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The Stratigraphy and Carbonate Environments of the Lincolnshire Limestone Formation (Bajocian) in Lincolnshire and parts of Leicestershire.

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ABSTRACT

The Lincolnshire Limestone Formation (Bajocian) of eastern England has been studied from three standpoints: biostratigraphy, lithostratigraphy and environmental analysis. New discoveries and a revision of earlier ammonite finds have permitted a re-assessment of the formation's age, relative to the standard Jurassic ammonite zonal scheme. Three distinct ammonite faunas, representative of the _discites_ Zone, and _ovalis_ and _laeviuscula_ Subzones of the _laeviuscula_ Zone, have been recognised. It has therefore been possible, for the first time, to subdivide the formation on the basis of its ammonite faunas. As neither the lowest nor highest lithostratigraphic units have so far yielded any ammonites, the minimum and maximum ages of the Lincolnshire Limestone remain unresolved.

The lithostratigraphy of the formation has been completely revised and eleven "formalised" members proposed: Sproxton, Greetwell, Leadenham, Lincoln, Scottlethorpe, Lindsey Shale, Metheringham, Blankney, Castle Bytham, Sleaford and Creeton. The base of the Lincoln Member is considered to be of fundamental importance in the internal correlation of the formation. It has been used as the datum level for all correlations. As the boundary between the ammonite faunas indicative of the _discites_ and _laevuiscula_ Zones appears to coincide with the base of the Lincoln Member, it may well be a significant biostratigraphic, as well as lithostratigraphic divide. Although less certain on present evidence, the base of the Sleaford Member may also prove to be an important biostratigraphic boundary, separating the ammonite faunas of the _ovalis_ and _laeviuscula_ Subzones of the _laeviuscula_ Zone.

Analysis of both sedimentological and faunal criteria has permitted a number of environments to be recognised. In broad terms the transgressive Lincolnshire Limestone sequence has prograding tidal-flat rhythms and "lagoonal" deposits erosively overlain by barrier-complex sediments. Various sub-environments, including barrier-inlet channels and barrier-island sediments, have been recognised within the barrier-complex.

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CHAPTER I

INTRODUCTION

I.1. AIMS AND SCOPE OF RESEARCH

I.1.a. Aims of Research

The principal aim of this project has been to develop a coherent lithostratigraphy for the Lincolnshire Limestone Formation of the Middle Jurassic of eastern England. The new scheme is intended to clarify the generalised and imprecisely defined stratigraphies of earlier workers (see Sylvester-Bradley, 1968, for review) and to replace their unwieldy and contradictory terminologies with a simplified, coherent nomenclature. In addition a detailed revision of the ammonite faunas of the formation has been undertaken and the stratigraphical position of these forms re-assessed. On the basis of this, a new internal biostratigraphy has been erected for the Limestone and a better understanding of the formation's position in the standardised Jurassic zonal scheme has been gained. Finally, the carbonate facies represented in the formation have been analysed and a depositional history outlined. The environmental inter-

-pretations have been based upon both sedimentological and faunal criteria.

I.1.b. Geographical Setting

The Lincolnshire Limestone crops out as a linear belt running northwards from Kettering, Northamptonshire to the Humber Estuary (Fig.1.1). It is believed to continue into North Humberside as the Cave Oolite. Between Scunthorpe and Sleaford, the Lincolnshire Limestone caps the westward facing escarpment called the "Lincoln Cliff", but further south its outcrop becomes less well defined, widening and swinging away from a sharp north-south alignment to a north-east - south-west trend.

Economically the Limestone is exploited for cement manufacture, agricultural lime, building stone (the Ancaster and Clipsham Stones) and low-grade roadstone. Such wide use has resulted in the excavation of a number of quarries which, with a few railway cuttings, provide the only exposures in the formation. There are no known natural exposures. Open-cast mining for the underlying Northampton Ironstone (Fig.1.2) formerly revealed numerous faces in the Lincolnshire Limestone in Northamptonshire and south Lincolnshire/Leicestershire but recently the south Lincolnshire ironfield has been abandoned and most of the workings restored for agriculture.

I.1.c. Geological Setting

The Lincolnshire Limestone constitutes the highest formation in the Bajocian succession of the East Midlands (Fig.1.2). Prior to this work much of the formation was considered to fall within the discites Zone of the Lower Bajocian (Kent, 1966; Barker and Torrens, 1971; Senior and Earland-Bennett, 1973; Parsons, 1974a; but see also Parsons, 1974b), but a revision of the ammonite faunas has shown this not to be the case. The range of the discites Zone faunas in the Limestone has been shown to be far more restricted than previously thought and to be succeeded by other faunas, indicative of the "higher" laeviuscula Zone. These also signify a Lower Bajocian age. However, there is still no evidence to support the view of Kent (in Swinnerton and Kent, 1976) that the Great Ponton Beds (uppermost Lincolnshire Limestone) represent still younger levels. Indeed the lithostratigraphical relationships of the Great Ponton Beds suggest that they can be correlated with beds elsewhere that have definitely been shown to belong in the laeviuscula Zone.

The Lincolnshire Limestone forms the principal carbonate unit in the "mixed facies belt", which makes up the Middle Jurassic of the East Midlands basin. Arkell (1933, p.210) considered the formation to be a "lens of limestone", appearing just north of Kettering and thickening to approximately 40 metres at Great Ponton, near Grantham, before thinning again towards the Humber Estuary (Fig.1.3). Although the variations along the strike section are relatively well known, the configuration of the dip section remains unresolved because the western limit of the formation is determined by present day erosion, while eastwards the Lincolnshire Limestone dips under younger strata. Despite this, some of the formation's major thinning trends can be determined from well and borehole logs (Fig. 1.4). More recently the data gained from the North Sea oil exploration (Kent, personal communication) has shown a general eastward thinning of the Limestone, suggesting that the Lincolnshire Limestone "sea" was probably situated in a N.E. - S.W. aligned gulf. This, probably shallow gulf, was bordered to the north by the Yorkshire Delta and to the south by the low-lying London Landmass. However the western (? land) and eastern limits are less certain. The generalised review of the geological history of the North Sea by Ziegler (1975) suggests that the Lincolnshire Limestone probably formed a carbonate fringe to the London Landmass, although the details at formational level are not fully known yet for the North Sea area (Kent, 1975, p.447).

Genetically the formation forms a marine intercalation between the more clastic-rich, paralic Grantham Formation (formerly Lower Estuarine Series, see Kent, 1975b) and Upper Estuarine Series, reflecting the transitional nature of the region as a whole between the deltaic facies of Yorkshire and more open marine conditions of southern England. However in neither case are the relationships between the East Midlands basin and those of Yorkshire and Southern England clearly known (Fig.1.5). To the north, the Humber Estuary forms a natural break in outcrop between Lincolnshire and Yorkshire, which is emphasised by the poorly-exposed nature of the Jurassic sequence immediately to the north and south of the waterway. Despite this, the Cave Oolite has long been considered, on lithological criteria, to be the North Humberside equivalent of the Lincolnshire Limestone (de Boer et al., 1958); a correlation supported by the discovery of a Hyperlioceras rudidiscites S. Buckman from the Cave Oolite at Eastfield Quarry, South Cave (SE 915325) by Senior and Earland-Bennett (1973). However Parsons (1974b) expressed considerable doubt as to the validity of this ammonite's identification and therefore, in light of the revision of the biostratigraphy of the Lincolnshire Limestone, the precise Cave Oolite - Lincolnshire Limestone correlation must remain unresolved. The other marine horizons in the Yorkshire basin (see Hemingway, 1974), which may reflect transgressions of the Lincolnshire Limestone sea into Yorkshire, have not so far yielded any ammonites (Hemingway, 1974, p.193) and therefore proposed correlations with these units remain largely speculative. However, on the basis of ostracod faunas, Bate (1967) suggested broad correlations between the Hydraulic Limestone/Ellerbeck marine horizon and the Lower Lincolnshire Limestone and between the Millepore Bed/Whitwell Oolite, Yons Nab Beds and Cave Oolite and the Upper Lincolnshire Limestone (Fig.1.6). Furthermore, he (Bate, 1967) claimed that the Scarborough Limestone was younger than the

Lincolnshire Limestone, an opinion that has recently been supported by ammonite evidence (Parsons, 1977). However, Knox (1973a) suggested that, on field relations, the Hydraulic Limestone was unlikely to be equivalent to the Ellerbeck Formation and that the initial Lincolnshire Limestone was more likely to be reflected (north of the Market Weighton structure) by the Blowgill Member of the Cloughton Formation (see Hemingway and Knox, 1973 for stratigraphical details), the Ellerbeck marine horizon not being developed in Lincolnshire.

The southern boundary of the Lincolnshire Limestone approximately coincides with the Oxford Shallows (Sylvester-Bradley, 1968). The complicated stratigraphical relationships in this area make it difficult to determine whether there was a marine connection between southern England and Lincolnshire at this time. At no point does the Lincolnshire Limestone pass laterally into shoreline deposits, and so the real limits of the basin remain unknown.

I.2. REVIEW OF PREVIOUS RESEARCH

I.2.a. Introduction

Previous research on the Lincolnshire Limestone was largely carried out in two distinct periods: pioneer work in the middle to late 19th century revealed the overall stratigraphical relationships of the formation, while in the 1930s - 1940s the internal relationships of the Limestone were more fully examined.

Although the earliest studies on the formation were by Brodie (1853) and Morris (1853), it was not until the independent research of Sharp (1873) and Judd (1875) that the Inferior Oolite age of the Linconshire Limestone was indisputably established. Morris (1853) had assigned it to the Great Oolite, while Brodie (1853) placed different parts of the Lincolnshire Limestone into the Inferior and Great Oolite; a practice apparently followed by Morris (1869). Later work (Cross, 1875; Jukes-Browne, 1885; Ussher et al., 1888; and Ussher, 1890) continued the steady accumulation of lithological and faunal details, which were collated in a valuable synthesis by Woodward (1894). Outstanding amongst these earlier contributions were the scholarly works of Sharp (1873), Judd (1875) and Ussher (1890), who unravelled the complex facies of north Lincolnshire.

As most of these earlier workers were concerned with establishing the overall stratigraphical position of the Lincolnshire Limestone, little attention was paid to subdividing the formation. However Ussher et al. (1888, p.44) and Ussher (1890, p.59) offered the first cogent internal classification of the formation for two areas in northern Lincolnshire and on the basis of these, suggested a correlation between the two sequences (Fig.1.7). Later Woodward (1894, p.174) ordered all the previously used terms for the subdivisions of the Lincolnshire Limestone into broadly equivalent stratigraphical groupings (Fig.1.8).

After this early work, the Lincolnshire Limestone was neglected until the 1930s, when both independent workers (Richardson and Kent, 1938; Richardson, 1939a, and 1940; Muir-Wood, 1939 and 1952; Kent, 1940, 1948 and 1953; Swinnerton and Kent, 1949; and Hallam, 1954) and the Geological Survey (Hollingworth and Taylor, 1946a, 1946b and 1951; Taylor, 1946; Wilson, 1948; and Evans, 1952) contributed a profusion of facts and ideas concerning the correlation and subdivision of the formation. Despite this, no truly coherent stratigraphical scheme, based upon detailed measured sections, was ever published. An outline stratigraphy was proposed by Kent (1940), wh described the generalised succession and major lateral facies variations. He (1940, p.51) also discussed the age of the formation in the light of the more recent ammonite discoveries (Batters, 1933; Baker, 1934; Kent and Baker, 1938; and Richardson, 1939a) and, above all, (op.cit., p.49) recognised the correlative value of _Acanthothiris crossi_ (J.F. Walker).

The Crossi Beds were the first consistently traceable horizon in the formation. Throughout his work, Kent (1940, p.49) generously acknowledged the debt to Mr. L. Richardson, who, judging from the diagram first published in Sylvester-Bradley (1968, fig.42; see Fig.1.9) and his field reports (Richardson, 1939a, 1939b and 1940), had a considerable understanding of the internal stratigraphy of the Lincolnshire Limestone. It is to be regretted that neither of these men published the full details of their work, as they could well have advanced our understanding of the Lincolnshire Limestone well beyond that which was evident from their writings.

The Geological Survey work on the Lincolnshire Limestone was a spin-off from the study of the Northampton Ironstone. Nevertheless Hollingworth and Taylor (1951; see also Taylor, 1963) produced an internal stratigraphy for the formation of south Lincolnshire, Leicestershire (Rutland) and Northamptonshire while the relationships of the facies seen in central Lincolnshire were summarised by Evans (1952). Furthermore Taylor (1946) demonstrated the existence of extensive, large-scale channelling of the Upper into the Lower Lincolnshire Limestone in Northamptonshire.

This period of research concentrated upon the problems of subdividing the Lincolnshire Limestone and despite the proliferation of local, and often contradictory, stratigraphical terms (Sylvester-Bradley, 1968), the work of Kent and Richardson provided a basis from which further studies could be developed. Furthermore the ammonite evidence collated by Kent (1940), and the preliminary work on the brachiopod faunas by Muir-Wood (1939 and 1952) began to give a firmer idea of the age of the formation within the Inferior Oolite.

Later, Kent (1966) completely revised and standardised the stratigraphical nomenclature of the Lincolnshire Limestone and reviewed much of the palaeontological evidence for the age of the formation. The new terminology was adopted, with only minor modifications, in subsequent work (Sylvester-Bradley, 1968; Kent, 1970; and in Swinnerton and Kent, 1976; but see Ashton, 1975). Advances were also made in the dating of the Lincolnshire Limestone (Bate, 1967; Barker and Torrens, 1971; Senior and Earland-Bennett, 1973; and Parsons, 1974b). On the basis of ostracod faunas, Bate (1967) suggested a broad correlation scheme for the Lincolnshire Limestone and Yorkshire Oolites (Fig.1.6), but the results of this study were rather inconclusive. However, Barker and Torrens (1971) reported the find of an ammonite that provided the first real evidence for the age of the Lower Lincolnshire Limestone in Northamptonshire, and Senior and Earland-Bennett (1973) produced what appeared to be significant ammonite evidence for the dating of the Upper Lincolnshire Limestone. However, Parsons (1974b) questioned the validity of much of the work of Senior and Earland-Bennett (1973), which has subsequently been shown to be mostly inaccurate (Ashton, 1976; and Ashton and Parsons, in prep.). Consequently the apparent advances made by Senior and Earland-Bennett (1973) are now known to be largely spurious.

I.2.b. Internal Correlation

The pioneer works of the last century were primarily concerned with understanding the overall stratigraphical relationships of the formation and, except for Ussher et al. (1888), Ussher (1890) and Woodward (1894), no internal subdivision of the Lincolnshire Limestone was attempted. In contrast, the second phase of work on the formation concentrated upon this very aspect and a number of generalised schemes were proposed (Kent, 1940; Hollingworth and Taylor, 1951; Richardson in Muir-Wood, 1952 and fig.42 in Sylvester-Bradley, 1968). These efforts were hindered by the lack of correlatively useful fossils and the complexity of the facies relationships.

I.2.b.i. Fauna: The Lincolnshire Limestone is characterised by a scarcity of ammonites (Arkell, 1933, p.210) and therefore the formation largely lacks the principal means by which reliable internal correlations can be made. Until recently the few ammonites that had been discovered were all thought to represent a single zone (the discites Zone of the Lower Bajocian; see Kent, 1966 for review of earlier finds; Barker and Torrens, 1971; and Senior and Earland -Bennett, 1973), and therefore a subdivision of the formation using ammonites seemed probable. However this view was undermined by Parsons (1974b), who claimed that the Sonninia (BMNH C 39337), from Castle Bytham (Richardson, 1939a), belonged to the Sonninia ('Fissilobiceras') ovalis (Qu.emend. S.B.) - fissilobatum (Waagen) group, and as such was indicative of the ovalis Subzone of the laeviuscula Zone, which is the next youngest Bajocian zone after the discites Zone (see Parsons, 1974a for details). Therefore the Lincolnshire Limestone apparently could be subdivided on the basis of ammonites, a contention that has been supported by subsequent research (Ashton, 1976; Ashton and Parsons, in prep.; and see Chapter III).

Although much progress has been made in developing an internal biostratigraphy for the formation (Chapter III), the relative scarcity of ammonites remains a major hindrance to the correlation of many sections. Furthermore the youngest horizons in the Lincolnshire Limestone have not so far yielded any ammonites and therefore even the modified biostratigraphical scheme presented in this thesis (Chapter III) remains incomplete.

In the absence of ammonites, correlations were attempted using macrobenthonic groups such as brachiopods (Muir-Wood, 1939 and 1952; and Kent, 1940, 1966 and 1967), gastropods (Huddleston, 1888, p.73; and Cox in Kent, 1966, p.62), bivalves (Kent, 1966, p.65) and corals (Kent, 1966, p.63) and, in one case, microfossils (Bate, 1967). For example, Kent (1967) correlated the base of the Clipsham Stone at the Soil Fertility Quarry, Clipsham (SK 978154) with the "Roadstone" bed at Castle Bytham (SK 990180; see Richardson, 1939a, p.43) on the basis of the common occurrence of

Zeilleria wilsfordensis Muir-Wood. Similarly the Barnack Rag, Weldon Beds, Ancaster Rag and Great Ponton Gastropod Beds were all thought to be laterally equivalent because they contained similar brachiopod and gastropod faunas (Kent, 1966, p.62). However, the most useful fossil for the formation's internal correlation proved to be the small rhynchonellid Acanthothiris crossi (J.F. Walker). Its importance as a marker was first recognised by Kent (1940, p.49) and further emphasised by Hollingworth and Taylor (1951). In a general way it does appear to be a valuable marker for the middle of the formation (the Crossi Beds), although A. crossi occurs at levels other than those encompassed by the Crossi Beds (Hollingworth and Taylor, 1951, p.18) and in detail even the Crossi Beds do not form a distinct stratigraphic unit in themselves. On the contrary, the Crossi Beds (with abundant A. crossi) occupy part of at least four clearly differentiated lithostratigraphic units, although it is true that these are all concentrated around the middle of the formation. Therefore Kent's (in Swinnerton and Kent, 1976) belief that A. crossi is an excellent marker is accepted here on the understanding that A. crossi (in abundance) indicates an approximate stratigraphic level only.

Besides the problem involved with A. crossi and the Crossi Beds, there are a number of drawbacks involved in accepting other correlations suggested by the benthonic faunas. Firstly, the majority of the faunas in the Lincolnshire Limestone appear to be facies-related, and consequently the correlation of indigenous faunas is really a correlation of like-environments, which may or may not be of a similar age. The "Nerinea" s.l. gastropods are one such facies-related group. Secondly, as many of the gastropod and brachiopod occurrences are as transported faunas, they tend to reflect the local sedimentation conditions rather than stratigraphically useful faunal successions. This is especially so when one considers that the enclosing lithological units concerned in many such correlations (for example those discussed by Muir-Wood, 1952) are most probably time-restricted, making significant evolutionary changes unlikely. Indeed Bate (1967) believed that the relatively rapid deposition of the Lincolnshire Limestone did not allow for significant evolutionary changes to take place in the ostracod faunas, which are fairly uniform throughout the whole of the formation. Finally, when examined in detail, many of the proposed correlations do not appear to be based on totally sound criteria. For example, there is no clear evidence in the work of Muir-Wood (1952) that attempts were made to collect brachiopods from horizons other than those where they occur prolifically. As all of these horizons were known (or suspected) to be at approximately the same level (Kent, 1940; and Muir-Wood, 1952, p.115) on general lithostratigraphical grounds, it is really not so surprising that the brachiopod faunas (which are all derived) appeared similar. It would have been far more valuable to know whether these same forms occurred at other levels in the Lincolnshire Limestone and in different facies before any importance was attached to their apparently restricted occurrence in the uppermost Lincolnshire Limestone (Kent, 1966, p.57). Certainly Muir-Wood (1952) presents little evidence to suggest a separation of the Great Ponton Terebratula and Gastropod Bed levels on faunal grounds.

In fact there seems little evidence in the literature to refute the conclusion of Sylvester-Bradley (1968, p.218) that, ".....(Lincolnshire Limestone) palaeontology has been so little studied that correlation is almost limited to the recognition of the Crossi Beds and even this bed presents problems.......".

I.2.b.ii. Lithologies: The Lincolnshire Limestone is typified by what Arkell (1933, p.210) termed, "..... bewilderingly rapid and frequent changes of facies.......". Despite this, even some of the earliest workers (Ussher et al., 1888; Ussher, 1890; and Woodward, 1894) proposed lithological correlations (Figs.1.7 and 1.8), showing a remarkably advanced understanding of the facies relationships. However, it must be remembered that the synthesis of Woodward (1894) relied heavily upon the work of Sharp (1873), Judd (1875), Ussher et al. (1888) and Ussher (1890).

Unfortunately this early work was not added to until the 1930s, when Richardson (1939a, 1939b and 1940; and see also Richardson and Kent, 1938; Muir-Wood, 1952; and Fig.1.9), Kent (1940) and to a lesser extent Hollingworth and Taylor (1951), developed very similar stratigraphies for the Lincolnshire Limestone. Although Kent (1940, p.49) acknowledged the contribution of Richardson in the development of this work, it is apparent from later work (Muir-Wood, 1952; and Kent, 1966, pp.62-62) that the two men did not agree on all points. In particular, far from placing the Upper/Lower Lincolnshire Limestone subdivisions immediately above the Crossi Beds, Richardson (see Muir-Wood, 1952) was in favour of drawing it between the Ancaster Freestone/Ancaster Rag levels at Ancaster (see Richardson, 1939b, p.473), although no such twofold division occurs on his 1939 cross section draft (Fig.1.9). The relative merits of these two arguments are discussed in Chapter II. What is common to both of these workers is the certainty that they attach to the lateral traceability of the Lower Lincolnshire Limestone subdivision and the uncertainty (see Kent, 1940, fig.1 and 1966, fig.2) associated with the correlation of the higher units, in particular the Ancaster Freestone and Rag, the Great Ponton Beds and the Clipsham and Weldon Beds.

Despite the advances made by Kent (1940), the failure to publish any measured sections on which the stratigraphical subdivisions were defined, left the proposed terminology without a lithological framework and consequently devalued the work. Inevitably in the absence of defined type sections, the stratigraphy was never rigidly applied by later workers and additional names were erected for some units (Hollingworth and Taylor, 1951). Elsewhere mis-interpretations of Kent's stratigraphy resulted in even fundamental divisions like the Upper/Lower Lincolnshire Limestone boundary in central Lincolnshire being re-defined in such a way that it contradicted all previous work (Evans, 1952). Consequently the stratigraphy became even more confused and imprecise and the nomenclature unnecessarily complicated. This situation remained until Kent (1966) reviewed the earlier terminological usage and proposed a standardised scheme (op.cit., fig.1). However, Kent (1966) again failed to base the revised terminology upon measured sections and the ill-defined, localised nomenclature persisted.

Later workers (Bate, 1967; Barker and Torrens, 1971; and Senior and Earland-Bennett, 1973), more concerned with the biostratigraphical relationships of the Lincolnshire Limestone, tended to adopt the scheme proposed by Kent (1966), although Sylvester-Bradley (1968) suggested some minor modifications. However the problems inherent in trying to apply a generalised scheme, like that of Kent (1940 and 1966), to specific sections became only too apparent in some of this later work. For example, in outlining the stratigraphy of Woolfox Quarry (SK 951136), using the scheme of Kent (1966), Senior and Earland-Bennett (1973) not only mis-identified the subdivisions but even confused the Upper and Lower Lincolnshire Limestone (see discussion in Ashton, 1976); in that particular quarry the Lower Lincolnshire Limestone does not conform to Kent's generalised stratigraphy.

Therefore, although an internal stratigraphy existed for the Lincolnshire Limestone prior to this work, its ill-definition rendered it largely unusable for more detailed work, and suggested the need for its revision.

I.2.c. External Correlation

The Inferior Oolite age of the Lincolnshire Limestone Formation was independently established on general afaunal and stratigraphical grounds by Sharp (1873) and Judd (1875). However, as the importance of ammonites to Jurassic stratigraphy became more apparent (see Arkell, 1933 for historical review), it was obvious that they could be used to refine the age of the Lincolnshire Limestone. Unfortunately the formation appeared to be practically barren of cephalopods and therefore its subdivision and correlation were impeded (Arkell, 1933, p.210). More recently though, fresh ammonite discoveries have been made (Barker and Torrens, 1971; Senior and Earland-Bennett, 1973; and Ashton, 1976) and the significance of the ammonite faunas re-assessed (Parsons, 1974b; Ashton, 1976; and Ashton and Parsons, in prep.) in the light of more modern stratigraphical work (Parsons, 1974a). This has resulted in the stratigraphical position of the Lincolnshire Limestone being more firmly understood.

I.2.c.i. Ammonites: The role of ammonites in the correlation of the Lincolnshire Limestone is fully discussed in Chapter III.

I.2.c.ii. Other fauna: The marked lack of ammonites in the Lincolnshire Limestone has resulted in more than usual importance being attributed to correlations based upon other invertebrate groups, especially gastropods, brachiopods, bivalves and ostracods. Many such correlations have their origins in the last century. Indeed as Kent (1966, p.66) pointed out, "The earliest detailed dating of a part of the formation was by Brodie (1853), who assigned the lower beds in the Grantham district to the horizon of the Oolite Marl of the Cotswolds (*bradfordensis* Zone) on the basis of (*Natica leckhamptonensis*), (formerly *N. cincta*) and other fossils". Although this correlation has been accepted time and again (Hudleston, 1888, p.72; Kent, 1966; Senior and Earland-Bennett, 1973) it was questioned by Parsons (1974b, p.116), who, referring to the work of Senior and Earland-Bennett (1973) said, "..... the authors ..... overlooked the overwhelming ammonite evidence which has since eliminated any possibility of the correlation of the Little Ponton Beds with the Oolite Marl". This example serves to illustrate the imprecision of many of the correlations (relative to ammonite zonal stratigraphy) based upon benthonic faunas.

Other proposed correlations, using gastropods, seem to have stemmed from the contention of Hudleston (1890, pp.195-196) that the "*Nerinaea*" s.l. from the Weldon and Great Ponton Beds have Bathonian affinities. This apparently influenced Arkell (1933, p.211) who stated, "Provisionally it may be assumed that the highest part of the Lincolnshire Limestone is probably of Upper Inferior Oolite date"; an opinion that has retained support up to the present time (Swinnerton and Kent, 1976, p.43), although with diminishing conviction (cf. Swinnerton and Kent, 1949 and 1976). On re-examination, the evidence favouring such a correlation seems to have derived most of its "strength" from repetition because in addition to advocating the Bathonian affinities of these gastropods, Hudlestone (1890, pp.195-196) also said "When to these difficulties (poor preservation) we add the prevalence of dimorphism, it must be allowed that the Nerinaeas of the upper beds of the Lincolnshire Limestone (Weldon and Great Ponton) constitute about as undesirable a group as any one could have to investigate". These obvious taxonomic problems and the continuing absence of substantiating evidence for a Bathonian age for these beds must cast considerable doubt upon the conclusions drawn from the gastropods, especially in the light of the litho-and biostratigraphical advances described in later chapters. The only firm evidence dating the Lincolnshire Limestone indicates a (lowest) Lower Bajocian age.

The brachiopods from the uppermost Lincolnshire Limestone have similarly been thought to indicate an Upper Inferior Oolite age (Kent, 1940, p.51) but here too the evidence is only suggestive. Except for that of Muir-Wood (1952), no detailed taxonomic work has been undertaken on these forms and it appears that the studied species cannot be readily related to brachiopods from other depositional basins (Muir-Wood, 1952).

In other cases the benthonic forms were thought to support the ammonite evidence and indicate a *discites* Zone age. This was particularly so with Trigonia hemisphaerica var. gregaria Lycett, and the brachiopods of the Crossi Beds. The former, occurring abundantly in the Kirton Cement-stones and Kirton Shale of the Lincolnshire Limestone (Kent, 1940, p.57 and 1966, p.67), is restricted to the Lower Trigonia Grit (discites Zone) of the Cotswolds (Arkell, 1933, p.214). Similarly, Acanthothiris crossi (J.F.Walker) and "Terebratulae" resembling Lobothyris buckmani and Tubithyris painswick-ensis" (Kent, 1940, p.52) from the Crossi Beds were also considered to support a discites Zone age because of their similarity to the brachiopod fauna of the Buckmani Grit of the Cotswolds, although the latter realisation that the Buckmani Grit species of Acanthothiris were different from those found in Lincolnshire (Kent, 1966, p.68) undermined this contention. However, of greater significance and another salutory lesson in the use of benthos for correlation, is the fact that the beds in which both T. hemisphaerica and A. crossi occur, have yielded ammonites of the ovalis Subzone (see Chapter III). It would appear therefore that the benthonic faunas of the Lincolnshire Limestone cannot be considered as anything other than generalised age indices, especially in the context of Jurassic ammonite zonal stratigraphy. This is particularly well illustrated by the work of Bate (1967), who detected little difference in the ostracod faunas throughout the Lincolnshire Limestone. Furthermore the ostracods did not provide any conclusive correlations between the Lincolnshire Limestone and Yorkshire Oolites (Bate, 1967) except to indicate that the Scarborough Limestone was in no way equivalent to the Lincolnshire Limestone, a view supported by ammonite work (see especially Parsons, 1977). On reflection therefore, the opinion of Bate (1967, p.134) that the relatively short time-span involved in the deposition of the Lincolnshire Limestone did not allow for significant evolutionary change in the ostracods may well apply to the benthos in general.

I.2.d. Structure

The Lincolnshire Limestone, like much of the English Mesozoic, is structurally simple. This was aptly summed up by Wilson (1948, p.86), who wrote, "Structurally, Lincolnshire is devoid of large scale folding and faulting; however, faulting on a small scale has affected the Middle Jurassic rocks ...... ". Despite this, the structural movements appear to have been important in controlling sedimentation duting the deposition of the Lincolnshire Limestone and in the way they have subsequently modified the formation's stratigraphical relationships. In this context three structural features appear particularly important:

(1) The Spital Anticline

(2) The Great Ponton Syncline (but see Chapter IV)

(3) The "Nocton Uplift" and associated step fault system of east Lincoln (see Evans, 1952, p.332).

In the Spital anticline region (Kent, 1966, p.61) the Bathonian Upper Estuarine Series can be seen to rest on "......an eroded remnant of the uppermost Crossi horizon, locally reaching the Kirton Cement Shale beneath", indicating the removal of much of the Upper Lincolnshire Limestone during a pre-U.E.S. phase of uplift and erosion. Elsewhere these movements have resulted in synclinal structures, such as that at Great Ponton in which the highest Lincolnshire Limestone was thought to have been preserved. Thus the potential stratigraphical relationships seen in different areas owes something to the intra-Jurassic movements, despite their relatively minor nature.

The Nocton Uplift, which is apparently related to, and possibly controlled by deep-seated Palaeozoic structures (Swinnerton and Kent, 1976), seems to have exerted some influence upon sedimentation during Lincolnshire Limestone times. Swinnerton and Kent (1976, p.80) described this area as a region with ".....abnormally high figures ...... for both gravity and terrestrial magnetism .....", that indicated the presence of older and denser rocks much closer to the surface than was to be expected. Seismic surveys and borings later showed there to be a broad anticlinal fold in the buried Palaeozoic rocks, so that the Carboniferous Limestone surface is about 300 metres shallower over the "uplift" than it is in the basin on the eastern and western sides. Except for the development of the surrounding fault zone, the structure superficially appears to be of little importance. Even so, the "uplift" does appear to act as a stable block, with the Lincolnshire Limestone being horizontally bedded over its top, interrupting the normal easterly dip of the strata (Swinnerton and Kent, 1976, p.81). It may, however, be of greater significance as a control on sedimentation. The Lias is known to thin across it and the Grantham Formation is altogether absent, the Lincolnshire Limestone resting on the Northampton Sand between Coleby and Lincoln (Swinnerton and Kent, 1976, p.81). This is admirably shown in the Greetwell Hollow section where the Grantham Formation horizon is occupied by a conglomerate of a few millimetres thickness. The distribution chart of the facies variants within the Northampton Sand produced by Evans (1952, fig.1), lends further support to the idea that this structure may be acting as a "high" and controlling sedimentation rather than being a remnant anticline from which certain horizons have been stripped. This relationship between the Nocton Uplift and sedimentation is discussed in the light of new evidence in Chapter V.

Apart from the features discussed above, Swinnerton and Kent (1976) describe the general structures of Lincolnshire and discuss how they affect the Lincolnshire Limestone outcrop.

I.2.e. Conclusions

The Lincolnshire Limestone is characterised by having:

(1) Complex, rapid vertical and lateral facies changes.

(2) A fauna characterised by the scarcity of ammonites and the

facies-related nature of the benthonic assemblages; both of which make internal and external correlations very difficult.

(3) A relatively simple structure.

Despite the problems presented by the lithofacies and fauna, a generalised stratigraphy has been developed for the formation, largely through the work of Kent (see particularly 1940 and 1966) and Richardson (see fig.42 in Sylvester-Bradley, 1968; and Kent, 1940, p.49) and it is this which has been used as the basis for this research project.

CHAPTER II

THE STRATIGRAPHY OF THE LINCOLNSHIRE LIMESTONE FORMATION: GENERAL CONSIDERATIONS

II.1. INTRODUCTION

The lithostratigraphy presented in this thesis is primarily based upon a study of the area between Lincoln and Woolfox Quarry (SK 951136), near Stamford (Fig.2.1). Although this does not cover the whole extent of the formation's outcrop, the thickest and most important development is encompassed. North of Lincoln few exposures are seen and the stratigraphical relationships of the Limestone are poorly known except around Kirton in Lindsey and Hibaldstow (Fig.2.1), where the middle and upper parts of the formation have long been exposed. Recently a deeper excavation in the Kirton workings (SE 940024) revealed the lowest subdivisions of the Limestone and its contact with the underlying Grantham Formation. The details of this new exposure and the stratigraphical amendments based upon it have already been reported (Ashton, 1975). Their relationships to the broader stratigraphical revision discussed here are shown in figure 2.2. The approach in both pieces of work has been very similar; the common aim being to establish coherent, well-defined and formalised lithostratigraphic subdivisions for the formation. The details of the new lithostratigraphy are presented in Chapter IV, but the proposed nomenclature scheme is shown in figure 2.2.

During the course of the lithostratigraphical work a number of significant ammonite discoveries were made (Ashton, 1976), which precipitated a complete revision of the ammonite faunas of the Lincolnshire Limestone. The re-examination of all the known and previously unrecorded finds and their localisation in terms of the new lithostratigraphy provided evidence for a major biostratigraphical revision of the Limestone. The results of this work, carried out with Dr. C.F. Parsons, are fully reported in Chapter III.

II.2. METHODS OF STUDY AND LIMESTONE TERMINOLOGY

II.2.a. Methods

In the unravelling of the stratigraphic relationships and carbonate environments of the Lincolnshire Limestone both field and laboratory techniques have been used. Essentially the work is based upon the detailed logging of all the available sections in the study area (Fig.2.1); bed by bed lithological descriptions have been supported by palaeoecological and sedimentological observations and the collection of representative faunas. In the laboratory, stained (see Dickson, 1965) and unstained thin sections, acetate peels and polished blocks have all been used to help qualify and supplement the field observations. Where relevant quantitative techniques have been applied.

II.2.a.i. Modal analysis: Representatives of the lithofacies of each stratigraphic subdivision have been "point-counted" to quantify the compositional make-up of the rocks and allow comparison with the classificatory scheme of Folk (1959). The technique and results of this work are shown in appendices 1 and 2.

II.2.a. ii. Palaeocurrent analysis: The prevailing current directions in the different depositional environments have been determined in two ways. The amount and direction of dip of the exposed foresets of cross-bedded units have been measured (Appendix 3). These represent the higher-energy depositional environments. However, in the low-energy lagoonal setting of the Leadenham Member the attitude of the semi-infaunal Pinna cuneata Phillips and to a lesser extent Pholadomyalirata (J. Sowerby) and Pleuromya uniformis (J. Sowerby) have been used to give some idea of the current activity in this "quiet setting". The technique and its results are presented in appendices 4 and 5 (see also Section IV.4.g.)

In this way each lithostratigraphic unit has been characterised and data made available for environmental interpretation.

II.2.b. Limestone Terminology

The limestones comprising each unit have been described from two viewpoints: field and laboratory observations.

II.2.b. i. Field descriptions of lithologies: A generalised descriptive terminology has been adopted in which a calcirudite - calcarenite - calcilutite nomenclature scheme is prefixed by the dominant grain type e.g. ooid-calcarenite. However, where a limestone has two or more major components occurring in approximately equal quantities a multiple prefix has been used. Generalised terms like peloid (McKee and Gutschick, 1969) and ooid have been preferred because of the difficulty in determining the exact nature of many grains in hand specimen; consequently, no particular mode of origin is implied by their use. The term ooid, as used here, refers to all spherical or ovoid allochems, which may or may not be ooliths. It is not equivalent to the ooid of Bathurst (1975), which is the "oolith" of this thesis.

II.2.b.ii. Laboratory descriptions of lithologies: Since a more accurate assessment of the nature of the grain types (and matrix) can be made in thin section, the allochems can be genetically grouped and the classificatory scheme of Folk (1959 and 1962) adopted. However the rigidly defined pellet category of his classification has been modified here to incorporate all those "peloids", that cannot be resolved into their original genetic grouping. Thus the "pel"-category used here refers to lumps of micrite of unknown (or uncertain) origin as well as genuine faecal pellets (Wilson, 1975, p.12). Bearing this amendment in mind, each lithology has been allocated a simple allochem-matrix "Folk-type" name e.g. pelmicrite. However, where a second grain-type is of importance a further adjectival prefix has been added e.g. intraclastic oosparite. Similarly when a terrigenous grain-type or allochem such as oncolite, that is not covered by Folk's main groupings, is abundant, it has been given an adjectival prefix e.g. quartzose pelmicrite or oncolitic biomicrite.

The impracticability of point-counting every slide examined means that the terminology suggested above is, to some extent, based upon subjective judgements, although the general quantitative guidelines of Folk (1959, p.15) have been followed and supported by modal analyses of representatives of the various lithologies.

II.3. <u>THE LINCOLNSHIRE LIMESTONE FORMATION</u>

II.3.a. <u>Introduction</u>

The Lincolnshire Limestone Formation, the major marine carbonate unit within the Middle Jurassic of the East Midlands, occurs as a lensoid mass of limestone sandwiched between the Upper Estuarine Series and the Grantham Formation (Fig.1.2), although locally it rests directly upon the Northampton Sands (Fig.1.9). The Limestone appears just north of Kettering and thickens rapidly to a maximum of about 40 metres at Bothby Pagnell, near Grantham, before thinning away irregularly to under 15 metres just south of the Humber Estuary (Fig.1.4). The formation is thought to persist into North Humberside as the Cave Oolite, which wedges out on the southern flank of the Market Weighton Structure (Fig.1.9).

Although typically scarce, the ammonites from the Lincolnshire Limestone are sufficiently numerous and distinctive to indicate the presence of <u>discites</u> and <u>laeviuscula</u> Zones of the Lower Bajocian (Chapter III). However, the highest beds (Creeton Member, see Fig.2.2), which have not so far yielded any ammonites, may represent a still younger age.

The formation is compositionally pure, having little clastic or other non-carbonate material present except in the Sproxton Member (Fig.2.2) and the facies of northern Lincolnshire/South Humberside (Kent, 1966; and Ashton, 1975). However, there is a wide range of carbonate lithofacies present in what Arkell (1933, p.210) termed, " ..... a general stratigraphical homogeneity" and rapid vertical and lateral facies changes typify the Limestone. Despite this diversity, a number of distinct lithostratigraphic subdivisions can be recognised (Fig.2.2). Some, such as the Leadenham Member, have a very uniform lithological make-up, whereas others, like the Sleaford Member, encompass a diverse, yet genetically related, group of lithofacies. As in many Jurassic formations, the recognisable subdivisions of the Limestone are often quite thin; for example, the Lincoln Member barely exceeds 1 metre in some localities, although, in contrast, the Sleaford Member is over 12 metres thick at Creeton (SK 999205; Fig.2.1).

As the formation is never seen completely exposed in a single section, no obvious unit-stratotype exists for the Lincolnshire Limestone. Because of this and the lithological complexity of the unit, the stratotypes of all the lower ranked subdivisions have been designated as the composite-stratotype for the formation (Hedberg, 1976, p.24). In this scheme the base of the type section of the Sproxton Member and the top of the stratotype of the Creeton Member become the basal and upper boundary-stratotypes respectively of the formation (Fig.2.2).

II.3.b. Former Terminology

The stratigraphical terminology associated with the Lincolnshire Limestone developed in two distinct phases; the pioneer work of the middle to late 19th century, provided a name for the whole formation, while the diverse terms applied to the internal subdivisions evolved during the second period of intensive research.

Although the earliest workers (Brodie, 1853; and Morris, 1853) did not coin a name for the formation, the terms Lincolnshire Limestone (Sharp, 1873; Cross, 1875; Judd, 1875; Jukes-Browne, 1885 and 1910; Ussher et al., 1888; Ussher, 1890; and Woodward, 1894), Lincolnshire Oolite Limestone (Judd, 1875) and Lincolnshire Oolite (Judd, 1875; and Jukes-Browne, 1885) were introduced and widely used. However, even at this pioneer stage the name Lincolnshire Limestone was gaining favour as Woodward (1894, p.174) indicated when writing, " ..... Lincolnshire Oolite Limestone now generally spoken of as the Lincolnshire Limestone". All later workers from Arkell (1933) onwards have followed Woodward (1894) and retained Lincolnshire Limestone as the formation name.

There were few attempts at subdividing the formation, during this early period, outside those of Ussher et al. (1888, p.44), Ussher (1890, p.59) and Woodward (1894, p.174). Any parts of the Limestone that were given individual names such as the Collyweston Slate (Brodie, 1853; Sharp, 1873; Judd, 1875; Jukes-Browne, 1885; and Woodward, 1894) were generally of contemporary economic value. Occasionally quarrymen's terms were incorporated into published sections (Sharp, 1873, p.257) but these did not gain widespread acceptance or usage.

From the late 1930s onwards both the Geological Survey (Hollingworth and Taylor, 1946a, 1946b and 1951; Taylor, 1946; Wilson, 1948; and Evans, 1952) and independent workers (Richardson and Kent, 1938; Muir-Wood, 1939 and 1952; Richardson, 1939a, 1939b and 1940; Kent, 1940, 1948 and 1953; Swinnerton and Kent, 1949; and Hallam, 1954) presented a profusion of facts and ideas on the subdivision of the Lincolnshire Limestone. The conflicting opinions generated by this concentrated, largely contemporaneous and independently produced work resulted in a proliferation of names for the various subdivisions, which were proposed for the formation by different workers (Figs. 2.3 to 2.8). The resulting terminologies were often contradictory (see Chapter IV) and largely because of this Kent (1966) proposed a standardised nomenclature scheme for the formation (Fig.2.9). This has been adopted by most recent workers (Bate, 1967; Barker and Torrens, 1971; Senior and Earland-Bennett, 1973; and Parsons, 1974b), although Sylvester-Bradley (1968) suggested a few minor amendments

II.3.c. Reasons for the abandonment of the terminology proposed by Kent(1966)

Despite the valuable contribution to the stratigraphy of the Lincolnshire Limestone made by Kent (1966), it has been considered necessary to revise his nomenclature scheme for the following reasons:

(1) The detailed work described in Chapter IV shows that the scheme presented by Kent (1966) is too generalised to represent the lithostratigraphical subdivisions seen to exist in the Lincolnshire Limestone. Consequently a parallel revision of the terminology to denote these new units is also required, especially as the new subdivisions do not coincide with those proposed by Kent (1966). The relationships between the stratigraphies and terminologies proposed by Kent (1966) and the present author are detailed in Chapter IV.

(2) The stratigraphy proposed by Kent (1966) is based upon a mixture of litho- and biostratigraphical criteria, which is not consistent with the guidelines for formal stratigraphical nomenclature (Hedberg, 1976). This "mixed approach" is clearly seen in figure 2.9. The majority of the terms used refer to lithological features such as the Ancaster Freestone and the Collyweston Slate, but some seem to be defined on their fossil content e.g. Crossi Beds, Nerinea Beds and are therefore not consistent with the lithostratigraphical approach adopted in this thesis.

II.3.d. Proposed Terminology

II.3.d.i. A radical versus conservative approach to terminology: A largely conservative approach to terminology was adopted in the revision of the lower Lincolnshire Limestone stratigraphy of South Humberside by Ashton (1975, p.422), who explained that, " The new terminology proposed was selected to minimise the introduction of new terms and maintain continuity of usage as far as possible". Such an approach seemed particularly justified in this case because the existing stratigraphical terminology was suitable for describing the relationships seen and the isolation of the newly exposed section (except for the adjacent and very similar Associated Portland Cement Company Quarry, SE943023) meant that additional evidence, suggesting the need for wider revision, was lacking. However, this kind of conservatism, where the existing terms are retained and adapted for us in the "new" stratigraphy, is only valid in cases where the retention does not result in further inprecision or ambiguity and is in agreement with the guidelines proposed for formal stratigraphical nomenclature (Hedberg, 1976). Only in the following instances would such an approach seem to be acceptable:

(1) When a term is so widely used and/or of such importance that its removal would produce more confusion than any revision might give clarification, e.g. the name Lincolnshire Limestone for the newly proposed formation.

(2) When one is dealing with an isolated exposure where substantiating evidence, for major stratigraphical revision, is lacking. The solitary exposure in the lower part of the lower Lincolnshire Limestone of South Humberside (Ashton, 1975) is a case in point.

(3) When a newly defined unit is, of almost is, stratigraphically coincident with the old unit so that continued usage of the old term would not cause undue confusion; and would seem preferable on the grounds of familiarity of usage to the introduction of a new term e.g. the retention of the Kirton Cementstones Member (Ashton, 1975).

In all other instances it would seem better to take a radical line replacing the old terminology with completely new, unambiguous terms so that no confusion is caused by the adaption of old terms to significantly redefined rock units. In the case of the Lincolnshire Limestone the terminology proposed for the subdivisions has evolved from a largely radical approach because of the conflicting definition of the old and new stratigraphical units. Only in South Humberside has the pre-existing terminology been adapted and re-used to any extent (Fig.2.10).

II.3.d.ii.<u>Guidelines adopted for the erection of new terminology</u>: The name selected for each rock unit has been based on the guidelines suggested by Hedberg (1976, p.40, pt.F). In general, each lithostratigraphic unit takes its name from the nearest permanent settlement to the quarry, in which the type section is exposed. Wherever this procedure is thwarted by prior use of the most suitable name or the unsuitability of the most obvious geographical name because of its association with earlier stratigraphies, a related geographical name has been selected. For example, the use of Kirton (from Kirton in Lindsey) by Ashton (1975) to title the Kirton Cementstones Member, prevented its re-use to define the "Kirton Shale" (Hedberg, 1976, p.41, pt.F 1b), although that unit's type section was similarly close to Kirton in Lindsey. Consequently, Lindsey was used to designate the Lindsey Shale Member (see Chapter IV).

II.3.d.iii.<u>Changes from the terminology proposed by Kent (1966)</u>: Comparisons of Figs.2.2 and 2.9 reveal many changes in the terminology proposed here from that selected by Kent (1966). However, the degree of significance attributed to these changes is variable. There is, for instance, no geological significance, outside that of formalising the terminology, attached to the introduction of the term Lindsey Shale Member to replace the Kirton Cement Shale. The replacement of Kirton by Lindsey was necessitated by the prior use of Kirton by Ashton (1975).

Both terms apply to exactly the same rock unit. However, for most of the new lithostratigraphic units (Fig. 2.2.) significant geological re-alignments have been made and consequently the relationships between the old and new terminologies vary accordingly. These variations range from:

(1) The introduction of a single name denoting a unit, which groups a number of geographical variants, that have always been seen to have some level of internal coherence e.g. the Greetwell Member encompasses part or whole of the Silver, Little Ponton and Nerinea Beds of Kent (1966): to

(2) the introduction of a new name to describe a more finely defined subdivision, which has been separated from the larger unit, in which Kent (1966) included it. The division of the Cathedral Beds from the Cementstones is an example: to

(3) the introduction of completely new terms to describe previously unrecognised subdivisions, that constitute a marked departure from the classificatory scheme suggested by Kent (1966). The Lincoln Member is a particular case in point.

As the nomenclature merely mirrors the stratigraphy it is to be expected that the major stratigraphical revision proposed here will have accompanying major terminological changes. Both the stratigraphic and nomenclature changes are discussed in Chapter IV.

II. 3.e. The Division into an Upper and Lower Lincolnshire Limestone

II.3.e. i. Introduction Traditionally the Lincolnshire Limestone has been divided into Upper and Lower sections (Woodward 1894; Richardson, 1939a and 1940; Kent, 1940, 1955, 1966, 1967 and 1970; Hollingworth and

and Taylor, 1946a, 1946b and 1951; Taylor, 1946 and 1963; Evans, 1952; Muir-Wood, 1952; Hallam, 1954; and Sylvester-Bradley, 1968), although the exact definition of these units varied from author to author. For example, Evans (1952) included the Crossi Beds in the Upper while Kent (1940) assigned them to the Lower Lincolnshire Limestone.

In northern Lincolnshire and South Humberside the independent terms Kirton Beds and Hibaldstow Beds have been used (Ussher et al., 1888; Ussher, 1890; Arkell, 1933; Richardson, 1940; Kent, 1940, 1948, 1953 and 1955; Wilson, 1948; and Swinnerton and Kent, 1976), although Kent (1955, p.208) indicated that he, at least, regarded them as approximate equivalents to the Upper/Lower divisions (but see also Kent, 1966, fig.1).

The dividing line between these subdivisions has been approximately taken at the level of the Crossi Beds, which have been assigned variously to the Lower (Richardson, 1939a and 1940; Kent, 1940; Taylor, 1946 and 1963; Hollingworth and Taylor, 1946a and 1951; and Muir-Wood, 1952) or the Upper Lincolnshire Limestone (Evans, 1952; and Hallam, 1954) or astride the subdivision (Kent, 1966; and Sylvester-Bradley, 1968). In the north of the region the Crossi Beds have been uniformly placed within the Kirton Beds (Richardson, 1940; Kent, 1940, 1948 and 1966; Wilson, 1948; and Swinnerton and Kent, 1976).

II.3.e.ii. The nature of the Upper/Lower Lincolnshire Limestone contact: The variation in the level of the Upper/Lower junction, described above, appears to stem from the differing opinions on the position of the disconformity that is supposed to separate the two subdivisions. Kent (1966) believed that the main erosive level usually occurred immediately above the Crossi Beds and was responsible for the erosive removal of those beds at Ancaster (Fig.2.9). Evans (1952) thought the junction occurred below the _Acanthothyris crossi_ Beds. Although these differences of opinion appear to be partly due to the restricted area discussed by Evans (1952), it is difficult to support either thesis in the light of the work described in Chapter IV. The major erosive level in the Limestone of central and southern Lincolnshire occurs within the Upper Lincolnshire Limestone, at the base of the Sleaford Member (Fig.2.2), although further south it is probably the Creeton Member that is responsible for the down cutting (see Chapter IV). This is essentially as Richardson (see Kent, 1966, pp.62-3) suspected, although the scheme proposed here also differs from his ideas (cf. Muir-Wood, 1952, p.115 and Chapter IV).

The level capping the "Crossi Beds", is as Kent (1966, p.62) points out, usually erosive, although only mildly so, with the tops of corals being planed off (at Woolfox Quarry, SK 951136). Elsewhere (Castle Bytham, SK990180 and Scottlethorpe, TF046204) the top of the "Crossi Beds" is gradational with the overlying unit, as is generally the case in central Lincolnshire, where Evans (1952) concluded that the erosive level must be below the _A.crossi_ Beds. Where more major downcutting has been postulated e.g. Ancaster, the present work has shown that it is not the basal Upper Lincolnshire Limestone that is doing the eroding but the Sleaford Member someway up the sequence. Therefore not only have the "Crossi Beds" been removed but also the lower parts of the Upper Lincolnshire Limestone (Metheringham and Blankney Members, Fig. 2.2.) A similar channelling also occurs at Great Ponton (Chapter IV). The details of these new proposals are more fully discussed in Chapter IV.

II.3.e.iii. _The upper and lower Lincolnshire Limestone: a re-appraisal:_
If the Upper/Lower Lincolnshire Limestone subdivisions are re-assessed

in terms of their depositional environments, the twofold division can be rationalised. Using such an approach, the Creeton, Sleaford, Castle Bytham, Metheringham and Blankney Members (Fig.2.2) can be grouped as a "high-energy" Upper unit, typified by "transported" faunas, sparite cement and cross-bedding; the Lower division, encompassing the remaining units outlined in figure 2.2., is largely composed of "low-energy", micritic limestones containing "in-situ" faunas. This scheme can be consistently applied throughout Lincolnshire and South Humberside. However, as both the Lower and Upper divisions contain a number of members, yet are not of formational status, they cannot be incorporated within the formalised lithostratigraphy. It is therefore proposed to designate them as informal subdivisions; the upper and lower Lincolnshire Limestone.

It might be argued that the retension of any informal subdivisions is unnecessary when a formal terminology is proposed, as any part of the formation ought to be easily referred to by the use of the appropriate formal subdivision. However, in the case of the Lincolnshire Limestone the upper and lower units (as re-defined here) represent useful collective terms for two broadly distinctive units within the formation, which have valuable use in the description of the Limestone's more general stratigraphical and environmental relationships.

II.3.e.iv. Conclusions: The intrinsic value of the traditional twofold division of the Lincolnshire Limestone has been largely lost in the dispute over the stratigraphical position of the junction of the two subdivisions, which were usually defined on the basis of a significant (separating) disconformity. In the work described here, it has become apparent that the major disconformity in the formation is really divorced from the Upper/Lower Lincolnshire Limestone question and that a more consistent and coherent bipartite subdivision can be made on genetic grounds, i.e. the contrast in the "energies" of the depositional environments. The re-defined, "high-energy" upper and lower energy lower subdivisions have been given informal status so that they can be valuably used without unnecessarily complicating the formalised lithostratigraphy (Fig. 2.2) described in Chapter IV.

II.3.f. Correlation

II.3.f. i Introduction; The correlation of and within the Lincolnshire Limestone Formation has always been a problem because of the lack of useful fossils and the complexity of the lithofacies. However, the re-examination of the ammonite faunas (Chapter III) has gone some way towards alleviating the problem, although the proposed biostratigraphic correlations are rather broad, with several distinct lithofacies occurring within each subdivision. Consequently a lithostratigraphic approach to the internal subdivision of the formation is still necessary.

II.3.f. ii. Ammonite correlation: The biostratigraphical advances discussed in Chapter III show that, contrary to the opinion of Kent (1966) and Senior and Earland-Bennett (1973), the lower Lincolnshire Limestone is of discites Zone age in its lower part only. The remainder, together with a substantial part of the upper Lincolnshire Limestone, belongs in the laeviuscula Zone. The highest unit (Creeton Member) has so far not yielded any ammonites and may be of a still younger age. Within each biostratigraphical division a number of lithostratigraphical units occur (Fig. 2.2) and these have had to be correlated by lithological means.

II.3.f.iii Lithostratigraphical correlation: Although the need for a workable lithostratigraphy is apparent, its development is hampered by almost as many difficulties as that of the biostratigraphy. The problems inherent in earlier schemes (see especially Kent, 1940 and 1966; Hollingworth and Taylor, 1951; and Evans 1952) reflect the difficulties presented by the " . ... bewilderingly rapid and frequent changes of facies ...." of the Lincolnshire Limestone (Arkell, 1933,p.210). In an attempt to overcome these difficulties a detailed bed by bed description of each exposure was undertaken because few readily recognisable and traceable units appeared to exist. From this detailed work a number of key horizons (usually erosive) and lithological changes were recognised and they provided the main lithostratigraphical framework. "Subsidiary" levels, of a more local nature usually, were also pinpointed and these supplied a useful "check" on the main correlations as well as further subdividing the formation. In fact, wherever possible, sets of criteria were used in preference to a single feature in order to eliminate over - simplifications such as the matching of two hardgrounds, which were independently located in the sedimentary sequence.

Of the major corelative levels recognised, the most important is the base of the Lincoln Member (Fig. 2.2), which can be traced from Woolfox Quarry (SK 951136; Fig. 2.1) northwards to Lincoln. Although the exact character of this level varies between southern and central Lincolnshire (Chapter IV), its persistence enables these variations to be recognised and the relationships to the diverse underlying facies elucidated. Because of this distinctiveness and widespread occurrence, the base of the Lincoln Member has been adopted as the datum line for the correlation of all the Lincolnshire Limestone sequences: its subsequent recognition as the probable dividing plane between the _discites_ Zone and _ovalis_ Subzone ammonite faunas (Chapter III) has not only reinforced this decision but suggested that it may also be a time plane. However, whether or not it proves to be such does not detract from the base's importance as a correlative horizon for the lithostratigraphy of the Lincolnshire Limestone.

II.3.f.iv. Conclusions: Despite the improved understanding of the correlative usefulness of the Lincolnshire Limestone ammonite faunas, the smallest subdivisions of the formation are lithological and can therefore only be defined and correlated upon sedimentological criteria. In this respect a number of important horizons (especially the bases of the Lincoln and Sleaford Members) and distinctive lithologies (the Leadenham and Sproxton Members in particular), together with a wealth of supporting data, have facilitated the development of a coherent lithostratigraphical framework (Fig.2.2). Although this lithostratigraphy appears to be closely related to the nascent biostratigraphy (Chapters III and VI), it is hoped that future ammonite finds will further refine the biostratigraphy and provide an independent, time-related framework by which the lithostratigraphic correlations can be more fully judged.

II.3.g. The Crossi Beds Problem

II.3.g.i. Introduction: From the time its importance was first recognised (Kent, 1940, p.49), *Acanthothyris crossi* (Walker) has been of unrivalled value to the internal correlation of the Lincolnshire Limestone. Furthermore, the Crossi Beds, in which *A. crossi* principally occurs, have become the main correlative subdivision within the formation (Sylvester-Bradley, 1968, p.218). However, during the course of this research, considerable doubt has been cast upon the viability of the Crossi Beds as a coherent stratigraphical unit and the value of *A.crossi* as a biostratigraphical marker. Therefore in the following sections the reasons justifying the replacement of the Crossi Beds by properly defined, coherent lithostratigraphical units are outlined and the limitations of A. crossi, as a correlation fossil, discussed.

II.3.g.ii. The Crossi Beds as a stratigraphical unit: The limestones containing A. crossi, which were formerly grouped within the Crossi Beds, have been shown to occur in three discrete members of the new lithostratigraphy (Fig. 2.11 and see Chapter IV), indicating that no consistent lithological relationship, that might favour their inclusion in a single stratigraphical unit, actually exists: the former union of the Crossi Beds has apparently been due solely to the presence of A. crossi. However, the implication that the Crossi Beds have been defined solely on palaeontological criteria is not wholly true because other lithologies such as the shales of the Lindsey Shale Member (formerly Kirton Shale), which also contain abundant A. crossi have never been included in the Crossi Beds; therefore an element of lithological discrimination has also been applied in establishing the unit. In spite of this, the lack of coherence amongst the limestones of the Crossi Beds is still considered too great an obstacle for their incorporation into the new lithostratigraphy as a single unit.

Similarly any new, expanded "Crossi Beds" encompassing all the beds containing A. crossi could not be accepted either because not only would such a unit be untenable in this lithostratigraphic scheme, but the occurrence of A. crossi at various horizons outside the Lindsey Shale - Crossi Beds level (Hollingworth and Taylor, 1951; and see section II.3.g.iii) makes such a unit impracticable. Thus the total abandonment of the Crossi Beds appears to be justified.

Against this, however, it might be argued that the Crossi Beds ought to be retained because of their historical importance and the correlative usefulness of A. crossi. Certainly it is true that A. crossi has been widely used in the past to correlate sequences within the Lincolnshire Limestone (Kent, 1940 and 1966; Hollingworth and Taylor, 1951; and Evans, 1952) but this practice has largely stemmed from the apparent absence of other suitable criteria (Arkell, 1933, p.211; and Sylvester-Bradley, 1968, p.218) for on closer examination the correlative value of A. crossi is seen to be rather suspect.

II.3.g.iii. The biostratigraphical value of Acanthothiris crossi (Walker): There can be little doubt that A. crossi was a sessile, benthonic brachiopod (Rudwick, 1965, p.614). On theoretical grounds therefore it is likely to have been facies-related. In reality, however, A. crossi occurs abundantly in both the oomicrites and biomicrites of the Crossi Beds and in the shales of the Lindsey Shale Member, suggesting a tolerance for more than one substrate, although in all of these cases the actual bottom conditions were probably not too different, being soft, stable and not subject to strong current activity. The apparent independence of substrate may not therefore be the case, especially as the brachiopod has never been recorded from sediments reflecting higher energy conditions or a noticeably different substrate (mobile oolites for example), even where such lithologies occur at the Crossi Beds level. Thus, although showing a certain amount of substrate-tolerance A.crossi appears to have definite ecological limits, which are recognisable in the sedimentary record and these probably affect (or control?) its distribution in the Limestone.

Despite this, the abundant occurrence of A. crossi at approximately the same stratigraphical level does suggest a degree of time control on the brachiopod's distribution. This would seem to be supported by the belief that A. crossi occurs at a fairly uniform level above the Northampton Sand Ironstone in the Lincoln area (Hollingworth and Taylor, 1951, p.17; and Evans, 1952, p.329) provided that the Lincolnshire Limestone transgression was reasonably synchronous over the area and that the sedimentation rates were about equal across the region. Unfortunately these suppositions are not without their problems:

(1) The Lincoln area, as defined by Evans (1952), was not "instantaneously" submerged, for progressive overlapping of older horizons can be demonstrated (Chapter IV).

(2) The understanding of the occurrence of A. crossi in the Lincoln area, as outlined by Evans (1952, p.329) seems to differ from that of Kent (1966) and the present author. In particular if one analyses the thicknesses of the units below the Hibaldstow Beds at Greetwell Quarry, Lincoln (TF 003721) presented by Kent (1940, pp. 50 and 55, and 1966, fig.2) and Evans (1952, fig.3) there appears to be a discrepancy between the relative position of the base of the Crossi Beds, as defined by each author, (Fig. 2.12), even though the overall thickness of the formation appears to be approximately the same. The present author's work suggests that A.crossi occurs abundantly in the bed that is considered to be the Crossi Bed of Kent (Fig. 2.13), although a single specimen has also been found below that level at Greetwell, in beds apparently included in the A.crossi Beds by Evans (Fig. 2.13). In neither case however do these occurrences coincide with the stratigraphical level of the Crossi Beds in south Lincolnshire (Fig. 2.11). It seems probable that at Greetwell (and in central Lincolnshire generally) the Crossi Bed of Kent marks the local acme of A. crossi or at least the lowest bed in which it occurs abundantly. In contrast Evans (1952) seems to have drawn the base of his A. crossi Beds at the first significant lithological boundary below the abundant occurrence of the brachiopod (= Crossi Bed of Kent; see Fig. 2.11). This base appears to be coincident with the base of the Lincoln Member at Greetwell (Fig.2.13;

but not everywhere in central Lincolnshire - see Chapter IV). From this it would appear that neither Crossi Beds unit is based upon the first appearance of A.crossi, which, if the Greetwell locality is typical, may well be so elusive as to be valueless.

In south Lincolnshire the Crossi Beds of Kent (1940 and 1966) probably also mark (or at least include) the local acme of A.crossi, which therefore apparently occurs at different levels (and times?) in the two areas (Fig. 2.11).

As neither the first appearance nor the local acme of A. crossi appears to be synchronous across the whole county, the brachiopod's use as a datum line cannot be justified. Therefore the value of A. crossi to biostratigraphical correlation has to be qualified. Within each of the central and southern Lincolnshire regions the abundant occurrence (local acme) of A. crossi does appear to be at approximately the same level and is therefore valuable as a generalised marker in the field. Furthermore, these abundant occurrences at broadly similar horizons, denote the middle of the formation, especially if the Lindsey Shale Member is also considered because it is the lateral equivalent of the beds containing A. crossi in south Lincolnshire (Fig. 2.11). However, A. crossi is by no means ubiquitous or especially abundant everywhere. At Harmston it has not so far been found while it occurs very sparingly at Ropsley, although in both cases the "Crossi Beds level" is obviously present.

Therefore, although in detail the occurrence of A. crossi does not seem to warrant its use as true time-related biostratigraphical datum (implied by Kent, 1940, p.49), when divorced from the concept of the Crossi Beds it can act as a useful marker horizon. Its importance though has been diminished by the recognition of the easily traced base of the Lincoln Member and the refinement of the ammonite biostratigraphy.

II.3.g. iv. Conclusions: The main lines of evidence favouring the abandonment of the Crossi Beds as a stratigraphical unit are:

(1) the limestones, which have formerly been included within the Crossi Beds, do not form a lithologically coherent group but fall into a number of the newly proposed lithostratigraphical units.

(2) the establishment of a Crossi Beds unit solely on the basis of the occurrence of A. crossi is untenable in the lithostratigraphic approach adopted here.

In addition the following points undermine the unqualified use of A. crossi as a time-related biostratigraphical marker:

(1) it occurs at a number of distinct stratigraphical horizons

(2) its first appearance does not seem to be synchronous across the whole county

(3) it apparently becomes abundant at different horizons in different parts of the county.

Therefore it seems difficult to accept the first appearance or the base of the probable acme of the brachiopod as a time-horizon, although the general occurrence of A. crossi in large numbers does coincide with the middle of the formation and in this way it is a useful marker.

