the area of greatest species diversity. Present day bryozoan species depth ranges from the western Mediterranean (Schopf 1969, Fig.5) indicate that the highest species diversity occurs at depths of about 50 metres, which is considered as the possible lower limit of depth range anticipated. Values obtained from the <u>Lithophyllum</u> rhodolite growth-forms suggest depths to about 45 metres (Johnson 1955, p.16-17 in a study of the genus <u>Lithophyllum</u>), rhodolites also being recorded near Bermuda (Parker 1957, p.2436) within the range 18 to 91 metres. The association of reteporiform bryozoans with this biofacies in central-western Malta, based on Stach's interpretation, also suggests high energy, though this is not in line with the interpretation of Lagaaij and Gautier (1965, p.55), and Cooke (personal communication), who consider this fenestrate group to be more typical of calmer or deeper areas. The conclusion, however, is that this biofacies is characteristic of depths in the order of 20-50 metres on the crestal areas of a Lithophyllum rhodolite bioherm as other evidence, previously stated, appears to be consistant with Stach's views in this particular case.

(iv) Cellariform and Vinculariform biofacies

This mixed facies is restricted to central-western Malta, west of the Coralline Algal Bioherm, and approximately conforms to the grey algal biomicrites of Fig.22b. This apparently contrasting association of high energy cellariform types and low energy vinculariform types is acceptable if the marly nature of the sediments is considered. This sediment suggests a low energy environment and is associated with lichenoid growths of Lithophyllum destephanii. This appears to be the calmer water growth-form of the L.destephanii rhodolites of the shallower areas of the bioherm and, in fact, many of the bioherm crest rhodolites show a laminar lichenoidean nucleus confirming this. It is believed that this environment was well suited both to the cellariform bryozoans, as the articulated nature of their internodes enabled a passive sheading of clay sediment from the colonies, and to the quiet water loving vinculariform types. On the basis of brachiopod depth ranges, to be discussed later, but mainly on the inter-relationship of this biofacies with the other three, it is believed that a depth range of 50-65 metres would be in order. This interpretation is again compatible with that of Annoscia and Fierro (1973) obtained from their recent bryozoan study around Sardinia, in which an identical association was interpreted as defining an area of rare wave and current activity.

(v) Conclusions

The difficulty of breaking down samples from parts of eastern Gozo partly accounts for the general lack of specimens in certain samples, however, there does appear to be a real reduction in specimen numbers on the western side of the bioherm in Gozo. Ultimately the bioherm is replaced westwards by the Ghajn Melel Beds, and the Terebratula-Aphelesia Bed is apparently replaced by scattered Chlamys latissima.

The ecological interpretation of the environment during the time of deposition of the Terebratula-Aphelesia Bed is as follows:

A broad but shallow north-south depression centred on Gozo and western Malta, possibly a continuation of the Blue Clay depression,extended through the islands (Fig.24a). Initially the prevailing westerly current transported reworked bioclasts, intraclasts and lithoclasts from areas of erosion to the west,into parts of the eastern side of this structure in Malta, probably settling out of suspension soon after entering the depression. In the western side of the depression in Gozo, believed to be an area protected from the currents by depth, a thriving population of Heterostegina sp. developed in water depths of 10-50 metres but contained few bryozoans (Ghajn Melel Beds). This development does not appear to have occurred in Malta, possibly indicating that the basin was imperfectly formed. Here, especially towards the south, clay suspensions were transported eastwards to settle out in deeper calm water at the foot of the Coralline Algal Bioherm (biofacies 4, Fig.31b). After passing over the basinal depression the prevailing westerly current is believed to have influenced sedimentation on the eastern side of the basin, causing high energy conditions along the rim. This location was favoured as the initial location of colonisation of the Coralline Algal Bioherm. Initially only isolated patches developed, now appearing on isopachyte maps as basins due to compaction effects, but these later spread along the entire rim area (Fig.23). At first, part of this bioherm was below wave base and the effect of current action, and widespread grey marly micrites identical to biofacies 4 were deposited, but as the bioherm increased in extent and amplitude turbulence affected all areas of the structure (biofacies 3, Fig.31b) except biofacies 4, which remained below the influences of this.

On the leeward side of the bioherm sheltered conditions prevailed and as the westerly current passed over the bioherm crest a certain amount of fine sediment settled out of suspension (biofacies 2, Fig.31b). This is the area of initial development of the Mtarfa Beds and in later times these conditions were to extend throughout eastern areas of both main islands. It is believed that the area furthest away from the bioherm, on the eastern side of Malta, was an area of shelving platform characterised by very shallow water depths. Upon reaching this area (biofacies 1, Figs.31a,b.) the prevailing westerly currents probably created intense turbulence and even extensive reworking of the sediments (now an intimate mixture of Greensand and Mtarfa Beds). In such a high energy regime only the cellariform bryozoans, with their articulated internodes, would survive, and even these would become disarticulated and reworked after death. This is substantiated by the worn nature of both bryozoa and other fossil fragments, particularly in samples from the eastern extremity of outcrop.

2. Brachiopods Associated with the Terebratula-Aphelesia Bed

(i) General

The Terebratula-Aphelesia Bed is mainly composed of the articulated and disarticulated shells of Terebratula terebratula Linné. These are frequently found foramen down in what might possibly be life positions. The bed is of fairly uniform thickness over most areas, and is continuous from the western side of the Coralline Algal Bioherm to the most easterly outcrops of the Mtarfa Beds and Greensand of both main islands. Only Terebratula is found in both bioherm and eastern areas of the Upper Coralline Limestone outcrops. Four main brachiopod species occur in this facies independent bed, which also appears to be a probable time horizon.

a. Terebratula terebatula, Linné.
b. Aphelesia bipartita, (Brocchi).
c. Megathiris sp.
d. Argyrotheca sp.

a. *Terebratula terebratula* Linné.

(i) General

Adults of this species vary between approximately 15mm. and 67mm. in length and are characterised by a strongly biplicate sinus, large circular collared foramen and thick shell (Plate 17a). No marked variance in length, width or inflation was identified when adults from the bioherm were compared with those from biofacies 1 in Fig.31. Juveniles are similar in overall form to the adults, but display an open deltidial region and may be as little as 0.2mm. in length (Plate 17c). Juvenile brachiopods are depicted on Fig.33b to illustrate size ranges, and major axis line $[y = (0.792)x - 0.057]$ with a standard error of A of 0.013 and B of 0.110.

(ii) Distribution

If the number of individuals per sample is studied it is seen that the juveniles are entirely restricted to the higher flanks of the Coralline Algal Bioherm, up to 20 individuals occurring in some samples (Fig.32a). Almost all juveniles are articulated. Adults, although distributed throughout both bioherm and all areas to the east, show a wide variation in size for the fully grown form. An average length, based on the mean length of a minimum of 10 adults from a 1 metre length of *Terebratula-Aphelesia* Bed, of less than 40mm. is found for all areas of the bioherm (Fig.32b), whereas sizes in excess of 50mm. are common in the specimens from areas east of the bioherm. Within the bioherm the highest values obtained were associated with the Ghajn Melel Beds facies north of Dingli, Malta, which is believed to represent an area of reworking associated with some form of current flow at the foot of the rhodolite bioherm area (see Fig.22b in the area designated brown calcisiltite). Plate 17a(i) shows a typical adult from the cellariform bryozoan biofacies east of the bioherm, 17a(ii) shows one typical of the cellariform and vinculariform biofacies, and 17a(iii) one typical of the encrusters biofacies of the bioherm flanks. Studies of articulation ratios show that there is a marked increase in disarticulation from west to east, being about 50% on the Coralline Algal Bioherm, but increasing to 100% in samples from eastern Malta.

When the total numbers of individuals obtained from each locality is plotted as a percentage of the total brachiopod count for that sample, the inter-relationships between the four species become apparent, Fig.33a showing both adult and juveniles. When this figure is compared with Fig. 22b and 31a, it is seen that there is a strong tendency for the highest Terebratula percentages to lie east of the bioherm in both islands. Biofacies 3, on the crestal areas of the bioherm, is almost entirely devoid of this species , as to a lesser extent is the grey marly algal biomicrite areas (Fig.31a, biofacies 4).

Figure 34a shows the positively skewed nature of Terebratula growth size distribution, over 66% of all specimens measured being juveniles under 4.5mm in length. This type of distribution is typical of present day brachiopods in which there is a high infant mortality. Craig and Oertel (1966) consider that any peaks appearing in the fossil population are a reflection of the original living population distribution. They also consider that positively skewed values best fit a model of constant growth with decreasing mortality. The values obtained for Terebratula terebratula may be directly compared with those of Terebratula inconspicua (Percival 1944), in which it was found that 66% of all individuals belonged to the first year class and with only 25% belonging to the third year class. It may possibly be that the sub-4.5mm. group of Terebratula terebratula reflects a comparable class grouping to the first year class of Percival. With these points in mind it is now easier to appreciate the population structure of Terebratula on the bioherm, in which there is a high spat settling rate in favourable areas, but with high juvenile mortality occurring soon afterwards, possibly as a result of inter-individual competition, competition with other brachiopods adapted to similar ecological niches such as Megathiris, and predation. The few individuals which do survive the juvenile stage appear to continue to maturity, though they attain a smaller size than their counterparts east of the bioherm.

In the area of biofacies 1, east of the bioherm, juveniles are never present in the Terebratula population and adults are larger and thicker shelled than their contemporaries on the bioherm. Ager (1967, p.159) states that brachiopods with robust shells are adapted to the highest energy conditions, and in addition (Ager 1965, p.146) further states that strongly biplicate forms occur in the shallowest water attaining a maximum size (p.151) in optimum conditions. All the evidence available here suggests that biofacies 1 provides the best conditions for Terebratula terebratula, but the absence of juveniles disagrees strongly.

(iii) Environmental Requirements for the Species

Today the greatest proportion of all known brachiopods occur intertidally down to 600ft. (183 metres)(Schuchert 1911, p.260-61). Terebratula sp. are tolerant of minimal turbidity and not too much wave action (Rudwick 1962).

Based on bryozoan studies and coralline algal growth-forms it is considered that within the bioherm. depth ranges of 40-50 metres appear to be most favoured. Here the individuals are sheltered from the strongest effects of current action from the prevailing westerly currents, yet may still obtain an efficient supply of waterborne nutrient. Although adult forms can probably tolerate a small amount of clay sedimentation, the juveniles are particularly sensitive to this and could easily be smothered. It is believed for this reason that juveniles are rare or absent from biofacies 4 (Vinculariform and Cellariform biofacies) to the west of the bioherm. The intense reworking of sediments in biofacies 1 (Cellariform biofacies with a possible depth of less than 20m.) was almost certainly too vigorous for spat and diminutive brachiopods to survive, even though there was a high chance of spat being carried eastwards with the water current. Periodic episodes of amelioration of strong currents possibly enabled limited colonisation of juvenile brachiopods and other biota, such as Dentalium sp. Providing that these conditions were maintained for at least the first year or so the juveniles would obtain a foothold in the environment and would have a moderate chance of reaching the adult stage. Re-establishment of high energy conditions within biofacies 1, subsequent to this, would result in the removal of all small species, and juvenile specimens of Terebratula terebratula, although sub-mature forms of Terebratula and adults would be able to survive the rigorous environment, developing thick shells to counteract the conditions. The means by which adult Terebratula was attached to the shifting substrate are difficult to appreciate as there are no large objects in the sediments of this biofacies onto which these forms could secure a foothold, whereas specimens on the bioherm could attach themselves to coralline algae or bryozoans. This problem has been partly resolved by examination of the specimen from biofacies 1 in Plate. 17a(i), which bears marks of attachment on the posterior lefthand side of the brachial valve consistent with those described by Brömley and Surlyk (1973) from the recent sediments of the Norwegian Sea, and from Cretaceous sediments. These oval pitted areas are believed to result from the attachment of the pedicle of another brachiopod, hence it would appear that anchorage of Terebratula terebratula in biofacies 1 was obtained by individuals attaching themselves to each other in small clumps.

Once security had been established and the brachiopods had reached maturity the lack of competition from other allied forms, together with the plentiful supply of nutrients brought by the westerly currents, would ensure that brachiopods within this environment would become more robust than their counterparts on the bioherm.

b. Aphelesia bipartita (Brocchi)

(i) General

This rhynchonellid brachiopod is characterised by a square shaped shallow sinus, high inflation and an arcuate beak (Plate 17b). Although the adult forms are clearly distinguishable from Terebratula in their more triangular outline and tapering beak, juveniles are superficially identical in both species. Well preserved specimens, however, show that juvenile Aphelesia bipartita is identified by a very elongated open deltidial area

(Plate 17d) and by the development of alar projections (Plate 17e) on the margins of the deltidial area closest to the hinge, which extend laterally as two concave triangular platforms. Vestages of these structures are to be seen on adult specimens. Collected specimens vary in length from 0.2mm. to 19mm., the range of sizes being depicted in Fig.35b. Juveniles generate a major axis line of $y = (0.784)x + 0.5$ with standard error for A of 0.057 and B, 0.269. The major axis for adults is $[y = (0.629)x + 3.782]$ with a standard error of A, 0.105 and B, 1.874. This discrepancy reflects an acceleration of growth of the length parameter during adult life.

(ii) Distribution

With the exception of Gozo, all areas containing juvenile forms also yield adults. Two major areas of juvenile development occur, one centred on the Gnejna area of Malta (Fig.34b), associated with biofacies 3 (Encrusters biofacies) of Fig.31a, and the other centred on biofacies 3, north of Dingli. In both cases total numbers are now suggesting that this uncommon species is not occupying ideal conditions for its development. Fig.35a illustrates a comparable distribution based on the percentages of Aphelesia in each sample including adults, compared with other species. Again there is a high concentration in biofacies 3 areas of Malta, but with a small development also in northern Gozo.

Although total numbers are small, the same positively skewed population distribution recognised in Terebratula appears to apply to Aphelesia (Fig. 34a), suggesting that comparable growth factors hold true for both species. The low inflation of several adults in the graph are the result of crushing during compaction of the rock. The lack of individuals in the 5mm. to 12mm. length division is also comparable to the graph of Terebratula and is almost certainly a reflection of the number of specimens that survive the juvenile stage and continue to maturity.

(iii) Environmental Requirements for the Species

This species appears to be very demanding in its location, which is always within the bioherm area and also appears to be centrally positioned in the area of maximum energy and shallowest depth (biofacies 3). It is therefore concluded that Aphelesia bipartita is best suited to depths shallower than 30 metres, in situations open to the influence of the dominant westerly current. The adults in northern Gozo do not entirely conform to this environment and are found in more sheltered marginal areas. It is uncertain whether this environment is sheltered as a result of greater depth, or whether it is a shallow environment protected by a positive feature, such as a shoal area within the Ghajn Melel Beds. The latter have been recognised in this area on the basis of ichnofauna data.

c. Megathiris sp.

(i) General

These diminutive biconvex brachiopods are characterised by a smooth shell surface and very shallow sinus fold. They bear disjunct deltidial plates and a sub-mesothyridid foramen (Plate 18b). The species bears a short crura, consisting of two descending branches which are free near the anterior but are attached to the median septum. These branches have not been seen during the present study, though the attachment points are clearly visible. Specimens range in length from 0.4 to 4.1mm. (Fig.37a) and generate a major axis line of $y = (1.116)x - 0.144$, with a standard error for A of 0.033 and B of 0.332.

Over 90% of all specimens collected were found to be articulated. This genus, Argyrotheca, and Megerlia appear to have been totally confused by Davidson (in Adams 1864). The importance of Megerlia was overestimated and both Argyrotheca and Megathiris were described together under the name Argiope decollata Chemnitz. Nomenclatorial confusion still exists with regard to the specific names of the Maltese Argyrotheca and Megathiris. The specimens under consideration are the same species as those of B57761-72, housed in the British Museum (Natural History).

(ii) Distribution

The highest numbers of individuals recorded per sample are from northern

Malta and south-eastern Gozo (Fig.36a), being over 20 per sample. A further area of over 20 per sample occurs associated with the encrusters biofacies of central-western Malta, with lower numbers occurring at points along the western coast of Malta. When these occurrences are plotted as part of the brachiopod community (Fig.36b and Fig.38b) a similar distribution is seen, but with westerly increasing values in northern Malta and Gozo.

If the population structure is examined both for individual localities and for the total specimen count (Fig.37a), it is apparent that although there is a strongly positively skewed distribution, both adults and juveniles are similar in overall size and do not exhibit the lack of individuals in the intermediate age groups seen in Terebratula and Aphelesia. This species of brachiopod shows many neotonous characteristics. The population structure strongly suggests that this species is characterised by adults which live a comparatively short life span when compared with other groups. The conclusion drawn is similar to that of Surlyk (1972, p.30) in his study of Maastrichtian brachiopods in Denmark, namely, that there is a selectional advantage in short lived forms which become sexually mature at an early age. These forms are most characteristic of situations susceptible to catastrophe, resulting in this case either from fluctuating rates of sedimentation or variable current strengths.

(iii) Environmental Requirements for the Species

Like Aphelesia, this species is entirely restricted to the bioherm, but is not so closely associated with the highest energy areas. Generally speaking it flanks the areas of Aphelesia on the bioherm crest of biofacies 3, but is also prominent in biofacies 4 (grey marly algal biomicrites), the northern flanks of the encrusters area in eastern Gozo, and northern Malta. The conclusion is that the species prefers fairly high energy conditions in estimated depths of 30-65 metres. In the algal micrite area, where catastrophe is mainly the result of periodic high clay sedimentation rates in a depth of 50-65 metres, the species also co-exists with Argyrotheca. These values are near the minimum end of the depth range of recent Aegean species

(32-260m, Elliott 1965, p.831) although the species would still find conditions favourable.

d. Argyrotheca sp.

(i) General

This second species of small brachiopod is characterised by a similar outline form to Megathiris, but with a longer hinge and multiplicate biconvex valves making some specimens resemble the Palaeozoic Spirifer (Plate 18a). The beak is fairly short and the foramen wide. The deltidial plates are sub-mesothiridid and the crura are separate, consisting of a short loop of two descending branches which converge anteriorly to join the end of the median septum. Juveniles and adults are always found together, the former being 0.75mm. in length or more, and adults averaging 4.5mm. in length, though some attain a length of over 7mm. These are displayed in Fig.37a. This shows the close relationship between Argyrotheca and Megathiris. The major axis for Argyrotheca, $y = (1.116)x - 0.144$ with a standard error of A, of 0.016, and of B, 0.167, is almost identical to that for Megathiris, though the width co-ordinates are displaced, representing a comparatively wider dimension per unit length of valve than for the latter species. The species under consideration apparently most closely conforms to the recent species, Argyrotheca cuneata Risso, but is also identical to B.M.N.H. specimens B85532-52.

(ii) Distribution

The distribution of specimens by numbers per locality (Fig.37b) superficially resembles that for Megathiris, with highest values being obtained from bioherm localities in eastern Gozo and central-western Malta, though it must be pointed out that the total numbers of specimens collected for this species (105) is far lower than for Megathiris (257). This suggests that conditions were not ideal for Argyrotheca, except possibly in Gozo. The percentage distribution maps (Fig.38a and 38b) indicate that the species is best suited to areas of biofacies 2 (Vinculariform biofacies) in north-eastern Gozo, and to combinations of biofacies 2 and 4 in central-western Malta. The north-eastern area of Gozo (biofacies 2) appears to be most favourable.

Fig.37a illustrates the same population structure as that for Megathiris, apart from the north-eastern Gozo adults, which plot at the top right hand end of the graph. The species also shows neotonous characteristics, suggesting that it may also be well suited for unstable environments. Studies of depth ranges of the modern Argyrotheca decollata (Davidson 1877, p.7), a Mediterranean species, are 20-60 fathoms (37-110 metres),although usually not shallower than 60m. (Elliott 1965, p.831). The clump-like distribution of both this species and Megathiris is probably a reflection of the early spat stage (Elliott, personal communication) in which the spat swarm around the adult colony for several days before settling nearby.

(iii) Environmental Requirements of the Species

It is believed that the species is best adapted to fairly calm environments, though it is equally obvious that clay sedimentation is tolerated. In the grey marly algal biomicrite area, where the species co-exists with Megathiris, a depth of 40-65 metres is envisaged,which falls at the lower end of the range of values quoted by Davidson (1877). On the rhodolite area of the bioherm the species confines itself to the sheltered areas of biofacies 2, in a depth possibly of about 45 metres. It is not known why conditions should favour this species to the exclusion of all other species, except adult Aphelesia, in north-eastern Gozo. The general size of Argyrotheca here and the subordinate nature of algae to micrite would suggest that conditions were optimum for the species and hence, may possibly have been deeper than other bioherm areas. This greater depth,together with the calm prevailing conditions would virtually exclude all other species from this environment.

e. Other Brachiopods Recorded in Samples

(i) General

Only two other genera of brachiopods have been collected from the samples examined and in each case only one specimen is recorded. *Terebratulina caput-serpentis* Linné from Karraba, Malta (406761), occurs in a fauna dominated by juvenile *Terebratula* and subordinate *Megathiris* and *Argyrotheca*; and the second species, *Megerlia truncata*, occurs at Il Qortin, Gozo (377899), where it is associated with *Argyrotheca* and subordinate *Aphelesia*, *Megathiris* and one *Terebratula*.

Davidson (1877, p.3) lists the range of *Terebratulina* as 80-808 fathoms off western Ireland (146-1477 metres), indicating that it is a poor depth indicator and may be expected at almost any depth. *Megerlia* is generally found below 60 metres (Hatai, 1965), suggesting that the environment of north-eastern Gozo (biofacies 2) may have been even deeper than anticipated and may be more than 60 metres in depth within this area.

f. Stratigraphic Checks on the Ranges of Bryozoa and Brachiopods

(i) General

The effect of time on both bryozoan and brachiopod populations was tested at ten localities on the bioherm (Locs. 14, 69, 140, 144, 375, 396, 404, 411, 415, 443) and several broad conclusions were obtained from the additional samples studied. Samples were taken from the base of the Upper Coralline Limestone at each locality. In addition loc.375 (Karraba) was also sampled just below and 1.5 metres above the *Terebratula-Aphelesia* Bed.

(ii) Bryozoa

All localities showed a marked increase in the percentage of encrusting bryozoans with time, at the expense of cellariform and to a lesser extent vinculariform types. This strongly implies that turbulence within the bioherm area increased as the bioherm evolved into a positive structure. It appears that the initial colonisation, although in calm water, was very close to wave base or the effect of strongly turbulent current action. The sample from above the *Terebratula-Aphelesia* Bed at Karraba, Malta, clearly indicated that there was almost no change in the percentage population structures higher in the bioherm, indicating that once the structure had developed it produced a moderately stable habitat.

(iii) Brachiopods

It was confirmed that neither *Terebratula terebratula* nor *Aphelesia bipartita* occur outside the *Terebratula-Aphelesia* Bed. Data from loc.404 confirmed that *Argyrotheca* and *Megathiris* prefer calm rather than high energy conditions, the numbers in each case decreasing from 20, where the encrusting bryozoa made up 50% of the sample, down to 1, where encrusters comprised almost 100% of the sample. Minor fluctuations in the encrusters percentages at loc.375 showed that *Megathiris* preferred higher energy conditions than *Argyrotheca*.

g. Conclusions

In summarising all the available data on the four brachiopods under consideration the following conclusions can be made:

SPECIES	DEPTH	REQUIREMENTS
Terebratula terebratula	under 20-50m.	Moderate to high energy conditions
Aphelesia bipartita	less than 30m.	High energy conditions
Megathiris sp.	30-65m.	Moderate energy, but tolerates sedimentation
Argyrotheca sp.	40-65m.	Calm conditions, tolerates sedimentation

3. Other Fauna Associated with the Brachiopod Bed

The distributions of 10 of the commonest bryozoan species, together with 11 species of the associated biota, have been examined using the bryozoan distribution maps as a basis for environment prediction. The conclusions are as follows:

Scrupocellaria, *Berinicea*, *Cribrilina*, *Cellepora* and *Lichenopora* all prefer locations on the flanks of the bioherm (biofacies 3), and in addition *Entalopora*, *Canda* and *Retepora* prefer conditions of highest energy on the crest of the bioherm. *Crisia* is found throughout all areas, but *Cellaria* is restricted to the eastern areas (biofacies 1), where strongly turbulent conditions with reworking existed.

Amongst the other biota the following were found to be characteristic of the bioherm (biofacies 3):

Echinus, *Cidaris*, *Chlamys multistriatus*, *Ostrea boblayei*, Crustacean fragments, *Serpula* and various gastropods, which were mainly represented by naticid countersunk borings, especially in the valves of *Aurila*, but also with subordinate numbers of muricid borings. Species more typical of calmer conditions, particularly in areas of biofacies 2 (vinculariform biofacies), are *Lima* and sponge spicules, although asteroid ossicles do occur in some areas. *Dentalium* was found to be characteristic of the cellariform biofacies (biofacies 1), though this may represent part of a later or lower energy fauna which has been subsequently intermixed with the sediment by bioturbation.