II.3.h. Discussion

The Lincolnshire Limestone forms a coherent limestone formation within the Middle Jurassic of Eastern England. Previous work has gone some way in determining its stratigraphical relationships but a largely generalised approach has devalued much of this work. Few measured sections, portraying the stratigraphical subdivisions proposed have ever been published while little attempt has been made to elucidate the depositional environments present in the limestones. Consequently a rather imprecise and often contradictory nomenclature/stratigraphy has resulted. Furthermore the biostratigraphy has never really been studied; prior to this work only one ammonite had ever been figured (Barker and Torrens, 1971) and the rather piecemeal approach to the subject had resulted in many erroneous identifications and inaccurate stratigraphical conclusions. However, in the work described in the following chapters an attempt has been made to revise the biostratigraphy and present a coherent, formalised lithostratigraphy for the formation. The probable environments of deposition are also discussed and a depositional history outlined.

CHAPTER III

THE AMMONITE BIOSTRATIGRAPHY OF THE LINCOLNSHIRE LIMESTONE FORMATION

III. 1. INTRODUCTION

Stratigraphic studies of the Lincolnshire Limestone have always been hindered by the apparent dearth of ammonites in the formation. The problems arising from this scarcity have been compounded by the imprecise localisation and indifferent curation of many specimens, and the loss and mis-identification of others (Fig. 3.1). Consequently the relationship of the Lincolnshire Limestone to other Jurassic sequences has remained poorly understood. Furthermore, no biostratigraphic subdivision of the formation using ammonites has been considered possible as the faunas were thought to be indicative of only a single zone, the _discites_ Zone (see Kent, 1966 for review of earlier finds; Barker and Torrens, 1971; Senior and Earland-Bennett, 1973; and Parsons, 1974a for the status of the _discites_ Zone). However, Parsons (1974b) and Ashton (1976) have recently challenged this view and suggested the possibility of subdividing the Lincolnshire Limestone on the basis of the ammonite faunas.

In this chapter the results of a thorough re-examination of all the available records and ammonite material from the Lincolnshire Limestone has been discussed. (This work forms part of a joint paper with Dr. C.F. Parsons, whose revision of the ammonite systematics contributed greatly to the conclusions forwarded here).

III.2. AMMONITE RECORDS

III.2.a. Introduction.

The total known ammonite discoveries from the Lincolnshire Limestone Formation are shown in figures 3.1 and 3.2. Although they represent a modest haul for over a century of research, the formation has had only three periods of intensive study (the late 19th century, the 1930s-1940s, and the late 1960s-1970s) during which most of these finds were made.

Figure 3.1. lists the discoveries that have been cited in the literature. Although most of these specimens were poorly localised, greater efforts have been made to locate accurately the more recent finds (Barker and Torrens, 1971; Senior and Earland-Bennett, 1973; and Ashton, 1976). However, some of these efforts were marred by a confused understanding of the formation's lithostratigraphy, resulting in the misinterpretation of the significance of the specimens involved (see discussion by Ashton, 1976 of Senior and Earland-Bennett, 1973).

The most recent discoveries and the previously uncited specimens present in private and museum collections are shown separately in figure 3.2.

III.2.b. Records from the 19th Century: Only four of the specimens collected in the last century have been located (Fig.3.1.); the others have apparently been lost. Although firm evidence exists to correlate three of the surviving specimens with ammonites in the Institute of Geological Sciences Museum (Fig.3.1.) the matching of the Ammonites polyacanthus Waagen from Little Bytham Quarry (TF 013178; see Fig.3.3.), recorded by Judd(1875), is less certain. However, as the only specimen known to have been collected from Little Bytham is the Sonninia (Euhoploceras) cf. polyacantha (Waagen) (IGS GSM 25604) it seems reasonable to assume that it is the ammonite referred to by Judd (1875), especially as it was curated prior to 1890.

III.2.c. Records from the 1930s-1940s

Although it has been possible to locate practically all of the ammonite finds collated by Kent and Baker (1938), in either the British Museum, the Institute of Geological Sciences Museum or Lincoln City and County Museum collections (Fig. 3.1), two specimens remain problematical. Of these the Fontannesia sp. (Kent and Baker, 1938), found during the excavation of Spittlegate Hill Reservoir, Grantham (Fig. 3.1 and Kent, 1966, p.67) does not appear to be present in any collection and has apparently been lost. The only ammonite from the Grantham area present in any museum collection is the Hyperlioceras sp. (BMNH. C73373), which is labelled "Grantham, ex. Grantham Museum" (Fig.3.2). However, it seems most unlikely that these are the same specimens as their gross morphologies should be very different.

The second problem concerns the whereabouts of the three Hyperlioceras aff. discites (Waagen) specimens (Fig. 3.1) recovered from Greetwell Quarry, Lincoln (TF 003721; and see Fig. 3.3). The details and approximate time of acquisition (1937) of specimens 355,37 and 355,37A in Lincoln Museum tally well with the records of Kent and Baker (1938), but for some reason the third specimen appears to have become isolated from this pair. However, in the British Museum a Hyperlioceras sp. (BMNH C38091) from Wragby Road Quarry, Lincoln (Fig. 3.3; Wragby Road and Greetwell are essentially the same pit) is recorded as belonging in the Kent Collection 1935. This maybe the third H. aff. discites specimen. The only other possible contender is the Hyperlioceras sp. (IGS ZK771), that was curated with the other Kent and Baker (1938) specimens. However, unlike the original record (Kent and Baker, 1938), a specific identification of this ammonite cannot be made because of its poor preservation, suggesting that it is less likely to be the third specimen.

In addition to the ammonites discussed by Kent and Baker (1938) four more specimens were recovered during this period (Figs. 3.1 and 3.2). The most important of these was a Sonninia sp. (BMNH C39337) from Castle Bytham Quarry (SK 990180; see Fig. 3.3), cited by Richardson (1939a). At that time, this specimen was the only unequivocal discovery from the Upper Lincolnshire Limestone (the "Bastard Freestone" of Richardson, 1939a, p.42; see also Fig. 3.4).

III. 2.d. Records from the late 1960s-1970s

In addition to the most recent finds (Kent, 1970; Barker and Torrens, 1971; Senior and Earland-Bennett, 1973; and Ashton, 1976), the records published in this period include discoveries made throughout the 1950s (Kent, 1966, p.67), and although the majority of these ammonites have been readily located in museums or private collections (see Fig.3.1), the Hyperlioceras sp. recorded by Kent (1970; = the Hyperlioceras rudidiscites cited by Senior and Earland-Bennett, 1973) has not been traced. Bearing in mind the mis-identifications of many of the previously recorded hyperlioceratids (see Fig. 3.1) it is unfortunate that such a potentially valuable specimen has been lost, especially as it came from the Upper Lincolnshire Limestone, where ammonites are particularly scarce.

During this period (1950 onwards) a number of other finds, not recorded in the literature, were also made (Fig. 3.2), including two Sonninia spp. (BMNH C48800 and C48801), that are both registered as coming from "10 feet above the base of the quarry (i.e. coral-bivalve bed)"at Castle Bytham. The "coral-bivalve bed" is presumably equivalent to the crossi bed of Kent (in Sylvester-Bradley, 1968), that marks the base of the main quarry floor, although lower levels can be seen in the pit (Fig. 3.4). Certainly the crossi bed contains abundant bivalves and corals. Furthermore, the only other coral bed recorded at Castle Bytham, the Castle Bytham Coral Bed (that forms part of the "Roadstone"; see Richardson, 1939a), is generally considered to occur some 3.8→6.0 metres above the main quarry floor (see Kent, in Sylvester-Bradley, 1968) and is therefore unlikely to be the bed referred to in the British Museum register.

Wherever possible the ammonites recorded from the Lincolnshire Limestone have been re-examined and in many cases re-identified (the results of which are shown in Figs. 3.1 and 3.2). The significance of these re-identifications are discussed in section III.5.

III.3. PREVIOUS CORRELATIONS

The Inferior Oolite age of the Lincolnshire Limestone Formation was independently established on general faunal and stratigraphical grounds by Sharp (1873) and Judd (1875) after Morris (1853) had incorrectly assigned it to the Great Oolite. During this pioneer period ammonite zonal stratigraphy and taxonomy were only in their embryonic stage of development and consequently it is difficult to assess the value of these earliest ammonite records (Fig. 3.1). However, in spite of this it is interesting to note that many of the early workers (Sharp, 1873; Judd, 1875; Jukes-Browne, 1885; and Woodward, 1894) agreed that most of the Lincolnshire Limestone belonged in the Ammonites Murchisonae Zone (A. Sowerbyi Subzone), although some (in particular Sharp, 1873, p.285) believed that higher zones were probably also represented.

With the later refinement of the ammonite biostratigraphy of the Jurassic and the development of an internal lithostratigraphy for the

Lincolnshire Limestone (Richardson, 1939a, 1939b, and 1940; Kent, 1940; and Richardson and Kent, 1938), the stratigraphical position of the more recent ammonite finds (Batters, 1933; Baker, 1934; and Kent and Baker, 1938) became better understood and consequently the age of the Lincolnshire Limestone more accurately known. The evidence available at that time was summarised by Kent (1940, p.51)as, " .... the lower half of the limestone belongs mainly to the discites zone (in the broadest sense) - early Middle Inferior Oolite - while the slightly transgressive upper beds presumably represent the later zones of the Middle Inferior Oolite, ..." This essentially re-iterated the view expressed by Buckman (1912, p.205) some years earlier and reflected the fact that, up to that time, the majority of ammonite finds (Kent and Baker, 1938 and see Fig.3.1) had come from the Lower Lincolnshire Limestone.

Later Kent (1966) contributed an updated and expanded review of the ammonite discoveries from the Lincolnshire Limestone. However, the ammonite evidence discussed had not greatly increased from that known in 1940; in fact only two additional specimens were reported for the first time - the "Hyperlioceras" sp. (BMNH C 47900) from the Upper Lincolnshire Limestone at Castle Bytham and the H. aff. discites Waagen (BMNH C 47901) from the Cementstones (see Kent, 1966, fig. 1) at Greetwell Hollow Quarry, Lincoln. The discovery of the H. aff. discites provided firm evidence of a discites Subzone (sowerbyi Zone) age for the higher levels of the Lower Lincolnshire Limestone. In addition the "Hyperlioceras" sp. was also thought to signify a similar age (Spath in Kent, 1966, p.68) for part of the Upper Lincolnshire Limestone. In the light of this fresh evidence Kent (1966, p.68) now concluded, "This shows that not only most of the Lower Lincolnshire Limestone falls within the discites Zone, but also that an important part of the Upper part is of this date - a total thickness of 60 feet or more".

The problem of the "humphriesianus - group" ammonite, first recorded by Cross (1875) remained, and Kent (1966) suggested that it might indicate the presence of a representative of the Scarborough Limestone -- a correlation denied by Bate (1967) on ostracod evidence. Certainly there seems no clear reason why so much importance should have been attributed to the Ammonites humphriesianus record, for other equally "unusual" finds apparently representing the higher Middle Inferior Oolite levels were also recorded in the last century (Sharp, 1873; Woodward, 1894, p.51). It seems strange that these and similar records should be ignored in later reviews (Kent, 1940 and 1966; Swinnerton and Kent, 1976) while the equally dubious A. humphriesianus specimen is given such elevated status. It would seem far better to treat all the 19th century discoveries, that have been lost, with equal sceptism. Certainly at present there is nothing in the known ammonite evidence to suggest so late an age for the Lincolnshire Limestone.

More recently Senior and Earland-Bennett (1973) recorded a "Hyperlioceras rudidiscites" specimen from the Upper Lincolnshire Limestone (Fig. 3.1), apparently confirming the conclusions of Kent (1966) that the lower part of the Upper Lincolnshire Limestone (approximately 5 metres rather than 20 metres stated by Senior and Earland-Bennett, 1973, p.325) was also of discites Subzone age. However, the re-identification by Parsons (1974b) of the Sonninia sp. (BMNH C 39337) as being closely related to the Sonninia (Fissilobiceras) ovalis (Qu. emend. S.B.) - fissilobata (Waagen) group challenged this view; Parsons (1974b) stated that such species " ....are more characteristic of a higher horizon than the discites Subzone of the "sowerbyi"Zone, that is the ovalis Subzone" (of the laeviuscula Zone; see also Parsons, 1974a).

The specimen (BMNH C 39337) from the basal Upper Lincolnshire Limestone at Castle Bytham was considered to represent a Subzone higher than that indicated by the "*H. rudidiscites*" specimens of Senior and Earland-Bennett (1973), although it came from a lower stratigraphical level. This apparent contradiction was partly resolved when the supposed stratigraphic position (in the Upper Lincolnshire Limestone) of one of the "*H. rudidiscites*" specimens (RCM 1969/279) was shown to be inaccurate (Ashton 1976; see also Fig. 3.1 for its re-identification). However, even if the identification of the second lost "*H. rudidiscites*" was also invalidated, the presence of another "*Hyperlioceras*" sp. (BMNH 47900; see Fig.3.1) from Castle Bytham Quarry at a level undoubtedly above that of the *Sonninia* sp. (BMNH C 39337) was discussed by Parsons (1974b) and perpetuated this apparent contradiction of *discites* Zone faunas occurring above *ovalis* Subzone (*laeviuscula* Zone) faunas.

III.4. LITHOSTRATIGRAPHICAL FRAMEWORK

In addition to revising the systematics of the ammonite fauna from the Lincolnshire Limestone, the stratigraphic position of the specimens has also been re-assessed in the light of the new lithostratigraphy, which is detailed in Chapter IV. As this disagrees with earlier schemes (see especially Kent, 1940 and 1966; and Richardson, see fig.42 in Sylvester-Bradley, 1968) on a number of important points, it has been considered necessary to assign the earlier ammonite finds to the new subdivisions in order to assess better their biostratigraphic significance. Wherever possible the allocation of an ammonite to a new lithostratigraphic unit (on the basis of its original horizon of recovery) has been independently tested by comparing the matrix of the specimen with the lithologies present in that unit. Some specimens were too poorly localised for precise re-allocation to be made, but in such cases a knowledge of the new lithostratigraphy of the locality in question allowed some refinement of the horizon of recovery to be achieved.

It is important to point out that this newly-proposed lithostratigraphy was developed before, and totally independently of, the biostratigraphy discussed in the following sections.

III.5. INTERNAL CORRELATION OF THE LINCOLNSHIRE LIMESTONE

III.5.a Stratigraphical distribution of the ammonites

Although the horizon of discovery of many specimens remains unknown, a re-assessment of the better localised ammonites, in terms of the new lithostratigraphy, shows that at least five separate members have yielded ammonites (Fig. 3.4 and 3.5). The numerical bias in favour of the lower Lincolnshire Limestone horizons is probably partly due to the depositional environments, reflected by the facies of the different members. Generally speaking the older members of the formation represent quieter-water "lagoonal" settings, while the two highest units (Sleaford and Creeton Members) were probably deposited in a very "high-energy" barrier complex, in which ammonites were unlikely to be preserved.

III.5.a. i. Greetwell Member: The most famous and prolific source of ammonites in the Lincolnshire Limestone has been the "Silver beds", which have for many years been exposed in a series of workings on the eastern outskirts of Lincoln (Richardson, 1940, fig. 29; = beds 4/5 at Greetwell Hollow, see Fig. 3.4). This horizon has yielded *Hyperlioceras* (*H.*) *subsectum*, *H.* (*H.*) cf. *subdiscoideum*, *H.* (*H.*) aff, *rudidiscites*', *Darellia* (*D.*) *polita*, and *Sonninia* (*Euhoploceras*) cf. *marginata*, as well as possibly the less well localised specimens, *Graphoceras* (*Ludwigella*) aff. *stigmosum* and *S.* (*E.*) aff. *marginata*. Further south the *Graphoceras* (*Ludwigella*) from Sproxton and the *S.* (*E.*) cf. *densicostata* from Waltham probably represent the two lowest ammonite finds from the Lincolnshire Limestone, excepting perhaps the *Fontannesia* recorded by

Kent and Baker (1938, p. 169). However, as this ammonite has not been found in any museum collection, it has not been possible to confirm its identification. Although outside of the study area, the horizon at Geddington, which has yielded a S.(E.) acanthodes may well be a lateral equivalent of the Greetwell Member.

III.5.a. ii. Leadenham Member: The distinctive matrix of the ?Darellia (?D.) cf. coela from Greetwell and S. (E.) acanthodes from Leadenham indicates an association with this member. In addition the H. (H.) subsectum from Kirton in Lindsey probably originated in the Kirton Cementstones Member (Ashton, 1975), which is laterally equivalent (in part) to the Leadenham Member (see Section IV.4.h.).

Both this and the Greetwell Member fauna are indicative of a discites Zone age.

III.5.a. iii. Lincoln Member: Whilst only one specimen of Sonninia (Fissilobiceras) aff. fissilobata has been collected in situ from the lowest bed of the Lincoln Member at Leadenham (Ashton, in press), there is good evidence to indicate that several other specimens of this taxon have also come from the same horizon (Fig. 3.2). Related forms may also have come from equivalent horizons at Ropsley and Greetham, although there is no firm evidence to support this suggestion. In addition S. (E) cf. dominans probably came from the Lincoln Member at Harmston (Ashton, 1976).

III.5.a. iv. Castle Bytham Member: This unit has yielded in situ specimens of S. (F.) cf. ovalis at Castle Bytham, whilst the Woolfox specimen of S. (F.) fissilobata is probably from a similar horizon.

Both this and the Lincoln Member fauna are indicative of a lower laeviuscula Zone, ovalis Subzone age (Parsons, 1974a).

III. 5.a. v. Sleaford Member: A single *Shirbuirnia* cf. *fastigata* has been recorded from this unit at Castle Bytham. This is the highest horizon known to have yielded ammonites in the Lincolnshire Limestone, except for the "*Hyperlioceras rudidiscites*" from Clipsham (Senior and Earland-Bennett, 1973) which has been inferred as coming from the younger "Clipsham beds" (= Creeton Member of this lithostratigraphy). However considerable doubt exists about the identification of this ammonite (which has been lost) because of the erroneous identification of many of the other "*Hyperlioceras*" specimens (see Figs. 3.1 and 3.2).

The *S.* cf. *fastigata* is indicative of an upper *laeviuscula* Zone, *laeviuscula* Subzone age.

III.5.b. Internal Correlation

It now appears that, contrary to the opinions of Kent (1966, p.68) and Senior and Earland-Bennett (1973, p.325), the Lincolnshire Limestone spans more than just the *discites* Zone. Since neither the lowest or highest members have yet yielded ammonites the precise biostratigraphic range of the formation remains uncertain, but the known ammonite faunas span the *discites* Zone and the *laeviuscula* and *ovalis* Subzones of the *laeviuscula* Zone (Lower Bajocian). Within the known distribution of the ammonite faunas there are two horizons where the biostratigraphic and lithostratigraphic boundaries appear to coincide, thus providing datum levels of some importance for the internal division and correlation of the formation. First, and most significant, the boundary between the *laeviuscula* and *discites* Zones faunas appears to parallel the erosive base of the Lincoln Member, which is readily traceable across Lincolnshire (Chapter IV) and therefore a very important datum level for internal correlation (Fig. 3.4; and Ashton, 1976). The significance of this biostratigraphic divide has been clearly demonstrated at Leadenham, where a number of *Fissilobiceras* specimens have come from the lowest bed of the Lincoln Member, while *discites* Zone ammonites have been recovered from the underlying Leadenham Member. Secondly, the boundary between the rocks of the _ovalis_ and _laeviuscula_ Subzones age appears to coincide with the erosive base of the Sleaford Member, although further finds are needed to support this tentative conclusion. However, as this litho-stratigraphical level is also widely traceable (Chapter IV) it too may prove to be a significant biostratigraphical/lithostratigraphical datum.

Thus, at present, the age of the Lincolnshire Limestone can be summarised as:

1) The Greetwell and Leadenham Members are of _discites_ Zone age. As no ammonites have been recovered from the underlying Sproxton Member (Fig. 2.2), it maybe older.

2) As ammonites indicative of the _ovalis_ Subzone of the _laeviuscula_ Zone have been collected _in situ_ from the Lincoln and Castle Bytham Members, the intervening Scottlethorpe Member must also be of this age. Furthermore the Lindsey Shale, Metheringham and Blankney Members, lying above the Lincoln Member and below the Sleaford Member, are lateral equivalents of the Scottlethorpe and Castle Bytham Members, it seems probable that these also belong in the _ovalis_ Subzone

3) Although the occurrence of the single _Shirbuirnia_ cf. _fastigata_ in the Sleaford Member at Castle Bytham indicates a _laeviuscula_ Subzone (_laeviuscula_ Zone) age for the lowest part (at least) of the unit, the need for supporting evidence is only too obvious.

4) The youngest subdivision of the Lincolnshire Limestone, the Creeton Member, which is separated from the underlying units by an erosive base, has so far failed to yield any ammonites at all; its age therefore remains problematical. It may be younger still than the _laeviuscula_ Zone, as it includes the "Great Ponton _Terebratula_ Beds", which have been considered, on the basis of the brachiopods, to be

possibly of "Upper Inferior Oolite" age (Upper Bajocian; Kent, 1940, p.50 and 1966, p.68). However, the evidence for this is by no means convincing (see Section IV.12.g.) and only the discovery of ammonites will really solve the problem.

III. 6. CONCLUSIONS

Despite the poor localisation of many of the specimens collected prior to this work, a thorough re-examination of all the ammonite records, together with new discoveries, has led to a better understanding of the age of the Lincolnshire Limestone. Furthermore, it is now known that the formation can be subdivided on the basis of its sparse ammonite faunas and, as the major biostratigraphic divisions appear to coincide with significant lithostratigraphic boundaries, important datum levels exist. These not only aid internal correlation but help elucidate the environmental history of the formation.

CHAPTER IV

THE LITHOSTRATIGRAPHY OF THE LINCOLNSHIRE LIMESTONE FORMATION

IV.1 INTRODUCTION

The lithostratigraphic revision of the Lincolnshire Limestone has been based upon a detailed study of the formation between Lincoln and Woolfox (SK 951136; Fig. 2.1) and the subdivisions of the new (formalised) scheme have been defined according to the stratigraphic procedure, advocated by Hedberg (1976). Essentially each unit has been fully described (type section, lithofacies, fauna, occurrence) and related to the stratigraphies of earlier workers. Although the lithostratigraphy was developed prior to, and totally independently of the biostratigraphy, already discussed in Chapter III, the apparent close agreement between the major bio- and certain lithostratigraphic boundaries is considered an independent support for the proposed lithostratigraphic correlations. In particular the lithostratigraphic importance attached to the base of the Lincoln Member (Fig.2.2) appears to have been vindicated by the biostratigraphic work. However there is still much future work to be done on the ammonite biostratigraphy of the

Lincolnshire Limestone. The new lithostratigraphical subdivisions of the Lincolnshire Limestone and their proposed correlations are shown in figures 4.1 and 4.2 (see "back-pocket" of thesis).

Although this research has been primarily concerned with the central and southern Lincolnshire regions, the isolated exposures around Kirton in Lindsey and Hibaldstow of South Humberside (Fig.2.1) have also been examined. The Hibaldstow section (SE 973008) has been tentatively assigned to the members typical of the upper Lincolnshire Limestone of central Lincolnshire (Fig. 2.2) but the lower Lincolnshire Limestone succession exposed around Kirton is somewhat dissimilar to that further south and its stratigraphy has already been discussed elsewhere (Ashton, 1975). However suggested correlations between the South Humberside and Lincoln successions are shown in figure 2.2 and the probable relationships of the various members have been discussed in the relevant sections of this chapter.

IV.2. SPROXTON MEMBER

IV.2.a. Introduction

The Sproxton Member, composed of a massive silty limestone and overlying dark coloured clay, is fully exposed in three south Lincolnshire quarries, where the Lincolnshire Limestone rests directly upon the Grantham Formation (Fig.4.3). These pits are at Sproxton (SK 866253, the type section), Stainby (SK 910233) and Thistleton (SK 903180). In addition a partially exposed sequence of the member is thought to occur at Metheringham (TF 053616, see Fig. 2.1).

IV.2.b. Former Terminology

The Sproxton Member in south Lincolnshire is thought to be directly equivalent to the Blue Beds of Richardson (1939b, p.466, Beds 8 - 10 of fig.40), although no trace of the Collyweston Slate facies is represented in any of the quarries examined (Bed 11 of Richardson, 1939b, fig.40 is probably the flaser bedding facies seen at the top of the Grantham Formation). In addition the member corresponds closely to the Blue Beds of Kent (1940 and 1966), Wilson (1948), and Swinnerton and Kent (1976), although neither Kent (1940) nor Wilson (1948) included the clay bed in their units. The lowest part of the Sandy Limestone Group of Hollingworth and Taylor (1951) is similarly believed to be equivalent to the Sproxton Member. However, in this context it is important to note that although the "Rag" and overlying clay of the Ironstone Companies approximate to the Sproxton Member, Hollingworth and Taylor (1951, p.18) erroneously compared the "Rag" to the Blue Bed of Richardson (1939b, fig 40, Bed 10), which is in fact only a single bed within the Blue Beds (Richardson, 1939b).

The relationship between the Blue Beds of Richardson (1939b) and the Sproxton Member is only considered valid for the area between Thistleton and Ancaster. The Blue Beds in the Lincoln district (Richardson, 1940, fig.29) are not part of the Sproxton Member nor are they even equivalent to the Blue Beds further south (Richardson, 1939b). On the contrary, the "Lincoln Blue Beds" are thought to occur at a completely different horizon, part of which comprises the Wragby Bed of this lithostratigraphy. The Sproxton Member is not developed in the vicinity of Lincoln. The evidence for this re-interpretation is discussed in section IV.2.g.

As the correlation of the Blue Beds across Lincolnshire, by Richardson, has generally been followed by others (Kent, 1940 and 1966; and Wilson, 1948), the Lincoln area Blue Beds of these authors are similarly not considered equivalent to the Sproxton Member.

IV.2.c. Geographical and Geological Extent

The Sproxton Member extends from the southern end of the study area northwards to Ancaster and is considered to correspond to the Blue Beds of Richardson (1939b, p.466) in this region. Further north its distribution is less certain, although the member is thought to persist northeastwards to Metheringham (Fig.4.1), where the lowest exposed bed has close lithological similarities to the Sproxton Member elsewhere.

Besides Metheringham, the only other central Lincolnshire section exposing the base of the formation is at Greetwell Hollow, Lincoln (TF 003721). Here the basal bed, an oolite (Base Bed of Richardson, 1940, fig.29), is overlain by a silty limestone, which forms part of the Blue Beds of Richardson (1940, fig.29). This "Greetwell"silty limestone is believed to correlate with a similar bed, which is stratigraphically higher than the Sproxton Member in the Metheringham sequence (Fig.4.1); this higher silty limestone horizon is called the Wragby Bed in the lithostratigraphy proposed here (Fig.2.2). Therefore the Sproxton Member does not appear to be represented in the Lincoln area; the Base Bed of Richardson (1940) is probably a condensed equivalent of that part of the Greetwell Member occurring between the Wragby Bed and Sproxton Member at Metheringham. Further more the earlier correlation of the Lincoln and south Lincolnshire Blue Beds would appear to be invalidated.

Unlike the demonstrable northward attenuation of the Sproxton Member, its distribution in other directions is poorly known because of the lack of exposures and the lack of any significant thickness variations. The member maintains a fairly constant thickness (a little under 2 metres; see also Hollingworth and Taylor, 1951) throughout its traceable extent, although Richardson (1939b, p.471) reported a thickness of 3.5 metres (11 feet 6 inches) for the Blue Beds at Rudd's Quarry, Houghton Hill near Grantham. In isolation, though, this record is of little value in elucidating any thickening trends.

In south Lincolnshire the Sproxton Member is seen to rest upon the Grantham Formation and in turn be overlain by the "Greetwell Member (Fig.4.1). The actual contact between the Sproxton Member and Grantham Formation is sometimes difficult to pinpoint in the field because of the decalcification of the lowest Lincolnshire Limestone (Taylor, 1963). However, from regional relationships, it is thought to be erosive despite the absence of major erosive features in any of the successions examined. In contrast the Sproxton Member/Greetwell Member contact is readily seen to be conformable in the south Lincolnshire sequences, although northward both the Sproxton Member and Grantham Formation are lost and the Greetwell Member sits directly upon the Northampton Ironstone. The wider significance of this northward truncation is discussed in Chapter V.

IV.2.d. <u>Field description of the lithologies</u>

In south Lincolnshire the lithologies of the Sproxton Member, reflecting the transition from the clastic Grantham Formation to the carbonates of the Lincolnshire Limestone, correspond closely to those described by Richardson (1939b, fig.40) for the Blue Beds. Essentially the member is composed of two parts (Fig. 4.3):

(1) a massive, silty or sandy limestone, the less consolidated base of which weathers back usually to reveal an impressive array of trace fossils on the base of the more indurated part of the bed (as at Stainby, see Fig.4.4). The bed is approximately 1.6 metres thick.

(2) an overlying clay bed.

IV.2.d.i. <u>Limestone Bed:</u> At Sproxton the basal part of the limestone is a buff-coloured, medium-grained sandy limestone (Lithology A) with subsidiary ooids and bioclastic grains. This grades up into the more "typical" fine-grained, homogenous, blue/grey, silty limestone (Lithology B; see Richardson, 1939b). The latter is very well sorted containing mica flakes, quartz grains and skeletal fragments. Lithology B passes up, via a "transitional bed", (Fig. 4.5) into a purer, well-sorted, fine-grained limestone that is quite different in outward appearance from the rocks below. It is a hard, smooth, creamy-grey, silty peloidal calcarenite (Lithology C), containing epifaunal bivalves, abundant worm tubes (identified as Serpula deplexa by Richardson, 1939b) and mica flakes. At Thistleton the worm tubes are common enough in places for the rock to be a "serpulite", while the junction between the "Blue Bed" and overlying creamy-grey limestone is crowded with abundant Rhizocorallium jeunese Zenker (see Fursich, 1974a).

IV.2.d.ii. Clay Bed: The stiff, black, well-laminated clay, capping the limestone, has shell rich layers (Richardson, 1939b, recorded a fauna of S. deplexa, S. "tetragona" and Ostrea sp.) and lensoid limestone beds included within it. This clay is a widely recognised level (Hollingworth and Taylor, 1951, p.18) varying in thickness from about 80mm (author's own measurement at Thistleton) to approximately 0.6 metres (Richardson, 1939b, p.466), but averaging 0.3 metres thick.

Although only the upper part of the Sproxton Member is seen (approximately 1.2 metres), some significant lithological variations occur at Metheringham. The lowest part of the section (0.7 metres) exposes a typically "Blue Bed" - like hard, grey/blue, fine-grained silty limestone, which weathers rusty brown. Mica and wood flakes, clay lenses and abundant trace fossils are also present, evoking comparisons with the Raventhorpe Member of South Humberside (Ashton, 1975). Above this bed is a honey-yellow, well-sorted, medium-grained peloidal calcarenite, containing abundant thick-shelled, disarticulated (convex side uppermost) bivalves. Complex, often branching burrows penetrate down from its upper surface, which is capped by a hardground, which is the lateral equivalent of the clay bed of south Lincolnshire.

IV.2.e. Laboratory description of the lithologies

At Sproxton, the massive limestone forming the basal part of the member shows a crudely gradational lithological sequence: a poorly-washed, quartzose oosparite (Lithology, A; Fig.4.6) passes up through the "typical" quartzose (dolomitic) biomicrite (Lithology, B; Fig.4.7) to a quartzose biopelsparite (Lithology, C; Fig.4.8). The most significant characters of these lithologies are shown in figure 4.9.

IV.2.e.i. Grains: The sub-angular to sub-rounded detrital quartz grains decrease in quantity and size from lithology A to C. This grain size decrease is mirrored to some extent by the allochems, although the ubiquitous skeletal fragments remain quite large throughout and impart a bimodality to lithologies B and C. Bivalves, and to a lesser degree gastropods, are the dominant bioclastic grains but foraminifera and echinoderm fragments are also present. Preservation is variable, ranging from completely unaltered in the case of calcitic forms like *Pinna* and echinoderms, to almost completely micritised grains. Originally aragonitic skeletons have always been replaced, the resultant sparite pseudomorphs sometimes having micrite envelopes. The peloids within Lithology C are very regular in size and shape, suggesting that they may be faecal pellets.

IV.2.e.ii. Matrix: Throughout all three lithologies, the grains are very abundant and closely packed. However only in lithologies A and C is there real evidence for a primary sparite cement, although C has many micritic areas, which may be the remnants of bioturbation. The matrix of Lithology B is less easily determined; the grains are plentiful enough for the rock to be grain supported but the matrix is composed of diagenetic ferroan dolomite microspar; this is particularly the case at Metheringham and Stainby. No primary sparite is evident.

IV.2.e.iii <u>Variations</u>: At Metheringham Lithology C has little silt but a wider range of skeletal grains; Bryozoa and brachiopods occur in addition to the usual types. Rare oncolites are also present. Although nominally a biopelsparite too, this rock contains less micritic matrix than its Sproxton equivalent and has a coarser, well differentiated sparitic cement. The peloids are not faecal but appear to be micritised grains of various types. They are larger (0.15 - 0.6 mm) and give the rock a coarser, more open-textured appearance.

IV.2.f. <u>Fauna</u>

Although no detailed collecting was undertaken from this member two faunal elements were especially conspicuous: serpulid worm tubes and trace fossils. Serpulid worms are characteristically abundant, forming a "serpulite" rock in places; Thistleton shows good examples (see also Richardson, 1939b). Biological reworking of the sediment, evident as bioturbation and discrete, usually horizontal burrows, is also rife. For example a wide variety of essentially horizontal traces are seen near the base of the member at Stainby (Fig. 4.4). Such intense biological reworking together with the dense colonies of the suspension feeding <u>R. jeunese</u>, at Thistleton, testify to the presence of the nutrient-rich water and substrate in the Sproxton Member environment, a situation that is not really surprising because at that time the "Lincolnshire Limestone Sea" would have been reworking the organic-rich sediments of the Grantham Formation, while further terrigenously derived nutrients may have been supplied from the nearby hinterland.

IV.2.g. <u>Discussion</u>

It has already been suggested that the Sproxton Member is equivalent to the Blue Beds of south Lincolnshire (Richardson, 1939b) but not those of the Lincoln district (Richardson, 1940), which are thought to be an independent and stratigraphically higher horizon, the Wragby

Bed (Fig. 4.10). This opinion contradicts the widely held belief of earlier workers (see Sylvester-Bradley, 1968 for a review) that the Blue Beds formed a single, homogenous unit at the base of the Lincolnshire Limestone Formation. The proposed re-alignment of Richardson's "Blue Beds" has been based upon the relationship between the recently deepened Metheringham sequence and those at Greetwell and in south Lincolnshire (Fig.4.10). The Greetwell and Metheringham sequences can be readily correlated by the almost identical beds LGHQ B́2 (approximately equivalent to the "Lincoln Blue Beds" of Richardson, 1940, fig.29), and MQ B́2, which form the Wragby Bed (Fig. 4.10). However, below the Wragby Bed at Metheringham a second "Blue Bed" occurs that is lithologically similar to the Sproxton Member in south Lincolnshire, with which it is grouped. Therefore at Metheringham the "Lincoln Blue Beds" horizon (= Wragby Bed) can be seen to be a separate, stratigraphically higher level than the "south Lincolnshire Blue Beds" (= Sproxton Member; see Fig. 4.10); clear evidence that the "Blue Beds" are not a single stratigraphical horizon.

This new correlation scheme highlights a number of other, previously unrecognised stratigraphical relationships:

(1) the attenuation of the Sproxton Member (= Blue Beds of Richardson, 1939b) north of Metheringham. This is mirrored sedimentologically by the lateral passage of the clay bed, capping the Sproxton Member in south Lincolnshire into a hardground at Metheringham and the complete absence of the whole unit at Lincoln (Fig.4.10).

(2) the condensed nature of the lower part of the Lincolnshire Limestone in the vicinity of Lincoln. The realisation that the "Lincoln Blue Beds" (Richardson, 1940) occur within the Greetwell Member (as the Wragby Bed) indicates that the Base Bed of Richardson (1940, p.249) can no longer be considered as an additional bed, ".......peculiar to this

section [Greetwell]....." but must be a condensed equivalent of that part of the Greetwell Member occurring between the Wragby Bed and Sproxton Member at Metheringham (Fig. 4.10). This means that the Bajocian succession at Lincoln is even less well represented than previously thought for some of the Lincolnshire Limestone is now known to be missing as well as the Grantham Formation. The position of the missing strata is marked by the basal conglomerate of the Lincolnshire Limestone (Fig. 4.11).

(3) the overlapping of the Sproxton Member by the Greetwell Member, which rests disconformably upon the Northampton Ironstone (Fig.4.10). This relationship has been implied diagrammatically by both Richardson (fig.42 in Sylvester-Bradley, 1968) and Wilson (1948, fig.9), although in their writings both followed the more traditional view of the "Blue Beds" extending across Lincolnshire as the basal unit of the Lincolnshire Limestone.

IV.3 GREETWELL MEMBER

IV.3.a. Introduction

The lithological and thickness variations present in the Greetwell Member polarise the unit into two distinct, geographically defined regions (Fig.4.12):

(1) Central Lincolnshire (Lincoln - Grantham), where the relatively thin (5 - 7 metres) sequences are composed of a mosaic of distinct litho-facies (ooid-, peloidal and quartzose calcarenites).

(2) South Lincolnshire (Grantham - Stamford), where the much thicker (11 - 12 metres) member can be subdivided, on the basis of recurring lithological patterns, into district lithostratigraphical units, which are widely traceable within that area (Fig. 2.2).

In order to accurately define this variable member fully, the following stratotypes have been adopted:

(1) Greetwell Hollow Quarry, Lincoln (TF 003721) as the type section for the whole member (Fig.4.13). More specifically this exposes the facies typical of the Central Lincolnshire region and also the Wragby Bed, a formal subdivision of the Greetwell Member in central Lincolnshire. This is the only quarry that reliably exposes the whole of the member in central Lincolnshire; Metheringham (TF 053616; see Fig. 4.1) is frequently flooded, concealing much of the lower part of the member.

(2) Sproxton Quarry (SK 866253) as a hypostratotype (Hedberg, 1976, p.38, pt.D2). The typical facies of the South Lincolnshire region are well seen in this sequence, which is the only section in south Lincolnshire to expose an unbroken sequence through the whole member (Fig. 4.14).

(3) Separate type sections for the individual informal subdivisions of the Greetwell Member present in south Lincolnshire, because subdivisions are not always developed to their best advantage at Sproxton.

IV.3.b. Former Terminology

Within a broad homogeneity, the Greetwell Member contains a wide range of lithologies that have apparently been classified into a number of different stratigraphical units by previous workers. Unfortunately precise details of the stratigraphical and geographical limits of these units, in terms of measured sections, are mostly lacking, and this prevents direct comparison with the Greetwell Member. Essentially the Greetwell Member comprises most of the strata between the Blue Beds and Crossi Beds of previous authors (Figs. 2.5 to 2.8) and is therefore approximately equivalent to the unit variously termed Silver Beds, Little Ponton Beds or Nerinea Beds (Kent, 1966, fig.1). The detailed relationships between the Greetwell Member and earlier stratigraphies are discussed in later sections dealing with the individual subdivisions of the member.

IV.3.c. Geographical and Geological Extent

The Greetwell Member can be readily traced from Lincoln to Woolfox (SK 951136) at the southern limit of the study area (Fig.4.12). Along this strike section the unit varies considerably in thickness (Fig.4.1) from a little under 5 metres at the type section(Greetwell) to over 7 metres at Metheringham and to a maximum measured thickness of just under 12 metres at Sproxton. This southerly increase in thickness can only be accurately monitored between Lincoln and Sproxton because further south, complete sections through the member are absent. However, as figure 4.1 indicates, near maximum thicknesses probably persist as far south as Thistleton (SK 903180) before notable thinning occurs again, although even at Greetham (SK 933146), where it is only partially exposed, the Greetwell Member is still over 9 metres thick.

The east-west changes in the Greetwell Member are less readily determined, despite the occurrence of the unit in quarries as far west as Waltham on the Wolds (SK 815253) and as far east as Little Bytham (TF 013178). This is mainly due to the absence of complete sections through the member in these "marginal" locations. However, the individual subdivisions of the member suggest that the unit is thinning in both directions relative to the "basinal-peak" around the Sproxton-Stainby area (Fig. 4.15).

In common with its other features, the major stratigraphical relationships of the Greetwell Member vary between central and south Lincolnshire. In south Lincolnshire the member invariably overlies the Sproxton Member. However in central Lincolnshire these straightforward relationships are lost and the following changes occur:

(1) the upper part of the Greetwell Member passes laterally northwards into the Leadenham Member (Fig.2.2), which is thus sandwiched between the Lincoln Member and the remainder of the Greetwell Member. This lateral facies change accounts for part of the difference in thickness of the Greetwell Member between central and south Lincolnshire.

(2) as the Sproxton Member becomes attentuated northward (Fig.4.10) the Greetwell Member overlaps onto the Grantham Formation and Northampton Sand Ironstone, the latter relationship being clearly seen at Greetwell.

The variations of the individual subdivisions of the member are discussed in later sections.

IV.3.d. <u>The Status of the Subdivisions of the Greetwell Member</u>

The Greetwell Member has been completely subdivided into the Market Overton, Thistleton, South Witham, Woolfox and Greetham Fossil beds in south Lincolnshire, but has been left undivided in central Lincolnshire except for the designation of the Wragby Bed. Of these subdivisions only the Wragby Bed has been given formal status.

The Wragby Bed has been given formal status for two main reasons.

(1) It is lithologically distinct and distinguishable from the other Greetwell Member beds and therefore complies with the requirements of formalised lithostratigraphical procedure (Hedberg, 1976).

(2) It is stratigraphically significant being one of the principal lines of evidence on which the re-assessment of the stratigraphical relationships of the Blue Beds (Richardson, 1939b and 1940) and Base Bed (Richardson, 1940) have been based (see section IV.2.g.).

In contrast, the subdivisions of the Greetwell Member in South Lincolnshire are considered unsuitable for designation as formalised lithostratigraphic units because:

(1) the recognition of the Woolfox, South Witham, Thistleton and Market Overton beds and the delimitation of their boundaries have primarily been based upon genetic considerations, which are unsuitable criteria for the erection of a formalised lithostratigraphy (Hedberg, 1976, p.36, pt.C.8.d). The units are thought to represent regressive sedimentary rhythms.

(2) with the definition of the Woolfox and South Witham beds, the Greetham Fossil beds have been arbitrarily isolated from the remainder of the member and given informal status, for they are not of sufficient lithological coherence or stratigraphic importance to warrant designation as a formalised unit.

IV.3.e. Correlation of the Greetwell Member

The correlation of the two different and geographically-isolated developments of the Greetwell Member is not readily achieved because of the lack of exposures in the crucial "transitional" zone (Ancaster-Grantham district). Similarly exposure failure prevents the lower Lincolnshire Limestone sequences of South Humberside and Lincolnshire being easily linked. However the available evidence permits some tentative correlations to be made.

IV.3.e.i. Internal Correlations: Although the recognition of the northward attenuation of the Sproxton Member clarified the stratigraphical relationships of the lowest Lincolnshire Limestone (Fig.4.10), the internal correlation of the contrasting south and central Lincolnshire Greetwell Member sequences is rather less clear. Despite the similarity of the lithofacies types in the two areas, south Lincolnshire is characterised by recurring regressive rhythms (Chapter V), which have no equivalent further north. However, the quartzose peloidal calcarenite forming the Wragby Bed is at the approximate stratigraphical level of the quartz-rich peloidal calcarenite capping the Thistleton beds (Fig.4.1). As quartz is scarce or absent in the lower parts of the rhythms and in the remainder of the central Lincolnshire Greetwell Member, this similarity may suggest a correlation.

However, the Wragby Bed itself cannot be directly traced any further south than Leadenham (Fig.4.1) because the siltiness, which is its distinguishing feature, has not been recognised at Ancaster (Railway Cutting exposure) even though the "appropriate" level is exposed; therefore, although the environmental factor (regression) that caused the parallel quartz enrichment of the Wragby Bed and upper Thistleton beds may have been one and the same, no direct stratigraphical evidence exists to link the two units. In the only central Lincolnshire quarry (Metheringham) to expose the Greetwell Member, between the Wragby Bed and Sproxton Member, the limestones show no particular kinship to those of the Thistleton or Market Overton beds; in fact they are ooid-calcarenites, that are quite typical of the central region. Despite this, the similarity of the massive oolites above the Wragby Bed at Metheringham to those of the South Wytham beds does point to the approximate stratigraphical equivalence of the Wragby Bed and top of the Thistleton beds. In addition, it implies that the Thistleton and Market Overton beds are represented by the condensed Greetwell Member sequence between the Wragby Bed and Sproxton Member at Metheringham; a sequence that thins even further towards Lincoln. Therefore the typical Thistleton and Market Overton beds development is "lost" somewhere in the non-exposed Ancaster - Grantham zone and although the two units may be broadly equivalent to certain beds in central Lincolnshire their exact genetic relationship with those beds is unknown because of this exposure failure. No transition between the south and central Lincolnshire facies is seen.

Although the stratigraphical position of the Leadenham Member and Woolfox beds (Fig.2.2) suggests they are broad equivalents, little direct tie-up is possible. However, the similarity of the hardground (with under-lying burrowed bed) at Greetham (capping the South Witham beds) and Leadenham (capping the Greetwell Member, see Fig.4.1) provides one possible link. Unfortunately over 38 kilometres separates the localities in question and the intervening sections frequently lack similar hardground developments.

However, this may be taking the implied correlations too literally. The south Lincolnshire sedimentary rhythms are separated by sharp erosive levels, which are thought to represent transgressive periods induced by periodic "accelerated" subsidence (Chapter V): these events can be widely traced across south Lincolnshire. Therefore the transgressive event may have manifested itself as a hardground in these geographically separated localities, which can therefore be correlated on genetic grounds (like the Wragby Bed and Thistleton beds). If this is the case then it is interesting to note that north of Leadenham, where the region is thought to have been gradually subsiding, there is a transitional contact between the Greetwell and Leadenham Members, but further south, between Leadenham and Ancaster, this contact is a hardground. From this it would appear that the Leadenham - Ancaster area represents the only genetically related transition seen between south and central Lincolnshire: the area has the hardground, typical of the south Lincolnshire sequence, but the Leadenham Member facies of central Lincolnshire. In spite of this, the actual Woolfox beds cannot be traced as far north as Ancaster, where the Greetwell Member facies, which interfinger with the Leadenham Member (Fig.4.1) are more typical of the central Lincolnshire area. This again indicates that the facies changeover within the Greetwell Member is in the "hidden" zone.

To summarise: although the hardground at the base of the Leadenham Member and the development of the Wragby Bed in central Lincolnshire may reflect similar lithological responses to events that are also recorded in south Lincolnshire, the actual contact and exact relationship between the lithofacies of the two areas are "hidden" because of exposure failure in the Ancaster - Grantham district.

IV.3.e.ii. Correlation with South Humberside: Until the recent excavation of a new quarry (SE 940024) by the Manton Stone Company, little of the Lincolnshire Limestone occurring below the Kirton Cementstones (Kent, 1966, fig.1) had been exposed north of Lincoln. The new section revealed a continuous sequence through the lower part of the formation and its contact with the underlying Grantham Formation (Ashton, 1975). The probable stratigraphic relationships between this section and the Lincolnshire Limestone further south are shown in Figure 2.2., although the contrasting lithologies of the two areas make direct comparison rather difficult. However, the similarity between the thick oolite of the lower Santon Oolite Member and the basal bed (= Base bed of Richardson, 1940) of the Greetwell Member at Lincoln suggests a correlation, which, if correct, indicates the absence of any representative of the Basal Hydraulic Limestone Member at Lincoln (Fig. 4.16). This southward attenuation of the lowest Lincolnshire Limestone parallels the northward attenuation of the Sproxton Member and provides additional evidence for the lower part of the formation being "condensed" around Lincoln. Unfortunately the lack of exposures prevents an accurate documentation of the southward thinning of the "northern basin" sediments but temporary exposures, in the Spital region, have shown there to be beds lying below the level of the Basal Hydraulic Limestone Member (C.F. Parsons, personal communication; and see also Kent, 1970, p.137). The optimum development of the "northern basin" must have therefore lain between Kirton and Lincoln (Fig. 4.16; see also Wilson, 1948, Fig.9).

Therefore during earliest Lincolnshire Limestone times the Lincoln area appears to have been a positive area (? mini-swell, see Chapter V), flanked to the north and south by more rapidly subsiding basinal areas, which also thinned away to the more widely recognised Market Weighton and London Landmass positive areas (Wilson, 1948, fig.9; Kent, 1940 and 1966; and Richardson in Sylvester-Bradley, 1968, fig.42). Exposure failure prevents the detection of any link (westward or eastward) between the northern and southern basins.

Returning to the known details of the contrasting stratigraphies at Lincoln and Kirton; if the proposed correlation of the oolites at the base of the Greetwell Member (Lincoln) and at the top of the lower Santon Oolite Member (Kirton) is correct, the Raventhorpe Member is at a similar stratigraphic level to the Wragby Bed. Furthermore, despite some obvious lithological differences, both units are typically "sandy", reflecting the influx of terrigenously derived quartz into the Lincolnshire Limestone sea. It is possible therefore that the two units may represent the same event, with the Ravensthorpe Member passing southward into the thinner Wragby Bed. If this is the case then:

(1) a source is provided for the Wragby Bed clastics and a reason for the bed's southward disappearance; and

(2) the influence of the Lincoln mini-swell is already waning.

The environmental aspects of the stratigraphic relationships, suggested by these possible correlations, are more fully discussed in Chapter V.

IV.3A. THE GREETWELL MEMBER OF CENTRAL LINCOLNSHIRE

IV.3A.a. Introduction

The Greetwell Member of central Lincolnshire is composed of a patternless mosaic of ooid- and peloidal calcarenites. The region extends from Lincoln as far south as the Little Ponton - Ropsley district (Fig.4.12), where successions in the lower part of the Lincolnshire Limestone are particularly scarce; this hinders the understanding of the relationship between the two areas, and prevents a firm boundary (if indeed one ever existed) being drawn between them. In the transition zone the Greetwell Member sequences are included within the central region if no sedimentary rhythms have been recognised. This has been the case with Little Ponton and Ropsley, although in both sections the member is poorly exposed and could possibly have "rhythms" in its lower, unseen parts.

IV.3A. b. Former Terminology

The Greetwell Member of central Lincolnshire is specifically equivalent to the Base Bed, Blue Beds and Silver Beds of Richardson (1940); the Blue Beds and Silver Beds (Kent, 1940 and 1966, fig.1; and Wilson, 1948) and the "Blue and Silver Beds" (Evans, 1952) in the Lincoln district, bearing in mind that these divisions also include the bed attributed to the Wragby Bed here. Further south, around Ancaster and Grantham, the precise limits of earlier stratigraphies are not so easily determined but the Greetwell Member is most probably equated with the Nerinea Beds (Richardson, 1939b; and Wilson, 1948); the Little Ponton Beds (Kent, 1940 and 1966, fig.1); and the Oolites (Swinnerton and Kent, 1976).

The relatively straightforward relationship between past and proposed terminologies in this region stems from the full development of the "Cementstones" (of previous authors) as far south as Ancaster. The base of this unit coincides with that of the Leadenham Member and therefore the Greetwell Member corresponds to those beds between the "Cementstones" and the base of the formation (or Blue Beds at Metheringham and further south). Only in the Ropsley - Little Ponton region does this relationship not hold good because the "cementstones" of this, more southerly area, belong in the stratigraphically higher Ropsley Beds of the Lincoln Member (Fig. 4.17) and are in fact equivalent to only the upper part of "Cementstones" further north; the "lower Cementstones", equivalent to the Leadenham Member are not developed this far south. Consequently, in the Little Ponton - Ropsley district, the Greetwell Member ranges up to the base of the Lincoln Member and includes the strata at the Leadenham Member level.

IV.3A.c. Field descriptions of the lithologies and fauna

Within the Greetwell Member of central Lincolnshire two main lithofacies (ooid-calcarenites - Lithofacies A; and peloidal calcarenites - Lithofacies B) occur as a random mosaic, which contrasts sharply with the recurring sedimentary sequences of south Lincolnshire.

IV.3A.c.i. Lithofacies A, "Leadenham Facies": This is a honey-yellow (but blue hearted), generally poorly-sorted ooid-calcarenite/calcirudite facies, within which complex burrow systems form a striking feature (Fig.4.18). Although "ooids" are the dominant constituent, skeletal grains, wood flakes and peloids also occur. At Ropsley and Dunston the rock assumes a crude bimodality with the ooids scattered in a peloid-rich matrix, but for the most part the rocks show a complete size gradation from peloid to coarsest ooid. Occasionally ooids become so abundant that a grain-supported, sparite-cemented, oolite results. The "clean" even-grained, moderately well-sorted oosparites of Metheringham represent the end-member of this trend. More normally the grains (despite forming a moderate to high percentage of the rock) are not so closely packed and a largely micritic matrix is present. However, the matrix is often difficult to determine in the field.

Complex burrow systems, which are excellently developed at Leadenham (Fig. 4.18), form an integral and typical aspect of this lithofacies. Although occurring throughout certain beds, the burrows are generally concentrated in the upper parts of the beds and are preserved in any one of three ways:

(1) Open burrows - the most spectacular of the three modes of preservation. Excellent examples are seen below the hardground capping the Greetwell Member at Leadenham (Fig. 4.18).

(2) Micrite infilled burrows - the most common preservation. This represents the infill of abandoned burrows with "normal" matrix. (Fig. 4. 19).

(3) Infilled with "friable", greeny "micrite" (very rare) - possibly faecal pellet infill, deposited by the animal during its habitation.

Fauna - fossils are reasonably common in these beds but some show signs of post-mortem transportation and may not, therefore, be indigenous to the environment represented by this facies. However, the presence of large, apparently unmoved, coral heads, some articulated bivalves and abundant trace fossils indicate that the environment was, at least during part of the time, favourable to colonisation.

The large, isolated colonial coral "heads" (Fig. 4.20) form a prominent part of the benthos and the massive thamnasteroid-types, containing ubiquitous "*Lithophaga*" sp. borings, appears to be the most common group, although branching, fasciculate colonies also occur. The remainder of the benthos is dominated by "*Nerinea*" spp., *Procerithium* spp., bivalves, solitary corals, terebratulids and algal tube colonies. These groups represent a wide range of adaptive types: epifaunal (corals, terebratulids and pectinid bivalves), infaunal (ubiquitous burrow systems) and more mobile semi- infaunal (*Nerinea*"spp.) life habits are all represented, suggesting a soft but stable substrate with abundant available holdfasts (for epifauna). Both suspension and deposit feeders are represented in the fauna.

IV.3A.c.ii Lithofacies B, "Lincoln Facies": This facies is composed of compact, blue-hearted, fine-grained peloidal calcarenites, that weather buff-yellow. Besides the abundant peloids, ooids (often outstanding as limonitic brown grains), wood flakes and rare fossil fragments form a subsidiary group of allochems, that constitute only a low percentage of the rock.

Burrows are generally rare in this lithofacies, although occasionally (at Leadenham for instance; Fig. 4.21), dense, complex networks, like those of Lithofacies A, are seen penetrating down from the top of a bed. The random orientations of these burrows suggest they are predominantly feeding rather than protective types.

Fauna - despite the relative scarcity of skeletal grains in the rock, actual fossils are often very common. In particular in the "true" Silver Bed at the Dean and Chapter Pit, Lincoln (the bed used to "face" Lincoln Cathedral) bedding surfaces are often covered with "Nerinea" spp., Pinna sp. and Gervillia sp.; a triumvirate also seen at Greetwell, where the approximate parallel alignment of the long axes of these fossils give the impression of current alignment (seen on loose blocks). It is interesting to note that despite its semi-infaunal habit, Pinna sp. (almost invariably seen in life position in the overlying Leadenham Member) is mostly seen "uprooted", lying parallel to the bedding. This, together with the possible current alignment, implies at least short periods of increased wave or current activity took place. Certainly the well-preserved fauna of largely whole (but disarticulated) valves denies the presence of currents strong enough to transport the shells any distance and indicates a generally quiet environment; a conclusion supported by the lithofacies and in contrast to Lithofacies A, where post-mortem breakage was much more evident.

In addition to the "typical" fauna, small gastropods, Lucina bellona d'Orbigny, Astarte minima Phillips, Rhizocorallium jeunese Zenker, Liostrea sp, Lopha sp. and a solitary coral "Montlivaltia" sp.nov.(?) have also been recorded, and the important ammonite faunas, discussed in Chapter III.

The availability of food in suspension and in the sediment is implied by the presence of <u>Gervillia</u> sp. and <u>Pinna</u> sp., and <u>"Nerinea"</u> spp. respectively. However the less diverse, yet more abundant fauna hints at a rather less predictable (shallower?) environment than that represented by the "Leadenham Facies".

Although the above description outlines the main features of Lithofacies B, at Leadenham there is a unique occurrence of parallel lamination, which is however similar to that found ubiquitously in the peloidal calcarenites of the Greetwell Member of south Lincolnshire (see Subfacies Cl of the Thistleton beds, section IV.3D.d.iii for example).

Despite the absence of any recognisable pattern in the relationship of the two main lithofacies, there is a recurring lithological sequence where the Greetwell Member passes up into the Leadenham Member. At most central Lincolnshire localities the more "typical" Greetwell Member lithofacies grade up into a calcilutite, which often stands out at the top of the unit as a thin, fine-grained, white limestone. Grains are generally scarce and poorly sorted; the most common are ooids, skeletal grains (gastropods, bivalves and algal nodules) and peloids. Bioturbation and burrows are also evident. This facies represents the transition from the Greetwell to Leadenham Member environments and indicates their natural juxtaposition in this area. However, further south (Leadenham - Ancaster district) this "transitional rock" is missing and a hardground is developed at that level; for example, at Leadenham (Fig. 4.22).

IV.3A.d. <u>Laboratory descriptions of the lithologies</u>

The principal characters of the two main facies present in the Greetwell Member of central Lincolnshire are shown in figures 4.23 (Lithofacies A) and 4.24 (Lithofacies B).

IV.3A.d.i. Lithofacies A: The "ooid" lithofacies varies from oncolitic wackestones (e.g. oncolitic biomicrite, Fig. 4.25) to oolitic packstones (e.g. skeletal oosparite, Fig. 4.26). Some of the variations are characterised in figure 4.23. Skeletal grains tend to be more common in the oncolitic rocks but the peloids and intraclasts have no particular pattern to their distribution. Silt is present in the more micritic lithologies. No algal tubules have been seen in the oncolites, which are recognised by their amorphous and sometimes discordant growth rims of micrite, and their large size (usually > 1 mm in diameter). The oncolites have a variety of "cores"; in the ones with an oolith nucleus, which are especially well developed in RQ.B2 (Fig. 4.27), the boundary between the regularly concentrically laminated oolith and amorphous micrite rim is blurred, presumably by algal borings in the original oolith surface. It is possible that the "rims" could be entirely attributed to algal borings but this seems unlikely, for in the many associated, smaller ooliths such rims are very rare and similarly in the few large ooliths (practically of the same size as the oncolites) the concentric laminae extend right up to the grain's margin. Also this "marginal" oncolite type grades into more clearly distinguishable oncolites seen in the other sections (Fig. 4.25). The oolith-cored oncolites tend to be of a regular size and circular cross-section, maintaining the original shape of the oolith. As they usually occur in the packstones, this may be a result of more intense agitation, compared with the oncolites of the wackestones. Other oncolites have skeletal cores, or composite nuclei, composed of two or more ooliths and/or skeletal grains; these are more asymmetrically shaped. A fourth type, essentially amorphous "micrite-lumps", are classified as oncolites, although their origin is more uncertain. Their general nature and association with the other oncolites suggests however that they may also be oncolites. Except for rare examples, the pale yellowish-green ooliths tend to be smaller than the oncolites and to have fine, concentric laminae coating the skeletal (predominantly bivalve fragments) or micritic (micritised?) nuclei. Although the ooliths have a regularly rounded outline, many are "superficial" in type and are not always spherical (Fig.4.26). In the intermediate lithologies (between the oncolitic wackestone and oolitic packstone end-members), the grains are bimodal with a larger suite of oncolites and coarse skeletal grains and a smaller suite of finer bioclasts and other small grains, which are not always readily identified. For example, although the interstitial allochems in LDCP B3 are nearly all ooliths (Fig. 4.28) those in RQ B2 are mostly classified as peloids; some however have hints of a remnant concentric structure and may be micritised ooliths. Others are possibly micritised skeletal fragments or even faecal pellets. Although bivalves are the dominant bioclasts, gastropods, foraminifera, ostracods, brachiopod and echinoderm fragments also occur. Micrite-envelopes are common, especially around the bivalve sparite pseudomorphs. The matrix of the various rock types varies with the grain content, the oncolite-rich micritic lithologies tend to have few grain-supported areas with patches of "original" sparite, while the closely-packed oolitic rocks have little micrite.

IV.3A.d.ii <u>Lithofacies B</u>: In contrast to A, Lithofacies B is compositionally quite uniform; a grain-supported biopelsparite, in which the quantity of "other" grains is rarely significant. However, the actual nature of the biopelsparite itself varies. For instance at Lincoln the rocks are bimodal with large skeletal fragments occurring in a "matrix" of peloids and small skeletal grains, which are cemented by primary sparite (Fig. 4.29). In contrast the rocks at Leadenham LQ B4c, see Fig. 4.30) are even-grained with only the subequally sized peloids and bioclasts present. When other grains, notably oncolites and ooliths, are present they invariably form part of the larger suite of grains. The uncommon oncolites are large simple or composite, asymmetrically rimmed grains. The mostly superficial ooliths tend to be smaller, more regularly rounded and clearly distinguished by their pale yellowish-green, concentric laminae. They have either skeletal or micritic nuclei. Some of the abundant peloids have similar laminated rims, suggesting that they too maybe incipient ooliths. However the majority of the peloids are featureless, largely ovoid "micrite-lumps", which are probably faecal pellets (because of their size and shape). Rare silt grains also occur amongst the peloids. The skeletal grains are often very abundant and large. Bivalves and gastropod sparite pseudomorphs predominate but echinoderm fragments and micritised foraminifera are also seen. The bioclasts occur "free" or more often with micrite-envelopes (especially bivalves). Frequently the bioclasts have syntaxial overgrowths and this is particularly noticeable with the *Pinna* and echinoderm fragments. The matrix is predominantly sparite cement, although it is quite "dirty" in places. Beneath some of the convex-up bivalve fragments a rather coarse sparite has developed in the largely grain-free areas.

IV.3B. WRAGBY BED

IV.3B.a Introduction

The relatively thin, sandy limestone forming the Wragby Bed is seen at only three localities: Greetwell Hollow Quarry, Lincoln (TF 003721), Metheringham (TF 053616) and Leadenham (SK 962523). Of these, Greetwell was chosen as the type section because the bed has its thickest (1.5 metres) and most "typical" development there, within the stratotype of the Greetwell Member (Fig. 4.31).

IV.3B.b Former Terminology

The Wragby Bed forms part of the Blue Beds of Richardson (1940, fig. 29; see also Fig.4.32), that occur in the Lincoln area and is also equivalent (in part at least) to the Blue Beds of Kent (1940 and 1966, fig.1), Wilson (1948), and Swinnerton and Kent (1976), and to part of the Blue and Silver Beds of Evans (1952). It must be noted however that the "Blue Beds" referred to here are those of the Lincoln area only, the more southerly "Blue Beds" (Richardson, 1939b) occur at a completely different stratigraphical level, the Sproxton Member horizon (Figs. 4.10 and 4.33).

IV.3B.c. Geographical and Geological Extent

As the Wragby Bed is seen in only three exposures its true geographical limits are difficult to determine. However, it does not appear to have been developed in south Lincolnshire, as it cannot be traced south of Leadenham, despite the presence of the appropriate stratigraphic level at the nearby Ancaster Railway Cutting (SK 997444; but also see section IV.3.e.)

IV.3B.d. Field descriptions of the lithologies and fauna

At both Greetwell and Metheringham the Wragby Bed shows a distinct sequence of lithologies:

(1) The base of the bed is an orangy-yellow, fine-grained sand, which contains subsidiary mica. It is a generally friable, well-sorted deposit, that grades up into the consolidated,

(2) fine-grained, quartzose peloidal calcarenite, containing a few ooids and skeletal fragments, neither of which are quantitatively significant. Occasional clay-infilled burrows are seen. This lithology passes up into,

(3) a bimodal ooid-peloidal calcarenite. The ooids increase in abundance towards the top of the bed where they form a significant amount of the rock, although even here they still "float" in the fine-grained, quartzose-peloidal matrix. Skeletal grains remain rare but diverse kinds of burrows are evident, particularly at the top of the

bed. Their density indicates a significant pause in sedimentation but no accompanying hardground development has been noted.

In contrast, the Wragby Bed at Leadenham lacks the sandy base and ooid-calcarenite top. Instead it is composed entirely of yellow, fine-grained, well-sorted, quartzose peloidal calcarenite with subsidiary mica and skeletal grains; a very similar lithology to (2) above. Except for the burrows, fossils are scarce throughout the whole of the Wragby Bed.

IV.3B.e. <u>Laboratory descriptions of the lithologies</u>

The principal characters of the two consolidated lithologies (2 and 3) present in the Wragby Bed are outlined in figure 4.34.

IV.3B.e.i <u>Lithology 2</u>: Within this quartzose pelsparite (Fig. 4.35), the amount of quartz decreases southwards from Lincoln to Leadenham (Fig. 4.34), with a corresponding increase in the importance of peloids. The size and ovoid shape of the peloids suggest that they are probably faecal pellets. Bivalves, often with micrite-envelopes, are the commonest bioclasts, although gastropods, foraminifera, and echinoderm fragments are also seen. At Metheringham rare oncolites and micritised ooliths, which are more typical of Lithology 3, occur at this level. Although the rock is grain supported, the small size of the grains results in the intergranular pore space being rather restricted and the very fine-grained sparite is not always clearly discernible. Some micrite also seems to be present, but it appears to be being altered to microspar; a process that is probably also responsible for the "diffuse margins" of many of the peloids. The sparite is partly dolomitised at Lincoln.

IV.3B.e.ii <u>Lithology 3</u>: The oncolitic biopelsparite (Fig.4.36) has an increased number of larger grains present in a Lithology 2 - type "groundmass". These larger grains are predominantly oncolites, picked out by their discordant growth rims, rarer ooliths and an increased number of skeletal grains. The peloids are much more variable in size and shape than in Lithology 2, and it is likely that they include "micritised grains" as well as faecal pellets. There is also less quartz present than in Lithology 2. The matrix is again very fine-grained sparite with subsidiary micrite.

IV. 3C MARKET OVERTON BEDS

IV. 3C.a. Introduction

The Market Overton beds constitute the lowest unit of the Greetwell Member in south Lincolnshire. The type section (2.2 metres thick) is exposed in Thistleton Quarry (SK 903180; Fig. 4.12), where the unit's most typical development of silty calcilutites and calcarenites is easily accessible (Fig. 4.37).

The name Market Overton was adopted for these beds because Thistleton Quarry was formerly known as "Market Overton No. 6 Pit" (Dr. J.A. Dickson, personal communication) during the period when it was actively worked for iron ore by British Steel. "Thistleton" itself was unavailable, having already been used for the overlying unit.

IV.3C.b. Former Terminology

The Market Overton beds have not previously been recognised as a separate unit, but have been variously included within the *Nerinea* Beds (Richardson, 1939a? and 1939b), the Little Ponton Beds (Kent,1940), the Oolites (Swinnerton and Kent, 1976), the Sandy Limestone Group (Hollingworth and Taylor, 1951), and the Little Ponton Beds - *Nerinea* (Pisolite) Beds (Kent, 1966, fig.1). These units appear to include much of what has here been assigned to the Greetwell Member.

IV.3C.c. Geographical and Geological Extent

The Market Overton beds, occurring between the Thistleton beds and Sproxton Member (Fig. 2.2), are only seen at Thistleton, Stainby (SK 910233), and Sproxton (SK 866253; Fig. 4.12). Their lateral relationships cannot therefore be accurately traced, although the maintainance of a uniform thickness (2.2 to 2.4 metres) in each of these localities, suggests that the beds were probably widely developed in south Lincolnshire.

IV.3C.d. Field descriptions of the lithologies and fauna

Although in detail a number of lithologies are seen in the Market Overton beds, there are two main lithofacies types:

(1) Lithofacies A - a sequence of silty calcilutites

(2) Lithofacies B - essentially a series of fine calcarenites rich in peloids and skeletal fragments, although various other "minor" lithology types make this something of a facies mosaic.

Lithofacies A consistently forms the lower part of the unit (up to 1 metre in thickness) with the generally thicker (up to 1.6 metres) Lithofacies B above.

IV.3C.d.i. Lithofacies A: This is essentially a sequence of soft, grey/white, blue-hearted, silty calcilutites. Although appearing barren, skeletal grains are the most abundant allochems in the beds, with subsidiary ooids (oncolites ?). Quartz grains, mica flakes and carbonaceous matter are also present. The sparse allochems are unevenly distributed throughout the rock. Occasional bioclastic lenses with scour bases also occur and one forms the basal 20 - 30 millimetres of the type section. The whole facies seems to have been heavily bioturbated and discrete sub-horizontal burrows are also present.

Fauna: the facies is characterised by worm tubes. Tiny gastropods, algal tube colonies (?), and rare disarticulated, epifaunal bivalves (valves are whole) are also present in the beds, while large *Thalassinoides* sp. networks are seen on the base of the unit. The largely unbroken nature of the bivalves and worm tubes, together with the general sediment type, suggest that the majority of the fauna has suffered little post-mortem transportation (except for the bioclastic lenses).

IV.3C.d. ii. Lithofacies B: The principal lithology present is a yellow-buff fine-grained, peloidal calcarenite. In addition to the dominant peloids, large skeletal grains (worm tubes, gastropods, bivalves), uncommon ooids, and wood also occur, either in clusters or randomly scattered throughout the rock. The contrast in grain size between the peloids and other allochems imparts a crude bimodality to the rock. The matrix is difficult to determine in the field, although the close packing suggests a grain-supported rock with the possibility of a sparite cement.

Two significant sub-facies occur within this main litho-type:

Subfacies B1: a laminated facies. This rock is generally parallel and more rarely cross laminated with individual laminae(mm scale) being picked out by differential weathering and less often by "lines" of skeletal debris, which form distinctive laminae, sometimes only one grain thick (Fig.4.38). These laminae are more fully described in section IV.3C.e.

Subfacies B2: a facies of minor "scour-and-fill" and bioclastic lensoid beds. These are relatively coarse-grained accumulations that are impersistently represented within laminated (most commonly) and unlaminated sequences of the peloidal calcarenites. They may be cut through by later cross-laminated sequences (Fig.4.38) or alternate with sequences of finer, parallel laminations or micrite (Fig.4.39) or sharply truncate earlier structures like burrows. In addition to the bioclastic grains, ooids and intraclasts are also found in these "beds".

Fauna - The peloidal calcarenite of Lithofacies B maybe very fossiliferous, having particularly abundant "Nerinea" spp. (as at Thistleton), worm tubes ("serpulite"bands at Stainby) and much rarer *Pinna* sp, which are seen in life position at Sproxton. Burrows, of all possible orientations are also abundant.

Quite distinct from, but occurring within, this peloidal calcarenite facies are ooid-calcarenite levels. These are coarser grained, relatively grain-poor and shelly, with "convex-up" epifaunal bivalves the dominant body fossil. Burrows, picked out as randomly orientated micrite streaks also occur and give the rock the general appearance of Lithofacies A of the Greetwell Member of central Lincolnshire.

IV.3C.e. Laboratory descriptions of lithologies

The chief petrographic features of the two main lithofacies are shown in figures 4.40 and 4.41.

IV.3C.e. i. Lithofacies A: Although essentially a uniform facies, composed of silty biomicrites with minor amounts of peloids, some minor variations are seen: the quartz content increases sharply up the Thistleton sequence (Fig. 4.40) from being a subsidiary constituent at the base to the major grain type at the top. Accompanying this upward trend there is a decrease in the amount of skeletal debris and its comminution. In bed TQ BA 1 the bioclasts are characteristically highly fragmented and rimmed with brown (oxidised) micrite-envelopes, whereas in TQ BA 3 they are mostly "free", much larger but less diverse; only bivalves, gastropods and rarer echinoderm fragments occur. In both cases however the calcitic skeletal grains have retained their original composition and structure while the aragonitic ones have been altered; bivalves and gastropods for example are seen as sparite pseudomorphs.

TQ BA 1: (Fig. 4.42) The diverse bioclasts of this bed are derived from worm tubes, gastropods, echinoderms, foraminifera (micritised skeletons), bivalves, brachiopods, Bryozoa and ostracods. The irregular shapes and general appearance of the subsidiary peloids suggest that they are more likely to be micritised skeletal grains than faecal pellets but their origin is uncertain. Although scattered throughout the rock, the silt and very fine sand is also concentrated in many of the discrete burrows, which stand out as paler grey, silt and peloid rich patches in the darker grey micrite; the paler colour is due to the alteration of micrite to microspar. The burrow cross-sections never exceed 2mm in diameter and microspriete is discernible in some of the longitudinal sections. As all orientations are seen in a single slice, the burrows are probably feeding rather than protective types. In addition to these, other similarly sized burrows occur packed with "rimmed" skeletal grains, peloids and silt, all set in a mixed sparite/micrite matrix.

TQ BA 3: (Fig 4.43): This is essentially a silty micrite with some skeletal fragments. The dominant quartz and accompanying white mica tend to be concentrated into silt rich layers, which alternate with silt-poor levels; both parallel the bedding. However, these are not evident throughout the slice and even where present, bioturbation and burrowing has disrupted their margins. This silty micrite appears to be the dominant lithology elsewhere (Sproxton and Stainby), although at Stainby an intermediate lithology is seen in which a higher proportion of skeletal grains and peloids are associated with abundant quartz. Bioturbation is rife throughout all litho-types and there is a tendency for the micritic matrix to be partially converted to microspar.

IV.3C.e. ii. Lithofacies B: Although Lithofacies B encompasses a range of different lithologies, it is typified by a peloidal packstone facies (Fig.4.41). However like Lithofacies A, minor variations are also seen in B. For example, at Thistleton, the "typical" facies, a pelsparite (Fig.4.44), has small numbers of bioclasts, intraclasts, ooliths and oncolites scattered within a peloid-rich matrix but at Sproxton (SNQ BA2) this incipient bimodality is more clearly developed; the peloids are, on average, considerably smaller than those of the Thistleton rocks and the skeletal grains also tend to be larger and more abundant (Fig.4.41). Quartz is also more abundant in the Sproxton rock. The peloids are probably a polygenetic group; some of the larger ones seen in TQ BA 5c appear to be incipient ooliths for they have rudimentary concentric laminae coating skeletal or micritic nuclei, while other moderately sized (≏o.2mm) compactly ovoid grains, seen at Sproxton, are undoubtedly faecal pellets.

However, the origin of the majority of the peloids, including the tiny ones seen at Sproxton, is debatable. The skeletal grains are similar in type and preservation to those of Lithofacies A. Additional allochem types, including superficial ooliths, oncolites and intraclasts (silt rich micrite) are seen sparingly in TQ BA 5c.

The principal variation from the "typical" lithofacies, is towards a more micritic rock that is transitional between the standard A and B types. Silty micrites, pelmicrites or biopelmicrites are characteristic lithologies. The lowest subdivision of the beds forming the B facies at Thistleton falls into this category and illustrates the transitional nature of these variations. Compositionally these rocks do not vary a great deal from A or B, generally having more abundant allochems (like B) set in a silty micrite matrix (typical of A). Texturally they are wackestones. Together with the typical B facies they form the "background" sediment within which the subfacies, B1 and B2 occur.

Subfacies B 1: Despite the uniformity of the "background sediment" of this lithofacies, the subfacies are extremely variable. For example there are at least three different lithologies occurring in either parallel or cross-laminated sequences:

(1) Alternating peloidal laminae: peloid-rich, sparite-cemented laminae alternate with micrite-rich, peloid-poor laminae, on an exceedingly fine scale; each lamina usually being less than 1 mm. These laminae tend to be parallel, and occasionally a single row of fossils highlights the lamination (Fig. 4.38). Although clearly picked out by differential weathering, neither the definition of the laminae nor their contacts is clear in peels or thin sections (possibly as a result of the fine scale and similarity of composition).

(2) Alternating peloidal and bioclastic laminae: these are more easily picked out because of the compositional difference and generally coarser scale of the laminae (up to 2 mm), which may be in either

parallel or cross-laminated series (Fig. 4.38). The molluscan and worm tube fragments may dominate the bioclastic laminae or they may simply augment the peloid-rich, sparite-cemented laminae of type 1; in this way types 1 and 2 inter-grade. The bivalve and ostracod valve fragments are preferentially arranged convex-side uppermost.

(3) Alternating bioclastic and micritic laminae: at Sproxton the white micritic laminae, with rare bioclasts, contrast strongly with the reddish-brown bioclastic laminae, which occasionally have subsidiary peloids and ooids (Fig. 4.39). In addition to the micritic laminae, which are as much as 3 mm thick (bioclastic laminae are usually thinner), lensoid "micro-beds" of up to 10mm thickness are seen. These tend to have irregular bases "infilling" bioclastic layers and flat tops, suggesting a "settling-out" origin for the lime mud (Fig. 4.39). Both parallel and cross-laminated sequences of this type occur.

Throughout this subfacies the cross-laminations and scours appear to be multi-direction and all lamination types are prone to disruption and even obliteration by bioturbation and burrows; at Sproxton for instance subvertical burrows of micrite cut down through bioclastic levels (Fig.4.39).

Subfacies B2: The bioclastic "scour-and-fill" features are excellently displayed at Sproxton, where the reddish brown bioclastic fine calcirudites stand out as "scour runnels" in the yellowish peloidal limestones Subsidiary ooids, intraclasts and peloids occur but skeletal, largely molluscan, fragments are the dominant allochems. Disarticulated valves are preferentially aligned parallel to the bedding, giving a "lineated" appearance to the rock, which has an "open" texture and sparite cement. Such "scour-and-fills" have been seen up to 35 mm deep and 200 - 300mm wide, although more persistent beds of this composition also occur. Like Subfacies B1, these deposits are also prone to cross-cutting by later, usually sub-vertical burrows.

IV.3D. THISTLETON BEDS

IV.3D.a. Introduction

The Thistleton beds' "typical" tripartite sequence of skeletal ooid- and peloidal calcarenites is most clearly developed within the 2.3 metres type section at Thistleton (SK 903180; Fig.4.45).

IV.3D.b. Former Terminology

The Thistleton beds have been previously included within the *Nerinea* Beds (Richardson, 1939a ? and 1939b), the Little Ponton Beds (Kent, 1940), the Oolites (Swinnerton and Kent, 1976), and the Little Ponton Beds - *Nerinea* (Pisolite) Beds (Kent, 1966, fig, 1). However their relationship to the stratigraphical scheme of Hollingworth and Taylor (1951) is less clear. At Thistleton, the Thistleton beds seem to be of a suitable composition and stratigraphic level to be included in the "Sandy Limestone Group" of Hollingworth and Taylor (1951, p.18). However, at South Witham (SK 917189), the beds occupy the same level as the Pisolite Group" (Fig. 4.46) which nominally overlies the "Sandy Limestone Group" (op,cit., p.18). As the Thistleton beds are known to occur at a fairly constant stratigraphic level (Fig.4.1), the "Pisolite" and "Sandy Limestone Groups" cannot just have the simple vertical relationship implied by Hollingworth and Taylor (1951, p.18) and some doubt must be cast upon the value of their particular stratigraphical scheme.

IV.3D.c. Geographical and Geological Extent

Little indication of the lateral relationships of the Thistleton beds can be deduced within the unit's traceable limits (Greetham, SK 933146, to Waltham on the Wolds, SK 815253; see Fig. 4.1). Only the vertical relationships are seen (Fig.2.2); the Thistleton beds always truncate the Market Overton beds and are in turn truncated by the South Witham beds. The amount of erosion that has occurred in either case is difficult to estimate, but the relatively consistent thicknesses maintained by the units involved suggests that any downcutting must have been fairly uniform over the region as a whole (excepting Greetham). Certainly the nature of the contacts in the field favours the opinion that only slight erosion of either the Market Overton or Thistleton beds has occurred. At Greetham, however, erosive downcutting by the South Witham beds is thought to be responsible for the Thistleton beds, thinning from 2.0 to 1.8 metres within the confines of the quarry (Fig.4.47). This accentuates the general southward thinning of the beds from Sproxton (SK 866253) where they are almost 3 metres thick, and parallels the trend of the formation as a whole (Kent, 1966, fig.2).

IV.3D.d. Field descriptions of the lithologies and fauna

In the type section, the Thistleton beds are composed of 3 distinct lithofacies (Fig.4.45):

(3) Lithofacies C - Fine-grained, peloidal calcarenite (top).

(2) Lithofacies B - Medium-grained, ooid-calcarenite.

(1) Lithofacies A - Skeletal calcirudite with sharply erosive base.

A similar sequence (A ⟶ B ⟶ C) occurs at Stainby (SK 910233) but at Sproxton and Greetham Lithofacies A is not developed and a simpler B ⟶ C sequence is seen instead, although the unit maintains a similar overall thickness (Fig. 4.1). In detail a "higher energy" subfacies (B 1) of Lithofacies B replaces Lithofacies A, producing a B1 ⟶ B2 ⟶ C rhythm. Lithofacies C consistently occurs at the top of both types of rhythm and nowhere are the sequences seen reversed.

IV.3D.d. i. Lithofacies A: this stands out strikingly from the quarry face as a yellow, massive "lineated" rock quite unlike the other beds in the section. In detail it is a buff-grey (when fresh), skeletal calcirudite, principally composed of bivalves and gastropods "set" in a clear sparite cement together with the subsidiary but very variable ooids. Although poorly sorted, the preferred, "convex-up" orientation of the abundant bivalves imparts the crude planar lineation to the rock (Fig.4.45). At Thistleton this lineation is replaced near the top of the bed by a very localised, crude, cross-bedding, which emphasises the role of currents rather than catastrophic agents (e.g. storms) in the deposition of this facies. The bed is not always a single, massive unit; at Stainby, for example, clay partings are found within it, indicating breaks in the "normal" sedimentation pattern.

IV.3D.d.ii Lithofacies B: At Thistleton this is essentially a yellow-brown, grain-rich, ooid-calcarenite. Amongst the ooids the larger ones are highly sphaerical and are probably true ooliths, while the smaller grains are possibly peloids or incipient ooliths. Although not especially common, the skeletal grains are large and, with the ooids, form a closely packed, grain-supported rock, which is probably sparite-cemented. Away from Thistleton this facies is usually divisible into two subfacies B1 and B2 that maintain a constant relationship (B1 underlying B2) when found together in the same sequence.

Subfacies B1: This is a grain-rich, ooid-calcarenite composed of a wide variety of ooids, peloids, and skeletal grains. In places the ooid/peloid mix gives the rock a crude bimodality, but generally there is a complete gradation in grain-size. The uncommon skeletal fragments are often large. The matrix is difficult to determine in the field but may be sparite cement as the rock appears to be grain supported.

Subfacies B2: This is not widely dissimilar from B1 compositionally but the allochems constitute a lower proportion of the B2 - rock and micrite is a more important constituent of the matrix. In addition B2 is often extensively burrowed (grey, micritic streaks); the form of the burrows appearing to be poorly developed examples of the "Lithofacies A burrow system" of the central Lincolnshire Greetwell Member.

IV.3D.d.iii Lithofacies C: This is a peloidal calcarenite lithofacies, which has subsidiary ooids together with mica, wood flakes and abundant fossils, amongst which the high-spired "Nerinea" gastropods are very evident. In places the "Nerinea" appears to be preferentially aligned. Bioturbation and burrowing are also rife. Largely single, sub-vertical burrows, often filled with greeny clay, occur and are reminiscent of the burrows of the Santon Oolite Member of South Humberside (Ashton,1975). Two environmentally significant subfacies are seen within this lithofacies:

Subfacies C1: This most striking subfacies is composed of finely-laminated fine-grained, well-sorted peloidal calcarenite (Fig.4.48). Outside of the lamination, "Skolithos-type" single, vertical burrows form the only other significant feature of the rock. Details of the laminae are given in section IV.3D.e.

Subfacies C2: Coarse, skeletal ooid-calcarenite bands occur interspersed within the fine-grained peloidal calcarenites. These are analogous to the "bioclastic lensoid beds" of Subfacies B2 of the Market Overton beds, although their composition is somewhat different.

In addition to these subfacies other minor lithologies complicate Lithofacies C. For example, at Thistleton, an intraclast layer (equivalent to the "round pebble conglomerates" of Braun and Friedman, 1969) composed of peloidal calcarenite intraclasts, some of which contain fragments of "Nerinea", occurs within a peloidal-ooid matrix.

IV.3D.e. Laboratory description of the lithologies

The principal characteristics of the lithofacies that compose the "type rhythm" of the Thistleton beds at Thistleton are shown in figure, 4.49.

IV.3D.e. i. Lithofacies A: This striking facies, typically an oolitic biosparite (Fig.4.50), is quite unlike most of the lower Lincolnshire Limestone litho-types in being a grainstone, with a very coarsely crystalline sparite cement. Bivalves and brachiopods (some terebratulids) are the predominant bioclasts, but echinoderm fragments are also seen. Whether the original skeletal material is preserved (brachiopods and echinoderms) or not (bivalves), the fragments mostly have micrite-envelopes. The sphaerical to sub-ovoid ooliths are bimodal but the vast majority are small (0.2 to 0.6 mm). Most are either "normal" or "superficial" in type, with skeletal or micritic (micritised?) nuclei. The third most common allochem group, intraclasts, are characteristically large, crudely rounded and composite grains, often composed of oolitic rock. Some may be oncolites as they have amorphous micrite rims. Peloids occur sparingly; in the only patch, where they occur in any quantity they appear to have coalesced, giving rise to a "pseudo-micritic" matrix. Their size, shape (ovoid) and included "exotic" granules suggest they are probably faecal pellets.

The rock as a whole is rather poorly sorted but the larger, elongate bioclasts appear to be preferentially aligned parallel to the bedding. The coarsely to very coarsely crystalline (see Folk, 1962, p.74) blocking sparite cement is "late", as it post-dates the compactional features. No early acicular cements have been seen.

IV.3D.e. ii. Lithofacies B: At Thistleton this facies is represented by a bimodal oosparite (Fig.4.51), in which peloids occur interstitally between the dominant, larger, reasonably well-sorted ooliths. The typically pale yellowy-green, near sphaerical ooliths are "normal" or superficial in type, having either skeletal (often echinoderm fragments) or micritic (micritised) nuclei; the latter are more common. Some of the larger ooids are probably oncolites as the inner core of concentric laminae (oolith) is replaced outwards by an amorphous micritic coat, which was probably accreted by algae; similar grains are seen in the Leadenham Facies (Section IV.3A.d.i.). Other grains, completely formed of amorphous micrite, may be intraclasts; these are very rare. The small and irregularly shaped peloids are probably polygenetic (faecal pellets and micritised grains). Although not common, bivalve, gastropod and brachiopod fragments also occur, together with rare silt grains. Two distinct generations of sparite are present, a blocking type infills the pore space left by the earlier acicular rim-cement.

The rock described above is from the type section and is typical of the "ideal" Lithofacies B. However in those sections, where there is no Lithofacies A, a subfacies of B (B1) replaces it and the typical B, retaining its usual position in the sequence, "becomes" Subfacies B 2. Although compositionally very similar B1 and B2 are texturally distinct, B1 being a grainstone like A, whereas B2 is a packstone as already described (see also Fig. 4.49).

Subfacies B1: This is a grain-rich rock in which ooliths are again very dominant (oosparite; Fig. 4.52). Most appear to be "superficial" with micritic nuclei but the larger ooids (range is 0.1 to 0.8 mm) are often completely micritised, making their true identity difficult to determine. Some have asymmetric outgrowths, which suggests that they may be oncolites but most, from their sphaerical shape and size appear more likely to be micritised ooliths. Even larger (1.0 to 2.2mm), more irregularly shaped and composite grains are probably intraclasts but these are rare. Similarly scarce bioclasts (0.5 to 4.4 mm) of bivalves, gastropods and foraminifera occur, together with a few interstitial peloids. As in the typical B facies, two cements are also present here; an early acicular rim-cement and a later infilling blocky type.

Subfacies B2: Although the "standard" Lithofacies B is typical of this subfacies, variations do occur. For example at Sproxton, a burrowed oolitic biopelsparite (SNQ BB 3a) is developed at this level. The burrows of this packstone stand out as micritic areas with included tiny silt and comminuted skeletal grains. Although nominally peloid-rich, many of the polygenetic peloids (0.62 to 0.31mm) are probably micritised, incipient ooliths. A number of normal, superficial and composite ooliths also occur, together with a variably sized (0.1 to 11.2 mm), diverse collection of skeletal grains and rare intraclasts. Bivalves and echinoderms are the most common bioclasts but forams, gastropods and ostracods are also present.

IV.3D.e.iii Lithofacies C: At Thistleton this facies is compositionally very uniform; all the beds are skeletal pelsparites (Figs.4.49 and 4.53). The dominant peloids, although fairly uniform in size are variable in shape and "wholeness"; some appear to have been "broken" but are probably micritised skeletal fragments. Other, more regularly-shaped peloids may well be micritised incipient ooliths or faecal pellets. The peloids often have diffuse edges, suggesting partial alteration to microspar. The bioclasts tend to be bimodal; a larger suite of fragments (>0.6 mm), composed almost exclusively of bivalve and gastropod sparite pseudomorphs (with micrite-envelopes) contrasts with the peloid-sized fragments of those two groups together with ostracods, foraminifera, brachiopods and echinoderms. The rare ooliths are usually superficial in type with micritic (occasionally skeletal) nuclei. Odd silt grains and large, irregularly-shaped allochems (intraclasts or oncolites?) make up the remainder of the rock, which invariably has a mixed sparite-micrite matrix, although some of the "micrite" has been formed by the coalescence of peloids. This lithotype forms the "background sediment" within which the environmentally significant subfacies (C1 and C2) occur.

Away from Thistleton the beds of this facies retain a remarkably similar texture and composition, which is dominated by peloids, subsidiary "bimodal" bioclasts and few other grains except for spasmodically abundant silt. For example at Stainby and, to a lesser extent, at Greetham, beds at this level and of this lithofacies are very rich in quartz. Indeed the bed at Stainby is probably a calcareous siltstone. It also shows quite clear evidence of being laminated (see Subfacies C1).

Subfacies C1: this typically shows very fine (sub-mm scale) parallel and cross laminations, which are clearly picked out by differential weathering (Fig.4.54). However, neither the laminae nor their contacts are clearly distinguishable in thin section, where they usually appear as alternating "dark" and "light" bands. The "light" laminae are composed of slightly larger peloids set in a sparite cement (maximum thickness 2mm) while the "darker" layers are more micritic with smaller, perhaps more closely spaced peloids (maximum thickness 1mm.). Similar light-dark laminations are seen in the quartzose beds of this level at Stainby. Although the peloidal laminations are the most dominant type, bioclastic and micritic laminae also occur, together with micritic "micro-beds", which are as much as 10 mm thick. This subfacies is thus equivalent to Subfacies B1 of the Market Overton beds. The laminations may be destroyed by burrowing and bioturbation (Fig. 4.55).

Subfacies C2: "Storm layers", rich in ooids and bioclasts, and up to 15 mm thickness occur (Fig.4.56). Although they scour slightly in underlying deposits, they maintain fairly parallel tops and bottoms. These too are often cut through by vertical burrows (Fig. 4.57).

IV.3E. SOUTH WITHAM BEDS

IV.3E. a. Introduction

The South Witham beds are characteristically composed of a sequence of massive oolites that, in places, are capped by peloidal calcarenites. The type section is at South Witham Quarry (SK 917189; see Fig. 4.12). where the thickest complete succession (4 metres) is seen (Fig. 4.58).

IV.3E. b Former Terminology

The South Witham beds have previously been included within the *Nerinea* Beds (Richardson, 1939a? and 1939b), the Little Ponton Beds (Kent, 1940), the Oolites (Swinnerton and Kent, 1976), and the Little Ponton Beds - *Nerinea* (Pisolite) Beds (Kent, 1966, fig.1). However, their position within the stratigraphy proposed by Hollingworth and Taylor (1951) is less clear cut. Figure 4.46 shows that in Thistleton Quarry (SK 903180) the South Witham beds occur above the level of the

"Sandy Limestone Group", making them equivalent to the "Pisolite Group" of Hollingworth and Taylor (1951). However, the "Pisolite Group" has been shown to be at different stratigraphic levels in different areas (see section IV.3D.b); for example at South Witham the "Pisolite Group" is at the same level as the Thistleton beds (Fig.4.46). This means that at South Witham the South Witham beds are on a level with at least part of the unit occurring above the "Pisolite Group" in the stratigraphic succession of Hollingworth and Taylor (1951), the "unnamed beds containing the Pholadomya Bed". This is supported by the similarity in the faunas of the Pholadomya Bed and the Greetham Fossil beds, which cap the South Witham beds (Fig. 2.2.).

IV.3E.c Geographical and Geological Extent

Despite being easily traced around south Lincolnshire, the lateral relationships of the South Witham beds are poorly known: a feature shared with the other subdivisions of the Greetwell Member in this area. The unit is thickly developed, as massive oolites, along the N - S axis between Stainby (SK910233) and Greetham (SK 933146; Fig. 4.12), but thins rapidly westwards from Stainby (Fig.4.59) suggesting that it may not persist far beyond its present western extent. In contrast there is no marked thinning to the east or south and the South Witham beds may well extend a good deal beyond the known limits in both directions.

The vertical relationships of the unit are relatively well known; the South Witham beds erosively rest upon the Thistleton beds and are usually succeeded by the Woolfox beds with an erosive or "hardground" contact. In fact the unit is typically "capped" by a hardground, which at Greetham, in particular, and Thistleton, has a prominent fossil bed (the Greetham Fossil beds) developed upon it. (Fig. 4.1).

Unlike the older Thistleton and Market Overton beds, the South Witham beds do not maintain a fairly uniform thickness throughout south Lincolnshire; the thickness variations seen may be due to:

(1) Original sedimentation differences - the unit is thickest where the formation, as a whole, is thickest and/or

(2) differential downcutting by the Woolfox beds, as the contrasting sequences at Stainsby and Sproxton (SK 866253) suggest (Fig.4.1).

IV.3E.d. Field descriptions of the lithologies and fauna

The South Witham beds are composed of two distinct but variable lithofacies:

(1) Lithofacies A - Ooid-peloidal calcarenite

(2) Lithofacies B - Fine-grained, peloidal calcarenite

IV.3E.d.i. Lithofacies A: This is essentially a massive bedded grain-rich ooid-peloidal calcarenite. Abundant ooids and subsidiary bioclasts are set in a peloid-rich matrix, the nature of which is generally difficult to determine in the field. The poorly-sorted rock may be bimodal or show a complete gradation in grain size. Burrows form an integral part of the facies. Although practically absent in the lower part of the sequence, they become both more abundant up the succession and also at the tops of the individual beds (South Witham Quarry).

Fauna: Although no detailed collecting has been undertaken, the following body fossils have been recorded: *Pholadomya ovalis* (J. Sowerby) in life position; *Modiolus imbricatus* (J. Sowerby); *Lima (Regalilima) oolitica* Lycett, articulated terebratulids, small, high-spired gastropods and solitary corals. Despite the occasional occurrence of well preserved forms like these, the beds do not appear very fossiliferous. Most forms are fragmentary, indicating that the fauna, if not derived, has been moved around within its "native" environment. Only rarely do "*in situ*" organisms like *Pholadomya* offer contradictory evidence.

The major variant in this facies is a much better washed (clear, sparite cement), grain-supported, ooid-calcarenite which forms the lowest visible part of the sequence at Little Bytham (TF 013178; Fig.4.60). A similar lithology forms the base of the South Witham beds at Stainby.

IV.3E.d. ii. Lithofacies B: Although only thinly and spasmodically represented, this is an important part of the South Witham beds, from an environmental aspect. It is analogous to Lithofacies B of the Market Overton beds and Lithofacies C of the Thistleton beds. Essentially this facies is a shelly, fine-grained, well-sorted, peloidal calcarenite. Rare ooids are scattered throughout the rock while the bioclasts tend to occur in lenses and clusters.

Fauna: Although the presence of "Nerin ea" spp. typifies this facies, Astarte divaricata (Cross), Pinna sp. and Gresslya sp. (both in life position) have been recorded. The fauna is not especially common but it is indigenous to the environment, in which these rocks were deposited.

Within Lithofacies B there is a major subfacies (B1) and a quantitatively minor, but environmentally significant subfacies (B2).

Subfacies B1: This has a less widespread development than the "parent" lithofacies and has only been seen at Stainby and Woolfox (SK 951136). Effectively it is composed of fine parallel laminations (1 to 2 mm scale), the details of which are outlined in section IV.3E.e. The laminations, which are usually picked out by differential weathering, are often impersistently developed and may be cut through by single, vertical "Skolithos"-type burrows (Fig. 4.61). The laminated levels may also be interbedded with micritic "micro-beds" (centimetre scale; Fig. 4.62), which are similarly penetrated by the vertical burrows (Fig.4.63). Except for the burrows (and bioclasts) this subfacies is devoid of fauna.

Subfacies B2: Associated with the micritic micro-bed levels, are rare micrite and peloidal limestone flakes. These white lithoclasts occur within the more yellow peloidal calcarenites of Lithofacies B at Stainby.

With the South Witham beds, the massive oolites of Lithofacies A usually pass up into Lithofacies B (South Witham, Woolfox, Sproxton and Waltham on the Wolds, SK 815253; Fig.4.1). However some variations are seen; for example at both Greetham and Stainby, Lithofacies B occurs within Lithofacies A, but in each instance the sediment is of the normal "B" type - nowhere do such intercalations show the characteristics of Subfacies B1 or B2. Therefore an idealised sequence through the South Witham beds may be considered as:

(3) Fine-grained, peloidal calcarenite showing parallel laminations and related features (Subfacies B1). This is the top of the sequence.

(2) Medium to coarse-grained, ooid-peloidal calcarenite showing abundant burrows (Lithofacies A).

(1) Medium- to coarse-grained, well-washed, ooid-calcarenite, with erosive base.

More often than not 1 is not developed, its place being taken by Lithofacies A, which has a shelly base and is devoid of burrows when occupying such a basal position. Similarly Subfacies B1 may be replaced by or occur with Lithofacies B.

IV.3E.e. <u>Laboratory descriptions of the lithologies</u>

The principal characters of the two main lithofacies are shown in figure 4.64.

IV.3E.e.i. <u>Lithofacies A</u>: This facies is primarily composed of sparite-cemented ooliths and peloids, the relative proportions of which vary quite substantially (Fig.4.64). Subsidiary intraclasts, bioclasts and rare oncolites may also occur. Effectively the lithofacies ranges from a peloid-rich end-member, e.g. skeletal oolitic pelsparite (Fig.4.65) through an intermediate stage (Fig.4.66) to an oolith-rich end-member, e.g. peloidal oosparite (Fig.4.67). All the lithologies tend to be bimodal; ooliths, intraclasts, oncolites and the larger bioclasts form the larger suite of allochems, while peloids, and the smaller ooliths and bioclasts comprise the "interstitial" group.

<u>Allochems</u>: The ooliths are of three types: normal, superficial and composite. The former two are mostly sphaerical to ovoid in shape, with either skeletal or micrite (micritised?) nuclei. Micritisation has affected the larger ooliths to varying degrees and it is only in the smaller ones that the internal structure is clearly seen. In SWQ BCla a few asymmetric ooliths occur. The composite ooliths, which are the rarest type, tend to be larger (0.5 to 1.4mm), usually incorporating two or more ooliths within an oolitic coating. Occasionally two ooliths are "cemented" together by an intervening area of micrite to form "grapestones", but most intraclasts are rounded, uncoated composite grains, which tend to be commoner in the more oolitic lithologies. Both ooliths and intraclasts may have partial, asymmetric oncolitic outgrowths of amorphous micrite and these, together with the micritisation, make the actual "pigeon-holing" of some allochems difficult. The interstitial peloids are invariably small and probably polygenetic; the preponderance of regularly shaped ovoids of the 0.062 to 0.2 mm size range suggests that many may be faecal pellets, although others are more likely to be micritised grains or parts of grains. Bivalves, preserved as sparite pseudomorphs with micrite-envelopes, are invariably the dominant skeletal group but echinoderm fragments (mostly spines) are also present. The bioclasts are always "bimodal" and in some cases can be very large (8.3mm).

<u>Matrix</u>: The matrix is principally sparite, which in TQ BCla appears to have been crystallised in two phases, a spasmodic, poorly-developed acicular rim-cement pre-dating on infilling blocky sparite. No similar development has been seen in any other slice. The uneven grain distribution results in some "grainstone" patches, but usually where there is a greater quantity of interstitial allochems there is more abundant micrite.

IV.3E.e.ii <u>Lithofacies B</u>: This lithofacies, composed of skeletal pelsparites, (Figs. 4.64 and 4.68), is very similar to those capping the Market Overton (Lithofacies B) and Thistleton beds' (Lithofacies C) rhythms. The rocks are well sorted with only a few larger grains scattered randomly within the dominant finer grained peloids and bioclasts Larger skeletal grains (mostly bivalves), oncolites and to a lesser extent intraclasts constitute the larger suite of allochems. The dominant peloids, although usually circular to ovoid in outline, vary in shape, reflecting their different origins; both faecal pellets and micritised grains (some incipient ooliths) are probably represented. Bivalves are the commonest bioclasts but echinoderm fragments, ostracods, foraminifera and gastropods are also seen. The oncolites, rimmed with amorphous micrite, are rare but conspicuous because of their size; skeletal fragments, partially micritised ooliths and "micrite-lumps" all act as cores. Rarer large intraclasts, silt grade quartz grains and asymmetric ooliths are occasionally present. Although predominantly sparite the matrix contains some micrite, which in places, occurs in concentrated discrete masses, a result of bioturbation.

<u>Subfacies B1</u>: This subfacies shows most of the features typical of analogous subfacies in the Market Overton and Thistleton beds. Parallel and inclined laminations of various compositions are the principal feature although these maybe cut through by vertical or subvertical, sometimes branching, burrows (Fig. 4.61), or completely obliterated by bioturbation (Fig. 4.69). The main lamination types are:

(1) Alternations of peloidal limestone, which although clearly picked out by differential weathering, are not readily seen in peels. The only real compositional difference appears to be in micrite content, although occasionally bioclasts occur preferentially in alternate laminae. Usually these laminations are only 1 mm thick but they can be 2 mm.

(2) Alternating yellowish peloidal/bioclastic and white micritic laminae are readily distinguished on both weathered surfaces (Fig. 4.69) and in peels (Fig. 4.70). The micritic laminae, of 0.3 to 3 mm thickness, contain few allochems, occasional bioclasts are seen and in some cases the micrite is riddled with tiny sparitic spheres (diameter 0.04 to 0.1 mm), which might be the remnants of algae or other organic matter. In contrast the peloidal, sparite-cemented laminae, containing bioclasts of bivalves, echinoderms and ostracods, some of which are coated, are grain supported, with little original micrite in the matrix; these range from 0.3 to 2.5 mm in thickness, although most laminae of both compositions tend to be closer to 1 mm thickness. A little minor scouring sometimes occurs at the base of the peloidal laminae but otherwise the contacts are ill-defined. The bioclasts are usually preferentially aligned parallel to the bedding even where they occur in the more micritic laminae.

In addition to the various laminations, white micritic "micro-beds" up to 20 mm thick also occur. Bioturbation sometimes mixes the micrite with the underlying peloidal levels (Fig. 4.63). At Woolfox one such bed shows very faint lamination in that impersistent rows of brown peloids mark the white rock. These micritic beds are also cut through by vertical burrows.

Subfacies B2: At Stainby rare white peloidal and micritic limestone flakes occur, which are 6 - 12 mm long and approximately 1 mm thick. It is possible that they are dessication flakes derived from the laminations of like-composition seen at this level, although no supporting evidence has been found anywhere else in this unit.

IV.3F. GREETHAM FOSSIL BEDS

IV.3F. a. Introduction.

The Greetham Fossil beds form a thin lensoidal unit, which is only seen in three quarries (Greetham, SK 933146; Thistleton SK 903180; and

South Witham, SK 917189) in south Lincolnshire. Greetham was chosen as the type section because it is the thickest (0.76 metres) and most easily defined sequence. The two typical lithofacies of the unit, a fossiliferous calcilutite and a burrowed ooid-calcarenite, are seen there.

IV.3F.b. Former Terminology

The Greetham Fossil beds probably correspond to the *Pholadomya* Bed of Hollingworth and Taylor (1951) as the stratigraphical position (Fig. 4.46) and faunal composition of the two units are very similar.

It is important to note here that Kent (1966, p.65) mis-interpreted the position of the *Pholadomya* Bed believing it to occur ".......at the top of the Cementstones". This cannot be the case; the strata included within the Cementstones of Kent (1966) and considered similar to the Kirton Cementstones by Hollingworth and Taylor (1951, p.18) occur between the *Pholadomya* Bed and Crossi Beds in south Lincolnshire (Fig.4.46). This indicates that the *Pholadomya* Bed is present at the base rather than the top of the Cementstones (Kent, 1966, fig.1). The Greetham Fossil beds are therefore more correctly associated with the Little Ponton - *Nerinea* (Pisolite) Beds than the Cementstones of Kent (1966).

Elsewhere the Greetham Fossil beds have been apparently included within the *Nerinea* Beds (Richardson, 1939a? and 1939b), the Little Ponton Beds (Kent, 1940), and the Oolites (Swinnerton and Kent, 1976).

IV.3F.c. Geographical and Geological Extent.

At Greetham and Thistleton the Greetham Fossil beds rest upon the hardground, capping the South Witham beds. However at South Witham no hardground exists at that level, although extensive burrowing in the top of the South Witham beds indicates a period of reduced, if not arrested, sedimentation. The upper contact of the fossil beds is less well known because it is only clearly seen at Greetham, where the Woolfox beds cut sharply into the Fossil beds, almost completely removing them in the south-eastern corner of the quarry (Fig.4.47).

The rather limited geographical occurrence of the Greetham Fossil beds may therefore be attributed to:

(1) later erosive removal by the Woolfox beds (Fig.4.47), or

(2) non-development due to the absence of a prolonged break in sedimentation for the development of a hardground and/or colonisation by a prolific fauna.

The Greetham Fossil beds may exist outside of the study area, for Hollingworth and Taylor (1951) recorded the Pholadomya Bed in the Exton district (SK 925113) south of Greetham. Even in this area though the fossil beds are sometimes absent (e.g. at Woolfox, SK 951136; because of erosion ?) indicating that this extended southerly development is by no means widespread.

IV.3F.d. Description of the lithologies

The thin Greetham Fossil beds have two distinct lithologies, which have a sharply transitional contact:

IV.3F.d.i. Lithology A (lower): This is a white, highly fossiliferous calcilutite (biopelmicrite), which contains rare ooids. The fine-grained sediment, containing a prolific and diverse fauna (see section IV.3F.e.) is also heavily bioturbated and burrowed.

IV.3F.d.ii. Lithology B (upper): The overlying beds are poorly fossiliferous. They are honey-yellow, burrowed ooid-calcarenites. The poorly-sorted grains, set in the micritic matrix, are principally ooids with subsidiary skeletal grains, peloids and possibly rare intraclasts. This lithofacies (and included burrows, mostly seen as grey, micritic streaks) is very similar to Lithofacies A of the Greetwell Member in central Lincolnshire.

IV.3F.e. Fauna

The spectacularly abundant and diverse fauna of the Greetham Fossil beds is restricted to Lithofacies A, the overlying beds of Lithofacies B are practically barren of body fossils, although they are extensively burrowed.

Figure 4.71 outlines the probable ecological niches occupied by the commoner species of the Fossil beds' fauna at Greetham, where the unit caps a hardground, encrusted by oysters and Chomatoseris sp.. The fossils, often in situ, are randomly and prolifically scattered throughout the beds; if any distributional pattern is discernible, it is that the burrowing bivalves, particularly Pholadomya, appear to be more common in bed BD1 than BD2, where "Nerinea"spp. dominate. In addition to the species listed in figure 4.71, worm tubes and "algal tube" colonies are also common and extensive burrowing and bioturbation has affected the beds.

At Thistleton, the Fossil beds are largely inaccessible and little collecting has therefore been possible. However, the oyster encrusted hardground appears to be developed there too and Pholadomya fidicula J. Sowerby, in life position, Pinna sp. and terebratulids have been seen. In contrast no hardground has been recognised at South Witham, where a Pinna cuneata - "Nerinea" spp. association dominates the biotope. However in all localities the lack of significant breakage in the other forms suggest that the fauna is largely indigenous to the Fossil beds.

IV.3G. WOOLFOX BEDS

IV.3G.a. Introduction

The Woolfox beds are "typically" formed of massive oolites. Woolfox (SK 951136) was preferred as the type section because it shows a relatively thick (almost 2 metres) and strikingly coherent development of the unit (Fig. 4.72).

IV.3G.b. Former Terminology

The terminology, which has previously been applied to the horizons occupied by the Woolfox beds is rather confused. It would appear that the Woolfox beds are probably equivalent to the lower part of the "unnamed beds" of Hollingworth and Taylor (1951), which occur between the Pholadomya

Bed and Crossi Beds (Fig.4.46); to part of the Nerinea Beds (? Richardson, 1939a) and the Oolites (Swinnerton and Kent, 1976). Where the Woolfox beds fit into the schemes of Kent (1940 and 1966) is rather less clear. At South Witham (SK 917189) Kent (1940, p.52) included within the Cementstones, approximately 3 metres of white limestone, occurring below the Crossi Beds; all lower beds being classified in the Little Ponton Beds. The Cementstones would therefore be broadly equivalent to the upper part of the "unnamed beds" (Hollingworth and Taylor, 1951) and the Lincoln Member and the upper part of the Woolfox beds of this lithostratigraphy (Fig.4.46.). The remainder of the Woolfox beds is presumably equivalent to the top part of the Little Ponton Beds (Kent, 1940, p.51) in this area. Following similar reasoning it is possible that the lower part of the Cementstones and upper part of the Nerinea Beds of Richardson (1939b) also equate with the Woolfox beds. Certainly Richardson (1939b, pp.466-467) discusses the occurrence of the Cementstones at South Witham at a level approximately akin to that of the Woolfox beds.

IV.3G.c. Geographical and Geological Extent.

The Woolfox beds, consistently overlain by the Lincoln Member, rest upon the South Witham or Greetham Fossil beds (Fig.2.2.). Erosion by the Woolfox beds is thought to have removed the Greetham Fossil beds from many areas, for instance at Greetham (SK 933146; Fig.4.47.) and only at South Witham has an erosive contact between the two units not been proven. Elsewhere the Woolfox beds also sharply truncate the South Witham beds (Fig.4.72 and 4.73.).

Although the relationship of the Woolfox unit with beds further north is unclear because of exposure failure in the Grantham

-Ancaster region, the general stratigraphical evidence suggests that the Woolfox beds are laterally equivalent to the Leadenham Member (Fig.2.2.). However at Ancaster (SK 997444), where the Leadenham and Greetwell Members interfinger, the lithofacies of the Greetwell Member are of the central Lincolnshire type, implying that the lateral contact between the central and south Lincolnshire facies of the Greetwell Member occurs within the "hidden zone" (Grantham-Ancaster), most probably around the Grantham area. There is no direct contact between the Woolfox beds and the Leadenham Member.

In other directions the lateral relationships of the Woolfox beds are equally enigmatic: the unit is seen in quarries at the western, southern and eastern limits of the study area/exposure, suggesting that the Woolfox beds originally extended beyond these limits. No firmer conclusions can be drawn because of the erratic thickness pattern displayed by the beds (Fig.4.1.).

IV.3G.d. Field descriptions of the lithologies and fauna.

The Woolfox beds have their most typical development at Woolfox, Greetham, Little Bytham (TF 013178) and to a lesser extent at Waltham on the Wolds (SK 815253). The typical lithofacies (A) is a yellow, medium-grained, grain-rich, ooid-calcarenite. The dominant ooids are very subsidiary intraclasts and skeletal grains are cemented by sparite. No sedimentary structureshave been seen.

Fauna: The majority of the fauna (solitary corals, bivalves, gatropods) charecteristically occur in "stringers" or clusters. The bivalves are usually epifaunal types such as oysters, pectinids and modiolids. Rarely sediment-infilled articulated bivalves are seen, although disarticulated but whole valves (often convex-side-uppermost) are more typical. This, together with the "rolled" occurrence of unbroken solitary corals suggests that despite being affected by currents, the fauna has not been transported far. Apparently "in situ" colonial coral clumps, which have been bored by "Lithophaga" and replaced by sparite, also occur. Overall the relative abundance of epifaunal, suspension-feeding organisms, some of which probably have a reasonable degree of mobility (pectinid bivalves) suggests that the substrate was unstable (mobile ooids) and the waters probably turbulent to maintain a reasonable food supply in suspension. The well washed nature of the ooid substrate points to the winnowing of organic-rich "fines" from the sediment, which would prohibit deposit feeding.

Elsewhere variations occur. At South Witham there is an "anomalous" sequence, a fine-grained, well-sorted, peloidal calcarenite containing few ooids, passes gradually up into a more typical ooid-calcarenite. The intervening sediments tend to be bimodal, ooid-peloidal calcarenties, which contain some burrows and a quite well-preserved fauna within which Pinna, Cervillia and "Nerinea" are prominent.

At Stainby (SK 910233), upward-decreasing energy conditions are reflected in a progressive decrease in sorting and washing of the sediment resulting in more fines and small grains in the matrix. A similar trend is developed to a greater extent in the thick Sproxton sequence (SK 866253), where the basal "typical Woolfox facies" passes up into heavily burrowed, grain-poor, ooid calcarenites, which have a mostly micritic matrix. (The burrows are like those of the South Witham beds' ooid-calcarenites.) In turn these beds grade into a fossiliferous calcilutite. Ooids are quite common in the lower half of this bed but practically disppear higher up. In contrast with the unit's more usual fauna, this bed has an abundant and largely indigenous fauna: Pholadomya in life position, "Nerinea", (?) algal tube colonies, bivalves and gastropods all occur well preserved. Capping the Sproxton sequence is a limestone, which is impersistently developed within the marly clay separating the Woolfox beds' limestones and the Lincoln Member. An identical bed is also seen at South Witham and more rarely at Woolfox. The limestone is a "dirty" ooid-calcarenite; however it is the prolific fauna at the top of the bed that makes it so significant. Although both the subsidiary gastropods and dominant epifaunal bivalves are whole the bivalves are all disarticulated and preferentially orientated "convex-up". In places a bared surface of this bed resembles a mat of Camptonectes sp. (? laminatus) and Modiolus sp. valves, suggesting that gentle currents have disarticulated and concentrated these shells into coquinas without notable transportation as breakage and wear are not very evident. This bed forms another valuable correlative marker with the Thecosmilia-rich base of the Lincoln Member in south Lincolnshire.

IV.3G.e. Laboratory descriptions of the lithologies.

The principal features of the typical Woolfox beds lithofacies (an oosparite; Fig.4.74.), are outlined in figure 4.75. At Woolfox, the dominant ooliths are quite variable in size, and range in shape from spherical to ovoid. Although mostly "normal" in type, superficial and rarer composite ooliths are seen; skeletal or micritic (micritised ?) fragments generally form the nuclei but in many ooliths the cores are indeterminate. Micritisation has obscured the internal structure of some grains, which are nevertheless recognisable as ooliths because of their size, shape and the occassional patches of remnant internal structure. The skeletal grains, although often large, are not quantitatively significant. Bivalves, preserved as sparite pseudomorphs with micrite-envelopes, are the most common type. Rare, large, composite intraclasts are also seen. The poorly-sorted allochems are set in a clean sparitic cement, which crystallised in two distinct phases; a poorly-developed acicular rim-cement pre-dating a blocky type of sparite. However the two generations of cementation are not ubiquitous, for only a blocky cement is seen at Greetham and Waltham on the Wolds.

At Waltham the exposed portion of the Woolfox beds is composed of skeletal oosparite (Fig.4.76) which is texturally a grainstone and generally quite similar to the typical lithofacies, although bioclasts are more important in the Waltham rocks. A number of larger intraclastic and oncolitic grains (1.0 to 2.1 mm.) and rare peloids also occur. However, of far greater significance is the nature of some of the ooliths. which in addition to a more clearly defined concentric structure, have a distinct radial fabric. This is picked out by radiating, discrete, "columns" of included-micrite (Fig.4.76.). The importance of this radial structure in the ooliths' make-up is emphasised by some of the grains actually being broken along it; these fragmented ooliths have been re-coated to form "secondary" ooliths (Fig.4.77.). The significance of these ooliths and their breakage is discussed in Chapter V.

IV.4. LEADENHAM MEMBER.

IV.4.a. Introduction

The Leadenham Member, composed of fossiliferous, chalky-white calcilutites, is arguably the most distinctive and easily traced unit within the entire Lincolnshire Limestone Formation. The type section at Howard's Quarry (SK 962523), near Leadenham, exposes a thick (a little over 3 metres) and typical sequence with a clearly defined top and base (Fig.4.78.).

In the quarries between Lincoln and Metheringham (Fig.2.1.) the Leadenham Member includes a thin sequence of more argillaceous limestones and alternating shales, the Cathedral Beds (Fig.4.1.). The full details of this formalised sub-division are discussed in a later section (IV.4A).

IV.4.b. Former Terminology.

Despite the distinctiveness of its lithologies, the Leadenham Member has not previously been recognised as a separate unit but appears to have formed the lower part of the Cementstones (Kent, 1940 and 1966; and Swinnerton and Kent, 1976), the Kirton Beds (Richardson, 1940) and Kirton Cementstones with *Acanthothiris crossi* (Wilson, 1948). The bases of the Leadenham Member and these earlier "Cementstones" are probably co-incident because the typical Cementstones facies contrasts sharply with the lithologies of the underlying beds in the Lincoln-Ancaster region, forming a natural stratigraphic divide (Fig.4.1.). However, compared to the Leadenham Member the thickness of the "Cementstones" (see for example Kent, 1940, p.55), means that they must have included younger beds, which have been attributed to the Cathedral Beds and/or Lincoln Member/Ropsley Beds here (Fig.2.2.).

The relationship between the Leadenham Member and the Cementstones of Richardson (1939b) and Kirton Cementstones of Evans (1952) is not so straightforward. The occurrence of the "Cementstones" at Little Ponton (SK 930230) and Copper Hill, Ancaster (SK 979427; formerly Newton and Scott's Quarry) cited by Richardson

(1939b, pp.466-467) are almost certainly records of the Ropsley Beds (and associated parts of the Lincoln Member, Fig.4.1.) while at South Witham (SK 917189) the "Cementstone facies" is developed across the Lincoln Member - Woolfox beds junction (Fig.4.46). Therefore the south Lincolnshire Cementstones of Richardson (1939b) are in no way equivalent to the Leadenham Member; nor indeed are any of the "Cementstones" (of all previous stratigraphies), that occur south of Ancaster (see especially Kent, 1966).

The Leadenham Member is not precisely equivalent to the Kirton Cementstones of Evans (1952) either, although in this case the relationships are rather more complex. Evans (1952) does not appear to have defined his Kirton Cementstones in a consistent manner across the central Lincolnshire area, and therefore the exact relationship of his unit to the stratigraphy proposed here varies accordingly. For example at Greetwell (TF 003721) the Kirton Cementstones embrace the Leadenham Member and Cathedral Beds, but at Leadenham itself the Kirton Cementstones include the Leadenham Member and much (all ?) of the overlying Lincoln Member and Ropsley Beds as well (fig. 4.79.). Although not exposed when he completed his work, the top of the Kirton Cementstones projected by Evans (1952, Fig.3.) would probably approximate to the base of the Scottlethorpe Member of this stratigraphy (Fig.4.79.). Therefore it would appear that Evans (1952) drew the base of his Kirton Cementstones at more or less the same level as the Leadenham Member and "Cementstones" of earlier workers (Kent, 1940, and 1966; Richardson 1940; and Wilson, 1948). However, the top of his unit can be demonstrated to coincide with at least two different horizons; the base of the Lincoln Member at Greetwell and the base of the

Scottlethorpe Member at Leadenham (Fig.4.79). The Kirton Cementstones of Evans (1952) therefore completely cut across the known stratigraphical divisions of central Lincolnshire.

IV.4.c. Geographical and Geological Extent.

The Leadenham Member has a relatively restricted N-S distribution from Lincoln to Ancaster (Fig.4.1.), where its interdigitation with the Greetwell Member (seen in railway cutting, SK 997444) suggests that its original depositional limit did not lie much further south. Furthermore, as the unit is not represented at either Ropsley (TF 002364) or Little Ponton, a little to the south, the member must have "died out" between these localities and Ancaster. Although the relatively restricted outcrop to the east and west prevents this "natural" southern margin being traced northwards, figure 4.80 summarises the probable depositional trends indicated by the available data.

In the series of outcrops between Lincoln and Metheringham (Fig.2.1.), the Leadenham Member, which overlies the Greetwell Member, is succeeded by the Cathedral Beds. However, westwards and south-westwards from this area the Cathedral Beds are cut out by the Lincoln Member, which comes to rest directly upon the Leadenham Member (Fig.2.2.).

IV.4.d. Field descriptions of the lithologies.

The typical Leadenham Member has a series of pure, chalky-white calcilutites (Lithofacies A), interrupted by a single more resistant ooid-calcarenite, with a bioclastic-rich base (Lithofacies B). Lithofacies B is not developed at Metheringham (TF 053616), where there is an anomalously thin Leadenham Member succession, or at Ancaster (Railway Cutting), where its place is taken by an interdigitation of the Greetwell Member. However, this interdigitation and Lithofacies B are probably genetically related (Chapter V).

IV.4.d.i. Lithofacies A: This is the dominant and characteristic facies of the Leadenham Member. Thinly-bedded, chalky-white, fossiliferous calcilutites are interleaved with brown clay or marl partings, which are often well laminated. Occasionally the partings are black and more organic-rich. The limestone beds vary in thickness from approximately 0.1 to 0.4 metres, although they are usually about 0.15 metres. Allochems are rare except for skeletal fragments (and fossils); only a few brown ooids and oncolites are seen, although peloids may constitute part of the matrix in places. The molluscan dominated fauna is often prolific and contains many *in situ* forms (Fig.4.81.; see section IV.4.f.). Bioturbation and burrowing are rife and the lowest beds (below Lithofacies B) are characteristically riddled with *Chondrites* sp. and *Zoophycos* sp. traces (Fig.4.82). Within these beds, small lenses of bioclastic and peloid-rich fine calcarenites, with gently scoured bases occur. These are usually a few tens of millimetres long and 5-10 mm. thick. Their significance is discussed in Chapter V.

Although this facies is widespread, minor variations, mostly in the content and composition of the allochems, occur. For example, at Harmston (SK 992619) the more creamy-coloured, blue-hearted calcilutites are typified by brown "algal tube modules". However, such variations are mostly slight and the rocks are readily identified as belonging to the characteristic lithofacies.

IV.4.d.ii. Lithofacies B: This variant usually occurs as an individual, rather thicker bed (usually 0.6 metres) low down in the Leadenham Member sequence. The creamy-yellow weathering, but blue-hearted bed generally has a distinctive basal layer (up to 75 mm. thick) of skeletal calcirudite. Bivalves, gastropods and worm tubes are particularly prominent components of this grain-supported layer, which at Dunston (TF 053634) has large Thalassinoides sp. networks covering its base. Above this, the bed becomes more of an ooid-calcarenite, with brown ooids, oncolites, skeletal fragments and peloids occurring in the rather poorly-sorted deposit. The percentage of grains, never especially high, decreases up the bed as the lithology grades into a calcilutite. The calcarenite does not appear to be grain supported. Some of the bivalves, noticeably Pinna sp., that were invariably in life position in Lithofacies A, are "uprooted" (although articulated) in this bed; they lie parallel to the bedding. Burrows are ubiquitous.

Variations within this facies (B) generally centre upon the bioclastic basal layer. For example, at Leadenham, the basal portion is an independent bed (0.23 metres thick), composed of a fine-grained calcarenite. No bioclastic basal layer has been recorded at either Greetwell or Branston (TF 023671).

IV.4.e. Laboratory descriptions of the lithologies

The principal feature of the lithofacies of the Leadenham Member are outlined in figure 4.83.

IV.4.e.i. Lithofacies A: This is essentially a biomicrite facies (Fig.4.84) which varies texturally from (dominant) wackestones to mudstone. However, within the biomicrites a number of biopelsparite packstone lenses occur (Fig.4.85).

The biomicrites have dominant bivalve and gastropod (often whole) skeletal elements and subsidiary fragments of echinoderms (spines, plates and ossicles), foraminifera, terebratulids, Bryozoa, worm tubes, especially Serpula (Tetraserpula) tetragona (Sowerby), and ostracods. Preservation is variable; essentially the calcitic skeletons have survived unaltered but the aragonitic tests have been replaced by secondary sparite. Many of the bivalves have micrite-envelopes and most foraminiferal tests have been completely micritised.

Non-skeletal allochems are rare; only silt grains and peloids have been recorded. The size and ovoid shape of the peloids suggest that they are probably faecal pellets. The matrix of the rock is invariably micrite.

Variations in this biomicrite lithology do occur. For example, bed C6 in the Dean and Chapter Pit, Lincoln (SK 977735) is practically devoid of skeletal allochems but has abundant silt grains and subsidiary mica and wood flakes (Quartzose micrite). The silt is concentrated into certain areas, which may be burrows or "reflections" of bioturbation. At Harmston, large (10 x 2 mm.), crudely concentrically laminated oncolites dominate the rock (oncolitic biomicrite). These have diverse but predominantly skeletal nuclei. No algal tubules have been seen in the micritic coatings.

In contrast to the grain-poor biomicrites, the pelsparite lenses are allochem-rich. The skeletal debris is compositionally similar to that of the biomicrites and the faecal pellets are much more abundant. There appear to be two distinct generations of sparite cement; the earliest forms non-ferroan calcite (often acicular) syntaxial rims to many skeletal grains, while the later, more blocky ferroan calcite cement, infills the remaining pore space. The scour bases and general ill-sorted jumble of grains suggest that these lenses are the result of minor storms or disturbances.

IV.4.e.ii.Lithofacies B: Although this facies encompasses the whole of the bed, which interrupts the "normal" Leadenham Member sedimentation, it is the basal skeletal calcarenite layer that is particularly significant. Like the biopelsparite lenses in Lithofacies A, this bioclastic layer is thought to be the product of a storm, which, in this case, was quite an important event as it affected deposition over a wide area. The remainder of the bed, presumably reflecting the restabilisation of conditions, is much more akin to "normal" Lithofacies A sediments, although it tends to be much more grain-rich.

The basal layer is a poorly-washed biosparite (Fig.4.86.). The diverse skeletal allochems are large and ill-sorted, although there is a tendency for the elongate grains to align themselves parallel to the bedding. The preservation and type of bioclast is similar to that in Lithofacies A although the grains are much more fragmented. This probably reflects the difference between the mechanical degradation suffered during storm transportation and the biological breakdown affected in the lagoonal environment of Lithofacies A. In addition, compactional stress has fractured even quite robust fragments like worm tubes. Many of the skeletal grains have micrite rims, some of which are probably micrite-envelopes although others are algal accretionary coats, i.e. oncolites. This is clearly seen in some grains where the micrite coat encloses foraminiferal tests and silt grains (Fig.4.87). Intraclasts, silt grains and rare peloids make up the rest of the rock's grains. At Coleby, (SK 981600) the rock is a packstone, with about equal amounts of sparite and micrite. However, elsewhere the micrite appears to be dominant and the rock is not always grain supported. For instance, at Leadenham the abundant skeletal grains are much smaller, more perfectly aligned parallel to the bedding and set in a micritic matrix.

The overlying bed has a variable composition ranging from oncolite or quartzose biomicrite to quartzose biopelmicrite. The rocks of this level generally have varying amounts of oncolites (ooliths), skeletal grains, peloids and silt grains and are texturally wackestones. They reflect the transitional period between the storm and resumption of typical lagoonal sedimentation conditions.

IV.4.f. Fauna.

The molluscan-dominated fauna of the Leadenham Member is characterised by colonies of semi-infaunal Pinna cuneata Phillips. This, together with Pholadomya lirata (J.Sowerby), Pleuromya uniformis (J.Sowerby), Natica adducta Phillips, and Astarte minima Phillips, forms the nucleus of a diverse, benthonic biotope (Fig.4.88.), which is believed to be endemic to the lagoonal environment, represented by the member's Lithofacies A, for a number of reasons:

(1) The infaunal and semi-infaunal species P.cuneata, P.lirata, P.uniformis and Gresslya abducta (Phillips) are invariably found in life position.

(2) The valves of the disarticulated bivalves are whole and randomly orientated. Disarticulation appears to be confined to epifaunal and some shallow infaunal species.

(3) Few "forms" show any sign of wear or breakage.

(4) The fauna shows no sign of size sorting.

(5) If not in situ, the faunal elements have a random distribution within the individual beds.

(6) The general sedimentological setting suggests that significant transportation of the fauna is unlikely to have occurred.

Although the litholical uniformity of Lithofacies A suggests that similar substrate conditions existed throughout Leadenham Member times, the fauna shows some important differences. The basal beds, below the Lithofacies B storm level, were intensively burrowed, with Chondrites sp. and Zoophycos sp. particularly prominent. Rarely was the "typical" molluscan fauna (or any body fossils) developed at this level, where the slow deposition of nutrient-rich, fine-grained lime mud must have been particularly conducive to the various soft-bodied deposit feeders, which produced the trace fossils. Having rapidly colonised the substrate of the nascent lagoon, the burrowing/feeding activity of these forms apparently made the sediment surface too "soupy" for it to be successfully colonised by the molluscan spat. The "infantile" molluscs presumably perished by "burial-suffocation" or by actually being ingested by the indigenous fauna, in what appears to be a perfect example of the trophic group amensalism concept of Rhoads and Young (1970). It was not until after the deposition of the storm bed, that the molluscan fauna became widely established and the dominance of the deposit feeders weakened. However Chondrites and other burrows remained quite common in these higher beds.

The molluscan fauna is an excellent example of a "time-averaged community" (Walker and Bambach, 1971). These workers pointed out the discrepancy between the life-span of most benthonic invertebrates and the time taken for the deposition of the enclosing bed. As the latter is so much larger than the former, the fauna of each bed must encompass a number of successive populations (each representing a seasonal or annual recruitment) and the related series of communities, whose structure will fluctuate (through time) with the seasonal/annual oscillations in the fortunes of its component species. Because of this, the total fauna of each bed represents the "time-averaged community" of that substrate; i.e. the sum of the various communities that may have existed at different times during the deposition of the bed. The seasonal fluctuations in recruitment/mortality, which would have modified the community structure at any one time are "levelled out" through time, and we see the "average community" for the time-span, represented by that bed. Such a succession of populations (and its effect on the community structure) can be well illustrated by reference to the semi-infaunal P.cuneata colonies. Within a single bed the posterior margins of the individual Pinna can be seen to be at a number of different levels, which must, because of the bivalve's mode of life (Fig.4.89.) correspond to different levels of the sediment-water interface. A number of populations must therefore be represented by the Pinna of each bed, as each sediment/water interface level would have its own population (Fig.4.89.). This too is a simplification as each calcilutite bed would have gradually accumulated with a continuously varying sediment-water interface level.