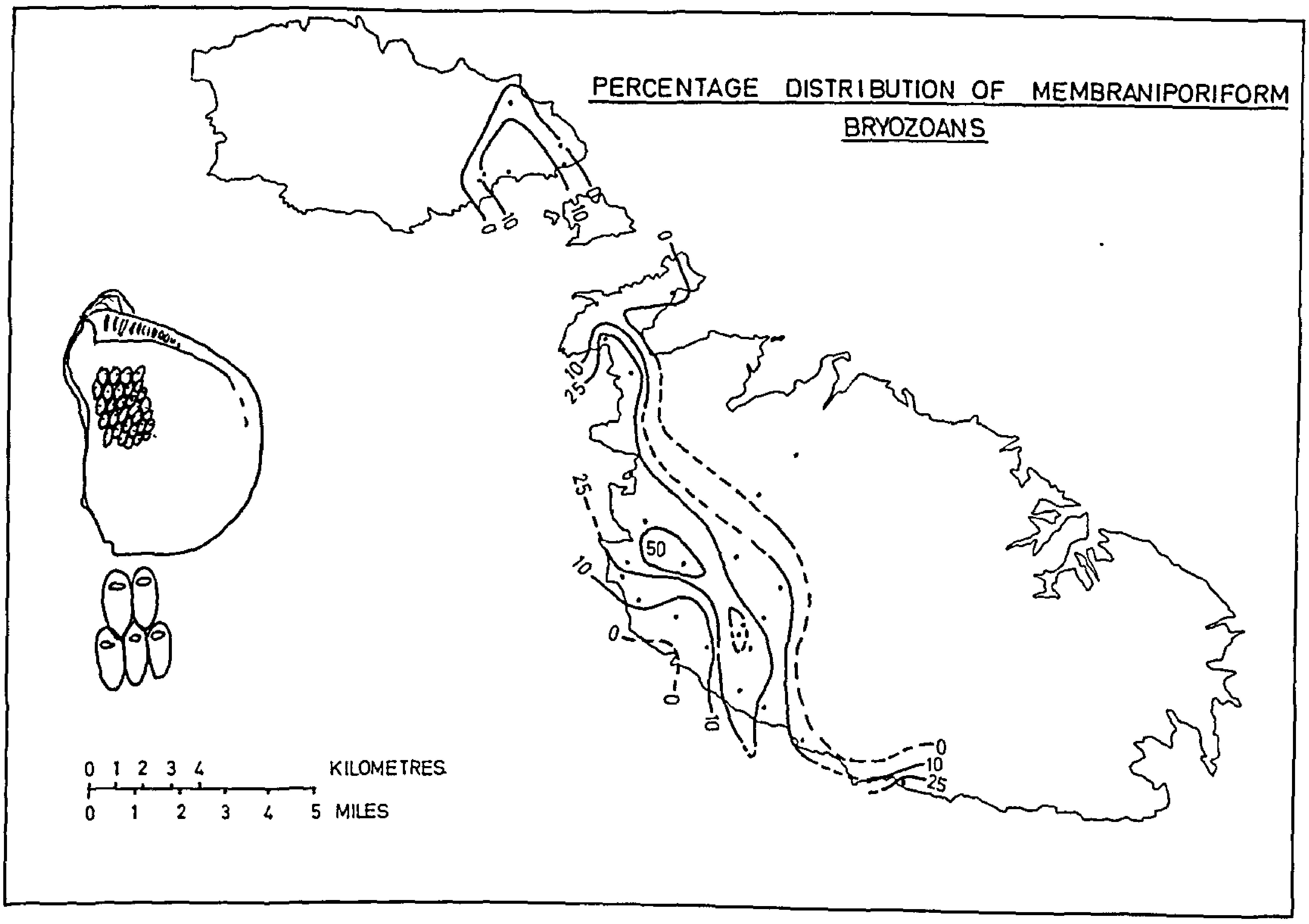


Fig. 28a

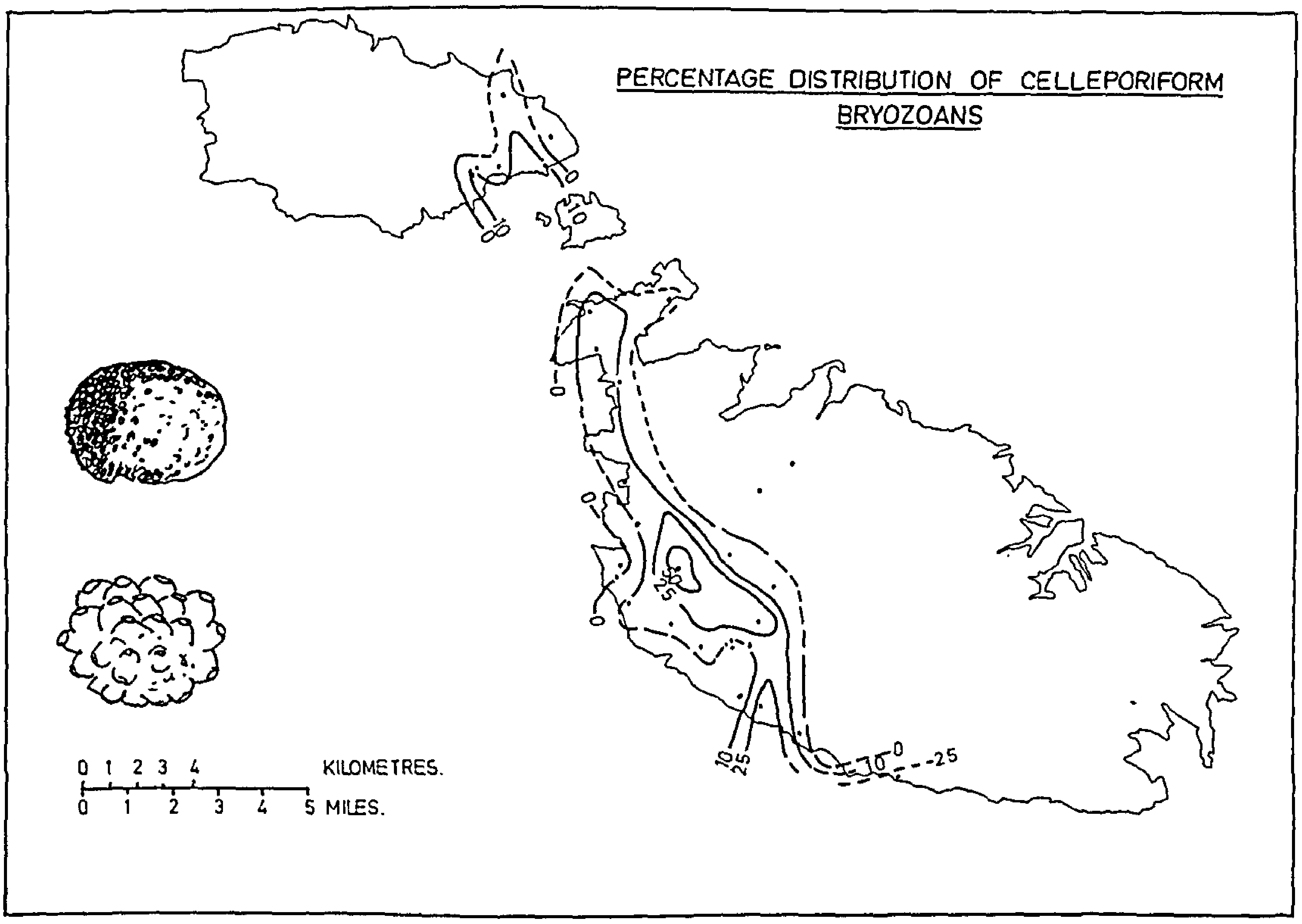


Fig. 28b

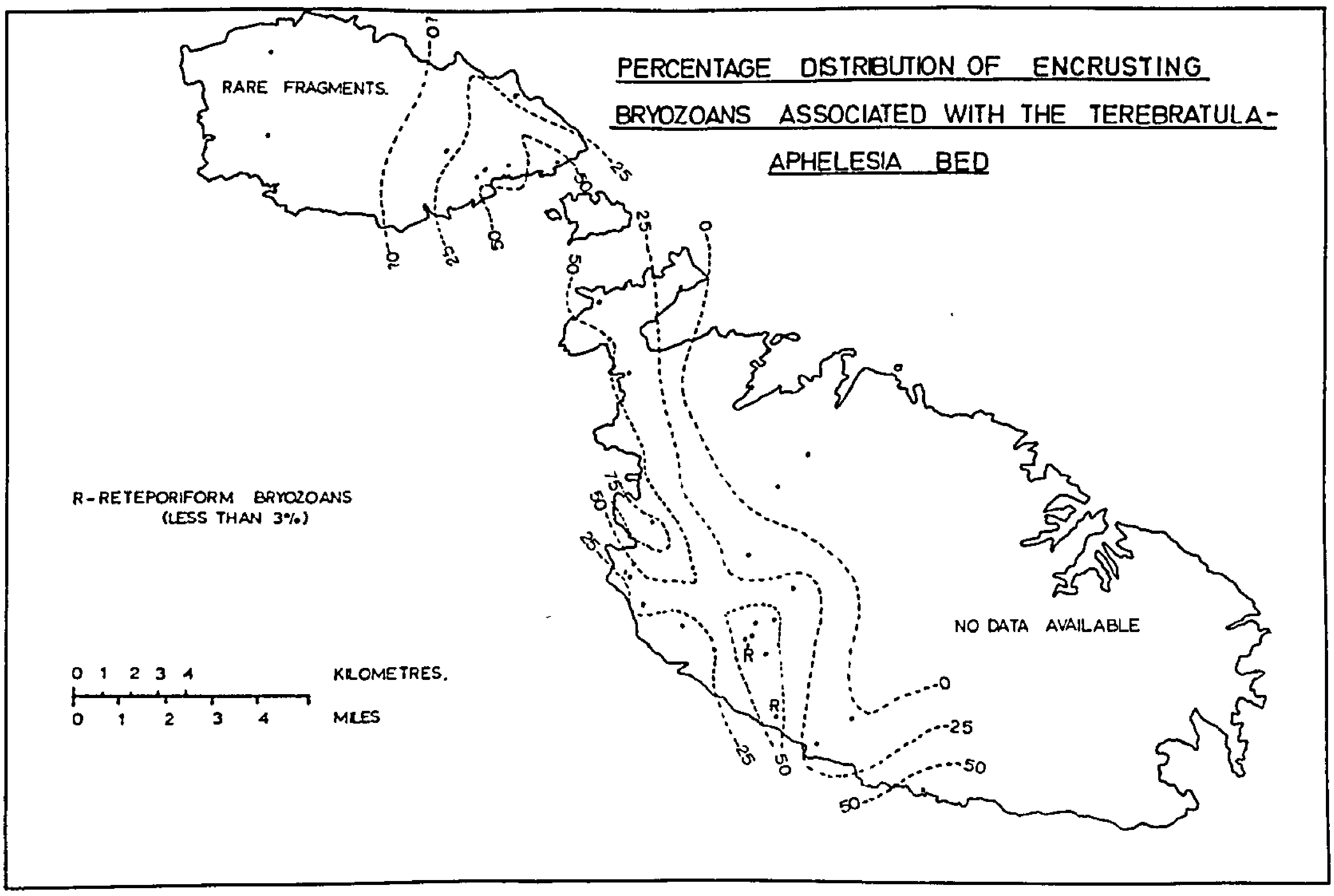


Fig. 29a

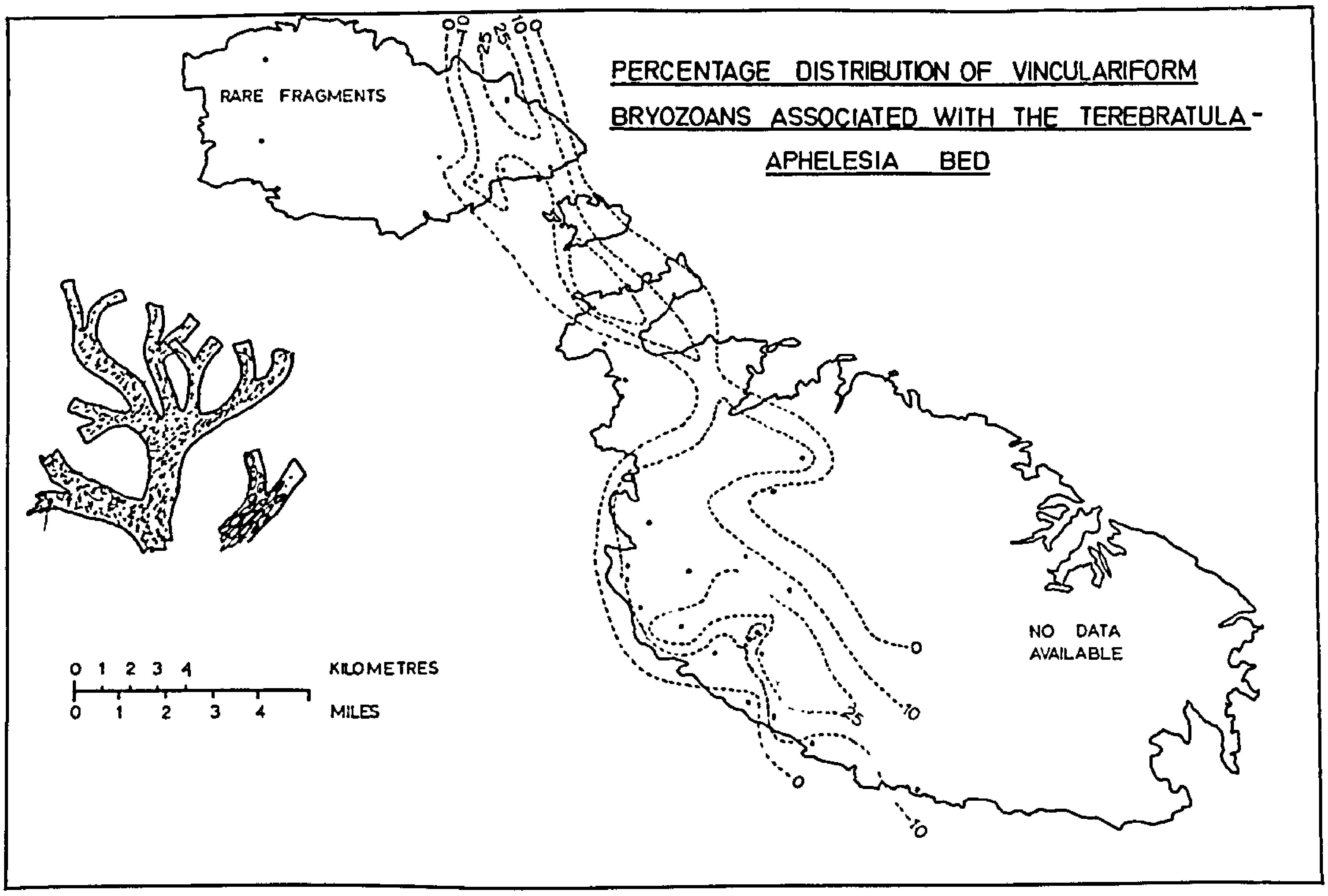


Fig. 29b

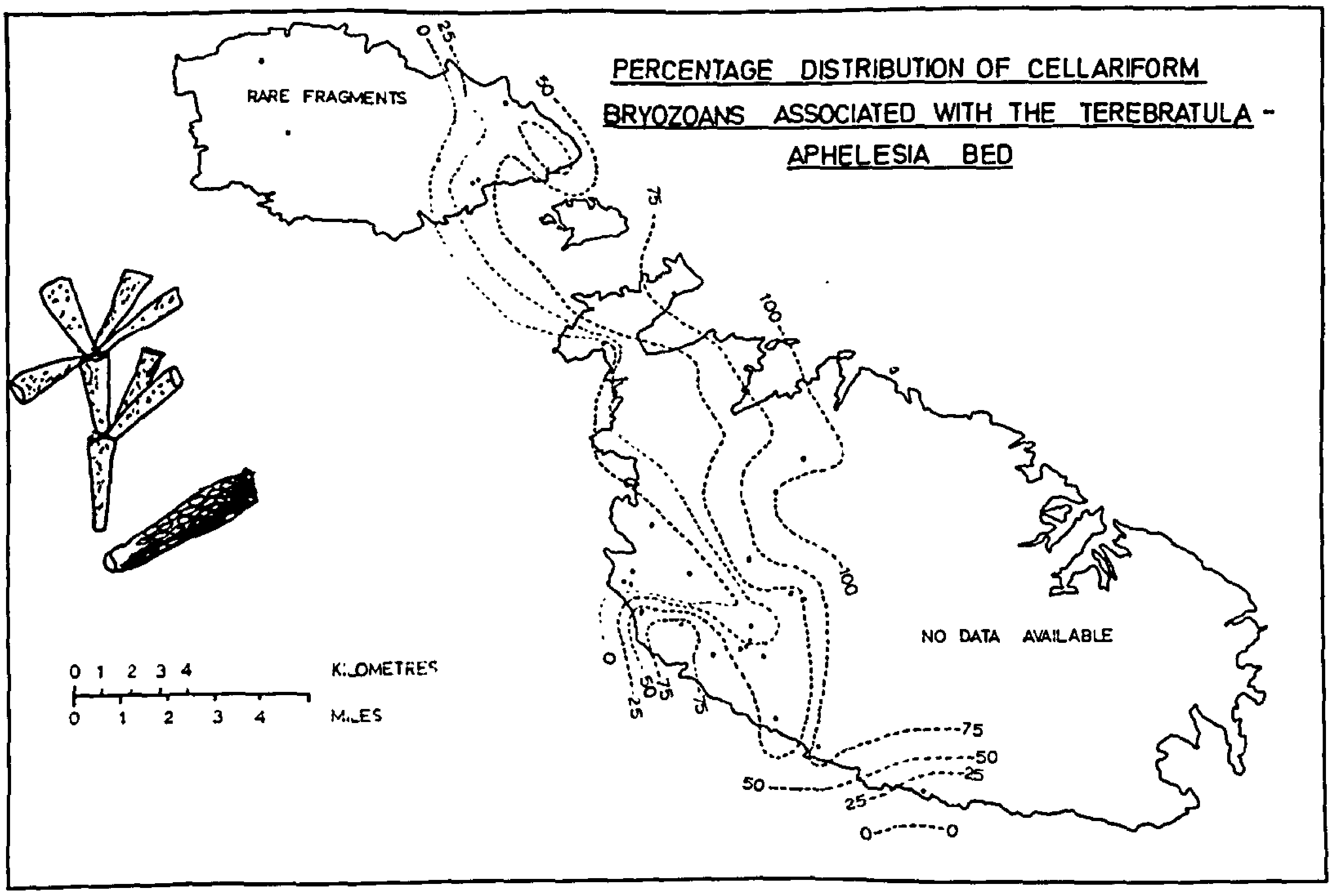


Fig. 30a

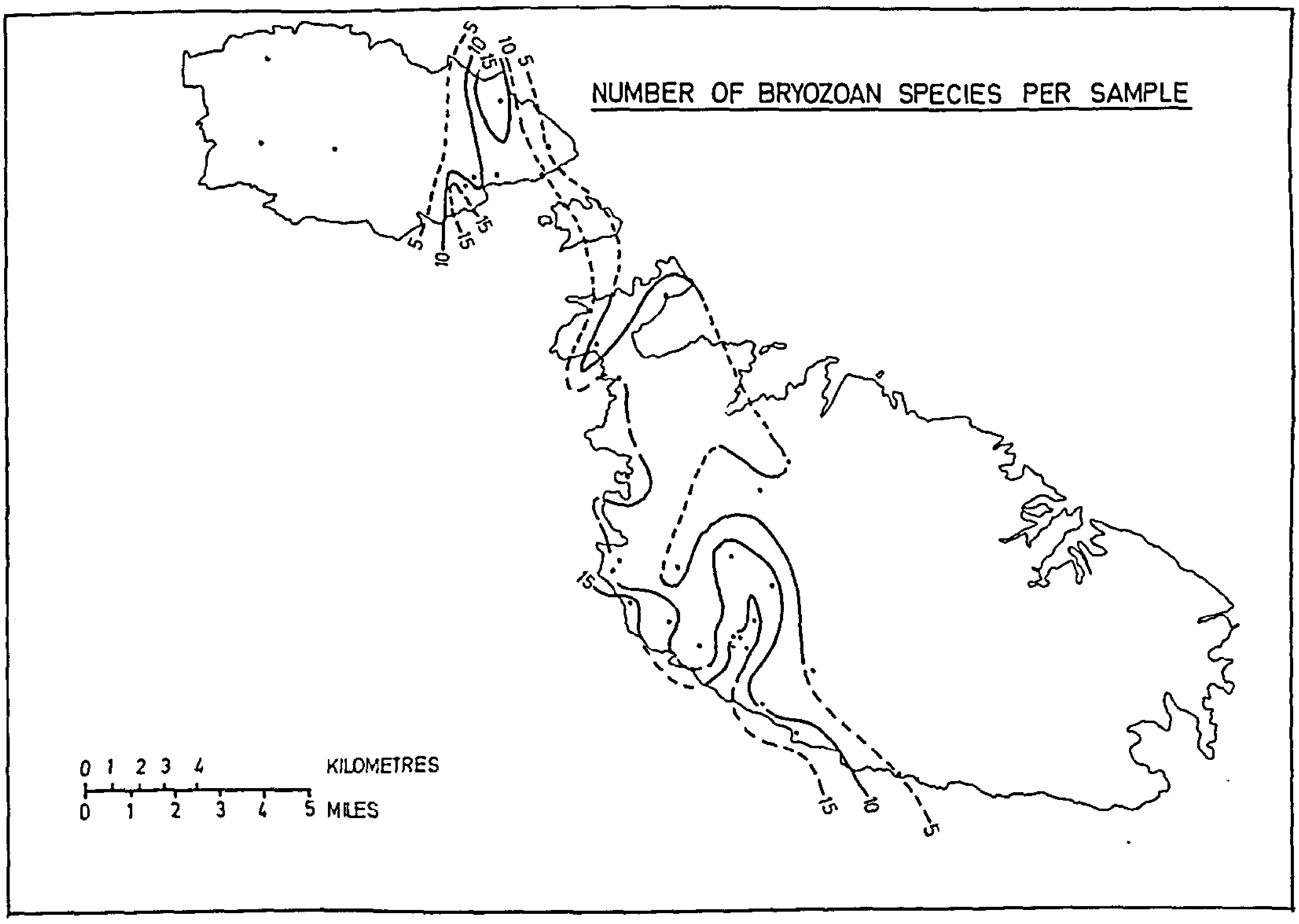
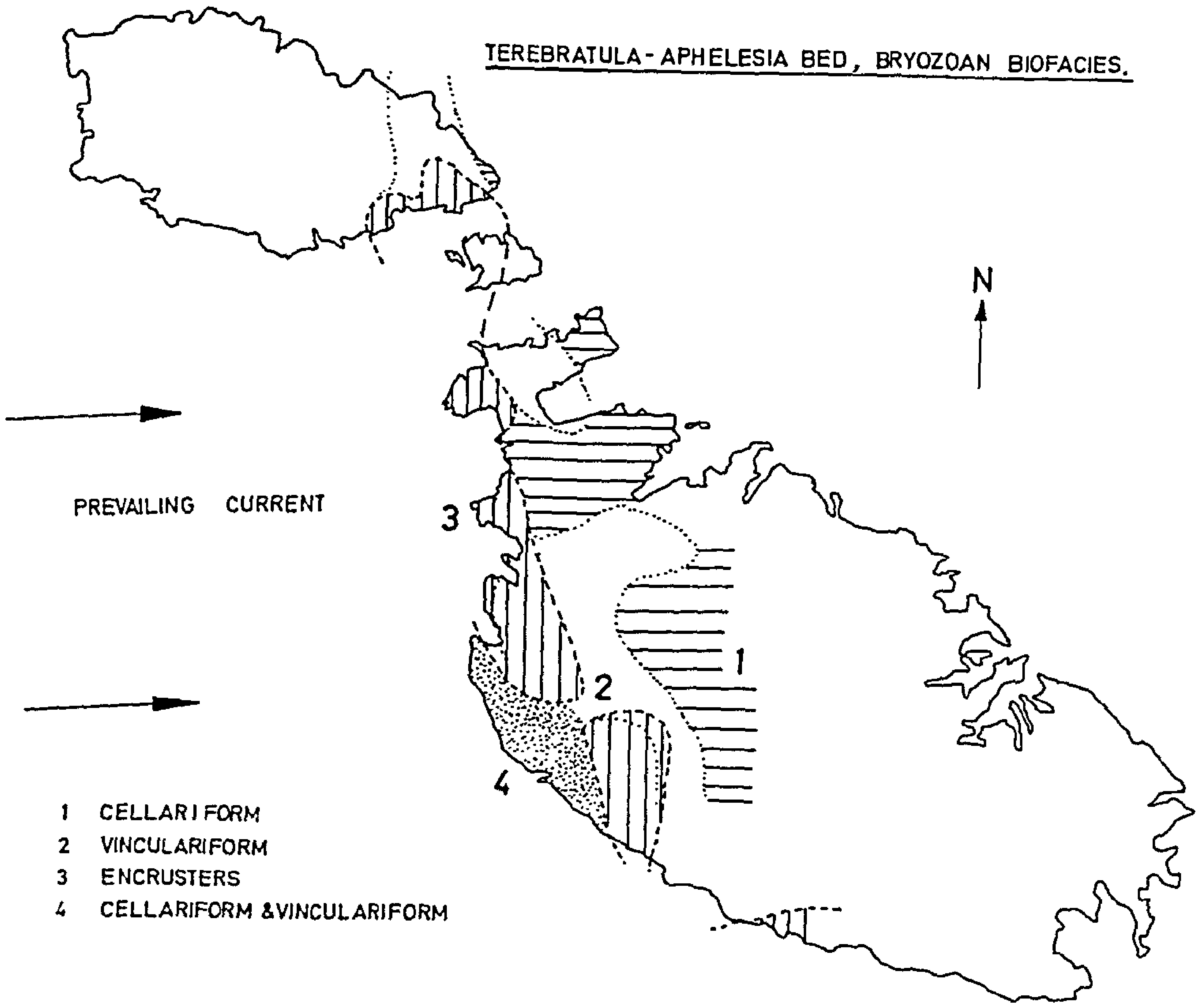


Fig. 30b



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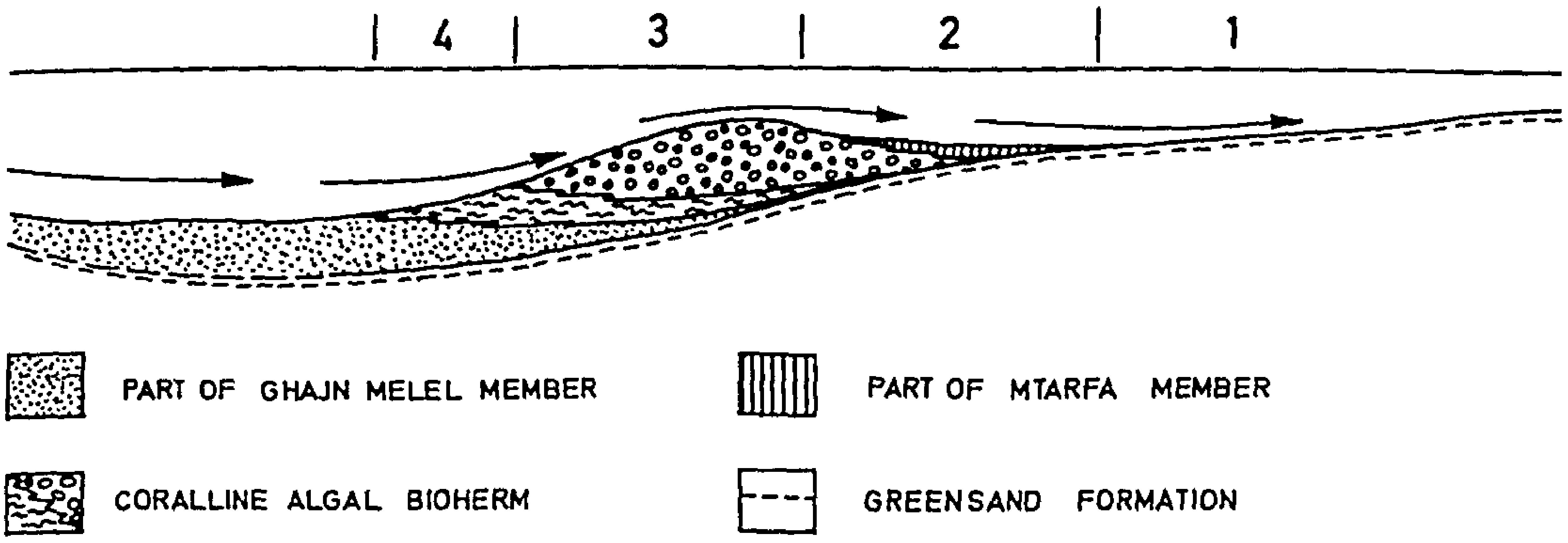


Fig. 31b

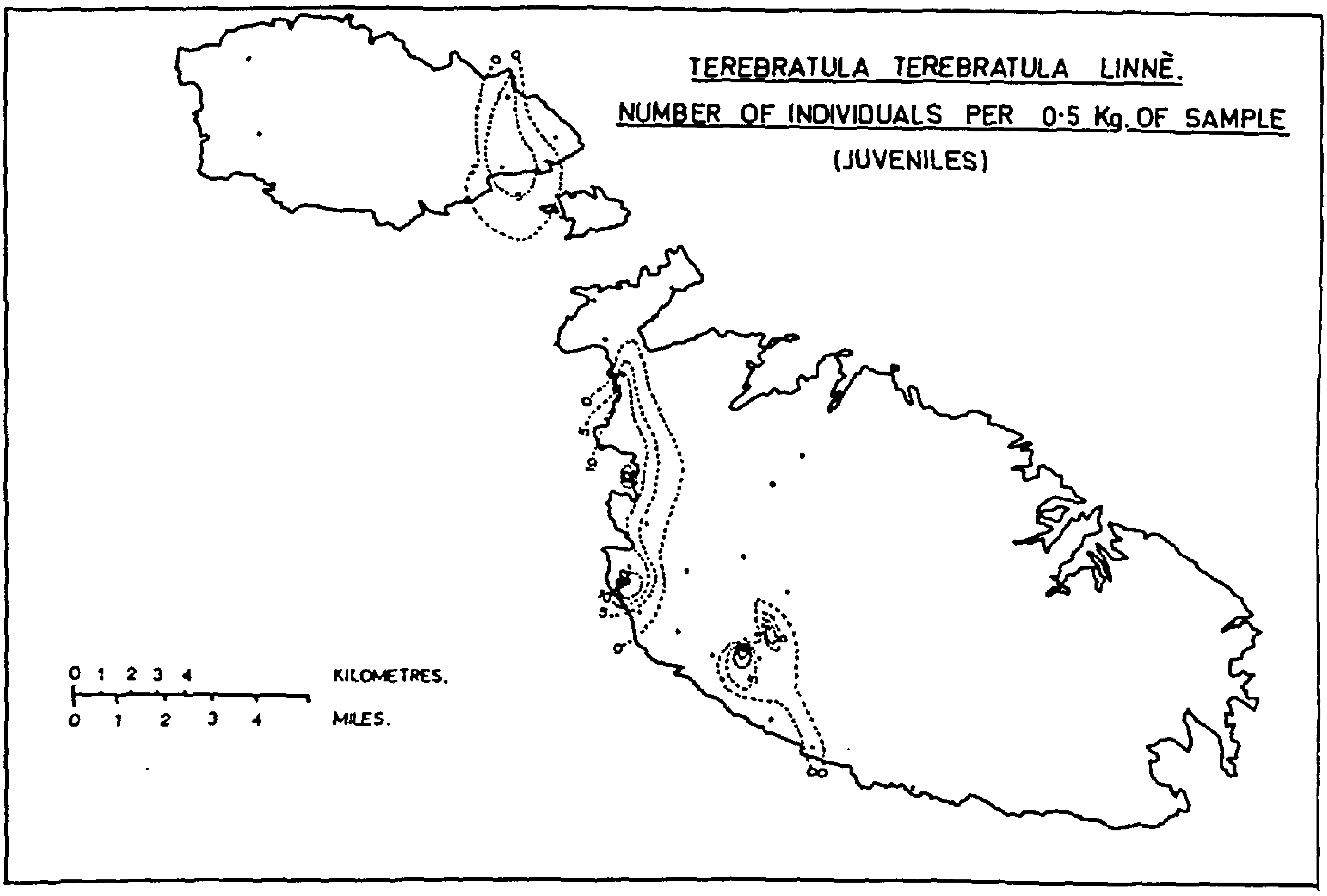


Fig. 32a

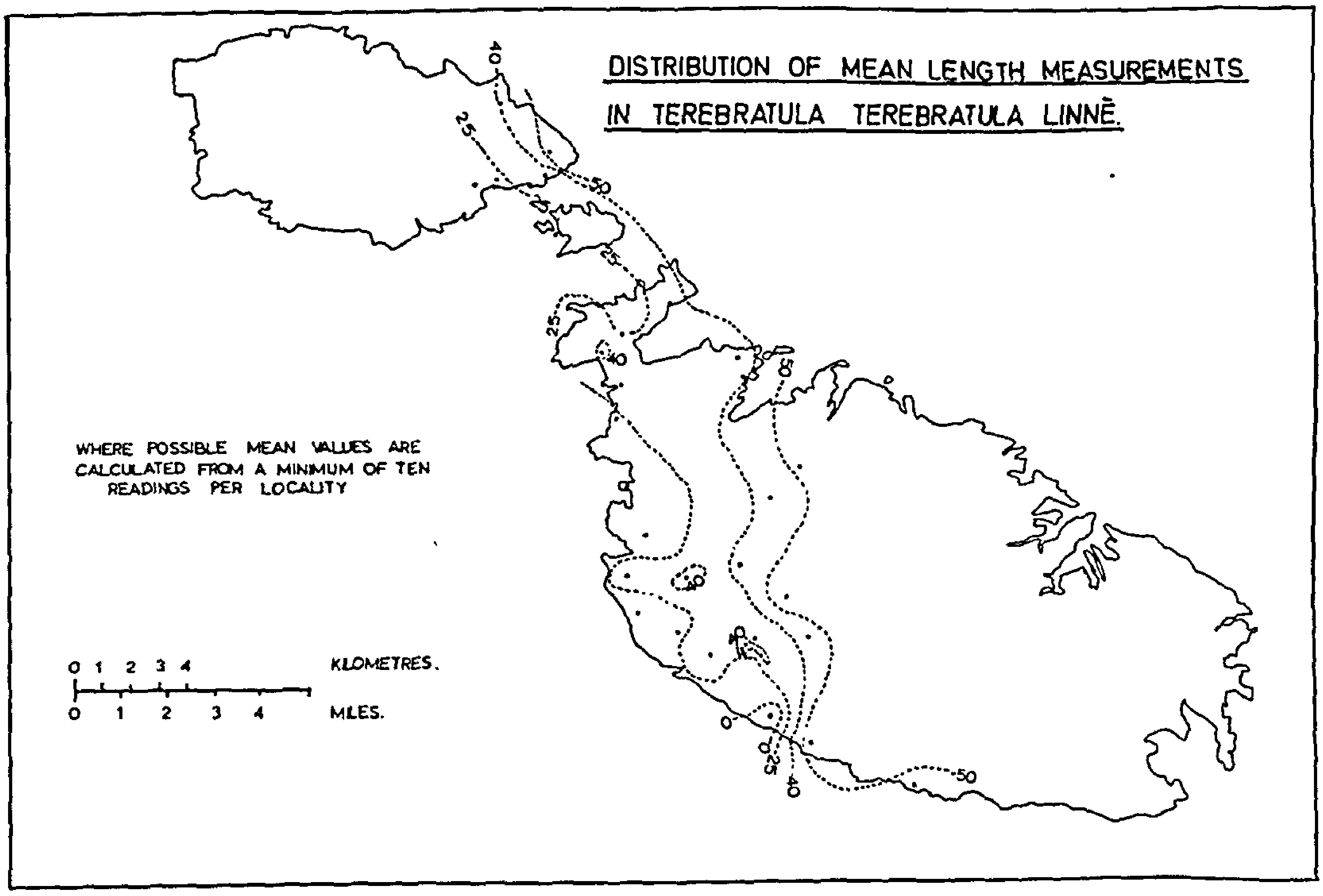


Fig. 32b

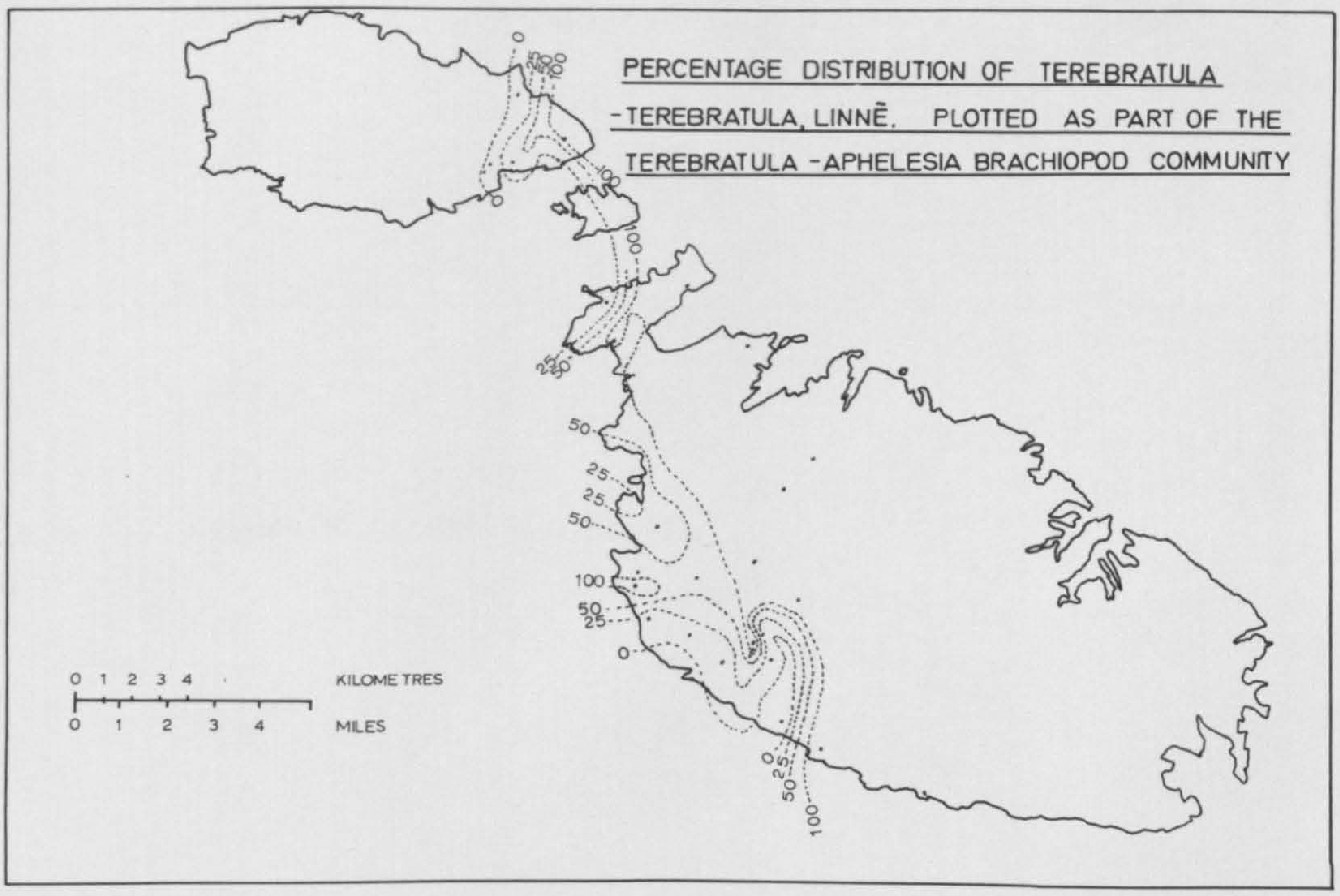


Fig. 33a

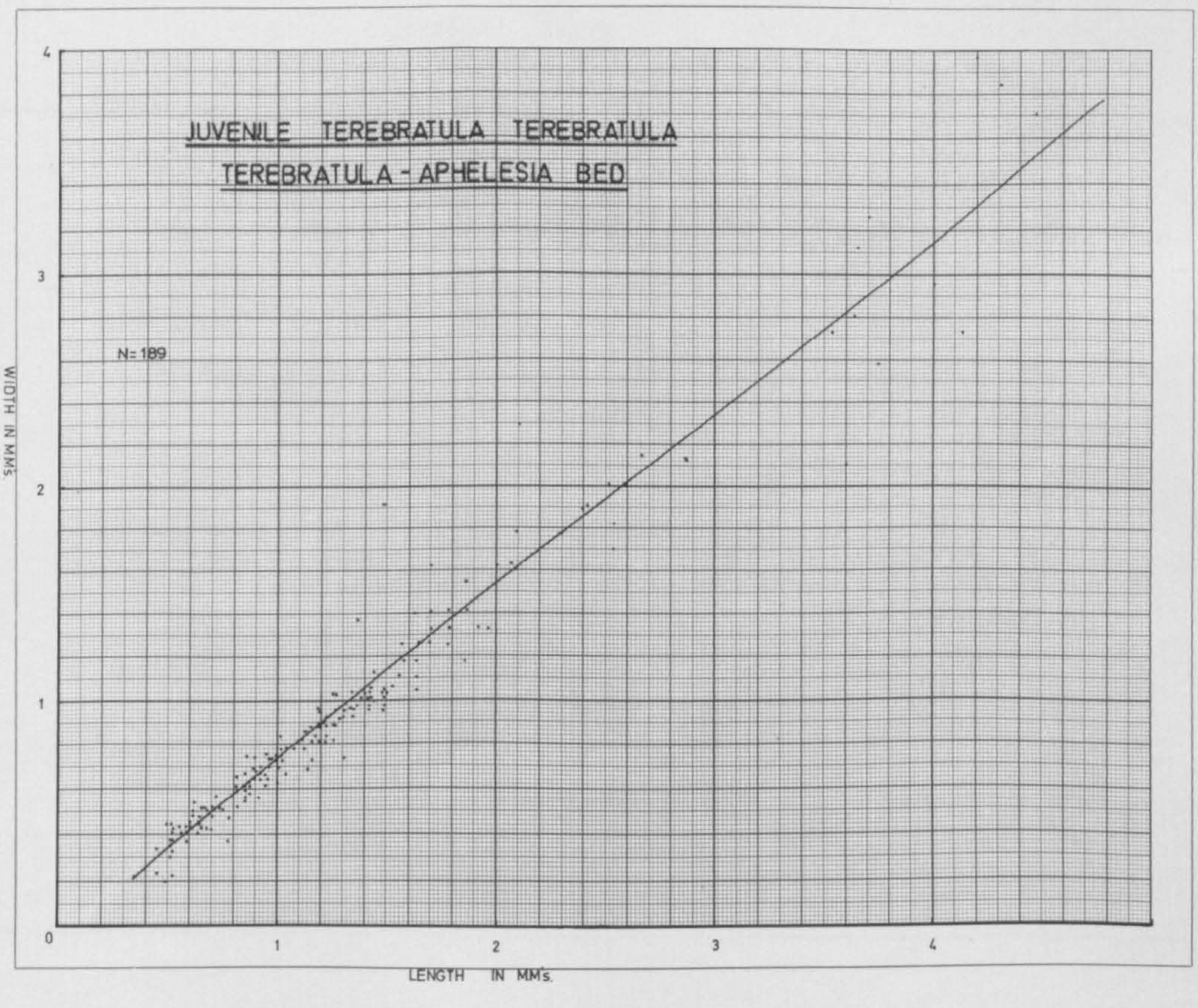
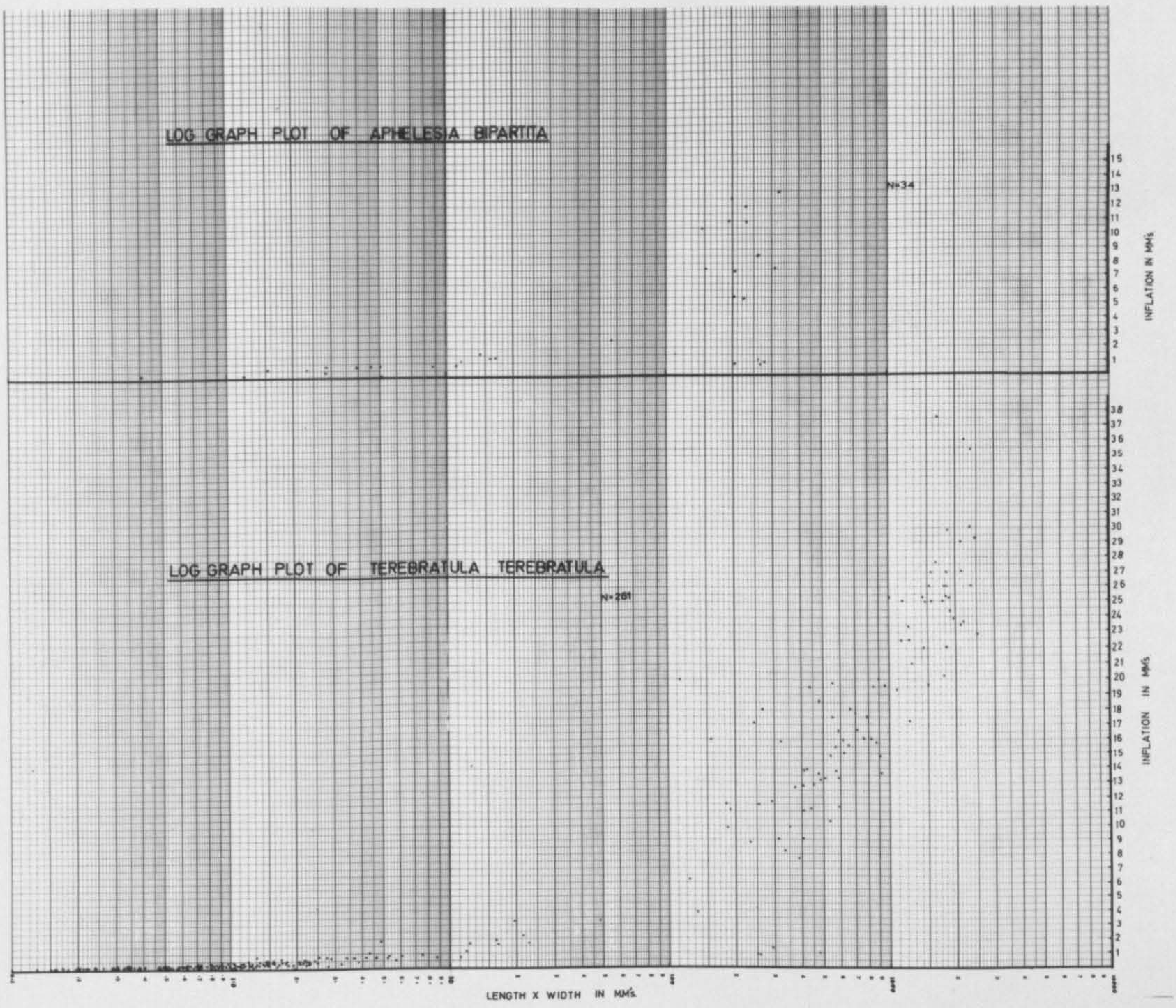