The presence of a soft substrate in the lagoon is clearly indicated by the predominance of infaunal bivalve species, although the reasonably common epifauna, suggests that holdfasts must also have been available (Fig.4.90.). It would seem likely that algae provided attachment for the high-level byssate dwellers (Parallelodon ?) while the abundant shell debris could have supported forms like the solitary coral and low-level byssate dwellers, some of which may have lived "free" in adulthood (Plagiostoma ?). Certainly there seems little evidence to suggest that the substrate was ever firm enough to provide suitable attachment for such species - a factor that may be responsible for the scarcity of brachiopods, as terebratulids are abundnant in the almost identical lithofacies of the Ropsley Beds (see IV.5A.f.), where infaunal bivalves are scarce, suggesting the presence of a rather firmer "bottom". Salinity does not appear to be important as other stenohaline groups (corals and echinoids) are present in the Leadenham Member (Fig.4.88.), although few in number. Turbidity, another possible control seems equally unlikely because of the abundance of other suspension feeders - unless the brachiopods were less able to cope with the conditions than the bivalves and corals. The findings of Fursich and Hurst (1974) do not seem to favour such a case, and therefore a soft substrate seems the probable reason for the scarcity of brachiopods.

The Leadenham Member seems to have represented a reasonably predictable, nutrient-rich environment if the diversity and composition of the fauna are considered. Food was exploited from within the sediment by deposit-feeders like Chondrites, from the surface of the sediment (by the gastropods ?) and from the over lying water mass by the prolific suspension feeders; a mixed fedding structure (Fig.4.90.). However, the abundance of suspension feeders suggests an element of competition that seems out of place in this biologically-accommodated assemblage (Sanders, 1968). On closer inspection though the competition may not be as important as it first appears, for a number of reasons:

(1) Only a few of the suspension feeders are important in terms of the biomass of the whole assemblage; these are P.cuneata, P.lirata and P.uniformis.

(2) Of these, P.cuneata, the dominant form, would have taken

its food from a level some way above the sediment/water interface and would therefore have been exploiting a different feeding level than P.lirata and P.uniformis (Walker, 1972). The latter two species would have taken their food from near the sediment/water interface.

(3) The next most abundant forms in the assemblage (in terms of biomass) after the three bivalves, would have probably been the deposit-feeding Chondrites and the carniverous (?) Natica sp.; neither would have been in direct competition with the suspension feeders, suggesting a fairly balanced trophic structure, where the trophic nucleus of the assemblage (Neyman, 1967) was probably composed of species essentially taking their food from different sources or levels (Walker, 1972).

(4) Competition amongst the suspension feeders may also have been reduced by the utilisation of different sized food particles, or different foods, or, in the case of the near-sediment surface feeders, by taking food re-suspended from the sediment (Marshall, 1970). As the diverse suspension feeders, other than P.cuneata, P.lirata, and P.uniformis, were probably insignificant in terms of the biomass of the assemblage, the problem of their "call" on the available food resources would be unimportant, especially if there was a plentiful supply of suspended food matter. The qualitative assessment of the "community structure" would seem to be supported from preliminary quantitative studies.

Overall the diverse benthonic fauna would suggest reasonably nutrient-rich waters of marine (or very close) salinities, overlying a soft, nutrient-rich substrate. This, together with the sedimentological conditions and restricted geographical distribution of the lithofacies indicates a genuine lagoonal setting.

IV.4.g. The use of *Pinna cuneata* Phillips as a palaeocurrent indicator.

During the course of collecting from the Leadenham Member, it was noticed that whenever in clusters, the *in situ* *P.cuneata* specimens seemed to have their dorso-ventral axes aligned (Fig.4.91. ; see also Davies, 1970). A more systematic survey was therefore undertaken in order to test this observation. The methods employed are discussed in Appendix 4 and the "raw" data on which the results were based is tabulated in Appendix 5. Essentially the orientation of the dorso-ventral axes of the bivalves were measured with respect to magnetic north (Fig.4.91.) and the "lineations" plotted on a rose diagram. A "lineation" rather than a "vector" was recorded because the preservation of the *P.cuneata* often made it impossible to determine the dorsal from ventral margin of the organism (see Appendix 4 for details).

IV.4.g.i. Thesis: If a group of organisms show a preferred orientation it is likely to have been of some benefit to them. In this case, where there might be a parallel alignment of the "long" dorso-ventral axes of the sedentary bivalve, the most obvious advantage would be to offset the frictional effects of the prevailing water currents by utilising the bivalves' streamlined form (Fig.4.92.). Secondly, such an alignment "with the current" would benefit the feeding and excretionary activities of the bivalves (Fig.4.92.). This would be the case even if the dorsal margins (of all the bivalves in any one collection) did not consistently "face" in the same direction, for it is likely that the inhalent current would be stopped during the ejection of faeces (Yonge, 1953). The actual position of the exhalent "compartment" upstream would not therefore be as disadvantageous as it might appear.

IV.4.g.ii.Value of the technique: If the *P.cuneata* were shown to be preferentially orientated in response to current activity, they could be used to monitor the presence and alignment of the "currents" in any environment, that might not reflect any current activity sedimentologically. The *P.cuneata* would be biological palaeocurrent indicators.

It is obvious from the general sedimentological setting that strong currents were not present in the Leadenham lagoon. However, this does not necessarily indicate their total absence; wind induced currents may have existed. Alternatively, the results of tidal action, sedimentologically recorded in the tidal channels and deltas, may have had an influence on the lagoons, if only to re-suspend the fine sediment, which is the result of the predominantly quiet-water setting. These currents may have affected the lagoon's biota without leaving any trace in the sedimentological record. Therefore a potential exists whereby such biological current indicators might be able to refine and modify the understanding of the palaeogeography of the time, which had been elucidated from sedimentological criteria; an example of new palaeontological data could be used to go beyond the limits of sedimentological data in assessing the palaeoenvironment.

IV.4.g.iii.Data: The rose diagrams for the *P.cuneata* "lineations", collected from various beds at Leadenham, Coleby, Dunston and Greetwell are shown in figure 4.93 together with the isopachyte of the Leadenham Member. There is much variability in the orientation of the *P.cuneata*, and in the relationship of these orientations to the presumed "palaeogeography" of the lagoon. Although some of the rose diagrams suggest a preferred orientation exists, none were confirmed when the data was subjected to Rayleigh's test of uniformity (Appendix 4).

IV.4.g.iv.Conclusions: Although rather inconclusive, the results could be taken, from a negative point of view, to indicate the absence of significant current activity within the Leadenham lagoon. However, the method is still considered valid and as some of the data gives a positive result (i.e. a preferred orientation; see Appendix 4) it might be that larger collections are needed to resolve the problem.

IV.4.h. Discussion.

Although the Kirton Cementstones of South Humderside and the "Cementstones" of the Lincoln - Ancaster region have traditionally been grouped together, they have, in their modified form, been classified separately; the Leadenham Member is correlated with Unit E of the Kirton Cementstones Member (Ashton, 1975; Unit F is thought to be equivalent to the Lincoln Member, Fig.2.2.). Unit E and the Leadenham Member are very similar in that both are composed of alternating limestones and shales. However, in detail they show a number of differences. For example, in Unit E the shales are more prominent than they are in the Leadenham Member, comprising approximately 50% of the Kirton sequence; the limestones are more argillaceous than those of the Leadenham Member and more nodular, not even forming continuous beds in places. Overall therefore there seems to have been a greater clastic influence in Unit E than in the Leadenham Member further south, where a very pure "carbonate regime" flourished. Faunally too there are distinct dissimilarities; the prolific molluscan fauna of the Leadenham Member is not seen at Kirton, where only a single Pleuromya sp. has been recorded from the limestones, although abundant <u>Catinula</u> sp. crowd the shales and <u>Chondrites</u> sp. occur profusely at the limestone/shale contacts. Such a low diversity oyster-rich biota suggests that the Kirton Cementstones Member (Unit E) may have been deposited in more brackish waters (Chapter V). These differences plus the stratigraphical uncertainties raised by the geographical isolation of the Kirton sections have influenced the choice of separate unit names for the "cementstone-facies" of South Humberside and central Lincolnshire, although the facies are clearly stratigraphical equivalents.

In contrast to this arbitrarily drawn northern stratigraphical boundary, the actual depositional limits of the Leadenham Member can be fairly accurately defined in mid-Lincolnshire. In the railway cutting section at Ancaster, the Greetwell Member facies are seen to interdigitate northwards into the Leadenham Member calcilutites (Fig.4.1.). The base of ARC C3 (this bed definitely belongs in the Greetwell Member) forms a distinct division between the base of the Greetwell Member intercalation and the underlying Leadenham Member, but the upper margin of the interdigitation is rather less easily defined because of the intermediary nature of the lithologies in ARC C4. In its lower part ARC C4 is more ooid-rich than is usual for the Leadenham Member, but in other lithological respects it is quite unlike any Greetwell Member beds. It has therefore been classified in the Leadenham Member although it is transitional in nature (Fig.4.1.). North of Ancaster the interdigitation dies out for at Leadenham, the next most northerly quarry to expose this level, the Leadenham Member sequence is more typical of the central Lincolnshire sequences as a whole. Despite the similarity of the thin beds LQ C6 and ARC C3a, the overlying beds at Leadenham are like the transitional lithologies of

ARC C4 and ought to be included in the Leadenham Member. Therefore, at most, only LQ C6 could represent the northward extension of the Greetwell Member interdigitation. However, as this bed is a fine-grained bioclastic calcarenite, like the basal layer of Lithofacies B of the Leadenham Member, it has here been included in that lithofacies and excluded from the Greetwell Member; the Greetwell Member intercalation is therefore believed to peter out just south of Leadenham. Genetically however, the Lithofacies B level (storm bed of the Leadenham Member) and the Greetwell Member incursion are probably related (Chapter V) and their division has to be on rather arbitrary grounds (in the transitional zone around Leadenham).

IV.4.i. Subdivision of the Leadenham Member.

At the top of the Leadenham Member in the Lincoln-Metheringham area, the alternating limestone/shale regime is significantly modified. The shales become more important and the limestones are more argillaceous; in addition, both lithologies are crowded with skeletal-oncolites. These differences suggest that the beds in question ought to be separated from the main body of the Leadenham Member. However, because of their relatively restricted geographical and geological extent, the beds have been formalised at the "Beds" rather than member level (Hedberg, 1976, p.33, pt.C4). Termed the Cathedral Beds, they are considered a formal subdivision of the Leadenham Member.

IV.4A CATHEDRAL BEDS.

IV.4A.a. Introduction.

The skeletal-oncolite bearing argillaceous limestones and shales of the Cathedral Beds have their stratotype (0.91 metres thick) exposed in the Dean and Chapter Pit, Lincoln (SK 977735; Fig.4.94.).

IV.4A.b. Former Terminology.

These beds have not previously been identified as a separate unit but have been included within the Kirton Beds of Richardson (1940), the Cementstones of Kent (1940 and 1966) and the Kirton Cementstones of Evans (1952). However, Richardson (1940, p.253) may have recognised them as "..... a band of shale full of little mudstone pellets", although it is difficult to evaluate where this band came in the section at Greetwell, Lincoln. Elsewhere Ashton (1975) has included similar oncolite-rich shales in the Kirton Cementstones Member exposed at the Manton Stone Company Quarry (SE 940024), near Kirton in Lindsey. In particular the Cathedral Beds level seems to be approximately equivalent to the topmost shale in Unit E of the Kirton Cementstones Member (Ashton, 1975, fig.3.), although a similar shale band occurs higher up that unit.

IV.4A.c. Geographical and Geological Extent.

The Cathedral Beds occur sandwiched between the Lincoln and Leadenham Members (Fig.2.2.) throughout their traceable extent from Lincoln south-eastwards to Metheringham (TF 053616). Although the unit's present distribution is very restricted, its general relationship with the Leadenham Member suggests that the original extent of the two subdivisions may well have been very similar. Certainly, the westward disappearance of the Cathedral Beds appears to be due to the erosive downcutting of the Lincoln Member rather than non-deposition because "typical" Cathedral Beds' oncolites have been found in the base of the Lincoln Member at Coleby (SK 981600).

Beyond these immediately surrounding areas the close similarity of some of the shales of the Kirton Cementstones Member (Ashton, 1975) to the Cathedral Beds suggest that the unit may have extended much further northwards than its present known limits but the lack of exposures prevent this from being confirmed. In contrast, it is unlikely that the Cathedral Beds were ever deposited south of Leadenham because of the general facies change.

IV.4A.d. <u>Field descriptions of the lithologies and fauna</u>.

The Cathedral Beds usually comprise a series of alternating argillaceous limestones and shales, both of which typically contain skeletal-oncolites. Superficially the limestones and shales may appear similar, grading imperceptibly into one another, so that in places, only the difference in hardness separates the two. However in most cases differential weathering has picked out the different layers.

IV.4A.d.i.<u>Limestones</u>: The oncolitic,argillaceous limestones weather khaki-brown from an original dark grey colour. Large oncolites, bioclastic grains, and rarer wood flakes and quartz grains have a random, but uneven distribution in the rock, resulting in rather poor sorting.

The dominant oncolites, which occur in varying proportions, tend to give the rock a characteristically speckled appearance as their buff-orange weathering (blue when fresh) stands out against the darker hues of the enclosing rock. Although not always recognised in smaller grains, the larger oncolites (up to 13 mm. in diameter) tend to have skeletal nuclei, around which roughly concentric laminae have been accreted to produce irregular grain forms. Amongst this irregularity however there appears to be a preponderance of biscuit-shaped grains. In some beds a second suite of more oolith-sized grains occur, but these are probably "incipient" oncolites.

Except for rare, whole small gastropods and unbroken but disarticulated bivalve shells, bioclastic grains are the only sign of zoological life. The prolific benthos of the Leadenham Member is completely absent. Bivalves, gastropods, echinoderms and brachiopods are the principal contributors to the skeletal debris.

IV.4A.d.ii.Shales: The well-laminated shales are similarly "speckled" with oncolites, whose buff colour again stands out against the black, fresh shale or pale brown-dirty khaki weathered surface (seen especially well at Washingborough Railway Cutting, TF 019702). Some oncolites appear to have been compacted to form "buff streaks" in the shale, which also has "white patches" of remnant aragonitic shell debris.

IV.4A.e. Laboratory descriptions of the lithologies.

The limestones of the Cathedral Beds are lithologically uniform, being skeletal-oncolite bearing quartzose biomicrites. Texturally they are wackestones, although the rocks' grain content is quite high.

Grains: Oncolites, skeletal and quartz grains are the dominant types present, but rarer, superficial ooliths, peloids, silt-grade flakes of white mica and black wood flakes also occur. The skeletal-oncolites, the most conspicuous grain type, are normally large (0.8 to 7.2 mm.). Most have grown discordantly and asymmetrically around skeletal nuclei (crinoid ossicles, bivalve, gastropod and brachiopod fragments) producing an irregularly shaped but crudely rounded grain (Fig.4.95). Some retain the original shape of the nuclei. Intertwined algal tubules of the "Girvanella" type are clearly seen within the green micritic coatings of the oncolites (Fig.4.96.).

The bioclastic grains are variable in composition, size (0.2 to 3.2 mm.), shape and preservation. Brachiopods, including punctate terebratulids, seem to be the dominant group, although bivalves, gastropods, worm tubes, foraminifera, ostracods, Bryozoa and crinoid ossicles are also present. The calcitic components have largely retained their original composition and structure but the major araganitic groups like bivalves and gastropods have replaced shells; they occur as sparite pseudomorphs. However, both groups may or may not have micrite-envelopes while many of the forams have completely micritised tests. The silt to very fine sand grade detrital quartz grains are largely sub-rounded and are very unevenly distributed.

Matrix: The grains are scattered randomly throughout what appears as a "dirty", finely crystalline matrix. The grains are rarely abundant enough or so closely packed for the rock to be grain-supported, suggesting that the sparite may be a neomorphic replacement; the following lines of evidence seem to support this contention (see Fig. 4.97.):

(1) The spar is largely composed of equidimensional crystals.

(2) Few plane crystal boundaries are present; the individual crystals have "wavy" margins.

(3) NO enfacial triple junctions have been seen.

(4) The crystal size does not increase into the intergranular "voids".

The combination of these characters, the presence of remnant micrite patches and the wackestone texture suggests that the original matrix was micrite. However a few peloids (probably faecal pellets) also occur but as the majority of the remnant micritic areas are structureless, it seems unlikely that they formed a significant proportion of the matrix. No pellet "ghosts" have been seen in the neomorphic spar.

A few areas of much coarser spar exist that may be original cement; the crystal boundaries are mostly planar and some enfacial junctions occur. However, these patches have diffuse margins, where grains have been truncated suggesting that the outline of the (possible) original void has been "blurred" by neomorphic aggradation. Consequently, the true nature of the sparite areas is difficult to determine.

IV.4A.f. Discussion.

The Cathedral Beds contrast strikingly with the underlying fossiliferous calcilutites of the Leadenham Member. The principal differences between the two units are:

(1) the Cathedral Beds have a greater clastic content, as shown by the increased proportion of shale over limestone and the greater quartz content of the limestones (cf. modal analyses in Appendix 2).

(2) the dominance of skeletal-oncolites in the Cathedral Beds

(3) the absence from the almost barren Cathedral Beds of the rich, molluscan-dominated, benthonic fauna, which is so typical of the Leadenham Member.

Therefore, although the Leadenham Member grades up into the Cathedral Beds, a significant, if subtle, change in the environmental conditions occurred. Essentially a clastic influx reduced the purity of the carbonate sedimentary regime, and destroyed the stable eco-system, which existed in the Leadenham Member lagoon.

IV.5. LINCOLN MEMBER.

IV.5.a. Introduction.

The Lincoln Member, so-called because of its widespread distribution and stratigraphical significance, is composed of ooid-calcarenites and calcilutites. However, the lithological make-up of the member varies widely and as well as distinctive central and south Lincolnshire sequences, two independent subdivisions can also be recognised within the unit; the Ropsley Beds of mid-Lincolnshire and the Little Bytham beds of southern Lincolnshire (Fig.2.2.). These subdivisions are thinly-bedded, white, fossiliferous calcilutites like those of the Leadenham Member.

Although the lithological variability of the member makes the designation of a stratotype difficult, Greetwell Hollow Quarry, Lincoln, (TF 003721) has been chosen because it shows a clearly defined and "typical" sequence (1.85 metres; Fig.4.98.) through the central Lincolnshire facies. In addition, a hypostratotype, Stainby (SK 910233; Fig.4.99.) has been selected to illustrate the south Lincolnshire facies and particularly the member's base (in that area). The Ropsley Beds and Little Bytham beds have their own type sections.

IV.5.b. Former Terminology.

Although stratigraphically the most important new unit to be described, the Lincoln Member, has never previously been recognised as a separate subdivision. It appears to have constituted part or all of the Kirton Beds (Richardson, 1939b and 1940), Cementstones and Crossi Beds (Kent, 1940 and 1966; and Swinnerton and Kent, 1976), Kirton Cementstones with *Acanthothiris crossi* (Wilson, 1948), Kirton Cementstones and *A.crossi* Beds (Evans, 1952), Oolites (Swinnerton and Kent, 1976), Lower Crossi Beds (Kent, 1966; fig.1.) and "unnamed beds with *Pholadomya* Bed near top" (Hollingworth and Taylor, 1951).

Between Lincoln and Metheringham (TF 053616), the Lindsey Shale occurs immediately on top of the member, which encompasses, as its topmost bed, the Lower Crossi Bed of Kent (1966, fig.1.). However, despite the fact that it is always overlain by a massive oolite (e.g. Fig.4.100) the lower boundary of the member occurs within what most authors have termed the Cementstones or Kirton Cementstones. In the Lincoln district therefore the Lincoln Member is equivalent to the upper part of the Cementstones (Kent, 1940 and 1966; and Swinnerton and Kent, 1976), the Lower Crossi Bed (Kent, 1966, fig.1, = Crossi Beds of Kent, 1940), the upper part of the Kirton Cementstones with A.crossi (Wilson, 1948), and the central part of the Kirton Beds of Richardson (1940). At Greetwell, the member includes the lower part of the A.crossi Beds of Evans (1952), although further south it is equivalent to the upper part of his Kirton Cementstones (Fig.4.79.). Evans (1952) apparently recognised the importance of the member's base at Greetwell but missed its significance as a stratigraphical divide for the whole area.

The earlier workers may have missed the importance of the basal oolite of the Lincoln Member because it is sandwiched between two sequences of "Cementstones-facies" rock in mid-Lincolnshire. However, figure 4.1. shows that the upper calcilutite division (Ropsley Beds) is quite separate stratigraphically from the lower (Leadenham Member) and that the oolite is an ever-present divide between the two.

The persistence of the Ropsley Beds southwards beyond the limits of the Leadenham Member seems to have encouraged previous workers to extent their "Cementstones" into mid-Lincolnshire (Richardson, 1939b) and beyond, because of the periodic occurrence of calcilutites in the Lincoln Member of south Lincolnshire. However in south Lincolnshire the Crossi Beds are at a higher level (Scottlethorpe Member of this work) so that the Lincoln Member only includes the "Cementstones" (Kent, 1940 and 1966), the upper part of the Oolites (Swinnerton and Kent, 1976) and the upper part of the "unnamed beds with Pholadomya Bed near top" (Hollingworth and Taylor, 1951).

IV.5.c. Geographical and Geological Extent.

The onset of Lincoln Member times was marked by a widespread event, which similarly affected the differing sedimentary regimes of south and central Lincolnshire. The member therefore overlies a number of stratigraphic units: the Cathedral Beds, Leadenham and Greetwell Members and Woolfox beds (Fig.2.2.). However, regionalised sedimentation soon returned and the unit is succeeded by the limestones of the Scottlethorpe Member in the south and the Lindsey Shale Member in central Lincolnshire. North of Lincoln, Unit F of the Kirton Cementstones Member (Ashton, 1975) is thought to be laterally equivalent to the Lincoln Member, although significant lithological differences differentiate the two units.

Within the confines of the exposed region, the Lincoln Member is ubiquitous and fairly uniform in thickness (including the Ropsley and Little Bytham beds) except for a noticeable thinning in the extreme south. Therefore there is little clue as to the true geographical limits of the unit, although it must extend beyond the present traceable boundaries. The southerly thinning probably only mirrors the overall wedging-out of the formation in that direction.

IV.5.d. Field descriptions of lithologies.

The Lincoln Member is lithologically variable; besides the distinctive Ropsley and Little Bytham calcilutite subdivisions, south and central Lincolnshire also have contrasting facies sequences. However, common to the whole unit is the erosive base and basal ooid-calcarenite bed.

IV.5.d.i. Central Lincolnshire: The type section at Greetwell (Fig. 4.1.) shows a gradational sequence of pale yellow -grey limestones (Fig.4.98.):

(1) The blue-hearted basal, grain-supported ooid-calcarenite (Lithofacies A) contains a wide array of grain types; ooids, bioclasts and oncolites, which are generally poorly sorted. This grey, hard, splintery limestone has a more micrite-rich base.

(2) The grain content of the overlying, buff-coloured ooid-calcarenite (Lithofacies B) generally decreases up the sequence until the rock is little more than a calcilutite with a few scattered ooids, skeletal fragments and fossils. The ooid-calcarenite is speckled with limonitic brown ooids, which tend to occur either randomly or in clusters. The grains are ill-sorted. Skeletal grains increase in importance up the sequence and large, whole bivalves such as Gresslya abducta (Phillips) and Plagiostoma rodburgensis (Whidborne) are also found in the higher, more calcilutitic levels. The whole rock is mud-supported and typified by burrowing systems akin to those developed in the Leadenham Facies of the Greetwell Member, although here the burrows are not seen "open" but tend to be preserved as "grey micritic streaks" in the rock.

(3) The top bed in this area (= the Lower Crossi Bed of Kent, 1966), is characteristically a grey, hard, splintery, blue-hearted ooid-calcarenite (Lithofacies B). Outwardly the bed resembles the basal ooid-calcarenite but it tends to be shellier, with Lucina bellona d'Orbigny, Acanthothiris crossi (J.F. Walker) and Thecosmilia sp. especially prominent, and in detail it is not as grain-rich, falling between Lithofacies A and B in allochem content, although like B it is mud supported.

Although similar sequences characterise the Lincoln Member in central Lincolnshire, variations do occur. At Harmston (SK 992619) the Lincoln Member is almost entirely composed of "clean", skeletal ooid-calcarenites, which reflect a more agitated environment than is normally the case in this member. Towards the top of this sequence however, some micrite infilled burrows and micrite lenses (ripple trough infills) also occur. Away from Harmston, the effects of the increased agitation are progressively lost with the calcilutite part of Lithofacies B becoming more prominent towards Lincoln. In the Dean and Chapter Pit (SK 977734) the calcilutite is developed to its best effect and includes a largely "in situ" fauna, together with a rich biostrome. Except at Harmston, Lithofacies A and B are consistently developed between Metheringham and Lincoln.

Southwards from Harmston, a pronounced facies-sequence change occurs. In the Leadenham-Ancaster-Little Ponton-Ropsley region (Fig.2.1.) Lithofacies A rapidly grades through the burrows ooid-calcarenite facies of Lithofacies B into the pure "lagoonal" calcilutites of the Ropsley Beds. No capping ooid-calcarenite (Lithofacies B) is developed in this area.

IV.5.d.ii. South Lincolnshire: At Stainby, on the south-western flank of the "Ropsley lagoon", the Lincoln Member has the following sequence: (Fig.4.99.):

(1) The typical basal, ooid-calcarenite (Lithofacies A) also encompasses the fossiliferous "lag" which is so characteristic of the member in south Lincolnshire. The distinctive horizon is especially well developed at Stainby, where the decalcified *Thecosmilia* sp. occur abundantly as iron-stained moulds in the heavily weathered base (Figs. 101 and 102). Elsewhere (e.g. Greetham, SK 933146) *L. bellona* and small gastropods also occur at this level but it is the *Thecosmilia* sp. that make the horizon so distinctive and easily traceable.

(2) Above the basal oolite the sequence passes quickly through a "transitional" grain-poor, ooid-calcarenite into grey, impure calcilutites (Lithofacies B), that have small, articulate, terebratulids as the dominant faunal constituent. At the very top of the member ooids and skeletal debris increase again.

Elsewhere this reversion to more grain-rich, buff-coloured lithologies (mostly ooid-calcarenites: Lithofacies A) at the top of the member is more pronounced and the calcilutites are consequently less well represented. As with central Lincolnshire, this facies pattern seems to be related to the presence of oolite shoals (which are not actually represented in the Lincoln Member). For example, eastwards of the calcilutite-rich Clipsham-Castle Bytham-Little Bytham area (Fig.2.1.) the "clean" and "dirty" ooid-calcarenites of the Scottlethorpe sequence (TF 046204) suggest the presence of an oolith-generating zone somewhere further east. Similarly the more southerly Greetham and Woolfox (SK 951136) sections, which are also dominated by ooliths, indicate another shoal off to the south (?). The environmental setting of these beds and the significance of the facies changes are more fully discussed in Chapter V.

IV.5.e. <u>Laboratory descriptions of the lithologies</u>.

The most distinctive feature of the Lincoln Member is its lithological variability. In particular the quantity and nature of the grain types range widely and this, together with the gradational nature of the lithofacies, has made the categorisation of lithofacies difficult. Essentially, the compositional range extends from oolitic grainstones to fossiliferous mudstones. The latter have been separated off as the Ropsley Beds and Little Bytham beds, while the grain-supported oolites (which are typical of the base of the member) have been designated Lithofacies A. The remaining "transitional" lithologies, compositionally diverse but texturally wackestones, have been incorporated into Lithofacies B (B was designated in section IV.5.d. primarily because of the stratigraphic importance of that particular bed; compositionally and texturally it readily fits into B). The principal characteristics of Lithofacies A and B are shown in figures 4.103 and 4.104, while those of the Ropsley Beds and Little Bytham beds are dealt with separately in later sections.

IV.5.e.i. Lithofacies A: This is the ubiquitous basal lithofacies of the member, which is usually composed of oolitic or skeletal oosparites (Fig.4.105), which are texturally grainstones or packstones. Although ooliths are the dominant allochems, bioclasts, oncolites, intraclasts and peloids also occur in varying proportions (Figs. 4.103 and 4.104). The distinctive spherical to ovoid ooliths are characterised by a pale greenish-brown colour and fine concentric laminae. Most have skeletal nuclei (commonly bivalve bioclasts), although peloids are often the nuclei of the superficial ooliths, which are dominant in some beds (WQ D1). Bivalves and gastropods (sparite-pseudomorphs) are the commonest bioclasts, with foraminifera (micritised skeletons), brachiopods, worm tubes and rare echinoderm fragments also occurring. Although some grains are preserved "free" most have micrite-envelopes and many are nearly completely micritised. Only the calcitic forms have any original skeletal material preserved. The oncolites, which are usually identified by their accretionary micritic coatings tend to be large grains and on occasions are not readily separated from intraclasts. The allochems of these rocks are bound by two generations of cement: an early, acicular rim-cement predating a blocky infilling sparite. Some micrite is also present and is dominant at some levels (SQ Dla).

IV.5.e.ii. Lithofacies B: The relative abundance of the different allochems and the total amount of grains vary in this lithofacies, encompassing a number of lithologies, which are texturally wackestones. Oncolites are usually dominant (oncolitic biopelmicrite, Fig.4.106), especially in the more grain-rich lithologies but in the "calcilutites", bioclasts are the commonest allochem with oncolites subsidiary (oncolitic biopelmicrite; Fig.4.107.). Peloids, which from their variable size and shape appear polygenetic, can be an important constituent of the rock. In places they are not always clearly differentiated but appear to have coalesced to contribute to the micrite matrix. Elsewhere they are seen tightly packed with a sparite cement. As with Lithofacies A, the bioclasts are mainly provided by bivalves, brachiopods, worm tubes, foraminifera and echinoderms, and the oncolites are typified by their large size, irregular shape and discordant growth-rims, which coat the core-grain. In many cases this appears to have been ooliths, which were presumably washed-in to this "quieter" environment. Micrite forms the matrix throughout. Essentially, the lithologies of this facies range from grain-rich oncolite-dominated wackestones (Fig.4.106) to skeletal-rich, grain-poor wackestones (Fig.4.107.).

Lithofacies B is very similar to the more grain-rich lithologies pf Lithofacies B, although the increased importance of ooliths (Fig.4.103.) and occasional primary sparite-cemented areas make it rather closer to Lithofacies A than most B's lithotypes.

IV.5.f. Fauna.

The degree of post-mortem transportation suffered by the fauna of the Lincoln Member appears to depend on the organism's sub-

-strate-niche and the "energy" of the enclosing deposit. Generally there is little sign of major transportation and much of the fauna, if not actually "in situ" seems to have been reworked within its original area of colonisation. Excluding the Ropsley Beds the Lincoln Member is only patchily fossiliferous, with the fauna (Fig. 4.108) largely concentrated in the more calcilutitic levels. This is probably because the oolites represented an unstable substrate, prohibitive to colonisation.

Four aspects of the fauna are of particular note:

(1) The base of the member in south Lincolnshire is especially striking for its abundant, often decalcified, Thecosmilia sp. specimens and associated L.bellona and gastropod fauna. When decalcified the Thecosmilia sp. appear as dark brown, iron-stained moulds in the rock (Fig.4.101.). All the fauna of this basal level appears to have been "rolled" but the absence of severe breakage suggests a "reworking" rather than large-scale transportation. This distinctiveness and traceability of this horizon has made it the most important stratigraphical level in the Lincolnshire Limestone. Large Thalassinoides sp. networks are also seen on the base in both south and central Lincolnshire.

(2) The remainder of the Lincoln Member in south Lincolnshire is poorly fossiliferous except for the largely sparite-replaced colonial coral heads and small, distinctive terebratulids. These are mostly articulated with sparite or geopetal infills and in places, e.g. Woolfox, where they occur in clusters, the (monospecific ?) brachiopods have a noticeable size variation, despite their overall smallness. The brachiopods may therefore be original life groupings especially as they occur in lower-energy, mud-supported ooid-calcar-enites.

(3) At Lincoln, the lower-energy, mud-supported ooid-calcarenites and impure calcilutites show two contrasting, substrate-related faunas. The beds at Greetwell contain a mixed epi-and in-faunal assemblage (Fig.4.109), which reflects a soft, yet stable substrate. The "in situ" deep burrowers and the largely whole (disarticulated) valves of the epi-and shallow infaunal bivalves, indicate that the fauna is indigenous to the beds in which it is found. By comparison, at about the same horizon in the Dean and Chapter Pit sequence, there is a shell accumulation that is dominated by epifaunal organisms (Fig.4.110). This structure appears to have been a "shell bank" biostrome rather than a patch-reef because it does not transect any bedding planes and the corals do not form a framework. However it is likely that the corals helped to stabilise dead bivalve shells and initiate the development of the biostrome, which then provided niches for hard-substrate dwellers like Symmetrocapulus sp., Lopha sp. and Ctenostreon sp.. Besides providing debris for the bank, byssate forms, often associated with the soft bottom assemblages, probably also took advantage of the readily available attachment sites and in turn contributed to the build-up of the shell bank. Away from the biostrome the more typical mixed epi-and infaunal, soft substrate assemblage also occurs at the Dean and Chapter Pit.

(4) The topmost bed of the Lincoln Member in central Lincolnshire is thought to be the Lower Crossi Bed of Kent (1966, fig. 1.). It contains the typical Acanthothiris crossi (J.F. Walker), abundant L.bellona and Thecosmilia sp. described by Kent (1940, p.50).

IV.5.g. Discussion.

The Lincoln Member is particularly important because of the widespread traceability of its base, which forms a distinctive lithostratigraphic marker horizon. In addition, the base of the unit appears to be a significant biostratigraphic divide, separating the ovalis Subzone ammonite faunas of the Lincoln Member (and above) from the discites Zone assemblages below (Chapter III). Together these factors make the base of the Lincoln Member the most important stratigraphic horizon within the whole of the Lincolnshire Limestone Formation.

IV.5.h. Status of the subdivisions of the Lincoln Member.

Within the Lincoln Member there are two, geographically isolated occurrences of a distinctive chalky-white calcilutite litho-facies, which warrant recognition as separate units: the Ropsley Beds and Little Bytham beds. In both cases the beds have largely gradational contacts with the enveloping Lincoln Member and the limits of the units are arbitrarily defined in many localities. The boundaries have been chosen to preserve the "purity" of the calci-lutite lithofacies within each unit.

The Ropsley Beds have been given formal status because they form a geographically and geologically coherent subdivision (Hedberg, 1976). However, the Little Bytham beds have only been afforded informal status because of their restricted geographical range; the beds have only been seen in the Little Bytham pit. As it is not known whether this restricted occurrence reflects their true distribution or whether the beds are part of a more widespread unit, the informal terminology would facilitate any nomenclature change that might be necessitated when the problem is resolved. For example, if the beds were shown to have a wider distribution they could be formalised in the same way as the Ropsley Beds. Alternatively, if linked to the Ropsley Beds, they would become part of that unit or if really limited to the Little Bytham area, they would be left undivided, as part of the Lincoln Member.

IV.5A <u>ROPSLEY BEDS</u>.

IV.5A.a. <u>Introduction</u>.

The Ropsley Beds, composed of thinly-bedded, white calcilutites with interleaved marl partings, occur as a lensoid mass within the Lincoln Member of mid-Lincolnshire (Fig.2.2.). Ropsley (TF 002364) has been preferred as the type section because it shows a relatively thick (0.84 metres), clearly definable sequence (Figs. 4.1. and 4.111.).

IV.5A.b. <u>Former Terminology</u>.

The similarity of the calcilutite lithofacies forming the Ropsley Beds and Leadenham Member has resulted in their classification together as part of the Cementstones (Kirton Beds) of Richardson (1939b), the Cementstones of Kent (1940 and 1966), Kirton Cementstones with <u>Acanthothiris crossi</u> of Wilson (1948) and Kirton Cementstones of Evans (1952). However, the two units occur at different stratigraphical levels, invariably separated by the basal oolite of the Lincoln Member (Fig.4.100), and have dissimilar geographic distributions, the Ropsley Beds being restricted to mid-Lincolnshire (cf. Figs. 4.80 and 4.112). Where their distributions overlap the Ropsley Beds probably form much of the upper part of the various "Cementstones" units. Further south, however, beyond the southern limit of the Leadenham Member, the Ropsley Beds may constitute practically all of the "Cementstones". Certainly the Cementstones at Little Ponton (Kent, 1966, p.65) more or less equate with the Lincoln

Member (including the Ropsley Beds, see Fig.4.1.). Nowhere are the Ropsley Beds equivalent to the Crossi Beds of any of the authors cited above.

IV.5A.c. Geographical and Geological Extent.

As the Ropsley Beds are completely enveloped within the Lincoln Member, their N-S limits are fairly easily defined (Fig.4.1.). However the E-W distribution of the beds is less readily documented because of outcrop failure in those directions.

From their centre of development in the Ancaster area, the Ropsley Beds can be demonstrated to taper away southwards via Ropsley and Little Ponton (SK 930320) and northwards via Leadenham (SK 962523), although in each instance the thinning is extremely gradual (Fig.4.112). As the contacts between the Ropsley Beds and the Lincoln Member are practically all gradational, the limits depicted for the northern and southern margins of the beds in figure 4.112 are the natural depositional limits of the "lagoonal" sediments. Although more oolitic sediments border the "Ropsley lagoon" to the north and south, the division between the two facies is not sharp because the Ropsley Beds represent the "purest" development of the "lagoon" and peripheral grain-poor oolites form a transitional facies with the more agitated oolites (Chapter V). However, at Copper Hill Quarry, Ancaster (SK 979427) there is an exception to this gradational pattern. Here, the top of the Lincoln Member and the unknown part of the Ropsley Beds have been removed by the downcutting of the Sleaford Member (Figs.4.1. and 4.113.). The undulating contact, which cuts across several beds, appears to have been lithified prior to the deposition of the Sleaford Member sediments, as it has been colonised by boring bivalves. The small, oolith-infilled bores stand out sharply against the chalky-white calcilutites (Fig.4.114.). The significance of this downcutting is discussed in Chapter V.

IV.5A.d. Field description of lithologies.

The Ropsley Beds consist of interleaved, thinly-bedded, white to grey calcilutites and brown clay or marl partings (Fig.4.111). Although often devoid of any inorganic grains, the limestones contain a variety of fossils and bioclastic debris, which has mostly been derived from the breakdown of brachiopod, bivalve, gastropod and coral skeletons. At some localities, e.g. Leadenham, peloids and irregularly-shaped limonitic brown ooids (oncolites ?) speckle the rock; the ooids usually occur randomly scattered or in clusters. Nowhere do the allochems form a significant part of the rock, the bulk of which appears to be micrite. Rare, discrete burrows and more common bioturbation are also seen.

IV.5A.e. Laboratory description of lithologies.

Typically, the Ropsley Beds are composed of biomicrites, which texturally are wackestones or mudstones (Fig.4.115.).

IV.5A.e.i. Grains: In addition to the dominant, bimodal, skeletal allochems, rare wood flakes, micritised ooids and silt grains are present with more common peloids. Brachiopods, bivalves and, to a lesser extent, gastropods are the dominant skeletal components. The brachiopods mostly punctate terebratulids, retain their general skeletal composition and structure, but the largely aragonitic molluscs are preserved as sparite pseudomorphs. In the case of the gastropods, the pseudomorphs are of two kinds: where the original internal cavity of the gastropod has been infilled with micrite, the pseudomorph is of the shell alone, but where no inflling has taken place, a sparitic cast of the gastropod's entire volume has resulted. Worm tubes, and Bryozoa are minor constituents. The skeletal grains are very variable in size (up to 10.4 mm.).

IV.5A.e.ii. Matrix: the matrix appears to be micritic but there are patches of incipient alteration to microspar and also denser micritic areas, which may have resulted from the coalescence of peloids; the size and shape of which suggest that they were probably faecal pellets. Overall, though peloid-coalescence does not appear to have been responsible for much of the micrite.

The often patchily "churned" appearance of the micrite strongly suggests bioturbation.

IV.5A.f. Fauna.

The environmental conditions prevailing during the deposition of the Ropsley Beds were favourable for marine benthonic invertebrates and quite a diverse fauna flourished. In addition to the forms from Ropsley recorded in figure 4.116, *Thamnasteria* sp., *Thecosmilia* sp., *Pholadomya lirata* (J.Sowerby) and oysters have been found at other localities. The fauna generally is thought to have suffered little post-mortem transportation because:

(1) the brachiopods and bivalves show a high articulation ratio,

(2) few fossils show signs of wear or breakage,

(3) some forms occur in their positions of life, e.g. *Pholadomya*,

(4) the disarticulated valves of bivalves and brachiopods have a random orientation. Current activity and transportation would have concentrated them into a convex-up, current-stable position.

(5) at Ropsley the abundant "*Terebratula*" sp. specimens

have a wide size variation along a single horizon, within a bed, suggesting little current sorting has occurred.

In general the fauna occurs randomly scattered throughout each bed but in one bed at Ropsley there is a tripartite subdivision. The basal layer is densely packed with apparently monospecific terebratulids, which are mostly articulated (94% of the 36 specimens counted), sparite-infilled, and of several different sizes. Together these factors suggest that the brachiopods represented an original population, comprised of a number of spat-falls. A few other forms, like *Mactromya* sp. are also present at this level. Above the terebratulids, the bed is barren (of macroscopic invertebrates) but the highest level contains a *Lucina bellona* d'Orbigny - *Montlivaltia* sp. association. Such a faunal succession, within a single bed, would seem to exemplify the "time-averaged community" concept of Walker and Bambach (1971) for no obvious lithological changes take place within the bed to promote the succession. Furthermore, the overall similarity of the limestones suggest a stable environment regime existed throughout the duration of the Ropsley Beds deposition.

Although, sedimentologically very similar, the Ropsley Beds and Leadenham Member have distinctly different faunas, the former is dominated by epifaunal organisms, especially terebratulids, while infaunal and semi-infaunal bivalve molluscs form the principal component of the Leadenham Member assemblages. Such a sharp difference in biotopes between almost identical lithofacies of a similar age seems unusual, especially as the substrate ought to have been very similar. The presence of occasional *Pholadomya* and the rather more common occurrence of other infaunal bivalves, like *L. bellona* argue against the possibility that "substrate hardening" might have been responsible for the difference. However, the dominant terebratulids, which have smooth, thin shells, typical of quiet-water environments (Fursich and Hurst, 1974) show none of the adaptations that Fursich and Hurst (1974) thought indicative of "soft, muddy substrates", and it may well be that the Ropsley Beds' substrate was firm without being prohibitive to burrowing; in comparison the Leadenham Member "bottom" must have been quite soupy (see Chapter V). In addition, the pedicle foramina of the Ropsley brachiopods are quite large, suggesting they attached themselves firmly to the substrate (or holdfast). However there is little reason to suspect that the strongly developed pedicle reflected an adaptation for turbulent conditions (Fursich and Hurst, 1974) because of the general sedimentological setting. The pedicle is more likely to have been retained to stabilise the small, thin-shelled terebratulids, which show no other morphological features compatible with such a function. This role would seem applicable regardless of whether the brachiopods were small adults or juveniles.

IV.5A.g. Discussion.

Although lithologically similar to the Leadenham Member, the Ropsley Beds have been separated from that unit for the following reasons:

(1) The two subdivisions occur at distinctly different stratigraphical levels (Fig.2.2.). Furthermore, the erosive base of the Lincoln Member, which invariably separates the units, is so widespread that a contiguous relationship between the two is unlikely to have been developed elsewhere.

(2) The two units have dissimilar geographic distributions (cf. Figs.4.80 and 4.112),

(3) A number of faunal differences also distinguish the two lithofacies.

In contrast the stratigraphical coherence of the Ropsley Beds and Lincoln Member is suggested by their gradational contact and the fact that the Ropsley Beds are completely enveloped within the member. Despite this the lithological distinctiveness of the Ropsley Beds warrants some kind of individual recognition

IV.5B. LITTLE BYTHAM BEDS.

IV.5B.a. Introduction.

The type and only section of the Little Bytham beds occurs in Little Bytham Quarry (TF 013178; Fig.4.117), south Lincolnshire. The chalky-white, thinly-bedded calcilutite sequence (0.77 metres thick) is completely enveloped within the Lincoln Member (Fig.2.2.).

IV.5B.b. Former Terminology.

Although Little Bytham Quarry is rarely mentioned by the 20th century workers, the Little Bytham beds probably formed part of the *Nerinea* Beds (Richardson, 1939a), Cementstones (Kent, 1966), Oolites (Swinnerton and Kent, 1976) and the "unnamed beds with *Pholadomya* Bed" (Hollingworth and Taylor, 1951). However, where they fit into the scheme suggested by Kent (1940) is not so apparent, as he never clarified the stratigraphy of southern Lincolnshire. In particular the geographical range of the Cementstones is rather confused; at one point Kent (1940, p.52) claimed that the Cementstones occurred at South Witham (SK 917189) but later suggested that "..... they came in a little to the north of Grimsthorpe ", i.e. north of South Witham (Fig.2.1.). As this ambiguity was never resolved, it is difficult to know whether the Little Bytham beds' level was occupied by the Cementstones or Little Ponton Beds of Kent (1940).

IV.5B.c. Geographical and Geological Extent.

Although the Little Bytham beds are only seen at Little Bytham, some indication of their possible extent is gained from the sequences in nearby quarries. No comparable lithofacies are developed in the Lincoln Member at Scottlethorpe (TF 046204) to the north-east), Castle Bytham (SK 990180, to the west) or Woolfox (SK 951136, to the south-west). Therefore, if the Little Bytham beds are part of a larger unit, they can only really expand to any extent, southwards or south-eastwards (Fig.2.1.), although a thin, northward projecting tongue could be developed to the west of Scottlethorpe. Alternatively, the beds may just be a very localised development around Little Bytham.

Despite the similarity of the stratigraphic position and lithofacies of these and the Ropsley Beds, there is no evidence that the two units link up, unless they do so via a "hidden" eastward branch or through the possible northern "tongue", postulated above.

IV.5B.d. Description of lithofacies and fauna.

The Lincoln Member sequence at Little Bytham is reminiscent of that at Ropsley; a basal grain-rich, ooid-calcarenite grades up into pure calcilutites, which form the Little Bytham beds. The unit is composed of a series of thinly-bedded, chalky-white calcilutites in which only rare ooids are scattered, together with dominant skeletal grains. Only tiny gastropods appear to be common and the beds are not fossiliferous.

IV.6. SCOTTLETHORPE MEMBER.

IV.6.a. Introduction.

The Scottlethorpe Member consists of a variable suite of ooid-bearing lithologies, which frequently contain Acanthothiris crossi (J.F. Walker). The sequence (2.1 metres thick) at Scottlethorpe Quarry (TF 046204) has been preferred as the type section. Although the base is sharp and easily picked out (Fig.4. 118), the top lies within a gradational sequence up into the upper Lincolnshire Limestone; it is arbitrarily drawn at the first recognisable break in the succession (Fig.4.118.).

IV.6.b. Former Terminology.

This essentially new unit includes part of the geographical range of the Crossi Beds (Kent, 1940 and 1966, but not the Upper and Lower Crossi Bed of Kent, 1966, fig.1.; Swinnerton and Kent, 1976; and Hollingworth and Taylor, 1951), and Acanthothiris crossi Beds (Evans, 1952). However the thickness of the Scottlethorpe Member (Fig.4.1.) exceeds that of the Crossi Beds (Kent, 1940, p.50; and Hollingworth and Taylor, 1951, p.18) by such a degree that the two units are obviously not stratigraphically identical even where they coincide. The member probably includes part of the units which were adjacent to the Crossi Beds. For example, the lowest few centimetres of the "Bastard Freestone" at Castle Bytham (SK 990180) see Kent in Sylvester-Bradley, 1968, p.223) is now certainly part of the Scottlethorpe Member. The lack of other detailed sections makes further precise comparisons impossible, but the Scottlethorpe Member most likely encompasses the lower part of the old "Upper Lincolnshire Limestone" generally in south-west Lincolnshire, for the relationships at Castle Bytham are typical for that area. In comparison the member has no connection at all with the Crossi Beds of any description (see Kent, 1966, fig. 1) north of Leadenham.

IV.6.c. Geographical and Geological Extent.

In south Lincolnshire and neighbouring parts of Leicester-

-shire the Scottlethorpe Member occurs sandwiched between the Lincoln Member and various units of the upper Lincolnshire Limestone (Fig.2.2.). Along the western belt of quarries running northwards from Woolfox (SK 951136) to Sproxton (SK 866253, Fig.2.1.), the member maintains a fairly constant thickness (approximately 1.7 metres) with only a few signs of "mild" erosion by the overlying Castle Bytham Member; for example at Woolfox the corals in the uppermost bed of the Scottlethorpe Member are sharply truncated. Eastwards from these quarries, the unit thickens (Fig.4.119) and has a gradational contact with the Castle Bytham Member. This is clearly seen in the type section (Fig.4.118). Further north from this area however, the relationships become more complex; at Great Ponton (SK 935303), the Scottlethorpe Member has been completely removed by the erosive down-cutting of the Sleaford Member, which rests on a level low in the Lincoln Member (Figs. 4.1. and 4.120). A parallel situation to this is also seen at Copper Hill Quarry, Ancaster (SK 979427, Fig.4.113), while at the nearby Castle Quarry (SK 987435), the downcutting has only penetrated into the Scottlethorpe Member itself. These down-cutting relationships are relatively localised however because in the intervening sequences (Ropsley, TF 002364 and Little Ponton, SK 930320) a more typical (complete) succession is seen, with the Scottlethorpe Member sandwiched between the Lincoln and the Metheringham Members.

To the north of Ancaster, the stratigraphic level of the Scottlethorpe Member is not seen until one reaches Metheringham (Fig.2.2.). No Scottlethorpe Member is developed here or further north. However, at Harmston (SK 992619) a thin marl band, between the Lincoln and Metheringham Members, is believed to be the western feather-edge of the Lindsey Shale and this is replaced eastwards by the limestone which may be the most northern extension of the Scottlethorpe Member. This interdigitating relationship between the Scottlethorpe and Lindsey Shale Members (Fig.4.1.) is more fully discussed in section IV.7. Regardless of the Harmston section, it is clear from general stratigraphical relationships that the Scottlethorpe Member does not persist far into central Lincolnshire; its possible distributional trends are summarised in figure 4.119.

IV.6.d. Field description of the lithologies.

In the type section, the Scottlethorpe Member, which has a sharply erosive base, is represented by the following sequence: the basal part of the unit is composed of poorly-sorted (skeletal) ooid-calcarenite (Lithofacies A). The ooids are variable in size and shape. Bivalves, brachiopods and, to a lesser extent, gastropods contribute to the skeletal debris, which is often a significant part of the rock. This grain-rich, ooid-calcarenite grades up into a grain-poor, ooid-calcarenite that is typified by straw-coloured ooids speckling a grey, micritic matrix (Lithofacies B). The poorly-sorted allochems, which are similar to those of the basal lithology, have an uneven distribution throughout the rock. At some localities this level is quite shelly. Higher still in the sequence, the percentage of grains diminishes further and only a few ooids occur, scattered in what is essentially a grey calcilutite (Lithofacies C). These beds are exceedingly fossiliferous with *Lucina bellona* d'Orbigny, the celebrated *A.crossi*, *Thecosmilia* sp., and very common terebratulids typifying the unit. The progressive decrease in energy conditions reflected in this sequence is reversed towards the top, where a fairly rapid transition back to "cleaner", grain-supported ooid-

-calcarenites occurs. This reversal is accompanied by an increase in grains and decrease in faunal content, such that the basal and top part of the sequence are virtually identical. To some extent however this symmetry is induced because the gradational upper limit of the member is drawn at the first "break" within the oolitic sequence that composes the lower/upper Lincolnshire Limestone junction here and in south-western Lincolnshire generally (Fig.4.1.). In particular, very similar transitions are seen at Castle Bytham and Little Bytham (TF 013178). However, in the more westerly quarries, especially Woolfox, Clipsham (SK 978154) and Stainby (SK 910233) the reversal to ooid-calcarenites at the top is "missing" and the Scottlethorpe Member is truncated by the Castle Bytham Member. It would appear from the general stratigraphical relationships, that the erosion involved was only slight. Similarly the rather sharply erosive base of the member, seen at Scottlethorpe, is not always so readily demonstrated. A clay band often intervenes between the Lincoln and Scottlethorpe Members, although its partial removal and the generally irregular base of the unit suggests some erosion has taken place, if only slight. Only at Castle Bytham is there any real evidence of a gradational lower contact to the member.

Further north, between Little Ponton and Harmston, the ideal sequence occurs in a modified and less constant form. The gradual transition from poorly-washed, grain-rich, ooid-calcarentites to fossiliferous calcilutites is replaced by a rather more rapid gradation, which equally swiftly reverts via a grain-poor, ooid-calcarenite phase to grain-rich, ooid-calcarenites, giving a symmetrical, sedimentary pattern (e.g. Castle Quarry, Ancaster). However, the erosive downcutting of the upper Lincolnshire Limestone affects what is seen of this sequence, although the lithologies involved are essentially the same as those seen in southern Lincolnshire.

IV.6.e. Laboratory description of the lithologies.

Although in broad field terms the member appears to be represented by three lithofacies, in detail the included lithologies represent a diverse spectrum of compositions and textures. Consequently the dividing lines between the lithofacies are not sharply defined. Essentially Lithofacies A and C represent the end members of a facies gradient, with B encompassing the "transitional" lithologies. Figure 4.121 shows the "typical" characteristics of each of the lithofacies.

IV.6.e.i. Lithofacies A: The typical lithology of this facies is an ill-sorted, skeletal oosparite (Fig.4.122) containing subsidiary intraclasts and rare peloids. Although rather large, the ooliths are readily recognised by their pale yellowish-green, concentric laminae; they are not oncolites. Most of the larger ooliths are superficial in type, while the smaller ones tend to be "normal"; both types have skeletal nuclei. Rare composite ooliths occur. The skeletal grains are equally variable in size; calcitic bioclasts, like terebratulids, retain their original composition and structure, but the aragonitic shells (bivalves and gastropods) have been replaced usually being preserved as sparite pseudomorphs, with micrite-envelopes. Bryozoa, foraminifera (micritised shells) echinoderm fragments and worm tubes also occur. The intraclasts tend to be large, composite grains, some of which, because of micritic rims, may be oncolites. Although in places peloids appear to have coalesced to give a "pseudo-micrite" matrix, quite clear sparite cements the rock and only subsidiary amounts of micrite are present. Texturally the rock is a packstone. Elsewhere, (Ropsley) this lithofacies is represented by an oolitic biopelsparite (packstone) in which rare, large ooliths (0.6 to 1.4. mm.) and bioclasts with micrite-envelopes are set in a well-sorted mixture of small skeletal fragments (0.1 to 0.3 mm.), ooliths and dominant peloids. The latter are probably polygenetic, being a combination of faecal pellets and micritised bioclasts or ooliths. Bivalves are the most common skeletal fragments.

Although the base of the member is usually occupied by Lithofacies A sediments, lithologies gradational with Lithofacies B can occur. For example, at Stainby, the basal bed is a grain-rich wackestone (bio-oomicrite) with sub-equal amounts of ooliths and bioclasts. The intraclast and peloid contents are variable. A rather uneven grain distribution results in some sparite-cemented grain-supported patches, but a micritic matrix is usual. The grain content and preservation is very similar to that of the "typical lithology".

IV.6.e.ii. Lithofacies B: This facies, being intermediary, is probably the most variable of all. Essentially, it encompasses grain-rich, mud-supported rocks, with widely varying grain types. However, in its "typical" form the facies is represented by a skeletal oomicrite (Fig.4.123), in which the dominant ooliths are of three categories: "normal", where the concentric laminae compose the majority of the grain, "superficial", where the coatings rim a large nucleus, and "composite" where two (rarely more) ooliths have been incorporated with an enclosing oolith rim. In all cases the nuclei are skeletal (bivalves, brachiopods, echinoderms, gastropods and Bryozoa which also occur as uncoated grains). Rarer, large, composite intraclasts and "micrite-lumps" (oncolites ?) are also present. Well-packed, grain-supported patches are seen with a sparitic cement, but overall the rock has a micrite matrix and is mud supported. Variations from the "norm" include: a "mixed-grain" biomicrite (SQ E2), which is a grain-rich wackestone with varying amounts of subsidiary oncolites, intraclasts and ooliths. This lithology is transitional with Lithofacies C.

IV.6.e.iii. <u>Lithofacies C</u>: This is perhaps the least variable of the lithofacies. The typical lithology, a biomicrite (Fig.4.124) has abundant skeletal grains showing all grades of comminution, which are probably due primarily to biological rather than mechanical breakdown. Brachiopods (terebratulids and rhynchonellids) and bivalves are the dominant forms but gastropods, corals, worm tubes, foraminifera, Bryozoa and echinoderm fragments are also seen. The calcitic skeletons have retained their original composition/ structure, but sparite pseudomorphs represent the formarly aragonitic skeletons, like bivalves. Polygenetic peloids (faecal and micritised grains), oncolites and ooliths make up the rest of the allochems. Bioturbation is suggested by the "churned" appearance of the matrix, which in some places, appears to be developing from peloid coalescence, as faint, peloid-sized outlines can be seen in the micrite. This interpretation is supported by the evidence in other slices where sparite-cemented peloidalareas grade into what appears to be coalesced peloids and finally into "micrite-with-peloid-outlines". It is possible that in some instances the rock may be a "compacted packstone" although it now appears as a wackestone. This more allochem-rich and allochem-diverse lithology is transitional to the lithologies of Lithofacies B.

IV.6.f. Fauna.

Only the calcilutite beds of the Scottlethorpe Member contain a noticeable benthonic fauna; this is dominated by *Lucina bellona* d'Orbigny, *Plagiostoma* spp., *A.crossi* and terebratulids. The more oolitic beds probably represented less stable substrate conditions and consequently these beds are practically barren.

Within the calcilutites, the fauna shows few signs of significant transportation. Many of the species are articulated (brachiopods and *L.bellona*) with sediment or geopetal infills while the disarticulated shells (epifaunal bivalves like *Plagiostoma* spp. and *Camptonectes* sp.) are unbroken and have a random orientation, i.e. not preferentially "convex-upwards". Furthermore, some *A. crossi* specimens are preserved with their delicate spines intact. However, the fauna appears to have been moved locally because, apart from the colonial corals, no forms seem to be in their position of life.

The majority of the species present are epifaunal; except for the deep-burrowing *Pholadomya lirata* (J.Sowerby), the abundant *L.bellona* (mobile, shallow infaunal) and "*Nerinea*" (semi-infaunal), the remaining forms must have competed for space and resources above the sediment-water interface. Colonial corals, mostly bored by "*Lithophaga*" sp., are a common feature of the unit, with the rather unusual *Thecosmilia* sp. bioherms (0.6 metres basal diameter and 0.4 metres high) being present at Clipsham (SK 978154; Fig.4.125) and Woolfox. These bioherms include an associated fauna of bivalves and gastropods.

The following faunal list has been compiled from collections made in the member, mainly at the Soil Fertility Quarry, Clipsham (SK 978154):

Brachiopods	*Acanthothiris crossi* (J.F.Walker)	abundant
	"*Terebratula*" sp.	abundant
Bivalves	*Lucina bellona* d'Orbigny	very abundant
	Plagiostoma rodburgensis (Whidborne)	
	P. crickleyensis (Cox)	
	P. richardsoni (Cox)	
	Plagiostoma sp.	
	Pholadomya lirata (J.Sowerby)	
	Lopha sp.	
	Lithophaga sp.	
	Camptonectes sp.	
	Chlamys sp.	
	Isognomen isognomoides (Stahl)	
Gastropods	*Natica* sp.	
	Bactroptyxis ? bacillus d'Orbigny	
	Pseudomelania (Oonia) latuiscula (Morris and Lycett)	
	Alaria ? roubaleti Schlumberger	
	Alaria ? pinguis Hudleston	
Corals	*Isastraea* sp.	
	Thecosmilia sp.	
	Chomatoseris sp.	

IV.6.g. **Discussion.**

Although the Scottlethorpe Member encompasses some of the strata that formerly constituted the Crossi Beds in southern Lincolnshire (Kent, 1940 and 1966; Hollingworth and Taylor, 1951;

and Swinnerton and Kent, 1976) it is not considered to be directly equivalent to that unit or indeed to be defined on the presence of A.crossi. The reasons for abandoning the "Crossi Beds" have already been discussed in Chapter II and it is not proposed to re-iterate the arguments here. However the principal differences between the Crossi Beds and the Scottlethorpe Member (points 1 and 2) and the limitations of A.crossi as an index for the new member (points 3 and 4) are outlined below:

(1) Kent (1940, p.50) originally described the Crossi Beds as "....usually 2-5 feet of partly oolitic light grey or buff limestone, frequently hard and splintery, which lithologically might be grouped as the highest bed of the Cementstones". Apart from the alleged association with the Cementstones, this description fits the more micritic bands present in the Scottlethorpe Member, but not the member as a whole. Divorced from any association with A.crossi, the micritic beds of the member can be seen to be integrally related to the oolites with which they should be incorporated to form a single lithostratigraphic unit.

(2) The Scottlethorpe Member only occurs in the more southerly parts of the Lincolnshire Limestone outcrop and does not extend north of Harmston. This distribution, which is more restricted than that of the Crossi Beds and the geographic range of A.crossi itself, reflects the true distribution of the coherent lithostratigraphic unit within which A.crossi happens to occur in south Lincolnshire.

(3) Within the more oolitic beds of the Scottlethorpe Member, A.crossi is scarce; this, together with its small size, makes the brachiopod an elusive stratigraphical guide. For example,

Kent (1940) did not record A.crossi in the Ancaster Quarries, but the present author has found a single specimen in bed AQ E2 at the Castle Quarry, Ancaster.

(4) The claims by Hollingworth and Taylor (1951, p.19) that "Its A.crossi abundance in the Crossi Bed,......is sufficiently striking to obviate confusion with higher horizons" is not substantiated by the present work. In south-west Lincolnshire A.crossi is often strikingly abundant in the micrites of the Scottlethorpe Member (= "Crossi Beds"), but in other areas where the "Crossi Beds" level is seen, such as Harmston (no recorded A.crossi)and Ropsley (few records), the recognition of the "Crossi Beds" by the relative abundance of A.crossi is by no means the foregone conclusion Hollingworth and Taylor suggest.

The disadvantages of having a stratigraphical unit based upon the occurrence of so elusive a fossil as A.crossi appear patently obvious and therefore the replacement of the "Crossi Beds" (in south Lincolnshire) by the Scottlethorpe Member is considered necessary and advantageous. In comparison to the "Crossi Beds", the Scottlethorpe Member is a coherent and relatively easily traced lithostratigraphic unit.

IV.7. LINDSEY SHALE MEMBER.

IV.7.a. Introduction.

Numerous quarries have been excavated in the thick development of the Lindsey Shale Member around Kirton in Lindsey (Fig.2.1.), where the shale has been used in cement manufacture for a number of years. One of these quarries (Fig.4.126; SE 940014), which shows the thickest sequence (4.2 metres) seen by the author, has been chosen as the type section. It has been previously described by Richardson (1940, p.255).

IV.7.b. Former Terminology.

The Lindsey Shale Member, which was probably first recognised by Ussher (1890,p.71), has been previously called the Kirton Shale (Kent, 1940, 1948 and 1953; and Swinnerton and Kent, 1976) or Kirton Cement Shale (Richardson, 1940; Wilson, 1948; and Kent, 1966). Unlike all the other newly proposed members, this is stratigraphically coincident with the unit it is "replacing"; only the name has been changed because of the prior use of "Kirton" by Ashton (1975), to title the Kirton Cementstones Member, invalidated its re-use here (see Hedberg, 1976, p.41, pt.Flb) and Lindsey was therefore substituted.

IV.7.c. Geographical and Geological Extent.

Although over 4 metres thick at Kirton (SE 940014), the Lindsey Shale thins to under a metre at Metheringham (TF 053616) beyond which it has not been recorded. There has been little indication gained of the member's areal extent because outside of the isolated Kirton exposures, it only occurs in a south-easterly trending linear belt of quarries between Lincoln and Metheringham (Fig.4.1.). However, the recently opened quarry at Harmston (SK 992619) has exposed a possible section through the member. In this quarry, sandwiched between the Metheringham and Lincoln Members, an eastward-thickening marl occurs which may be the western feather-edge of the Lindsey Shale Member (Fig.4.127). If this interpretation is correct, then Harmston not only shows the Scottlethorpe Member interdigitating with the Lindsey Shale Member but also illustrates the probable relationship of the "Upper Crossi Bed" to the main "Crossi Beds" (Fig.4.127).

Another significant aspect to be highlighted by the Harmston section is that the thinning of the Lindsey Shale Member is probably stratigraphic. Nowhere does the overlying Metheringham Member cut down into the shale and in the field the weathered contacts appear gradational; shale passes up into micritic limestones and then into well-washed oolites. No evidence exists for the Metheringham Member having an erosive base.

The Lindsey Shale variously overlies the Kirton Cementstones Member in South Humberside (Ashton, 1975) and the Lincoln Member in central Lincolnshire, but always passes up into the Metheringham Member (Fig.2.2.).

IV.7.d. Lithologies.

The Lindsey Shale is unique amongst the stratigraphical subdivisions of the Lincolnshire Limestone in not being principally composed of limestone. The unit consist of brown-weathering, black shale, which often has thin, impersistent limestone bands occurring near the base. The limestone/shale contacts are usually gradational.

IV.7.d.i. Shale: The fossiliferous marly shale is generally well laminated, the laminae being highlighted by colour banding. Occasional small ooids, mica flakes and abundant shell debris are also present. The texture of the shale varies from hard, friable and decidedly shaly to a softer, sticky, clay-like consistency.

The composition of the shale was obtained from a semi-quantative X.R.D. analysis of its acid insoluble residue (33.5% by weight of the rock). This indicated the presence of montmorillonite as a major phase and mica, quartz and kaolinite as minor phases; a composition very similar to that recorded for the shales in the Kirton Cementstones Member (Ashton, 1975).

IV.7.d.ii. Limestones: The thin (140 mm. on average), grey, argillaceous calcilutites have a few "coated grains" and skeletal fragments scattered throughout the matrix. Occasionally the limestones appear to have had a biostromal origin (Crog-balls of Richardson, 1940, p.255) with colonial corals acting as the binding agent.

In the past, occasional "reef-like masses" (Swinnerton and Kent, 1976, p.45) have been encountered during quarrying. These were termed "False Formations" by the quarrymen as they usually dipped westwards at a low angle in contrast to the easterly dip of the Limestone. Before the advent of modern quarrying techniques the "False Formations" were left as isolated masses and one such remnant remained during the early development of the Manton Stone Company Quarry (SE 940024; Fig.4.128). It consisted of a crudely alternating series of marls and argillaceous limestones, many of which were fossil biostromes. The developing mass must have at any one time, covered many square metres of sea floor, for the well-exposed western face was over 22 metres long.

IV.7.e. Fauna.

The rather poorly-preserved, fragile fauna of the Lindsey Shale Member can be prolific. Collections from the shale at two of the quarries at Kirton (SE 940014 and SE 940024) have yielded abundant Trigonia hemisphaerica Lycett, Acanthothiris crossi (J.F.Walker) and ostracods (see Bate, 1967) together with less common Plagiostoma sp., Camptonectes sp., Pseudotrapezium sp., and Pteroperna sp.. Richardson (1940, p.255) also recorded Lucina bellona d'Orbigny, Gervillia sp., and Pholadomya lirata (J.Sowerby).

An even more prolific fauna is present in the "False

Formations", especially in the limestone bands. The following faunal list has been compiled from collections from the "False Formation" exposed at the Manton Stone Company Quarry (SE 940024):

Bivalves	*Plagiostoma* spp. (abundant)
	Lopha sp. (abundant)
	Ctenostreon sp.
	Lithophaga sp. (abundant)
Gastropods	*Symmetrocapulus tessoni* (Deslongchamps)(abundant)
	Pleurotomaria sp.
	Natica sp.
Brachiopods	*Acanthothyris crossi* (J.F.Walker)(abundant)
	Parvirhynchia kirtonensis Muir-Wood (abundant)
	an epithyrid
Corals	"*Thamnasteria*"-like colonial corals (abundant)
Worm tubes	
Barnacles	*Eolepas oolitica*
	E. aalensis
Ostracods	Abundant (see Bate, 1967).

Perhaps the most significant feature of the fauna is the abundance of hard-substrate-related forms. For example, among the bivalves, the borer *Lithophaga* is prominent, while *Lopha*, *Ctenostreon* and *S.tessoni* (a limpet-like gastropod) and the goose barnacles, *E.oolitica* and *E.aalensis* all relish hard substrates. It appears that the disarticulated valves of shells, especially *Plagiostoma* sp.

formed a base over which thamnasteroid corals colonised, stabilising the substrate. This in turn provided a variety of niches for organisms preferring hard rather than soft substrates, while the more shaly areas within and around the biostromes were probably colonised by the brachiopods such as A.crossi (see Rudwick, 1965) and ostracods. Once established, the biostromes standing above the general sediment surface but without noticeable relief, seem to have been self-perpetuating as the "False Formation" extends throughout the full thickness of the member. At various times however, individual biostromes were "swamped" by shale, killing off the corals and softer bottom conditions prevailed before a further biostrome was initiated.

IV.8. METHERINGHAM MEMBER.

IV.8.a. Introduction.

The Metheringham Member, composed of ooid-calcarenites, forms the lowest unit of the upper Lincolnshire Limestone in central Lincolnshire. The readily accessible and clearly defined sequence (approximately 2.4 metres thick) at Metheringham (TF 053616) was chosen as the type section (Fig.4.129).

IV.8.b. Former Terminology.

This member has not previously been recognised as a separate subdivision of the upper Lincolnshire Limestone but appears to have been included as part of the units termed the Ancaster Freestone (Richardson, 1939b, but not plate 29A or B and p.473; Hollingworth and Taylor, 1951; and Kent, 1966, fig.1.) or Ancaster Beds (Kent, 1940; and Swinnerton and Kent, 1976), or Hibaldstow Beds (Richardson, 1940 ?; see also Syvester-Bradley, 1968, fig.42; Kent, 1940 and 1966, fig.1; and Evans, 1952). However, the

Metheringham Member has neither the same geographical extent nor the equivalent stratigraphical thickness as these "older" units. On the contrary, it usually comprises only the lowest portion of the Ancaster/Hibaldstow Beds; for example only the lowest 2.1 metres of the Ancaster Freestone exposed in the Little Ponton Railway Cutting (SK 930320; see Kent, 1966, p.65) belong in the new member. Furthermore, the Ancaster Freestone, seen in both Ancaster Quarries (SK 987435 and SK 979427, see also Richardson, 1939b, plate 29B) is not considered equivalent to the Metheringham Member at all, but is thought to be part of the "higher" Sleaford Member, which has erosively removed both the Blankney and Metheringham Members at Ancaster and therefore assumed an anomalously low stratigraphic position (Fig.4.2.). The Ancaster Freestone (= Sleaford Member) at Ancaster is not therefore thought to be equivalent to the lowest part of the upper Lincolnshire Limestone in other areas, as previously suggested by earlier workers (see Sylvester-Bradley, 1968, for review) but should have been correlated with the stratigraphically higher levels, that have usually been matched with the Ancaster Rag (Richardson, 1939b, plate 29B). Correspondingly, the Ancaster Rag at Ancaster has here been equated with still higher levels and re-named the Creeton Member in this classification (Fig.2.2.).

IV.8.e. Geographical and Geological Extent.

Despite having a wide geographical distribution (Little Ponton to Lincoln, and possibly as far north as Hibaldstow, see Fig.2.2.), the Metheringham Member is rather poorly exposed. Only three complete sequences are known (Little Ponton Cutting; Ropsley, TF 002364; and Metheringham) and of these only Metheringham occurs in a single uninterrupted succession. Because of this it is difficult to determine any thickening/thinning trends, although the Ropsley/Braceby area has noticeably thicker sections than elsewhere (Fig.4.2.). However this may not be of any particular significance, as this area approximately coincides with the thickest recorded Lincolnshire Limestone development (Kent, 1966, fig.2.).

South of Little Ponton, the Metheringham Member has not been recorded. At Castle Bytham (Sk 990180), where the next complete sequence through this level is seen, the Castle Bytham Member has replaced the Metheringham and Blankney Members (Fig.2.2.). Unfortunately, the contact between these lateral equivalents is not seen, although in the intervening districts (between Castle Bytham and Little Ponton) patchy occurrences of the lower part of the upper Lincolnshire Limestone show that the Castle Bytham Member facies occupies the basal 2 - 3 metres of upper Lincolnshire Limestone as far north as Stainby (SK 910233). Therefore the Metheringham Member must grade (?) into the Castle Bytham Member somewhere south of Little Ponton.

Although consistently overlain by the Blankney Member, the Metheringham Member rests upon different units of the lower Lincolnshire Limestone; it overlies the Lindsey Shale Member between Lincoln and Metheringham and the Scottlethorpe Member (Fig.2.2.) further south, whereas the Blankney/Metheringham Members contact is usually sharp without being noticeably erosive (hardground development occurs in some places, see Fig.4.2.), the nature of the lower contact is not so easily categorised. Where the Scottlethorpe Member is overlain the Metheringham Member sometimes has a shelly base (Ropsley), indicating a mildly erosive contact, as does the sharp, irregular junction between the units at Little Ponton. In contrast, the

the contact between the Metheringham and Lindsey Shale Member invariably looks gradational in the field (Fig.4.130), especially as weathered faces, and this suggests that the southward thinning of the shale may in fact be "natural" rather than due to the erosive downcutting of the upper Lincolnshire Limestone. However, which ever member is involved, it seems unlikely that much erosion has occurred at this level.

IV.8.d. Field descriptions of the lithologies and fauna.

Essentially the Metheringham Member is composed of poorly-fossiliferous, clean ooid-calcarenites, which may have significant proportions of peloids in the matrix; these impart a crude bimodality to the rock. Nowhere are sedimentary structures seen.

At Metheringham, the base of the yellowish-grey weathering, but blue-hearted strata shows large *Thalassinoides* sp. and other horizontal burrow networks penetrating the nutrient-rich Lindsey Shale (Fig.4.131). Abundant *Acanthothiris crossi* (J.F. Walker) and worm tubes occur in the shale between the burrows. The basal levels are usually composed of clean, well-sorted, sparite-cemented ooid-calcarenites, although in places the very lowest levels appear more micrite-rich. Higher up, peloids become an important constituent of the limestones, which are bimodal, ooid-peloid-calcarenites at the top of the unit.

Elsewhere this Metheringham pattern is not so obviously developed. For example, at Braceby Long Hollow (TF 010351) there is no discernible pattern at all, with two contrasting lithologies occurring randomly both laterally and vertically: a moderately well-sorted, sparite-cemented ooid-calcarenite and a crudely bimodal ooid-peloid-calcarenite. In the more northerly eexposures between Harmston and Kirton in Lindsey, a definite basal bed is developed, which grades up into the more typical, ooid-calcaranites. It is generally a shelly, poorly-sorted "dirty" ooid-calcarenite; micrite is the principal matrix component. The fauna, with cerithiid gastropods, Lucina bellona d'Orbigny and other bivalves accompanying the often prolific A.crossi (e.g. Kirton, SE 940014), forms a prominent part of this bed (0.45 metres thick), which was termed the "Upper Crossi Beds" by Kent (1966, fig.1.). Southwards the bed loses its distinctiveness, until at Metheringham it cannot be separated from the basal metre or so of rock (Fig.4.2; see also Richardson in Sylvester-Bradley, 1968, fig.42 .). However the patchy occurrence of a micritic matrix at this level, at Metheringham, mirrors the sequence of the more notherly exposures.

Apart from the "Upper Crossi Bed" level, the Metheringham Member is notable for its lack of fauna. Rare bivalve or gastropod fragments are seen and the occasional epithyrid, but generally the inimical, mobile substrate appears to have inhibited benthonic colonisation.

IV.8.e. Laboratory descriptions of the lithologies.

The characteristic lithofacies of the Metheringham Member is an oosparite in which the dominant ooliths and associated allochems are usually poorly sorted. Texturally, the rock is a grainstone (e.g. bed MQ H1, see Figs.4.132 and 4.133). The mostly "normal" ooliths (some superficial and composite ones occur), are of two main types: a small (0.2 to 0.5 mm.) suite of yellowish-green, spherical to ovoid ooliths, with a well-developed concentric structure contrast with larger (0.6 to 0.9 mm.) similarly shaped grey/black grains, in which the internal fabric is hardly discernible because of micritis-

-ation. This twofold grouping is not however ubiquitous and in some sections the ooliths are more homogeneous. The nuclei of both types (rarely seen in micritised ooliths) vary in size and shape but are usually composed of peloids or bioclasts (gastropods, bivalves, Bryzoa and echinoderm fragments). Of the other, subsidiary allochems, bioclasts are notable by their scarcity, the gastropod and bivalve sparite pseudomorphs (with micrite-envelopes), echinoderms, Bryzoa and foraminifera never form a significant part of the rock. Oncolites and peloids, on the other hand, can be important constituents, while intraclasts are only spasmodically present. The oncolites are generally distinguished by their large size and amorphous micritic rims, which often coat ooliths and micritised bioclasts. These "oncolitised" ooliths form a significant proportion of the highest bed at Metheringham (Fig.4.132). The generally ovoid peloids (polygenetic origin probably) often occur in clusters and may coalesce to produce "pseudo-micrite patches". Two generations of cement usually bind the allochems together: a poorly-developed, early isopachous acicular cement, rims the grains while a medium to coarsely-crystalline blocky sparite infills the remaining intra-granular pore space.

Higher up the Metheringham sequence, the "typical oosparite" lithofacies is lost with the oolith content of the rock decreasing and peloids becoming more important, together with detrital quartz. These changes culminate, at the top of the type succession, in a silty oncolitic pelsparite (bed MQ H6, Fig.4.132), in which large oncolites and bioclasts "float" in the abundant small peloids and quartz grains. Texturally the rock is a bimodal packstone. The apparent absence of ooliths is due to their "oncolitisation". Although this upward transition from oolites to peloid-dominated limstones is only seen at Metheringham (though it is probably typical of central Lincolnshire), the more southerly successions have increased proportions of interstitial peloids "contaminating" the characteristic oosparite at some levels.

The distinctive basal bed (= Upper Crossi Bed), occurring between Harmston and Kirton in Lindsey varies a good deal. For example at Greetwell (TF 003721) it is a poorly-sorted, oosparite packstone, similar compositionally to the more typical Metheringham Member oosparites, although with more mud in the matrix. The packstone istypical of the Lincoln/Harmston area as a whole. However, at Kirton (SE 940014) this level is a biomicrite (wackestone; Fig. 4.134) with abundant bioclasts of bivalves, gastropods, foraminifera, brachiopods, echinoderms, worm tubes and Bryzoa.

IV.8.f. Discussion.

North of Metheringham, the overall homogeneity of the Metheringham Member is lost as a distinct, shelly, "dirty" oolite, containing A.crossi, occurs at the base of the unit. This bed, which can be traced as far north as Kirton in Lindsey (Fig.4.2; see also Sylvester-Bradley, 1968, fig.42) differs from more typical Metheringham Member beds in its abundant faunal content (Richardson, 1940, p.255) and texture, raising the problem of the bed's stratigraphical affinities; a problem upon which there has been no real agreement in the past. For example at Kirton in Lindsey, where it is most clearly developed, the "Upper Crossi Bed" was included in the Kirton Beds by Richardson (1940, p.255), who therefore implied an association with the Lower Lincolnshire Limestone. However in later work, he correlated much of the Kirton Beds with the Ancaster Freestone of the Upper Lincolnshire Limestone (see Sylvester-Bradley, 1968, fig.42.).

In comparison, Kent (1966, fig.1 and p.61) classified the bed individually as the Upper Crossi Bed but grouped it with the Hibaldstow Beds of the Upper Lincolnshire Limestone.

Wherever seen, the bed appears to grade up into the oolites of the Metheringham Member and down into the Lindsey Shale Member, so that it is not genetically excluded from either unit. However, at Kirton (SE 940014) the oolitic nature of the bed makes it more akin to the Metheringham Member than the limestones of the Kirton Cementstones Member (Ashton, 1975; part of Richardson's Kirton Beds); because of this and the fact that the most obvious lithological division occurs between the Lindsey Shale and the limestone above, the problematic bed has been included within the Metheringham Member here. Although this broadly follows the procedure of Kent (1966) the bed has not been individualised in any way because its southward gradation into the member at Metheringham is thought sufficient reason for it to be considered as a basal faciesvariant of the Metheringham Member.

Although the inclusion of the enigmatic bed within the upper Lincolnshire Limestone broadly follows the later thinking of Richardson (in Sylvester-Bradley, 1968, fig.42), the relationships seen at Harmston (SK 992619) demonstrate that the approximate correlation of the upper part of the Kirton Beds with the Ancaster Freestone further south, suggested by Richardson (in Sylvester-Bradley, 1968, fig.42) is unlikely; rather the Lindsey Shale Member (= Kirton Cement-Shale of Richardson, 1940) appears to be equivalent to the Scottlethorpe Member and as such is part of the lower Lincolnshire Limestone as defined in this thesis (Fig.2.11).

At the eastern end of Harmston Quarry, typical Metheringham

Member oolites with a basal "dirty" oosparite (= Upper Crossi Bed) overlie a thin marl, which in turn rests upon oolites forming the Lincoln Member. (The position of these oolites immediately above the distinctive Leadenham Member calcilutites leaves no doubt as to the relative stratigraphical position of this part of the sequence). However, towards the western end of the quarry the marl band is largely replaced by limestone (Fig.4.127), which resembles those of the Scottlethorpe Member further south; this is thought to be the Scottlethorpe Member interdigitation with the very attenuated Lindsey Shale Member. There seems little reason to doubt the existence of the Lindsey Shale at Harmston, for at the relatively nearby quarries of Metheringham and Dunston (TF 053634) the shale is still about one metre thick, having thinned only very gradually from Lincoln. If this correlation is indeed correct, theh firm evidence is provided for the Lindsey Shale Member being in the lower, rather than the upper Lincolnshire Limestone (Fig.2.2.).

IV.9. BLANKNEY MEMBER.

IV.9.a. Introduction.

The Blankney Member is essentially comprised of thinly-bedded, peloidal, ooid- and quartzose peloidal calcarenites, the latter often spectacularly rich in "Nerinea" spp. gastropods (Fig.4.135; see also Richardson, 1940, p.249). Despite taking its name from Blankney Quarry (TF 062592), the stratotype of the member is at Metheringham (TF 053616) where a complete section (approximately 2.1 metres thick) is more clearly seen (Fig.4.136); quarrying is rarely deep enough at Blankney to expose the base of the member. However the lithofacies seen at Metheringham (quartzose peloidal calcarenites) is not characteristic of the whole member; and a hypostratotype, Braceby Long Hollow Quarry (TF 010351; Fig.4.137) has been selected to illustrate the twofold lithological division, more typical of mid-Lincolnshire.

IV.9.b. <u>Former Terminology.</u>

Like the Metheringham Member, the Blankney Member forms a discrete unit, which was previously undivided from the beds termed the Ancaster Freestone (Richardson, 1939b but not plates 29A and B; Hollingworth and Taylor, 1951; Kent, 1966 fig.1.), the Ancaster Beds (Kent, 1940; Swinnerton and Kent, 1976) and Hibaldstow Beds (Richardson, 1940 ?, see also Sylvester-Bradley, 1968, fig.42; Kent, 1940 and 1966, fig. 1; and Evans, 1952). The few recorded thicknesses attributed to the Ancaster/Hibaldstow Beds (minimum thickness 7.0 metres, see Kent, 1940, p.52 and 1966, p.65; and Evans, 1952, p.329) suggest that both the Metheringham and Blankney Members (maximum combined thickness of 4.8 metres at Braceby Long Hollow, see Fig.4.2) are easily accommodated within that unit, and therefore the Blankney Member is unlikely to have been even partially equivalent to any higher beds. This assumes however that the Ancaster Freestone of Ancaster (Richardson, 1939b, p.473) is not lithogenetically related to the Ancaster/Hibaldstow Beds elsewhere, and that neither the Metheringham nor Blankney Members are associated in any way with the Ancaster Freestone of Ancaster (see section IV.8.b.).

IV.9.c. <u>Geographical and Geological Extent</u>.

The Blankney Member is readily traced eastwards across mid-Lincolnshire, via a series of abandoned quarries, from Spittlegate Hill, Grantham (SK 937342) to Dembleby Farm (TF 034371; see Fig.2.1.). Throughout these pits the member always rests upon the Metheringham

Member and is in turn overlain erosively by the Sleaford Member (Fig.4.2.); relationships that are consistently seen wherever the Blankney Member is developed.

Southwards from the Grantham-Dembleby district, the member is only seen at Little Ponton (SK 930320); further south exposures at this level are particularly scarce and it is not until Castle Bytham (SK 990180) is reached that a complete succession through these horizons is seen. There, the stratigraphy is quite different with the Castle Bytham Member having laterally replaced both the Metheringham and Blankney Members (Fig.2.2.). In contrast, northwards from mid-Lincolnshire, the Blankney Member can be readily traced via Brauncewell (TF 028518) to Blankney and Metheringham, where it has its maximum development of over two metres. In these quarries the bipartite division, typical of Brauncewell and further south, is lost, being replaced by the more homogeneous quartzose peloidal calcarenite facies, rich in "Nerinea".

Beyond Metheringham, the Blankney Member cannot readily be followed: the approximate level at Greetwell is not accessible and few exposures exist north of Lincoln. However, in an abandoned quarry just south of Hibaldstow (SE 973008; see Fig.2.1.) the Blankney Member is thought to accur sandwiched between lithofacies resembling those of the Metheringham and Sleaford Members. Despite the attractiveness of this theory it would seem unwise to attach too much credence to the evidence of a single, isolated exposure; supporting evidence is needed. If this correlation is confirmed, however, it will show that in sharp contrast to the lower Lincolnshire Limestone, the geological history of the upper Lincolnshire Limestone of this northern region was similar to the rest of the county.

IV.9.d. Field descriptions of the lithologies and fauna.

At Metheringham, the thinly-bedded, yellowish-orange weathering, quartzose peloidal calcarenites (Lithofacies A), often strikingly rich in high-spired gastropods, are typically fine grained and well sorted. The silt content, most evident in the lower beds, where "dogger-like" concretions are developed (Fig.4.138), decreases upwards. The sediment surrounding the "doggers" is often quite friable. Ooids occur in the uppermost beds.

Besides the ubiquitous, high-spired gastropods that appear to have a preferred N-S alignment (especially at Blankney) few body fossils occur at Metheringham. However, dense concentrations of vertical burrows are seen on weathered, loose blocks (Fig.4.139). Although some appear "paired" in plan view, only rarely have connective relationships been seen between adjacent pipes and the majority of these burrows are therefore thought to be of the Skolithos type. In other localities, where this kind of lithofacies sequence is seen (Blankney and Ropsley, TF 002364) the "body fauna" is similarly restricted; a few large, disarticulated and "convex-up" terebratulid valves are seen at Blankney, and similarly preserved epi-faunal bivalves and rare solitary corals augment the "Nerinea" fauna at Ropsley. In addition, the "knobbly" hard beds at the base of the Blankney section may be preferentially cemented accretions around large burrows, such as Thalassinoides (Fursich, 1974) although this has not definitely been shown to be the case.

The Blankney Member in mid-Lincolnshire (Brauncewell to Braceby, Fig.2.1.) shows a variety of lithofacies sequences and lithologies, which can be resolved into two principal lithofacies types. At Braceby Long Hollow contrasting peloidal (Lithofacies A) and ooid-calcarenites (Lithofacies B) alternate rapidly up the sequence, which is initiated and concluded by ooid-calcarenites. However, at Dembleby Lithofacies B grades up into A (in broad terms) whereas at Brauncewell the reverse sequence is seen.

IV.9.d.i. Lithofacies A: The compact, peloidal calcarenites are mostly fine grained and well sorted, with "*Nerinea*", worm tubes and water-worn and fragmented epifaunal bivalves, such as *Camptonectes* and *Inoceramus* being the principal faunal elements.

IV.9.d.ii. Lithofacies B: The bimodal, ooid-peloidal calcarenites have low to moderate amounts of ooids floating in a peloid-rich matrix. Some large irregular intraclasts (?) also occur.

West of Braceby, at Spittlegate Hill and Little Ponton, ooid-dominant calcarenites, which only occur sporadically further east, provide a third lithofacies type.

IV.9.d.iii. Lithofacies C: This consist of poorly-sorted ooid-calcarenites with subsidiary intraclasts and skeletal grains, predominantly bivalves and gastropods. This facies may give way at the top of both the Spittlegate and Little Ponton sequences to a more even-grained sparite-cemented ooid-calcarenite.

At Spittlegate, these more ooid-rich beds occur at the top of the sequence, overlying micritic limestones, while the Little Ponton succession is almost entirely composed of the "dirty oolites" (Lithofacies C), with only the central part having an increase of micrite in the matrix.

The isolated upper Lincolnshire Limestone sequence at Hibaldstow in South Humberside is initiated by an even-grained, cleanly-washed ooid-calcarenite (Lithofacies C), that passes up into bimodal ooid-peloid-calcarenites (Lithofacies B). Higher still the unit shows laterally impersistent, small-scale, fining upward sequences, in which coarse-grained, ill-sorted, ooid-calcarenites with subsidiary intraclasts and skeletal grains ("Nerinea", corals and rare bivalves; a variant of Lithofacies C) grade up into fine-grained, well-sorted, barren peloidal calcarenites (Lithofacies A). Each rhythm is of the order of 10 - 20 cms.. The whole sequence is capped by a rippled unit of cleanly-washed, moderately well-sorted ooid-calcarenite (Lithofacies C).

As these lithofacies are more akin to those of the Blankney Member than any other upper or indeed lower Lincolnshire Limestone unit, they have been tentatively assigned to this member.

IV.9.e. Laboratory descriptions of the lithologies.

The Blankney Member is typified by pelsparites (Lithofacies A and A') which in many mid-Lincolnshire localities have subsidiary amounts of mixed peloid-oolith limestones (Lithofacies B). The quantitatively less important Lithofacies C oolites represent the oolith-dominated end of the member's compositional range (Fig.4.140).

IV.9.e.i. Lithofacies A: This facies is composed of very well-sorted quartzose pelsparites (Fig.4.141), which, in addition to the peloids, contain variable amounts of detrital quartz and minor quantities of bioclasts and ooliths. Although sparite (a poorly-developed, rim-cement pre-dates a blocky, infilling sparite) is clearly dominant over micrite, these rocks are texturally packstones. However, much of the micrite may have resulted from peloid breakdown, for many of the amorphous-micrite grains lack a definite shape, suggesting an original "softness". Other peloids are spherical to ovoid (faecal ?) but the overall shape range suggests a polygenetic origin for the peloids as a whole. The randomly scattered, subrounded to subangular quartz grains occur with minor quantities of white mica. Gastropods, bivalves (commonest), echinoderms, foraminifera and ostracods constitute the scarce bioclasts, while the few "normal" ooliths are outnumbered by incipient ones, which are not easily distinguished from the peloids.

South from central Lincolnshire, this lithofacies is reflected by Lithofacies A', which is differentiated from A by its lack of abundant quartz and grainstone texture (Fig.4.142).

IV.9.e.ii.Lithofacies B: The peloidal and skeletal oosparites (Fig.4.143) of this facies tend to be finer-grained than the oosparites of Lithofacies C. The dominant ooliths are small, and generally near-spherical with peloidal nuclei; many could be termed "incipient" and resemble large peloids in many cases. Variable quantities of peloids and bioclasts (Bryozoa, bivalves, gastropods, echinoderms and foraminifera) together with rare, large, often irregularly-shaped intraclasts, make up the remainder of the rocks, which are cemented by a coarsely-to-very-coarsely crystalline, blocky cement. An early, acicular rim-cement is also sparodically developed. Texturally grainstones, these rocks vary from being bimodal to quite well sorted.

IV.9.e.iii.Lithofacies C: This, the least "typical" facies of the member, is coarser grained than the lithologies comprising the other lithofacies. Like B, it is dominated by ooliths but these are "high-energy types" with good concentric laminations coating predominantly peloid nuclei. Although most of the very dominant "normal" ooliths are spherical to ovoid, less regular shapes are seen in the superficial to composite ooliths. Bioclasts are the second most abundant allochems in these skeletal oosparites (Fig.4.144). Echinoderm and bivalve fragments are the commonest types but brachiopods and Bryozoa also occur. Minor amounts of intraclasts (large, amorphous micrite-lumps or composite grains) and interstitial, polygenetic peloids make up the remainder of the grains, which are set in the mixed sparite-micrite matrix of these poorly-sorted packstones. Sparite is dominant over micrite, which may partly be the product of peloid breakdown. As with B, a poorly-developed, early rim-cement pre-dates a medium - crystalline, blocky sparite.

IV.9.f. Discussion.

Although lithologically diverse, the Blankney Member is readily recognised in mid-Lincolnshire because its characteristically fine-grained, peloid-calcarenites contrast with the generally coarser-grained, ooid-dominated sediments of the enveloping Metheringham and Sleaford Members, However, similar peloidal lithologies also occur at the top of certain sedimentary rhythms in the Sleaford Member (in particular at Blankney Quarry), although nowhere do these attain the thickness seen in the Blankney Member. Furthermore, the kind of sedimentological setting and facies sequence seen in the Sleaford Member are readily distinguished from those in the Blankney Member. Therefore, the dominance of the peloidal facies imparts a degree of lithological distinctiveness and consequently correlative value to the Blankney Member, which has been used to tie otherwise problematic sections (like Brauncewell) into the proposed upper Lincolnshire Limestone lithostratigraphic scheme.

In the more westerly exposures (Spittlegate Hill and Little Ponton), where the peloidal influence is much reduced, the thin bedding and general stratigraphical sequence usually enables the unit to be recognised.

IV.10. CASTLE BYTHAM MEMBER.

IV.10.a. Introduction.

The Castle Bytham Member, forming the basal part of the upper Lincolnshire Limestone in south Lincolnshire, is mainly composed of ooid-calcarenites and subsidiary calcilutites. The type section at Castle Bytham (SK 990180; see Fig.4.145) exposes a reasonably thick (2.9 metres), clearly defined and accessible sequence, which has yielded some important ammonite specimens (Chapter III).

IV.10.b. Former Terminology.

The Castle Bytham Member is laterally equivalent to the Metheringham and Blankney Members of central Lincolnshire, and, as such is at the "Ancaster Beds level" of earlier workers. In constitutes part of the Ancaster Beds (Kent, 1940; see also Kent in Sylvester-Bradley, 1968, p.233; and Swinnerton and Kent, 1976) and the Ancaster Freestone (Richardson, 1939b, but not plates 29A and B; Hollingworth and Taylor, 1951; and Kent, 1966, fig.1.). In detail the type section is equivalent to most of the Bastard Freestone (Richardson, 1939a, p.43 = Bed 2 of the Ancaster Beds of Kent in Sylvester-Bradley, 1968, p.223) and part of the overlying "unnamed beds" (Richardson, 1939a = lower part of Bed 3 of the Ancaster Beds of Kent in Sylvester-Bradley, 1968, p.223).

South of Castle Bytham, the lithostratigraphy of the upper Lincolnshire Limestone is complicated by the erosive nature of many of the units. Myriad terms have been introduced to designate the local successions (see Sylvester-Bradley, 1968, for review), which have only been tentatively correlated and imprecisely defined geographically. For example, the "Freestone of Lings" (Richardson, 1939a; and Kent, 1940 and 1966, fig.1) and Ketton Freestone (Kent, 1940 and 1966, fig.1; Hollingworth and Taylor, 1951),which are usually considered to be the southerly equivalents of the Ancaster Beds,have never had their northern margins defined,and it is possible that the Castle Bytham Member could be partly equivalent to those units also. However, the member is not part of the Clipsham Stone as outlined by Swinnerton and Kent (1976, p.38) and such a low stratigraphical position for the Clipsham Stone has not generally been advocated (Kent, 1940, p.51; Richardson, 1939a, p.42; and Hollingworth and Taylor, 1951, p.19) even by Swinnerton and Kent themselves (1976, fig.9). The position of the Clipsham Stone in the scheme proposed here is discussed in section IV.12.b.

IV.10.c. Geographical and Geological Extent.

The scarcity of sections through the Castle Bytham Member makes it difficult to determine the member's geographical distribution and to elucidate its stratigraphical relationships. From the available exposures the member appears to occur throughout south Lincolnshire (Sproxton, SK 866253, to Woolfox, SK 951136). Further north it is replaced by the Blankney and Metheringham Members (Fig.2.2.), although nowhere is the transition seen (see section IV.8.c.). Within the south Lincolnshire area no clear-cut thickness variations are evident. Along the NE-SW line of good exposures (Scottlethorpe, TF 046204, to Woolfox) the little variation there is, appears to suggest a thickening away from Castle Bytham in both directions (Fig.4.2), but as these differences are so slight, little significance can be attached to them.

The contact between the Castle Bytham Member and the underlying Scottlethorpe Member of the lower Lincolnshire Limestone is variable; at Woolfox the Soil Fertility Quarry, Clipsham (SK 978154), corals in the top of the Scottlethorpe Member are truncated, indicating erosion prior to the deposition of the Castle Bytham Member. Similarly erosive contacts are suggested by the sequences at Sproxton, Stainby (SK 910233) and South Witham (SK 917189), where ooid-calcarenites rest upon "lower-energy" calcilutites and grain-poor ooid-calcarenites (Fig.4.2). In contrast the base of the type section (Castle Bytham) is arbitrarily drawn at the first break within the gradational sequence that characterises not only the lower/upper Lincolnshire Limestone succession at Castle Bytham, but also those at Scottlethorpe and Little Bytham (TF 013178; Fig.4.2).

Where seen, the Castle Bytham Member is cut into by overlying units: the Sleaford Member at Castle Bytham and Scottlethorpe, where "typical" south Lincolnshire successions are developed, and the Creeton Member at the Soil Fertility Quarry, Clipsham (Fig.4.2). In this locality the Sleaford Member has apparently been removed by the downcutting of the Creeton Member (= Clipsham Beds, see section IV.12.b.).

IV.10.d. Field descriptions of the lithologies.

The grey, grain-poor and grain-rich ooid-calcarenites and subsidiary calcilutites of the member frequently appear in a distinctive arrangement, which is characterised by the type section. At Castle Bytham, the base of the member is arbitrarily drawn within a sequence of "clean", poorly-sorted, sparite-cemented ooid-calcarenites (Lithofacies A), which pass up into crudely bimodal, ooid-dominated limestones. Although variable, these beds are essentially poorly-sorted, with dominant ooids and intraclasts set in a more micrite, peloid-rich matrix (Lithofacies B). Higher still grain-poor ooid-calcarenites and/or calcilutites (Lithofacies C) occur, indicating a further reduction in current activity, which is accompanied by an increase in the abundance of benthonic organisms. Terebratulids appear to be the most important group. The allochems at this level, although quantitatively insignificant, are variable with ooids, peloids and intraclasts, occurring scattered randomly throughout the beds. Above the calcilutites, the current activity starts to increase again upwards to complete a crude, high-low-high energy cycle and impart a lithological symmetry to the member. The calcilutites (the low-energy axis of the symmetry) are replaced by burrowed, moderately well-sorted, micrite-rich ooid-calcarenites (Lithofacies B), which are themselves followed by poorly-sorted, sparite-cemented, ooid-calcarenites (Lithofacies A).

Away from Castle Bytham the symmetrical pattern is also seen at Little Bytham and Scottlethorpe (Fig.4.2), although the latter is a completely oolitic sequence without calcilutites; the "central energy low" is reflected only by an increase in micrite in the matrix giving the oolites a "dirty" appearance. However, no such pattern is evident at the Soil Fertility Quarry, Clipsham, where the succession is composed of poorly-washed, ooid-calcarenites throughout, although a more micritic matrix appears to be present in the uppermost beds. Elsewhere (Sproxton, Stainby and Woolfox) only the basal part of the member is seen, but here too, grain-rich, poorly-washed ooid-calcarenites give way to impure calcilutites, that may be quite fossiliferous. For example, at Sproxton, epifaunal bivalves (pectinids and Ctenostreon) have been seen in addition to gastropods, brachiopods and burrows.

IV.10.e. Laboratory descriptions of the lithologies.

Although three distinct lithofacies have been suggested for the Castle Bytham Member, they form part of a "facies gradient", within which arbitrary divisions have been drawn. The end members (Lithofacies A and C) are fairly readily characterised, but the intervening Lithofacies B is diverse. Therefore the lithofacies characteristics, shown in figure 4.146, illustrate only representative lithologies found in the facies spectrum. Essentially a textural range from grainstone - packstone - wackestone is seen.

IV.10.e.i. Lithofacies A: Characteristically, this is a poorly-sorted oosparite (Fig.4.147), which has subsidiary amounts of bioclasts, intraclasts and peloids associated with the very dominant ooliths. The quite closely-packed allochems are bound by two generations of cement: a poorly-developed, isopachous rim-cement, pre-dating a medium-to-very-coarsely-crystalline blocky sparite. Little interstitial micrite is seen and the rock is texturally a grainstone. The ooliths vary in size and, like their Metheringham Member counterparts, the larger ones have often suffered extensive micritisation and good concentric structures are only seen in the smaller grains. The spherical to ovoid ooliths have epeloidal or bioclastic nuclei and are predominantly "normal" in type, although micritisation obscures the structure in some cases. A few superficial and even rarer multi-nucleate composite ooliths also occur. Bioclasts are the second most abundant allochem group, with bivalves generally predominating, but gastropod, echinoderm, brachiopod and worm tube fragments are also seen. The calcitic elements survive unaltered but the aragonitic forms are usually preserved as sparite-pseudomorphs with micrite-envelopes. Minor amounts of intraclasts and/or polygenetic peloids may also be present.

IV.10.e.ii.<u>Lithofacies B</u>: This facies ranges from peloidal oosparites (Fig.4.148), that are texturally grainstones/packstones, to biopelsparites (Fig.4.149), which are close to the packstone/ wackestone boundary. The former lithology, which is closely aligned to Lithofacies A, is bimodal with the small interstitial peloids contrasting with the dominant ooliths, subsidiary bioclasts (bivalves, gastropods, brachiopods and foraminifera) and very rare intraclasts. The ooliths are very similar to those of Lithofacies A, except that some have oncolitic outgrowths. The diverse peloids may well be polygenetic. At this end of the spectrum sparite is dominant over micrite, the latter appearing to result from coalescence of peloids. In micrite-free areas, an "early rim" and "later blocky" cement are seen. "Towards" Lithofacies C micrite becomes more important and eventually dominant. Bed CBQ G3b illustrates this end of the lithological range. It is difficult to decide whether this rock is a poorly-sorted packstpne or wackestone, for although micrite is dominant, much of it appears to have been developed by peloid coalescence. Compositionally the rock is close to Lithofacies C however, for bioclasts (bivalves, Bryozoa, brachiopods, echinoderms and foraminifera) are the commonest allochems, followed by peloids, the exact abundance of which is difficult to decide because of their coalescence. Minor amounts of ooliths, intraclasts, oncolites and detrital quartz are also present.

IV.10.e.iii.<u>Lithofacies C</u>: This facies is represented by poorly-sorted oncolitic biomicrites (Fig.4.150) in which oncolites and bioclasts (mostly bivalves, gastropods and Bryozoa) are by far the commonest grain types. Texturally a wackestone, the micrite gives way to sparite in protected areas under shells, and again it appears as though some of the micrite has resulted from the coalescence of peloids, which together with rarer silt and micritised ooliths make up the remainder of the rock. The oncolites are large, often composite, and rounded grains. Many are algally-coated, micritised ooliths and intraclasts. Although approximately ovoid in shape, many have asymmetric, amorphous micrite growth-rims, in which darker brwon "lines" depict times of growth cessation.

IV.10.f. Fauna.

Of outstanding interest in the fauna of the Castle Bytham Member are the three Sonninia (Fissilobiceras cf. ovalis (Buckman ex.Qu.) specimens from Castle Bytham, that are the only representatives of the ovalis Subzone of the laeviuscula Zone to have been recovered from the upper Lincolnshire Limestone (see Chapter III). The occurrence of two of these specimens high in the Castle Bytham Member sequence (Figs 3.2 and 3.4) and of a Shirbuirnia cf. S.fastigata Buckman (indicative of the younger, laeviuscula Subzone of the laeviuscula Zone; see Chapter III) low in the overlying Sleaford Member (also at Castle Bytham) allows the upper boundary of the ovalis Subzone to be quite narrowly delimited in this locality and a hitherto unrecognised biostratigraphical subdivision of the upper Lincolnshire Limestone to be demonstrated. Evidence confirming a similar age (or any age) for the other Castle Bytham Member sequence is lacking.

The benthonic fauna is dominated by epifaunal and vagile, shallow infaunal species (Fig.4.151). Few, if any of the forms are found in life position, and the skeletal debris and "convex-up" orientation of disarticulated bivalves suggest that the bottom was for some time at least, current washed. However the degree of current activity probably varied, as reflected by the range of lithofacies. Also the calcilutites' fauna of articulated terebratulids was very likely indigenous to that substrate. Certainly a substrate-fauna relationship is suggested by the terebratulids apparent restriction to this lithofacies, which may reflect their dislike of turbid waters and mobile substrates (Hurst and Fursich, 1974). Similarly the colonial corals only seem to occur in the ooid-calcarenite lithofacies, and they too, because of their preference for turbulent waters, may be substrate-related. Generally however, the epifaunal nature of much of the fauna (which makes it more susceptible to reworking and breakage) and the definite, if sporadic, current activity, make sediment-fauna relationships difficult to determine, although it would seem from general preservational considerations, that much of the fauna has probably not been transported very far. In contrast, the disarticulated A.crossi valves at the base of the Stainby sequence testify to either the reworking of the underlying Scottlethorpe Member or quite active currents during Castle Bytham Member times because A.crossi usually occurs articulated wherever it is found.

IV.10.g. Discussion.

The only major problem concerning the Castle Bytham Member lies in its relationship with the stratigraphically equivalent Metheringham Member (Fig.2.2.). As both of these units are essentially ooid-calcarenites it might have seemed more reasonable to have grouped them together in a single unit as previous correlations have tended to do (see Sylvester-Bradley, 1968, for review). However, quite different environmental conditions are reflected by the litho-and biofacies present in these units: in the case of the Metheringham Member the oolites are well-washed and barren of fauna, suggesting a mobile, current-swept substrate, while a muddier, more stable bottom is indicated by most of the sediments and faunas of the Castle Bytham Member. This would therefore seem to favour a classification into separate members, particularly in view of the unit's geographical separation.

IV.11. SLEAFORD MEMBER.

IV.11.a. Introduction.

The Sleaford Member, the thickest single unit within the upper Lincolnshire Limestone, is composed of a complex of lithofacies of which skeletal and ooid-calcarenites, and "oncolitic" calcirudites are the most common. Cross-bedding is frequently developed. Copper Hill Quarry, Ancaster (SK 979427) was chosen as the type section because it is one of the few sequences to show a completely exposed succession (4.83 metres thick) with a clearly distinguishable base and top (Fig.4.152). However, as it is representative of only part of the lithofacies complex, Castle Bytham (SK 990180) and Blankney (TF 062592) have been designated hypostratotypes to illustrate some of the member's other lithofacies and facies sequences.

The name Sleaford has been adopted rather than Ancaster to avoid any confusion with the well-known Ancaster Freestone and Ancaster Rag units of earlier terminologies.

IV.11.b. Former Terminology.

The stratigraphical subdivisions proposed for the Lincolnshire Limestone by earlier workers have been, for the most part, poorly defined. Few boundaries have been depicted on measured sections, making it difficult to correlate exactly the "new" and "old" strati-

-graphic terminologies. However, in the case of the Sleaford Member, a few sections have been published, which allow certain relationships clearly to be understood. For example, at Ancaster, the Sleaford Member is directly equivalent to the Ancaster Freestone, as defined by Richardson (1939b, p.473 and plate 29B) Newton and Scott's Quarry is now called Copper Hill Quarry). However, such a relationship between the Ancaster Freestone and the Sleaford Member only applies to the Ancaster village quarries for, as mentioned in section IV.8.b., the Ancaster Freestone of Ancaster is thought to belong to a higher stratigraphic level than the other beds usually attributed to the Ancaster Freestone (or Ancaster Beds) by earlier workers, e.g. those at Little Ponton (SK 930320; see Kent, 1966, p.65). Furthermore, the Ancaster Freestone of Thompson's Quarry, Wilsford Heath near Ancaster (SK 992409; see Richardson, 1939b, plate 29A) certainly does not belong in the Sleaford Member (see section IV.12.b.). Elsewhere the only other beds that are known to be precise equivalents of the Sleaford Member are the Ancaster Beds (part of 3 and 4 to 7 inclusive) at Castle Bytham (Kent in Sylvester-Bradley, 1968, p.223); a part of these was included in the "Roadstone" of Richardson (1939a; see Fig.3.4.).

More generally, the Sleaford Member is believed to be equivalent, in part at least, to the Ancaster Freestone and Great Ponton Gastropod Beds (including the _Amberlya_ Bed) of Richardson (1939b), Kent (1940 and 1966); the Ancaster Freestone of Wilson (1948) and Hollingworth and Taylor (1951); the "coarse, shelly oolites and psiolites of Great Ponton" of Hollingworth and Taylor (1951); the Ancaster Beds and Great Ponton Beds of Swinnerton and Kent (1976) and directly equivalent to their Ancaster Beds at Castle Quarry, Ancaster (SK 987435) and the Hibaldstow Beds of Ussher (1890), Richardson (1940), Kent (1940, 1948 and 1966), Wilson (1948), Swinnerton and Kent (1976), and Evans (1952).

IV.11.c. Georgraphical and Geological Extent.

At Castle Bytham, a "complete" upper Lincolnshire Limestone succession shows the Sleaford Member sandwiched between the Creeton and Castle Bytham Members (Fig.4.2.). However, a little to the south, at the Soil Fertility Quarry, Clipsham (SK 978154), the Sleaford Member appears to have been cut out by the Creeton Member, which rests directly upon the Castle Bytham Member (Fig.4.2.). Such downcutting may persist southwards, restricting the Sleaford Member to areas north of Clipsham (see section IV.12.c.), where it is known to be widely developed, probably as far north as Hibaldstow (SK 987435; Fig.2.2.).

Between Castle Bytham and Ashby de la Launde (TF 052570) the member is constantly overlain by the Creeton Member, with either a mildly erosive or "hardground" contact (Fig.4.153). At Ashby itself however, the Creeton Member development is very thin and it appears to be "dying out"; further north it is doubtful if the Creeton Member is preserved and the Upper Estuarine Series probably rests directly upon the Sleaford Member, although nowhere is the appropriate level exposed to confirm this hypothesis.

In contrast to the relative simplicity of the upper boundary of the Sleaford Member, the relationships of its lower contact are complex. North of Castle Bytham the base of the unit is not seen until Great Ponton Quarry (SK 935303), where the member rests erosively upon the Lincoln Member of the lower Lincolnshire Limestone (Fig.4.120). Similar extensive downcutting has occurred at Copper Hill, Ancaster (SK 979427 ; Fig.4.113), the Wilsford Heath quarries (SK 987414 and SK 992409, see section IV.12.b. and Brodie, 1853), and to a lesser extent at Castle Quarry, Ancaster (SK 987435 ; Fig.4.2.).

However, this downcutting is localised, for more normal mid-Lincolnshire sequences, where the Sleaford Member rests upon the Blankney Member (Fig.2.2.), are seen in the quarries between Little Ponton and Dembleby Farm (TF 034371) and in sections to the north of Ancaster. Further instances of localised "channelling" are also thought to occur at Creeton (SK 999205), where an anomalously thick Sleaford Member succession (over 12 metres) occurs (Fig.4.2.) and in the south-eastern corner of Greetwell Quarry (TF 003721).

As the member shows striking thickness changes it is difficult to elucidate its distribution by thickening/thinning trends. The available evidence shows that the thickest sequences occur around Blankney, Great Ponton and Creeton, which are all areas where the formation as a whole tends to be at its thickest.

IV.11.d. Field description of the lithologies and fauna.

Although typically composed of cross-bedded oolites, the Sleaford Member is in fact a facies-complex, including a wide variety of lithologies, which range from "biohermal micrite" to "pisolitic" oolites to peloidal limestones. In many cases the lithotypes are arranged in distinct sedimentary sequences amongst which both coarsening- and fining-upwards rhythms are represented. Because of this complexity the member's facies have been grouped into four main types, which are represented, to some extent at least, by the proposed stratotypes:

(1) Cross-bedded oolites

(2) Fining-upwards rhythms

(3) Caorsening-upwards rhythms

(4) "Biohermal micrites"

However, although these particular quarries are stratigraphically the most important, they do not fully cover the range of facies or rhythms seen, and other successions often provide better examples. For this reason each of the facies groupings has been discussed with respect to "ideal examples" regardless of their absence/presence in the stratotypes.

IV.1ȧ.d.i. <u>Cross-bedded oolites: Lithofacies group A</u>: The cross-bedded oolites form the most common single lithofacies type (Lithofacies A1) of the whole member and although they constitute most of the type section (Fig.4.2), Brauncewell Quarry (TF 028518) arguably shows the most spectacular development of this facies: thick cross-bedded units (3.2 metres) of poorly-sorted, ooid-calcirudites and subsidiary "clean", well-sorted ooid-calcarenites are excellently displayed (Fig.4.154). The "raggy" levels are particularly rich in oysters, although gastropods and worm tubes also occur. The quite steep (mostly 10° to 30°), planar foresets dip approximately east-southeastwards (Fig.4.155) and show crude grading, which is more clearly developed at Creeton. There, the much smaller-scale, cross-bedded units with low angle, slightly concave foresets "drawn-out" into bottom sets (Fig.4.156) have coarse-grained, poorly-sorted, bioclastic-rich layers grading up into medium-grained, well-sorted, even-grained oolitic layers. Such foreset grading, which is a common feature of this lithofacies, also reflects the lithological spectrum of Lithofacies A1 as a whole and together with the cross-bedding, is typical of the sequence seen at Spittlegate Hill (SK 937342), Little Ponton Railway Cutting, Castle Quarry, Ancaster, South Rauceby (TF 029452) and the railway cutting (SK 937298) and quarry at Great Ponton, as well as the pits already mentioned. The fauna of these beds is largely comminuted, except for many of the mechanically stronger gastropods, and the abundant <u>Lopha</u> seen in the railway cutting sequence at Great Ponton, where "wedge" co-sets occur instead of the more typical tabular variety. Similar "wedge-sets" are also seen at North Rauceby (TF 021474).

North of these localities, the cross-bedded oolites are often rich in "pisoliths", which can be very large (50 x 20 mm. seen). At Blankney, such grains occur prolifically within a "background sediment" of ooid-calcarenites. The resultant poorly-sorted, "pisolitic" ooid-calcirudites (Lithofacies A2) display multi-directional cross-bedding (Fig.4.157) and similar crude foreset grading to that of Lithofacies A1; the "pisoliths" tend to occur in the coarser, basal layers and are generally preferentially concentrated within certain layers. Similar cross-bedded calcirudites also occur at Ashby de la Launde and Thompson's Bottom Quarry (TF 026555), where an important associated facies is also seen.

Above a thick, cross-bedded "pisolitic" ooid-calcirudite unit at Thompson's Bottom, a parallel-bedded sequence of "pisolitic" ooid-calcirudites occurs, in which thin ($<$ 15 mm.) "wafers" of white micrite are developed (Fig.4.158). Although often appearing structureless, some faint parallel lamination and aligned, elongate "sparite-speckles", which may be "birdseyes" structures, can be seen (Fig.4.159; see aslo section IV.11.e.). Similar wafers of white finely-laminated, micritic limestone are also seen at North Rauceby (Fig.4.160) but there the wafers are "lensoid" ($<$ 20 mm.), due to the scouring down of the overlying oolites. For convenience of reference, these micritic beds have been grouped together as Lithofacies A3.

IV.11.d.ii. <u>Fining-upwards rhythms: Lithofacies group B</u>: Underlying the cross-bedded, "pisolitic" ooid-calcirudites at Blankney are a series of three fining-upwards rhythms (1 to 3 metres thick; Fig. 4.161); each is separated from the rocks below by an erosive base, but all the facies contacts within an individual rhythm are gradational. Each rhythm approximates to the "typical" sequence outlined below:

(3) Hard, compact, fine-grained, well-sorted peloidal calcarenite, Lithofacies B3 (top).

(2) A crudely bimodal, peloidal ooid-calcarenite, Lithofacies B2.

(1) A tabular cross-bedded, ooid-calcarenite with an erosive base, Lithofacies B1.

The foresets of the basal unit, which in places have a peloid-rich base (reworking of unit below ?), are low angle, planar and graded; essentially coarse-grained, poorly-sorted admixtures of sparite-cemented ooids, intraclasts and bioclasts grade up into well-sorted ooid-calcarenites. However, no such grading is seen in the topmost rhythm, where the shellier ("Nerinea", terebratulids and bivalves) basal unit has noticeably "drawn-out" bottomsets, which dip northwards in contrast to the southerly dip of the cross-beds in the two lower rhythms (Fig.4.2.). The cross-bedding, which is picked out by "Nerinea" lined foresets, is only poorly developed in the lowest rhythm and the increase in importance of Lithofacies B1 up the rhythmic succession is a significant feature of the sequence. Lithofacies B2 and B3 are compositionally quite uniform throughout all three rhythms; some "pisoliths" occur in the uppermost rhythm, which has complex burrow networks penetrating down into it, like those at nearby Ashby (Fig.4.162). However, one noticeable difference occurs in B3 of the lowest rhythm; unlike the higher rhythms, it has a relatively rich fauna of globate and high-spired gastropods, Montlivaltia and Lucina. In fact this bed is much more akin to certain levels at North Rauceby , where fine-grained peloidal calcarenites, rich in Lucina, "Nerin ea", Plagiostoma, Pholadomya, Montlivaltia and large and small terebratulids occur in the midst of what is essentiallyaan oolitic sequence. Generally the shell beds rest upon sharp surface, but as many of the oolitic levels are relatively thin, ($<$ 0.5 metres), with scour bases and rarer, bimodal cross-bedding, there is some relationship to the Blankney setting, although the Rauceby facies lack the rhythmical arrangement.

Elsewhere other variations of the fining-upwards sequence are seen. For example, one cross-bedded unit (J2) within the Copper Hill succession grades up from a coarse-grained, poorly-sorted skeletal ooid-calcarenite into a finer, pure, even-grained ooid-calcarenite. Similarly at Braceby Long Hollow (TF 010351) trough-shaped scours with "pisolitic-rich lags" pass up into ooid-calcarenites, which are in turn cut into by another "lagged" scour. A further variation occurs in Bed J1 at Castle Bytham, where the upward transition involves a decrease in grain content and concomitant loss of the cross-bedding from the skeletal ooid-calcarenite, rather than an actual "fining" of the grain size. A similar rhythm, but lacking any cross-bedding, is also seen at Ropsley (TF 002364).

IV.11.d.iii. Coarsening-upwards rhythms: Lithofacies group C: The most striking kind of coarsening-upwards rhythms involve the "pisolitic" rocks that are characteristic of the Sleaford Member in mid-Lincolnshire. As with the fining-upward sequences, the individual rhythms are separated by erosive contacts but the internal facies contacts are transitional. At Haceby (TF 028369) two such "pisolitic" rhythms are seen but the base of the lower one is not exposed; the complete sequence, approximately 1.5 metres thick, (J4; see Fig.4.2.), is composed of a sequence of bimodal peloidal ooid-calcarenites (with layers rich in "Nerinea", articulated Lucina and disarticulated Trigonia), within which large "pisolith" grains become increasingly important until they dominate the sediment at the top of the rhythm (Fig.4.163). The pisoliths are set in a poorly-sorted ooid-calcarenite. Although there is an overall upward increase in the "pisolith" content, it is not gradual, as "pisolitic" layers also occur within essentially peloidal ooid-calcarenite levels. The base of this particular rhythm is rich in rolled "Nerinea" gastropods. The lower rhythm at Haceby (J1) shows a similar overall sequence (Lithofacies C1 → C2 → C3; Fig.4.164), although the lower portion tends to be an ooid-calcarenite with impersistent graded layers (< 10 mm. thick) in which well-sorted ooid-calcarenites alternate with finer-grained peloidal- or bimodal peloidal ooid-calcarenites. Similar sequences to these are also seen at Newton (TF 041369) and Burton Coggles (SK 982254), while an interesting variant occurs at Dembleby Farm. There the coarsening-upwards rhythm has an erosive basal unit of cross-bedded, well-sorted ooid-calcarenites, which on passing up, loses its cross-bedding and becomes enriched in the large "pisolith" grains (Fig.4.165); a similar rhythm is also seen at North Rauceby. A further type, also seen at Dembleby, shows fine-grained, well-sorted peloidal calcarenites, grading up into coarser-grained, ooid-calcarenites, which higher up become crowded in "pisoliths". A "truncated" version of this rhythm, without the "pisolitic" top, is also seen elsewhere in the Dembleby sequence and at Haceby. All of these variations are schematically represented in figure 4.166.

At Castle Bytham, another coarsening-upwards rhythm occurs in Unit J4; a bimodal peloidal ooid-calcarenite grades up into a cross- bedded, coarse-grained ooid-calcarenite. This does not have an erosive base.

IV.11.d.iv. "Biohermal Micrites"; Lithofacies-group D: At Castle Quarry, Ancaster, the relatively thin Sleaford Member sequence is characterised by patch reefs, which stand out in the quarry face as unbedded, grey calcilutite masses. The individual reefs are only about one metre high and wide, although it is possible that they have hidden inter-connections. Colonial corals apparently provide the binding framework, within which a multitude of bivalves and brachiopods lived; many are preserved articulated and unbroken, indicating their association with the "living reef". Of particular note amongst the fauna are the abundant encrusting serpulids and Lopha, and the boring Lithophaga. Another similar small-scale, patch reef, rich in colonial corals, Lopha and terebratulids, occurs within a thick calcilutite bed at Castle Bytham (J3). Although lacking any biostromal or biohermal development a thin calcilutite horizon, similar to the Castle Bytham bed, also occurs within the largely cross-bedded, oolitic succession at Copper Hill, Ancaster.

A related feature, a Lopha biostrome, is developed within a light brown, friable marl at the top of the member in the Great Ponton railway cutting sequence. This appears to be composed solely of encrusting, monospecific Lopha, which are also common in the underlying carbonates. Presumably the decrease in sedimentation rate, reflected by the marl, allowed the build-up of the biostrome, which could not be established in the mobile oolite environment, represented by the rest of the Sleaford Member.

IV.11.d.v. Variations from the main lithofacies groupings: At the localities where the Sleaford Member cannot be classified into one of the major facies groups, the sediments are usually ooid-calcarenites with varying amounts of subsidiary bioclasts, intraclasts and peloids set in a largely sparitic sement. Scottlethorpe (TF 046204) is such a locality. Occasionally, poorly-developed, cross-bedding may be developed (Little Ponton Quarry, SK 931325) but generally sedimentary structures are absent. In the "dirtier" ooid-calcarenites, terebratulids, *Lucina* and high-spired gastropods sometimes flourish (Scottlethorpe), but these sediments are not usually fossiliferous.

IV.11.d.vi. Cross-bedding directions: An important point concerns the cross-bedding relationships of the Sleaford Member. The major cross-bedded units have a southerly component in their dip direction, although occasionally herring-bone cross-bedding is also seen (Fig.4.167). Within the cross-bedded sequences that infill the major scours into the lower Lincolnshire Limestone (Copper Hill, Ancaster; Great Ponton;and ? Creeton; see Fig.4.2) the cross-bedding dips approximately south-westwards (Fig.4.168) whereas in those sequences that have not scoured significantly into the underlying beds the foresets dip southwards (Fig.4.169) or east-southeastwards (Fig.4.155). In the more complex rhythmic facies sequences the cross-bedding is multidirectional, as exemplified by the Dembleby sequence, although it can appear bipolar (Figs.4.157 and 4.161). The possible significance of these variations is discussed in Chapter V.

IV.11.e. Laboratory description of the lithologies.

Despite wide diversity, the lithofacies of the Sleaford Member have been resolved into four main groups, which have their main petrographic features outlined below.

IV.11.e.i. Lithofacies-group A: This group of lithofacies encompasses the "typical" cross-bedded oolites (Lithofacies A1) and the quantitatively less important cross-bedded pisolitic oolites (Lithofacies A2). The principal characteristics of both are shown in figure 4.170.

Lithofacies A1: Although ooliths always form a prominent part of these grainstones, the varying bioclast content gives a compositional range from even-grained oosparites (Fig.4.171), where bioclasts are hardly represented, to bio-oosparites (Fig.4.172), where ooliths may even be subordinate to bioclasts. Such variations occur on a bed-to-bed scale or within a bed, where foreset grading for instance, can result in bioclast-rich and poor layers. Spherical to ovoid normal ooliths, showing well-developed, concentric laminae are far commoner than either superficial or (very rare) composite types. Although peloids predominate, bioclast nuclei are also seen, and occasionally the concentric laminae extend to the oolith's core with no nucleus being visible. The calcitic elements amongst the bioclasts (Bryozoa, echinoderms, brachiopods, bivalves, gastropods, foraminifera and worm tubes) retain their original skeletal structure and composition, but the aragonitic forms are preserved as sparite pseudomorphs. Practically all the skeletal fragments have a micrite-envelope and the more elongate grains tend to be aligned parallel to the depositional surface. In addition to the prolific ooliths and bioclasts, rarer intraclasts and occasional oncolites make up the remainder of the rock. The mostly rounded but irregularly-shaped intraclasts are either micrite lumps or composite grains, some of which have a distinctive composition and texture, e.g. pelsparite packstone or quartzose micrite. However, some of the intraclasts have a thin oolitic coating and are technically superficial ooliths. In general, the "pure" oosparites are well sorted, while the bioclast-rich oolites are poorly sorted, except in the instances where some form of grading (or layering) has occurred. In such a case an open-textured (grainstone), generally coarser-grained accumulation of bioclasts, intraclasts and ooliths passes up into a more closely-packed, finer-grained, nearly pure oolite layer. Although variable in the coarser layer, the sorting is generally quite good in such graded units. In all lithologies, an early acicular isopachous rim-cement, which is especially well-developed around the ooliths (but is often absent from the micrite-envelopes of the bioclasts) predates a blocky sparite cement. The crystal size of the latter varies from medium to very coarsely crystalline (Folk, 1962).

The above description has been principally compiled from the rocks from the Sleaford Member of the Copper Hill, Ancaster and Creeton sequences, where the member cuts down into the lower Lincolnshire Limestone. The other major cross-bedded oolitic successions, such as Brauncewell and Spittlegate Hill, where no such downcutting is seen, are generally composed of "mixed-grain" biosparites. These are generally poorly-sorted grainstones with dominant bioclasts and varying amounts of ooliths, intraclasts, peloids and oncolites.

Lithofacies A2: The presence of oncolite grains (Fig.4.173) distinguishes this grainstone facies, which is characterised by cross-bedded oncolitic oosparites (Fig.4.174; see also Fig.4.170) from Lithofacies A1. The large, rounded, generally complex oncolites, with an ovoid or elongate ovoid shape, are usually composed of micrite, which has a "clotted" appearance. Bioclasts, ooliths or quartz grains may be included with the grain and this suggests an original "stickiness". Except for a denser micritic rim and some hints of discordant growth, circular(0.1 to 0.2 mm. diameter mostly) or elliptical sparite-infilled vugs are the only internal structures seen, although tiny sparite-infilled (?) tubules (6 μ wide) occur in some grains. If correctly identified these would suggest that the grains are skeletal-oncolites. The remaining allochems are incipient ooliths (superficial $>$ normal), peloids, bioclasts (bivalves, gastropods, echinoderms, brachiopods, and foraminifera) and rare intraclasts. Together with a few oncolites, these often form the upper, finer oosparitic layer of the graded couplet; the lower laminae being composed almost exclusively of oncolites. Sorting within layers is quite good, but where no layering is seen the rocks are poorly sorted. Although there is a ubiquitous, late blocky cement, an early isopachous cement is only seen in the finer layers; it never rims the oncolites, although an acicular cement lines the insides of many of the internal vugs.

<u>Lithofacies A3</u>: Within the thin, white micritic wafer beds (Fig.4.158) of Thompson's Bottom Quarry, fine-scale parallel lamination is seen. In certain patches these laminations "buckle" up into micro-mounds, which have approximately 4 mm. relief and an 8 mm. basal diameter (Fig.4.175). Although the internal fabric of the "horizontal" parallel laminations shows micritic laminae (0.1 to 0.4 mm. thick), much of which appears to be coalesced peloids, separated by discontinuous rims of "laminar fenestrae" (Fig.4.176), the centres of the mounds are heavily fenestrated and the laminae are not easily distinguished. The sparite-infilled fenestrae themselved vary from small, irregular forms (0.1 x 0.1 mm.) to large and distinct laminar ones (2.6 mm. long, 0.2 mm. high), in which the bases tend to be regular and near-planar, and the tops much more irregular. Densely-packed pelmicrite with rare bioclasts (mostly foraminifera) and ooliths

encloses the laminated-fenestrated lenses. These laminations would seem best classed as algal stromatolites, with the elongate vugs being laminar "birdseyes" (cf. Shinn, 1968a).

Although similar laminated micritic "wafers" are seen at North Rauceby (Fig.4.160), no clear evidence for their being stromatolites is present; they do not have associated "birdseye" vugs. The wafers are burrowed through and scoured into by the associated oolitic sediment and these relationships, together with the laminations and associated silt content compare favourably with the "micritic micro-beds" of some Greetwell Member deposits (see section IV.3E.e.ii. for example). The laminations could have been physically deposited or algally produced.

IV.11.e.ii. <u>Lithofacies-group B</u>: In the fining-upwards rhythms of Blankney, which typify this facies group, cross-bedded oosparites grade up into pelsparites. However, as each rhythm is slightly different, the highest one is fully described and the variations from it are then discussed.

<u>The uppermost Blankney rhythm</u>: The main lithological characteristics of this rhythm are shown in figure 4.177. Throughout the rhythm, the ubiquitous grainstones are cemented by two generations of sparite: an early isopachous, acicular rim cement pre-dates a blocky type.

The basal lithofacies (B1), an even-grained cross-bedded oosparite (Fig.4.178) is principally composed of "high-energy" ooliths, in which the internal fabric is usually very clear; the thickness of the oolitic coatings varies with both normal (dominant) and superficial ooliths being represented. The former are near-spherical while the latter sometimes have less regular shapes. Peloids are the most common nuclei, especially in superficial ooliths but skeletal grains are seen and some ooliths have no obvious nucleus at all, the laminae extending to the centre of the grain. Besides ooliths, a few interstitial peloids also occur, together with rather more common intraclasts (micrite-lumps or composite grains), most of which have a thin, oolitic coating and are technically superficial ooliths. The actual base of this rhythm is a skeletal pelsparite, composed of a rather poorly-sorted agglomeration of dominant peloids, bioclasts (bivalves, gatropods, terebratulids, Bryozoa, ostracods and foraminifera) and rarer intraclasts and ooliths. Some silt also occurs. This subfacies presumably represents the reworked top of the previous rhythm.