Fig. 33b



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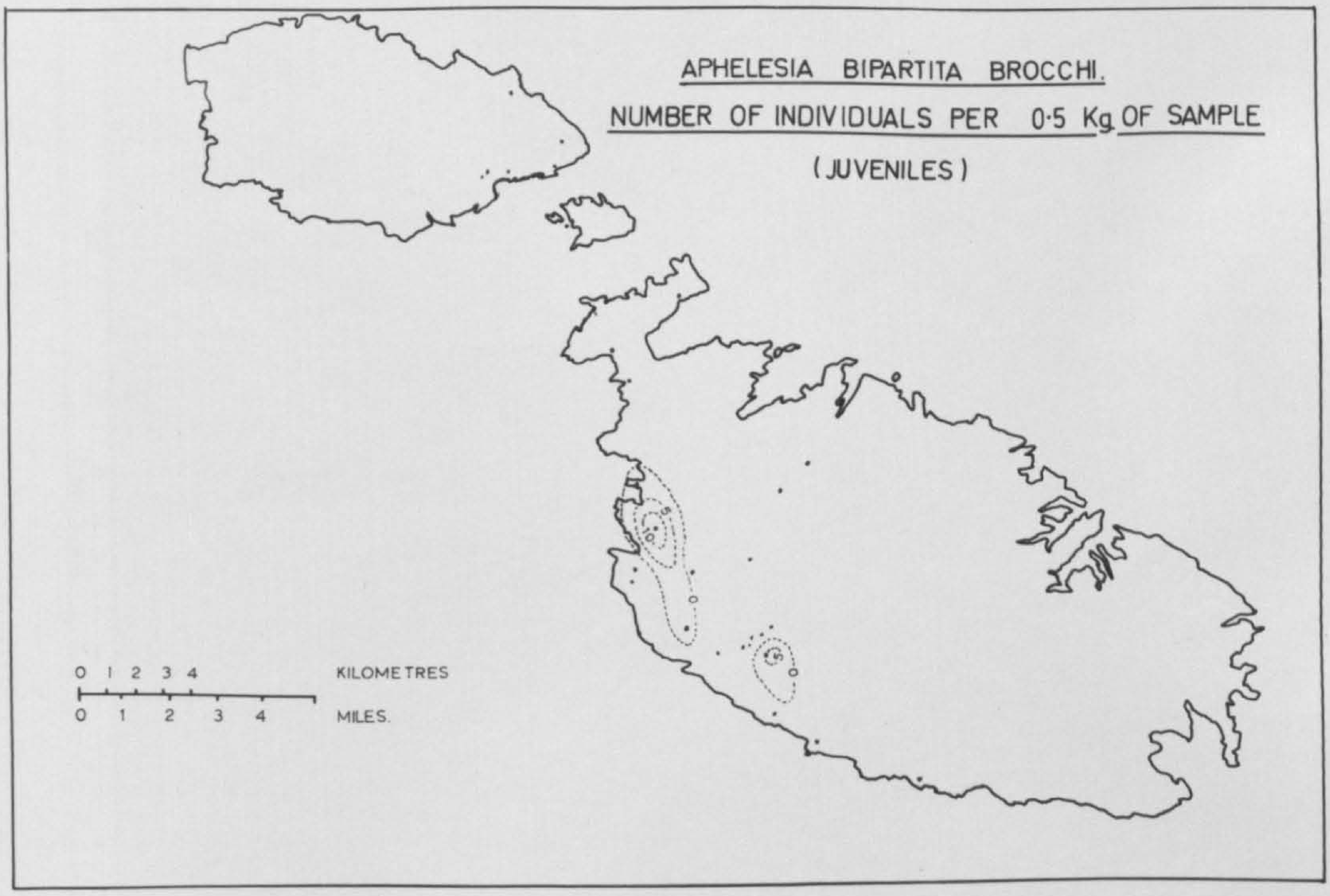


Fig. 34b

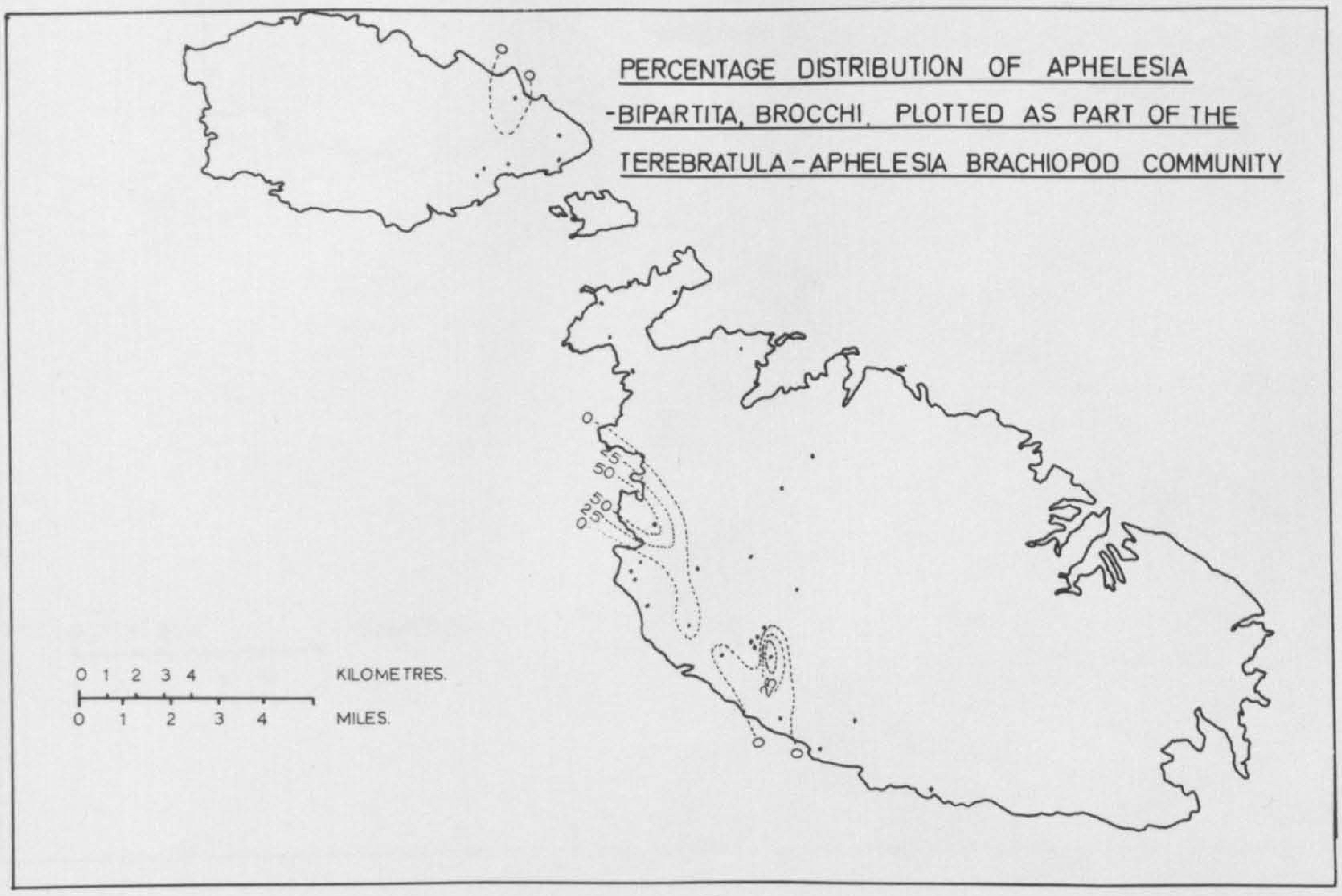


Fig . 35a

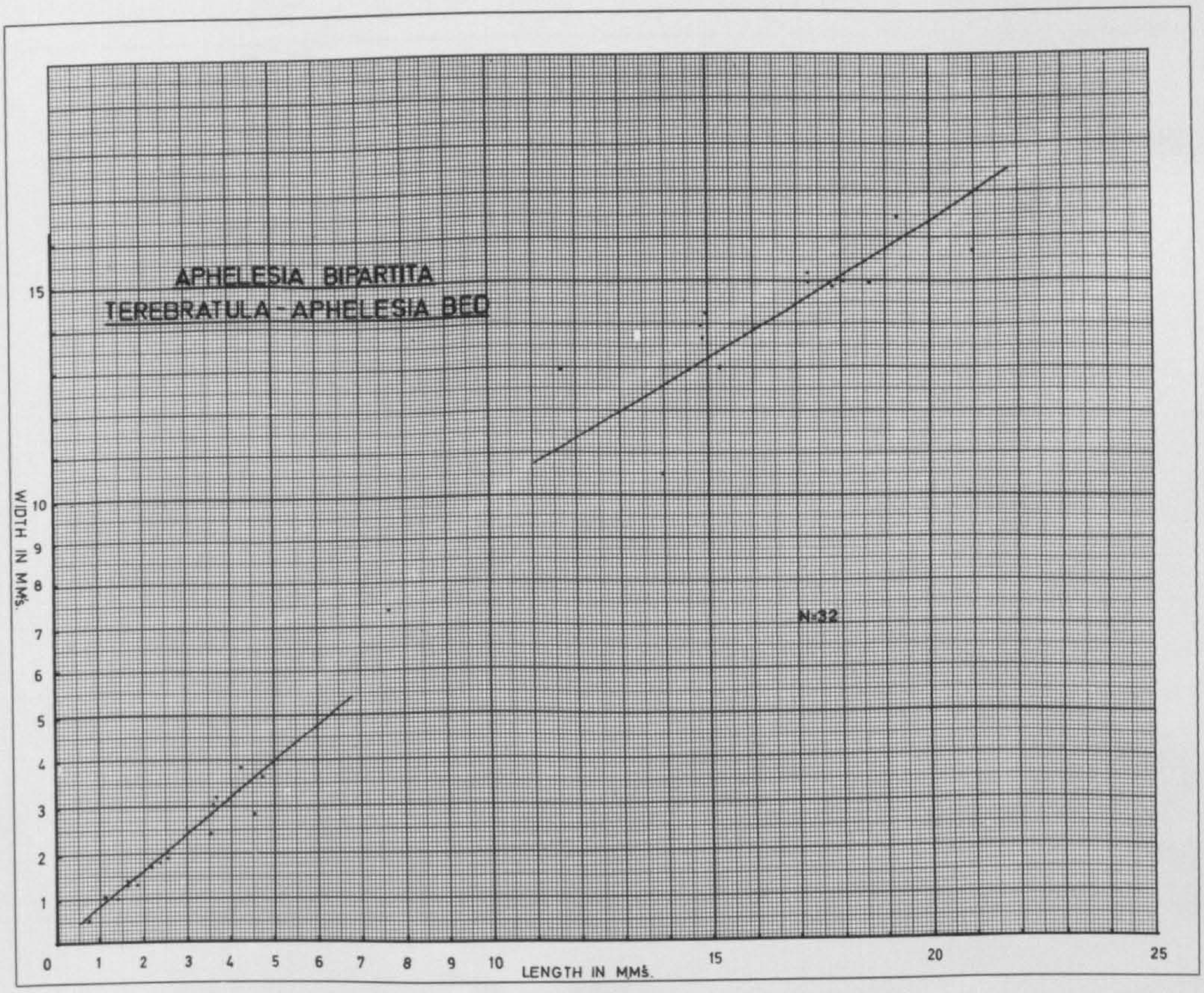


Fig. 35b

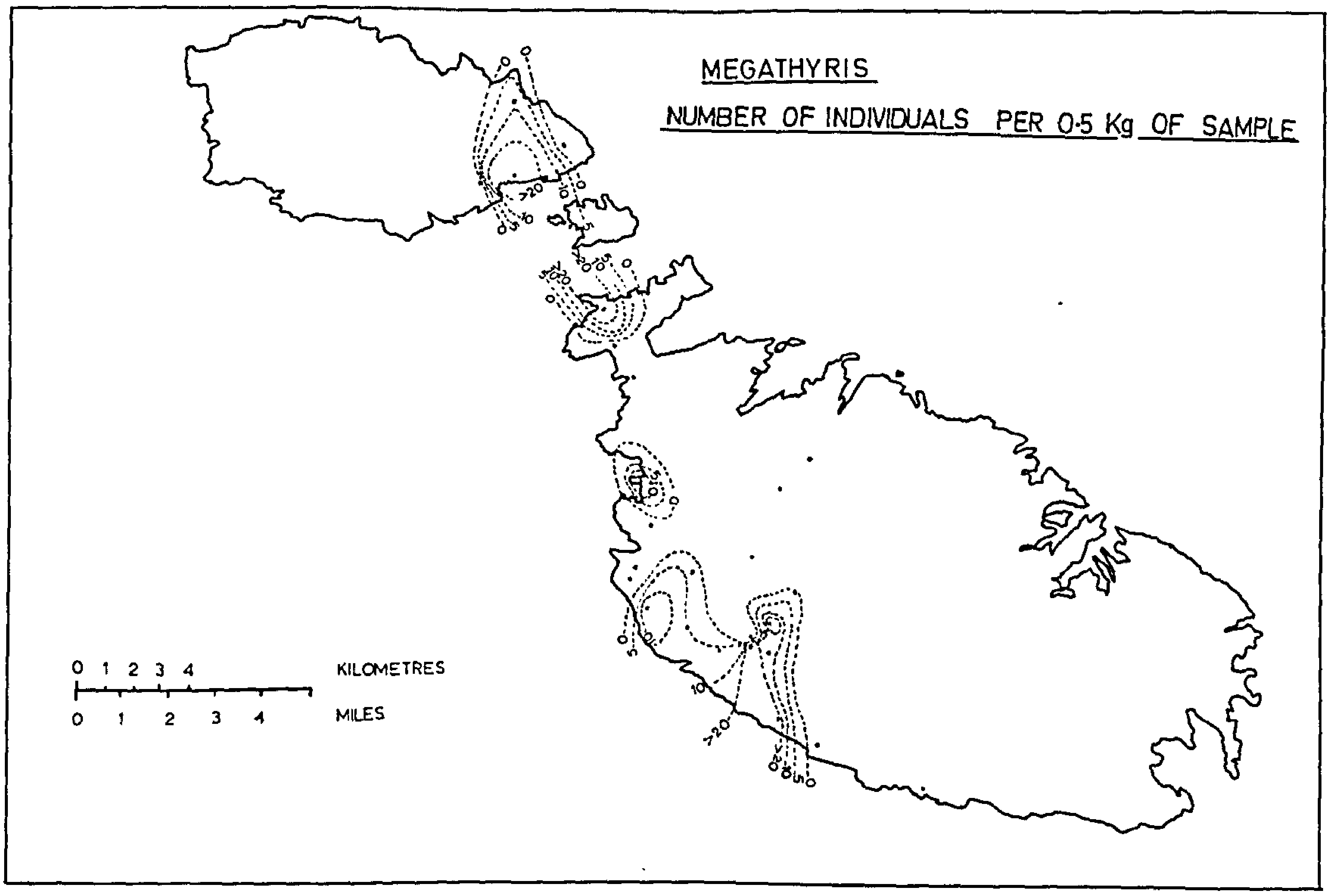


Fig. 36a

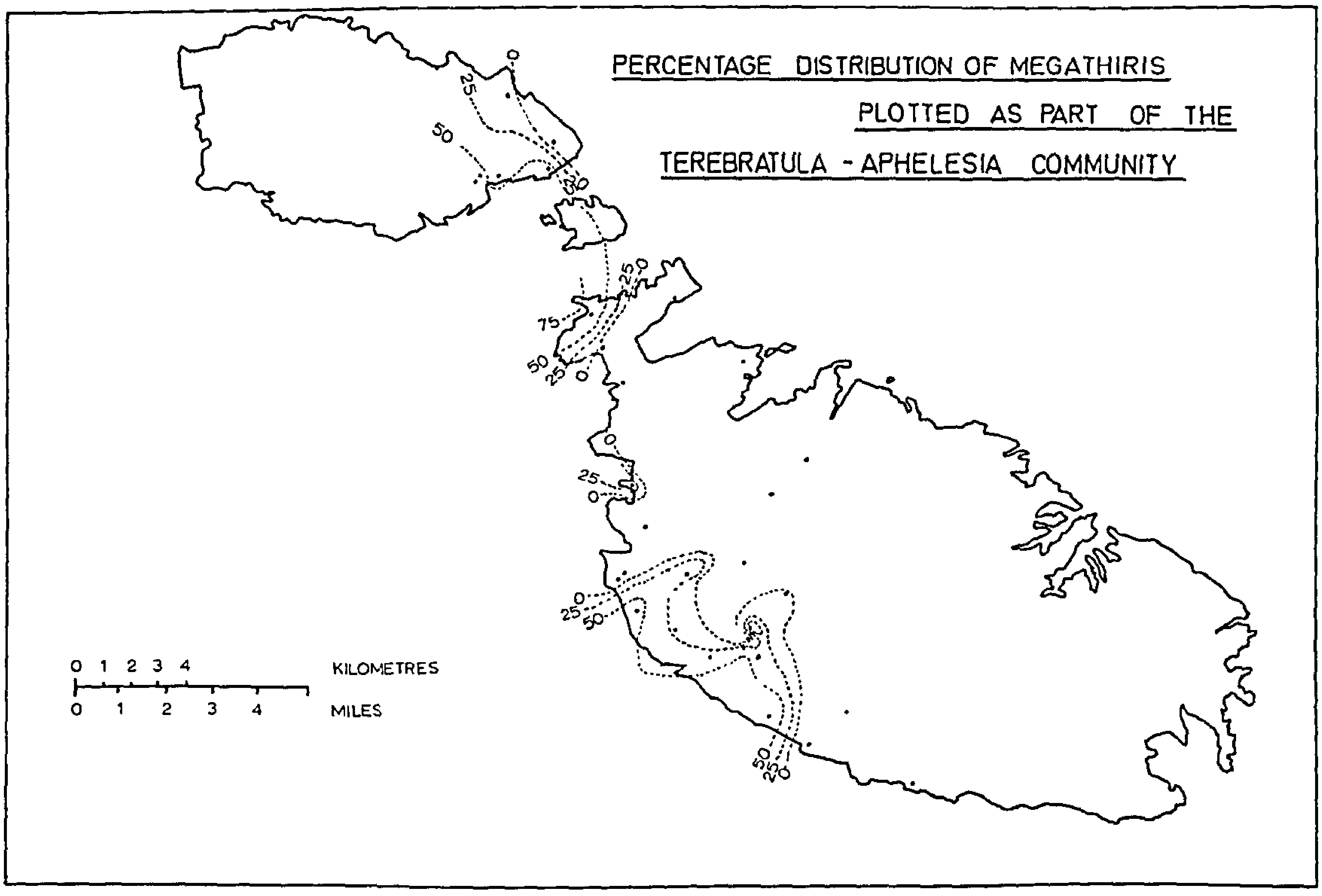


Fig. 36b

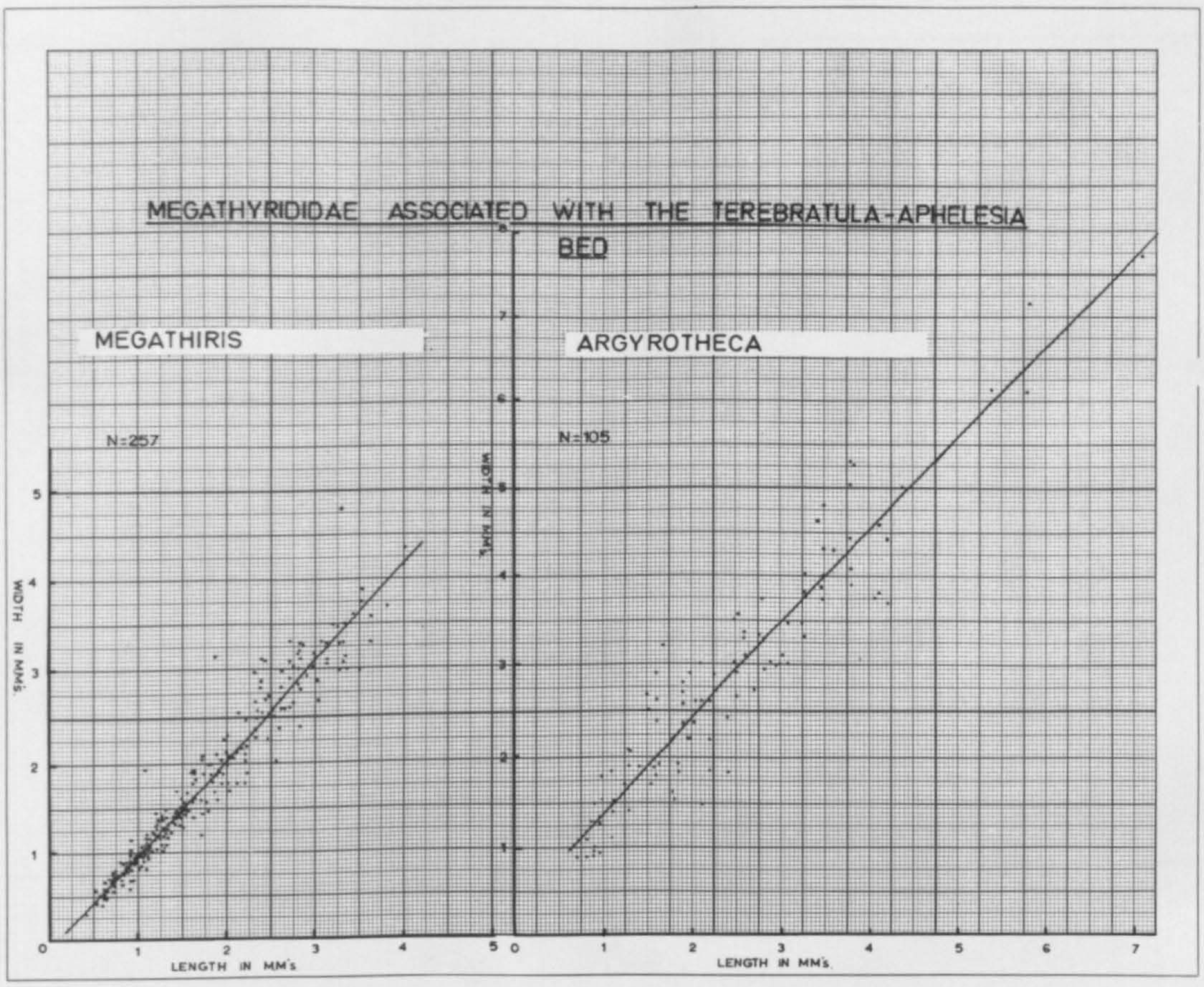


Fig. 37a

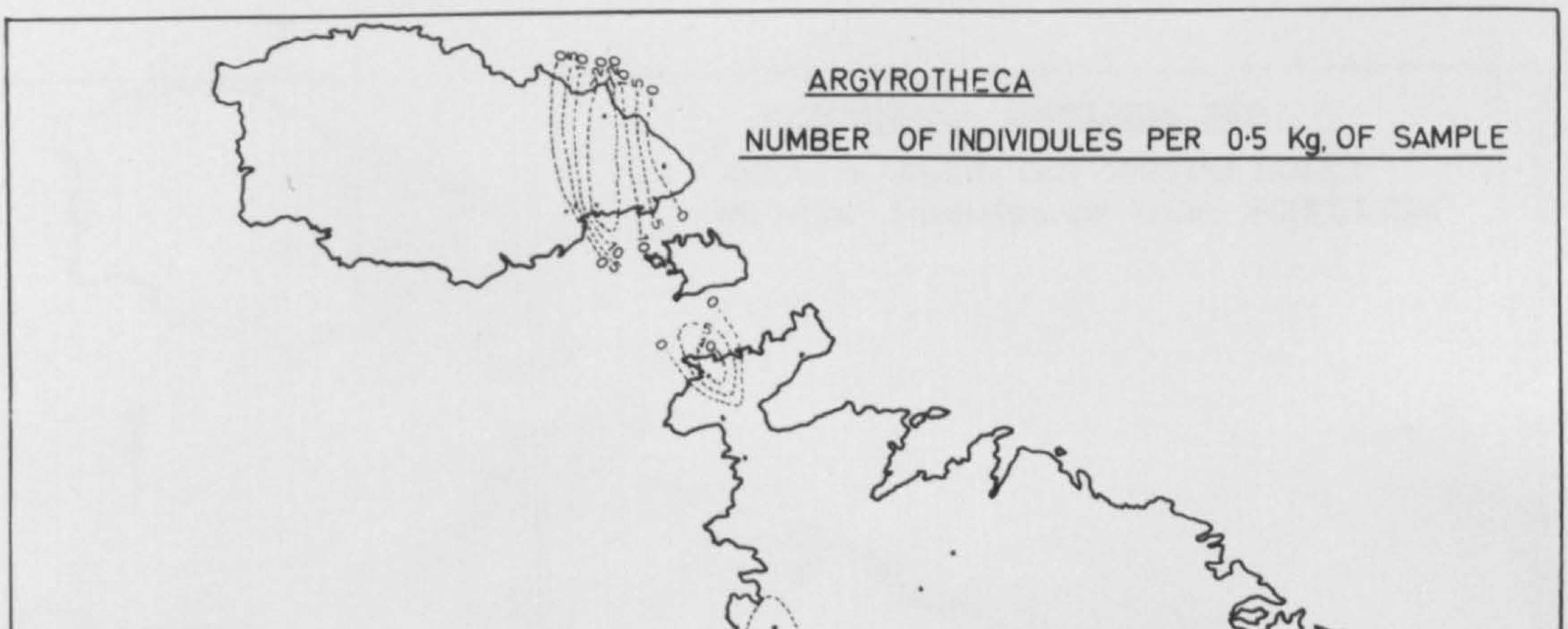


Fig. 37b

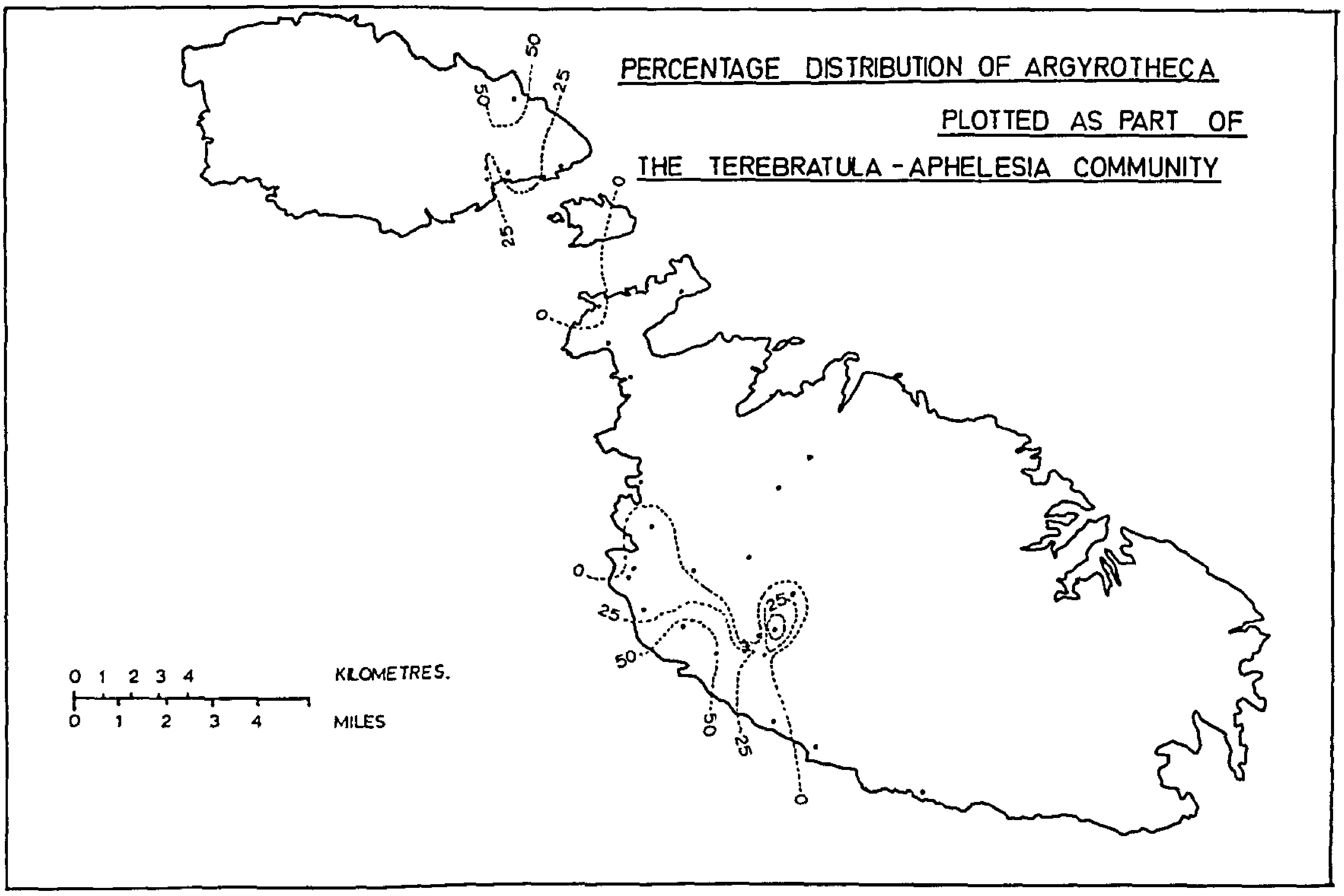


Fig. 38a

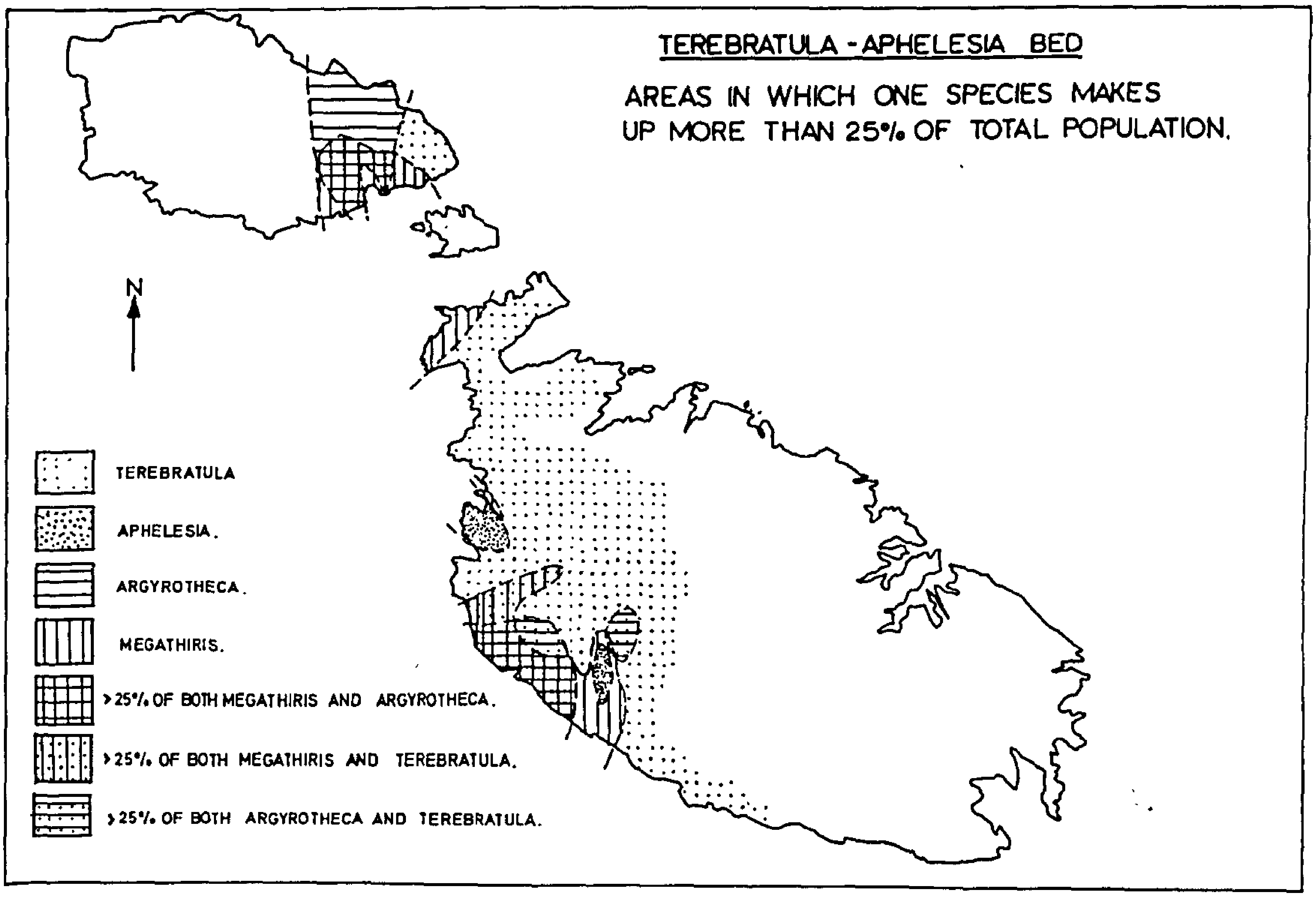


Fig. 38b

SEMI-QUANTITATIVE DIAGRAM OF FAUNA AND FLORA ASSOCIATED WITH THE TEREBRATULA - APHELESIA COMMUNITY.

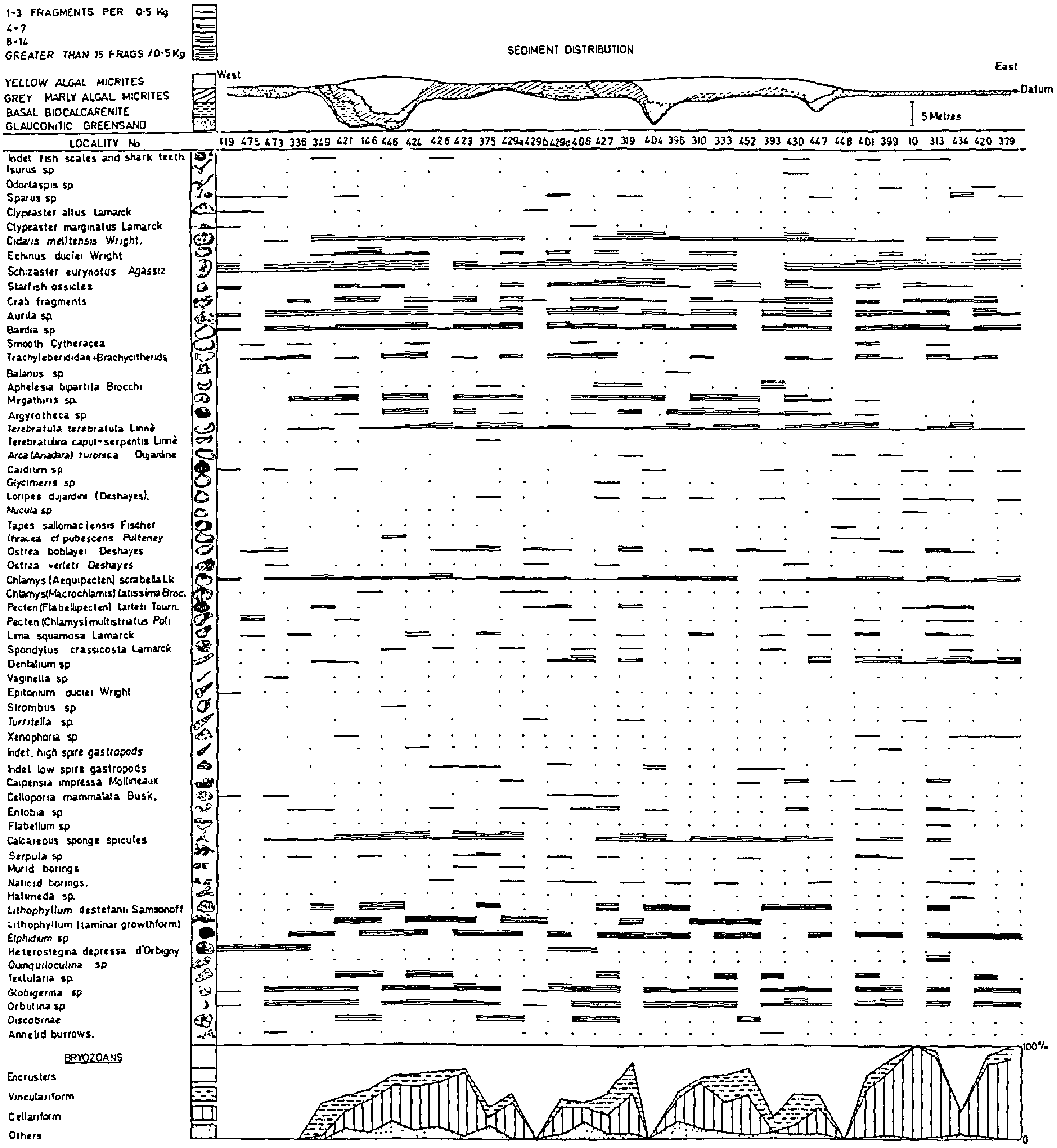


Fig. 39

CHAPTER 11

ROCK COLOURING AND ORIGIN OF LITHOCLASTS IN MALTESE STRATA

Throughout the preceding chapters constant reference has been made to derived clasts of exotic sediment brought into the area from outside the present confines of the Maltese Islands. These data and their interpretation will now be discussed.

a. Distribution of Allogenic Clasts

The form and location of most of the material has already been noted in previous chapters but will be briefly re-examined. It may be conveniently subdivided up into the following groups:

(i) Early Limestone Clasts
(ii) Phosphorite Clasts
(iii) Glauconite, Limonite and Gypsum Clasts
(iv) Later Limestone Clasts.

(i) Early Limestone Clasts.

These are of local distribution and are generally restricted to the erosion surface separating Lower Globigerina Limestone from Lower Coralline Limestone. They are mainly associated with the Zabbar High along the San Leonardo coast and, in western Malta, at Ras il Bajjada (502646). In both areas the clasts approach a modal composition which is quite comparable to parts of the Xlendi Member, and in particular the finer grained beds.

(ii) Phosphorite Clasts.