Lithofacies B1 passes up into a peloidal oosparite (Lithofacies B2; Fig.4.179) in which the allochems are either poorly-sorted or crudely differentiated into size layers. The included ooliths (dominant), peloids, intraclasts and bioclasts (mostly bivalves) form a transitional facies between the oosparite and pelsparite "end-members" of the rhythm. Capping the rhythm is a very well-sorted, pelsparite (Lithofacies B3; Fig.4.180) which is dominated by variably-shaped (polygenetic) peloids and subsidiary bioclasts (foraminifera, bivalves and ostracods). Subrounded to subangular detrital quartz grains also occur. Diverse foraminifera, with micritised skeletons are strikingly abundant in this facies.

Variations in the Blankney rhythms: In addition to the lithologies of each rhythm, which reflect changing energy conditions, variations in the nature of the rhythms as a whole indicate an overall increase in energy conditions up the succession. This conclusion is based on the following factors:

(1) The thickness of the cross-bedded unit (Lithofacies B1) increases with each succeeding rhythm (Fig.4.2.).

(2) Texturally the highest rhythm is composed solely of

grainstones; the lower rhythms incorporate packstones and even wackestones.

(3) Lithofacies B3, the peloid-rich rhythm top has a mixed wackestone/packstone texture in the lowest rhythm, a packstone texture in the middle rhythm and a grainstone texture in the topmost rhythm.

(4) Within Lithofacies B3 of the two lowest rhythms, detrital quartz is quite common (the rocks are quartzose pelsparites) but it is practically absent in that facies of the highest rhythm.

(5) There is a reasonably common and largely indigenous benthonic fauna present in Lithofacies B3 of the lowest rhythm. This is not seen in higher rhythms.

The possible significance of these variations are discussed in Chapter V.

IV.11.e.iii.<u>Lithofacies-group C</u>: These oolitic rhythms are characterised by the introduction and gradual upward increase in oncolite abundance. Although similar and related sequences are seen elsewhere, the most typical of these rhythms are exposed at Haceby; one such Haceby rhythm is described below and the principal characteristics of its lithofacies (C1 → C3) are shown in figure 4.181.

<u>Lithofacies C1</u>: The basal part of the rhythm is typically a bimodal oosparite (Fig.4.182) in which a large suite of micritised, spherical to ovoid ooliths occurs with a group of smaller allochems (mostly ooliths and peloids). Occasional bioclasts (bivalves and foraminifera) are also seen. Ooliths, which are not always bimodal, are the dominant grain type. The sparite, cementing this grainstone, crystallised in two distinct generations: an early acicular rim-cement pre-dating a blocky sparite.

<u>Lithofacies C2</u>: This grainstone facies is usually composed of poorly-sorted oncolitic oosparites, in which the ooliths are generally more

abundant than oncolites, Bioclasts (bivalves and Bryozoa) are uncommon. The ooliths are similar to those seen in Lithofacies C1, although some have been "cemented" to form grapestone grains, while others have acquired oncolitic coatings and so form one of the three main oncolitic types. The other two groups of larger, micritic oncolites are distinguished by having few vugs or many vugs; these sparite-infilled vugs range from 0.04 to 0.2 mm. in diameter. The larger oncolites (see also section IV.11.e.i; Lithofacies A2) are rounded and either irregularly ovoid (3.9 x 2.1 mm.) or elongate ovoid (4.0 x 1.0 mm.) in shape. Only a blocky sparite cements the rock.

Lithofacies C3: The capping, poorly-sorted oncolitic oosparite (Fig. 4.183) differs in a number of respects from Lithofacies C2: the oncolites are more abundant than the ooliths, micrite is dominant over sparite and the rock is texturally a packstone. The spherical to ovoid ooliths, which are less heavily micritised than in C1 and C2, have normal outnumbering superficial types. Bioclasts (bivalves, gastropods and echinoderms) remain uncommon and the occasional grapestone grain is still seen. The oncolites (Fig.4.184) are very large composite grains which often incorporate other oncolites. An outer, vug-rich micritic rim surrounds oncolitic oo-pelsparite packstone areas, which must originally have been intraclasts although this is not always obvious. On the inside of the enclosing oncolitic coat, an earlier, acicular cement is seen indicating on original "void", which may have resulted from algal overgrowth of a depression within the original intraclast grain. Other oncolites have an internal network of sparite-infilled tubes (0.04 to 0.08 mm. wide) radiating outwards from the grain's core. These suggest that some of the grains may be skeletal-oncolites or even rhodolites. Although micrite predominates, in the more "open" areas the usual two generations of sparite cement can be recognised. Some at least of the micrite may be the result of peloid coalescence.

Variations: There are a number of variations on this coarsening-upwards model (see section IV.11.d.iii.), including cross-bedding in the basal oosparite. However, the major lithological variation involves there being a peloid-rich base to the rhythm. This kind of rhythm is typified by bed J8 in the Dembleby Farm sequence, where a very well-sorted quartzose pelsparite (packstone) grades up into a bimodal peloidal oosparite (grainstone); the very top of the bed is rich in oncolites. This varies from the main rhythm type in also having a more open-textured "top".

Related to this kind of sequence is another rhythm (DFQ, J7), in which a bimodal oolitic pelsparite (packstone) passes up into a well-sorted oosparite (grainstone), which lacks the oncolites of the "normal" coarsening-upwards rhythms. A similar sequence, again having a bimodal, oolitic biopelsparite (packstone) grading up into an oosparite (grainstone) is seen at Castle Bytham (bed J4), but in this instance, cross-bedding occurs at the top of the bed (oncolites are not represented here either).

IV.11.e.iv. Lithofacies-group D: This group encompasses two main lithotypes:

(1) the complex patch-reef boundstones of Castle Quarry, Ancaster, in which a variety of encrusting, boring and associated benthonic forms occur, associated with dense primary micrite and sparite-infilled voids.

(2) the non-reef "micrites", which reflect quiet-water deposition. These may or may not be rich in body fossils, but they are

usually burrowed and/or bioturbated. Compositionally they range from poorly-sorted biomicrites (wackestones) through biopelmicrites (wackestones), which are composed of fairly well-sorted, ovoid peloids (0.062 to 0.15 mm. range) and associated bioclasts (bivalves, brachiopods, gastropods, foraminifera up to 1.2 mm.), to well-sorted, skeletal pelsparites (packstones), which have a combination of polygenetic peloids and incipient ooliths (joint size range: 0.062 to 0.31 mm.), and bioclasts (terebratulids, echinoderms up to 3.2.mm.) all set in a mixed micrite and sparite matrix (micrite dominant).

Neither of these lithotypes are quantitatively important.

IV.11.f. Discussion.

The widely held belief that the Great Ponton *Terebratula* Beds are the youngest unit of the Lincolnshire Limestone, has resulted in the Great Ponton Gastropod Beds being correlated with the "highest" units seen elsewhere: the Ancaster Rag, Clipsham Stone and Weldon Beds with Barnack Rag (see Kent, 1966, fig.1.). Such a correlation scheme is not followed here; the Gastropod Beds and their "pisolitic" equivalents (Kent, 1940, p.53), are included in the Sleaford Member and as such are considered equivalent to the strata that usually occurs immediately below the youngest units mentioned above, i.e. at the "Ancaster Freestone level". In particular, the Gastropod Beds are thought to be directly equivalent to the Ancaster Freestone at Copper Hill, Ancaster (Richardson, 1939b, p.473 and plate 29B), which is the type section of the Sleaford Member, and to much of the strata below the "Clipsham Beds" at Castle Bytham (Richardson, 1939a, see also Fig. 3.4.). This re-alignment has been based upon a re-examination of the lithological affinities of the beds and the stratigraphical relationships seen in the newly opened quarry at Great Ponton.

The main lithofacies (cross-bedded, skeletal oolites) of the Gastropod Beds is very similar to that composing most of the Sleaford Member at Creeton, and to a lesser extent those at Copper Hill, Ancaster. The preponderance of gastropods, that is supposed to typify the unit is not particularly noticeable in the railway cutting section at Great Ponton (SK 937298) and in view of the rather widespread and often prolific occurrence of gastropods elsewhere at other levels, notably in the Creeton Member, they are not considered unduly significant. What is thought to be far more important is the preponderance of southerly-dipping cross-beds in the oolites; the characteristic direction of the Sleaford Member. Thus the general sedimentological features of the Gastropod Beds appear to be quite compatible with its inclusion in the Sleaford Member, although the principal arguments for the proposed re-alignment of the beds are stratigraphic.

Until recently the base of the Gastropod Beds was not exposed in the Great Ponton succession and therefore any conclusions about its stratigraphic position were based upon interpreted rather than observed relationships (cf. Kent, 1940, p.53 and Kent, 1966, p.65). However, in the newly opened Great Ponton Quarry, the base of the beds can be directly observed, resting erosively upon a remnant of the Lincoln Member, of the lower Lincolnshire Limestone (Fig.4.120); a similar relationship to that seen at Copper Hill, Ancaster (Fig.4.2.). As the base of the Lincoln Member contains the characteristic Thecosmilia (see section IV.5.f.) there can be little doubt about the stratigraphic level, especially as typical Greetwell Member peloidal calcarenites underlie the Lincoln Member (Fig.4.120). For the first time therefore, the true stratigraphic position of the Great Ponton

Beds can be seen; they do not occur above equivalents of the Ancaster Freestone as suggested by Kent (1966, fig.1.) but at the same level, downcutting deeply into the lower Lincolnshire Limestone (Fig.4.2.). Such a stratigraphic alignment is supported by the postulated association of the Terebratula Beds (lying above the Gastropod Beds) with the Creeton Member sequences elsewhere (see section IV.12.g.).

Although the new evidence allows the Great Ponton Beds to be more readily assimilated into the lithostratigraphy of the formation, is does raise one problem; that of the total thickness of the Lincolnshire Limestone in this region. Kent (1940, p.51) inferred that the preservation of the "higher units", the Great Ponton Beds, in the synclinal downwarp south of Grantham could account for the expanded thickness of the formation recorded in a well at nearby Boothby Pagnell (SK 972308; Kent, 1940, p.54). However, as it now seems likely that these units are not stratigraphically higher than the majority of the upper Lincolnshire Limestone, an alternative explanation for the thickening must be sought (although synclinal warping is not completely dismissed, see section IV.12.g.). The thickening of the known subdivisions of the formation seems the most likely cause. For example, at Creeton, the Sleaford Member sequence is practically 12 metres thick (base unseen), although elsewhere it never exceeds 9 metres. When one remembers that at maximum the formation is only 40 metres thick, and usually considerably less, it is not difficult to imagine the co-development of a few such expanded sequences producing the necessary thickening.

Overall, there seems little reason to consider the Great Ponton Beds as in any way unique (see also section IV.12.). Both the sedimentological and stratigraphical characteristics of the beds appear to correspond with those of the "new" Sleaford Member, with which they are classified.

IV.12. CREETON MEMBER.

IV.12.a. Introduction.

The Creeton Member, principally composed of cross-bedded, skeletal and ooid-calcarenites is the youngest subdivision of the Lincolnshire Limestone Formation. Although the member takes its name from Creeton Quarry (SK 999205), Castle Bytham (SK 990180) has been chosen as the type section (4.8 metres thick; Fig.4.185) because the Creeton sequence is dangerously inaccessible. However, as the Creeton Member succession at Castle Bytham is incomplete, Creeton has been adopted as the boundary - stratotype (Hedberg, 1976, p.24.) for the top of the member (Fig.4.186).

IV.12.b. Former Terminology.

Precise stratigraphic details, with which the Creeton Member can be related to earlier terminologies, are only known for the quarries around Ancaster (see Richardson, 1939b; and Swinnerton and Kent, 1976), the Castle Bytham pit (Richardson, 1939a) and the Great Ponton Railway Cutting (SK 937298; Kent, 1966, p.65). At Copper Hill Quarry, Ancaster (SK 979427, = Newton and Scott's Quarry), the Creeton Member is directly equivalent to the Ancaster Rag, as defined by Richardson (1939b, p.473 and plate 29B); a definition which has also been followed by Kent (1940 and 1966) and Wilson (1948) for that pit and Castle Quarry, Ancaster (SK 987435). However, Kent (in Swinnerton and Kent, 1976) has recently re-named the Ancaster Rag, at Castle Quarry, the Great Ponton Gastropod Beds, confirming his earlier suggestion (Kent, 1940 and 1966) that these two units were lateral equivalents; a correlation that is not followed here (see also section

IV.11.f.). On the contrary, the Ancaster Rag of the Ancaster quarries is believed to be equivalent to the Great Ponton _Terebratula_ Beds of Richardson (1939b) and Kent (1940 and 1966, p.65), and consequently also analogous to the upper part of the "coarse shelly oolites and pisolites of Great Ponton" of Hollingworth and Taylor (1951) and the Great Ponton Beds of Swinnerton and Kent (1976). The reasons for this correlation are discussed in section IV.12.g.

Despite the exact equivalence of the Ancaster Rag and Creeton Member at Copper Hill (Fig.4.187) such a relationship does not hold everywhere. For example at Thompson's Quarry, Ancaster (here called the Glebe Quarry, Wilsford Heath, SK 992409) the Creeton Member includes not only the Ancaster Rag of Richardson (1939b, plate 29A) but also his Ancaster Freestone. This implies a correlation between the Ancaster Rag of Copper Hill (as defined by Richardson, 1939b, p.473) and the Ancaster Rag and Ancaster Freestone of Wilsford Heath (as defined by Richardson, 1939b, plate 29A). The following considerations are thought to support this proposal:

(1) A detailed study of the thickness of the Ancaster Rag (Richardson, 1939b, plate 29A) in both Wilsford quarries (Fig.4.187) shows that it thins rapidly down from over 3 metres to under 1 metre towards Copper Hill Quarry, indicating that it is unlikely to be the sole equivalent of the Copper Hill Ancaster Rag, which is nearly 5 metres thick and only a little over 1 kilometre away; unless the Ancaster Rag is developed in isolated pockets. If this latter suggestion is the case then the Ancaster Freestone of Copper Hill would have to thicken rapidly up to encompass the Wilsford Ancaster Freestone, for over 5 metres of Ancaster Rag separates the Ancaster Freestone from the Upper Estuarine Series at Copper Hill, whereas the

two units are practically in contact at Wilsford (Fig.4.187). Alternatively, the acceptance of the Wilsford Ancaster Rag as a laterally impersistent subfacies within the underlying unit implies that the Copper Hill Ancaster Rag is equivalent to at least part of the Wilsford Ancaster Freestone.

(2) Although on the evidence available it is impossible to say which of the two possibilities is most likely, the work of Brodie (1853) tends to favour the latter explanation. As his section shows, Brodie (1853, p.54 and see Fig.4.188) saw the Wilsford quarries at a time when they were excavated to a much greater depth and as a result he was able to record beds that clarify the relationships between the Wilsford Heath and Copper Hill sequences. Essentially Bed 2 of Brodie (1853) is equivalent to the Ancaster Rag of Richardson (1939b, plate 29A), while Bed 3 represents the Wilsford Ancaster Freestone (Richardson, 1939b, plate 29A) and Bed 4, by its description, seems to be the Wilsford equivalent of the Copper Hill Ancaster Freestone, especially as it rests upon "soft white stone" (Bed 5 of Brodie, 1853) which cannot be anything other than the Kirton Cement-stones of Richardson (1939b, p.473), as no other Lincolnshire Limestone facies approximates to such a description. Therefore, except for the "Ragstone" subfacies at the top (Bed 2 of Brodie, 1853), the Wilsford Heath sequence is remarkably like that at Copper Hill (Fig.4.188) with the Ancaster Rag of Copper Hill being equivalent to the "Ancaster Freestone" (including Ancaster Rag subfacies) of Wilsford Heath.

(3) On general lithological grounds, there seems little against this correlation as both the Copper Hill Ancaster Rag and the Wilsford Heath Ancaster Freestone are essentially composed of oosparites, although it is true that the Copper Hill beds have much

more strongly developed cross-bedding and more skeletal debris. However, cross-bedding is seen in the Wilsford Ancaster Freestone, with foresets dipping northwards in like manner to those of the Ancaster Rag at Copper Hill. Similarly skeletal-rich areas are also present, indicating that the differences with the Copper Hill Ancaster Rag are a matter of degree.

(4) A subsidiary factor in this argument is that in the Ancaster Rag of Copper Hill and Wilsford Heath and Ancaster Freestone of Wilsford Heath (all = Creeton Member) the cross-bedding direction is predominantly to the north (Fig.4.189), while in the Ancaster Freestone of Copper Hill (= Sleaford Member) it is predominantly to the south (Fig.4.168).

In the light of this re-interpretation the contention of Kent (1966, p.63) that "It seems ...... unlikely that the "Ancaster Rag" of Newton and Scott's Quarry, only some 15 - 20 feet above the Cementstones (Richardson, 1939B,p.473) is the same bed as that at the top of the limestone at Thompson's Quarry, as this would involve very deep channelling or strong thinning for which there is at present no evidence in mid-Lincolnshire" appears to be unfounded. Admittedly, the two "Ancaster Rags" are, to some extent, different lithologies, but they do appear to form part of a single stratigraphical unit. As for their relative stratigraphic heights above the Cementstones, figure 4.188 shows the Ancaster Rag (= Beds 2 and 3 of Brodie, 1853) at Thompson's Quarry to be only 5 metres above the Cementstones; well within the figure of 15 to 20 feet given by Kent (1966, p.63) for Copper Hill. Furthermore, the comparative thickness for the Ancaster Rag of c.6.86 metres at Thompson's Quarry (= Beds 2 and 3 of Brodie, 1853) and 4.88 metres at Copper Hill (where the top is not seen) are hardly incompatible; there is no need to invoke "strong thinning" or "very deep channelling". However, the rapid thinning of the Ragstone subfacies (Bed 2 of Brodie, 1853) over a few hundred metres (Fig.4.187) shows that such thickness variations are not unknown, while the erosive downcutting of the Ancaster Freestone at Copper Hill is evidence of "channelling" in mid-Lincolnshire. Although this downcutting has long been recognised (Richardson, 1939b; and Kent, 1940 and 1966), the full extent of the erosion is only appreciated when it is realised that much of the upper Lincolnshire Limestone has been removed (Fig.4.2.) and not just a little of the lower Lincolnshire Limestone, as implied by Kent (1966, fig.1.). It is not the base of the upper Lincolnshire Limestone which is doing the downcutting, but an horizon within the upper Lincolnshire Limestone. Consequently the apparent "low level" of the Ancaster Freestone and Rag at Copper Hill does not signify a "real" low stratigraphical level at all. If one accepts this, then it is not unreasonable to find, at Thompson's Quarry, the Upper Estu ine Series sitting directly upon lateral equivalents of the Ancaster Rag of Copper Hill.

There is one consideration that might be thought to conflict with the outlined hypothesis: the total thickness of the upper Lincolnshire Limestone in the Ancaster area. Kent (1966, p.63) states that "The thickness given by surface sections ..... fall considerably short of the total thicknesses proved in nearby wells, some of which show up to 60 feet of raggy and pisolitic beds and freestones above the Cementstones of the Lower Lincolnshire Limestone." The section illustrated by Brodie (1853) shows a total of 11.73 metres of upper Lincolnshire Limestone at Wilsford Heath, compared to a probable maximum of 10 metres at Copper Hill. As these two sections demonstrably cut out part of the upper (conservatively estimated as 4.5 metres) and lower Lincolnshire Limestone, the 18.5 metres in "nearby wells" which may be outside the zone of "channelling" does not seem unreasonable or incompatible with the stratigraphic scheme proposed here.

At Castle Bytham, the Creeton Member is directly analogous to the Clipsham Beds of Richardson (1939a, p.42.), suggesting that the Clipsham Stone should also be incorporated within the member; a classification that is adopted here. The presence, within the Clipsham Stone, of the same type of raggy subfacies (= Bed 2 of Brodie, 1853) as that seen at Thompson's Quarry is considered good supporting evidence for the correlation. In this case, therefore, the Creeton Member is also equivalent to the Clipsham Beds of Kent (1940), the Clipsham Stone of Swinnerton and Kent (1976) and the "coarse shelly oolites and pisolites of Clipsham" of Hollingworth and Taylor (1951).

IV.12.c. Geographical and Geological Extent.

Although the Creeton Member is seen to be the youngest subdivision of the Lincolnshire Limestone Formation in south and mid-Lincolnshire, north of Sleaford it is not easily traced. This is primarily due to the paucity of upper Lincolnshire Limestone exposures, although even in pits where "suitable" stratigraphical levels occur, the member has not always been recognised. For example, at Blankney (TF 062592) beds very near the top of the formation (cf. total thickness of the Lincolnshire Limestone for this are given by Kent, 1966, fig.2, with Fig.4.2.) are exposed but no Creeton Member facies is seen. However, a little to the south, at Ashby de la Launde (TF 052570) the Lincolnshire Limestone/Upper Estuarine Series junction is thought to be exposed and here the uppermost 0.5 metres of limestone, resting upon a heavily burrowed, almost "cavernous" surface, are pure cross-bedded, ooid-calcarenites, very like the typical Creeton Member lithofacies. As the unit is so thin here, its absence at Blankney is perhaps not so surprising. However, whether this absence is due to non-deposition or pre-Bathonian erosion (Swinnerton and Kent, 1976) is not readily obvious. Certainly the northwards thinning of the member (Fig.4.2.)might seem to favour the former explanation, until it is appreciated that the thinning itself may be a function of the later differential uplift and erosion. Swinnerton and Kent (1976) favoured the existence of a synclinal downwarp around Grantham, which preserves the higher Lincolnshire Limestone subdivisions, while areas to the north and south have suffered relatively greater amounts of denudation, during which these younger units have been removed prior to the deposition of the Upper Estuarine Series.

In mid-Lincolnshire, the Creeton Member is always seen to rest erosively upon the Sleaford Member, and this relationship appears to persist as far south as Castle Bytham. However, beyond here the Creeton Member (= Clipsham Beds) is believed to cut down through the Sleaford Member and into the Castle Bytham Member (Fig.4.2.), as witnessed at the Soil Fertility Quarry, Clipsham (SK 978154; Fig.4.190). Further south in Northamptonshire, the Weldon Beds, which have been correlated with the Clipsham Beds (Richardson, 1939a) also cut down through lower horizons of the Lincolnshire Limestone and even through the Grantham Formation (Taylor, 1946). If the correlation proposed by Richardson (1939a) is correct, it may mean that the Sleaford Member is restricted to areas north of Clipsham, because of the erosive downcutting of the Creeton Member horizon.

Although the above strike profile was fairly readily deduced from the available evidence, the geographical distribution of the Creeton Member cannot be so readily determined because of the linear (N-S) development of the exposures and the rarity of complete sections. Together these poblems prevent any distributional trends being developed from thickness variations within the unit.

IV.12.d. Field description of the lithologies.

The Creeton Member is pricipally composed of cross-bedded cleanly-washed, ooid-calcarenites (Lithofacies A) and subsidiary skeletal calcarenites or calcirudites ("Ragstone", Lithofacies B). At Castle Bytham (type section) the Creeton Member succession, resting upon the hardround-capped Sleaford Member (Fig.4.153) is dominated by ooid-calcarenites of Lithofacies A. Essentially a massive, two metres thick, tabular cross-bedded, ooid-calcarenite basal unit, itself capped by an oyster-encrusted hardgpound, gives way to a thin, burrowed oolitic horizon, which is, in turn, overlain by more "clean" cross-bedded ooid-calcarenites. In contrast to the basal unit, which has south-westerly dipping foresets, the cross-bedding at this level dips north-eastwards. Higher still (K3b, see Fig.4.191) coarser, more bioclastic-rich limestones are seen, which have bipolar cross-bedding. The lithologies at this level vary from poorly-sorted, ooid-dominated ooid-skeletal-intraclast-calcarenites to very coarse, skeletal-dominated, poorly-sorted, skeletal ooid-intraclast-calcarenites. Capping the whole are beds (K4), which are similar to those immediately underlying the Upper Estuarine Series at Creeton, suggesting that little of the Creeton Member is missing at Castle Bytham (see also Fig.4.2). These youngest Lincolnshire Limestone beds are, like most of the member, cross-bedded (foresets dip south-westwards) ooid-calcarenites. However, of particular interest are the graded foresets in which skeletal calcirudites pass up into well-sorted ooid-calcarenites; both lithologies are sparite-cemented. Similar "foreset grading" is also seen at Corby Glen (SK 987244) and Burton Coggles (SK 982254), where the Creeton Member successions are very like that at Castle Bytham.

The Creeton succession only differs from the Castle Bytham section in detail; the basal part of each of the lowest two units (K1 and K2; see Fig.4.2) tends to be micritic, although in each case there is a fairly rapid transition upwards into more typical sparite-cemented oolites. However the bipolarity of the member's cross-bedding is even more clearly demonstrated here as K2 can be seen to have foresets dipping both north-eastwards and south-westwards in different parts of the quarry (Figs. 4.186 and 4.192).

Away from the type localities, the Creeton Member tends to be represented by two distinct facies, as exemplified by the successions at Wilsford Heath, where an upper skeletal-rich Lithofacies B (directly equivalent to the Ancaster Rag of Richardson, 1939b, plate 29A but not 29B) rests erosively upon an oolitic Lithofacies A (equivalent to the Ancaster Freestone of Richardson, 1939b, plate 29A but not 29B, and the Ancaster Rag as defined by Richardson, 1939b, p.473 and plate 29B; see Fig.4.193). Although this relationship of Lithofacies B overlying Lithofacies A is seen elsewhere, (Clipsham for example), Lithofacies B can be considered as an impersistent facies variant of the dominant oolitic Lithofacies A, both on a sub-divisional scale, as at Wilsford (see Fig.4.187), and on a bed by bed or even sub-bed scale, as at Castle Bytham. That is to say, at Wilsford, Lithofacies B forms a distinct unit, that has a consistent relationship with Lithofacies A (Fig.4.2.) but elsewhere (Castle

Bytham, Bed K3b) Lithofacies A and B may simply represent lithological extremes within the same bed, which may on "gross" features be grouped into either Lithofacies A or B. Therefore at Wilsford, within the dominantly skeletal calcirudites and calcarenites of Lithofacies B, lenses or beds of Lithofacies A can be found, and similarly, within Lithofacies A, areas of Lithofacies B may be present.

IV.12.d.i. Lithofacies A: This is essentially a yellowish, cross-bedded,"clean" ooid-calcarenite. Although the ooids are dominant and often so well sorted for the rock to have an "even-grained" texture, subsidiary skeletal grains (mainly bivalves and gastropods with subordinate worm tubes and echinoderm fragments) and intraclasts also occur in less well-sorted patches.

The cross-bedding is not obvious in either of the Wilsford quarries but at the nearby Copper Hill Quarry, Ancaster, tabular cross-bedding types (Figs.4.152; predominantly north-eastwards dipping foresets, Fig.4.189) are seen, often with graded foresets in which either coarser-grained ooids or skeletal grains pass up into finer-grained ooids. In addition, the foresets at Medwell's Clipsham (SK 988160) are frequently low angled and planar, which with the very strong parallel alignment of "planar" grains indicates very strong current activity. In comparison to the north-easterly dip of the foresets in the Ancaster quarries, south-easterly directions of dip have been recorded for this facies in Medwell's and the Soil Fertility Quarry, Clipsham, especially in the basal beds.

IV.12.d.ii. Lithofacies B: At Wilsford Heath, this pinky-yellow weathering, but blue-hearted facies is most simply classified as a cross-bedded, coarse-grained skeletal calcarenite or calcirudite, although in detail it has two subfacies:

Subfacies B1: A poorly-sorted, skeletal ooid-calcirudite in which the skeletal grains (dominated by bivalves and gastropods but with subsidiary brachiopods, corals and echinoderms) predominate over ooids and subsidiary intraclasts. The rock is cemented by sparite.

Subfacies B2: A moderately well-sorted, ooid-dominated calcarenite that has significant but always subsidiary amounts of skeletal debris (mostly coarse grained) present. This too is sparite-cemented. Essentially the two subfacies reflect variations in the relative proportions of different grain stypes with bioclasts > ooids in Subfacies B1 and the opposite relationship in Subfacies B2. In both instances however the skeletal grains are far more abundant than in Lithofacies A. Relationships between the two subfacies differ; at Wilsford B1 tends to grade up into B2, both within individual beds and through the unit (Lithofacies B) as a whole, but elsewhere, at Bidewell Lodge, Clipsham (SK 968145) for instance, there seems to be no consistent relationship between the two subfacies.

As with Lithofacies A the cross-bedding direction appears to vary geographically. At Wilsford facies B has foresets consistently dipping to the north-west (Fig.4.194) while at Old Somerby (SK 959337), Bidewell Lodge and Medwell's the prevailing current direction is towards the north-east (Fig.4.195). However in the latter locality, multi-directional and distinct herring-bone cross-bedding are evident, suggesting very shallow water.

Although in mid-Lincolnshire there is a tendency for the Creeton Member to show a reversal in cross-bedding direction, from south-westerly to north-easterly dipping, up the sequence, accompanied by a transition from Lithofacies A to B (e.g. Haceby Lodge, TF 028369; Fig.4.196), many exceptions to this "rule" exist. For example,at Little Ponton Quarry (SK 931325) the basal beds of the member are cross-bedded to the south-west (some herring-bone cross-bedding also; Fig.4.197) but are composed of typical Lithofacies B. Conversely, at Copper Hill, Ancaster, the whole of the member, composed of Lithofacies A, has cross-bedding dipping north-eastwards, without a south-westerly component even in the lowest beds. Such "anomalous" relationships are not really so unusual when one considers that Lithofacies A and B represent the end-members of a compositional continuum and that B frequently erodes into A, as exemplified by the Haceby Lodge section (Fig.4.196). In one part of this quarry terebratulid-rich Lithofacies B beds (foresets dip to the north-east) practically cut down onto the Sleaford Member, removing all sign of Lithofacies A, which has foresets dipping to the south-west. Therefore the absence of a basal unit cross-bedded to the south-west need not be so unexpected.

Of even greater significance in the Haceby section however, is the nature of the Lithofacies B beds; they are abundantly rich in terebratulids like the Great Ponton _Terebratula_ Beds of Kent (1940 and 1966), which have foresets dipping both north-eastwards and south-westwards. Because of this and their general Lithofacies B composition they have been included in the Creeton Member. If this is indeed the case, then the equivalents of the _Terebratula_ Beds are not nearly so geographically restricted as Kent (1940 and 1966) maintains. Although their absence north of Ashby de la Launde is accepted, the Creeton Member (= Great Ponton _Terebratula_ Beds and equivalents) can be traced southwards from there to Clipsham and probably a good deal further south if the correlation of the Weldon and Clipsham Beds by Richardson (1939a) proves to be correct.

IV.12.e. _Laboratory description of the lithologies._

The compositional variation seen in this member is principally due to the variations in the relative proportions of ooliths and bioclasts composing the limestones. At one end of this compositional spectrum, the rocks are practically pure oolite (Lithofacies A), with only minor amounts of bioclasts, while the opposite extreme has very dominant bioclasts and only subsidiary ooliths (Lithofacies B). However the amount of ooliths in B is usually greater than the percentage of bioclasts in Lithofacies A. Between the two extremes the relative amounts of the two major allochems vary, but most of the rocks are termed skeletal oosparites (and grouped with Lithofacies A) because of the volumetric bias in favour of ooliths in the classificatory scheme proposed by Folk (1959). However, it must be emphasied that although these two lithofacies types are sometimes separated on a unit vs. unit basis, as at Wilsford Heath, they are also seen as variations between beds and even within individual beds, as foreset grading for instance. Thus, on all levels, the two contrasting lithofacies form part of a compositional continuum (Fig.4. 198).

IV.12.e.i. Lithofacies A: This facies, either in its purest oosparite form (Fig.4.199) or as a skeletal oosparite (Fig.4.200) dominates the member and constitutes the type sections. Essentially the well-sorted grainstones are composed of dominant ooliths, subsidiary bioclasts (echinoderms, Bryozoa, bivalves, gastropods, brachiopods, worm tubes and foraminifera) and minor quantities of intraclasts, all of which are bound by a poorly-developed, early, acicular, isopachous rim-cement and medium-to-coarsely-crystalline blocky infilling sparite. The ooliths show good concentric structures and although ranging from spherical to ovoid in shape, a far higher percentage of near-spherical (or spherical) grains exist compared with the Metheringham and Castle

Bytham Members' oosparites for instance. Although some ooliths are concentrically laminated throughout, without showing any obvious nucleus, most have peloidal or bioclastic (echinoderms, gastropods or bivalves mostly) nuclei, the former being in the majority. "Normal" types dominate but superficial and composite ooliths are present, together with exceedingly rare asymmetric types (cf. Freeman, 1962). In the highest bed exposed at Castle Bytham (CBQ K4) the ooliths have very "ragged" margins, which suggest boring or early solution, as all of the "embayments" are infilled with the later blocky cement.

The ooliths of the Wilsford Heath Lithofacies A are somewhat different from those described above, being smaller (0.3 to 0.5 mm.) and "peloidal" in appearence. This appears to be mainly due to ubiquitous micritisation, although some of the ooliths are superficial with geniune peloidal nuclei. This variation is associated with a lack of cross-bedding, so typical of the usual Lithofacies A oosparites, and its significance is discussed in Chapter V.

IV.12.e.ii. <u>Lithofacies B</u>: The poorly-sorted biosparites (Fig.4.201) of this facies are also grainstones, which show two generations of cementation like Lithofacies A. The dominant bioclasts usually show quite strong alignment parallel to the depositional surface and the presence of so many large, irregularly-shaped grains gives the rock a very "open" texture (Fig.4.201). Bivalve, gastropod, brachiopod, foraminifera and echinoderm fragments are all present in varying proportions. As is generally the case in the Lincolnshire Limestone the aragonitic forms (mostly molluscs) are preserved as sparite-pseudomorphs with micrite-envelopes, while the calcitic skeletons retain their original composition and structure, although they are often bored by algae. The subsidiary, usually micritised ooliths are of all the three types seen in A, but in this case superficial ones appear to predominate.

Within the diverse array of "transitional" oosparites "layering" is seen, which reflects foreset grading in some cases. In most cases coarser-grained, skeletal-rich grainstone layers grade up into finer, purer oolitic layers, thus reflecting on a small scale the Lithofacies B - A gradient. However, another feature blurs this relationship to some extent: significant quantities of interstitial micrite occur in the oosparite layers, which can be seen to have been introduced from "suspension" as it tends to:

(1) rest on the tops of horizontal planar grains,

(2) show level upper surfaces,

(3) be often absent from the underside of grains, where the occurrence of an early rim-cement indicates the former presence of an original void.

However, its association with the depositional environment is reflected by its restriction to certain layers, a fact which tends to rule out any possibility of its being vadose silt. Similar "layering" or grading, involving contrasting sizes of ooliths is seen in the Creeton Member at Copper Hill, Ancaster.

IV.12.f. Fauna.

The fauna of the Creeton Member is dominated by gastropods and bivalves, with brachiopods, echinoderms, corals, Bryzoa and worm tubes also being represented in varying, though usually subordinate, proportions. An important deviation from this occurs at Great Ponton, where terebratulids are by far the most prolific faunal element. The following faunal list, compiled from collections made from Bidewell Lodge Quarry, Clipsham, is considered typical of the unit's fauna as a whole, especially Lithofacies B (see also Richardson, 1939b, p.467 for faunal list from beds belonging in the Creeton Member). In most cases only tentative identifications have been attempted because of the uncertain state of the taxonomy of the groups involved as little modern systematic work has been undertaken; the identifications are largely based upon the works of Phillips (1829), Morris and Lycett (1850-53), Lycett (1863), Hudleston (1887-1896) and Cox and Arkell (1948-50).

Bivalvia:

- *Lucina despecta* Phillips
- *Opis similis* Sowerby
- "*Venus*" *parallela* Phillips
- *Astarte* sp.
- *Trigonia* sp.
- *Modiolus* sp.
- *Cucullaea* sp. and other arcids

Gastropoda:

- *Procerithium* spp. (very abundant)
- *Capulus rugosus* Sowerby
- *Trochus* sp.
- "*Phasianella*" sp.
- "*Chemnitzia*" sp.
- "*Nerin ea*" spp. (sensu lato)
- *Nerinella* sp.
- *Natica* sp.
- Specimens belonging in the "*Amberlya-Littorina*" group of Hudleston (1892) and "*Monodonta-Turbo*" group of Hudleston (1894).

Brachiopoda: a number of terebratulid and rhynchonellid species occur.

Echinodermata: various fragmented tests, spines and plates of regular echinoids have been recovered.

Cnidaria: fragmentary specimens of corals including a thamnasteroid-type colonial form a small part of the fauna.

Elsewhere Plagiostoma, Liostrea, Lopha, Camptonectes, Pentacrinus ossicles, worm tubes and Bryzoa have also been recorded, while at Great Ponton Weldonithyris elongata Muir-Wood and W.pontonensis Muir-Wood appear to be the only named species within the prolific fauna of the Terebratula Beds (Kent, 1966, p.65).

As the sedimentological setting suggests, the fauna is exotic, its transorted nature being indicated by the following features:

(1) The preservation of the fauna is poor; breakage and wear are prominent in all fossil groups present. Even gastropods, perhaps mechanically the strongest skeletal component (Chave, 1964) are broken, and Procerithium shows all gradations in the smoothing off of its characteristic ornament. The ornamentation of other groups is similarly affected.

(2) Some brachiopods and all bivalves are disarticulated.

(3) The fauna often shows current induced orientations; the larger valves of disarticulated bivalves often occur convex-side uppermost, the current stable position. In addition, the fauna is often "concentrated", i.e. as foreset lags and consequently lacks a "natural" distribution throughout the rock, which typifies indigenous faunas like those of the Leadenham Member.

(4) There appears to be an element of size sorting in that few big specimens are usually present.

(5) The fauna is composed of epifaunal and shallow, largely vagile, infaunal species, which would be the groups most susceptible to transportation by strong currents.

IV.12.g. Discussion.

Like the Sleaford Member, the Creeton Member incorporates beds that were previously assigned to different stratigraphical levels by Kent (1966, figs. 1 and 2) and Richardson (fig.42 in Sylvester-Bradley, 1968). The principal differences between the correlation schemes presented by these earlier workers and the present author are shown in figure 4.202. Essentially both Richardson (1939a and 1939b) and Kent (1966) suggested that the Ancaster Rag, Clipsham Stone and Weldon Beds (with Barnack Rag) were broadly equivalent to the Great Ponton Gastropod Beds (with their pisolitic equivalents), whereas here a correlation of the Ancaster Rag and Clipsham Stone (the Weldon Beds occur outside of the study area) with the Great Ponton *Terebratula* Beds is favoured. The Great Ponton Gastropod Beds (and their pisolitic equivalents) have been assigned to the Sleaford Member for reasons discussed earlier (see section IV.11.f.).

The proposed re-alignment of the *Terebratula* Beds has been suggested by the evidence gained from a re-appraisal of their lithostratigraphic relationships and a re-evaluation of the age relationships of the enclosed terebratulid fauna. One of the major reasons for the apparent geographical restriction of the *Terebratula* Beds (Kent, 1966, fig.1) appears to have been that the unit's principal characteristic, the prolific terbratulid fauna, has only been recognised in a few localities around Great Ponton (Kent, 1940, p.53);

the sedimentological setting of the fauna appears to have been largely ignored and therefore the chance of a lithostratigraphic link-up overlooked. The terebratulids are set in cross-bedded,skeletal oolites, which have foresets dipping approximately to the south-west and north-east (i.e. sedimentological features quite typical of the Creeton Member). Furthermore, at the top of the Haceby Quarry, a terebratulid-rich horizon occurs, which may be the eastern extension of the Terebratula Beds referred to by Kent (1940, p.53) especially as this subdivision locally channels down into the lower division (Fig.4.196; see also section IV.12.d.). As this same horizon unquestionably belongs in the Creeton Member it also provides a direct faunal link between that member and the Terebratula Beds at Great Ponton. Therefore the Terebratula Beds, as seen at Haceby, can be considered as a local variant of the "normal" Creeton Member skeletal oolites, and it would seem reasonable to expand this interpretation to include the main body of the Terebratula Beds at Great Ponton, especially as their overall lithostratigraphic setting favours such a conclusion (the underlying Great Ponton Gastropod Beds show similar facies and down-cutting relationships to the Sleaford Member elsewhere; see section IV. 12.f.).

Despite the general stratigraphic and sedimentological evidence favouring the inclusion of the Terebratula Beds in the Creeton Member, the problem of the terebratulids themselves remains, especially as they were thought to be indicative of a younger age than that generally assigned to the rest of the formation. However the validity of the criteria on which this stratigraphic alignment has been made is questionable on a number of counts. Firstly, it appears to have been the prolific concentration of brachiopods in the Great Ponton area rather than the faunal composition that has favoured the designation of the *Terebratula* Beds as a separate stratigraphic unit, because smaller-scale accumulations also occur in the Clipsham Stone (Creeton Member) at Medwell's, Clipsham and indeed throughout much of the upper Lincolnshire Limestone.

None of these smaller accumulations have been assigned to the *Terebratula* Beds, despite the presence of common types (Muir-Wood, 1952). Secondly, and perhaps of greater importance, is the contention that some of the brachiopods resemble undescribed species from the basal Upper Inferior Oolite of Southern England (Kent, 1940, p.51), implying therefore that the *Terebratula* Beds possibly represent higher levels than are seen elsewhere in the Lincolnshire Limestone. No detailed taxonomic work on the brachiopods outside that of Muir-Wood (1952) has been attempted, so the "evidence" for this conclusion is largely speculative. Indeed, Muir-Wood (1952, p.114) stated ".....Lincolnshire Limestone species....... are distinct from those of the Inferior Oolite of the Cotteswolds (Gloucestershire), Somerset and Dorset as well as Yorkshire", suggesting that any positive correlation between the Lincolnshire Limestone species (largely assigned by her to new genera and species)and groups elsewhere is, at best, rather tentative; a point well illustrated by taking a closer look at the works of Muir-Wood (1952).

Few of the species and none of the genera described by Muir-Wood (1952) are restricted to the *Terebratula* Beds and therefore any age deductions made from them must equally apply to the other units (Clipsham Stone, Weldon Beds, Great Ponton Gastropod Beds etc.) in which these brachiopods are found - even though these same units were considered to be "older" than the *Terebratula* Beds by Kent (1966, Fig.1).

Also, in discussing the affinities of these new genera, Muir-Wood (1952) did not produce evidence to favour an Upper (as implied by Kent, 1940, p.51) rather than Middle Inferior Oolite "age" (as the ammonite evidence suggests) for the brachiopods. On the contrary, in the case of the genus Microrhynchia, Muir-Wood (1952) stated that the nearest relatives of this group have not been found in beds younger than the Lias. Despite this, the genus was still assigned to the "? Upper Inferior Oolite" (Muir-Wood, 1952, p.124), which suggests rather circular reasoning; on general stratigraphical grounds the rocks, from which these brachiopods were collected are thought to belong to the Upper Inferior Oolite, therefore the fossils extracted from them are also probably Upper Inferior Oolite in "age" and thus the presence of these fossils tends to confirm the suspected Upper Inferior Oolite age of the rocks.

In conclusion therefore, the brachiopods from the Terebratula Beds do not appear to provide sufficiently strong evidence for the separation of the Terebratula Beds from the rest of the Upper Lincolnshire Limestone because the age, suggested by these brachiopods, is by no means unequivocal and, for the most part, similar forms occur in other units that have been placed at lower stratigraphical levels. It would seem that these brachiopod accumulations (as transported assemblages in cross-bedded oolites) reflect the local sedimentation history rather than any biostratigraphical succession of the Great Ponton area, and as such, are not of any great significance as stratigraphical aids.

In the absence of useful palaeontological criteria one has to turn to a lithostratigraphical approach, and here, as discussed earlier, the evidence strongly favours the inclusion of the

Great Ponton *Terebratula* Beds in the Creeton Member. Adoption of this scheme however means that the rather restricted geographical distribution of the Great Ponton *Terebratula* Beds advocated by Kent (1966, fig.1) is no longer acceptable other than in a biofacies sense, as the Creeton Member (without the prolific terebratulid fauna) occurs between Ashby de la Launde and Clipsham and possibly a good deal further south if the Weldon Beds really are equivalent to the Clipsham Beds, as postulated by Richardson (1939a).

Apart from the Great Ponton *Terebratula* Beds the famous building stone locality of Medwell's, Clipsham, poses a problem. Like the Ancaster Stone of Wilsford Heath, the unit's base is not seen, hindering an understanding of the unit's stratigraphic relationships. However, at the nearby Soil Fertility Quarry, Clipsham, there is , in addition to an old pit, showing a typical Clipsham Stone succession, a new face exposing lower levels. This appears to have been thrown up by a minor fault separating the two pits. At the top of the new face there is a strongly cross-bedded, skeletal ooid-calcarenite unit, which has cross-beds dipping southwards, as are the cross-beds in Lithofacies A at Medwell's. For this reason, and its general sedimentological nature, the succession at the Soil Fertility Quarry is considered to be the basal part of the Clipsham Stone and therefore the basal part of the Creeton Member. This correlation (as the Creeton Member) of the uppermost beds at Castle Bytham with the Clipsham Stone follows that suggested by Richardson (1939a). However the contention of Kent (1967) that the Clipsham Stone in the new pit of the Soil Fertility Quarry is the sole representative of the upper Lincolnshire Limestone cannot be accepted, for some 3 metres of upper Lincolnshire Limestone (the Castle Bytham Member) exists between it and the Crossi Beds (included in the Scottlethorpe Member here), that occur near the base of the section.

In conclusion therefore, there seems strong evidence favouring the inclusion of the Great Ponton Terebratula Beds, Clipsham Stone, Ancaster Rag and Ancaster Freestone of Wilsford Heath (see Richardson, 1939b, plate 29A) in the same lithostratigraphic unit, the Creeton Member, along with many other like-successions, which occur south of Ashby de la Launde. There is no sound evidence for considering that the Great Ponton Terebratula Beds occur at a higher stratigraphic level than all other units within the Lincolnshire Limestone, as suggested by Kent (1966).

IV.13. CONCLUSIONS.

The new lithostratigraphy detailed in this chapter represents a major stratigraphical revision of the Lincolnshire Limestone Formation. Except for the Kirton Cement Shale (here termed the Lindsey Shale Member), none of the units proposed by Kent (1966, fig.1) have been retained. His terms have been abandoned because:

(1) they denote units which were never properly designated by type sections (no measured sections "illustrating" the stratigraphy were ever published).

(2) none of the new subdivisions correspond exactly, or even closely, to the unit that they have replaced. The retension of the "old" name would therefore create unnecessary confusion. The Lindsey Shale Member forms the single exception to this, its name having been changed because of the prior use of "Kirton" (see Ashton, 1975).

(3) the creation of a new coherent lithostratigraphy seemed to warrant the erection of a completely new terminology in order

that the ambiguities and uncertainties inherent in the "old" terminology (see Sylvester-Bradley, 1968, for review) could be finally removed.

The new lithostratigraphy has been based primarily upon the recognition of two horizons (the bases of the Lincoln and Sleaford Members), which have allowed county-wide correlation (Figs. 4.1. and 4.2). Although the base of the Sleaford Member has been recognised as locally important before (as the base of the Ancaster Freestone at Ancaster for example), the base of the Lincoln Member has never been previously recognised and therefore its significance has never been appreciated. Here, however, it is considered to be of fundamental importance in the understanding of the internal relationships of the Lincolnshire Limestone, and it has been adopted as the datum level for all lithostratigraphic correlations. The subsequent recognition of this horizon as the probable divide between rocks of _discites_ and _laeviuscula_ Zone ages has only compounded its importance. Within the broad framework provided by the two major correlative horizons, a number of other levels have been recognised, which have allowed the intervening parts of the formation to be further subdivided.

Despite the wide revision of the stratigraphy proposed by Kent (1966) that the new scheme represents, the broad twofold division into upper and lower Lincolnshire Limestone is still considered valid, although here too the relationships are not quite as Kent (1966) envisaged them. In the following sections the major changes in the stratigraphy of the lower and upper Lincolnshire Limestone are itemised and the lower/upper relationship is discussed.

IV.13.a. Major revision of the "Lower Lincolnshire Limestone".

The "old" terminology referred to in this and subsequent subsections is that proposed by Kent (1966). The details of the revisions discussed here are given in the "Former Terminology" sections of the new units described earlier.

(1) Between Lincoln and Greetham the "Blue Beds" have been shown to occur at two distinct stratigraphic levels. They do not consistently form the base of the formation. In south Lincolnshire the "Blue Beds" have been incorporated into the Sproxton Member, which is the basal unit of the formation. Around the Lincoln district however, the "Blue Beds" occur within the formation and have been differentiated as the Wragby Bed in this stratigraphic scheme. The recognition of the two "Blue Beds" levels within the Metheringham (TF 053616) section has illustrated the "condensed" nature of the lowest part of the Lincolnshire Limestone around Lincoln. The environmental significance of this "condensation" has been outlined in section V.2.e.

(2) The recognition of certain laterally persistent erosive levels in south Lincolnshire has allowed the local subdivision of the Greetwell Member, which is approximately equivalent to the formerly undivided "Little Ponton Beds" and their geographical equivalents.

(3) Besides its major contribution to the understanding of the internal correlation of the Lincolnshire Limestone, the recognition of the Lincoln Member has also shown that the "Cementstones" are not consistently developed across the county. Furthermore, the "Cementstones-facies" rocks belong in two quite separate lithostratigraphic units, the older and larger of which has been termed the Leadenham Member; the younger constitutes the Ropsley Beds, which are a formalised subdivision of the Lincoln Member.

(4) The Cathedral Beds have been recognised as a

distinctive and laterally traceable unit within the Leadenham Member. These beds do not appear to have been previously recognised.

(5) The correlative re-alignments resulting from the recognition of the Lincoln Member have shown that the "Crossi Beds" are not a coherent unit (see also section II.3.g.). In south Lincolnshire the "Crossi Beds" have been incorporated into the Scottlethorpe Member, while in central Lincolnshire they constitute part of the Lincoln Member. The "Upper Crossi Bed" has been included in the Metheringham Member.

(6) The Scottlethorpe and Lindsey Shale Members have been shown to be approximately lateral equivalents that are seen to interdigitate at Harmston (SK 992619), For this reason the Lindsey Shale Member has been included in the lower Lincolnshire Limestone (cf.Kent, 1966).

IV.13.b. <u>The relationship between the "Upper" and "Lower Lincolnshire Limestone"</u>.

The new correlative scheme has shown that the major erosive level of the formation occurs within the upper Lincolnshire Limestone (base of the Sleaford Member), effectively splitting it into two: the older part is made up of the Metheringham, Blankney and Castle Bytham Members, while the Sleaford and Creeton Members compose the younger portion. The actual lower/upper Lincolnshire Limestone junction is rarely erosive, and never significantly so (cf. Kent, 1966). The realisation that the erosive base of the "Ancaster Freestone" at Ancaster forms part of this widespread erosive horizon ("Ancaster Freestone" = Sleaford Member at Ancaster) has shown that the down-cutting there is far greater than previously appreciated; a significant part of the upper, as well as much of the lower Lincolnshire Limestone, has been removed. Stratigraphically therefore, the Ancaster sections are anomalous. Similar severe downcutting by the Sleaford Member has also been demonstrated at Great Ponton.

IV.13.c. Major revisions of the "Upper Lincolnshire Limestone".

The realisation that the Ancaster successions are anomalous has invalidated much of Kent's "Upper Lincolnshire Limestone" correlation and terminology. Therefore reference to his "Ancaster Freestone" level in this section specifically excludes the actual "Ancaster Freestone" of Ancaster. In the light of this the major revisions can be summarised as:

(1) The lowest part of the "Ancaster Freestone" level can be subdivided into the Castle Bytham Member in south Lincolnshire and the Metheringham and Blankney Members further north. All these units underlie the major erosive level, which forms the base of the Sleaford Member.

(2) The upper part of the "Ancaster Freestone" level constitutes the Sleaford Member. At Ancaster the "Ancaster Freestone" is directly equivalent to the Sleaford Member.

(3) At Great Ponton, where a similar downcutting to that seen at Ancaster occurs, the Sleaford Member is thought to be directly equivalent to the "Great Ponton Gastropod Beds". In this lithostratigraphy therefore, it is the "Ancaster Freestone" and not the "Ancaster Rag" that is considered to be equivalent to the "Great Ponton Gastropod Beds"; this contradicts a recent suggestion by Kent (in Swinnerton and Kent, 1976).

(4) A further, less pronounced, erosive level separates off the top of the Lincolnshire Limestone from the underlying units. At Ancaster, the Creeton Member is prepresented by the "Ancaster Rag",

while at Great Ponton it is equivalent to the "Great Ponton *Terebratula* Beds". No sound evidence is thought to exist for suggesting that the "Great Ponton *Terebratula* Beds" are younger than the rest of the Lincolnshire Limestone (cf. Kent, 1966).

(5) The "Clipsham Stone" is also included in the Creeton Member, although here the correlation is rather more tentative.

The relationships which the subdivisions proposed by both Kent (1966, fig.1) and Richardson (fig.42 in Sylvester-Bradley, 1968) have to the new formalised lithostratigraphy are shown in figure 4.203, together with the new biostratigraphic divisions.

CHAPTER V

THE CARBONATE ENVIRONMENTS OF THE LINCOLNSHIRE LIMESTONE FORMATION

V.1. INTRODUCTION

The development of a lithostratigraphic framework is a vital prerequisite to palaeo-environmental analysis. However, the occurrence of similar facies within different stratigraphical units raises the problem of whether to discuss the environmental interpretations member by member, or to generalise about specific facies-types, regardless of their stratigraphical position. In this chapter the former approach has been adopted and the members have been dealt with chronologically. Where appropriate two or more members have been discussed together. In this way an attempt has been made to present a coherent picture of the changing environmental patterns that occurred throughout the deposition of the formation. Unnecessary repetition in discussing like-facies occurring in different stratigraphical units has been largely avoided by cross-reference. The different aspects of deposition, reflected by the individual members, have been synthesised in a final section to produce a model illustrating the likely overall environmental setting prevalent during the deposition of the formation. In broad terms the Lincolnshire Limestone facies are thought to represent deposition along a barrier coastline, which was developed on the western margin of the East Midlands epeiric sea. The superposition of barrier deposits (upper Lincolnshire Limestone) upon "lagoonal" sediments (lower Lincolnshire Limestone) illustrates the overall transgressive nature of the formation's sedimentary succession. Four main facies-belts are represented: tidal flats, quiet-water lagoonal, agitated lagoonal, and barrier complex. However each can be divided into a number of sub-environments.

V.2. THE DEPOSITIONAL ENVIRONMENTS OF THE SPROXTON AND GREETWELL MEMBERS

V.2.a. Introduction

The earlier description of the Greetwell Member highlighted the geographical differentiation of its lithofacies; the rhythmical facies succession of south Lincolnshire contrasting with the random mosaic of central Lincolnshire (section IV.3). The lithofacies of each geographical region have been dealt with individually. The nature and variation of the rhythmical sequences (within which the Sproxton Member occurs) have been discussed in terms of an ideal rhythm, composed of an upper tidal-flat portion and a lower, often bipartite, subtidal portion. Each portion has been interpreted separately and a comparison made with similar modern environments. Controls on the rhythmical sedimentation have also been discussed. The principal environments represented in the central Lincolnshire area have been interpreted and compared with the south

Lincolnshire facies.

V.2.b. The "Ideal Rhythm" of the Greetwell Member of south Lincolnshire

The principal characteristics of the "ideal rhythm" of the Greetwell Member are depicted in figure 5.1. and the individual lithofacies of the stratigraphical units that correspond to each lithofacies-group are shown in figure 5.2. Fuller details of the lithofacies have already been given in section IV.3.

Although the ideal rhythm is based upon the Thistleton beds' succession at Thistleton (SK 903180), it is not identical to it or any other sequence. Rather, it is a compilation of the features, characterising those levels in all recorded sections; this is particularly the case with lithofacies-group 3. Although lithological variations occur to a greater or lesser extent within each of the lithofacies-groups, it is the consistent occurrence of the peloidal facies of group 3 at the top of each rhythm (except the Woolfox beds) that typifies these repetitive successions. In the most general terms each rhythm can be envisaged as a lower oolitic division and an upper peloidal limestone division (cf. Armstrong, 1975); the latter is separated from the overlying rhythm by either a hardground or sharp erosive base (Fig. 4.73). Although lithologically the most uniform, the peloidal limestones of group 3 contain a variable array of subfacies, amongst which the parallel and cross-laminated sequences are the most significant. These laminations cannot always be observed from the very top of each sequence, as shown in the "ideal rhythm", but are restricted to the "group-3 level". The major deviations from the ideal are related to variations in successive rhythms rather than lateral changes within individual rhythms, although the latter also occur (section IV.3. and Fig.4.1.). These have all been discussed in section V.2.d. and possible reasons for the variability have been outlined.

V.2.c. The Interpretation of the "Ideal Rhythm".

No definite criteria for establishing the bathymetry of shallow water carbonates exists outside the tidal zone, where a number of features have been recognised as unequivocal indicators of at least partial emergence or subaerial influence in modern tidal flats (see especially Shinn et al, 1969; and Ginsburg, 1975). Of these indicators "birdseyes" (Shinn, 1968a), desiccation features, laminations, penecontemporaneous dolomite (and associated evaporitic minerals) and algal stromatolites (see especially Logan et al; 1964) have generally been considered as the most reliable for interpreting ancient carbonate environments (Laporte, 1971; Lucia, 1972; Wilson, 1975; and Ginsburg, 1975, p.234). However, not all of these features are restricted to tidal-flat deposits; for example, mud cracks can occur in a wide variety of environments (Reineck and Singh, 1973). Therefore some combination of the various features, together with an understanding of the overall sedimentological setting, are needed to determine an ancient tidal environment satisfactorily. In the absence of the above features, which in fact are more typical of supratidal and higher intertidal settings, the identification of a low intertidal/high subtidal realm in ancient carbonate successions is often difficult to establish (Lucia, 1972, p.188), although the presence of intertidal channel sediments is one possible criterion (Klein, 1965). Because of such difficulties, most of the rhythmically-deposited shallow water carbonate sequences that have been documented, show supratidal characteristics (e.g. Laporte, 1967 and 1971; Matter, 1967; Roehl, 1967; Braun and Friedman, 1969; and Ginsburg, 1975); few cycles lacking such clear-cut evidence of exposure have been discussed (but see Wilson, 1975). Furthermore, as many of the described rhythms involve mixed evaporite-carbonate sequences (sabkha cycles), the arid and semi-arid coastal setting has been emphasised, and examples from more humid climates appear to be less common (but see Hoffman, 1975).

Despite the almost complete absence of the "key" features, the ideal rhythm of the Greetwell Member is believed to represent a shallowing-upwards sequence, which culminated in low intertidal deposition (Lithofacies-group 3; see Fig.5.1.). The reasons for this interpretation are discussed below.

V.2.c.i. Lithofacies-group 3: Tidal-Flat Deposits: The peloidal limestones of this group, capping the ideal rhythm, have a number of features that are indicative of tidal-flat deposition; the most important are parallel and cross laminations (Fig.5.1.). These are usually alternations of micrite-poor and micrite-rich laminae. The micrite-poor laminae contain prolific grain-supported peloids and/or bioclasts set in a clear sparitic cement; in contrast the micrite-rich laminae contain few allochems, except in one particular type of lamination, where peloids are quite plentiful, though usually smaller than those in the intervening sparite-cemented bands (for details see sections IV.3C.e.ii, IV.3D.e.iii, and IV.3E.e.ii.). These alternating calcarenite-calcilutite laminae are considered analogous to the tidal rhythmites of Reineck and Singh (1973, p.108, compare especially fig.184 with Fig.4.69), which are of the same scale, each lamina being approximately 1 mm. thick. Essentially the "sand layers" (in this case peloidal and/or bioclastic laminae) are deposited by tidal-current activity, while the "mud" (micritic laminae) is deposited from suspension during stand-still phases of high or low water (transport process D of Klein, 1971). The preferred alignment, parallel to the bedding, and convex-upward attitude of the bioclasts in the calcarenite laminae, emphasises the role of currents in their deposition. Such an origin is consistent with the "errant" alternating peloidal laminae (see section IV.3C.e.ii) and the micritic "micro-beds". The peloidal laminae are near-equivalents of the "evenly-laminated sands" of Reineck and Singh (1973, p.109), sharing their poor definition, which is a result of the compositional similarity of the adjacent laminae; the peloidal laminae are only clearly seen on weathered faces (see Fig.4.54 for example). The thicker micritic "micro-beds" of this lithofacies are probably expanded equivalents of the more "normal" mud laminae (Reineck and Singh, 1973, p.108), although the fine one-grain thick stringers of peloids, which impart a vague lamination to the micritic "micro-beds" in some cases (see section IV.3E.e.ii and Fig.4.63), invoke comparisons with the "thinly-laminated muds" of Reineck and Singh (1973, p.112). Finally, the cross laminations are quite consistent with a tidal-flat origin, as they probably represent migratory ripples in some cases (Fig. 4.54), scour-and-fill structures in others (Fig.4.38) and even migratory small-scale shell bars (Fig.4.39; cf. Friedman and Sanders, 1974). There is no evidence what-so-ever to suggest these laminations are cryptalgal.

The tidal-flat environment, suggested by the laminated deposits, is supported by a number of other sedimentological features:

(1) Rapid and usually small-scale vertical sedimentary changes that occur within the predominantly laminated subfacies. For example, interspersed with the various types of tidal rhythmites, and thicker micritic "micro-beds" are storm bands, which are typical coarser grained with near-parallel planar tops and bases, the latter slightly scoured; these deposits are usually ooid or bioclastic layers, which stand out as coarser bands within the fine peloidal calcarenites (Fig.4.56; cf. Laporte, 1971, table 1).

(2) Minor scour-and-fill structures, exemplified by the runnel-shaped features seen in some sequences (section IV.3C.e.ii). These were considered typical of tidal-flat deposits by Laporte (1971, table 1; see

also Klein, 1971).

(3) Round-pebble conglomerates (see Braun and Friedman, 1969). A possible example occurs in the Thistleton beds at Thistleton.

(4) Desiccation flakes, which have been recorded at Stainby (see section IV.3E.e.ii). However, their extreme scarcity and the absence of associated desiccation cracks and edgewise conglomerates calls for further comment (see section V.2.c.ii).

(5) Detrital quartz; although the amount of detrital quartz present in the limestones decreases up through the Greetwell Member, it occurs chiefly in the tidal-flat deposits, which cap these regressive rhythms. Similar quartz-rich, but essentially carbonate tidal-flat deposits have been recorded by Zamarreno (1975) and Braun and Friedman (1969), who suggested that detrital grains in general were washed onto the flats by sheet floods. Such a mechanism would also be reasonable in this situation.

(6) Sediment type; the dominant peloidal calcarenites and subsidiary calcilutites are quite typical of both ancient and modern carbonate tidal-flat settings (Illing et al, 1965; Laporte, 1967; Shinn et al, 1969; and Lucia, 1972). For the most part the peloids appear to be indurated faecal pellets, probably of the abundant "Nerinaea" gastropods, which dominate this facies (cf. Purser and Loreau, 1973, fig.10). However, the differentiation of the group 3 facies into two main types is particularly significant here; laminated peloidal-micritic limestones and bioturbated gastropod-rich pelsparites (see section IV. 3D.d.iii for example). Except for the absence of dolomite these parallel the subdivisions of facies 1 of Zamarreno (1975, p.290) and the presence or absence of lamination may reflect a similar environmental difference to that suggested by Ginsburg and Hardie (1975, p.206, but cf. Zamarreno,

1975, p.295 and see section V.2.c.ii), i.e. the bioturbated pelsparites represent subtidal deposition while the laminated sediments are the result of intermittent flooding and exposure (inter or supratidal). Alternatively, the gastropods may also have been intertidal and simply destroyed the laminations by their vagile semi-infaunal life-style. The absence of the gastropods from the laminated sediments proves neither hypothesis, although it perhaps indicates that a relatively low position was favoured in the tidal-flat regime for the group 3 facies as a whole. There is no consistent relationship between the laminated and bioturbated limestones, which occur as a random mosaic and thus represent either different aspects of the same environment or closely adjacent environments, parts of which are on a tidal flat (= laminated lithofacies).

Certain faunal aspects, which are not in themselves conclusive evidence, also support a tidal-flat interpretation:

(1) Trace fossils; the burrows that cut through the laminated sediments (Fig.4.61) are mostly vertical and subvertical, generally single or more rarely branching; all features typical of protective burrows of very shallow water settings (Heckel, 1972). Similar narrow pellet-infilled vertical burrows were recorded from Liassic intertidal-flat deposits by Colacicchi et al.(1975). In addition the frequent destruction of the tidal lamination by bioturbation is a characteristic feature of tidal flats (Shinn et al.,1969).

(2) The low diversity of the fauna; "Nerin ea" gastropods are often the only body fossils present. Even with the trace fossils, the total fauna has a low diversity, which is in keeping with the "unstable" tidal-flat environment (Lap rte, 1971; and see also Sanders, 1968).

(3) The "Nerin ea" themselves are thought to be typical of shallow subtidal, possibly low intertidal settings (M.Barker personal communication). Although never seen in the laminated facies, the

gastropods are often closely associated with such sediments (Fig.4.48) and may, by their semi-infaunal habit, be responsible for destroying the laminae.

Although the laminations, the principal feature on which the tidal-flat interpretation is based, can occur in other settings such as estuaries and, in some cases, deltas (Reineck and Singh, 1973), the general sedimentological sequence of the rhythms, with the included marine fossils, clearly favours a carbonate tidal-flat environment. However, there are a number of notable features, equally characteristic of ancient and modern tidal flats, that are missing from the Greetwell Member rhythms and their absence warrants discussion and some qualification of the tidal-flat interpretation.

V.2.c.ii.<u>Comparison with ancient and modern tidal-flat deposits</u>: Our KNowledge of modern carbonate tidal-flat sedmimentation is based upon research on Sharks Bay (Logan et al., 1974), the Persian Gulf (Purser, 1973), Florida (see especially Ginsburg, 1964), and Andros Island (see especially Shinn et al., 1969), where penecontemporaneous dolomite, "birdseyes", mud cracks, laminations, algal "laminites" and tidal channels appear to be the most characteristic features on which the interpretation of ancient tidal flats might be based. Of these "key features" only laminations are present in the Greetwell Member rhythms. The nature of these laminations and the absence of the other characteristic features requires some comment.

Shinn et al. (1969) clearly demonstrated that the laminations (physical not cryptalgal) on Andros were only preserved in supratidal environments (beach ridges and levees), associated with "birdseyes" and desiccation features. This observation has been largely substantiated by research in other modern (Shinn, 1973 , Schneider, 1975; but see

Ginsburg and Hardie, 1975) and ancient carbonate settings (Laporte, 1967; Matter, 1967; Roehl, 1967; Wanless, 1975; and Zamarreno, 1975); the comparative absence of laminations in the intertidal and shallow subtidal zones has been largely attributed to the destructive activities of infaunal organisms (Shinn et al., 1969). Despite this broad agreement, such a setting is not considered tenable for the Greetwell Member rhythmites, which are believed to represent a low intertidal-high subtidal setting for the following reasons:

(1) The Greetwell Member rhythmites have already been shown to correspond closely to clastic tidal rhythmites described by Reineck and Singh (1973); the rhythmites shallow water origin is not therefore considered to be in doubt.

(2) The preservation of such laminated deposits is typical in the low intertidal zone of clastic tidal flats, although both the high intertidal and subtidal deposits are usually lacking in primary sedimentary structures due to biogenic activity (van Straaten, 1961; but cf. Klein, 1971). Supratidal lamination is also preserved but is readily distinguishable from the intertidal type by its irregularity (van Straaten, 1961).

(3) The absence of desiccation features, "birdseyes" and early dolomite from the Greetwell Member deposits, and the presence of burrows is thought to mitigate against their being supratidal deposits. The presence of sparse micrite and peloidal limestone flakes at Stainby, does, however, indicate the proximity to and/or sporadic presence of a "desiccation zone" i.e. intertidal. Such flakes tend to be washed seaward (Braun and Friedman, 1969) and their scarcity would therefore suggest a "seaward position" on the tidal flat.

(4) The presence of certain other sedimentological features, such

as scour-and-fill structures (see section V.2.c.i), indicates a tidal-flat origin for some of the group 3 sediments (see Laporte, 1971).

(5) The association of marine "Nerinea" gastropods with the laminated sediments (Fig.4.48) suggests that a lower shoreface origin for the laminations is likely. Recent studies on "Nerinea" suggest that a high subtidal-low intertidal habitat is not unreasonable for these gastropods (M.Barker, personal communication).

(6) The preservation in the Macumber Formation (Carboniferons) of analogous laminated sediments (below laminated dolomites, which have abundant "birdseyes" and desiccation features) has been reported by Schenk (1967). He considered them to represent the low intertidal environment. Similarly, other laminites have been recorded from modern high subtidal settings by Logan (1974), although they have often been destroyed by bioturbation.

The apparent scarcity of ancient carbonate analogues of these intertidal/subtidal rhythmites contrasts sharply with the preservational record of similar clastic sediments and supratidal carbonate laminites. This may be due to a number of factors. In modern carbonate tidal flats (for example Shinn et al., 1969) lime mud seems to be the predominant sediment type, apart from the higher energy settings (levees etc.); well-defined rhythmites would be unlikely to form in such deposits, and consequently if most ancient settings were similar, carbonate rhythmites may be genuinely rare. However, if the Greetwell Member rhythmites' analogy to clastic sequences is taken one step further, it could be argued that the laminated peloidal calcarenites would pass into calcilutites higher up the shoreface, paralleling the landward graduation from sand to mud, seen in most clastic tidal flats. In this case, and ignoring for the moment the possible effect of grain size, there is no reason why "clastic" sedimentary structures should not be represented in carbonate tidal-flat sequences and preserved in the low intertidal zone as they are in ancient clastic successions. The destructive role of the infauna (Shinn et al., 1969; Shinn, 1973 ; and Logan, 1974) should be no more effective in carbonate than clastic sequences. In the light of modern ecological work on faunal diversities (Sanders, 1968; see also Valentine, 1973), it seems unlikely that the more tropical carbonate settings would have a more prolific infauna than even their temperate clastic counterparts, for it is the unpredictability of tidal environments (whether temperate or tropical) rather than any simple temperature control that "regulates" the diversity and density of faunas. However, in the more tropical (modern) carbonate settings, hypersalinity is more frequently encountered, and algae tend to flourish (see for example Hagan and Logan, 1974), free from the restrictive attention of marine predators (Garrett, 1970). The "baffling" effect of algal mats stabilises sediment and along with the possibility of inorganic precipitation, induces the deposition of lime mud, effectively biasing the modern carbonate shoreline towards being a "mud" rather than "mixed" tidal flat (Reineck and Singh, 1973). Finally, the absence of physical laminations in ancient carbonate tidal flats may be the result of interpretive bias; their apparent restriction to supratidal settings at the present day may have encouraged sedimentologists to follow straight-forward analogies. For example, Zamarreno (1975) readily attributed her lithofacies 1 sediments to a levee and beach-ridge setting similar to those described by Shinn et al. (1969) without offering supporting evidence (other than that the laminae were partly dolomitised); no desiccation features or "birdseyes" were apparently present, nor do the sediments occur within a succession that makes such an interpretation likely (op.cit., fig.33.13). Some doubt must therefore be attached to her interpretation. Thus although cryptalgal laminations have been widely used to designate ancient intertidal settings, only Schenk (1967) has clearly attributed physical laminations to a non-supratidal setting.

Even accepting the low intertidal/high subtidal origin for the Greetwell Member rhythmites, the absence of higher tidal zones (or rather their indicators) requires some consideration, especially in view of their widespread development in other ancient sequences (see Lucia, 1972 and Ginsburg, 1975 for reviews). In the case of the Greetwell Member there appear to be three possible reasons for the absence of supratidal (or high intertidal) "indicators" (desiccation features, algal stromatolites, "birdseyes", and penecontemporaneous dolomite):

(1) Non preservation/development,

(2) Erosive removal by the subsequent transgression, which initiates the next rhythm (Erosion),

(3) The geographical situation of the south Lincolnshire exposures in relation to the ancient tidal-flat complex (Geographical factor).

Non preservation/development: Although the almost complete absence of desiccation features, save a few desiccation flakes, seems to suggest that the Greetwell Member sediments suffered little exposure, it is possible that the well-washed peloidal calcarenites were not especially conducive to "mud-cracking", as a more micritic sediment would be. Furthermore mudcracks, which may also develop subaqueously, are not always developed, even in exposed muddy sediments; M.Bradshaw (personal communication) claims that only one set of such cracks have been observed in over 200 separate occurrences of laminated tidal-flat deposits of the Great Estuarine Series of eastern England. In the absence of cracking the principal mechanism for the generation of desiccation flakes and therefore edgewise conglomerates is lost. However, the few flakes that are preserved appear to be largely composed of peloidal limestone, suggesting that the sediments were not completely unsusceptible to "drying out".

The present-day restriction of algal stromatolites to harsh environments is mostly due to the feeding activity of grazing gastropods (Garrett, 1970; and Gebelein, 1976). In particular strongly cohesive mats are only developed in supratidal and high intertidal environments, out of range of the intertidal browsers, although lower intertidal and subtidal mats occur in the hypersaline parts of Sharks Bay (Logan et al., 1974). In subtidal situations, where mats are only weakly developed (Scoffin, 1970), disruption by burrowing organisms prevents any preservation of algal laminations. Thus algal stromatolites, as far back as the Mesozoic at least, probably reflect high intertidal-supratidal environments, unless there is clear evidence of hypersalinity restricting the activity of grazing molluscs, as in the present-day Sharks Bay. As abundant gastropods occur in the Lincolnshire Limestone and no evidence of hypersaline conditions exists, any algal mats (if any were developed) may well have been restricted to supratidal zones.

"Birdseyes" may not be represented in the Greetwell Member because the peloidal sediment lacked sufficient coherence to support the voids, which seem to be most commonly developed in lime muds (Shinn, 1968a). Alternatively the ubiquitous biogenic reworking of the sediment may have released gas bubbles, that could have produced "birdseye-vugs". (The wetting-drying method of formation is considered unlikely in the absence of other desiccation features.)

Finally, the absence of penecontemporaneous dolomite could also be directly related to the sediment's position on the tidal flat, as

Schenk (1967) invoked for his laminites. There is no modern record of penecontemporaneous dolomitisation occurring in low intertidal sediments. However, a second factor may be of greater importance here: climate. Although early dolomite is not restricted to semi-arid or arid climates (cf. Shinn et al., 1965; see also Folk and Land, 1975), it is more readily developed in such settings and it might be therefore that the more humid Middle Jurassic climate was inhibitive to widespread dolomitisation. Certainly none has been recorded in the emergent deposits of the Great Oolite of Oxfordshire (Palmer and Jenkyns, 1975), although the geographical setting was somewhat different to that seen in Lincolnshire. Furthermore, the Dorag (Badiozamani, 1973) and similar schizohaline methods of dolomitisation (Folk and Land, 1975) do not seem applicable in this case, except that rain water dilution may have perhaps caused some dolomitisation in supratidal environments (Folk and Land, 1975, p.65).

Although there are perhaps contributory factors in the absence of these supratidal (or high intertidal) features the most feasible seems to be the non-development (or preservation) of that particular environment in the successions examined; an explanation supported by all the other evidence available from the tidal-flat deposits, which appear to represent only the lower intertidal environment.

Erosion: The coincidence involved in postulating the erosive removal of all the supratidal deposits during the transgressive onset of each ensuing rhythm discredits this as a possible explanation for the absence of the "supratidal environment". It has not seriously been considered.

Geographical Factor: In epeiric seas like those of the Jurassic (Hallam, 1975) the gradient of the seaward slope would probably have been very gentle, (Irwin, 1965), and therefore, even where the tidal range was not great, the individual tidal-flat zones could have been very extensive; far in excess of the 16 kms. width of the Andros Island tidal flats (Shinn et al., 1969) or the 10 kms. of the Persian Gulf sabkhas (Purser and Seibold, 1973). Therefore in the rather restricted area covered by the south Lincolnshire outcrops (the rhythms have only been traced for 15 kms.) it is possible that only the low intertidal and higher subtidal zones were developed with the more emergent levels lying off to the west (?), i.e. although the tidal flats were prograding seaward, the south Lincolnshire exposures were so situated (seaward) that they remained either subtidal or just intertidal even at the "height" of the regression. More exposed tidal flat zones never extended across this area (see section V.2.d.).

In conclusion: the group 3 lithofacies probably represent the low intertidal zone of an ancient tidal-flat complex, the absence of more emergent zones being due to the geographical position of the exposures in relation to the overall geography of the "flats", which may have been centred to the west (and/or south-west) of present-day outcrops. The fact that these tidal-flat deposits cap regressive rhythms may account for the absence of any tidal channels, which ought to be represented in such sequences, for Shinn et al. (1969) pointed out that in contrast to the transgressive flats of NW Andros, the regressive flats of SW Andros had no tidal channels. Alternatively it may imply a low tidal range (Walker and Harms, 1975, p.107). Despite the regressive origins of the individual tidal-flat sequences, the rhythms form part of an overall transgressive succession; the usual case in preserved ancient tidal flats (Laporte, 1971). The regressive rhythms' origin and relationship to the Lincolnshire Limestone transgression are more fully discussed in sections V.2.d.iii and V.2.e..

V.2.c.iii. Lithofacies-groups 1 and 2: Shallow subtidal deposits: These facies groups appear to reflect different "agitation levels" within the shallow subtidal zone. The principal sedimentary and faunal characteristics of these two facies-groups are shown in figure 5.1. and the lithofacies of the individual stratigraphical units which belong to each group are shown in figure 5.2. The locally abundant molluscs, terebratulids and corals, and the presence of Bryozoa and echinoderms as debris reflect the overall marine nature of the sediments.

Lithofacies-group 2: This, the "low agitation" group, is lithologically varied, ranging from silty biomicrites to oosparites. However, the rocks are mainly bimodal or poorly-sorted packstones, having predominant but variable proportions of ooliths and peloids set in a "poorly-washed" matrix of subsidiary micrite and sparite. Various other grain types (oncolites, bioclasts, intraclasts) also occur in the packstones.

The general poor sorting of the allochems, and the presence of some primary micrite in the matrix suggests a low degree of agitation, as does the largely indigenous fauna (moved but without significant large scale post-mortem transportation) but the presence of boring (micrite-envelopes) and accreting (oncolites) algae clearly indicate a shallow rather than deep "quiet" environment, within the photic zone (Bathurst, 1967b). Swinchatt (1969) claimed that an abundance of algal bored grains suggested deposition in waters less than 37 metres deep and probably less than 15-18 metres. As micritisation of the allochems is widespread and indeed typical of this group of lithofacies, it seems likely, especially in view of their juxtaposition to the intertidal deposits, that these sediments were laid down in very shallow water. However, the low agitation is unexpected in view of the current-induced laminations in the intertidal deposits and the presence of oncolites.

Most authors have attributed oncolites to agitated subtidal settings (Logan et al., 1964; Gebelein, 1976; and Tucker, 1977), although the oncolites of this facies-group do not satisfactorily fit into any of the "modes" described by Logan et al. (1964). They usually show thin, discordant, asymmetric growth rims around nuclei composed of other allochems, and these features suggest an irregular, rather slow growth, probably induced by only weak and/or episodic agitation. A similar low-agitation environment is also suggested by the composite and (very rare) asymmetric ooliths, and "grapestone" allochems, as well as the abundant burrows, which are seen in these facies (see also section V. 2.f.). Grapestones require a period of stability for inter-granular cementation to be achieved (Illing, 1954; Purdy, 1963; and Bathurst, 1975, p.132), while the composite (= compound ooliths of Carozzi, 1964) and asymmetric ooliths similarly indicate only episodic agitation. Carozzi (1964) envisaged periods of oolitisation (reworking) interspersed with quiescent times when aggregation could occur; such a mechanism seems perfectly consistent with the Greetwell Member evidence. The few asymmetric ooliths, although nowhere near as "extreme" as the examples discussed by Freeman (1962), support the general lines of evidence favouring a largely stable substrate. Nowhere is there evidence for high agitation, with which modern onoclites are frequently associated (Logan et al., 1964) and it is possible that these Jurassic oncolites are not truly analogous to the modern counterparts.

Ooliths often dominate the facies and, in addition to the composite sort, there are two other main types: normal and superficial. The latter have relatively thin oolitic coatings around the nuclei, which are usually bioclasts or, more often, micrite (micritised?) grains. Similar thinly coated ooliths with "peloidal" nuclei (and associated with widespread micritisation) have been noted in shallow parts of Bimini lagoon, where the substrate is stabilised by subtidal gelatinous algal mats (Bathurst, 1967a), and in lagoons in the Persian Gulf (Loreau and Purser, 1973). Although Bathurst (1967a) claimed an in situ developmmnt for his grains, there tends, in the Bahaman carbonate areas, to be a general reduction in both the numbers of ooliths and the thickness of the oolitic coatings away from the highly turbulent oolith generating shoals toward the less agitated oolitic-grapestone facies (Newell et al., 1960). Such a facies gradient would seem to fit the Lincolnshire Limestone situation, for the presence of "normal" ooliths (which presumably grew in more agitated waters) in this facies suggests a degree of "washing in", although the in situ growth of some superficial ooliths (cf. Bathurst, 1967a) is not ruled out. In fact the "oncolitically coated ooliths" of this facies illustrate the two-stage life of many of these allochems.

The group 2 lithofacies would therefore seem to correspond to the "stable sand habitat" of Newell et al. (1959; = oolitic and grapestone facies of Purdy, 1963; see also Bathurst, 1975, p.121). Much of the stability may have been due to the presence of gelatinous, subtidal mats, which are capable of stabilising carbonate sands even in shallow, turbulent conditions (Purdy, 1963; Bathurst, 1967a, 1967c, and 1975; Scoffin, 1970; and Neumann et al., 1970), despite leaving no fossil trace of their former presence (Bathurst, 1967c). These mats deteriorate periodically and are destroyed by burrowing, a probable fate in this facies. During times of deterioration or destruction the increased agitation may have been responsible for rolling the "oncolites" and reworking the other "complex grains", as might the increased turbulence when ooliths were washed into the "lagoonal" area. It is possible that these "quiet-water oncolites" of the Greetwell Member were a related feature of the subtidal mats.

To summarise: The evidence for generally stable, low-energy substrate conditions, with only episodic agitation, is provided by the presence of superficial ooliths, composite ooliths, grapestone grains, "quiet-water oncolites" and well-developed burrow systems. Poor sorting and the presence of some mud suggests inefficient winnowing. However, many of the above grain types require periodic agitation or reworking in between periods of quiescence, and the common occurrence of "normal" ooliths indicates transport of "exotic" grains into this environment. The general stability of these shallow-water substrates was probably provided by the presence of subtidal gelatinous algal mats, which were periodically destroyed, allowing sediment reworking to take place. This may have happened at different places at different times. A broad analogy can be drawn with the stable sand habitat of Newell et al. (1959), and Talbot (1974) has described "fossil" examples of similar facies, which he also related to subtidal-mat-controlled stable sand substrates.

Lithofacies-group 1: The biosparitic (low relief shell bank) and oosparitic grainstones of this facies indicate a more agitated environment. Current activity is reflected in the winnowing of mud, the alignment of grains parallel to the bedding (usually convex-side uppermost) and, at Thistleton, very crude cross bedding. Furthermore substrate mobility is suggested by the relative scarcity of burrows and the preponderance of mobile, epifaunal suspension feeders within the fauna. However colonial coral clumps were able to survive, which argues against really unstable (high energy) conditions. This lithofacies probably represents a stage nearer the oolite shoal area in the energy gradient of Newell et al. (1960), although it is not equivalent to the "unstable oolite sand habitat" of Newell et al. (1959).

Together therefore Lithofacies groups 1 and 2 represent a rather low-energy, marine subtidal deposit, suggestive of a protected environment (tidal flats being indicative of protected shorelines, Purser, 1975), which is fringed on the one side at least by tidal flats (Lithofacies-group 3), and presumably seaward by a protecting "barrier", on which the majority of the sea's energy was dissipated.

V.2.c.iv. Boundaries between rhythms: Although sharp contrasts are sometimes found locally within rhythms, the major divides occur between rhythms, and can be widely traced (Fig.4.1). Usually sharp erosive bases (Figs. 4.72 and 4.73) or hardgrounds (Fig.5.3) separate the intertidal facies of the lower rhythm from the subtidal deposits of the overlying rhythm. The hardgrounds are not extensively exposed in plan, except at Waltham on the Wolds (Fig. 5.3.), and only rare bores or encrusters have been seen in some sections; it has not always been possible therefore to determine the precise extent of the hardgrounds, even within individual quarries. However at Waltham, the hardground has been extensively bored, indicating its "exposure" in subtidal conditions (Goldring and Kazmierczak, 1974; Palmer and Fursich, 1974; and Bramley, 1975), and there are hints of an early acicular "rim" cement that may have had a submarine origin (Purser, 1969; and Shinn, 1969). However, this is by no means clearly developed and even where similar, though better developed rim cements are seen in hardgrounds (Stainby), the very close packing of the peloids and presence of intertidal micrite make it difficult to determine their interrelationships. The presence of isopachous or meniscus relationships at grain contacts (Purser, 1969) cannot be satisfactorily deduced (cf. Fursich and Palmer, 1975). However the presence of the sporadically developed early cement, and the faunal evidence make submarine cementation not unreasonable.

V.2.c.v. Interpretative model for the "Ideal Rhythm": The regressive nature of each rhythm is evident from the superposition of intertidal upon subtidal deposits, reflecting the progradation of tidal flats out into a protected inshore embayment (Fig.5.4.). In the ideal case it is envisaged that the higher-energy subtidal deposits (group 1) were deposited farthest offshore in a more agitated environment, which passed shorewards into a stable (algal mat stabilised?) sand regime, and finally into tidal flats of the lower shoreface. Storms may periodically have affected all facies but the most discernible record was left on the tidal flats. However, this idealised pattern needs some qualification: as the entire sedimentary regime probably occupies a protected "lagoon", all of the subtidal deposits are relatively "low energy" and so similar as not to signify separate bathymetric zones along the lines envisaged by Irwin (1965). On the other hand, the grainstone facies (group 1) possibly represents areas without a stabilising mat cover or those nearer the agitated barrier zone (which need not be deeper). The fact that the grainstones grade laterally (in a number of directions) into more typical packstones of group 2 argues against a simple bathymetric relationship. However, the overall pattern of intertidal deposits prograding over subtidal sediments is valid and where seen, the higher-energy limestones (group 1) always occur at the base of the rhythm.

Each rhythm is terminated by renewed transgression as the intertidal facies are erosively overlain by subtidal deposits. The erosive base or hardground contact between rhythms is believed to represent the transgressive phase of each rhythm (Sellwood, 1970; and Talbot, 1973) and therefore the rhythms are of the asymmetric ABCABC type when fully developed; a typical feature of shallow water carbonate sequences

(Duff et al., 1967; and Wilson, 1975). During the ensuing standstill, regression proceeds in the form of renewed tidal-flat progradation. Thus the transgressive phase is a period of negative sedimentation, and regression a time of positive sedimentation.

V.2.d. Variations from the ideal rhythm and their interpretation: Apart from the incorporation of the Sproxton Member into the lowest rhythm (α) with the Market Overton beds, the main variations tend to be of degree rather than kind, and can be best summarised under lateral and vertical changes; the former reflect variations within individual rhythms, the latter between rhythms.

V.2.d.i. The Sproxton Member: Although composed of sandy limestones, the Sproxton Member represents a subtidal phase of sedimentation immediately after the initial "Lincolnshire Limestone transgression" and is therefore analogous to the lower parts of the younger all-carbonate rhythms of the Greetwell Member. The quartzose composition of the Sproxton Member is probably a direct result of the reworking of the underlying Grantham Formation prior to the establishment of carbonate sedimentation, for such a transgression ought largely to suppress the supply of terrigenous material by raising base level. It might be argued that the presence of a clay, overlying the sandy limestones, reflects the culmination of the initial transgression (rather than just a pause in sedimentation), and that the Market Overton beds alone represent the regressive phase. However it seems more likely that the low-lying coastal plain, represented by the Grantham Formation, would have been rapidly flooded, and that the Sproxton Member is best considered as an equivalent deposit of the peloidal ooid-calcarenites of the higher rhythms.

V.2.d.ii. Lateral variations within individual rhythms: Each rhythm has a distinctive development, which can be readily traced across south Lincolnshire. For example, massive oolites typify the South Witham beds, and silty calcilutites characterise the basal portion of the Market Overton beds. Despite this general uniformity, variations in the thickness and composition of the rhythms do occur. The lowest two rhythms maintain a fairly constant thickness, but the younger ones vary quite widely; for instance the South Witham beds from 2.3 to 4.9 metres in thickness, but as these variations largely mirror those of the formation as a whole, they are probably insignificant. Compositionally too, it is the higher rhythms that show the greater variation, notably the sporadic development of group 3 lithofacies in the South Witham beds (Fig.4.1). However, the Thistleton beds also have some interesting variations; for example, the group 3 lithofacies of this rhythm thickens westwards until at Waltham on the Wolds it is nearly twice as thick as elsewhere (Fig.4.1.). As laminated horizons are well developed at Waltham this thickening may indicate greater proximity to the ancient shoreline. If this was a reliable trend then a westerly land area would be possible, as previously suggested by Bradshaw (1975, fig. 1.), although the isolation of the quarry in question prevents any firm conclusion being drawn. However, a further factor supports the inference: ooliths with a radial texture, some of which have been broken and re-incorporated (as the nuclei) into normal marine ooliths, occur in the overlying South Witham beds at Waltham. Such ooliths are usually associated with hypersaline lakes (Friedman et al., 1973; and Kahle, 1974) and it could be that they developed in hypersaline standing water, ponded on the higher parts of the tidal flats. As the sediments in which they are found are unlikely to represent such environments, the ooliths have most likely been washed in from their generation zone and incorporated with marine ooliths in a shallow subtidal environment.

V.2.d.iii. Vertical variations in the rhythms: Although the individual rhythms are of differing thickness, it is the variations in the thickness and development of the group 3 lithofacies that are the most significant vertical changes. These can be summed up as :

(1) A progressive decrease in the proportion of the total rhythm that Lithofacies-group 3 makes up (an approximate measure of the inter-tidal proportion). This is exemplified by the Stainby sequence; the peloidal limestones of group 3 total 40% of rhythm α (Sproxton Member and Market Overton beds), 25% of β , 5% of γ , and are completely absent from Δ (Fig.4.1.).

(2) the progressive loss of Lithofacies-group 3 up the sequence; it is represented in all localities where rhythms α and β are exposed but is only sporadically represented in γ and is completely absent from Δ .

Together these indicate that the influence of the prograding tidal flat progressively wanes with time, suggesting that these regressive pulses are only minor fluctuations in the overall transgressive sequence represented by the Greetwell Member succession in south Lincolnshire. Thus each transgression, which initiated a new rhythm, was more successful than the last (with regard to the south Lincolnshire area) and the tidal flat does not prograde as far or persist as long (in any one area) as it previously did (Fig.5.5.). The culmination of this pulsatory transgression is seen in the Woolfox beds, where no intertidal-flat deposits are recorded. To some extent the gradual establishment of permanently subtidal conditions over south Lincolnshire is also reflected in the quartz content of the tidal-flat deposits; this decreases in successive rhythms until it is of little consequence in the South Witham beds (Fig.5.6.). The nature of the subtidal deposits also shows a change through time; the silty biomicrites (Lithofacies A) of the Market Overton beds reflect very low-energy conditions, but as the sea became more and more dominant the equivalent level in higher rhythms became more grain-rich and was probably subjected to greater turbulence (with a corresponding decrease in quartz content because of winnowing). Overall, therefore, the invasion of south Lincolnshire by the Lincolnshire Limestone sea was achieved in a number of advances rather than one catastrophic stroke.

V.2.e. Controls of the Rhythmic Sedimentation.

There is general agreement that asymmetrical regressive sedimentary rhythms are a common feature of epeirogenic sea successions, and that, in addition to subsidence (to preserve the record) some other control is required to produce the rhythms (Wells, 1960; Duff et al., 1967; Sellwood, 1970; and Wilson, 1975). Duff et al. (1967) proposed "sedimentary", tectonism (including subsidence), eustasy and climate as the most likely of such controls (cf. Wilson, 1975, p.51). As already outlined, the ideal rhythm seen in south Lincolnshire is considered to have been initiated by a transgression, resulting from accelerated subsidence, and during the ensuing still-stand (after the rapid relative rise in sea level) accumulation apparently outstripped subsidence and the "basin" was gradually in-filled by the prograding tidal flats (cf. Talbot, 1973). Thus the Greetwell Member rhythms could be envisaged as a result of tectonic (subsidence) and sedimentary (tidal-flat progradation) processes. However, the rhythms themselves and some associated sedimentary features - e.g. diminishing presence of quartz, suggest an overall net transgression up the succession. Although this could have simply resulted from a localised tectonic effect, like an increasing rate of subsidence, the recognition of a eustatic sea level rise at this time (Hallam, 1969) provides a ready alternative (or contributory) mechanism for the increasing success of the pulsatory transgression. Despite the differences in scale, the rhythms discussed by Sellwood (1970) and Talbot (1973) represent similar situations, the latter especially so because the gradual reduction of terrigenous influence seen in the Lincolnshire Limestone rhythms was also noted by Talbot (1973).

In addition to contributing to the control of the Greetwell Member rhythms, tectonism seems to have had wider significance in the disposition of the Lincolnshire Limestone at that time (discites Zone; see Fig. 5.7.). The Greetwell and Leadenham Member successions of central Lincolnshire reflect a gradual subsidence (see section V.3.), which contrasts sharply with the pulsating subsidence of south Lincolnshire; the formation's succession in central Lincolnshire shows no major "breaks", except in its southern part (Ancaster - Leadenham), where the Greetwell - Leadenham Member contact is marked by a hardground, which may be equivalent to the hardground separating the South Witham and Woolfox beds (see section IV.3.e.i.). Furthermore, the Lincolnshire Limestone sequence of central Lincolnshire is condensed relative to south Lincolnshire (Fig. 5.7.) and the Grantham Formation is only sporadically developed north of Leadenham (Evans, 1952; see also Kent in Swinnerton and Kent, 1976; Fig. 5.7.); at Greetwell the Lincolnshire Limestone sits directly upon the Northampton Ironstone. The Lincoln district in particular, and central Lincolnshire generally (the "condensation" decreases southwards from Lincoln) appears to have acted as a relatively stable area of negative subsidence (Grantham Formation and lowest Lincolnshire Limestone times) or gradual subsidence (later discites Zone times), while south Lincolnshire underwent greater, if episodic, subsidence. Thus the Lincoln area apparently acted as a mini-swell for part of the Bajocian at least, only succumbing to marine sedimentation with the increasing "success" of the Lincolnshire Limestone transgression. The Gradual, if sporadic, incoming of the Grantham Formation and lowest Lincolnshire Limestone southwards (from Lincoln) suggests that the swell may have been tilted in that direction (Richardson, see Sylvester-Bradley, 1968, fig. 42; and Wilson, 1948, fig. 9.), although the structure of the region is too poorly known to be sure. Therefore, although the "Nocton Uplift" of central Lincolnshire has long been known to affect the present day structure of the Lincolnshire Limestone (Swinnerton and Kent, 1976), its probable former importance as a control on sedimentation is now also established.

Lincoln occurs on a faulted zone (E-W alignment) and the presence of further faults (N-S) away to the east (Evans, 1952, p.332) suggests the possibility of the mini-swell being fault-controlled, although again it must be stressed that the geological relationships are too little understood for any positive conclusions to be drawn. However, as both Wilson (1948, fig. 9.) and Richardson (see Sylvester-Bradley, 1968, fig. 42.) indicate a much more rapidly thickening sequence north of Lincoln, a fault control is not beyond the realms of possibility. In such a case, the "block" would tilt southwards where its margin would be more elusive and transitional; the situation seen in the Lincolnshire Limestone. Although further work is required on the earlier formations to substantiate this idea, the existence of an intermittently active mini-swell in early - mid Jurassic times is a distinct probability.

V.2.f. <u>The Central Lincolnshire Lithofacies and their Interpretation</u>.

V.2.f.i. <u>Introduction</u>: In marked contrast to the rhythmical arrangement of the lithofacies in south Lincolnshire, those of the central Lincolnshire Greetwell Member form a mosaic, in which no particular pattern has been discernible. Essentially two contrasting facies types exist: Lithofacies A, which is a variable collection of "oolitic" lithologies typified by complex, branching burrow systems, and Lithofacies B, which has a more uniform peloidal composition. Both are considered to be subtidal.

Each lithofacies has been separately interpreted below and the significance of particularly notable features, such as the burrow systems, have been discussed. The importance of the Wragby Bed, which is the only consistently recognisable horizon in this area, has also been outlined.

V.2.f.ii. <u>Interpretation of Lithofacies A (Leadenham Facies)</u>: The Leadenham Facies has been so-called because of its particularly good development at Leadenham, where the most spectacular examples of the complex burrow systems are to be seen (Fig. 4.18.). As a whole the lithofacies encompasses an array of "oolitic" lithologies, which range from oncolitic wackestones (e.g. oncolitic biomicrite) to oolitic packstones (e.g. skeletal oosparite), and have a reasonably diverse fauna within which colonial and solitary corals, gastropods, bivalves, terebratulids and "algal tube colonies" are especially prominent (see sections IV.3A.c.i. and IV.3A.d.i. for lithological and faunal details). In broad terms these lithologies reflect differences in agitation levels within a shallow, low-energy subtidal setting (cf. V.2.e.iii.).

The energy gradient is most obviously monitored by the variation in mud content, which mirrors the degree of current winnowing, and the general poor sorting of the allochems. Towards the low-energy end of the spectrum, an essentially muddy sediment is dominated by skeletal grains and "low-energy oncolites" (cf. V.2.c.iii.). Turbulence is presumably low in these areas and the oncolites have irregular shapes; their internal structure does not compare with any of the modes described by Logan et al. (1964). In the higher-energy sediments, the allochems become progressively more abundant, better sorted and winnowed. Ooliths form a bigger percentage of the overall allochem content (Fig.4.23.) and often compose the nuclei of oncolites, which tend to be more spherical in these lithologies; this may be a product of the shape of the nuclei and/or the greater agitation to which these grains have been subjected. The ooliths are variable in nature but many are "superficial", which is consistent with their low-energy, back-barrier setting, away from the major turbulent oolith-generating zone (cf. Newell et al., 1960).

The lack of turbulence, as indicated by the characteristics of the sediments, and the largely indigenous nature and composition of the fauna, suggests deposition in quiet-water environments of marine salinites. The preponderance of algae in oncolites and "micrite-envelopes" indicates shallow waters (cf. Bathurst, 1967c and Swinchatt, 1969). The whole facies compares favourably with the "Stable Sand Habitat" of Newell et al. (1959; = Oolitic and Grapestone Facies of Purdy, 1963), although the geographical setting is quite different. The Greetwell Member is most likely to have been deposited in a broad "lagoonal" area, on the protected inshore side of an off-shore barrier complex (see sections V.7. and V.8.).

V.2.f.iii. The Complex Burrow Systems of the Leadenham Facies: Although many of the subtidal oolites of the south Lincolnshire sequences contain what may be poorly-preserved examples of these burrow systems, their most spectacular development, as open burrows, occur in the central Lincolnshire area. The burrows, which have a circular cross-section, varying in diameter from 3 mm. to 8 mm., are arranged in complex systems that often penetrate to a depth of over 0.5 metre from the top of a bed. Many Y-shaped junctions, where the diameter is greater than normal, typify the system. The burrows appear not to be lined although some of the open ones have a veneer of limonitic material that gives them a smooth inner surface. They can occur open or micritic-infilled and all graduations of infilling are seen (see section IV.3A.c.i.). Although the burrows are inclined at all angles between the horizontal and vertical, most have a strong vertical component (Fig.4.18). The burrows occur in very dense concentrations in some beds; the density of burrows and occurrence of branching are equally concentrated between the top of the bed and the limit to which the burrows penetrate. It has not been possible to determine the nature of the burrows aperture.

The above characteristics show strong similarities to modern alpheid and callianassid shrimp burrows (Weimer and Hoyt, 1964; Shinn, 1968b; Farrow, 1971; and Braithwaite and Talbot, 1972), especially in that they have relatively narrow burrow diameters, multiple branches and frequent directional changes. In detail however it is difficult to match the Leadenham Facies burrows with either of these modern systems. The morphology of the burrow system, the absence of a burrow-lining (but cf. Shinn, 1968b, p.889) and perhaps the size of the Leadenham Facies burrows (but cf. Braithwaite and Talbot, 1972, p.276) rule out the possibility of their having been excavated by callianassid-type shrimps. In particular the Leadenham Facies burrows lack the initial near-vertical, penetrative shaft (Braithwaite and Talbot, 1972, p.276) and distinct horizontal room - and - gallery systems (Farrow, 1971, p.475;

and Shinn, 1968b. p.884; and fig. 10) of the callianassid systems. However, the unlined alpheid burrows, which branch very close to the sediment-water interface and have multiple, irregular side branches (Shinn, 1968b), seem to provide a better comparison, although here too the size and shape of the burrow cross-section (cf. Farrow, 1971, p.482) is not directly comparable. In general the Leadenham Facies systems are smaller (burrow diameter) and more uniformly complex than the modern systems; they also seem to have a stronger vertical component and smaller burrow diameter than some Bathonian burrow systems, which may have been formed by alpheids (Fursich and Palmer, 1975). However, the presence of a strong vertical component may be a result of environmental rather than taxonomic considerations. Shrimp burrow developments in quiet-water environments have a more pronounced vertical component (Farrow, 1971, p.480). Alternatively, extensive horizontal systems may be a result of a thin sediment cover (op.cit., p.490).

Despite the broad similarity of the Leadenham Facies burrows to modern shrimp burrows, and alpheids in particular, sufficient differences remain to cast doubt on an exact comparison. The originator of the Leadenham Facies burrows is therefore tentatively considered to be an undetermined shrimp-like crustacean. The burrows cannot be readily matched with any ichnogenera (cf. for example Fursich and Palmer, 1975, and Fursich, 1973, 1974b and 1975).

Environmentally the burrows fit readily into the (subtidal) quiet-water lagoonal setting envisaged for the Leadenham Facies. Although modern shrimp burrows often occur intertidally (Weimer and Hoyt, 1964; Shinn, 1968b; and Farrow, 1971) they range down into the subtidal realm (Weimer and Hoyt, 1964; Shinn, 1968b; and Braithwaite and Talbot, 1972). The dense concentration and strong vertical component of the burrow systems strongly favour sheltered lagoonal settings (Farrow, 1971, pp.480 and 488). Furthermore, the presence of open systems (cf. Shinn, 1968b), together with the high burrow density, may reflect slow rates of sedimentation and early lithification. The presence of the open burrow systems (associated with a hardground at one level) and densest burrow concentrations in central Lincolnshire where the Greetwell Member is relatively condensed (cf. south Lincolnshire, Fig. 4.1.) would seem to favour this proposal. In most respects, therefore, the evidence from the burrows tallies with the environmental setting (quiet-water, back-barrier lagoon) determined from the lithofacies, and certain levels, rich in the burrows, are comparable to the more stable areas of the "Callianassa sandsheets" of Farrow (1971; cf. "Platform Interior Sand Blanket" of Ball, 1967; and Braithwaite and Talbot, 1972, fig.2.).

V.2.f.iv. Interpretation of Lithofacies B (Lincoln Facies): Lithofacies B is almost invariably composed of fine-grained, grain-supported biopelsparites (packstones or grainstones), in which rare ooliths, wood flakes and oncolites complement the dominant peloids and subsidiary bioclasts. Although burrows are generally rare, a sometimes prolific faunal association of Pinna, Gervillia, and "Nerin ea" typify the facies. A unique occurrence of parallel lamination has been recorded in one bed at Leadenham, otherwise sedimentary structures are lacking (see sections IV.3A.c.ii, and IV.3A.d.ii. for details). This lithofacies is closely comparable with the unlaminated pelsparites of Lithofacies-group 3 of the South Lincolnshire Greetwell Member (see Fig. 5.1.).

Although the absence of parallel laminations and their associated features (see section V.2.c.i.) would seem to preclude the possibility that these deposits are tidal-flat sediments, their general similarity to the unlaminated pelsparites of south Lincolnshire suggests that they were deposited in very shallow subtidal conditions. As the rocks are grain supported and well sorted, they have probably suffered more agitation than is generally the case with the Lithofacies A deposits, a possibility that is supported by the preservation of Lithofacies B's fauna. The low-diversity fauna is invariably "moved" and the bivalves are disarticulated, often appearing to be preferentially aligned in one direction (the main species are all elongate). The Pinna are always uprooted, although the fauna is rarely broken. These factors suggest that persistent but fairly low-energy currents swept the area, while periods of increased current activity were responsible for the uprooting of the Pinna (and Gervillia ?; cf. Fursich, 1977, p.348). It is also interesting to note that the very shallow subtidal back-barrier environment postulated for this lithofacies (and therefore its fauna) is similar to the habitats proposed for comparable Corallian species by Fursich (1977).

In purely sedimentological terms, this peloidal facies is readily comparable with those of the shallow lagoons of the Trucial Coast (cf. Purser and Evans, 1973; Evans et al., 1973; and Purser and Loreau, 1973, fig. 10) and of very shallow subtidal settings in the Bahamas (cf. Ginsburg and Hardie, 1975, p.206). Compared to Lithofacies A, this lithofacies would seem to represent very shallow water (just subtidal) in which current-activity is persistent (sorting, faunal alignment) and occasionally, quite strong (Pinna uprooting).

V.2.f.v. Significance of the Wragby Bed: The Wragby Bed is an important stratigraphical horizon in central Lincolnshire, that is essentially composed of a basal fine-grained sand, which grades up via a quartzose peloidal calcarenite into a peloidal ooid-calcarenite (for details see sections IV.3B.d. and IV.3B.e.). Environmentally it may reflect a minor regressive phase.

Southwards from Lincoln, where the Wragby Bed has its thickest development, there is a decrease in the detrital quartz content of the bed suggesting that the clastic source was most probably situated near Lincoln (or further north, see section IV.3.e.ii.), where the presence of the decaying "Lincoln High" may have had an influence. It seems from general stratigraphical evidence that the "High" tilted southwards from Lincoln and thus, as it was slowly overcome by the Lincolnshire Limestone transgression, the Lincoln area was the last district to succumb to marine sedimentation. As the Wragby Bed was deposited soon after (in terms of sedimentary thickness at least) the "High's" final submergence, land may still have existed close to Lincoln (westwards ?). However, as the lack of exposures prevents the geometry of the Wragby Bed being determined, this proposal is only tentatively forwarded.

This minor regression may have manifested itself in South Humberside as the Raventhorpe Member (Ashton, 1975) while in south Lincolnshire the Wragby Bed level coincides approximately with the top of the regressive rhythm of the Thistleton beds. Thus all three sedimentary provinces show signs of regression at approximately the same time, although the mechanisms of each clastic influx may differ.

V.2.f.vi. Conclusions: During Greetwell Member times the slow subsidence of the "decaying" Lincoln High produced shallow subtidal conditions in central Lincolnshire and two main lithofacies were deposited. Although the absence of any discernible pattern in the distribution of the two lithofacies has made it impossible to be certain of their bathymetric relationships, it is likely that Lithofacies B was deposited in a shallower, more current-swept environment than A.

However, Lithofacies A itself shows a range of "turbulence levels", which may have been depth-related although exposure to current activity (regardless of depth) could equally well explain the differences seen. Overall therefore the central Lincolnshire lithofacies are thought to reflect deposition in different sub-environments of a relatively quiet-water, shallow back-barrier "lagoon", an environment also suggested by the faunas of the lithofacies.

V.2.g. Conclusions.

Deposition during the early stages of the Lincolnshire Limestone transgression was greatly influenced by the "Lincoln High". Initially, it appears to have "resisted" the transgression and to have been flanked to the north and south by more rapidly subsiding "basins"; over much of central Lincolnshire no evidence exists for the lowest stratigraphical subdivisions of the formation that are developed in the "basins". In due course the "High" also became submerged, although its influence on sedimentation did not cease. It formed a relatively stable area of gradual subsidence, upon which a mosaic of two subtidal lithofacies were deposited, in marked contrast to the rhythmically deposited sequences of south Lincolnshire. These rhythms resulted from a combination of episodic accelerated subsidence and tidal-flat progradation during the ensuing still-stands. The "Lincoln High" therefore caused a geographical polarisation of the sedimentary facies during earliest Lincolnshire Limestone times. The lithostratigraphic successions in south, central and north Lincolnshire (cf. Ashton, 1975) all show distinct differences from each other, reflecting variations in the depositional environment. Although the polarisation decreased as the transgression continued, it persisted until the onset of Lincoln Member deposition in *laeviuscula* Zone times.

Although the "Lincoln High" asserted a profound influence upon sedimentation at this time, the nature of the deposits indicate the presence of an off-shore barrier (see sections V.7. and V.8.), which was probably the single most important control on sedimentation in the Lincolnshire Limestone. Both theoretical considerations (Irwin, 1965) and the actual existence of low-energy deposits, such as tidal-flat rhythmites and "lagoonal" oolites in the lowest parts of the formation, suggest that the barrier was established from the onset of Lincolnshire Limestone deposition (cf. Purser, 1975, p.342). The development of the barrier effectively separated a broad near-shore lagoonal area from the remainder of the Jurassic epeiric sea (Hallam, 1975). In fact the Lincolnshire Limestone sediments can be broadly grouped into "lagoonal" deposits (lower Lincolnshire Limestone) and barrier-complex sediments (upper Lincolnshire Limestone). The superposition of the latter upon the former indicates that the formation, as a whole, represents a transgressive succession. However, minor regressive phases, such as the tidal-flat rhythms of the Greetwell Member, are also recorded within the formation's sequences.

With the final "decay" of the "Lincoln High", post-<u>discites</u> Zone sedimentation in the Lincolnshire Limestone became less complex; the younger stratigraphical units reflect the steady landward advance of the more off-shore facies belts uniformly across "basins" and "high" alike. The nature of the environments represented in these facies belts are discussed in the following sections of this chapter.

V.3. THE DEPOSITIONAL ENVIRONMENTS OF THE LEADENHAM MEMBER.

V.3.a. Introduction: Evidence for Lagoonal Sedimentation.

Although most of the lower and much of the upper Lincolnshire

Limestone can be broadly referred to as back-barrier or "lagoonal" sediments, only the Leadenham Member and parts of the Lincoln Member (Ropsley Beds and Little Bytham beds) were deposited in what are considered classical quiet-water lagoons of limited geographical extent.(Fig. 4.1.). The sediments of the Leadenham Member are typical quiet-water biomicrites (cf. Talbot, 1973), in which an often prolific infauna is present; the fineness of the sediment (calcilutites) and the largely in situ fauna testify to a protected environment, consistent with the back-barrier lagoon setting proposed here (see also section V.8.).

Despite the gross uniformity of the Leadenham Member deposits, significant variations occur, both in the sediments and fauna, which pin-point important events in the history of the lagoon. These events, and the general sedimentary environment, reflected by this unit, are discussed in the following sections. The significance of the Cathedral Beds is also outlined. Finally, an outline history of the lagoon is attempted, in which the sedimentary features and palaeoecological aspects (see section IV.4.f.) are drawn together.

V.3.b. Sub-environments of the Leadenham Member.

V.3.b.i. The Sediment of the Leadenham Lagoon: The micrite or lime mud which dominates this member is traditionally associated with quiet-water, protected "lagoonal" settings (Newell, 1955; Newell et al., 1959; Purdy, 1963; Matthews, 1966; Stockman et al., 1967; Bathurst, 1967b and 1975; Purser and Evans, 1973; Schenk, 1975; and Wilson, 1975), although the geographical settings of the lagoons have not always been strictly comparable to the Leadenham Member situation.

The precise origin of the lime mud remains an open question (Bathurst, 1975, p.276). It would appear that in the various modern settings, different mechanisms of origin for the lime mud predominate, although all mechanisms may contribute in any one area (cf. Purdy, 1963; fig. 3.); inorganic precipitation (Bathurst, 1975, p.204 and p.276; see also Purdy, 1963), skeletal breakdown (Matthews, 1966) and algal decay (Stockman et al., 1967) are thought to be chiefly responsible for its production, although geologically the end products (micrite) would be indistinguishable (Matthews, 1966, p.452). The prevailing climatic conditions and geographical setting of the Lincolnshire Limestone sea, together with its abundant fauna probably provided suitable conditions for all the mechanisms to have been operative. Only the breakdown of invertebrate skeletons, mostly by the work of boring algae (see section IV.4.e.i.), can actually be determined from thin section studies; the extent of its contribution is indeterminable. The role of the other possible mechanisms remains unproven.

V.3.b.ii. <u>The Sedimentary Environment of the Leadenham Lagoon</u>: The main characteristics of the skeletal mudstones and wackestones (Lithofacies A, see sections IV.4.d.i. and IV.4.e.i.) of the Leadenham Member indicate slow sedimentation onto a soft, stable substrate, flooring a lagoon of uncertain, but probably shallow depth.

<u>Turbulence</u>: In addition to the fineness of the sediment (see section IV.4.e.i.), the absence of current-induced structures suggests a lack of turbulence (cf. Newell et al., 1959; and Purdy, 1963). The apparent lack of a preferred orientation amongst the <u>in situ</u> <u>Pinna</u> specimens of the lagoon (see section IV.4.g.) might be considered as support for such a view, although this kind of negative evidence can never be conclusive. Alternatively, the abundance of <u>in situ</u> forms and the lack of breakage in disarticulated and/or "moved" specimens (mostly epifaunal species) does confirm a general lack of current activity strong enough to scour out the infauna or transport the epifauna significantly

(cf. Fursich, 1977). Furthermore the random orientation of the skeletal fragments suggests an environment where biogenic reworking predominates over physical forces (cf. Ball, 1967). However periods of increased turbulence and even major storms are documented in the sedimentary record of the lagoon (see section V.3.b.iii.).

Sedimentation Rate: The extensive bioturbation and burrowing of the sediments, together with the epifaunal encrusting of probably "dead" benthos indicate rather slow sedimentation rates (Fursich, 1977). A similar conclusion is implied by the accumulation of successive generations of benthos within a single bed (cf. Seibold et al., 1973); the resultant associations are good examples of what Walker and Bambach (1971) termed "time-averaged communities" (see section IV.4.f.).

Nature of Substrate: The substrate was undoubtedly soft because of the abundant fauna (body fossils, and burrow and bioturbation traces); hard-substrate dwellers were restricted to inhabiting shells of dead organisms. However, as many of the infaunal molluscs were probably "immobile" types (Fig. 4.90), the substrate is also likely to have been stable, for a significant amount of sediment movement would stifle the normal feeding activity of such groups. It might also be argued that a degree of "firmness" in the substrate aided the burrowers, as no burrow-wall re-inforcements, like those adopted by *Callianassa major* Say (Weimer and Hoyt, 1964) for example, have been seen in any of the burrows. Such stability could have been a product of the slow sedimentation rate (which allowed a degree of early lithification, cf. Fursich, 1977, p.347) rather than vegetation-binding, which is seen in some modern lagoons (Newell et al., 1959; and Brasier, 1975). However, despite the presence of herbivorous gastropods (Fig.4.90), subtidal gelatinous algal mats (Bathurst, 1967c and 1975) may have aided the stabilisation to some extent, seagrasses having not evolved at this time (Brasier, 1975). Whether or not algae played a role, the stability was mainly due to the absence of physical agitation (except for periodic disturbances) because of the protection afforded by the off-shore barrier (cf. Purser and Evans, 1973, p.223; and see section V.7.).

Modern Analogue: The general environmental conditions prevalent in the Leadenham lagoon are readily comparable with certain areas of the Great Bahama Bank: the Muddy Sand and Mud Facies of Newell et al. (1959) and Mud (probably Pellet-Mud) Facies of Purdy (1963), although the overall environmental setting of the lagoon is much more in keeping with that of the Trucial Coast's lagoons (cf. Purser and Evans, 1973). The mud is thought to have accumulated in a very protected back-barrier zone, where slightly deeper water existed compared to that in the more agitated oolitic areas further south (cf. Woolfox beds, see section IV.3G.d. and V.2.c.iii.). Depths are not easily calculated but it appears unlikely that they were great because of the lithologic associations. Certainly similar facies accumulate off Andros Island in depths of less than three fathoms (Newell et al., 1959). The salinity was probably not far away from "normal marine" because, although molluscs dominated the benthonic communities, echinoderms and terebratulids are found as body fossils and Bryozoa have been seen in thin section. In this sense the Leadenham Lagoon is quite unlike the Trucial Coast situation, where a combination of high evaporation rates, minimal run-off and lack of circulation have led to increased salinities (Purser and Evans, 1973, p.223). As the Bajocian climate was probably more humid and circulation also probably greater, hypersalinities did not apparently develop in the Leadenham Lagoon to any great degree or for any length of time. Conversely the effects of the Lincolnshire Limestone transgression probably reduced run-off significantly in this region, (although the hinterland was probably low-lying and not therefore heavily drained) so that hyposalinities did not develop by freshwater influx (but see section V.3.d.).

V.3.b.iii. Interruptions in the Lagoonal Sedimentation; Storm Beds: Until fairly recently storm beds have not been widely recognised in the sedimentary record. However, with the increasing availability of information on modern storm deposits (Ball , 1967; Perkins and Enos, 1968; Goldring and Bridges, 1973), fossil examples have become more widely recognised (Ball, 1971; Brenner and Davies, 1973; and Kelling and Mullin, 1975).

Within the "typical" calcilutite sequences of the Leadenham Member, there are two lithological variations, which can be attributed to storms or minor periods of increased turbulence.

Minor "storm" lenses: Minor lensoid beds, composed of poorly-sorted biopelsparites with a packstone texture, scour into the background calcilutite sediment at several levels. The characteristic of these lenses strongly suggest that they are a result of minor and very localised increased turbulence. Although they do not really seem to warrant qualification as storm beds, they do reflect a degree of agitation in excess of that considered typical for the lagoon. For convenience, these are termed "disturbance lenses".

Major storm bed: Widely traceable within the Leadenham Member successions is one bed, which appears to be the product of a significant storm. It has a twofold compositional subdivision: a basal poorly-sorted skeletal calcarenite grades up into a wackestone, which is predominantly composed of bioclasts withvarying, but subsidiary, quantities of peloids, quartz and oncolites. Together these lithologies constitute Lithofacies B of the member (for details see sections IV.4.d.ii and IV.4.e.ii.).

The basal skeletal calcarenite (with mildly erosive base) contains a diverse array of skeletal allochems, which are much more heavily fragmented than those of Lithofacies A, reflecting perhaps the difference between mechanical and biological breakdown. The composition, size and widespread occurrence of this sheet-like deposit, are all suggestive of a storm origin (cf. storm lag of Brenner and Davies, 1973; and see also Ball, 1971). It clearly represents deposition in higher-energy conditions than those normally operative in the lagoon. Although the bioclasts often have random orientations there is a tendency for them to be aligned parallel to the depositional surface in some areas, a feature also noted by Brenner and Davies (1973, p.1690) and Ball (1971, table 1) even though such ordering might be considered unusual for storm deposits. Similarly the often extensive amounts of interstitial mud (cf. biosparites of storm lags of Brenner and Davies, 1973) are to be expected, when a storm re-works a soft, muddy substrate. Indeed the high mud content of the storm lag and the similarity of the included bioclasts with those of the rest of the lagoon suggest the storm re-worked the lagoon's sediment and fauna rather than transporting in significant quantities of material from outside.

The skeletal bed passes up into wackestones, which are less readily interpreted. In certain respects (increased abundance of allochems and occurrence of uprooted Pinna), these beds appear transitional between the storm lag and the normal lagoonal sediments. Although the subsequent burrowing would have obliterated any original sedimentary structures that might have been present, part of the wackestone bed may have settled out from suspension in the wake of the storm. Alternatively, more agitated conditions could have persisted for some time after the major event, before "normal" lagoon conditions re-established themselves. The latter proposal appears to take some support from the fact that at the lagoon's southern margin (Ancaster) the storm bed horizon correlates with the Greetwell Member incursion (Fig. 4.1.), which itself indicates that higher energy conditions had encroached upon the lagoon's periphery and persisted for some time. The inference is that a period of increased agitation followed the main storm (because of a slight decrease in the barrier's effectiveness ?) and "normal" lagoonal conditions were not re-established immediately.

V.3.c. Sub-environments of the Cathedral Beds.

The broadly comparable lithologies (limestone/shale alternations), and parallel distribution of the Cathedral Beds and Leadenham Member suggest a similar gross depositional environment for the two units: a lagoon. The restriction of the Cathedral Beds to the northern area of the Leadenham Member outcrop is, in part at least, due to the downcutting of the Lincoln Member (see section IV.4A.c.). However, in detail, there are a number of dissimilarities between the two units, which suggest definite, if subtle changes in the environment had taken place. The onset of Cathedral Beds' deposition is characterised by an influx of clastics with the shales becoming proportionally much more significant than they were in the Leadenham Member, and detrital quartz (with accompanying white mica and wood flakes) similarly so in the limestones. At the Dean and Chapter Pit, Lincoln, this influx was heralded by an increased quartz content in the higher lagoonal limestones, suggesting that a minor and localised regression in the Lincoln district may have been responsible for the deposition of the Cathedral Beds. Alternatively, the increased clastic influence could have come from the north (see section V.3.d. and cf. Ashton, 1975). In either case the clastics would have been accompanied by a freshwater influx, which may have been responsible for the loss of the prolific molluscan-dominated benthos of the Leadenham Member. No benthonic specimens have been seen in the Cathedral Beds, although marine stenohaline groups do occur as bioclastic grains in thin section. The simplest view of the Leadenham Member - Cathedral Beds environmental change therefore, is that of a "silting-up" of the northern part of the lagoon. However, throughout the Cathedral Beds, skeletal-oncolites ("Girvanella"-type tubules, see section IV.4A.e.), comparable to the calcareous-walled-algal-filament-oncolites described by Leeder (1975), are abundant. Such oncolites have been attributed to an "agitated shallow subtidal environment" by Leeder (1975, p.225) but it seems difficult in view of the general lithofacies characteristics, to accept this unquestioningly for the Cathedral Beds' examples; clearly the shales and argillaceous limestones, lacking any sign of agitation, were not deposited in a turbulent environment. Indeed the prominence of biscuit-shaped skeletal-oncolites suggests, by analogy with the modern rhodolites (Bosellini and Ginsburg, 1971, see especially fig. 12), rather lower-energy conditions, although it is possible that some of the flattening may have been due to subsequent compaction. Similarly the presence of marine salinites should not be accepted for the skeletal-oncolites without supporting evidence, for the loss of the Leadenham Lagoon benthos must have been the result of some ecological factor, of which a reduction in salinity would seem quite likely (in view of the sedimentary evidence). Although Leeder (1975, p.219) implied a marine setting for his Carboniferous oncolites, he did point out (op.cit., p.211) that the nearest living relatives of the calcareous-walled-filamentous-algae under discussion, were calcareous blue-green algae, which nowadays inhabit freshwater streams and lakes (see also Fritsch, 1950); the apparent change in habitat of this lineage being a result of biological competition from the Rhodophyta (red algae) in the Cainozoic (see Monty, 1972, for details). Although a marine interpretation is usually proffered for similar skeletal-oncolites (cf. Imbrie et al., 1964; and Laporte, 1967), Hudson (1970, p.33), influenced by the work of Black (1933), has commented upon the range of salinities modern algae (and by implication fossil forms) tolerate, although in this case they were not calcareous-walled-filamentous-algae. Thus, it would appear that whilst most of these skeletal-oncolites, from lithological and palaeontological associations, occur in marine salinites, the algae may have had the facility for living in other, notably reduced salinities in the past (as their relatives do today). A clastic and accompanying freshwater influx is therefore tentatively proposed as the reason for the deposition of the Cathedral Beds and the destruction of the stable Leadenham lagoon ecosystem (see also V.3.d.).

V.3.d. <u>A Comparison with the South Humberside Sub-environment</u>.

Within the isolated Lincolnshire Limestone sequences exposed around Kirton in Lindsey, Unit E of the Kirton Cementstones Member (Ashton, 1975) is considered to be the lateral equivalent of the Leadenham Member. The lithofacies of this unit are broadly comparable with those of the Leadenham Member (both are composed of alternating limestones and shales), although in detail the beds of Unit E show a number of differences:

(1) Shales form a greater proportion of the overall sequence;

the shales are usually subequal in thickness to the limestones (cf. Ashton, 1975, fig.3 with Fig.4.1.).

(2) the limestone beds sometimes lose their continuity, passing into a series of large nodules.

(3) the limestones show signs of secondary accretion.

In all these respects the Kirton Cementstones (Unit E) shale/limestone alternations are similar to those of the Blue Lias of Dorset, and both primary and secondary processes are thought to have contributed to their formation, as appears to be the case in the Lias (Ashton, 1975, p.427; and cf. Duff et al., 1967, pp.163-168).

Unlike the Blue Lias and the Leadenham Member, the beds of Unit E lack a diverse benthonic fauna. Only one _Pleuromya_ has been found in the limestones, although abundant ostracods and _Catinula_ are present in the shales; _Chondrites_ occurs prolifically throughout (Ashton, 1975, p.427). It would seem therefore that significant ecological differences exist between the Kirton lagoonal area and the Leadenham Lagoon, regardless of whether the Kirton successions represent a northern extension of the Leadenham Lagoon or a totally independant lagoon. The increased importance of shales in the Kirton sequences suggests a greater terrigenous influence, with the added implication that the shales are a result of clastic impulses superimposed upon the "background" precipitation of calcium carbonate (cf. Duff et al., 1967, p.167). This proposal in turn suggests the possibility of freshwater influx while the occurrence of pyrite in the shales (Ashton, 1975, p.427) indicates a probable lack of circulation and near-stagnant bottom conditions. The reduced faunal diversity (yet high densities in the shales), could therefore be explained by the reduction in salinity and slightly stagnant conditions. The dominant _Catinula_ oysters would probably be able to tolerate hyposalinites, as might the ostracods. As the organism responsible for producing the *Chondrites* traces is unknown (Simpson, 1957; and Kennedy, 1975), it is possible that it too may be euryhaline, although *Chondrites* traces are usually associated with marine sediments (Simpson, 1957; Seilacher, 1967; and Kennedy, 1975).

The area around Kirton may therefore have represented a lagoonal setting, into which the influx of fine-grained clastics and freshwater caused a reduction in salinities and temporary cessation of calcium carbonate precipitation (cf. Duff et al., 1967, p.167). The proximity of the Yorkshire Jurassic Delta provided a ready source for the clastics (cf. Ashton, 1975), although the run-off could also come from the west. These factors, together with the reduced circulation, inhibited colonisation by most stenohaline marine organisms, although the presence of the *Catinula*-*Chondrites*-ostracod association probably meant that the salinites were not much below "normal marine".

V.3.e. Conclusions: A History of the Leadenham Lagoon.

Towards the end of *discites* Zone times, the steady subsidence of the decaying "Lincoln High" (see section V.2.e.) and the increasing effectiveness of the off-shore barrier-complex (cf. Purser and Evans, 1973, p.226), which may have become partly emergent (see section V.7.c.v.), provided the very protected setting in which the Leadenham Lagoon developed.

During the early stages of its existence the lagoon was rapidly colonised by a diverse array of soft-bodied benthonic organisms, which extensively burrowed the substrate. Although innumerable other burrows are present, *Zoophycos* and *Chondrites* traces are particularly conspicuous at this level, an association not widely recognised previously. (cf. Seilacher, 1964; Osgood and Szmuc, 1972; but see Kennedy, 1975,p.384).

The abundance of these deposit-feeders (Simpson, 1957; and Osgood, 1975) undoubtedly indicates that the lagoon's sediment was nutrient-rich and that it accumulated relatively slowly. However, their activity probably resulted in the prevailing substrate becoming "soupy" and therefore prohibitive to successful colonisation by spat of other benthonic forms that are seen in higher beds of the lagoonal succession. Whether the spat perished by "burial-suffocation" or ingestion by the indigenous fauna is not clear but the situation would seem to exemplify the "trophic group amensalism" theory of Rhoads and Young (1970).

Following this early period, a major storm disrupted the "normal lagoonal sedimentation", and a storm-lag was deposited over much of the area (see section V.3.b.iii.). This storm sedimentation was accompanied by a northward encroachment of the more agitated South Lincolnshire facies (Greetwell Member) into the southern end of the lagoon, around Ancaster. However, after an ensuing period of more agitated conditions, which were sufficient to uproot Pinna specimens, quiet-water sedimentation was re-established and lime mud slowly began to accumulate again. This time, however, a mollusc-dominated "community" successfully colonised the lagoon, although soft-bodied infaunal species were still conspicuous, especially Chondrites.

The diverse benthonic associations (= "time-averaged communities" of Walker and Bambach, 1971; see section IV.4.f.) dominated by Pinna cuneata, Pholadomya lirata, Pleuromya uniformis, Natica adducta, and Astarte minima occupied an array of niches: deep (P. uniformis) and shallow (A. minima) infaunal, semi-infaunal (P. cuneata) and epifaunal (Parallelodon) species are all represented (Fig.4.90). In addition, these forms were also of diverse feeding-types, which ranged from carnivores to deposit-feeders to suspension-feeders; the latter took their food from many different levels above the substrate-water interface (see Fig. 4.90; and section IV.4.f. and Walker, 1972, for general theory). Combining these facts with the information gained from the lithofacies, the environment of the lagoon can be broadly summarised as: an area of low turbulence and slow sedimentation in which reasonably nutrient-rich waters of marine or near-marine salinities overlay a soft, stable, nutrient-rich, muddy substrate. The benthonic associations of this "predictable" environment are broadly comparable to those from the Cretaceous Comanchean rocks (Goodland Limestone) discussed by Scott (1972). He considered that those faunas reflected a stable, turbulence-free environment of moderately rich resources; very similar conclusions to those drawn here.

This stable environment persisted throughout the remainder of Leadenham Member times, when environmental changes contributed to its destruction. In the northern part of the lagoon (Lincoln-Metheringham) the influx of clastics (minor regression) and associated freshwater "swamped" the lagoon and destroyed its stable ecosystem (see section V.3.c.). Only skeletal-oncolites were able to tolerate the new environmental conditions of the Cathedral Beds. Despite these changes the "lagoonal" regime persisted, and further south "normal" lagoonal sedimentation continued. However, whether "silting up" (via Cathedral Beds' deposition) or persisting in its "normal state" the lagoon was completely destroyed by the "oolitic surge", which heralded the onset of Lincoln Member sedimentation. This surge, which is thought to have been the product of a short-term lagoonward migration of the barrier complex (for details see section V.4.b.ii.), obliterated the existing sedimentary pattern. After the effects of the surge had waned, a new environmental regime, differing considerably from that of the late <u>discites</u> Zone times, developed.