The earliest phosphorite preserved in the islands is also associated with the erosion surface referred to in (i) above, but this is an <u>in situ</u> development and has no associated pebbles. Phosphorite pebbles do, however, become increasingly important in the Lower Globigerina Limestone, attaining a maximum size in the C1 and C2 Conglomerate beds. As stated in previous chapters the pebbles are of several types, though phosphatised Globigerina biomicrites not unlike the true Globigerina Limestone, and glauconitic biomicrites, are the two most common types. Many of these pebbles, particularly in the conglomerate beds, consist of fresh to waterworn casts of corals, molluscs and also shark teeth. Several show signs of being bored by Entobia sp. and bryozoans, suggesting that the material has originated from very shallow areas. It is clearly seen that both pebble sizes and bed thickness increase to a maximum towards the western side of the islands. Individual beds also appear to converge in that direction,except for the C1-C2 amalgamation of eastern Gozo noted by Wigglesworth (1964). Many of the individual conglomerate horizons are also associated with marine erosion or non-deposition, the effects of which are also clearly seen to become increasingly more severe towards the western side of the islands. In the C2 Conglomerate Bed dark grey or brown glauconite phosphorite clasts first appear in large quantities, and continue to the top of the Ghajn Melel Member of the Upper Coralline Limestone. These are frequently in the form of shell casts of Mollusca, but are never as plentiful as the lighter brown phosphorite clasts. They do, however, appear to succeed them in importance, and in fact, typical light brown phosphorite pebbles are rarely seen above the Upper Globigerina Limestone. These dark grey glauconite clasts contain a similar molluscan assemblage to those of the phosphorite conglomerate beds, suggesting an origin in a similar environmental situation,although solitary corals are unrepresented. They are best displayed in sediments overlying the basal Upper Coralline Limestone erosion surface of western areas of the islands, at which level sharks teeth, common in the Globigerina Limestone, make their last appearance.

(iii) Glauconite, Limonite and Gypsum Clasts.

Although sporadic grains of allogenic glauconite occur in all the formations from Lower Globigerina Limestone to Upper Coralline Limestone, they are most important in the upper part of the Blue Clay and in the Greensand. In lower horizons the glauconite is usually restricted to the western sides of the islands, especially in the C1 Conglomerate Bed, where it occurs in the Dingli Cliffs of Malta and to a lesser extent in succeeding conglomerate beds. The sudden appearance of abundant glauconite in the upper part of the Blue Clay at Halk it Taffel and Tal Lippija, Malta, and Kemuna Tower, Gozo marks the first major influx of exotic sediments into the area, which do not contain significant quantities of phosphorite. It would appear that the source area changed from one supplying phosphorite to one supplying glauconite at some time during Blue Clay sedimentation. This voluminous glauconite influx is again restricted to outcrops lying towards the western extremities of the islands, from which this material almost certainly came. In the case of Kemuna Tower, Gozo (354880), large volumes of broken foraminifera testify to the transported and reworked nature of the glauconite containing sediments involved.

A similar association of glauconite occurs in the Greensand Formation, being again thickest in western Gozo, but thinning to less than 1 metre in eastern Malta. This sediment appears to be associated with an episode of zero sedimentation at the close of Blue Clay times. Both this deposit and the glauconite bed in the Blue Clay are significant in that the rare light brown phosphorite pebbles are less than 1mm.in diameter, whereas larger dark brown to dark grey, phosphatic mollusc cast pebbles, containing glauconite, attain appreciable proportions. Associated with these are variable quantities of partly rounded gypsum clasts up to 2mm.in diameter and occasional limonitic clasts which, however, attain greatest significance in the overlying Ghajn Melel Member. The general association of the glauconite with coarse shell debris, obviously derived pebbles of both lithoclast and fossil casts, together with the frequently smoothed surface texture of the pellets, strongly implies a reworked origin for the component.

Above the Greensand glauconite decreases in importance, being represented by scattered reworked grains in the Ghajn Melel Member and rare grains at the base of the San Leonardo Beds, the latter also associated with pale brown phosphorite pebbles.

(iv) Later Limestone Clasts

Several erosion surfaces in the Upper Coralline Limestone are associated with limestone clasts of a similar nature to the foraminiferal limestones of the Lower Coralline Limestone. At Wied il Mielah, Gozo (287923) , miliolid biosparite breccia occurs in association with the basal Upper Coralline Limestone erosion surface, and similar rounded pebbles of limestone, associated with a somewhat higher surface, are seen in the outlier at Ras il Wardija, Gozo (269833). A further erosion surface between the Tal Pictal Beds at Tat Tomna and Cerkewwa, Malta, also yields occasional Limestone pebbles of a similar nature to the underlying Tal Pictal Beds. Clearly these erosive episodes are associated with local erosion and this is further confirmed by the occurrence of angular blocks of Blue Clay in the basal Upper Coralline Limestone sediments of Ghajn Barrani on the north Gozo coast. Channel bottom deposits in the San Leonardo outlier of eastern Malta yield further well rounded limestone pebbles of three distinct types, namely, pale grey biomicrites, brownish limonitic clasts and black clasts, though the latter two are of a very powdery nature. Finally, the youngest conglomerate recognised in the

Miocene sequence to date is that occurring in isolation close to the top of Tas Salvatur, Gozo (329915), where large rounded pebbles up to 400mm. occur and appear to consist of locally derived material from the Tal Pictal Beds.

b. Distribution of Rock Colouring within the Formations.

Many of the changes in derived component type with time are also reflected in changes of overall rock colour within the formations, which in turn appear to reflect fundamental changes in chemical composition. The dominant minerals affecting colour within the Maltese succession are:

(i) Limonitic minerals
(ii) Kaolinite

(i) Limonitic Minerals

The oldest rocks exposed in the Lower Coralline Limestone are pale yellow in colour, but this is rapidly replaced by pure white limestone of the Attard Member. This member is succeeded by pale brown biosparites of the Xlendi Member, and a brown to yellow colour continues to be a characteristic of the succession until the C1 Conglomerate Bed. At about this time there appears to have been drastic reduction in the ferruginous content of the strata, resulting in the development of a white to pale grey sequence of biosparites of the Middle Globigerina Limestone, throughout all areas of the islands. A local change back to a yellow biosparite facies in the upper third to half of this sub-formation, in western Gozo, marks a return to more limonitic conditions, which are most obviously seen at the C2 boundary, where white Middle Globigerina Limestone is seen to underlie yellow Upper Globigerina Limestone. This yellow colour occurs both at the top and the base of the Upper Globigerina Limestone and probably throughout parts of the Blue Clay, though its effects are masked there by the darker coloured clay minerals.

In the basal part of the Upper Coralline Limestone there is strong evidence to suggest that the limonitic colouring, here proveable as being a result of breakdown of goethite from derived foraminiferal fragments within the Ghajn Melel Member, ~~is seen to~~ diminishes eastwards, as does overall grain-size. The Ghajn Melel Member in the west is stained a dark golden brown, whereas the time equivalent Mtarfa Beds of the east are pale yellow and appear superficially to resemble the Globigerina Limestone in general colouration. Above this level there is a sharp return to pure white limestone sedimentation, well seen at the contact between the Mtarfa Beds and the Rdum il Hmar Beds of Rdum il Hmar, Malta. This appears to have been the final major change in rock colouration, as all succeeding strata are of a pale grey colour, except where affected by Quaternary terra rossa infiltration.

(ii) Kaolinite

Although this mineral is probably present in small quantities throughout most of the succession it only contributes significantly to rock colouration in the upper part of the Middle Globigerina Limestone of westen Malta, in the B Bed of the Upper Globigerina Limestone, the Blue Clay Formation, and finally the basal part of the Coralline Algal Bioherm within the Upper Coralline Limestone Formation. In all cases the presence of Kaolinite, proved by X-ray diffraction analysis, imparts a grey colour to the strata, the intensity of the colour depending on the amount of $CaCo_3$ present in the rock, as outlined in Chapter 5. The kaolinite content fluctuations appear to be far less related to erosion episodes than do the limonite influxes, suggesting that the two may be controlled by independent factors.

c. Interrelationships between Allogenic Components, Erosion and Rock Colour

The obvious association between erosive episodes and the influx of allogenic material and limonite, the latter possibly originally in the form of a fine suspension, permits the development of a broad picture of the conditions prevailing during Miocene sedimentation. Much of this material is almost certainly derived from areas to the west of the islands and also north of Gozo. This latter conclusion is based on the interpreted current transport directions, obtained by pebble size and bed thickness analyses in the Globigerina Limestone (Chapter 4), and from bryozoan growth-form studies and foreset data in the Upper Coralline Limestone (Chapters 7 and 8). This is further supported by the limonitic colour of the basal Upper Coralline Limestone, which decreases eastwards from a deep brown in the more proximal Ghajn Melel Beds, to a pale yellow colour in the easter Mtarfa Beds. The comparatively unabraded nature of much of the material in the conglomerate beds leads to the belief that the source area was at no great distance from the present Maltese coastline.

The continual arrival into the Maltese area of phosphorite, apparently containing a comparable fauna throughout this time, suggests that there was either constant erosion of a particular bed throughout the Miocene or, more likely, that a stable facies was established in which phosphorite was continually being produced. Periodic erosion of this area may then have transported the material into the Maltese area.

The glauconite is also closely related to the phosphorite as the two invariably occur together, although phosphorite is dominant below the Blue Clay and glauconite dominant above.

d. Conclusions Regarding the Nature of Sedimentation outside the Islands

The presence of extensive and frequent erosional episodes within the Maltese strata, particularly in western areas of the islands, strongly suggests that areas immediately to the west of the islands acted as very unstable, yet positive, areas throughout Oligo-Miocene times. As stated in Chapter 4 the depth of accumulation of the phosphorite deposits must have been minimal, and, in conforming to current theories of phosphorite formation, must have been situated on the flanks of a rise-like area subjected to strong oceanic currents. This latter feature is thought to have prevailed throughout the Miocene, thus supporting the conclusion.

The large derived glauconite phosphorite clasts within the Greensand and upper part of the Blue Clay are, upon modal analysis, very comparable to the overall Greensand composition, suggesting that the Greensand formation might be a great deal more extensive in the source areas and possibly earlier in age. It possibly succeeded the Globigerina Limestone phosphorites within the same environmental area at this later stage of Miocene sedimentation.

If these points are accepted then it becomes clear that influxes of allogenic material into the area of the Maltese Islands must reflect episodes of erosion in the area of primary phosphorite and glauconite production on the margins of the rise. The stronger the erosive phase, the larger would be the fragments entering the area, and the greater would be the disconformity between or within formations. The limonitic material must also be associated with the primary area of erosion, although it is uncertain whether all materials involved were Oligo-Miocene in age or whether earlier sediments were available for erosion.

e. Theory of Origin of the Allogenic Material

The materials involved may be divided into the following two groups.

(i) Exotic Rock Clasts and Limonite

(ii) Kaolinite and Biotite

(i) Exotic Rock Clasts and Limonite.

The dominant easterly movement of waters over the Maltese area during the Oligo-Miocene appears to conform with present day movement of surface waters in this part of the Mediterranean (Stanley 1972, p. 94). During the Oligo-Miocene this current appears to have been periodically brought to bear on a tectonically unstable shallow water area of the Malta-Ragusa Rise, lying immediately west of the Maltese Islands (see Figs. 8b and 40). In this unstable area upwelling currents affected a shallow environment of high biological activity, resulting in the production of phosphates,as referred to in Chapter 4. It would also appear that a great deal of iron mineral formation was also occurring in the area,although as it was already oxidised to goethite and limonitie by the time it entered the Maltese area the original composition is difficult to speculate upon.

It is considered that during minor erosive episodes within the source area currents transported limonitic suspensions eastwards, with the result that all sediments forming at that time took on a yellow to brownish primary colouration, as exemplified by the Ghajn Melel-Mtarfa Members. It is likely that the yellow colouring within the Globigerina limestone is also partly the result of *in situ* pyrite oxidation. However, the development of goethite concretions, especially towards the top of the formation, clearly indicates that iron was available either from the sea water or from limonitic suspensions incorporated within contemporarneous sediments.

During the intense phases of erosion, when current transport was at its strongest, large clasts would be ripped up from the area west of the islands. The earliest clasts present in the islands suggest that these came from locally exposed Lower Coralline Limestone outcrops, but later much phosphorite and glauconite, from the positive area on the margins of the Malta rise, entered the area (Fig. 8b). The presence of bored wood in the Upper Globigerina Limestone of Qammieh, Malta (Cooke 1896, p. 503), and teeth of Mastodon angustidens in the conglomerate bed at Marsalforn, Gozo (Adams 1879), suggest the likelihood of land areas or small islands existing in association with these erosive areas to the west and north of the present islands.

Towards the top of the Blue Clay large volumes of water-worn glauconite associated with partly worn gypsum grains, goethite and limonite clasts clearly indicate that for the second time there was local erosion of sediments comparable to the Blue Clay, the biproducts of which were being swept eastwards by the prevailing current. This eroded clay area must apparently overlie pure white limestones of Lower Coralline Limestone aspect, as a little later on in basal Upper Coralline times white biomicrite breccias and conglomerates appear in the western extremities of Gozo, associated with an extensive erosion surface previously referred to.

Glauconite and abraded gypsum grains cease to be important after Greensand times, suggesting that there was a general lowering of the area of submarine, or even subaerial, weathering to situations below the effects of the current. From this time onwards the derived components all appear to be of penecontemporaneous origin, such as the reworked foraminifera of the Ghajn Melel Beds or the occasional pebbles of Tal Pictal Beds higher in the sequence. This is couded with a sudden cessation of limonite present in the strata at the close of Ghajn Melel-Mtarfa Member times. This strongly implies that the long established source areas, lying to the north and west of the islands, were finally covered by new sedimentation, which had the result of removing the source of supply from the effect of the eastward transporting current. The occasional phosphorite mollusc casts that occur in the Gha'jn Melel Member and Coralline Algal Bioherm are invariably very waterworn, and are believed to represent clasts which have been locally liberated from underlying beds rather than to have been transported directly from their original source area.

Throughout the remaining Upper Coralline Limestone time a great deal of reworked local allochem material was progressively swept eastwards in the form of shoals, many of which closely approached sea level. Gradually the lagoon or shelving platform area east of the islands was infilled by this sediment and the entire area took on an intertidal shoal aspect,represented by the Gebel Imbark Member.

(ii) Kaolinite and Biotite

Kaolinite is difficult to account for in the Maltese sediments, especially when it is considered that in Oligo-Miocene times the Maltese area lay towards the crest of a mid-Tethyan sea rise. Present day systems operating in this area of the Mediterranean may possibly give a clue to those of the Miocene,as the overall configuration of the Mediterranean area at that time, together with its theoretical latitude, are not greatly dissimilar to those of today. Venkatarathnam (in Stanley 1972, Fig. 11, p. 467) indicates that most of the Kaolinite entering the Eastern Mediterranean today is derived from arid areas of the North African continent by means of strong south-westerly winds. This mechanism could also conceivably explain the puzzling occurrence of detrital minerals such as topaz, rutile, feldspar and quartz. It is considered that these minerals would be impossible to obtain in a carbonate dominant environment capping a mid-sea rise by normal aqueous transport. Another equally possible explanation involves the hypothetical production of volcanic products in areas to the west of the Maltese Islands during the Oligo-Miocene. Venkatarathnam (1971, p. 279) states that kaolinite , lying at the present day due south of Sicily, may have originated from volcanic peaks in the vicinity of Pantelleria, but has been subsequently dispersed by surface waters moving eastwards. He also considers that aeolian processes may also have had some effect on the assemblage. No evidence exists within the islands to substantiate this latter theory, except that quite euhedral books of biotite mica frequently occur in Blue Clay samples. Folk (1968, p. 87) considers that the dominance of biotite possibly indicates that such sediment has received contributions from volcanic ash.

In conclusion, it is considered that the sudden increase in the rate of clay sedimentation at the onset of Blue Clay times was sufficient to terminate phosphorite production, which develops best in areas of minimal deposition. It may also be that the subsequent development of glauconite at this time was made possible by the availability of minerals such as biotite within the accumulating Blue Clay.

SUCCESSIVE HYPOTHETICAL CROSS-SECTIONS THROUGH THE MALTESE AREA DURING DEPOSITION

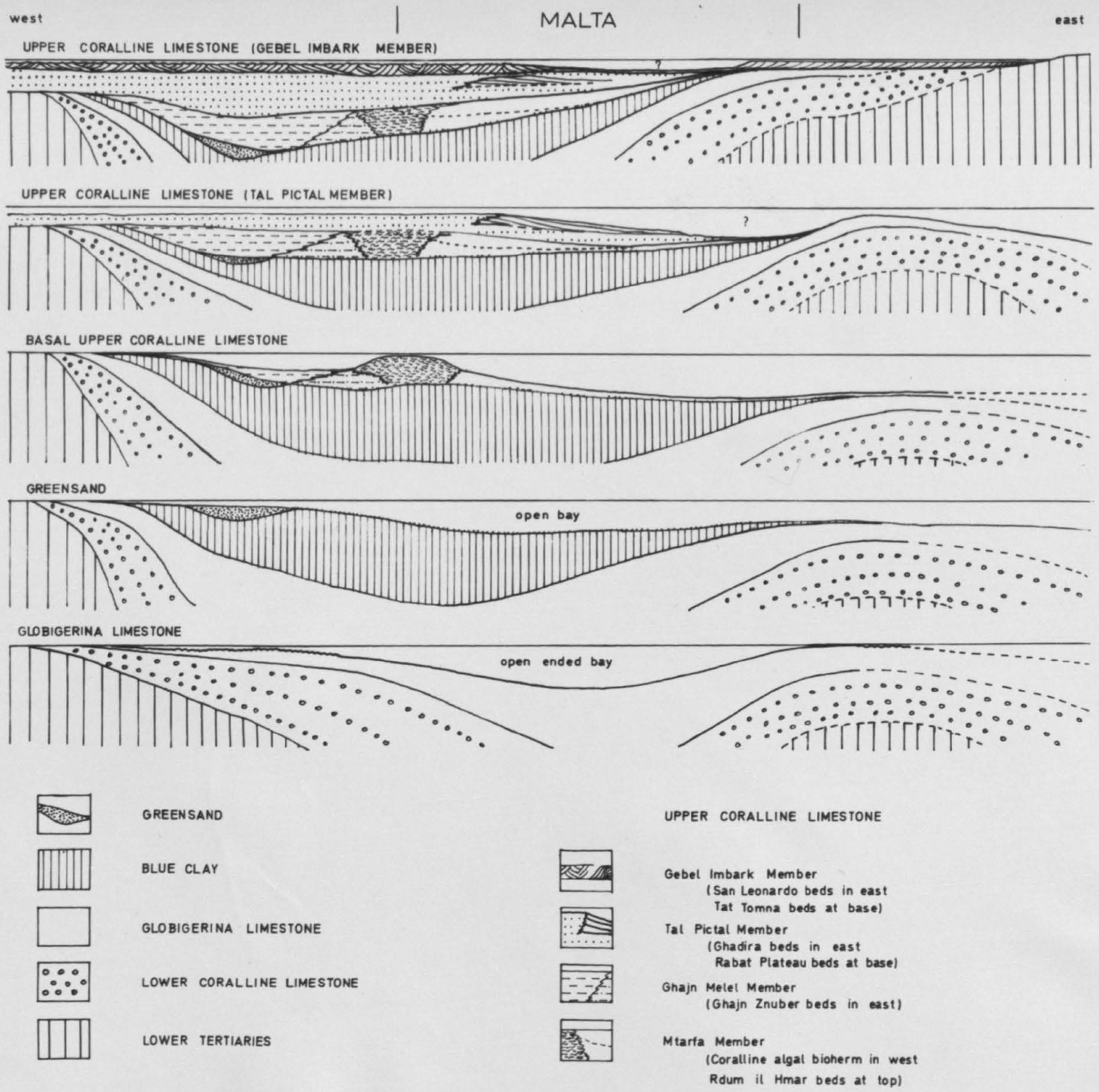


Fig. 40

CHAPTER 12

SOLUTION SUBSIDENCE STRUCTURES

1. Introduction

(i) General

Throughout Malta and Gozo, but particularly in western areas of those islands, a large number of circular to elliptical structures occur (Fig.41) which have previously been designated as "sinks". Spratt (1843) briefly noted these structures, and Murray (1890) recorded the positions of several of the larger ones on his geological map of the Maltese Islands, although he referred to them merely as "circular faults", offering no explanation for their origin or occurrence. Hobbs (1914, p.8) recognised the extensive distribution of these structures, together with their close association with the major fault systems of the islands, although it was Trechmann (1938) who first suggested that they probably resulted from cavern roof collapse. These structures, though on a much larger scale, are most comparable to subsidences affecting Cretaceous rocks in south-west Ireland (Walsh 1967).

At outcrop the structures are invariably elliptical in outline and have vertical walled margins. They vary in diameter from about 40 metres up to a maximum of 400 metres, and may outcrop in the form of a hill, where resistant beds have been lowered into softer strata, as for example, Tas Salvatur, Gozo (329915), or as basin-like depressions such as Qawra, Gozo (274900). Until the present study the term "sink" was still applied to these structures, however, it soon became apparent that the term was incorrectly applied as the structures are not merely pipes permitting access of surface water into subterranean cavern systems. They are true collapse structures affecting considerable volumes of sediment, which have been lowered into depressions produced by "circular" faulting, or are collapse structures affecting the seabed during normal sedimentation which were subsequently rapidly infilled by penecontemporaneous marine sediments. Because of the confusion in previous terminology relating to these structures it has been decided to adopt the term "solution subsidence structure", which was used by Walsh et al. (1972) in their description of the pocket deposits of Derbyshire.

Solution subsidence structures are widely distributed throughout the islands, although the restricted exposures of many of them led some early workers to the conclusion that all were the product of cavern roof collapse into cave systems of post-Miocene age. Although this is a correct interpretation for many of the smaller structures, the present study shows that at least 10 of the largest subsidences formed by submarine cavern collapse. It appears that collapse of cavern systems, postulated as early as Tertiary in age, locally modified seafloor deposition. Within the resulting local seafloor depressions a thick sequence of sediments accumulated, which showed little similarity to their time equivalent counterparts forming locally in unaffected seafloor areas.

A second phase of cavern development occurred in late Tertiary time and was probably associated with regional uplift and faulting. This cavern formation appears to have enlarged the pre-existing cavern systems, causing a second episode of solution subsidence formation in many areas, and also reactivated further subsidence of the existing Miocene structures.

2. General Details

Field data indicate that the Miocene solution subsidence structures may be divided into two main formational episodes, the lower connected with erosive episodes associated with the Scutella bed, and C1 and C2 Phosphorite Conglomerate Beds of the Globigerina Limestone, and the higher with the erosive intervals within the base of the Upper Coralline Limestone. A possible third episode illustrated by the Ghajn Abdul structure is also recognised and is associated with the youngest Upper Coralline Limestone sediments.

Post-Miocene subsidences are numerous in all formations, although, as with their Miocene counterparts, they generally occur most frequently on the western sides of the islands (Fig.41). Both Miocene and later subsidence structures are very similar in form, being circular or elliptical in plan, though several, such as the Xlendi Outlier, have been modified by later faulting. Although the vertical walled nature of the margins of several of the structures are clearly defined, particularly where the sedimentary infilling has been preferentially removed by erosion, many of the others have their faulted margins partly obscured by the penecontemporaneous infill. Despite this, many of the subsidences can be proved conclusively to have collapsed through several hundred metres of older strata without major disturbance either to the country rock surrounding them or to their sedimentary infillings.

Later faulting has fractured the previously intact rims of many of the Miocene subsidences and is apparently related to renewed activity of the collapse mechanism. This has resulted in further displacement of the fault-bound plugs of sediment. The close association of both the Miocene subsidences and the later ones also points to the possibility of rejuvenation of the same mechanism of formation for the latter structures.

The primary infill of the subsidences requires full consideration as it is by the nature of this material that the age correlations for each structure are based. Post-Miocene structures are generally infilled by Quarternary soils, usually conforming to terra rossa in composition, but these may frequently be altered to caliche (Plate 19c). When observable, the initial infilling of newly formed subsidence structures consists of large angular boulders, which probably collapsed from the unsupported rim walls of the subsidences soon after formation. In some cases, such as the Sliema seafront, extensive cementation by calcite has occurred prior to soil infilling.

The Miocene subsidences, being submarine in origin, differ from the later structures in that marine fossils are associated with the penecontemporaneous sediments, such as at Tal Harrax. The sediments post-dating seafloor subsidence are usually characterised by poor sorting, scour and fill structures (Plate 20a), and in some cases by slumping. Lensoidal thickening of beds is also seen at some horizons within these structures (Plate 19b). Many of these primary features are unknown within the contemporaneous strata outside the confines of the subsidences, creating the impression that the sedimentary infillings within the faultbound subsidence margins have been derived by spillage, over the rim shoulders of materials from neighbouring areas. Once within the confines of a subsidence this sediment appears to have gravitated towards the centre of the seafloor depression.

Angular blocks of lithified and semi-lithified sediment, often several metres long, are present around the internal margins of many subsidences and are associated with intricate contortions within the early unlithified subsidence infill (Plate 20c). These blocks often aid in the correlation of the subsidence infill with unaffected areas. Where pre-subsidence sediments are visible beneath the infill it is possible to date accurately the moment of seafloor collapse and, if capping sequences are also present, the actual amount of seafloor depression can be calculated. Usually, however, only one of these is present, but this is sufficient to determine the time of collapse quite accurately.

3. Miocene Subsidence

It is significant that all the recognised Miocene subsidence structures are closely associated with episodes of intense shallowing of water. These episodes are recorded by the presence of phosphorite conglomerates, usually in beds less than 1 metre thick, in the lower Miocene sediments, and by extensive erosion planes in the upper units. The subsidences recognised to date may most conveniently be divided into three phases, each apparently separated from the next by a prolonged period of comparative stability. These are as follows:

c. Phase 3 Later Upper Coralline Limestone subsidence
b. Phase 2 Basal Upper Coralline Limestone
a. Phase 1 Scutella bed and Globigerina Limestones

a. Phase 1 Scutella bed and Globigerina Limestones

(i) Dwejra North Outlier (271897)

This is a 340 metres diameter elliptical structure lying on the coastline of western Gozo. It is almost entirely inundated by the sea, the exposed parts being represented by a small portion of the eastern rim, together with contemporaneous sediments, and a small outcrop just off the coast, representing the western margin of the structure. The structure lies in Xlendi Member strata of the Lower Coralline Limestone, just below the Scutella bed.

Examination of the faulted margin, where accessible, shows it to be approximately vertical but has apparently suffered submarine erosion prior to being infilled, as the infilling sediments are cemented against smooth walls and project into hollows and pockets in the walls. The few metres of sediments exposed within the structure consist of pale grey and cream coloured, unsorted carbonates, overlying a phosphorite conglomerate horizon. These clearly dip in towards the centre of the subsidence and are underlain by yellowish biosparites, also thought to be part of the penecontemporaneous infilling. The sediments are undoubtedly marine as they contain tests of Echinolampas sp., many Cidaris spines, abundant fragments of Scutella subrotunda, especially close to the subsidence margin, disarticulate Ostrea sp., and abundant fragmentary bryozoa. The sediment infill is correlated with the Scutella bed, which occurs about 2 metres higher around the rim of the structure. Its total displacement is unknown.

(ii) Xlendi Outlier (295877)

Although this structure is smaller in diameter than the previous one, it is far better preserved (Plate 19a,b and Plate 20a, b). The structure occurs in Xlendi Member and consists of an apparently vertical walled,irregular shaped structure containing over 80 metres of poorly sorted biosparite. The fault margins of the structure resemble those of Dwejra North, in that no slickenside development is seen. The contained sediments are plastered against the fault walls (Plate 20b), infilling cavities and irregularities in these. They are penecontemporaneous with subsidence, consisting of brown to orange poorly sorted biosparites, containing occasional echinoids and abundant phosphorite pebbles. Despite later modification of the subsidence by minor faulting, the sediments are clearly seen to exhibit a primary dip towards the centre of the depression. Lensoidal thickening of beds, particularly the later ones, is seen towards central areas of the preserved subsidence infilling. Scour and fill structures are the commonest primary structures of the infill, and all appear to indicate mass sediment transport towards the lowest point within the subsidence.

The lowest strata preserved within the structure is normal yellow Lower Globigerina Limestone containing Cavolinia sp., and is considered to represent pre-collapse seafloor sediments which were subsequently lowered into the structure. The penecontemporaneous infill commences with coarser Globigerina Limestone containing much glauconite and abundant small phosphorite pebbles, and rapidly culminates with a prominent conglomerate horizon (Plate 20b) which can be followed into the centre of the subsidence. Above this the coarse poorly washed lithoclast biosparites, typified by scour and fill channels, commence. Finally, a thin bed of sub-centimeter sized phosphorite pebbles occurs close to the top of the preserved infill and is capped by paler coloured Globigerina Limestone similar in aspect to the pre-collapse sediments.

The subsidence infill is dated as C1 Phosphorite Conglomerate Bed in age,on the basis of a 3 metre lens of poorly washed lithoclast biosparite, containing scour and fill channels which occurs close to the north-eastern rim of the subsidence. This lens is confined within the C1 Conglomerate Bed and is bounded both above and below by phosphorite pebbles. Apart from the lens no other abnormality is recognised between the typical lower Globigerina Limestone below the C1 Bed,and the White Middle Globigerina Limestone above the C1 Bed in this area. Post Miocene movement may be up to 30 metres and has produced further subsidence of the infill within the structure. It is recognised by small crescentic faults within the infill sediments and larger faulting, which has fractured and displaced the rim margins of the structure, particularly on the northern side.

(iii) Tal Harrax Outlier (276890)

This is a poorly exposed structure, at least 400 metres in diameter, which lies to the south-east of Dwejra Bay (see Fig.43). It appears elliptical in outline, however, it is complicated by later faulting. The exposed penecontemporaneous marine infill consists of pale grey marls exhibiting scour and fill structures, and several horizons of sub-centimeter sized phosphorite pebbles. 13 metres of subsidence infill is exposed which thins to less than 2 metres when followed towards the southern margin of the structure. The youngest infill consists of nodular and bedded khaki coloured cherts, which are not recognised outside the subsidence structure. Fossils are common in these beds, consisting of spines and test fragments of Cidaris sp.; and Ostrea sp., Terebratula sp., and other indeterminate shell debris occurs in the bedded cherts.

Approximately 12 metres of grey and cream, typical Middle Globigerina Limestone biomicrite cap this infill and, hence, confirm the time of subsidence as being close to C1 Bed times. Post-Miocene subsidence may amount to 100 metres, as a plug of Blue Clay has subsided into the central regions of the structure.

(iv) Qawra Outlier (274900)

Of all subsidence structures present in the islands this one is best exposed, as Blue Clay, the dominant infill, has been progressively removed by erosion. This has resulted in the exposure of the intact vertical margins of the subsidence, which stand as high walls of Lower Coralline Limestone surrounding the 400 metre diameter subsidence amphitheatre. The Blue Clay is seen to conformably cap the marine penecontemporaneous subsidence infill in the road section between the fishermen's huts and the church, in the north-western corner of the structure, and therefore places the age of the infill as Upper Globigerina Limestone. This infill, although exposed on the west, east and south sides of the subsidence, is best seen at the southern end (Plate 20d), where large angular boulders of phosphorite, and what appears to be C1 Conglomerate Bed occur in close association with brown to orange, poorly washed lithoclast biosparites. In addition, articulated shells of the brachiopod Megerlia sp. occur in this sediment. This Upper Globigerina Limestone sediment is unlike sediments outside the structure, which consist of a thin succession of clayey Upper Globigerina Limestone. In all exposures of penecontemporaneous subsidence infill the primary dip is towards the centre, and scour and fill structures are recognised. The amount of primary subsidence is unknown, although post-Miocene subsidence, consisting of "circular" faulting affecting the infill close to the primary fault margin of the subsidence, has lowered Blue Clay at least 100 metres down into the centre of the structure.

b. Phase 2 Basal Upper Coralline Limestone

(i) Ghajn Barrani Outlier (344915)

This 260 metres diameter elliptical structure is located in the top of the Blue Clay of Northern Gozo. It has clearly been initiated at the base of the Ghajn Melel Beds of the Upper Coralline Limestone, as coarse, unsorted brown biosparites, which form the penecontemporaneous marine infilling, can be followed laterally in the cliff section and extend into more typical finer Ghajn Melel sediments beyond the confines of the subsidence. This subsidence was initiated immediately after an episode of strong erosion. Large lithified blocks of Blue Clay were produced by this erosion and now occupy the basal layer of the subsidence infill, with the largest blocks lying at the lowest point in the structure. Scour and fill structures are common in the upper levels and small scale slumping is recognised. Sediments capping the subsidence infill can be followed along the cliff section and show that the 23 metres of penecontemporaneous subsidence infill can be correlated with 6 metres of similar, though finer grained, sediments, occurring beyond the margins of the structure. Slight post-Miocene movement is recognised, mainly as faulting close to the original, though hidden, subsidence walls. A small outcrop excavated by the sea on the northern margin of the structure clearly shows that the peripheral walls associated with the subsidence are vertical.

(ii) Qolla S-Safra Outlier (329923)

In northern Gozo, just west of Marsalforn, a further 75 metres diameter circular subsidence structure occurs and weathers out in positive relief, as the limestones involved (Qolla S-Safra Beds and Ghajn Melel Beds) are less severely affected by erosion than are the surrounding Globigerina Limestone and Blue Clay. The Blue Clay merely lines the walls of the subsidence and is poorly exposed. However, the Qolla S-Safra Beds are clearly seen and mainly comprise the penecontemporaneous marine infilling, resting on the Il Gelmus Member of the Greensand Formation. 7 metres of penecontemporaneous infill is present, consisting of sorted yellow biosparite. Blocks of semi-lithified,although identical; sediment, have entered the basal parts of the infilling during formation, and are associated with contortions and slumping within the infill sediments. These infill sediments are capped by Ghajn Melel Beds, thus indicating that subsidence was approximately contemporaneous with that of the Ghajn Barrani Outlier. The subsidence infill is further correlated with 2 metres of identical sediments seen at Tas Salvatur (329913), 1 km. to the south. Post-Miocene subsidence is in the order of 63 metres, as the Qolla S-Safra Beds now lie at the same elevation as the top of the Upper Globigerina Limestone.

(iii) Wied il Mielah Outlier (287923)

A 160 metres, irregularly outlined subsidence occurs in isolation, in north-western Gozo. It now rests within Middle Globigerina Limestone,although its high glauconite content and coarse bioclastic nature indicates that it belongs with the basal Upper Coralline Limestone. Only 2 metres of sediments are exposed, commencing with a breccia of exotic white miliolid limestone fragments. This is considered to equate with the basal Upper Coralline Linestone erosion surface. Post-Miocene movement may be as great as 90 metres.

(iv) Citadel Outlier (316893)

A further subsidence structure, weathering out in positive relief, occurs at the Citadel, Gozo. It is 170 metres in diameter and is circular in cross-section. Penecontemporaneous subsidence infill consists of 21 metres of sorted biosparites, containing bryozoa and other marine fossils. Scour and fill structures are visible in the inaccessible upper horizons and, on the western side, sediments are seen to dip into the centre of the structure. The infill is correlated with 11 metres of identical sediments on Il Gelmus (310894), 400 metres to the north. This confirms the collapse time as being approximately contemporaneous with Ghajn Barrani.

c. Phase 3 Later Upper Coralline Limestone Subsidence

(i) Ras il Wardija (269883)

This is a 40 metres diameter circular subsidence, which occurs in south-western Gozo. The subsidence infill is of Upper Coralline Limestone age and weathers out as a positive feature. Although 4 metres of packed yellow biosparies and biomicrite infill rest on Blue Clay, the latter is poorly exposed, as it is concealed beneath the caprock and entirely surrounded by Globigerina Limestone. Boulders of Ghajn Melel Member, and lithoclasts which may equate with the Tal Pictal Member, are enclosed within the basal part of the penecontemporaneous marine infilling and point to a younger age for this structure than for previous ones. The erosion plane producing these boulders is unrecognised elsewhere in the islands but, being situated on the western side of Gozo in an area prone to many local erosive episodes, and now with few Upper Coralline Limestone outcrops, this is not surprising. Post-Miocene subsidence associated with this structure may be as much as 34 metres, this figure being based on the calculated possible thickness of the missing sediments between C2 Conglomerate Bed and probable subsidence horizon within the Upper Coralline Limestone.

(ii) Ghajn Abdul Outlier (287894)

The Ghajn Abdul Outlier is 400 metres in diameter and is almost circular in outline. The structure now rests in Blue Clay, but, as the base of the penecontemporaneous infilling is buried, it is impossible to state the full amount of initial displacement, or the precise horizon in the Upper Coralline Limestone at which it occurs. The subsidence infill consists of 24 metres of thinly laminated white biosparite and biomicrite, containing rare crustacean and pectinid remains. Scour and fill structures are common throughout the beds and the lowest horizons are characterised by large boulders of molluscan biosparite up to 4 metres in diameter. These resemble some of the boulders of limestone seen at Ras il Wardija and are similarly correlated with the Tal Pictal Beds. Associated with these boulders are large scale contortions and slump structures (Plate 20c) affecting the penecontemporaneous infill. This infill dips into the centre of the structure from all sides and the greatest numbers of boulders occur at the lowest points in the exposed infill, particularly on the south and west sides of the structure. The contorted beds indicate that many of the boulders have entered the structure from the south-western side at a time when the initial sediments were still unlithified.

The capping sequence to the hill is similar to that on Tas Salvatur and hence, indicates a possible correlation with a horizon high in the Upper Coralline Limestone. Post-Miocene movement in this instance is calculated at approximately 34 metres.

4. Subsidence Mechanism

a. Evidence for pre-Miocene Cavern Development

The only direct evidence obtained to show that the subsidences collapsed into cavern systems of pre-Miocene age is from western Gozo. Both the Xlendi and Qawra subsidence structures penetrate up to 100 metres of Oligocene, Lower Coralline Limestone in this area. The occurrence of large cavities deep within the buried Lower Coralline Limestone is recorded in British Petroleum's Naxxar borehole (unpublished), of eastern Malta. These are recorded to a depth of many hundreds of feet and are likely, at least in part, to be of pre-Miocene age. The Naxxar borehole does not reveal any major evaporite horizons to account for subsidence, hence, cavern development in a subaerial environment, produced by percolating groundwater, must be considered.

Indirect evidence for the possible existence of major Miocene erosive phases, at least in areas close to the west of the Maltese Islands, is plentiful and has been discussed in Chapter 11. Some of the erosive episodes are considered to have resulted in subaerial erosion in areas to the west of the islands. No direct evidence exists, however, for uplift of sufficient magnitude to raise any part of the Maltese Islands more than a few metres above sea level. The vughy nature of much of the sediment penetrated in the Naxxar borehole suggests that uplift may well have occurred at several intervals since the Cretaceous. The lack of sizable vughs and caverns encountered in this borehole is partly to be expected, as examination of Fig.41 reveals that solution subsidence structures increase in numbers and dimensions in a westerly direction in both islands, being largest in western Gozo. This is taken to indicate that the underlying cavern systems of the islands also increase in dimensions in a westerly direction, probably indirectly showing that uplift was greatest in that area. It is considered that these pre-Miocene cavern systems resulted from carbonate solution associated with a regional uplift in the west, rather than solution of evaporites. Solution of the latter is finally rejected on the basis of Miocene sediment distribution studies, which show that most basin-like structures developed within the islands are either centrally situated or are located on the eastern side of Malta. If this is consistent with unexposed underlying sequences it is likely that the Naxxar borehole should have penetrated considerable thicknesses of evaporites, assuming that they were present as a result of basinal development. By the same logic the western Gozo area would not be expected to yield evaporites, because of its location, and hence, should not show subsidence effects produced by evaporite solution.

In conclusion, it is believed that the Maltese Islands have undergone many episodes of uplift and erosion throughout the whole of the Oligo-Miocene episode, and it therefore appears reasonable to postulate that this has also been the case in the underlying, unexposed lower Tertiary sediments.

b. Theory of Formation

It is postulated that a particularly intense period of uplift and erosion occurred in western areas of the Maltese Islands during the early Tertiary (Fig.42). This was sufficient, at least in western Gozo, to create a land area possibly as much as 100 metres in elevation. Widespread subaerial solution and cavern development occurred in this new land surface. Under these conditions cavern system dimensions would be determined by land elevation and water table level. Hence, it is considered reasonable to suggest that, in a land area of low elevation, much of the cavern development was very close to the surface. Subsequently, submergence (B. in Fig.42) lowered the rocks to a situation in which they once more came under the influence of marine sedimentation. In this environment the thin cavern roof would withstand the increasing weight of overburden as long as tectonic conditions remained stable. If, however, uplift subsequently occurred, indicated by the presence of erosion surfaces in the case of the Maltese Miocene, the resulting crustal warping may have been sufficient to trigger off collapse of the weak cavern roof materials. This would cause the collapse of a vertical column of seafloor sediments into the cavern (C in Fig.42).

An elliptical seafloor depression would result from this and would immediately proceed to become infilled with unsorted sediments brought into it by the erosive water currents. This effect has been simulated in flume experiments by Jopling (1965, p.789), in which rapid base level lowering produced torrent bedding, containing structures comparable to those within the Maltese subsidences. The poor sorted nature of the Maltese sediments is also consistent with this type of mass sediment movement. Angular blocks of both lithified and semi-lithified wallrock from the unsupported rim margins of the structure would also tend to fall into the subsidence, and would cause contortion and slumping of the primary unlithified infill. Ultimately the depression would become infilled and normal marine sedimentation would proceed as before the event (D. in Fig.42).

The effect of crustal upwarping as a triggering mechanism for subsidence could explain the apparent synchronous nature of collapse of the structures associated with each of the first two phases. Perhaps the effects of warping were restricted to the extreme west of Gozo during phase 1, whereas, the phase 2 subsidences were triggered off by uplift of both western and central regions of Gozo.

The palaeogeography of the Maltese Islands at this time appears to have had much in common with the Florida peninsula and Bahamas. Continental areas of low elevation extended around the northern offshore areas of Gozo, and extended down the western offshore areas of Malta as a series of low islands inter-connected by wave-cut platform. Low land areas also extended intermittantly in eastern offshore areas of Malta. Between these lay a series of interconnecting lagoons receiving shallow water bioclastics and periodic influxes of conglomerates and breccias derived from the inter-island erosion areas, particularly to the west and north. The extent of the subaerial regions appears to have fluctuated with time, due to regional tectonic adjustments, so that on occasions western and south-eastern areas of the Maltese Islands became either land or areas subject to marine erosion. At other times the land areas were reduced to small islands, thus allowing the influx of planktonic bioclastics into the area now represented by the Maltese Islands. The occurrence of solution subsidence structures, apparently formed subaerially but now lying in 140 to 150 fathoms of water, off the southern Florida peninsula (Jordan 1954) further strengthens the comparison between the two areas.

Although the precise horizon of pre-Miocene cavern development is uncertain, it may tentatively be correlated with an erosional episode in Libya noted by Selly (1969, p.422), which also appears to occur throughout other areas of north Africa. The unconformity brings Burdigalian strata into contact with lower Oligocene rocks.

Finally, it is worth commenting on the surprising vertical displacements of these relatively small, elliptical plugs of subsidence infill, many of which have subsided through a considerable thickness of Blue Clay before entering Globigerina Limestone, apparently without suffering major fracture, or even tilting. These Maltese examples are by no means unique in this respect, as was shown by Stockdale (1936, p.522) in respect to the "Montlake Sink" of the Cumberland Plateau, Tennessee. This 390 feet (119 metres) diameter subaerial structure has undoubtedly subsided through 800 feet (244 metres) of strata, most of which was non-calcareous in nature. Smaller diameter structures within the Millstone Grit of Wales (Thomas 1963, p.47) have been proved to have penetrated 250 feet (76 metres) of non-calcareous sediments before entering the Carboniferous Limestone. These two examples show conclusively, that the maximum of 65 metres of Blue Clay present within the Maltese Islands would provide no great obstacle to the effect of subsidences extending their effects from earlier Tertiary strata, into the Upper Coralline Limestone.

5. Post-Miocene Subsidence

It is generally accepted that the Maltese Islands became a land area at about the close of Miocene times, and have remained above sealevel, with minor exceptions, until the present day. The rich Quaternary mammalian faunas within the islands indicate that the land areas were once a great deal more extensive than at present and probably had direct connections with mainland Europe until relatively recent times (Spratt 1867).

a. Pre-Quaternary Subsidence

All the post-Miocene subsidences marked on Fig.41, with the exception of the Maqluba structure, are believed to fall into this group. Many are recognised merely by the presence of an elliptical surface depression, although the subsidences plugged by Upper Coralline Limestone in Gozo form positive features. In both islands there is a close association between these structures and the regional faulting. The finest example of this type of subsidence is that of Ghajn Znuber in western Malta (Plate 19c). The 80 metres diameter, vertically walled depression is infilled with 60m. of sediment, consisting of large angular blocks of Upper Coralline Limestone close by the rim walls and calcreted red soil infilling the central area. The cavern horizon is not seen. The post-Miocene movement within the Miocene subsidences of Gozo is also believed to fall into this category, as also is the regional graben development of south-western Gozo.

b. Quaternary Subsidence

An extensive network of caverns developed at this time, particularly in the Coralline Limestones, and is represented by the Ghar Dalam and Ghar Hasan networks of the Lower Coralline Limestone,and the cave systems of the Mellieha and Rabat areas within the Upper Coralline Limestone. The systems lie quite close to the present day land surface and are small in comparison to the earlier systems. These solution subsidences are difficult to differentiate from the older ones, but the Maqluba subsidence in Malta, which is reputed to have collapsed in the 14th century, is believed to fall into this group. The cavern development is tentatively dated as Quaternary on the basis of the rich mamalian faunas associated with them.

c, Subsidence Mechanism

(i) Evidence for Reactivation of Subsidences

The Quaternary subsidence structures are believed to have formed by simple roof collapse of material overlying cavern systems at shallow depth. The pre-Quaternary structures are, however, a little more difficult to account for as they are usually aligned along the major fault systems, or are close to known Miocene subsidences, as in the case of western Gozo. Positive evidence of renewal of solution within the pre-Miocene cavern horizon is restricted to the Miocene subsidences of Gozo,where a second episode of movement is recognised in almost all described structures. It is thought that this second phase of cavern development occurred at about the same horizon as the pre-Miocene episode, as this horizon also lies well below present day sealevel. The Qawra subsidence clearly supports this,as part of the Blue Clay has been let down well into the Lower Coralline Limestone by the second subsidence episode. Subsidence displacements during this episode are considerably greater than those associated with the Miocene events. This is taken to imply that subaerial conditinns prevailed for much longer during the post-Miocene episode, and may well have occurred throughout Pliocene times, resulting in the development of cave systems of vast size.

The question of whether subsidence preceded faulting may now be resolved. Faulting in western Gozo is dominantly east-west and runs from one subsidence structure to the next (see Fig.43, from Wigglesworth 1964). Upon intersecting the rim of each structure, the fault deviates around its perimeter before continuing the original trend again. Faulting within the subsidence infill is always of a minor nature and usually takes the form of small cresentic, normal faults associated with the post-Miocene subsidence. The conclusion must, therefore, be that the faulting is later than the subsidences of the pre-Quaternary episode. These faults probably gained access to the surface via the weakest points in the cover sequence where cavern formation and subsidence already existed.

(ii) Theory of Formation

It is suggested that the late Miocene uplift, coupled with general sealevel lowering, was sufficient to cause re-emergence of the pre-Miocene cavern horizon. Reactivation of solution along these old, partially collapsed cavern levels occurred, and was only terminated by subsequent sealevel rise and submergence by faulting. (See Text Fig.42E,F.). Perhaps the east-west graben development in the Qawra and Xlendi regions represents the ultimate collapse of roof materials overlying vast cavern systems, which was brought about by the major regional faulting episode. This may account for the radiating networks of minor faults associated with the regional pattern. These are best seen around the Xlendi structure and may reflect local adjustment of floundering blocks of collapsed cavern roof material, which lie at very shallow depths in these localities.

FIGURE 41

Distribution of Solution Subsidence Structures within the Maltese Islands

a. Xlendi Outlier

b. Dwejra North Outlier

c. Tal Harrax Outlier

d. Qawra Outlier

e. Ghajn Barrani

f. Qolla S-Safra Outlier

g. Wied il Mielah Outlier

h. Citadel Outlier

i. Ras il Wardija Outlier

j. Ghajn Abdul Outlier

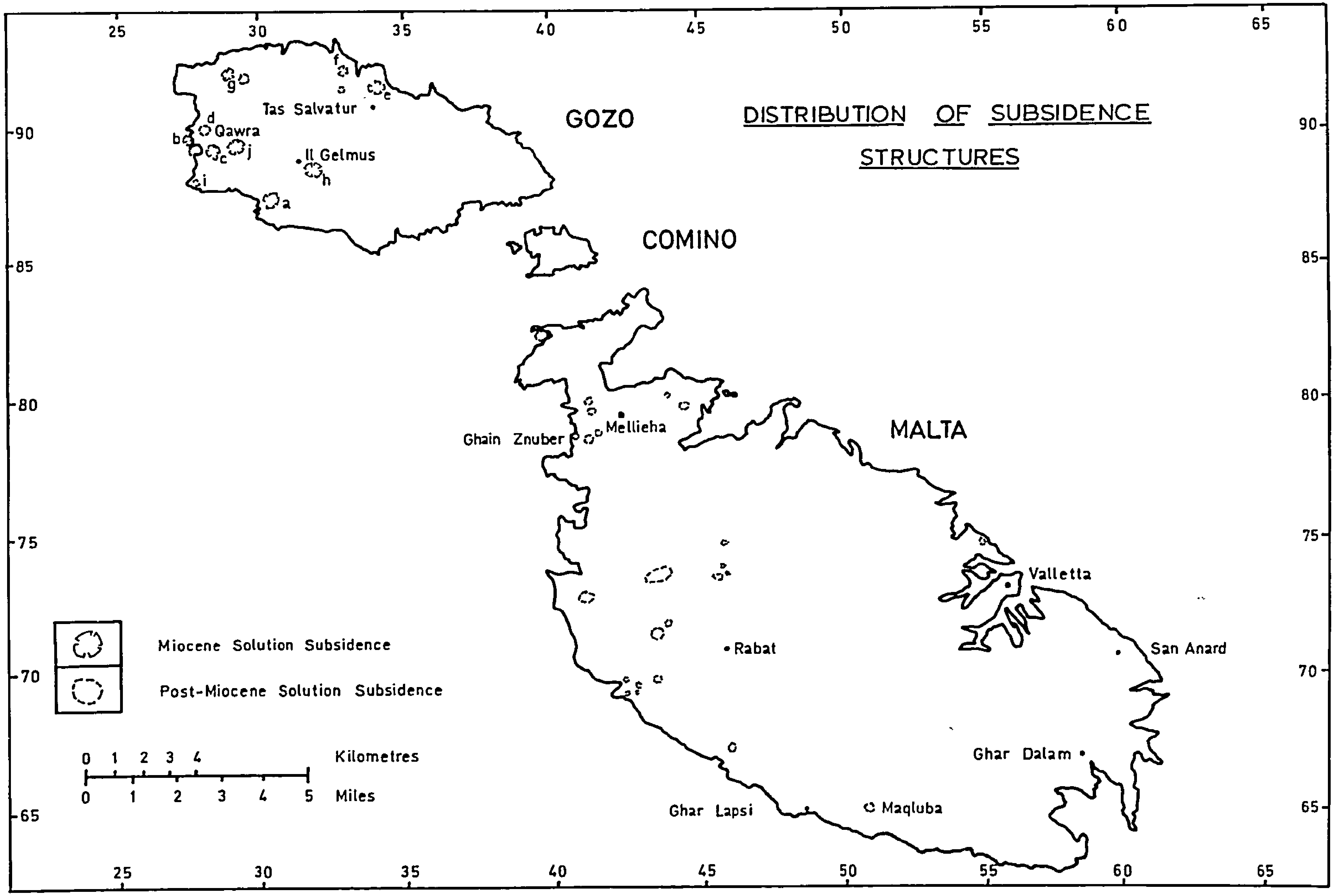

DISTRIBUTION OF SUBSIDENCE STRUCTURES
GOZO
COMINO
MALTA
Tas Salvatur
Qawra
Il Gelmus
a
b
c
d
e
f
g
h
i
j
Ghain Znuber
Mellieha
Valletta
Rabat
San Anard
Ghar Dalam
Ghar Lapsi
Maqluba
Miocene Solution Subsidence
Post-Miocene Solution Subsidence
0 1 2 3 4 Kilometres
0 1 2 3 4 5 Miles
25
30
35
40
45
50
55
60
65
90
85
80
75
70
65

Fig. 41

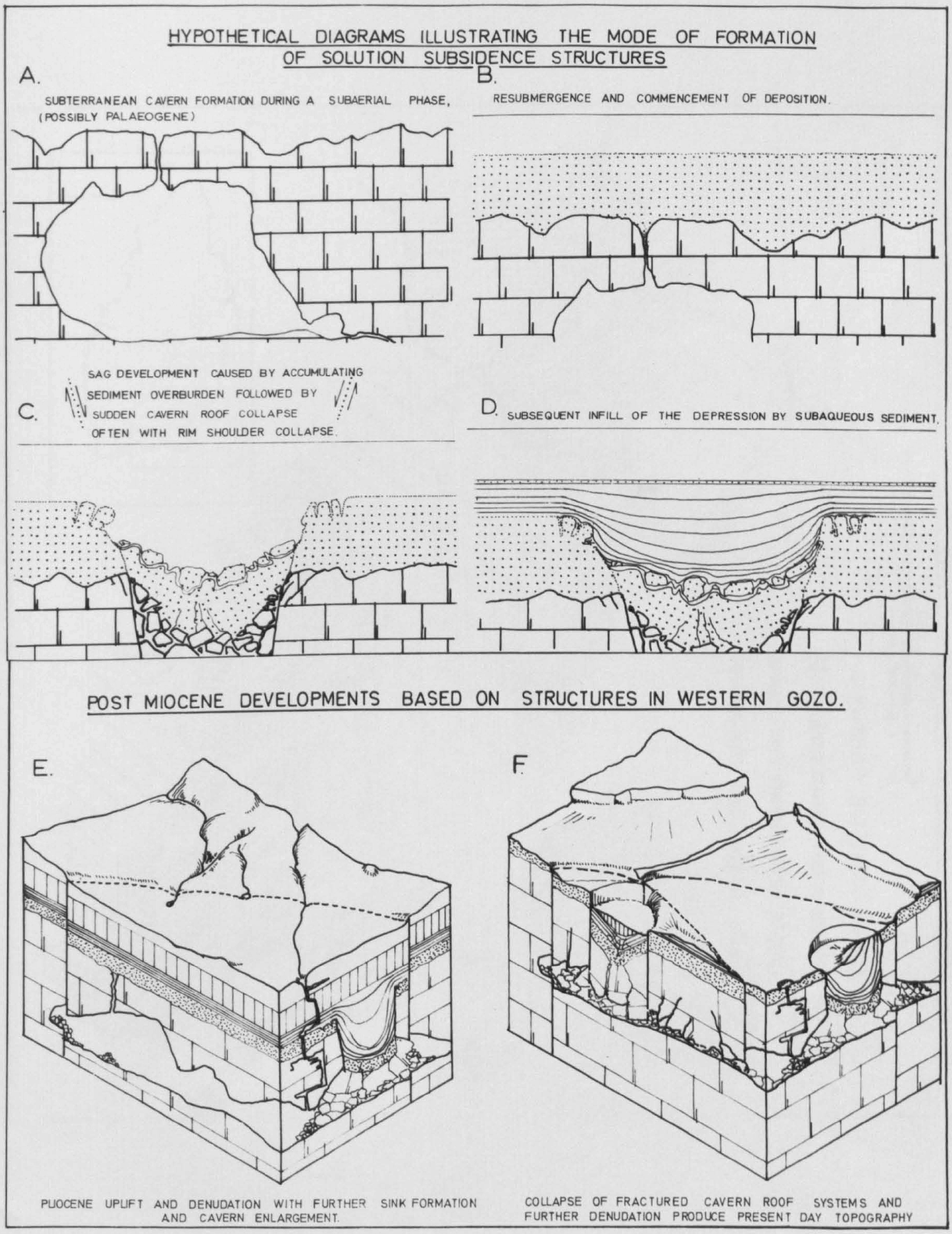
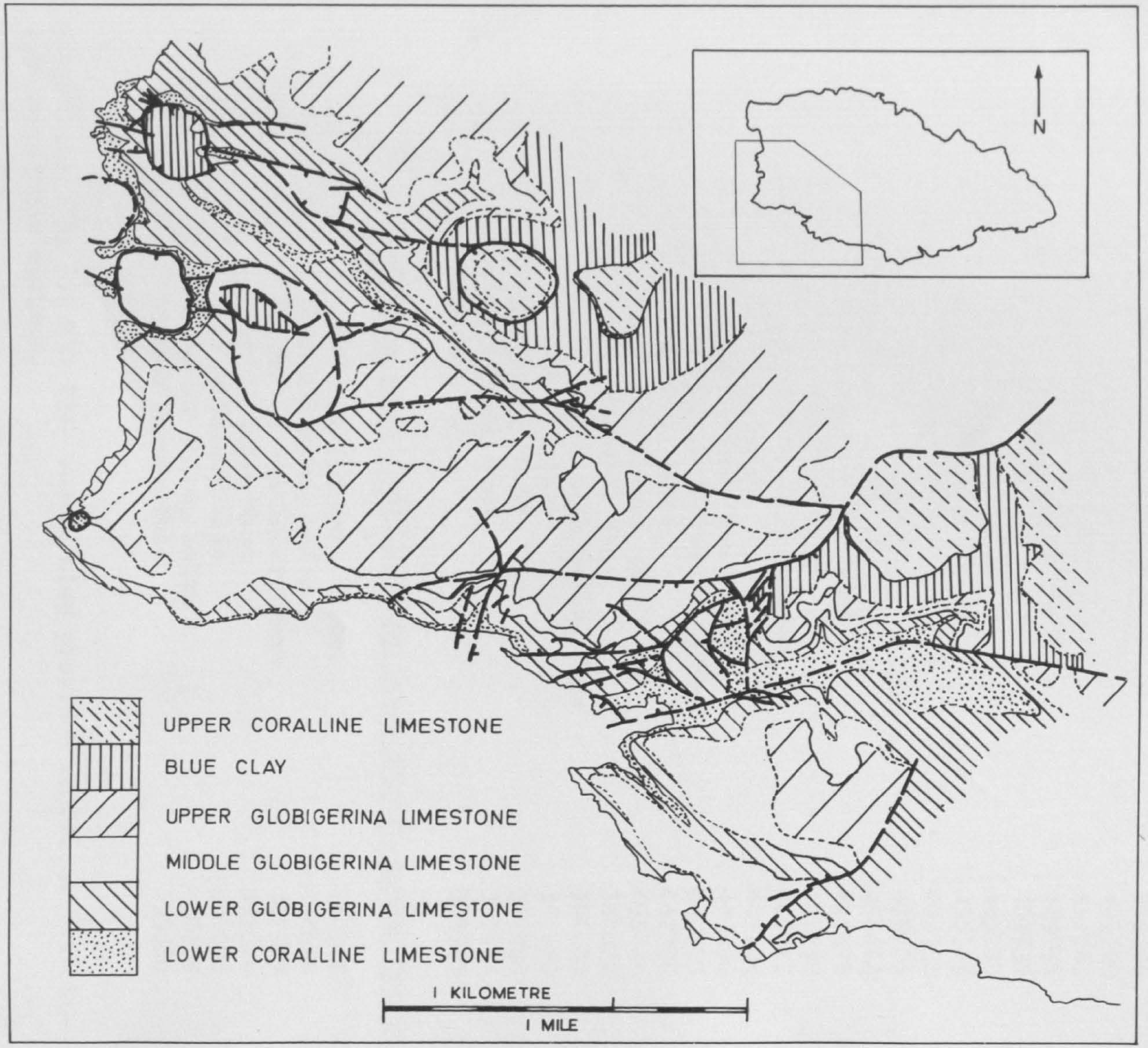

HYPOTHETICAL DIAGRAMS ILLUSTRATING THE MODE OF FORMATION OF SOLUTION SUBSIDENCE STRUCTURES
A.
SUBTERRANEAN CAVERN FORMATION DURING A SUBAERIAL PHASE, (POSSIBLY PALAEOGENE)
B.
RESUBMERGENCE AND COMMENCEMENT OF DEPOSITION.
C.
SAG DEVELOPMENT CAUSED BY ACCUMULATING SEDIMENT OVERBURDEN FOLLOWED BY SUDDEN CAVERN ROOF COLLAPSE OFTEN WITH RIM SHOULDER COLLAPSE.
D.
SUBSEQUENT INFILL OF THE DEPRESSION BY SUBAQUEOUS SEDIMENT.
POST MIOCENE DEVELOPMENTS BASED ON STRUCTURES IN WESTERN GOZO.
E.
F.
PLIOCENE UPLIFT AND DENUDATION WITH FURTHER SINK FORMATION AND CAVERN ENLARGEMENT.
COLLAPSE OF FRACTURED CAVERN ROOF SYSTEMS AND FURTHER DENUDATION PRODUCE PRESENT DAY TOPOGRAPHY

Fig. 42

SUBSIDENCE STRUCTURES OF WESTERN GOZO



(MODIFIED FROM WIGGLESWORTH 1964)

Fig. 43

APPENDIX I : List of Sampling localities figured in Chapter 10

Locality No.	Name	Grid Reference
10	Road Tal Hezjen, Malta	453752
119	Ghar Ilma, Gozo	292892
146	Mgarr, Gozo	367870
310	Mgarr Coast, Gozo	373874
313	Rdum il Hmar, Malta	428823
319	Il Ponta, Malta	419705
333	Cirkewwa, Malta	398920
336	Rdum, Malta	400810
349	Il Prayet, Malta	406796
375	Karraba, Malta	406760
379	Gebel Ghawzara, Malta	466762
393	I'Irdum I'Imdauar, Malta	409745
396	Qlieghi, Malta	402731
399	Id Dwejra, Malta	445733
401	Mtarfa, Malta	455717
404	Santi Gap, Malta	423728
406	Ta Dekozzu, Malta	438705
420	Il Fawwara, Malta	456664
421	Madelena Chapel, Malta	445676
423	Ghajn Taites, Malta	427699
424	Wied ta Gioraaina, Malta	406712
426	Tal Mas, Malta	401724
427	Ta Santa Catarina, Malta	444696
429	Il Bajjat ta Decozzu, Malta	440703
430	In Negret, Malta	442706
434	Deneb il Baghal, Malta	493644
446	Mgarr Harbour, Gozo	368872
447	L'Skoll tal Barbajanni, Gozo	386870
448	E of Qala, Gozo	393880
452	Il Qortin, Gozo	377899
473	Il Gelmus, Gozo	310894
475	Gordon, Gozo	298921

Sample Localities Used for Extra Stratigraphic Control

14	L'Irdum L'Imdauar, Malta	412747
69	Rdum Dikkiena, Malta	444676
140	It Qortin Tan-Nadur, Gozo	367905
144	East of Qala, Gozo	393880
411	Ghar Bitija, Malta	436680
415	Ghajn Il Kbira, Malta	466679
443	Kemuna Tower, Gozo	355880

Localities 375, 396 and 404, above, also provided additional stratigraphic sample control.

APPENDIX II: MODAL ANALYSIS PERCENTAGES

	Miliolid Lst.	Attard Member										Xlendi Member										
Grid Reference	492713	495714	485783	388875	575626	493644	480755	493644	397733	494716	417788	800397	500646	497757	483649	401808	295871	511692	511692	609688	507640	[illegible]796
Lamellibranchs Gastropods						1.0		0.2	1.0	1.5	8.9	3.8	2.4			0.4	1.2	2.1		1.2	1.4	0.3
Planktonic Forams.												0.2					0.9					
Benthonic Forams.	3.2		2.0	6.1	2.0	9.7	10.8	11.6	8.6	3.5	1.7	21.7	32.4	21.3		62.6	61.9	24.8	6.2	37.5	10.3	29.9
Indet. Forams.	35	10				6.5						6.8						5.8		2.4		
Bryozoans			6.1	6.3	2.5	11.5	1.0	2.6	2.4	0.5	10.2	9.2	7.3	3.8				7.7	0.6		5.3	6.3
Coralline Algae		30	56.3	47.0	40.0	20.2	26.5	43.5	47.2	18.1	14.4	0.8	7.8	40.9		9.8	1.7	25.6	66.8		33.8	13.0
Indet.Algal? Clasts			6.8			1.6							3.3									
Echinoids	2.5		2.4	2.8	1.4		3.4		4.4	2.3		2.3		15.7	1.0	11.0	20.0	7.3	2.0	3.4	9.0	6.4
Micrite				39.7	53.9	49.9	55.9			74.0		55.5	46.7		49.0							
Microsparite	59.7	60	26.3					4.8						18.3		16.6	15.4	28.4		52.3	40.5	
Sparite																			24.6			47.2
Pelleted Micrite							2.4	37.7	36.3		64.7				50.0			2.5				
Intraclasts																				3.4		

APPENDIX II: MODAL ANALYSIS PERCENTAGES (Continued)

	Xlendi Member (Cont.)		Il Mara Member								Lower Globigerina Limestone										Middle Globigerina Limestone		
Grid Reference	500646	442707	609689	609688	563658	600710	587721	494716	390807	569662	406739	397733	575628	393810	417701	494716	444674	501642	607704	295878	501642	59[illegible]645	418700
Lamellibranchs	1.6	1.0		} 1.2	0.2	8.0	2.7		} 3.8							0.3		1.1	2.0		0.2		
Gastropods																							
Planktonic Forams.							0.5		0.2		0.1	0.6			1.0	28.8	60.4	1.7	6.0	42.6	10.9	28.6	8.1
Benthonic Forams.	13.2	75.4	29.1	37.5	31.8	3.6	36.0	3.2	23.2	5.6	0.9		16.0	2.9				1.3	0.1	2.2		10.3	
Indet. Forams.			67.3	2.4				35.0	5.3			?		42.2	4.9								
Bryozoans	23.2	0.8				1.4	29.4		9.2		37.6	19.2	12.9						0.1				
Coralline Algae	2.8					12.0	1.6		0.8										0.5				
Indet. Algal clasts																							
Echinoids	1.8	3.6	1.8	3.4	2.0	0.6	3.6	2.5	2.3	0.8			4.8	2.9				4.5	0.5	0.8	3.2	0.9	
Micrite	57.6		2.2	52.3	66.0	73.6			55.5	89.9	59.8	80.2	67.3	52.0	50.0			90.5	90.8	54.6	85.7	60.2	92.0
Microsparite								59.7															
Sparite		19.6																					
Pelleted Micrite							27.9				2.4												
Intraclasts				3.4																			
Brachiopods										5.0													
Glauconite																1.7		0.9					
Phosphoritic Micrite																69.8	39.6						
Lithoclasts																				0.4			

APPENDIX II: MODAL ANALYSIS PERCENTAGES (Continued)

	Middle Globigerina Lst. (Cont)					Upper Glob. Lst.		Ghajn Melel Beds						Ghajn Znuber Beds									
Grid Reference	417699	414701	401724	425685	277893	597657	406736	323887	309916	315893	3289	311895	316905	368904	350897	440695	412762	425685	357889	407790	436680	412762
Lamellibranchs											3.0				1.0	0.3		4.8	3.7	5.5	3.7	1.4
Ostracodes																						
Planktonic Forams.	8.1	33.4	10.1	1.9	7.1	16.2	29.1			0.2			3.0		[illegible]	0.5					0.7	0.4
Benthonic Forams.					3.3	1.0	3.8		14.0	17.9	40.3		56.6	7.4	37.0	10.9	45.8	29.6	32.0	19.4	35.8	27.9
Indet. Forams.					0.8	0.6																
Bryozoans																		0.1	5.0	9.5	2.7	0.9
Coralline Algae																1.1		0.2				
Indet. Algal Clasts																						
Echinoids						0.2						7.1	0.6	1.8		0.8		1.6	1.6	1.5	6.0	0.3
Micrite	92.0	67.2	90.6	98.1	88.8	82.5	60.9		83.0						35.0							
Microsparite								99.9		82.1	32.5	99.9	1.0	36.1			5.0					
Sparite																47.5		19.0	19.3	6.9	22.2	26.4
Pelleted Micrite																						
Intraclasts							6.6															
Glauconite								0.1	1.6	0.2		0.3	0.6			1.1	1.1	0.2	1.3	2.5	2.7	2.4
Lithoclasts											15.9		40.0	37.4	4.6	4.8	10.0	33.2	27.4	44.9	23.3	20.3
Reworked Forams.											0.5			17.5	22.4	33.1	52.9	11.4	8.9	10.1	4.3	19.8

APPENDIX II: MODAL ANALYSIS PERCENTAGES (Continued)

	Ghajn Znuber Beds (Cont.)		Mtarfa Beds											C.A.Bioherm				Rdum il Hmar Beds				
Grid Reference	404784	444674	451751	466679	444730	483754	438790	459665	459665	459665	491646	483754	452804	494716	401812	401812	411733	449744	456662	437724	400810	461679
Lamellibranchs	1.4	1.8	4.6	12.1	4.7		8.6	1.5	0.6	0.8	17.0	4.6	0.2		0.2				0.1	2.6	2.4	7.3
Ostracodes			1.4	0.8	2.8		0.8															
Planktonic Forams.	0.1	0.2			0.3		0.4	0.4	0.4	1.6	4.0	1.0										
Benthonic Forams.	32.5	27.1	6.4	0.4	8.8	32.7	1.8	1.9	3.4	2.6	4.4	12.2	12.2	0.8	1.2	0.8	3.8	13.5	1.2	11.6	1.8	4.7
Dentalium											7.4											
Bryozoans	1.6		3.4		3.1	1.2					1.0		0.6				0.6				1.4	
Coralline Algae							0.1	0.6				2.2	6.6	40.5	50.2	45.7	33.2	4.0		10.3	1.0	0.2
Indet. Frags.												9.8	4.6									
Echinoids	1.0	1.7	9.0	2.4	4.7		4.6	0.8	3.0	2.0	2.4	2.2	4.2		1.2		6.3	0.5	1.2	5.5	0.8	2.6
Micrite			61.2	83.4	75.8	57.4	83.6	95.0	92.6	92.6	58.6		65.7	53.5	48.4	53.5	55.2		97.6		92.6	1.7
Microsparite												65.1						60.1		70.0		
Sparite	33.0	32.6																				
Pelleted Micrite																		21.2				84.0
Glauconite	1.5	0.6	14.0								3.2											
Lithoclasts	16.1	23.2																				
Reworked Forams.	12.8	12.8																				

APPENDIX II: MODAL ANALYSIS PERCENTAGES (Continued)

	Rdum il Hmar Beds (Cont.)				Rabat Plateau and Tal Pictal Beds																
Grid Reference	437724	456662	425825	449744	422757	442719	305882	361902	417788	454669	348865	422757	424691	425691	297907	412788	412788	2889	417788	305882	303882
Lamellibranchs	3.0			4.8	3.0	2.4			2.4						6.3	1.4	0.8	10.6			2.8
Ostracodes					0.1											0.5					
Planktonic Forams.			2.0	0.2																	
Benthonic Forams.	3.4	1.0	48.0	8.7	5.9	7.6		0.3	7.1			4.3	7.6	5.3	6.3	3.2	2.7	13.4	1.6		8.8
Indet. Forams.																					
Bryozoans					0.6						1.2				47.3	1.1	5.7				
Coralline Algae	10.4			4.8	32.2	15.8			7.3		33.2	69.2	25.1	23.5	2.8	28.6	42.5	8.5	1.6		
Indet. Frags.			10.0						5.5									10.9			
Echinoids	6.8		0.5		1.3	3.0			0.9						1.6	7.6	1.8	1.3			
Micrite		99.0	49.5		2.5	68.5	38.3								20.6	37.2	8.7	17.0			37.4
Microsparite	76.0										66.2								93.2		
Sparite				52.3	39.5	5.4		29.4		35.3		26.4	57.3	70.0	14.6	16.2	37.2	38.2		35.6	2.8
Pelleted Micrite				29.7	15.0				80.1	0.7					1.1	0.8	0.3		1.1	4.0	45.8
Intraclasts								15.3						1.2		3.2					
Glauconite																					
Lithoclasts																					
Ooliths							61.3	59.4		63.7										64.2	
Coral																		0.9	3.4		

APPENDIX II: MODAL ANALYSIS PERCENTAGES (Continued)

	Ghadira Beds										Ghar Lapsi	Tat Tomna Beds						San Leonardo Beds	
Grid Reference	408806	408806	408806	422757	422757	422775	422775	422775	472653	408806	492645	416790	432685	420758	417738	396848	416790	600705	601706
Lamellibranchs									4.4		1.0	3.4			2.0	0.9		0.5	1.3
Ostracodes																		0.5	
Planktonic Forams.																			8.8
Benthonic Forams.	2.4	1.0								3.2		20.3			1.2	4.1			
Indet. Forams.																			
Bryozoans																			
Coralline Algae						44.2			3.5			1.3			1.2				
Indet. Frags.			24.7	0.4	2.8		30.2			3.0									7.4
Echinoids	1.0											1.7						21.8	25.7
Micrite													39.6						56.8
Microsparite			59.0							50.2				38.4				75.7	
Sparite	38.3	34.0		45.6	47.0	33.8	53.0	98.8			99.0	16.5			39.9	48.9	20.7		
Pelleted Micrite									43.7				60.2	61.5	56.0	31.0	24.5		
Intraclasts																			
Glauconite																			
Lithoclasts																		1.5	
Ooliths	59.5	62.6	16.0	54.0	50.1	21.9	16.6	1.2	48.4	43.6		56.7				14.9	54.8		

APPENDIX II: (Continued)

SOLUTION SUBSIDENCE STRUCTURES

Grid Reference	279883	279883	279883	328923	295878
Lamellibranchs			1.8		
Ostracodes					
Planktonic Forams.					
Benthonic Forams.	1.8	0.8	9.0	34.8	
Indet.Forams.					
Bryozoans					
Coralline Algae	46.4		3.0		
Indet.Frags.		28.8	2.1		35.1
Echinoids	0.6	3.0	2.4		
Micrite					
Microsparite					
Sparite	46.8	67.6	44.7	64.6	
Pelleted Micrite					
Intraclasts					
Glauconite	3.4	0.9	3.4	0.8	
Lithoclasts	1.0				64.9
Ooliths			31.7		

APPENDIX III : Maps used in the Study of the Maltese Islands

1. War Office.Malta 1:10560 (6 inches to 1 mile) GS GS 3852 reproduced by the Ordnance Survey 1939.

2. War Office.Gozo and Malta 1:31680 (2 inches to 1 mile). 2 sheets (GS GS 3859, Edition 4), 1954.

3. The Allied Malta Newspapers Ltd. (Progress Press) Survey Map, Malta, Gozo and Comino 1:3200, Valletta.

SUMMARY

Although the geology of the Maltese Islands has been studied for a considerable length of time, this has mainly been from the viewpoint of palaeontology, stratigraphy and water resources. The aim of the present study has been to revise the litho - stratigraphy of the islands and to provide a working subdivision within the Upper and Lower Coralline Limestone Formations. Despite previous unsuccessful attempts at subdivision the new members and beds proposed by the author are believed to be acceptable because they are based on the recognition of distinct facies. The existence of these is supported by both palaeoecological and sedimentological data obtained during the present study. Particular attention has been paid to isopachyte studies , in order to consolidate new data obtained on the intermediate formations.

Detailed studies of allogenic sediments within the Maltese succession have provided data on those parts of the formations beyond the limits of the present confines of the Maltese Islands.

A new find of articulated fossil fish remains by the author, at Il Fawwara, Malta, provided palaeoecological material for a detailed study of a localised environment in the basal Upper Coralline Limestone. A broader regional study was also undertaken at about the same horizon on the Terebratula-Aphelesia bed. This is a new stratigraphic marker horizon defined by the author. Throughout these studies the ecological implications of the various bryozoan growthforms encountered have been fully taken into consideration when interpreting the palaeoenvironments involved.

Finally, a series of solution subsidence structures were examined and 10 were found to have been initiated during normal Miocene sedimentation. These are believed to be associated with a pre-Miocene episode of uplift and subaerial denudation in western Gozo. Further post-Miocene subsidence and regional graben development are also recognised.

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ADDENDUM

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PLATE 1

Throughout all plates the scale of field photographs is denoted by the hammer which has a shaft length of 340mm. and a head length of 165mm.

Lower Coralline Limestone Formation

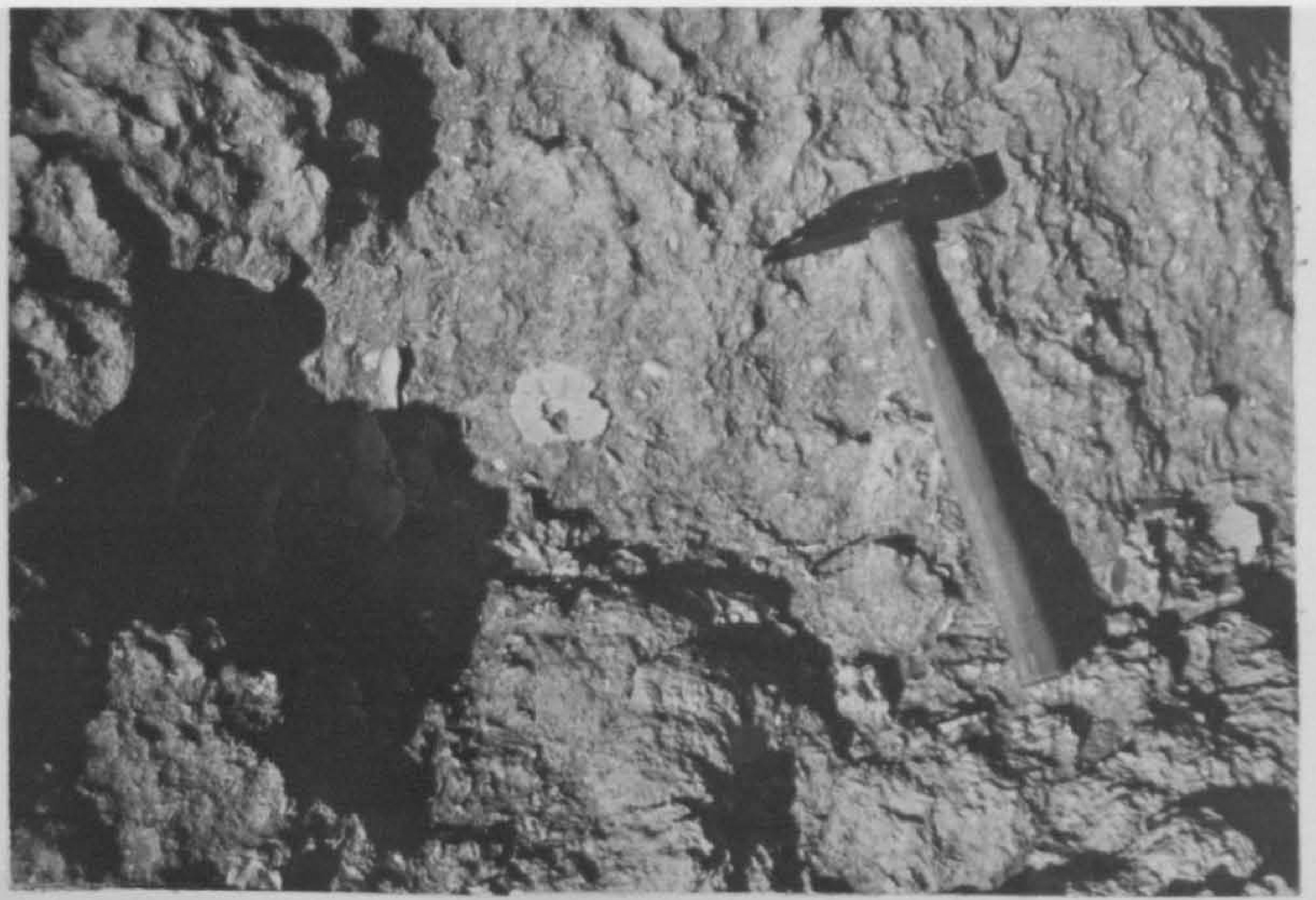
a. Il Mara Member. Lepidocyclina rock at Qammieh, Malta (400807).

b. Xlendi Member. Biosparites containing Scutella subrotunda, Qammieh, Malta.

c. Attard Member. Rounded rhodolites in biosparite, Attard Quarries, Malta. (490711)

d. Vertical cliffs of Lower coralline Limestone at Xlendi, Gozo (287877).

a.



b.

c.

d.

PLATE I.

PLATE 2

Lower Coralline Limestone Formation

a. Attard Member. Archaeolithothamnion intermedium, Attard quarries, Malta. (490712).

b. Xlendi Member. Lithothamnion sp. Wied Qirda, Malta, (511692).

c. Xlendi Member. Algal biosparrudite showing well rounded coralline algal fragments Wied Qirda, Malta (511692).

d. Attard Member. Carbonate mound showing penecontemporaneous biomicrite infill (i) and associated with a vugh in foraminiferal biosparite (ii). Deneb il Baghal, Malta (493645).

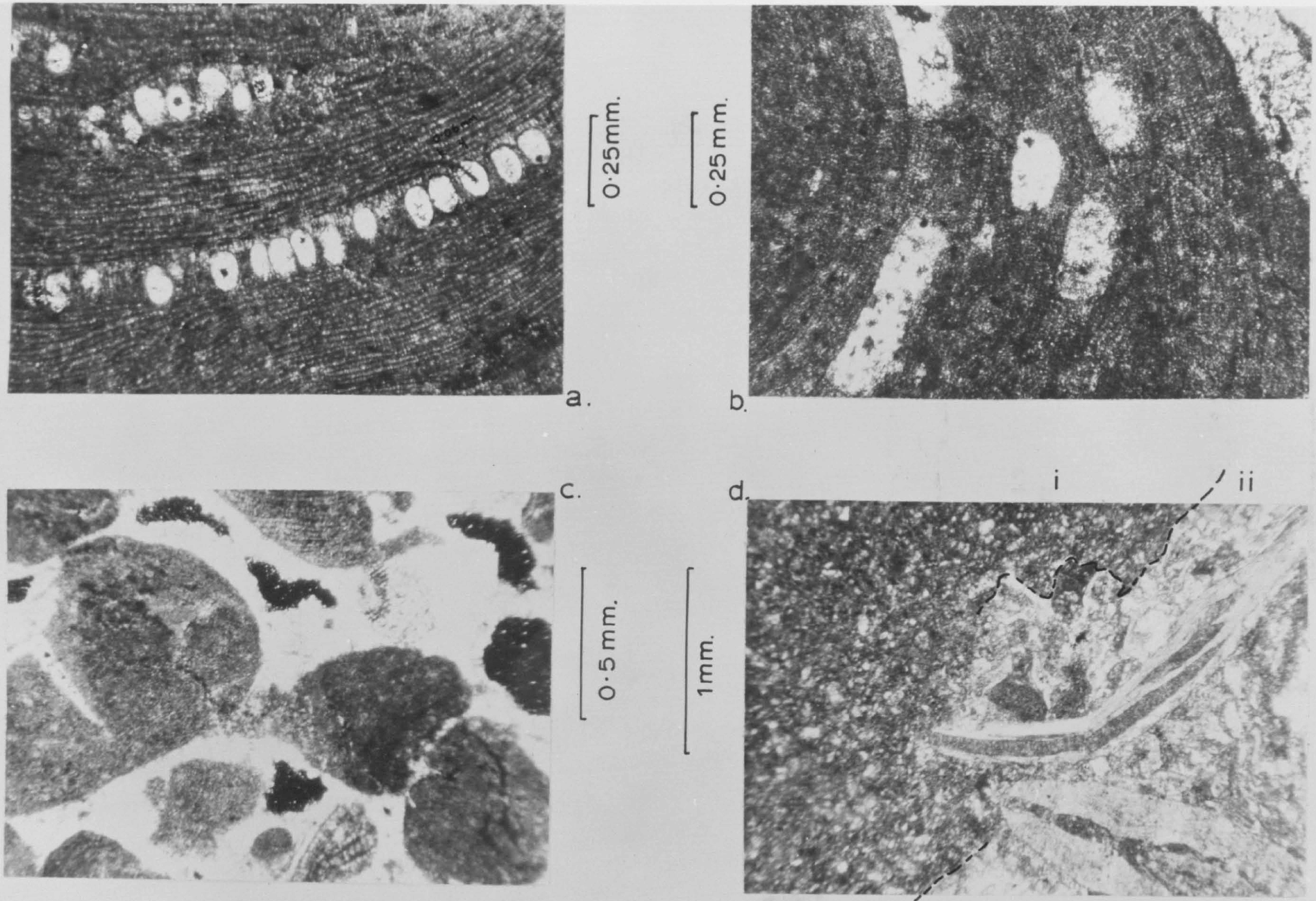


PLATE 2.

PLATE 3

Globigerina Limestone Formation

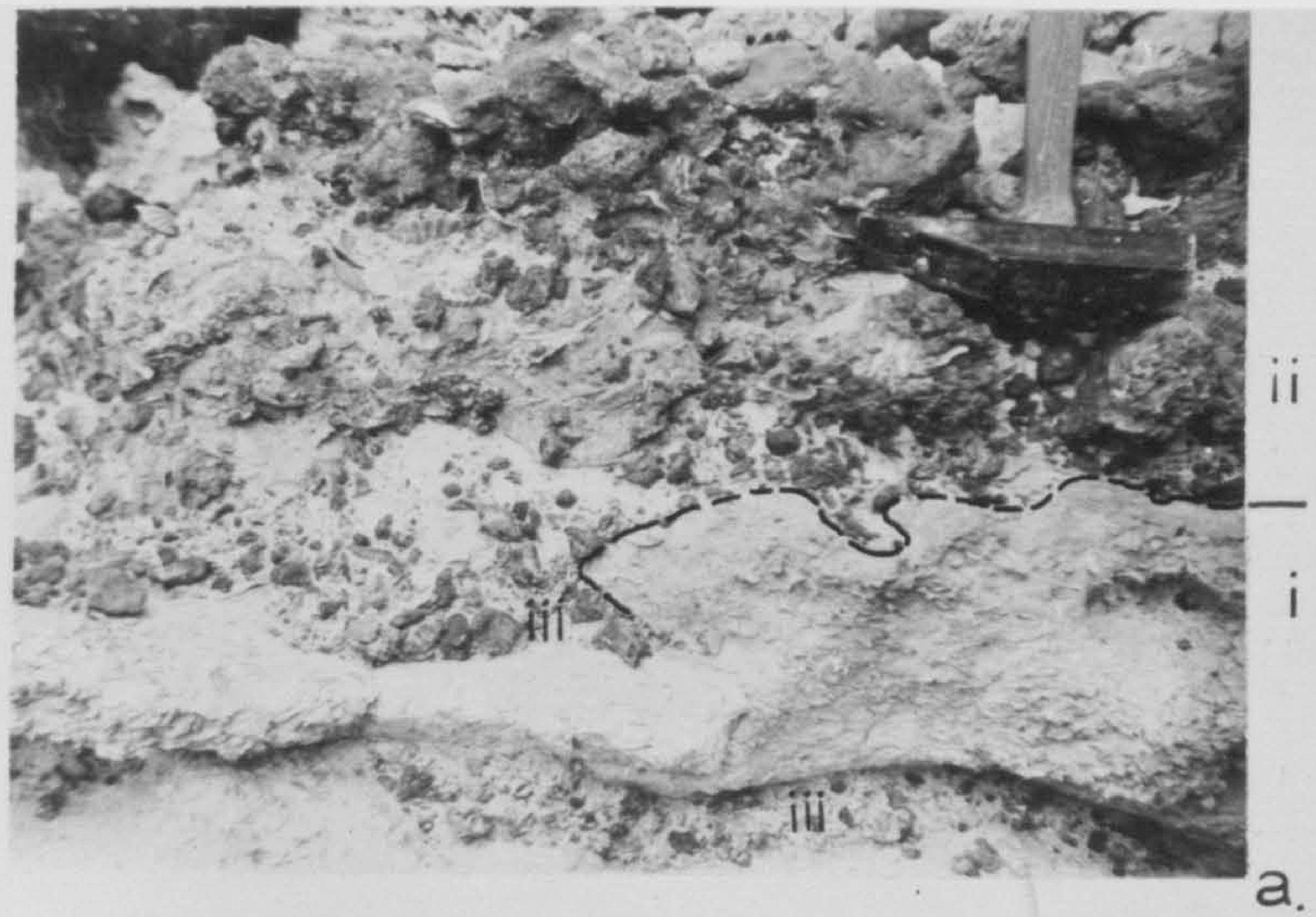
a. C1 Phosphorite Conglomerate Bed. Lower Globigerina Limestone Il Mara facies (i) below, and phosphorite conglomerate with Chlamys fragments above (ii), the latter infilling solution widened crustacean burrow systems (iii), Il Blata, Malta (396727).

b. C1 Phosphorite Conglomerate Bed. Typical planar eroded top (i) and with a base resting on gently tilted and fretted Lower Globigerina Limestone (ii), Fomm ir-Rih, Malta (406737).

c. Lower Globigerina Limestone. Thalassinoides burrow systems, Ghar id-Duhhan, Malta (610700).

d. Middle Globigerina Limestone. Neptunian dykes penetrating down from an unnamed conglomerate bed (i), Imtahleb, Malta (418700).

e. C2 Phosphorite Conglomerate Bed. Dune development of the C2 bed (i), above eroded and burrowed Middle Globigerina Limestone (ii), South of Marsalforn, Gozo (333915).



a.

b.

d.

c.

e.

PLATE 3.

PLATE 4

Globigerina Limestone Formation

a. Middle Globigerina Limestone. Biomicrite containing planktonic foraminifera, Is Serc, Malta (600647).

b. Middle Globigerina Limestone, Chert beds. Rhombs of dolomite (i) set in a chert replaced micrite, Il Guide, Malta (414701).

c. C1 Phosphorite Conglomerate Bed. Phosphatised planktonic foraminifera biomicrite pebble (i), in contact with globigerina limestone matrix (ii). Secondary leaching (iii) has caused migration of phosphate and iron into adjacent margin of matrix surrounding pebble, Ponta tal Qlieghi, Malta (397733).

d. Upper Globigerina Limestone. Planktonic foraminifera set in micrite, Delimara, Malta (603644).

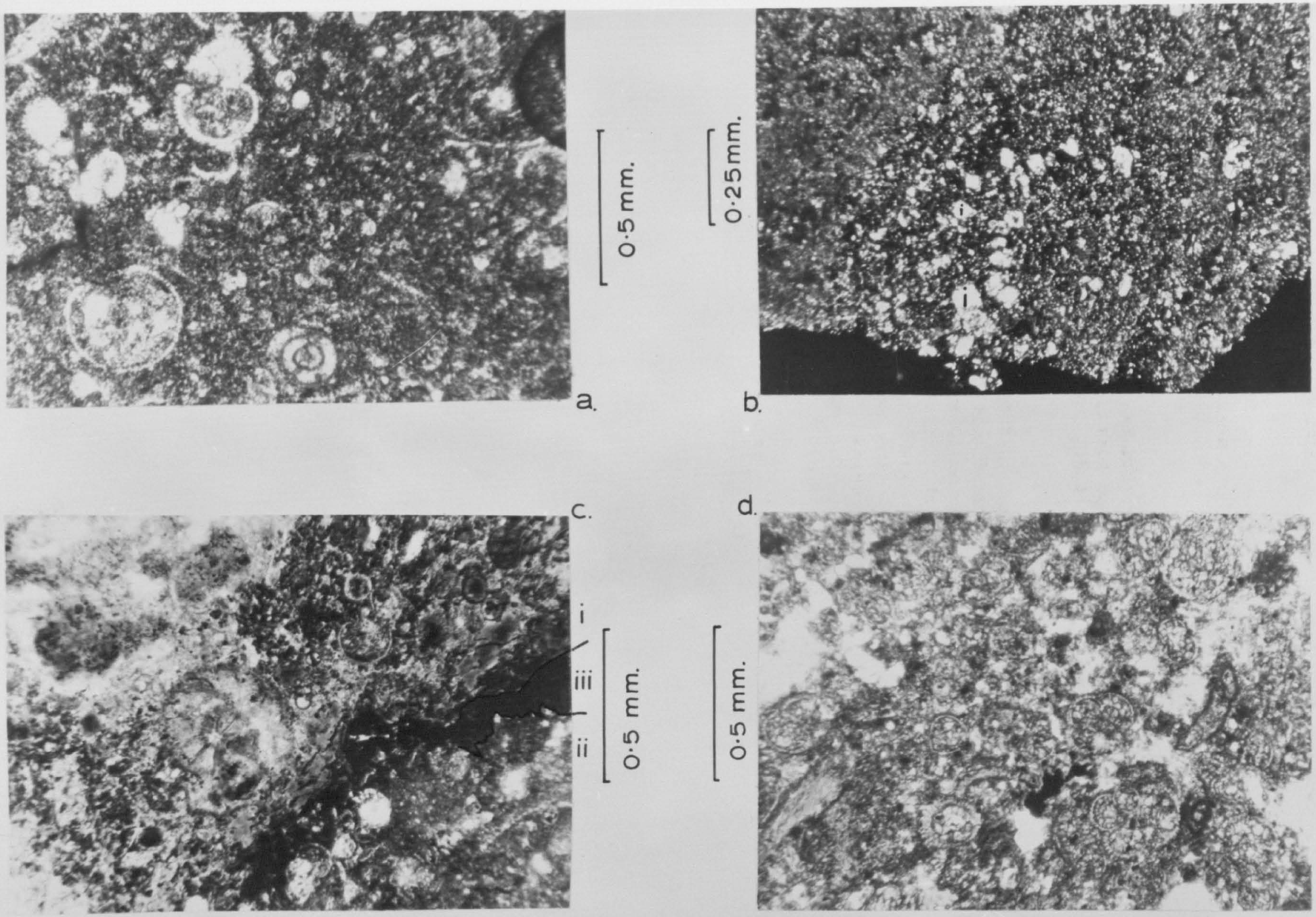


PLATE 4.

PLATE 5

Globigerina Limestone Formation

a. C2 Phosphorite Conglomerate Bed. Typical fining upwards development of this bed with development of pre-C2 jointing below, Qammieh, Malta (401808).

b. Lower Globigerina Limestone. Infilled channels typical of both the Upper and Lower Globigerina Limestones of north-western Gozo, east of Zebbug, Gozo (317913).

c. Upper Globigerina Limesonte. Honeycomb weathering in Bed C. Softer Bed B below, Qammieh, Malta (401808).

d. Upper Globigerina Limestone. Alternations of well cemented biomicrite ribs with softer horizons in Bed A; beds B and C above and Middle Globigerina Limestone below, Delimara, Malta (603644).

a.

b.

c.

d.

PLATE 5.

PLATE 6

Blue Clay and Greensand Formations

a. Blue Clay. Alternating bands of pale and dark grey marls, Rdum Idelli, Malta (407790).

b. Greensand. Hydrochloric acid insolubles; waterworn glauconite (i), oxydised pellets (now goethite)(ii), and detrital gypsum (iii), Ghar Ilma, Gozo (292893).

c. Greensand. Il Gelmus Member (i), with Coralline Algal Bioherm outlier unconformably capping it (ii), Ghar Ilma, Gozo (292893).

d. Ghajn Melel Member. Ghajn Znuber Beds: biosparites containing *Clypeaster altus* (i), articulated *Chlamys latissima* (ii), *Ostrea verleti* (iii) and *Cellepora* sp., Il Minzel, Malta (409767).

e. Greensand. Thin section of a glauconitic phosphorite pebble from the Il Gelmus Beds, (i) glauconite, (ii) Foraminifera debris, (iii) gypsum clasts., Ghar Ilma, Gozo (292893).

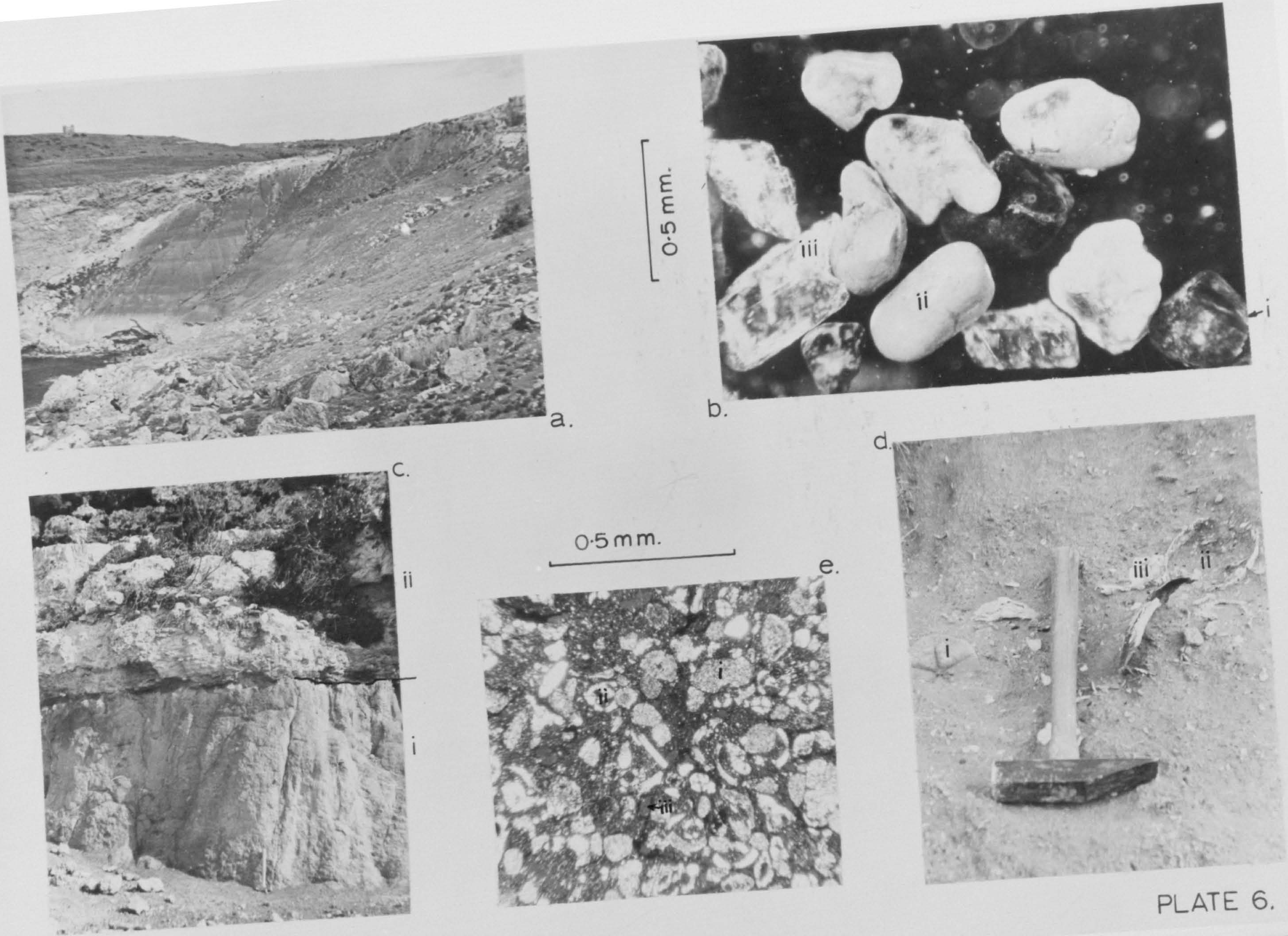


PLATE 6.

PLATE 7

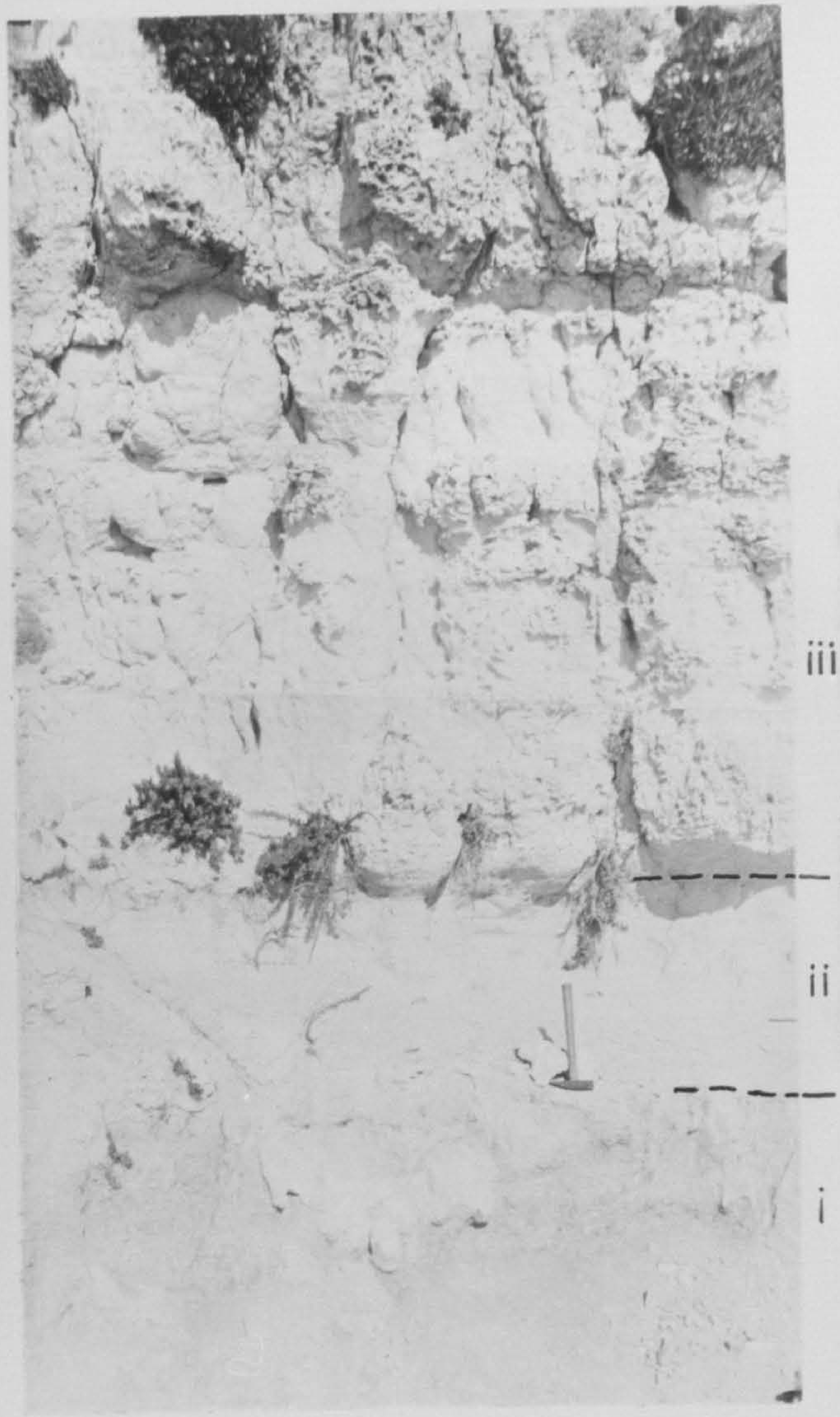
Upper Coralline Limestone, Mtarfa Member

a. Coralline Algal Bioherm. Spheroidal Lithophyllum rhodolites (i) and Calpensia impressa (ii) set in a yellow micrite matrix, St. Caterina, Malta (444696).

b. Il Fawwara Fish Bed. Greensand (i), overlain by thinly bedded micrites containing well preserved fish (ii), capped by the Mtarfa Beds (iii), Il Fawwara, Malta (457665).

c. Coralline Algal Bioherm. Terebratula Bed in grey marls at the base of the unit, Tal Mas, Malta (401724).

a.



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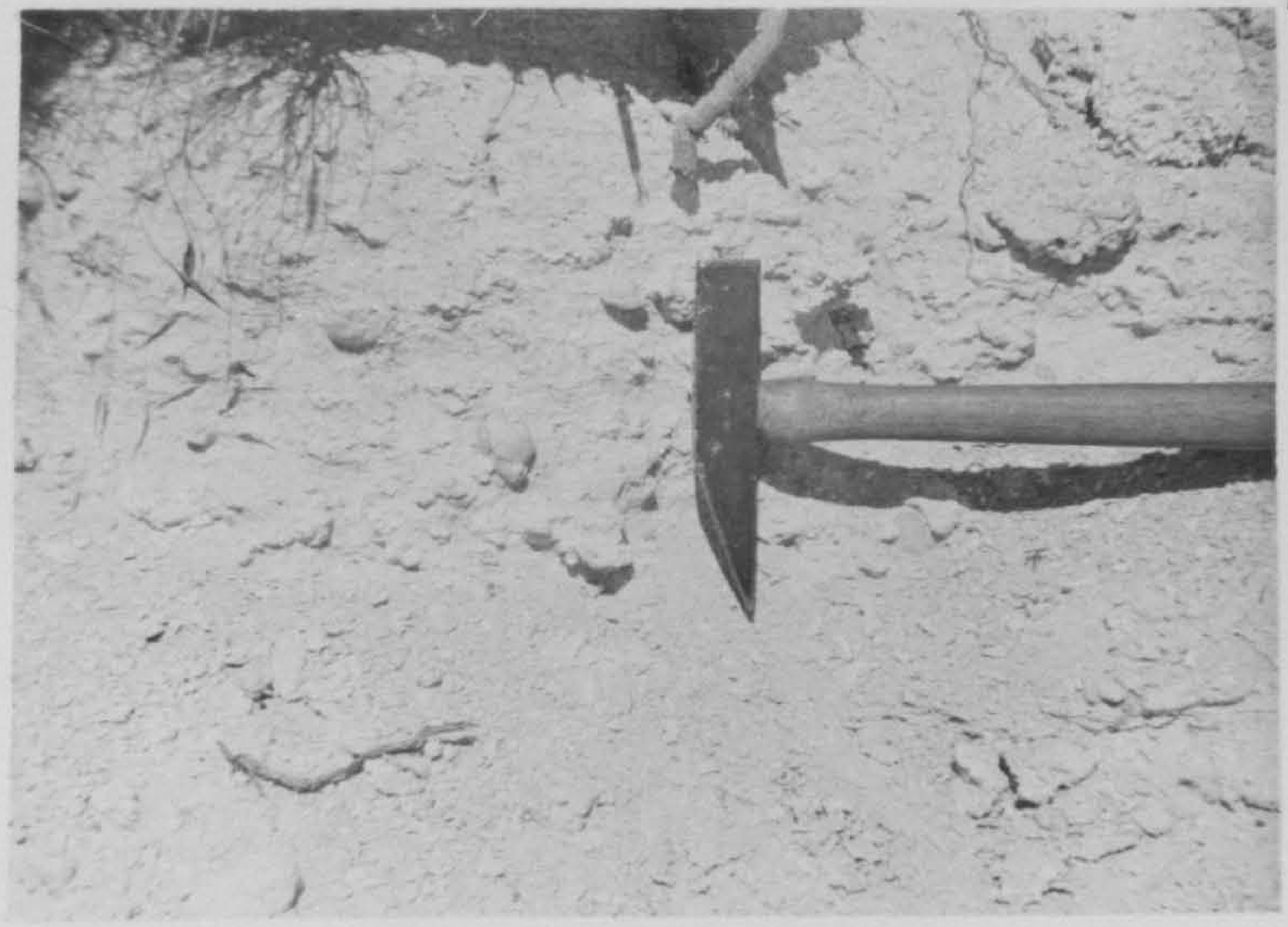


c.

PLATE 7.

PLATE 8

Upper Coralline Limestone, Mtarfa Member and Ghajn Melel Member

a. Mtarfa Beds. Yellow biomicrite with aragonitic shell casts, San Giorgio, Malta (459665).

b. Ghajn Znuber Beds. Reworked glauconite (i) and transported limonitised foraminiferal fragments (ii), associated with in situ foraminifera (iii), in a sorted biosparite, Hotba el Bajda, Malta (411763).

c. Ghajn Melel Beds. Low-ferroan calcite rhomb development around limonitic nuclei in an original limonitic micrite, south-east of Victoria, Gozo (323887).

d. Coralline Algal Bioherm. *Lithophyllum destephanii* showing oogonia and associated roof leasions, Tal Mas, Malta (401724).

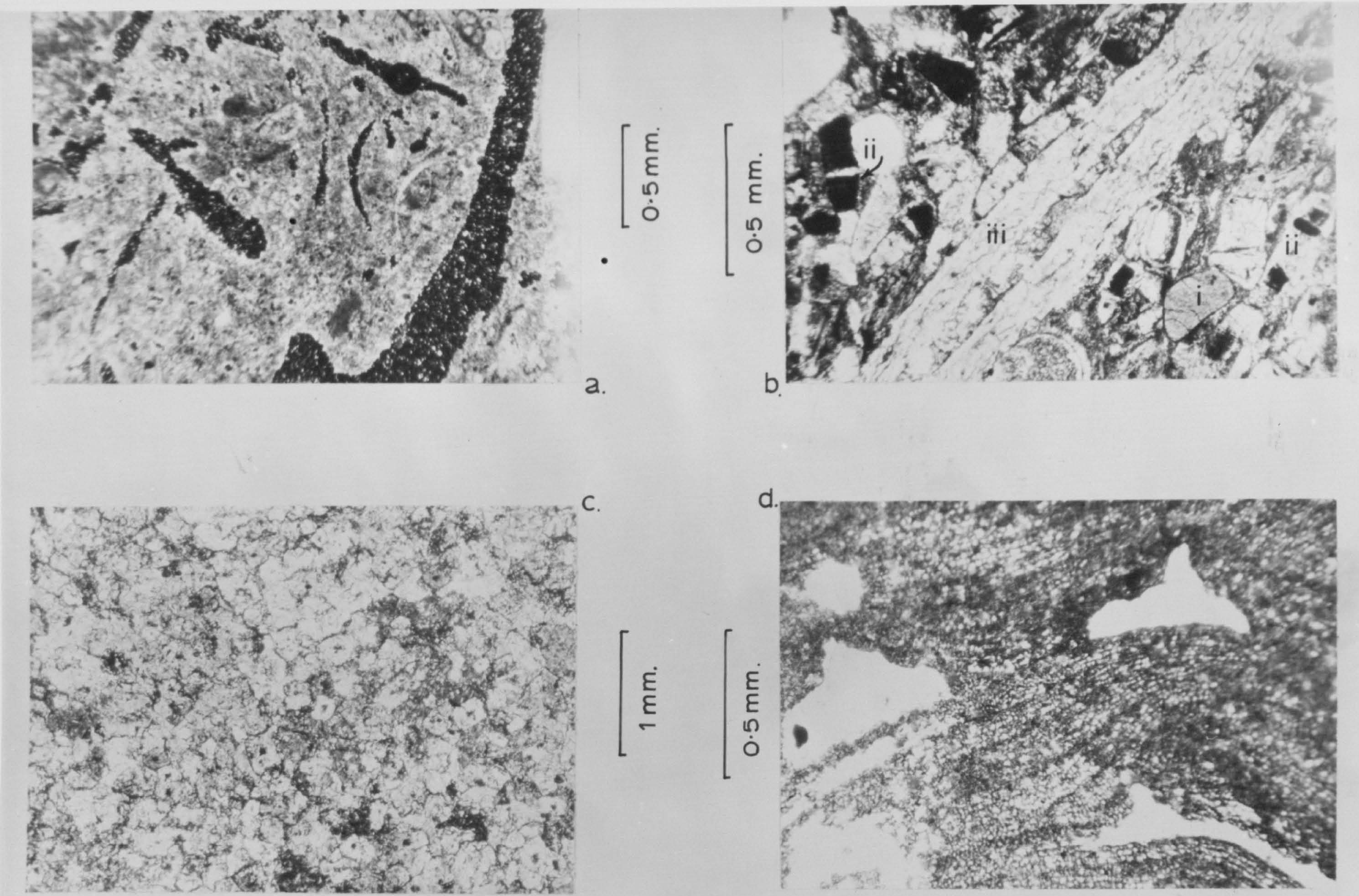


PLATE 8.

PLATE 9

Upper Coralline Limestone, Mtarfa and Tal Pictal Members

a. Rdum il Hmar Beds. White chalky biomicrites, Rdum il Hmar, Malta (427823).

b. Ghadira Beds. Megaforesets of oobiosparite, Il Ghadira, Malta (407805).

c. Rabat Plateau Beds. Biosparites, partly recrystalised, extensively dissolved and belonging to the Rabat Plateau Beds (i), overlying micritic Coralline Algal Bioherm (ii), Ghar Bittija, Malta (436680).

d. Tal Pictal Beds. Lensoidal development of partly micritised carbonate mounds (i), in an unsorted biosparite matrix, Tal Pictal, Malta (425691).

e. Ghadira Beds. Tangential foresets at the base of the beds, ic-Cumnija, Malta (420806).

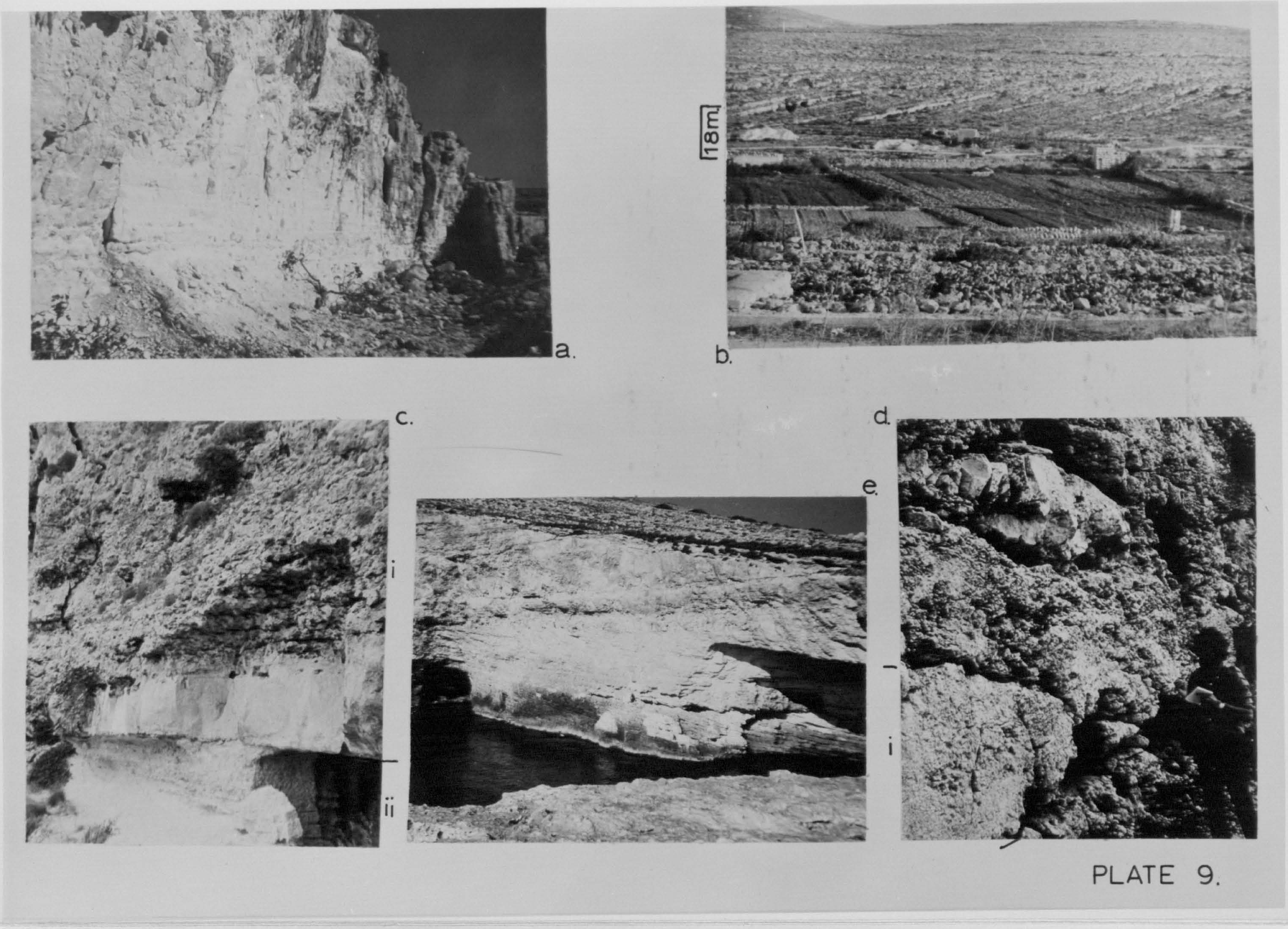


PLATE 9.

PLATE 10

Upper Coralline Limestone, Tal Pictal and Gebel Imbark Members

a. Tal Pictal Beds. Detail of a carbonate mound containing mollusc casts and coral genus A species b., east of Victoria, Gozo (306881).

b. Tal Pictal Beds. *Lithophaga* bored carbonate mound (i), surrounded by offmound biosparites, Tat Tomna, Malta (417788).

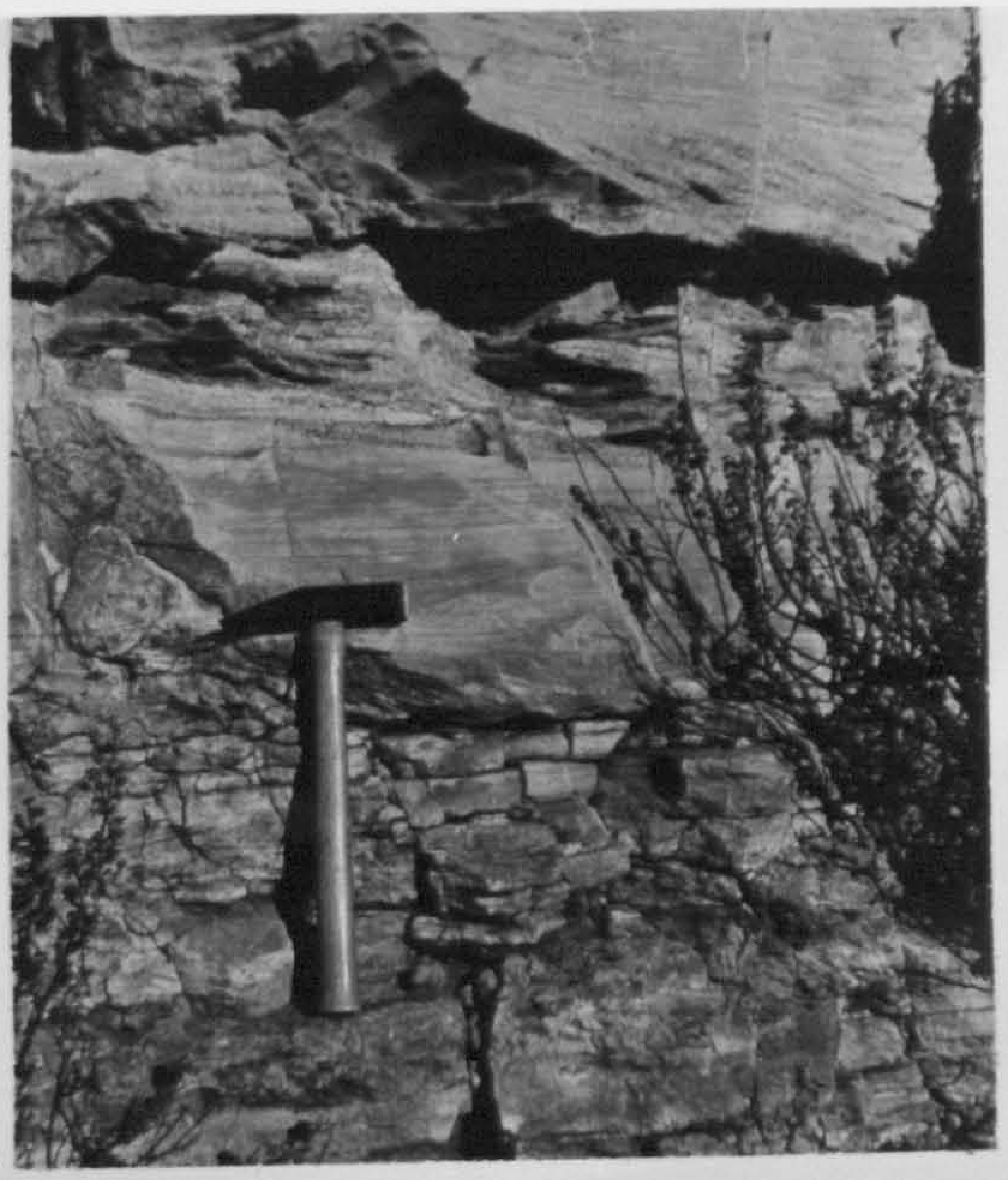
c. Tat Tomna Beds. Cross-laminated pelsparite and cosparite, Tat Tomna, Malta (420789).

d. Ghar Lapsi Beds. Thinly laminated biosparites (i), overlain by the Rabat Plateau Beds (ii), and tilted by the Maghlek Fault, In Neffiet, Malta (491644).

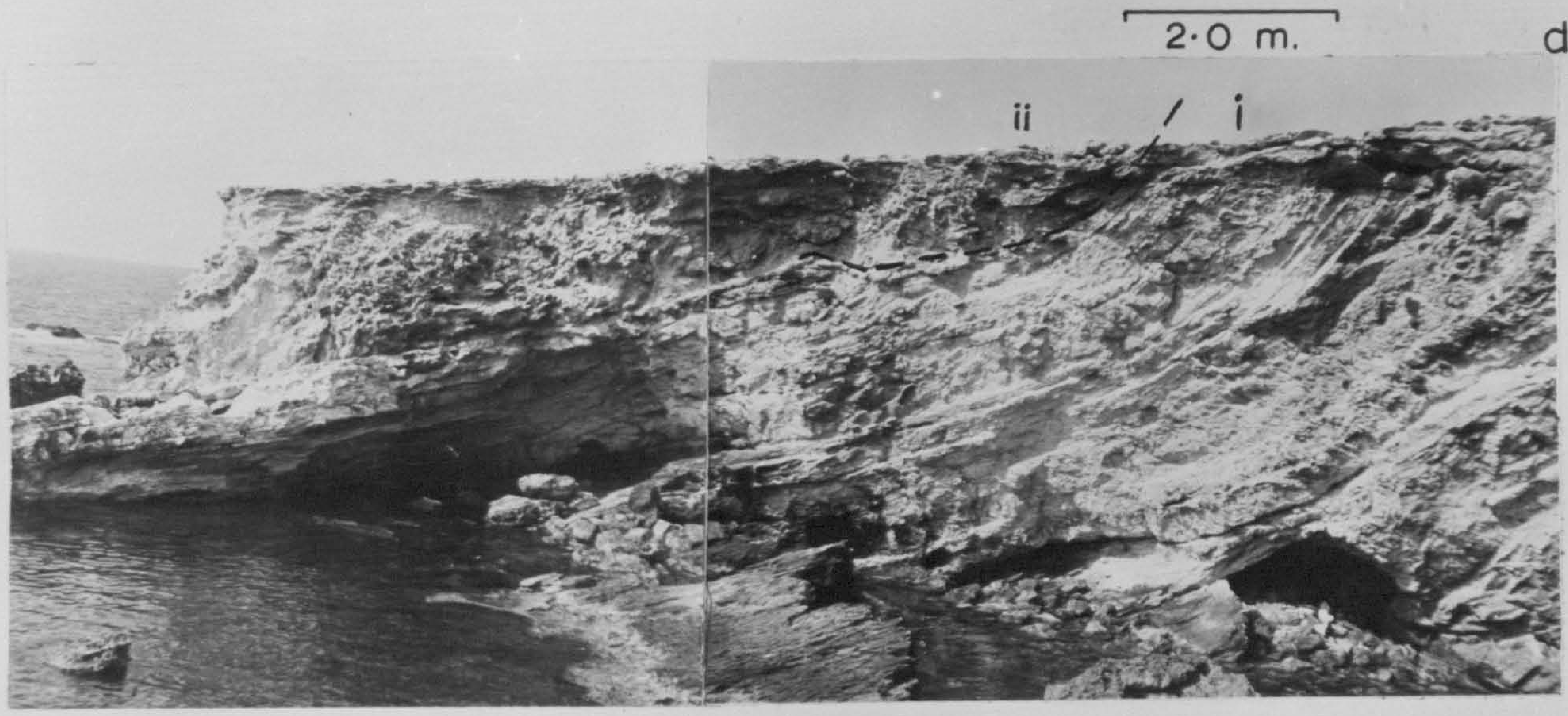
e. Ghajn Abdul. Concretionary limestone directly overlying solution subsidence infill, Ghajn Abdul, Gozo (286895).

a.

b.



c.



d.

e.

PLATE 10.

PLATE 11

Upper Coralline Limestone, Tal Pictal Member

a. Rabat Plateau Beds. Biomicrite containing micritised coralline algae set in a sparry low ferroan calcite matrix, Ta' Brieghen, Gozo (348865).

bl Ghadira Beds. Oosparite showing superficial oolith development on foraminifera and pellet nuclei, subsequently cemented by sparry low-ferroan calcite, Ghadira, Malta (408806).

c. Tal Pictal Beds. Outer layers of a carbonate mound showing encrusting foraminifera and coralline algae set in a micritised matrix which may originally have consisted of other coralline algae (i). Adjacent mound flank biosparites (ii), Ghajn Tuffieha, Malta (422757).

d. Tal Pictal Beds. Geopetal infill of micrite and blocky sparite within a lensoidal carbonate mound, Il-Qaws, Malta (425691).

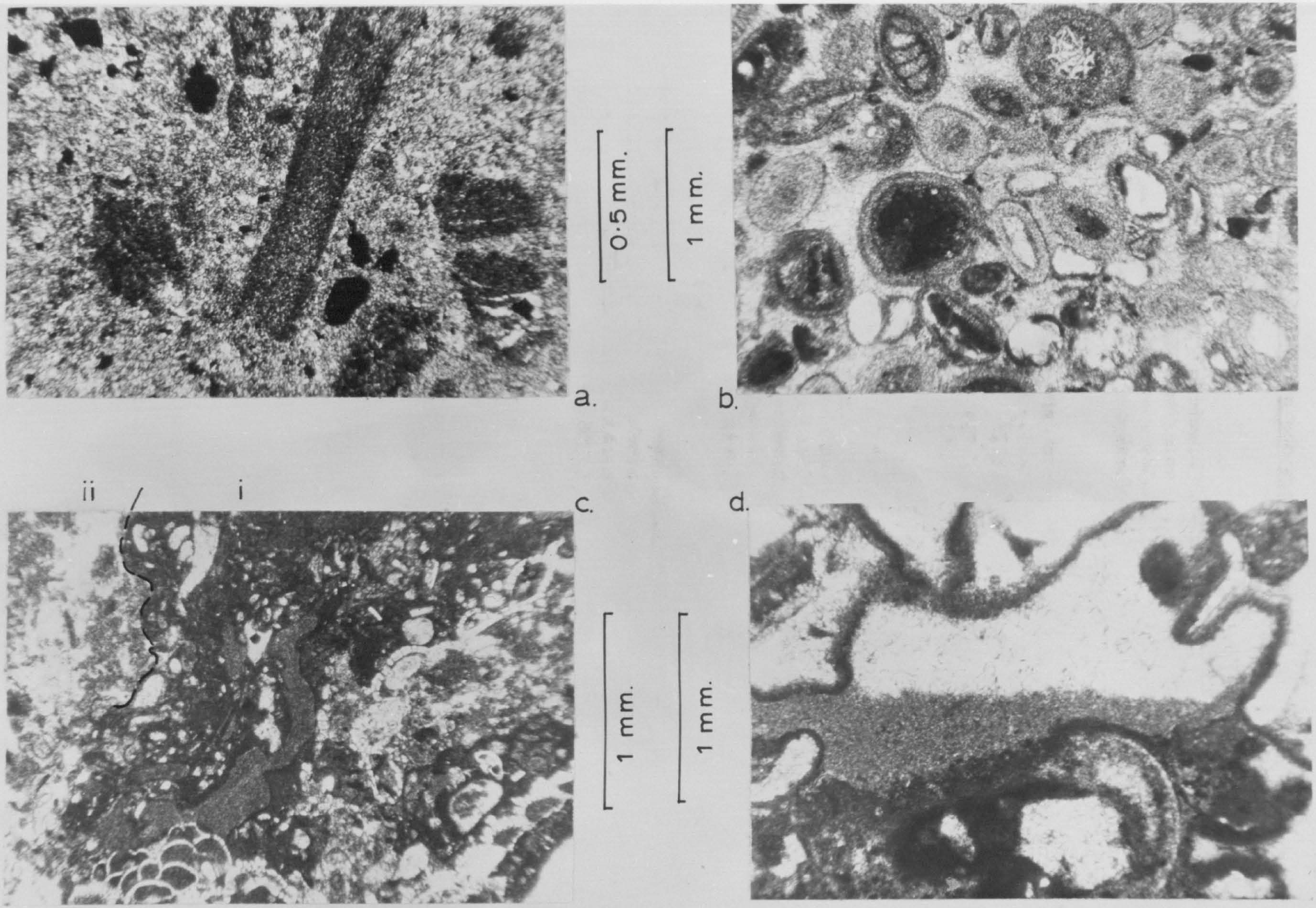


PLATE 11.

PLATE 12

Upper Coralline Limestone, Gebel Imbark Member

a. Tat Tomna Beds. Oopelsparite showing ooids and pellets, some with sparitised centres, set in a non-ferroan sparry calcite matrix, Tat Tomna, Malta (416790).

b. San Leonardo Beds. Trough bedded biosparite (i), overlain by a 1 metre marl bed (ii), and capped by a further thinly bedded biosparite containing channel development, San Leonardo, Malta (601705).

c. San Leonardo Beds. Eroded and faulted Middle Globigerina Limestone (i), unconformably overlain by San Leonardo Beds biosparites, San Leonardo, Malta (600707).

d. San Leonardo Beds. Biosparite, now extensively recrystallised but still showing gastropod and lamellibranch fragments, San Leonardo, Malta (601705).

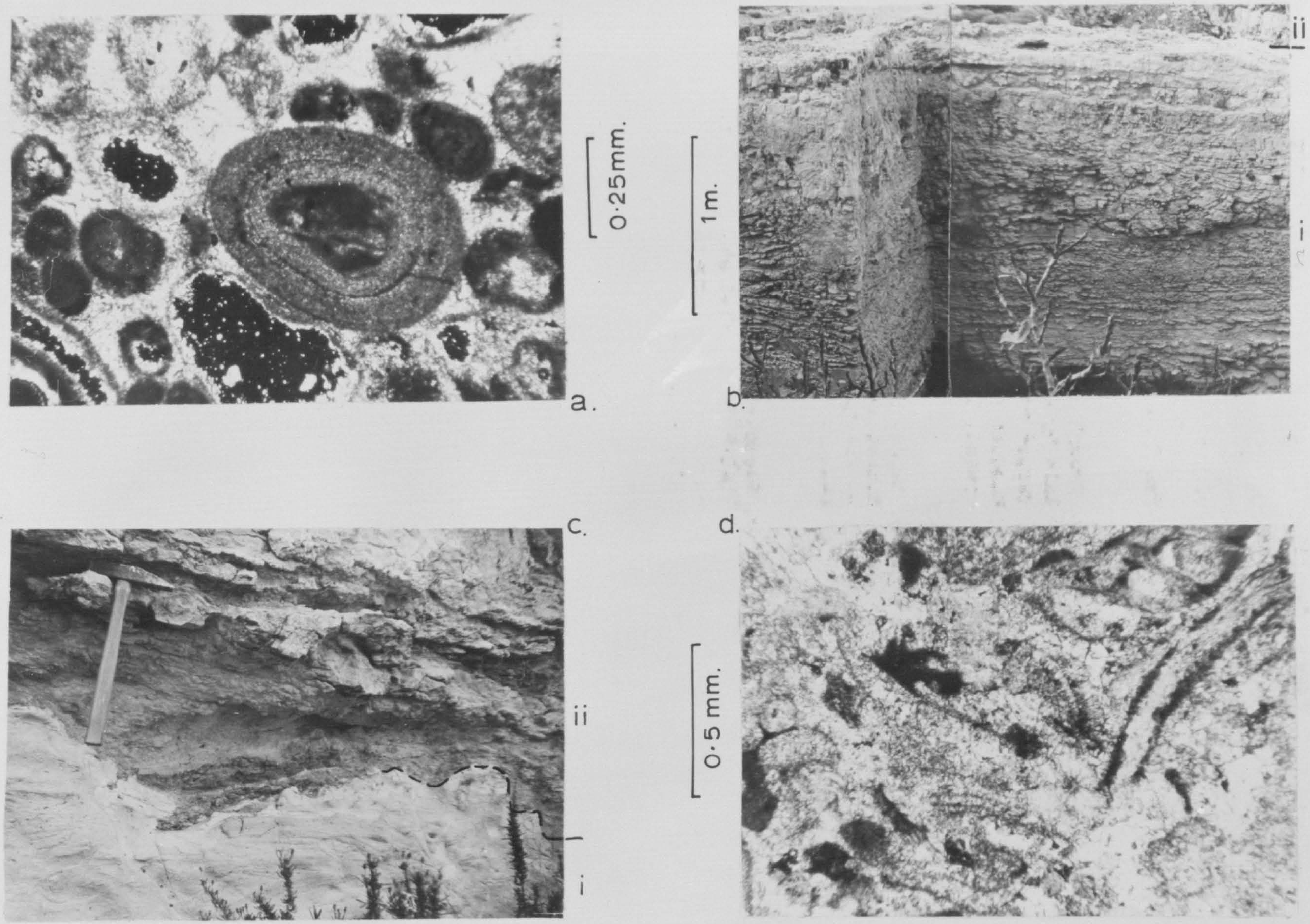


PLATE 12.

PLATE 13

Diagenesis

a. Blue Clay. Octahedral pyrite growing on botryoidal goethite, Tal Blata, Malta (452804).

b. Rdum il Hmar Beds. Foraminifera shell cast infilled by rhomboidal none ferroan calcite crystals, Rdum il Hmar, Malta (428824).

c. Blue Clay. Goethite infilling of cellular woody tissues, now casts, in driftwood from Rdum il Hmar, Malta (428824).

d. Goethite pseudomorphing octohedral pyrite within an *Aturia* test, north of Il-Mansab, Malta (407790).

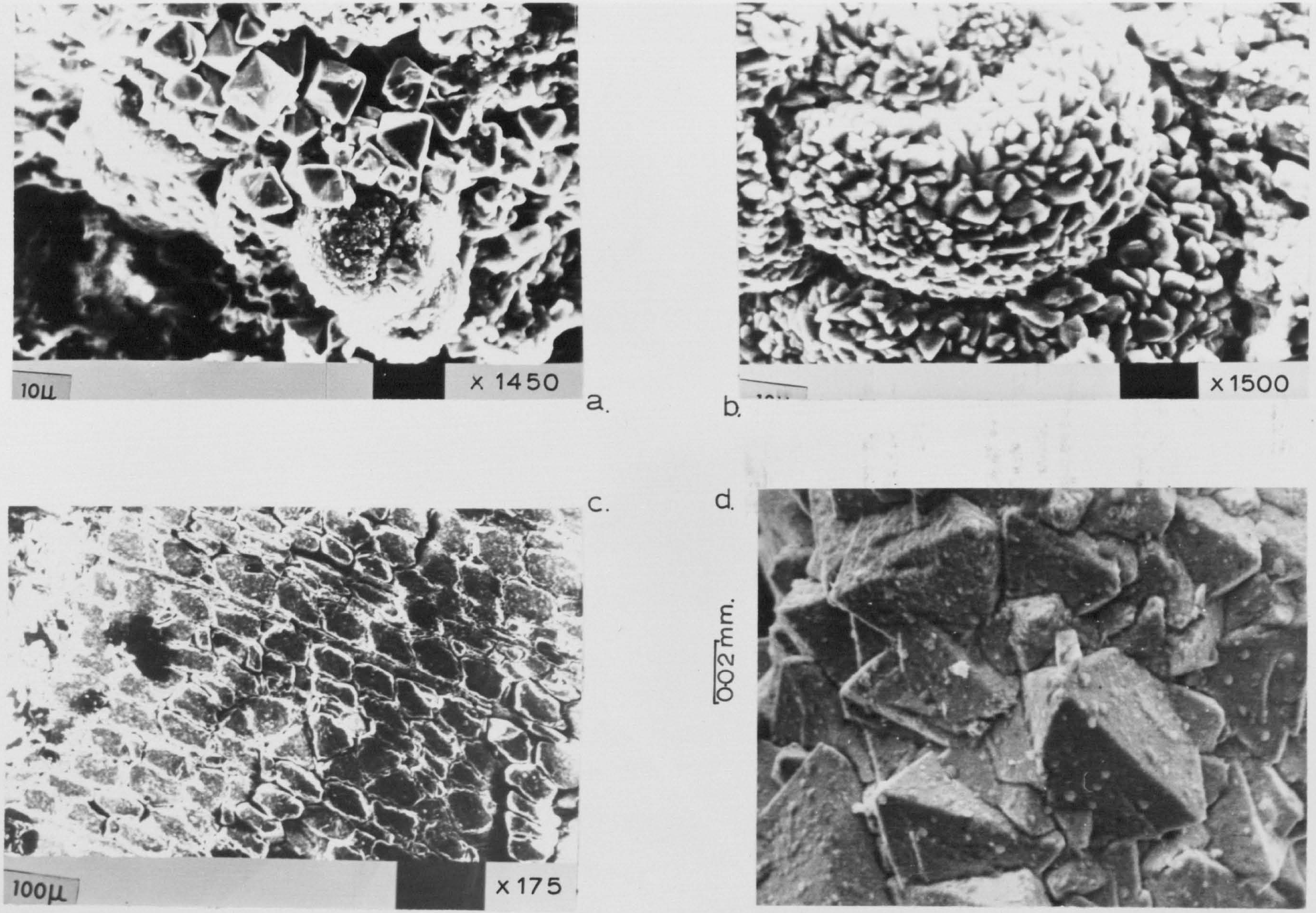


PLATE 13.

PLATE 14

Upper Coralline Limestone, Il Fawwara Fish Bed.

a. Bregmaceros albyi, Sauvage. A typical specimen showing the characteristic large otolith and occipital spine and elongated pectoral fin spines. (Malta Museum specimen M/V1349).

b. Coprolite containing fish bones, scales and five otoliths of Bregmaceros albyi.

c. Hexagonal plates, with tubercular carinae, of Syngnathus sp.

d. Bedding plane containing fossilised Fucus sp.? (i), encrusted by membraniporiform bryozoans (ii), and also containing lunulitiform bryozoans (iii), and shell debris.

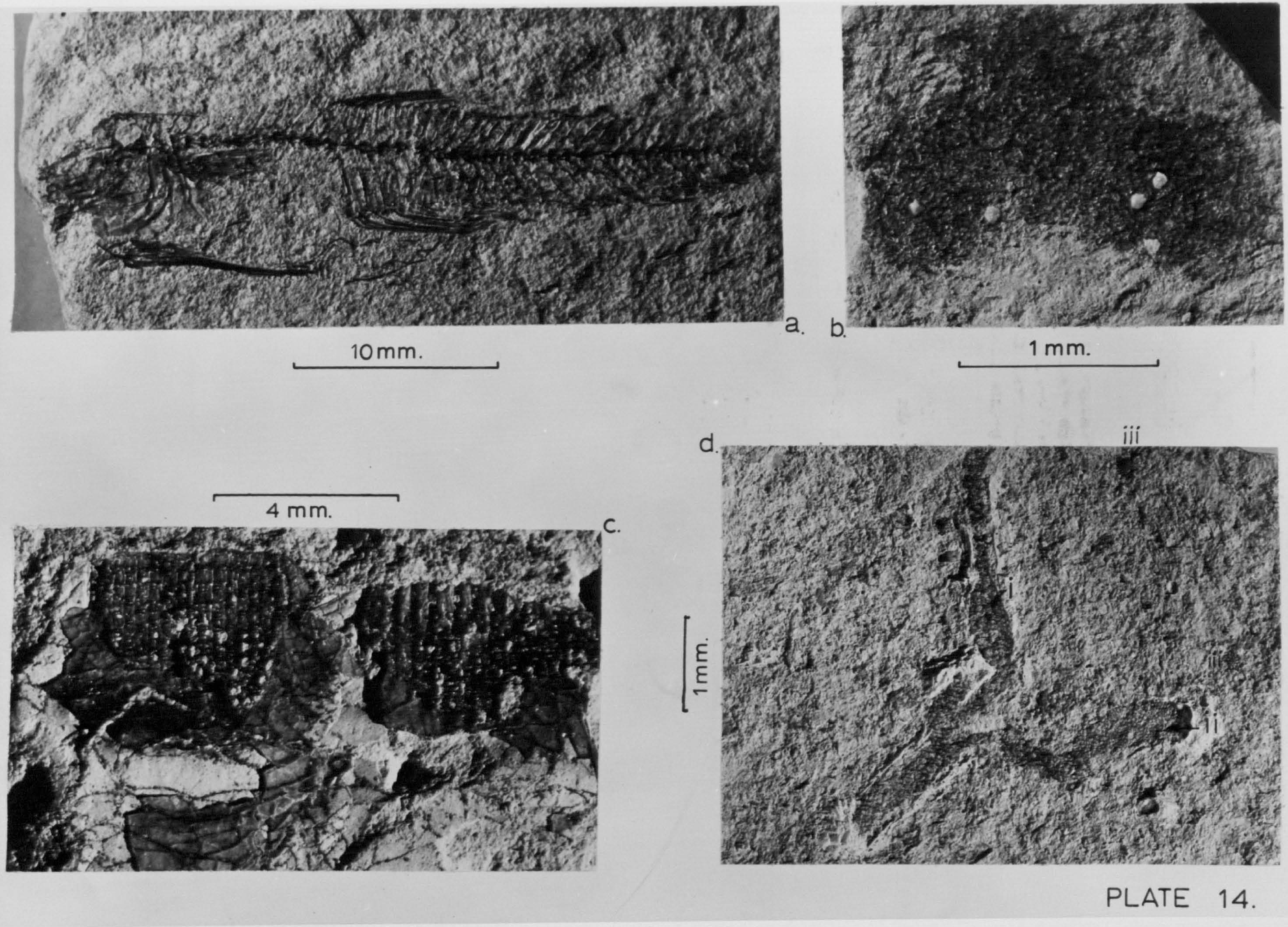


PLATE 14.

PLATE 15

Coralline Limestone Biological Framebuilders

a,b, Attard Member. Detail of coral genus A species a.(cast), Ix Xaghra tal Maghlek, Malta (488652).

c. Upper Coralline Limestone. *Lithophaga* borings in coral genus A species b.(cast), west of Mellieha, Malta (417788).

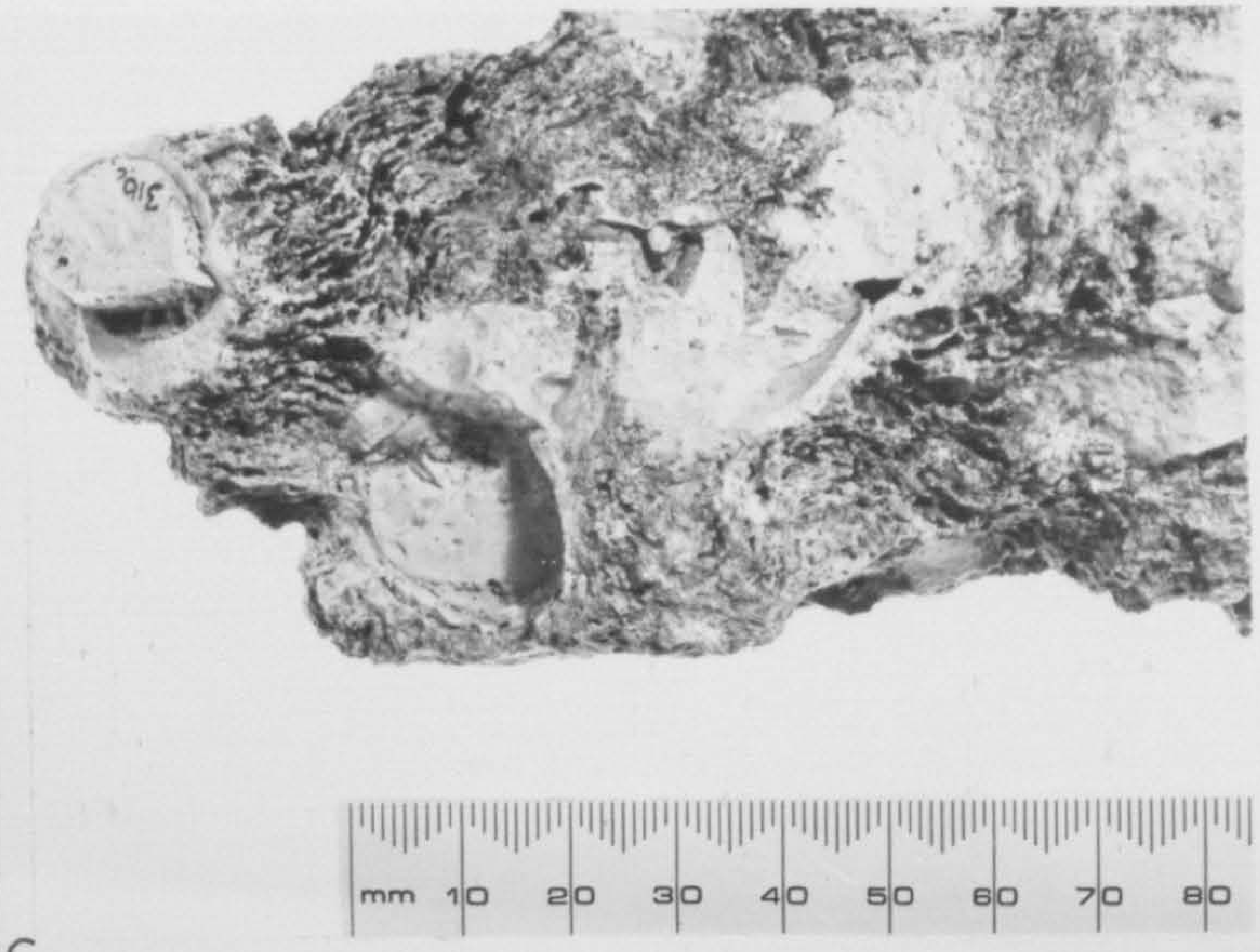
d. Tal Pictal Beds. Carbonate mound (i), outline dotted, showing *in situ* coral development (ii) and eroded top, Tat Tomna, Malta (417788).

e. Coralline Algal Bioherm. *Lithophyllum destephanii*. Lichen-like growthform from a basal horizon, Tal Lippija, Malta (410768).

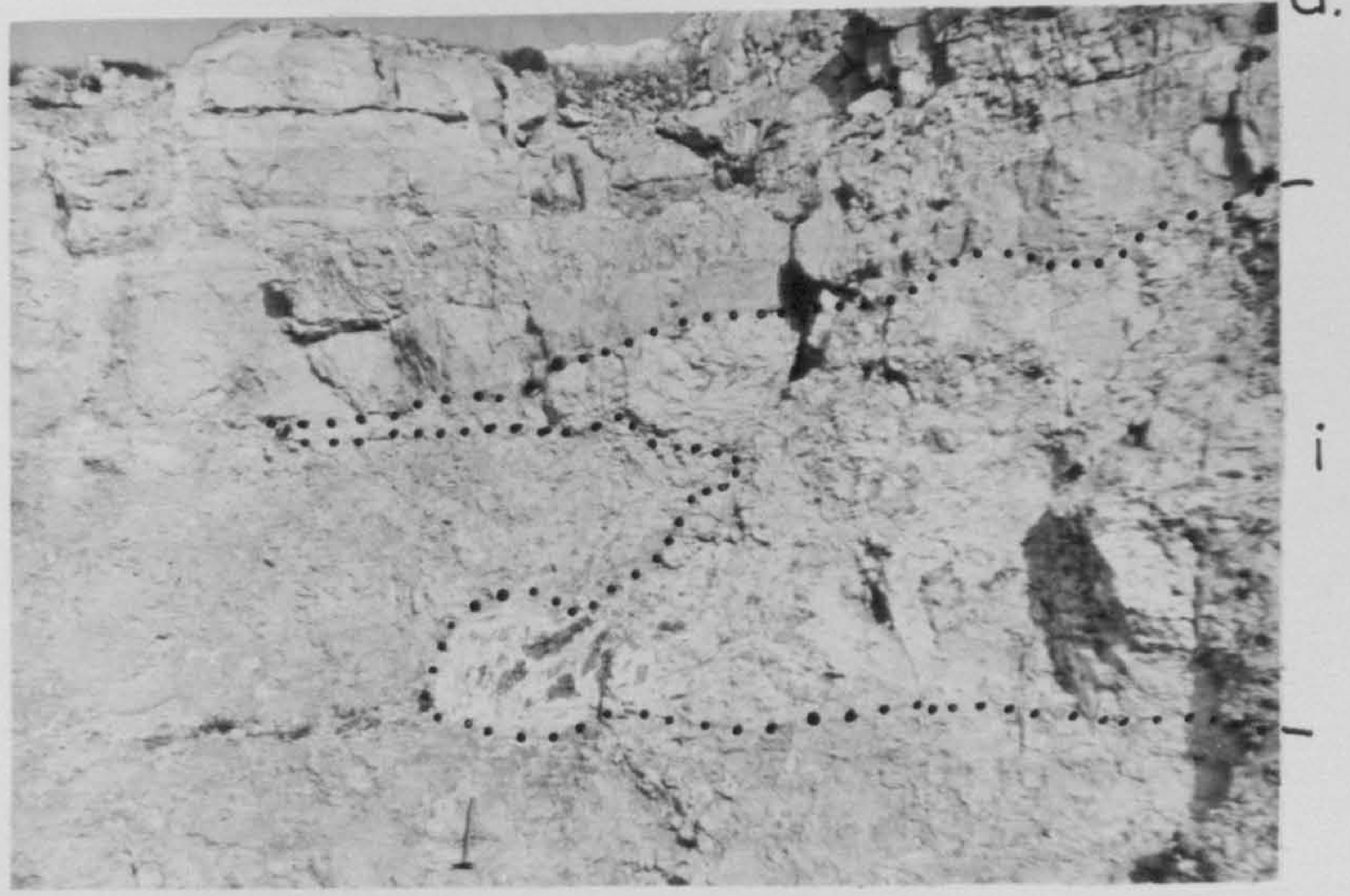
a.

b.

c.



d.



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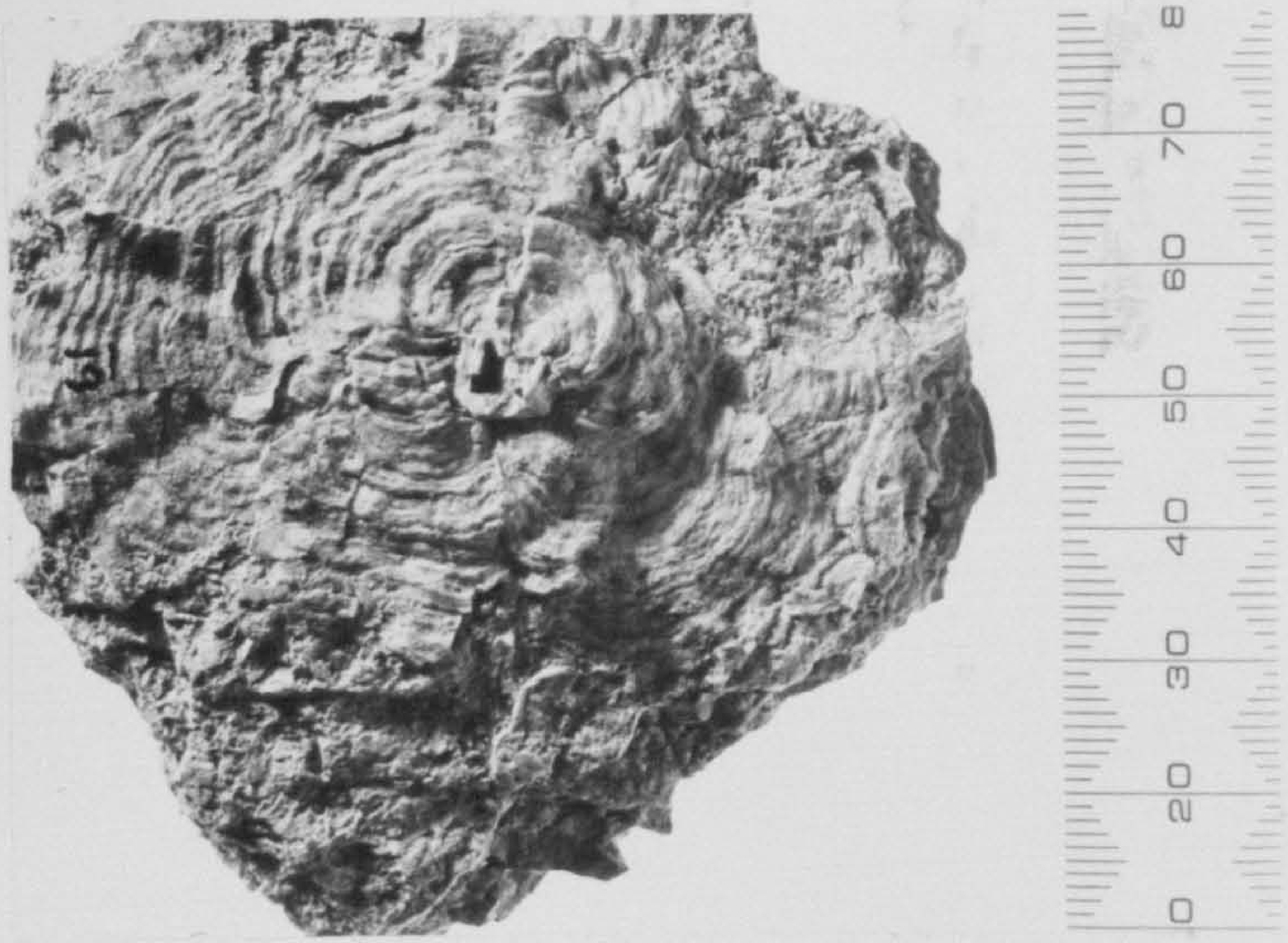


PLATE 15.

PLATE 16

Unrecorded Fossils from Malta

a. Blue Clay. Spine bearing, limonitised plastron of *Schizaster eurynotus*, north of Il Minzel, Malta (409763).

b. Blue Clay. Detail of the spatulate distal terminations to the spines, (same loc. as a.).

c. San Leonardo Beds. A charophyte gyrogonite, San Leonardo, Malta (601705).

d. San Leonardo Beds. Cast of *Amnicola* sp. from same marl bed as c. (same loc. as c.).

e. Rabat Plateau Beds. Vertical multi-"Y" branching ichnofossils, possibly root structures, in oolite, Ta Zuta, Malta (456668).

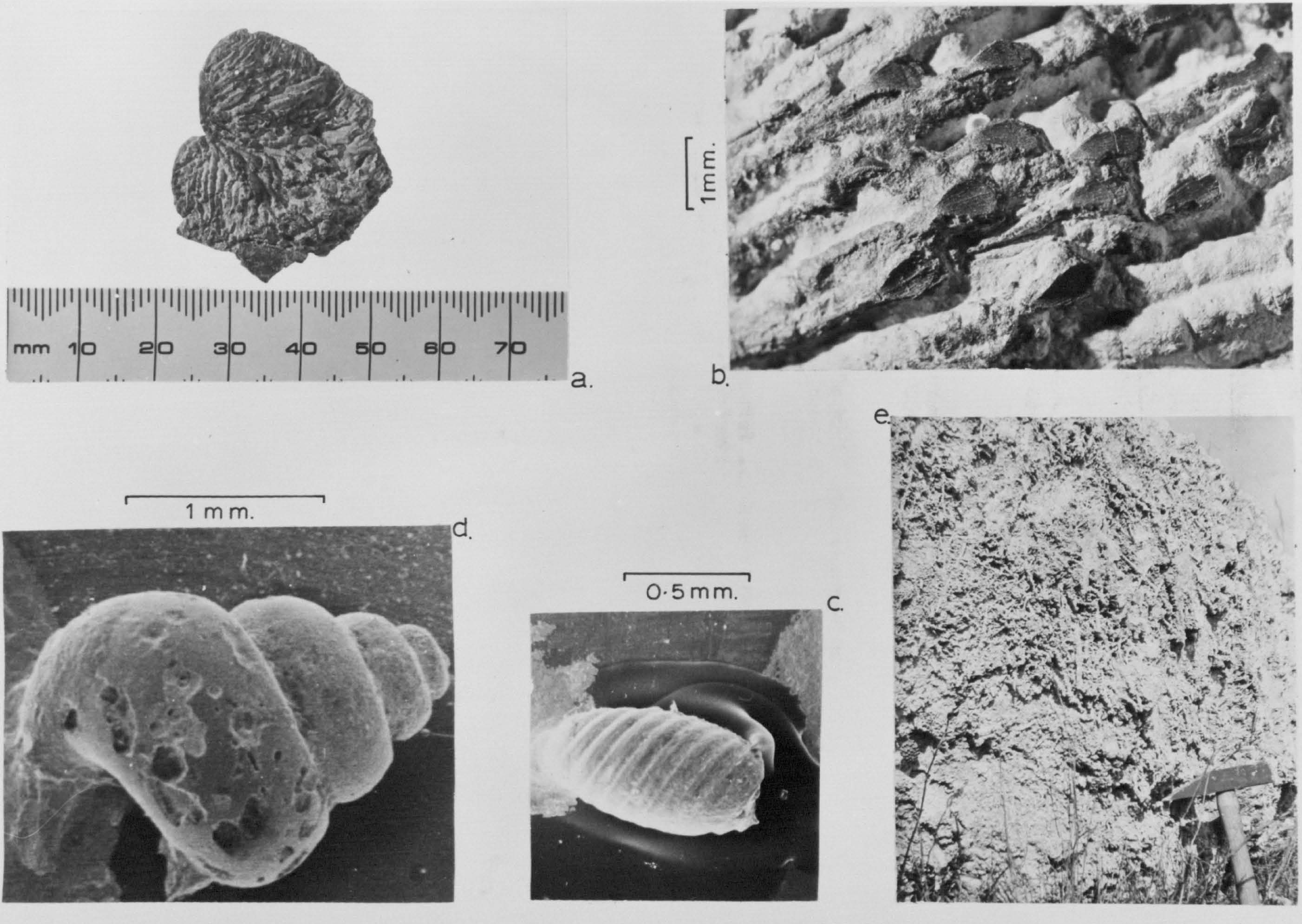


PLATE 16.

PLATE 17

Terebratula-Aphelesia Bed

a. Adult *Terebratula terebratula*,(i) from areas east of the bioherm, (ii) from the grey marly basal unit, (iii) from the flanks of the Coralline Algal Bioherm.

b. Adult *Aphelesia Bipartita* from the crestal areas of the bioherm.

c. Juvenile *Terebratula terebratula*.

d. Juvenile *Aphelesia bipartita*.

e. Alar projections (i) around the open deltidial area of *Aphelesia* used in distinguishing juveniles of *Aphelesia* from *Terebratula*.

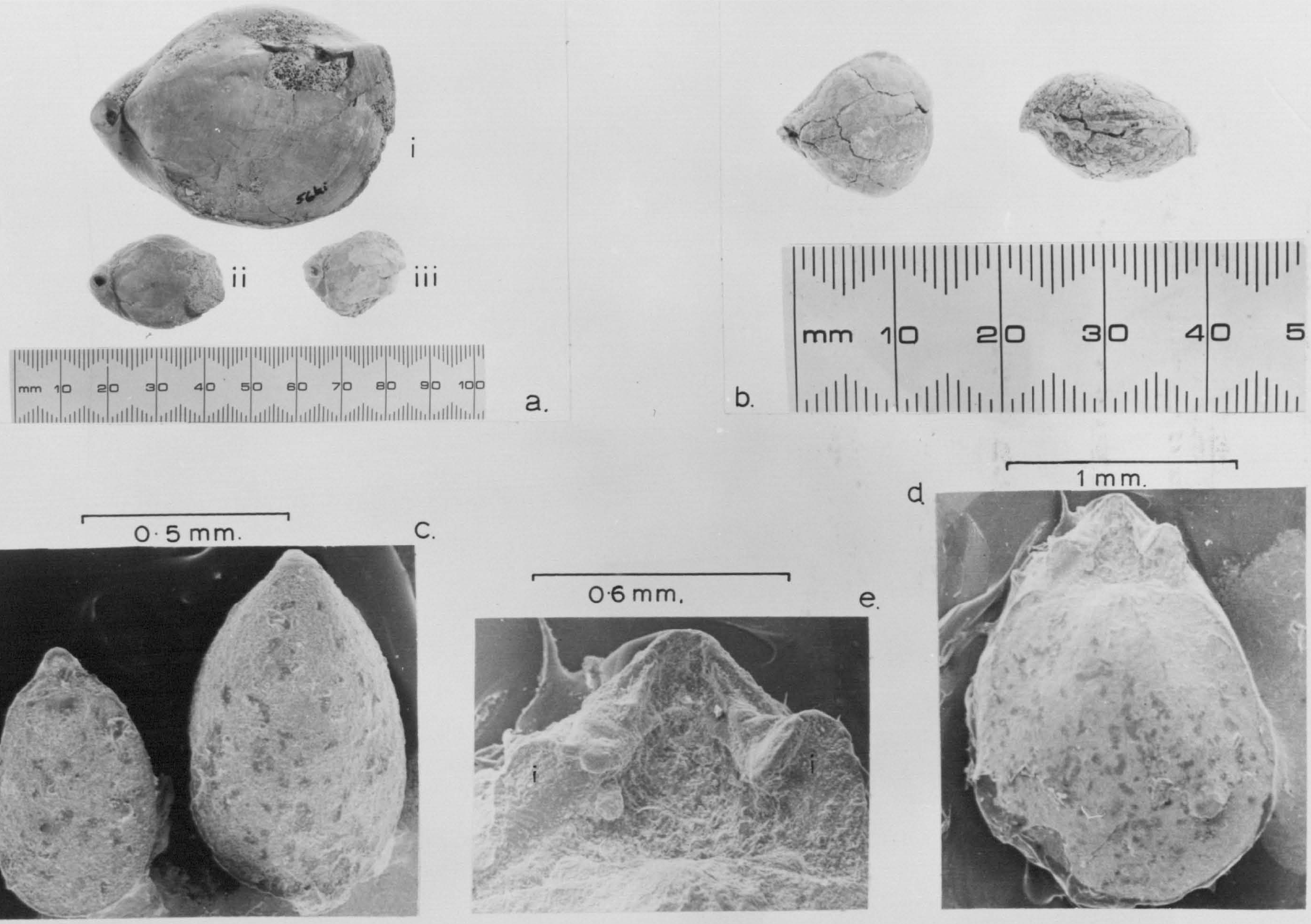

i
56ki
ii
iii
mm 10 20 30 40 50 60 70 80 90 100
a.
mm 10 20 30 40 5
b.
0·5 mm.
c.
0·6 mm.
e.
i
i
1 mm.
d

PLATE 17.

PLATE 18

Terebratula-Aphelesia Bed

a. *Argyrotheca* sp. young adult.

b. *Megathiris* sp. young adult.

c. *Cellaria* sp. A typical cellariform bryozoan internode growth-form from the area furthest east of the bioherm.

d. A typical membraniporiform A bryozoan growth-form from the crest of the bioherm.

e. A typical vinculariform bryozoan growth-form from the sheltered area to the east of the bioherm.

f. *Batipora* sp. A typical celleporiform bryozoan growth-form from the crest of the bioherm.

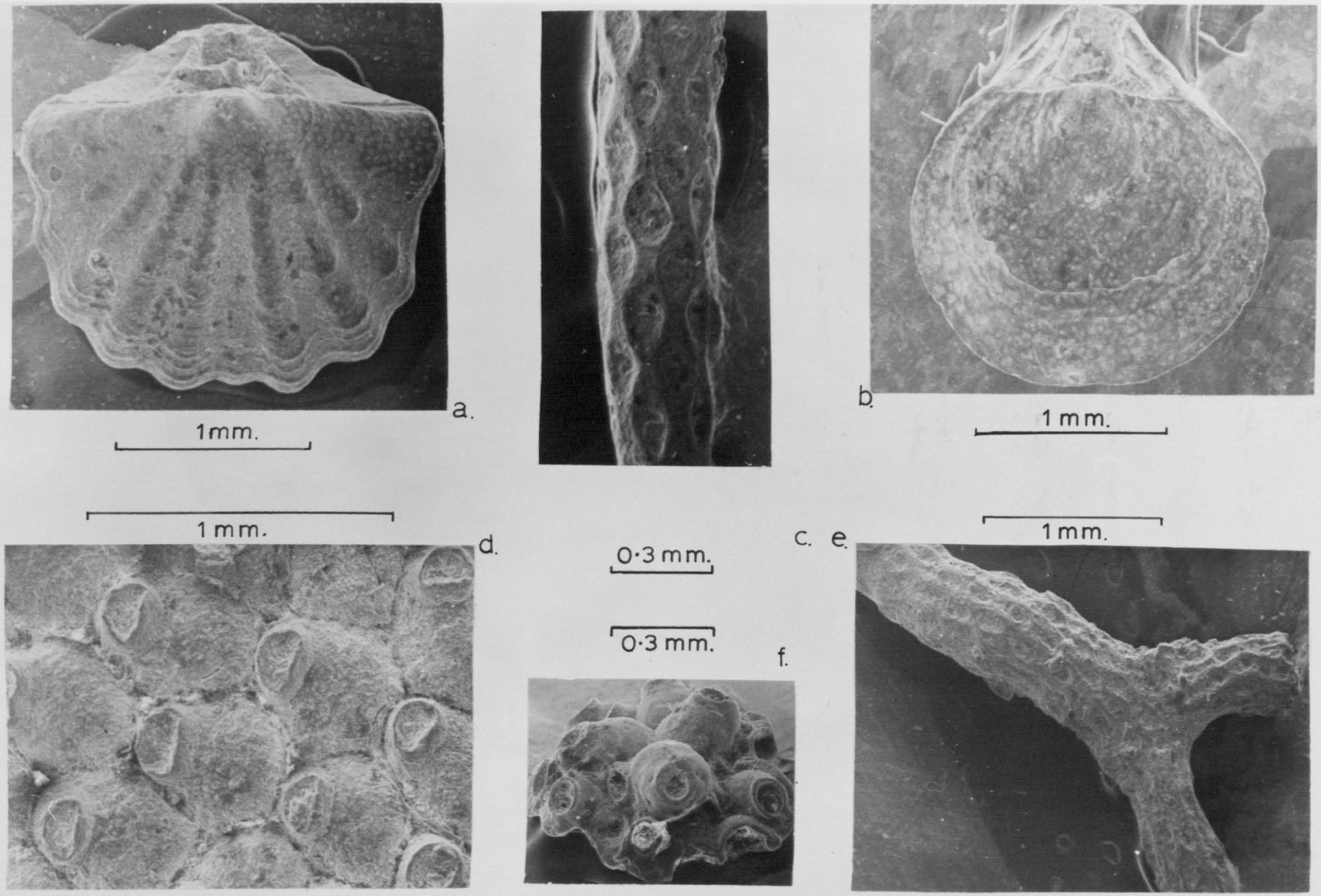


PLATE 18.

PLATE 19

Solution subsidence infill and tectonic features

a. Xlendi solution subsidence structure. Folded Miocene sediments in an elliptical faultbound subsidence structure. Subsidence margins dashed, east of Xlendi, Gozo (296876).

b. Xlendi solution subsidence structure. View from "X" plate 19a, showing the lensoidal nature to the subsidence infill.

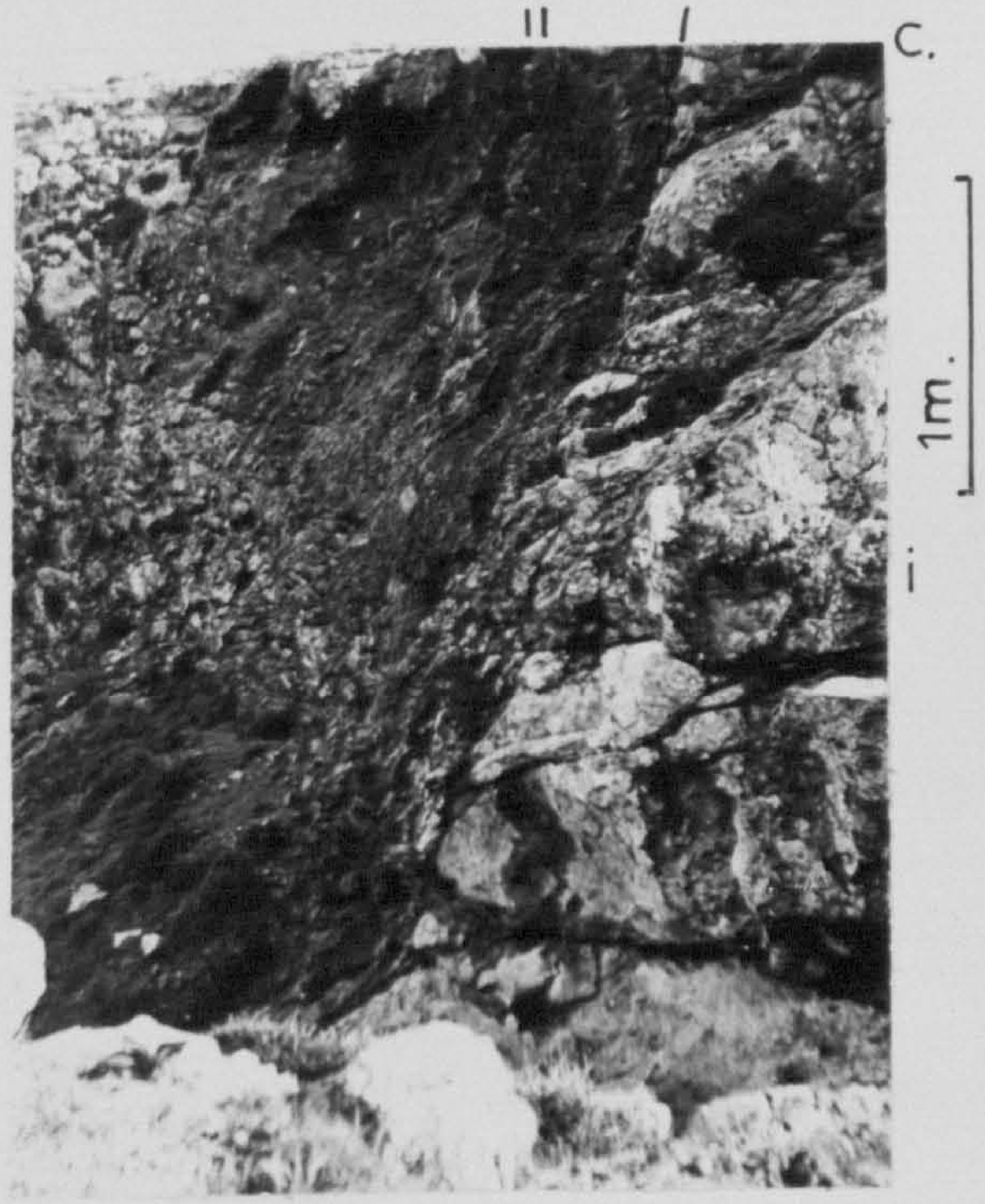
c. Ghajn Znuber solution subsidence structure. "Circular fault" margin separating Upper Coralline Limestone (i), from the terra rossa infill, now calcreted, which contains angular boulders of Upper Coralline Limestone (ii), Ghajn Znuber, Malta (407787).

d. Qammieh Fault. Double fracture plane with Blue Clay (i), separates Lower Coralline Limestone (ii), from Upper Coralline Limestone (iii), Qammieh, Malta (401808).

a.

b.

c.



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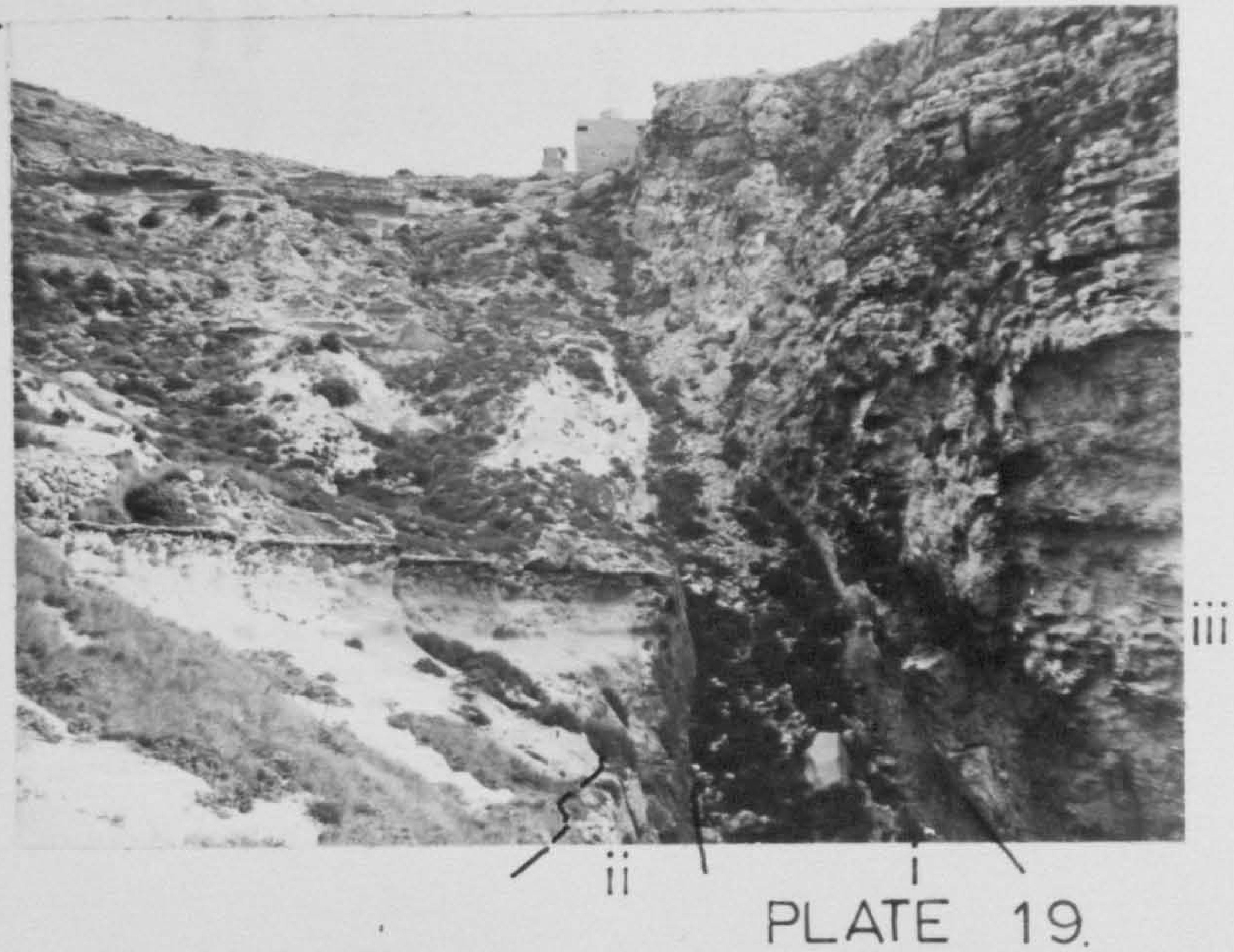


PLATE 19.

PLATE 20

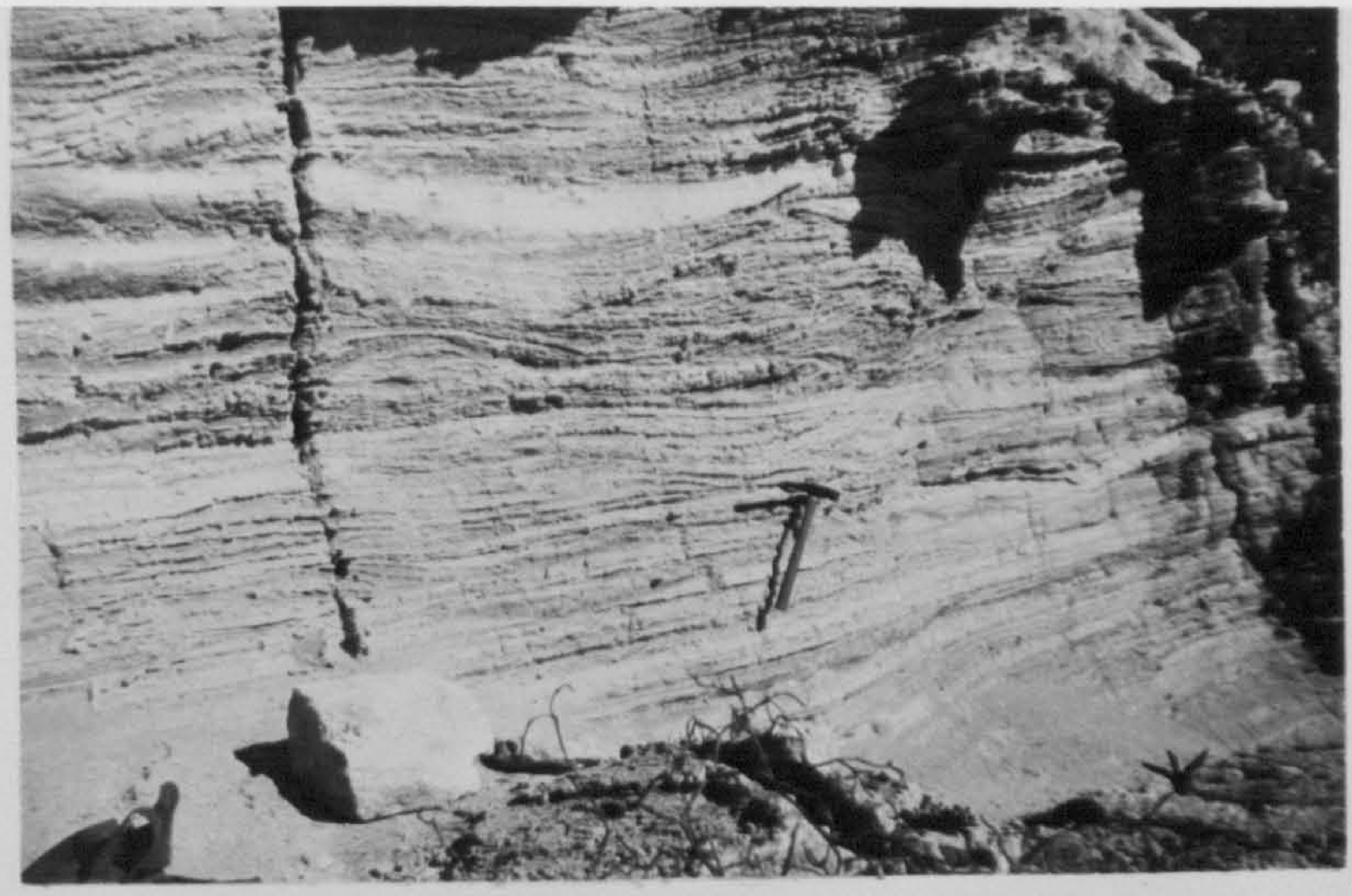
Solution subsidence structures

a. Xlendi infill. Poorly washed lithoclast biosparite infill showing scour and fill structures and migrating channel development, east of Xlendi, Gozo (296876).

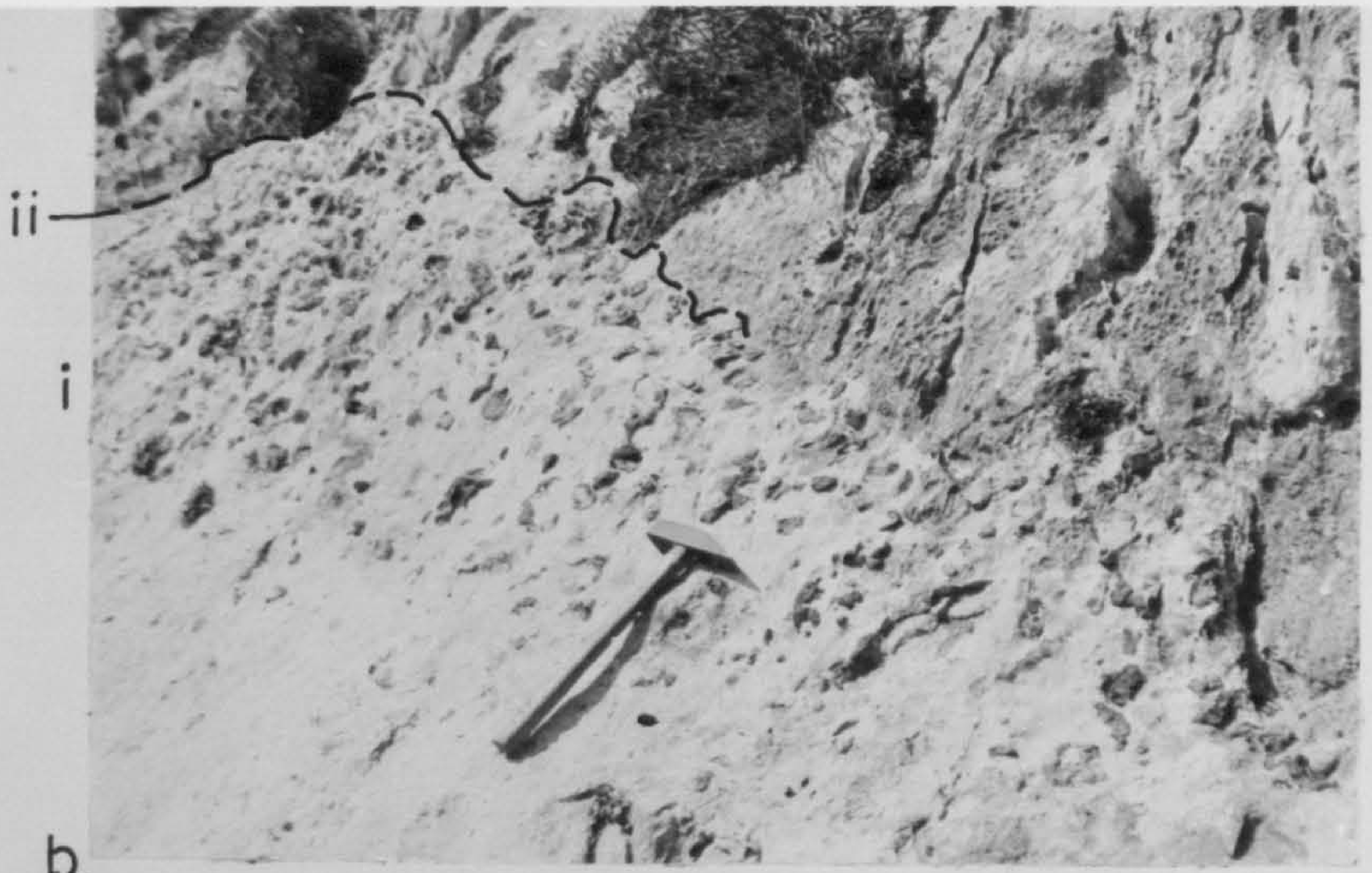
b. Xlendi infill. Early biomicrite subsidence infill containing phosphorite pebbles (i), in contact with the Lower Coralline Limestone subsidence margin (ii), (same location as a.).

c. Ghajn Abdul infill. Large molluscan biosparite boulder (i), set in a contorted solution subsidence infill of white thinly laminated biomicrite, Ghajn Abdul, Gozo (287893).

d. Qawra infill. Solution fretted, phosphatised Globigerina Limestone boulders and breccia set in a poorly washed lithoclast biosparite infill, Qawra, Gozo (273898).



a.



b.

c.

d.

PLATE 20.