V.4. THE DEPOSITIONAL ENVIRONMENTS OF THE LINCOLN MEMBER.

V.4.a. Introduction.

Although widely variable, the lithofacies of the Lincoln Member can be grouped into two broad categories: Tthe "Lincoln Member Oolites" and the calcilutites of the Ropsley Beds and Little Bytham beds. All lithologic gradations from oolitic grainstones to fossiliferous mudstones are seen however, and the subdivision is arbitary. Essentially, the Ropsley-type fossiliferous calcilutites represent pure lagoonal deposits, similar to those described in the Leadenham Member (see section V.3.), while the "oolites" represent the more agitated (yet still low-energy) environments, marginal to the main lagoon areas. In broad terms all of the Lincoln Member deposits are "lagoonal", as they accumulated in a protected back-barrier situation.

In the following discussion the sub-environments represented in the "Lincoln Member Oolites" and Ropsley Lagoon calcilutites have been treated separately, although an outline environmental synthesis has been attempted in the concluding section.

V.4.b. Sub-environments of the "Lincoln Member Oolites".

V.4.b.i. Introduction: The widespread distribution and ready traceability of the member has made it both stratigraphically and environmentally important, especially as its biostratigraphical age is also fairly well documented (see Chapter III). From the environmental point of view, these factors have allowed lateral as well as vertical facies patterns to be determined and a crude facies-map to be attempted (Fig.5.8.). Although the lithofacies show the usual tendency to polarise into central and southern Lincolnshire types, the same overriding controls on facies distributions seem to have operated in both areas, and therefore generalisations about the whole county can be made. However, before the lithofacies patterns are outlined the significance of the basal oolite is discussed; this bed is common to the whole member (Fig.4.1.) and as it rests erosively upon a series of different units, its origin would seem to warrant some comment. It is only after the deposition of this rather uniform basal oolite that the complex facies patterns of the rest of the Lincoln Member developed.

V.4.b.ii. The Significance of the Basal Oolite: The basal oolite of the Lincoln Member is usually composed of poorly-sorted, oncolitic or skeletal oosparites, which have a very mixed allochem content; in addition to the ooliths, varying quantities of bioclasts, oncolites, intraclasts and peloids occur (Lithofacies A; see section IV.5.e.i.). Texturally, the oolite is either a packstone or a grainstone. In south Lincolnshire the bed has a very conspicuous basal shell lag, which is characterised by decalcified Thecosmilia corals (Figs. 4.101 and 4.102; see section IV.5.f.).

In isolation the oolite would not seem especially important environmentally; it could be readily attributed to the higher agitation areas of the lagoon and compared to similar facies in the Greetwell Member (Lithofacies-group 1; see section V.2.c.iii.). Its real significance is hinted at by its midly erosive superposition upon a number of different lithofacies, belonging to separate stratigraphical units (Fig. 4.1.). This relationship suggests that the basal oolite was swept across the entire region to blanket the "lagoonal regime", which had developed by this time (discites Zone). The subsequent Lincoln Member sedimentation shows that in the ensuing, early laeviuscula Zone times, a new, less geographically polarised lagoonal regime evolved. Although the base of the Lincoln Member is erosive, the degree of erosion is relatively slight and no significant downcutting has been recognised;

instead there appears to have been a reworking of the previously deposited sediments. The nature of the basal shell lag in south Lincolnshure would seem to support such a proposal (see section IV.5.f.).

The problem is to determine what kind of "event" or mechanism destroyed the existing environmental pattern, without significantly altering the gross environmental regime (for lagoonal sediments lie immediately above and below the basal oolite in some localities). It has been argued elsewhere (see section V.5.b.iii.) that the facies patterns involving lithologies showing only subtle changes in "energy levels" (like those in the Lincoln Member) may have no real significance. They represent only fortuitous sections through areas where the facies migrated complexly. Such patterns have usually only had a localised occurrence. This "event" which initiated Lincoln Member sedimentation has been documented county-wide and is therefore of major environmental significance; a belief that is supported by its associated biostratigraphical importance (Chapter III).

Similar lithofacies to the basal oolite are more commonly associated with the high-energy back-barrier oolite belt of the Metheringham and Castle Bytham Members (see section V.6.b.), although they are also sparingly seen in the Greetwell Member. In the most simple terms, the migration of this high-energy back-barrier belt across the old lagoonal system could have produced the facies pattern seen. The migration is unlikely to have been catastrophic because of the absence of major downcutting and the lack of cross-bedding in the basal oolite. In geological terms it is recorded as an "event"; a migrating pulse of the barrier system (see section V.7.) landward, which superimposed the more off-shore facies belts upon near-shore "lagoonal" sediments. The younger Lincoln Member sediments indicate that the effect of the pulse was short-lived and that lagoonal sedimentation was soon re-established (see section V.4.b.iii. below).

Alternatively, the "event" could be envisaged as a breakdown in the barrier system of the time (recorded by the erosive base of the Lincoln Member), followed by a period of increased agitation (basal oolite) before a new barrier complex developed to protect the ensuing lagoonal system of the Lincoln Member. Thisproposal seems less likely because of the nature of the sediments involved; the sheet-like geometry of the basal oolite and the evidence for reworking (mixed allochem content and shell-lag's nature, see section IV.5.f.) are not really consistent with deposition in an unprotected shelf sea. Higher-energy deposits are to be expected (Irwin, 1965). This simple argument would seem to refute another variation on this theme: that the erosive base of the member marked the landward passage of the barrier itself, which was replaced by a second complex that provided the protection for the Lincoln Member Lagoons. However, the features of the basal oolite are comparable with a temporary lagoonward pulsation of the barrier-complex. The "pulsation" may have been triggered by a minor transgression (resulting from accelerated subsidence ?) or the temporary breaching of part of the barrier. In either case a temporary period of increased agitation resulted. A relatively rapid restoration of the complex presumably followed which allowed the lagoonal conditions to redevelop, although the new environmental pattern was quite distinct from that which it had replaced.

<u>Summary</u>: The sheet-like basal oolite of the Lincoln Member records a temporary landward movement of the off-shore barrier-complex, which "swamped" the existing lagoonal regime. Subsequently, the barrier retreated or re-stabilised and a new lagoonal regime developed which had

a different geography to the original. The cause of the barrier's movement is thought to have been either a minor transgression or the temporary breaching of part of the barrier.

V.4.b.iii.Sedimentary Environment: The sediments of the Lincoln Member lying above the basal oolite encompass a range of lithologies which, although broadly low energy, reflect varying degrees of bottom agitation. Oolitic grainstones (Lithofacies A) grade, through an array of intermediary lithologies, into grain-poor skeletal wackestones (Lithofacies B), which are almost identical to the lagoonal facies of the Ropsley Beds. Essentially there is a broad twofold division into grain-supported, largely oolitic lithologies (Lithofacies A), and mud-supported oncolitic or bioclastic-dominated limestones (Lithofacies B; see sections IV.5.d. and IV.5.e. for details). These facies reflect different sub-environments of a lagoonal, back-barrier setting, which can be lithologically matched with the "Stable Sand Habitat" of Newell et al. (1959; see also Purdy, 1963), and the "Platform Interior Sand Blanket" of Ball (1967). As the details of similar facies in both the Greetwell (see sections V.2.c.iii and V.2.f.ii) and Scottlethorpe Members (see section V.5.b.) have been discussed at some length, it is not proposed to re-iterate them here, although attention ought to be focused on the very common occurrence of "quiet-water oncolites" (cf. section V.2.c.iii) in the wackestones of Lithofacies B. It is the distribution of these facies and its significance that is considered of prime importance here.

The "transgressive" event, which swept across the discites Zone lagoonal system, blanketed the whole of Lincolnshire with an oolitic bed. The sedimentary sequences, which accumulated upon this basal oolite, reflect areas where both stable sedimentary regimes existed and those where the facies belts oscillated to and fro. To illustrate this, the sequences in two areas will be discussed in greater detail: the Harmston-Lincoln and Scottlethorpe-Greetham districts (see Fig. 5.8.).

<u>The Harmston-Lincoln District</u>: At Harmston the "anomalous" Lincoln Member sequence (Fig. 4.1.) is almost completely composed of "clean oolites" (Lithofacies A) reflecting agitated substrate conditions. This contrasts with the "typical" sequence seen in most other central Lincolnshire localities (see section IV.5.d.i.), where the basal oolite grades through burrowed oomicrites to biomicrites before more oolitic lithologies cap the sequence. The degree of development of the biomicrites (about the middle of the member) is greater the further the locality is away from Harmston, i.e. the Harmston oolitic succession presumably represents an oolitic shoal which persisted throughout the broadly lagoonal regime of the Lincoln Member and exerted a degree of influence upon the sedimentation of surrounding areas. Away from the oolite shoals, more typical lagoonal conditions were able to develop; in some cases (Ropsley Lagoon) they persisted throughout much of the Lincoln Member times while in others (Lincoln area) they were more ephemeral features. At Lincoln the nascent lagoon was colonised by a soft-substrate fauna, broadly equivalent to that of the Leadenham Member (cf. Figs. 4.90 and 4.109). In addition, within the Dean and Chapter Pit, a biostrome with a fauna partly adapted to life on hard substrates (limpet-like gastropods and "cementing" bivalves) is also seen (see section IV.5.f.). Apart from the main Ropsley Lagoon the "lagoonal phase" was relatively short-lived, and more agitated oolite-rich facies (Lithofacies B) usually oscillated back across the area (cf. R.C.L. Wilson, 1968). Whether these movements were directly attributable to the oolitic shoals such as Harmston, is not certain, but they must have been a source of some of the ooliths.

<u>The Scottlethorpe-Greetham District</u>: This area shows similar features (Fig.5.8.). The Lincoln Member sequence in the Clipsham-Castle Bytham-Little Bytham area contain very low-energy lagoonal sediments. Eastwards, however, towards Scottlethorpe and southwards towards the Greetham/Woolfox region, oolites become progressively more important until there is little in the way of "lagoonal calcilutites" developed. This suggests that similar Harmston-like oolite shoals occurred around Scottlethorpe and a little to the south of Greetham (see section IV.5. d.ii.), as both these areas are dominated by agitated oolite deposits.

V.4.b.iv. <u>Conclusions</u>: The post-basal oolite times of the Lincoln Member are typified by oolite shoals and lagoons. The areas between these features contained sediments of a quiet-water nature, which reflected the relative dominance of the shoal or lagoon at that particular time. Such sedimentary patterns seem to be quite typical of back-barrier lagoonal settings (cf. Purser and Evans, 1973; and Evans et al., 1973).

V.4.c. <u>Sub-environments of the Ropsley Beds</u>.

V.4.c.i. <u>Introduction: Evidence for Lagoonal Sedimentation</u>: Although this discussion primarily concerns the Ropsley Beds, most of it is also directly applicable to the Little Bytham beds, which represent a second, less well documented, lagoonal development in south Lincolnshire (see section IV.5B). In both cases the biomicrite deposits occur in areas of limited geographical extent, passing gradationally out into the "Lincoln Member Oolite" province. The development, in a back-barrier situation, of a number of relatively small lagoons, separated by more-oolitic tracts, has been noted by Basan (1973) in southern Florida, and similar occurrences are also seen along the shore of the Persian Gulf (Purser and Evans, 1973, fig. 9.).

Lagoonal deposition has been proposed because of the geographically restricted occurrence of pure lime mud sediments, containing an often prolific indigenous benthos. Similar deposits have been traditionally associated with quiet-water sedimentation in "lagoonal" settings (Newell, 1955; Newell et al., 1959; Purdy, 1963; Matthews, 1966; Stockman et al., 1967; Bathurst, 1967c and 1975; Purser and Evans, 1973; Schenk, 1975; and Wilson, 1975), although the "lagoons" have not always been in strictly comparable geographical settings to those of the Ropsley Beds.

Although the precise origin of the lime mud remains a contentious issue (Bathurst, 1975, p.276), it is likely that suitable conditions existed in the Ropsley Lagoon for all the major lime mud producing mechanisms (inorganic precipitation, algal or skeletal breakdown) to have contributed to its formation. However, it is by no means clear whether they all did (cf. section V.3.b.i.).

V.4.c.ii. Sedimentary Environment of the Ropsley Lagoon: As the lithofacies and hence depositional environment of the Ropsley Beds are so similar to those of the Leadenham Member (cf. V.3.b.ii.) only an outline of the major points will be re-iterated here.

Turbulence and Salinity: The general lack of turbulence in the Ropsley Lagoon is indicated by the fineness of the sediment, the lack of current-induced structures, and the indigenous nature of the fauna. Although few forms have been seen *in situ* (mainly because the benthos is epifaunal), the fauna is thought to have suffered little post-mortem transportation because:

(1) the brachiopods and bivalves show a high articulation ratio,

(2) few fossils show signs of wear or breakage

(3) the disarticulated valves of the bivalves have a random orientation.

(4) the terebratulid specimens of the same species have a wide size range (within a single horizon); this suggests a lack of current sorting.

These considerations, together with the general abundance of the fauna, indicate very stable conditions, in what must have been a marine lagoon for stenohaline groups such as brachiopods and corals form a significant part of the benthos. The fine balance between evaporation and run-off, provided by the prevailing Bajocian climate, together with marine circulation via the barrier inlets (see section V.7.c.ii.), is thought to have maintained marine salinities in these very protected settings (cf. section V.3.b.ii.).

Sedimentation Rate: Again the presence of encrusters, such as oysters, suggests relatively slow sedimentation rates (Fursich, 1977) as does the bioturbation.

Nature of the Substrate: Although burrowing bivalves have been collected they are relatively rare. This, together with the predominance of epifaunal species, suggests that the substrate may not have been as conducive to burrowing as that of the Leadenham Member. This problem is more fully discussed in the following subsection (V.4.c.iii.).

Despite the lithological similarity, the benthonic faunas of the Leadenham and Ropsley Lagoons are quite different. The nature and significance of these differences are discussed in the following subsection (V.4.c.iii.).

Modern Analogues: As with the Leadenham Lagoon, the general sedimentary facies of the Ropsley Beds can be equated with those of the "Muddy Sand and Mud Facies" (Newell et al., 1959) or "Mud and Pellet-Mud Facies"

(Purdy, 1963) of the Great Bahama Bank, although the overall environmental setting of the lagoon(s) is more in keeping with that of the Florida (cf. Basan, 1973) or Trucial Coast lagoons (cf. Purser and Evans, 1973).

V.4.c.iii. A Comparison between the Leadenham and Ropsley Lagoons: It has already been suggested that the lithofacies, and hence depositional environments of these two units (and the Little Bytham beds) were very similar. The overall geographical setting, lack of turbulence, slow sedimentation rate and substrate conditions all appear to be alike; only the indigenous faunas of the two units differ. The differences are both taxonomic and, more importantly in this case, ecological. The Leadenham Member fauna is dominated by infaunal and semi-infaunal molluscs, while the Ropsley Lagoon benthos is characterised by epifaunal terebratulids, which often occur in dense populations. In this respect they parallel the occurrence of the semi-infaunal *Pinna* colonies, which characterise the fauna of the Leadenham Lagoon. In such apparently uniform settings why should two completely different benthonic faunas develop?

It is difficult to envisage a simple reason for the differences, especially as the two units are so closely linked in time and space. The major controls on benthonic faunal distributions are generally considered to be temperature, salinity, substrate, food supply and turbulence (Raup and Stanley, 1971) together with the overriding control of environmental predictability (Sanders, 1968). Of these, temperature, salinity and turbulence appear to be practically identical in the two units; it is possible that the Leadenham Lagoon could have had slightly reduced salinities because of the dominance of molluscs, but the rare occurrence of regular echinoderms (but see Kier, 1977) suggests that this was unlikely to have been the case. The rather less tangible factor of food supply is difficult to evaluate. Little is certainly known about the food of fossil brachiopods (cf. Fursich and Hurst, 1974; and Steele-Petrovic, 1976) and how it relates to that of the bivalves. It might be argued that the first group (molluscs or brachiopods) to become established precluded colonisation by the other by dominating the food supply but such lines of reasoning lack any sound factual basis, and at best can only be considered as very spectulative (but see Fursich, 1977, p.381). Apart from the all-embracing concept of environmental predictability (Sanders, 1968), which does not really seem relevant to this problem, only the substrate remains as a possible control.

Although the effect of substrate conditions on benthonic colonisation is well documented (e.g. Rhoads and Young, 1970; and Fursich and Hurst, 1974), Fursich (1976a,b) has recently cast considerable doubt on simplistic correlations between substrate and benthonic faunas. He discovered that similar (Upper Jurassic) faunas can occur in different substrates and different faunas may, inhabit the same type of substrate. The latter situation is the case here. However, it is possible that the substrates may have subtle differences which are not deducible from the available lithological criteria. For example, it might be that the Leadenham Lagoon substrate was too "soupy" for successful terebratulid-spat colonisation, due to the extensive burrowing (cf. Rhoads and Young, 1970). In contrast the relative absence of extensive burrowing in the Ropsley Lagoon provided a firmer substrate on which the terebratulid spat could colonise and thrive. The role of "holdfasts" must also be taken into consideration in any such argument, for epifaunal species, like terebratulids, usually attach themselves to holdfasts rather than directly onto the substrate.

In view of the number of imponderables it would appear that a detailed faunal analysis of the two contrasting lagoonal faunas is required before a solution, or more informed guess, can be made, supposing a factor other than chance actually controlled the development of the two faunas.

V.4.c.iv. Conclusions: The general lithological similarity between the sediments of the Leadenham and Ropsley Lagoons suggests similar depositional environments: very protected, back-barrier lagoons. Depsite this similarity, the faunas of the two lagoons are quite distinct, raising the problem of whether some "hidden" ecological factor differentiated the environments of the lagoons in some subtle yet significant manner.

V.4.d. Conclusions.

The erosive base of the Lincoln Member records a temporary lagoonward progradation of the off-shore barrier complex, which resulted in the deposition of an oolite blanket across the whole county, and the destruction of the existing sedimentary regime. Following this "event" a new sedimentary pattern developed, which reflected a rather complex environmental mosaic. Although essentially an area of continued quiet-water, back-barrier deposition, different regions were dominated by oolitic shoals (e.g. Harmston) or lagoons (e.g. Ropsley). The intervening areas had "mixed successions", which reflected the fluctuating influence of oolite shoal or lagoonal sedimentation through time. In general terms, the zenith of lagoonal development was reached around mid-Lincoln Member times. A crude facies map of this time is shown in figure 5.8.

V.5. THE DEPOSITIONAL ENVIRONMENTS OF THE SCOTTLETHORPE AND LINDSEY SHALE MEMBERS.

V.5.a. Introduction.

Despite their lithological differences, the Lindsey Shale and Scottlethorpe Members have been grouped together because they are broad stratigraphical equivalents (Fig.4.1.), which represent different aspects of the same back-barrier environment. Both units display features typical of quiet-water sedimentation, and in this respect are quite characteristic of the "lagoonal" deposits, composing the rest of the lower Lincolnshire Limestone. The replacement of limestone (Scottlethorpe Member) by shale (Lindsey Shale Member) northwards at this level is thought to be due to the increased southerly influence of the Yorkshire Delta at this time (cf. Ashton, 1975).

The sub-environments of each unit are discussed separately below and broad comparisons are made with the rest of the lower Lincolnshire Limestone in a concluding section.

V.5.b. Sub-environments of the Scottlethorpe Member.

V.5.b.i. Introduction: The Scottlethorpe Member is composed of a wide variety of limestone lithologies, which can be arbitrarily grouped into three lithofacies: A, B and C. Lithofacies A is typified by grain-rich, poorly-sorted (skeletal) ooid-packstones; B by grain-poor, poorly-sorted ooid-wackestones; and C by skeletal wackestones, that can be very fossiliferous. Although all three lithofacies are indicative of low-energy conditions (sedimentary structures are absent), a diminishing energy gradient (A to C) is recognisable. This is especially well reflected by the decrease of non-skeletal allochems (A to C) and the change from grain-supported (A) to mud-supported textures (B and C;

see sections IV.6.d. and IV.6.e. for lithological details). In broad terms the lithofacies can be matched with the "Platform Interior Sand Blanket" of Ball (1967) and the "Stable Sand Habitat" of Newell et al. (1959), although the geographical setting is somewhat different. The Scottlethorpe Member facies are thought to have been deposited in a protected back-barrier environment more akin to the lagoons of the Trucial Coast (Purser and Evans, 1973).

V.5.b.ii. Sedimentary Environment: The poor-sorting and lack of widespread winnowing in the Lithofacies A sediments is indicative of quiet-water sedimentation, comparable with that suggested for the low-energy subtidal oolites of the Greetwell Member rhythms (cf. section V.2.c.iii.). The predominance of mud -supported lithologies, in Lithofacies B and C, which in extreme cases are lacking in all but bioclastic allochems (some of Lithofacies C), suggest even more tranquil depositional environments than those envisaged for the Greetwell Member oolites. In fact the sediments of the Lithofacies B and C reflect the "bridge" between the low-agitation oolites and the "true" lagoonal conditions, as typified by the calcilutites of the Leadenham Member. The reduction in allochems and the increasing predominance of bioclasts over ooliths, reflects a lack of agitation beyond that seen in the Greetwell Member.

This lithologic change is mirrored by the often abundant occurrence, in Lithofacies C, of an indigenous benthos, which shows few signs of significant transportation. Most of the brachiopods and *Lucina* are articulated, while the disarticulated specimens (usually epifaunal bivalves like *Plagiostoma* and *Camptonectes*) are unbroken and have a random orientation (not preferentially convex-up). In addition, some *Acanthothiris crossi* occur with their long, delicate sensory spines (Rudwick, 1965) intact. Against this, few forms are found in their position of life, although as most are epifaunal species this is not surprising. Most bivalves would be expected to become disarticulated soon after death, if they occupied epifaunal niches, so the high evidence of disarticulation is not, in itself, particularly significant. At most therefore the movement of the benthos was very localised.

The substrate represented in Lithofacies C must have been soft as well as stable (unagitated) because of the common occurrence of shallow infaunal and semi-infaunal species (*Lucina*,"*Nerinea*") as well as the rare deep burrowers like *Pholadomya lirata* and general burrowing. Furthermore, the replacement of an atrophied pedicle by spines and "shell thickening", as the principal stabilisation mechanisms in *A. crossi* (see Rudwick, 1965), is indicative of the presence of both soft substrates and quiet-water environments (cf. Fursich and Hurst, 1974). However, there must also have been an abundance of holdfasts available for the epifaunal bivalves, terebratulids and colonial corals.

Moving up the energy gradient away from Lithofacies C, evidence of agitation is most obviously reflected in the increasing importance of ooliths. Although the superficial types could have developed in the "lagoonal" setting (Bathurst, 1967a), and would have been typical of such an environment (Purdy, 1963; Newell et al., 1960; and Ball, 1967), the occurrence of more "normal" ooliths is indicative of washing-in from the higher-energy generative zones (cf. Newell et al., 1960). This therefore implies at least periodic conditions of increased agitation. Also the presence of allochems, such as oncolites and composite ooliths, requiring at least episodic periods of agitation (cf. Carozzi, 1964) raises the problem of whether the substrate stability is, in part, induced by subtidal gelatinous mats (Purdy, 1963; Bathurst, 1967a, 1967c and 1975; Scoffin, 1970; and Neumann et al., 1970). In the case of the Lithofacies B, the muddy matrix suggests that conditions were so tranquil that there was no need to invoke the presence of such mats, although they may none the less have existed. In contrast, they may be needed to explain the combination of "agitated" and unagitated" features in Lithofacies A, which is very similar to the Greetwell Member oolites in this respect (cf. section V.2.c.iii.).

V.5.b.iii.<u>Lithofacies Patterns</u>: As the lithofacies of the member are thought to reflect an energy-gradient, their stratigraphical distribution ought to give some idea of the fluctuation of environmental conditions through time. For example the type section shows an A-B-C-B-A vertical facies sequence. This might be most simply interpreted as an encroachment of the higher-energy back-barrier facies (more akin to those of the Castle Bytham Member; see section V.6.b.) across the area; their progress being interrupted by a re-establishment of lagoonal conditions midway through the period of deposition. However, this is seen to be too simplistic a view when the facies patterns are looked at in detail. Firstly, although the base of the member is usually typified by lithologies of Lithofacies A, wackestones more akin to Lithofacies B sometimes occupy that level; this shows that the facies belts were by no means continuous across the area at any one time. Secondly, and more importantly, the "ideal" A-B-C-B-A pattern often breaks down in detail, especially in mid-Lincolnshire (Castle Quarry, Ancaster, for example, see section IV.6.d.), where Lithofacies C is often not present at all. This, and other similar variations, indicate that the facies distributions were complex and not related to simple oscillations of broadly N-S aligned parallel facies belts. At best, the lithofacies patterns can be considered as mirroring the fluctuating migratory directions of the sub-environments represented by this low-energy facies-complex. The three lithofacies are merely arbitrary divisions within the facies continuum; they probably did not have fixed relationship in space or time, but changed continuously in response to the varying environmental conditions.

V.5.b.iv. Conclusions: The low-energy facies-complex represented by these sediments is quite consistent with the broadly "lagoonal" back-barrier mosaic of environments envisaged as their depositional setting (cf. Purser and Evans, 1973). Lithologically they are also comparable with the "Platform Interior Sand Blanket" of the Bahamas (Ball, 1967; see also Newell et al., 1960; and Purdy, 1963).

V.5.c. Sub-environments of the Lindsey Shale Member.

V.5.c.i. Composition: The Lindsey Shale is predominantly composed of brown fossiliferous, marly shale, although a few argillaceous limestone bands also occur, particularly towards the base of the unit. The acid insoluble residue of the shale contained montmerillonite as a major phase, and mica, quartz and kaolinite as minor phases (for details see sections IV.7.d.).

V.5.c.ii. Sedimentary Environment: The dominance of shale and lack of breakage of its enclosed fauna indicate quiet-water deposition in a protected environment. Although such conditions are found in a number of different settings, the stratigraphical relationships of the Lindsey Shale suggest a back-barrier environment. Between Metheringham and Lincoln the member is underlain by other low-energy "lagoonal" deposits (Lincoln Member, see section, V.4.), and overlain by the higher-energy back-barrier sediments of the Metheringham Member (see section V.6.b.), which are in turn overlain by unequivocable barrier sediments (Sleaford Member; see section V.7.c.). In central Lincolnshire therefore the relatively thin Lindsey Shale sequences undoubtedly form part of the back-barrier lagoonal-complex. It might therefore be argued that the persistence of the shale northwards to Kirton in Lindsey is evidence for the barrier extending in that direction too; although the high-energy back-barrier sediment belt has been recognised as far north as Hibaldstow, none of the stratigraphically higher units (= barrier sediments) are exposed north of Lincoln. However, the lower Lincolnshire Limestone successions of South Humberside (Ashton, 1975) are quite similar to those further south, suggesting comparable depositional environments (quiet-water, back-barrier), although the northerly clastic influence, which is responsible for the Shale's northern thickening, does complicate the picture in this region (cf. section V.3.d.). Despite this "protected" setting and probable influx of clastics from the north, the fauna is indicative of marine salinities; there is no evidence to suggest that any reduction in salinity occurred, as may have been the case in Unit E of the Kirton Cementstones Member (see section V.3.d.).

V.5.c.iii. Nature of the Substrate: The fauna of this member contains elements that are adapted to both soft and hard substrates (see section IV.7.e.). The principal macrofaunal components of the shale, such as *A. crossi* are clearly indicative of a soft substrate (Rudwick, 1965), as is the mobile shallow-infaunal *Trigonia hemisphaerica*. However, the byssate epifaunal bivalves, like *Plagiostoma*, *Camptonectes*, *Pteroperna*, and *Pseudotrapezium* required "holdfasts", although *Plagiostoma* may have lived "free" as an adult. As Richardson (1940) also recorded burrowing forms like *Lucina* and *Pholadomya lirata*, there can be little doubt that the principal substrate represented by the shale was soft, yet probably stable because *A. crossi* is unlikely to have been able to cope with excessive turbidity (Rudwick, 1965).

The streamlined byssate bivalves, like *Pteroperna*, do suggest current activity however, as do the shell accumulations which provided the "hard substrate niches", notably within the "False Formations" (see section IV.7.d.). The "False Formations" were apparently initiated by certain shell accumulations being stabilised by thamnasteroid coral colonisations. These provided a hard substrate on which such forms as *Symmetrocapulus tersoni* (limpet-like gastropod), *Lopha*, *Ctenostreon* and *Lithophaga* could thrive, together with goose barnacles. The biostromes probably stood proud of the surrounding soft shale substrate, although without significant relief. Because of this they became self-perpetuating for their slight elevation was sufficient to trap further shells, while the death of the often prolific indigenous fauna provided abundant additional material for their upward growth. In this way the "False Formations", which are composed of irregular alternations of these biostromes and intervening shales, were built up (they extend throughout the vertical thickness of the shale). However at various times, parts of the biostromes were "swamped" by shale, which probably killed off the corals (cf. Ali, 1977), and brought a temporary halt to their upward development. Lateral outgrowth and re-colonisation by an unaffected part of the biostrome probably re-initiated development in an affected area. The biostromes covered many tens of metres of the sea floor, occurring as "hard substrate islands" in a sea of soft shale.

V.5.c.iv. Significance of Montmorillonite: For some years now the occurrence of montmorillonite in the Bathonian has caused speculation about the likelihood of Jurassic volcanism in the north European area (Hallam and Sellwood, 1968); a possibility that has since turned to reality by the discovery of volcanics in the Middle Jurassic of the North Sea (see Kent, 1975a for review). This has tended to cement the conviction that the Jurassic montmorillonite occurrences owe their origin to volcanic activity (Sellwood and Hallam, 1974; and Bradshaw, 1975), although Bradshaw (1975) and Amiri-Garroussi (1977) have warned against a simple correlation between these two features. Although the presence of montmorillonite in the Lindsey Shale could be considered as indicative of Bajocian volcanism, especially as associated volcanics occur in the Middle Jurassic sequences of the North Sea (Hallam and Sellwood, 1976, p.314), insufficient work has been done to link categorically the Lindsey Shale montmorillonite with volcanism. Further work is required to confirm or refute this possible association.

V.5.c.v. Conclusions: Overall, the Lindsey Shale environment seems to have been one of protected, quiet-waters in a back-barrier, "lagoonal" environment, which was colonised by a variety of marine epi- and infaunal benthonic species. There does not appear to have been any reduction in salinity associated with the clastic influx from the north, which was responsible for the members' thickening-up towards South Humberside.

V.5.d. Conclusions.

Although a full synthesis of the environments is given in section V.8. at the end of this chapter, it is perhaps worth summarising the environmental pattern seen in the lower Lincolnshire Limestone. The subtidal deposits of the lower Lincolnshire Limestone reflect quiet-water deposition in a protected back-barrier environment. Within this low-energy regime, a number of agitation levels, attributable to different hydrodynamic conditions, can be recognised; these range from the "classic" lagoonal environments, represented by the Leadenham Member and Ropsley Beds to the agitated grainstones of Lithofacies-group 1 of the Greetwell Member cycles. The packstones and wackestones of the Sproxton, Greetwell, Lincoln and Scottlethorpe Members represent the intermediate levels in this agitation-spectrum. The Lindsey Shale Member, lithologically distinct because of the increased influence of clastic input from the north, is clearly "lagoonal".

These "protected environments" are thought to have occupied a shallow subtidal belt between the tidal-flat deposits of the west and south-west, and the higher-energy back-barrier and on-barrier sediment belts off-shore (eastwards).

V.6. THE DEPOSITIONAL ENVIRONMENTS OF THE METHERINGHAM, BLANKNEY AND CASTLE BYTHAM MEMBERS.

V.6.a. Introduction

As the clean oolites of these units are sandwiched between the "lagoonal" deposits of the lower Lincolnshire Limestone and the barrier sediments of the Sleaford Member, they can be considered as carbonate analogues of the "back-barrier clean sands" of Dillon (1970, p.97 and fig.2; see also Kraft, 1971). Having accumulated in the lee of a protective barrier, the oolites reflect agitation levels intermediate between those of the current and wave-swept seaward barrier and the "quiet" lagoonal waters inshore. In broad terms the lithofacies can be matched with parts of the "Platform Interior Sand Blanket" of Ball (1967; see also Newell et al., 1960; and Purdy, 1963).

The nature of parts of the Blankney Member permits some qualification of this gross environmental interpretation to be made (see section V.6.c), as do the differences in the various lithofacies, composing the Metheringham and Castle Bytham Members (see section V.6.b.).

V.6.b. Sub-environments of the Metheringham and Castle Bytham Members.

The oolites of these two members can be split into two broad groups: the Metheringham Member and Lithofacies A of the Castle Bytham Member constituting Lithofacies-group 1, while Lithofacies B and C of the Castle Bytham Members comprise Lithofacies-group 2.

V.6.b.i. Lithofacies-group 1: In its most typical form the Metheringam Member is represented by oolitic grainstones, which reflect agitation levels sufficient to winnow fines but not to sort the sediments to any appreciable extent (see section IV.8.e.). The absence of any sedimentary structures testifies to the lack of the higher-energy conditions seen in the barrier sediments. However, in comparison to the oolites of the lower Lincolnshire Limestone, the quantitative dominance of "normal" ooliths over all other allochems (together with the grainstone texture) suggests greater proximity to the ooliths' generative source i.e the barrier (Newell et al., 1960), while the absence of benthos indicates the presence of an inimical mobile substrate (see section IV.8.d. ; and cf. Sellwood and McKerrow, 1974), that would be expected to characterise an immediate back-barrier setting, where current-washing was probably frequent. In this context the ooliths of the Metheringham Member are quite informative. They often occur in two distinct groups: a larger suite (o.6 to 0.9 mm.) of heavily micritised ooliths, contrast with a smaller (0.2 to 0.5 mm.) group, which show good concentric structure. It may be that in this area, the impersistent washover currents, having largely lost their energy crossing the barrier, are only able to agitate (in situ) the smaller ooliths regularly; the larger ones which remain immobile for longer periods, are more easily "attacked" by boring algae. Alternatively (or as well as) the smaller ooliths may be transported more frequently, i.e. they might be swept to and from the barrier in various periods of flood and ebb flow, until increasing size renders them immobile for longer and longer periods. Thus these cleanly washed oolites probably represent what Ball (1967, p.582) considered the theoretical "bridge" between the actual high-energy barrier sediments and those of the "Platform Interior Sand Blanket" that have biogenic reworking outstripping current reworking. In such oolites (= Metheringham Member and Lithofacies A of Castle Bytham Member) the current activity, insufficient to form sedimentary structures, is nevertheless able to prohibit widespread colonisation by producing an agitated substrate; biogenic reworking is thus eliminated.

V.6.b.ii. Lithofacies-group 2: The oolitic packstones (Lithofacies B) and fossiliferous wackestones (Lithofacies C) of this group reflect "quieter" environments than the facies of group 1. The increase in interstitial mud, the wider range of even less well-sorted grains and the occurrence of some asymmetric oncolitic outgrowths on the allochems all indicate a reduction in agitation. Furthermore the presence, albeit sparingly, of detrital silt emphasises the lack of winnowing, while burrowing and bioturbation reflect the stabilisation of the substrate. Certainly the presence of indigenous terebratulids in Lithofacies C points to a fairly stable substrate as this group of brachiopods are thought to dislike mobile substrates (Fursich and Hurst, 1974). Whether this stabilisation was aided by, or even induced by gelatinous subtidal algal mats (Purdy, 1963; Bathurst, 1967a and 1967c; Scoffin, 1970; and Neumann et al., 1970), as suggested for some of the Greetwell Member sediments (see section V.2.c.iii.), is not clear. However, the presence of oncolites, which increase in the wackestones (Lithofacies C) does indicate the widespread occurrence of algae and associated mats would not be unreasonable. The oncolites are of the quiet-water type discussed in the Greetwell Member (see section V.2.c.iii.), lacking the well-laminated internal structure of modern agitated water forms described by Logan et al. (1964).

V.6.b.iii.Facies patterns: As with many of the lower Lincolnshire Limestone units, representatives of various "agitationlevels" are present, reflecting the migration or oscillation of the various back-barrier environments. In the stratotype of the Castle Bytham Member the facies pattern is symmetrical; the initial agitated grainstone facies gradually retreating from the area, to be replaced by more stable "lagoonal" facies, which support a largely epifaunal or shallow infaunal benthonic association (see section IV.10.f.). These, in turn, are replaced by the higher-energy deposits. Whether these differing environments reflect a bathymetric gradient is not evident; clearly, there is no need to invoke deeper water for the wackestone facies and shallower for the grainstones as it is the overbarrier (or through-barrier) currents that most likely influence the type of facies deposited. However the persistent occurrence of oolitic grainstones at this stratigraphic level is indicative of a back-barrier environment (cf. Dillon, 1970, fig. 2.).

V.6.c. Sub-environments of the Blankney Member.

From the available field evidence, the barrier (Sleaford Member) appears to have been emergent in central Lincolnshire (see section V.7.c.v.). It is interesting to note therefore that at Metheringham and Blankney, the Blankney Member is composed of exceedingly quartz-rich pelsparite packstones, which are similar to the unlaminated pelsparites of the Greetwell Member (Lithofacies-group 3, see Fig.5.2.). As the latter were thought to have been deposited in a very shallow subtidal setting (see section V.2.c.i.) it would not be unreasonable to suggest a similar intepretation for the Blankney Member deposits (in this area), especially as a number of features support such a view:

(1) the pelsparites are rich in "*Nerinea*" gastropods (Fig.4.135), which probably preferred shallow waters (M. Barker, personal communication).

(2) some beds have dense colonies of vertical burrows (see section IV.9.d. and Fig.4.139). These are generally thought to be single tubes of the *Skolithos* type, although it is possible that some are paired, the absence of spreite suggesting affinities with *Arenicolites* (cf. Knox, 1973b; and Fursich, 1974b,c.). In either case, relatively high-energy, shallow-water deposition is indicated (Farrow, 1966; Seilacher, 1967; Heckel, 1972; Crimes, 1975; Frey, 1975, table 2.1; and Rhoads, 1975).

A shallow subtidal environment is therefore probable for these beds, although intertidal deposition is not entirely ruled out; obviously such intensive burrowing (*Skolithos* and gastropods) would have readily destroyed any sedimentary structures that might indicate a low intertidal setting (the lack of desiccation features would seem to make higher tidal zones unlikely). In the light of this evidence the detrital quartz appears to be a "concentrate" in the well-sorted pelsparites of this back-barrier shore zone; the barrier prevented its movement out to sea.

Further south, away from the area where clear evidence of barrier emergence exists, the Blankney Member loses its quartz content and signs of extensive burrowing (although this is elusive in quarry faces, even at Metheringham where the best examples have been seen on a weathered block). Instead, with an increased oolith content, the pelsparites (grainstones in this area) merge with those of the Metheringham Member, although "*Nerinea*" gastropods still occur and peloidal limestones predominate. It may be that throughout their occurrence, the peloidal calcaren ites of the Blankney Member represent a shallower subfacies of the back-barrier environment but only where the barrier is emergent are features, typical of a shoreface, seen. In south Lincolnshire, the total absence of this facies may indicate the persistent submergence of the barrier.

V.6.d. Conclusions.

From a comparison with modern work (Newell et al., 1960; Ball, 1967; Dillon, 1970; and Evans et al., 1973) it would appear that the facies of these three members can be related to a back-barrier environment, where the wave and current activity has built up a sequence of oolitic grainstones and subsidiary pelsparites. In certain areas, the latter may represent the shallow subtidal deposits of the back-barrier shoreline.

V.7. THE DEPOSITIONAL ENVIRONMENTS OF THE SLEAFORD AND CREETON MEMBERS.

V.7.a. Introduction: the Recognition of Barrier Sediments.

Despite the volume of research on Holocene barrier coastlines, relatively little is known of fossil barrier systems (Bridges, 1976), and no satisfactory model for their interpretation in the sedimentary record has so far emerged, although both Davies et al. (1971) and Shelton (1967) have proffered models for specialised situations. Most workers agree that, in addition to their internal complexity (Jindrich, 1969; and Kraft et al., 1973), barrier deposits can be most easily recognised by the fact that they separate lagoonal from offshore marine sedimentary sequences (Hoyt and Henry, 1967; Potter, 1967; Weide, 1968; Dickinson et al., 1972;

and Purser and Evans 1973). However, the differentiation of these elongate "depositional-strike-sand-bodies" (Weide, 1968) into barrier islands, bars, spits and tidal deltas is largely dependent upon a recognition of the component parts of such complexes (Dickinson et al., 1972; and Kumar, 1973), which will often have been complicated in "fossil" situations by reworking and erosion (Hoyt and Henry, 1967). Thus there still remains a good deal of truth in the contention of Hoyt, (1967, p.1125) that " .... our facility for recognising ancient barrier sediments is imperfect ....", although the increasing amount of work on modern barrier shorelines is alleviating this problem.

In the case of the Lincolnshire Limestone, the widespread occurrence of "quiet-water" sediments, including tidal-flat and lagoonal deposits, in the lower Lincolnshire Limestone, indicates the presence of a protected off-shore"barrier" upon which most of the sea's wave and current energy must have been dissipated. The occurrence of mature carbonate deposits, containing an array of "high-energy" sedimentary structures (cf. Potter, 1967; and Davies et al., 1971) upon these "lagoonal" sediments would seem to represent such a barrier, although later uplift and erosion robbed the Bajocian sequence of any younger deposits that might have represented the off-shore marine portion of the ideal barrier sedimentary association (Hoyt and Henry, 1967, p.84). The superposition, with a marked erosive contact (Fig.4.2), of barrier (Sleaford Member) upon lagoonal sequences is typical of transgressive barrier complexes (Dickinson et al., 1972; and Purser and Evans. 1973). Furthermore the gradual, if erratic, increase of high-energy conditions up the Lincolnshire Limestone succession (culminating in the Sleaford and Creeton Members) reflects the lateral passage seaward from lagoonal to back-barrier to barrier conditions. The sedimentary associations would therefore seem to point to a barrier-coastline depositional environment and the following discussion will outline the criteria for believing that the Sleaford and Creeton Members represent different sub-environments of the actual barrier.

V.7.b. Barrier Islands vs. Offshore Bars: a Terminological Controversy.

The earlier inconsistent use of various terms (barriers, barrier islands, bars) relating to offshore sand bodies prompted Price (1951) to propose a standardised terminology, part of which suggested the following restricted usages:

(1) Offshore bar: any normally submerged bar formed offshore.

(2) Barrier island: the island(s) of sand, or sand and gravel or shingle, lying offshore. It is separated from the shore by a coastal lagoon or "sound".

Essentially this simple system differentiated submergent (bars) from emergent (barrier islands) sand bodies and it became widely accepted in geomorphological studies (Hoyt, 1967; Weide, 1968; and Kraft et al., 1973). However, in ancient sedimentary sequences, it is not always easy to delineate such a fundamental division (Davies et al., 1971, p.551.), especially in transgressive sequences where aeolian dunes and other emergence indices are likely to suffer marine reworking (Kraft et al., 1973, p.330). Therefore there appears to be a place for a non-definite term (in terms of emergence) that can be applied to offshore sand bodies, which protect inshore areas, where quiet-water sedimentation can proceed. The use of the general term "barrier" would seem to fulfil such a role, as Davies et al. (1971, p.551.) suggested, and it is adopted here. In "fossil" situations more precise knowledge of the depositional environments could be qualified, i.e. the term "barrier island" could be used when emergence can be demonstrated (cf. Palmer and Jenkyns, 1975) or alternatively, "offshore bar" might be used when emergence can be clearly shown not to have occurred.

The application of such a blanket term avoids certain other complications, such as the choice of a term to describe a barrier that is both emergent and submergent along different parts of its development (cf. Purser and Evans, 1973). Furthermore its use evades any implications concerning the overall sedimentary regime that the use of bar might have: barrier (be it submergent or emergent) suggests a protected back-barrier area, whereas Weide (1968) implied that "bars" have normal marine sediments on both sides, which is not always the case (cf. Ball, 1967).

V.7.c. Sub-environments of the Barrier: the Sleaford Member.

V.7.c.i. Introduction: Nature of the Barrier: In broad terms the composition and complex relationships of the lithofacies composing the Sleaford Member (cf. Laporte, 1969) suggest deposition in a barrier complex, which was transgressive, as its erosive superposition upon the "lagoonal" sediments of the lower Lincolnshire Limestone indicates (Dickinson et al., 1972; and Purser and Evans, 1973.). For the most part clear evidence of emergence is missing (but see section V.7.c.v.) and, although emergent indices are prone to reworking as transgression proceeds (Kraft et al., 1973), it is likely that much of the barrier was in fact submergent, especially in south Lincolnshire. However, the barrier formed a sufficiently persistent feature to reduce marine circulation and allow "protected" sedimentation in its lee, and in this respect it is comparable with some Bahaman "submerged" barriers (Ball, 1967).

Barriers are generally complex features, encompassing a wide variety of different sub-environments (Ball, 1967; Davies et al., 1971; Kraft, 1971; Basan, 1973; Evans et al., 1973; Kraft et al., 1973; Kumar, 1973; Purser and Evans, 1973; and Bridges, 1976), which are thought by some (Potter ,1967, p.352) to be extremely difficult to differentiate in the "fossil" state. Although certain recognition is frequently difficult or impossible to achieve, a degree of subdivision of the barrier-complex is possible after detailed facies analysis (cf. Bridges, 1976) and it has been possible to identify some of the sub-environments of the Lincolnshire Limestone barrier complex: barrier-inlet, barrier bars, on-barrier drainage channels, and lee-barrier rhythms have been recognised and are described in the following sections. Further sub-environments (tidal deltas and spillovers), represented in the Creeton Member, are also discussed in a later section (V.7.d.).

V.7.c.ii. <u>Barrier-Inlet Sediments: General Features</u>: In the sequences exposed at Ancaster and Great Ponton, the Sleaford Member cuts down into the lower Lincolnshire Limestone; in both cases approximately eight metres of strata, equivalent to the Blankney, Metheringham and Scottlethorpe Members and the upper part of the Lincoln Member, are absent. Although the base of the Sleaford Member is not exposed at Creeton, the "exaggerated" thickness of the member suggests that it too may infill a similar downcutting. However, the "completeness" of the stratigraphical sequences seen between these localities indicates that the down-

-cutting is only localised in a N-S direction, which suggests channelling (Fig.4.2.). Unfortunately the general distribution of exposures prevents the precise monitoring of this "channelling" in an E-W direction, although the available evidence favours a SW-NE channel alignment, as do the "in-channel" cross-bedding directions (but a NW-SE trend cannot be ruled out completely). Thus, these three sections, which puncture the "normal" barrier sequences, appear to represent the barrier-inlet channels, a conclusion which is supported by the associated sedimentary sequences.

Despite their high preservation potential (Hoyt and Henry, 1967) the nature of "fossil" barrier-inlet sequences (sometimes called tidal channels or tidal inlets) is poorly documented (Kumar, 1973), although a number of modern tidal channels in carbonate areas have been described (Jindrich, 1969; Basan, 1973; Purser and Evans, 1973; and Evans et al., 1973). In general terms the cross-bedded, mature oolites and skeletal oolites (Lithofacies A1, see section IV. 11.e.i.) of the inlet sequences in the Sleaford Member compare favourably with the sediment-types described from these modern Bahaman and Persian Gulf settings. The largely tabular cross-bedded sets infilling the inlets probably represent migrating straight-crested megaripples (or possibly intra-channel bars), the modern counterparts of which have been described by Basan (1973) and Evans et al. (1973). The sets range up to 1.5 metres thick and have mostly planar foresets dipping at 14-26°. Although these angles are rather less than those cited by other workers (Basan, 1973, p.47; and Jindrich, 1969), the common presence of "foreset-grading" (cf. Klein, 1965) suggests that they are probably avalanche deposits (Imbrie and Buchanan, 1965). However, at Creeton, many of the concave foresets have markedly "drawn-out" bottom sets (asyntotic), indicating deposition by higher velocity currents (Reineck and Singh, 1973; = accretion deposits ? of Imbrie and Buchanan, 1965). In all three localities where these channel deposits are seen, foresets dip approximately south-westwards, suggesting landward-facing lee-slopes and a flood-tide origin. Observations on modern barrier-inlets (in carbonate and clastic regimes) have shown that megaripples can "face" either seaward (Hoyt and Henry, 1967; and Jindrich, 1969) or landward (Hoyt and Henry, 1967; Basan, 1973; and Purser and Evans, 1973), depending on the dominance of the ebb or flood current. However, Basan (1973) has noted that the megaripples (and bars) in some Florida channels were inactive and in some cases stabilised by marine grasses; he attributed their origin to hurricane or other storm periods, when current activity would be higher. The "higher-energy foresets" of Creeton may suggest a storm origin (in part at least) for the Sleaford Member inlet deposits, although stabilisation by grasses could not have been possible in the Jurassic (Brasier, 1975). However, megaripples normally form in the lower flow regime of channels (Reineck and Singh, 1973) and Jindrich (1969) did not suggest storm deposition for the megaripples he described. It would appear therefore that both "normal" and storm currents have probably contributed to inlet deposition in Lincolnshire, although the effects of both were most likely episodic.

<u>The Ancaster Barrier-Inlet</u>: The Ancaster quarries expose the best example of a barrier-inlet sequence. At Copper Hill the channel has scoured down into the Ropsley Beds (Lincoln Member), producing an uneven channel floor, which was either consolidated prior to the erosion or cemented during its exposure in the channel, as abundant "<u>Lithophaga</u>" bores cut into the eroded surface (the bores

are not related to the stratigraphic bedding). As these beds are biomicrites it is not possible to determine any cementation relationships, and the presence of only "Lithophaga" bores means that the channel floor may have been only "firm" rather than "hard" (Goldring and Kazmierczak, 1974). However, at the nearby Castle Quarry, the equally uneven and hardened channel floor (with "Lithophaga" borings) has been cut in the oolites of the Scottlethorpe Member and the genesis of the cements can be deduced; although an early isopachous rim-cement suggests that the hardening was probably achieved in a submarine setting (cf. Kendall and Tucker, 1973), it does not tell us whether the hardening was prior to, or post the channel cutting. Hard substrates within channels have been noted in modern settings (Basan, 1973; and Evans et al., 1973) but the mechanism and timing of the hardening has not been studied. The fact that lagoonal sediments have been cut into at Copper Hill indicates that either the barrier-inlet scoured down into "older" back-barrier sediments as it migrated shorewards or that its down-cutting extended into the lagoon to form lagoon channels, which occur in the Trucial Coast (Evans et al., 1973); in all probability both processes were operative, although only this barrier-inlet sequence is preserved. No channels were seen in the Leadenham Member deposits.

The channel-infill, largely cross-bedded oolites and skeletal oolites would seem best attributed to migrating, landward-facing megaripples (Basan, 1973; and Evans et al., 1973). However, at Castle Quarry there are a number of patch reefs, enclosed within the high-energy oolites and these are analogous to the small fringing reefs that occur along the main "lagoon" channels of the

Trucial Coast (Evans et al., 1973, p.253). Equivalents of these have not been seen at either Creeton or Great Ponton.

Despite the difficulty in determining the geography of this and the other channels, an approximate SW-NE axis is suggested by the cross-bedding directions seen within the channel (Fig. 4.168), although these results from the interplay of the in-channel current regimes and the inlet's configuration (Hoyt and Henry, 1967). Furthermore, the existence of a tidal delta building out north-eastwards, which is preserved in the Creeton Member overlying these Ancaster channel sequences, also supports such an orientation (see section V.7.d.iii.). From the stratigraphical relationships of the Ancaster and Wilsford Heath successions (see section IV.12.b.) it seems probable that channelling also occurred in the latter area and therefore the channel, if orientated SW-NE, must have had a width of 2-3 kilometres, unless the downcutting encompasses a degree of barrier-inlet migration. Alternatively a NW-SE channel alignment would reduce the necessary width considerably, although from general stratigraphic and sedimentological considerations such an orientation seems unlikely. A width of 2-3 kilometres for barrier-inlets is not unreasonable for Georgian coastal inlets can be over 3 kilometres wide (Dickinson et al., 1972), while some of the Trucial Coast channels are several kilometres in width (Loreau and Purser, 1973; and Evans et al., 1973). However, other carbonate barrier-inlets are much smaller (< 1 kilometre; see Jindrich, 1969; and Basan, 1973) and therefore inlet-migration may have been operative (but see discussion below). In terms of depth the Ancaster Inlet (and indeed the Creeton and Great Ponton examples) is well within the limits observed in modern settings; depths of up to 15 metres have been recorded in the Georgian Coast inlets (Dickinson et al., 1972) while the lagoonal channels of the Trucial Coast range down to 10 metres (Loreau and Purser, 1973; and Evans et al., 1973) and the smaller-scale Bluefish Channel in Florida (Jindrich, 1969) is over 3 metres deep in places. At most the Ancaster Inlet is unlikely to have exceeded 5 metres in depth.

The Problem of Barrier-Inlet Migration: Although Hoyt and Henry (1967) pointed out the high preservation potential of barrier-inlets, it was not until the work of Kumar (1973) that a model for their recognition was advanced; he outlined a channel-spit -dune sequence (op.cit. fig. 6.), which was based upon a migrating channel system. In many respects this model parallelled that for meandering river systems. As none of the Sleaford Member inlet successions show such complex sequences, the Lincolnshire inlets are not thought to have migrated to any extent, although they may have oscillated back and forth over the same tract; such oscillations could help to explain the width of the Ancaster Inlet if it had a SW-NE orientation. Bridges (1976) suggested that under the conditions of relatively rapid barrier retreat, inlet migration might be minimal. Although the sharp basal contact of the Lincolnshire Limestone barrier sequence clearly indicates its transgressive nature (cf. Dickinson et al., 1972, p.208), the speed of this landward migration is less easily estimated. The absence of foreshore sands (no low-angle bedding, $< 10^\circ$, has been observed in the Sleaford Member) and the presence of relatively thin barrier sequences ($<$ 10 metres even if the Sleaford and Creeton Members are combined) are suggestive of steadily transgressing narrow barriers (0.2 to 2 kilometres, see Bridges, 1976) but the probable time involved (assuming one ammonite zone approximately equals one million years, see Hallam, 1975, p.23) is large compared to both the inlet migration rates and barrier migration rates discussed by Bridges (1976). It may well be that the Sleaford Member represents the last (and only one preserved) of a series of barrier-complex sequences that may have developed during Lincolnshire Limestone times.

Regardless of the time factor the main point remains that the inlet sequences seen, while conforming to the broad diagnostic features outlined by Hoyt and Henry (1967) do not represent the complex "migratory" successions detailed by Kumar (1973), and for this reason the Lincolnshire barrier-inlets are not thought to have migrated to any great extent. This conclusion is supported by the presence of the lower stratigraphic units, which have been removed in the channelled areas, at all the intervening localities.

V.7.c.iii. On-Barrier Sediments: The cross-bedded units that compose Lithofacies A1 and A2 of the Sleaford Member (see section IV.11.d.i.) pose a number of interpretative problems; those associated with significant downcutting (Ancaster, Creeton and Great Ponton) have been interpreted as barrier-inlet deposits and discussed previously (see section V.7.c.ii.). The remainder, to be dealt with here, can be classed as "winnowed carbonate sands" (cf. Tyrrel, 1969; and Laporte, 1969).

Although the barrier-inlet sediments have foresets dipping uniformly south-westwards, the on-barrier deposits display a variety of cross-bedding directions, which practically always have a major southerly component. In detail the major units (principally Brauncewell, Spittlegate Hill and Little Ponton) have south-easterly or southerly dips, which contrast with those of the barrier-inlet deposits. This suggests the probability of some kind of longshore current activity. In present-day coastal situations, where barriers are actively migrating under the influence of longshore currents (cf. Ball, 1967; Shinn, 1973; and Kumar, 1973) it is common to get cross-bedding resolved into two directions: one reflecting onshore currents, which may be in channels, while another, at approximately 90° to the first, reflects the longshore accretion of the barrier (cf. Ball, 1967, fig. 36.). Although the contrasting cross-bedding directions seen in the Sleaford Member (cf. Fig.4.168 with Figs. 4.169 and 4.155) possibly correspond to such a situation, the actual nature of the "longshore-accretion sediments" is not clear.

Longshore currents are usually associated with spit development across barrier-inlets or into open embayments (Kumar, 1973; and Shinn, 1973). The previous discussion on barrier-inlet deposits (see section V.7.c.ii.) concluded that no barrier-inlet/spit-complex sequences, like those described by Kumar (1973) were recognisable in the Sleaford Member; only barrier-inlet deposits appeared to be present. Indeed the fact that the "longshore" cross-beds of the Sleaford Member overlie the back-barrier peloidal grainstones of the Blankney Member (Fig. 4.2.) is quite out of keeping with Kumar's model. However, it has rather more in common with the chenier-beach accretion model of Shinn (1973): this too involves spit development but in an inshore setting. The spit deposits, which are characterised by "festoon" cross-bedding, with dip directions ranging through 360°, are often completely replaced by the simpler cross-bedded units of the "chenier" (as accretion continues). These, therefore, came to rest upon the tidal-flat deposits that accumulated in the lee of the spit during the earlier stage of chenier development (Shinn, 1973, fig. 10.). Although no tidal-flat deposits appear to be present in the underlying Blankney Member, shallow subtidal conditions were probably typical of this time (see section V.6.c.). Despite the attractiveness of this theory the scale of cross-bedding and angle of dip seen in the Sleaford Member units are not consistent with those described by Shinn (1973, p.187; cf. also Ball, 1967). In particular the submarine accretion sets (Shinn, 1973, p.191) are too small-scale and there are no equivalents of the low-angle beach-ridge deposits, although they could have been removed by the on-going transgression. Furthermore, the early submarine cements of the Sleaford Member deposits are not consistent with a chenier origin. Although these criticisms would not be levelled at the spit-platform model described by Kumar (1973, p.281), again it is difficult to envisage such accretion in this particular setting; the spit would have to be building landward primarily, over its own lee-sediments rather than into inlet situations.

In the absence of a satisfactory comparison with any spit-accretion models, the cross-bedded units have been compared to sub-aequeous dunes (megaripples), bars and ridges that could have migrated along or at an angle to the barrier's long axis, although some beds have a dip more consistent with a cross-barrier migration (towards the southwest). Thus a setting similar to the "Mobile Sand Belt" of Ball (1967) could be envisaged. In particular the massive avalanche sets seen at Brauncewell (over 3 metres; see Fig.4.154) could be readily matched with the "ridges" described by Ball (1967, p.558), although the exact nature of the cross-bedded units are difficult to determine because of the uncertainty of their geometry.

(cf. Shelton, 1967). However, at Brauncewell the foresets of the major avalanche units occassionally dip in the "opposite" direction (cf. Thompson, 1937) suggesting that the "ridges" are some kind of complex-bars. Other, less massive features, which sometimes overlie the major units, could have been parasitic subaequeous dunes or smaller bars. Within a very shallow high-energy setting such as this, the easterly dipping units (e.g. Thompson's Bottom Quarry) are probably attributable to ebb-flowing currents, the tidal situation being demonstrated not only by the wide range of cross-bedding directions but by the decidedly bimodal foreset directions seen at Blankney (Fig.4.157).

Stratigraphically this kind of facies belt (Sleaford Member) migrating landward, would be expected to overlie its own "lee" deposits and this is the situation seen. However, the presence of two major cross-bedding directions within the member's deposits does suggest a significant longshore component to the predominantly on-shore currents, which cross the barrier and themselves mirror both ebb and flood-tidal activity (see also section V.7.d.).

V.7.c.iv. <u>On-Barrier Drainage Channels</u>: At Braceby Long Hollow Quarry the lowest part of the Sleaford Member is characterised by broad but relatively shallow ($<$ 0.5 metres) channel-like scours, which are infilled with oolites and an oncolitic lag deposit. A series of these channels, which trend approximately NE-SW, occur in section, and each downcuts southwards into the one below. The infilling oolites show either crude cross bedding (dipping towards the SW) or small-scale, lens-shaped "wedges", which may represent formerly migrating lingoid ripples.

The general size of these channels, together with their very distinctive and prominent lag deposits and infilling oolites, compared favourably with the "local drainage channels" of some South Florida Banks (Basan, 1973, p.47). Such channels are thought to form by the headward erosion of channel distributaries (op.cit.; and cf. also Pierce, 1970, p.231.). Batophora -covered shell debris characteristically forms the lags in these modern channels and thus provides a ready comparison with the oncolites of the Braceby scours (see also Gebelein, 1976).

As these Braceby channels drain south-westwards and are located near the base of the Sleaford Member, they were presumably draining the "back" of the barrier (cf. Pierce, 1970) and would therefore be overlain by more on-barrier sediments in a transgressive sequence, as is the case here. The landward orientation of the rippled and cross-bedded oolites, infilling the channels could have resulted from either over-barrier flood-current activity or, more probably ebb-flow drainage, in which the retreating waters would have been concentrated into the channels and would have consequently had velocities high enough to produce the bedforms seen; in the back-barrier setting envisaged, ebb-flow would still have produced landward "facing" bedforms. In contrast the over-barrier flooding would have been more widely dispersed and therefore less effective, although it may have been responsible for the less well-defined cross-bedding.

V.7.c.v. <u>"Barrier Island" Sediments: Evidence for Emergence</u>: At Thompson's Bottom Quarry in central Lincolnshire, a number of thin, white micritic beds (Lithofacies A3) occur within a series of thinly-bedded, oncolite-rich pelmicrites and oolites, which overlie a thick, cross-bedded oncolitic oosparite sequence (Lithofacies A2). Within the micrite beds both parallel laminations and "micro-mounds" (Fig. 4.175) have been seen, and these have been tentatively identified as algal stromatolites (see section IV.11.e.i.). Between the micritic laminae, laminar fenestrae occur, the "birdseyes" of Shinn (1968a), who attributed their origin to shrinkage from exposure and desiccation. Taken together these features indicate deposition in a high intertidal or supratidal environment (Laporte, 1967; Shinn, 1968a; Ginsburg, 1975; and cf. Palmer and Jenkyns, 1975).

As these laminites and their associated "birdseyes" occur above undoubted barrier sediments (Lithofacies A2), they provide firm evidence of the barrier's emergence (cf. Palmer and Jenkyns, 1975) and in parts of central Lincolnshire at least, the barrier could be classified as a true "barrier island" (cf. Price, 1951).

Distribution of "Emergent Horizons": Firm evidence of emergence is restricted to the Thompson's Bottom occurrence of algal stromatolite/"birdseyes" deposits. However, at North Rauceby, similar parallel-laminated, thin, white micritic beds (see section IV.11.e.i.) occur within an oolite sequence, which is partially cross-bedded, i.e. typical on-barrier sediments. Although no "birdseyes" or "micro-mounds", suggestive of algal growth, have been recognised in these sediments, their general features (laminations, thin bedding, micritic composition) are reminiscent of the "micritic micro-beds" of the tidal-flat deposits of the Greetwell Member (see section V.2.c.i.); it is therefore suggested that the North Rauceby sediments originated in a similar environment. The very sharp margins of the vertical burrows, punching through the micrites, and similarly sharp scoured bases of the downcutting oolites, suggest that the micrites were quite well consolidated prior to these penetrations; such consolidation could have resulted from drying out. These two localities, 8 kilometres apart on a due N-S line may have therefore formed part of the same barrier island or have been representatives of different islands within a barrier chain; as no barrier-inlet sequences are known to occur in the sequences between these localities, the former is considered the more likely. Certainly modern barrier islands are often considerably longer than 8 kilometres (Kraft et al., 1973; Purser and Evans, 1973; and also cf. Palmer and Jenkyns, 1975, fig. 9.).

The dearth of such "emergence indices" could be the result of :

(1) natural scarcity due to lack of barrier islands

(2) non-preservation: all such relatively "subaerial" features exposed on barrier islands are subject to reworking and destruction if the barrier system is transgressive (cf. Kraft et al., 1973).

(3) non-detection: these small-scale features have only been observed in small, abandoned quarries with heavily-weathered faces. Most of the neighbouring pits are large and actively worked.

<u>Depositional Environment</u>: Where seen the thinness ($<$ 20 mm.) and restricted lateral extent of the micritic horizons suggest that the micrites were deposited in transient "protected" areas, probably ephemeral barrier-top ponds (cf. Dickinson et al., 1972, p.200) or abandoned barrier distributaries; fine sediment was trapped following times of emersion at high tides or during storms (cf. Perkins and Enos, 1968), and as it settled out algae may have aided in its trapping (cf. Palmer and Jenkyns, 1975). In the period following tidal retreat orstorm abeyance, the "ponds" were exposed, dried out

and desiccated, resulting in the formation of "birdseyes" and possibly the "buckling" of the algal mats, which produced exaggerated areas of "fenestrae" beneath the "micro-mounds".

Preservation of such ephemeral features was probably due to burial either by subsequent storm or high tide deposition, although the "ponds" may have survived a number of periods of emersion, depending on their geomorphology and situation on the barrier island. The covering sediments could have been deposited by sheet wash (cf. Imbrie and Buchanan, 1965) or by ripple migration; in either case minor scour occurred, and some of the micritic sediments were lost. A similar kind of setting was envisaged by Palmer and Jenkyns (1975) for barrier-top deposits in the Great Oolite of central England.

V.7.c.vi. Barrier Sediments: Major Rhythmic Sequences: Within the facies complex of the Sleaford Member, rhythmically-deposited sediments (ABC, ABC type) are prominent in a number of localities; Blankney and Haceby expose particularly important successions, although other, less strikingly rhythmic sequences are seen elsewhere. The possible origins of the Blankney (fining-upwards) and Haceby (coarsening-upwards) types are discussed separately below, and the genesis of the remaining, less distinctive, rhythms are collectively evaluated in a final sub-section.

Fining-upwards Rhythms - Blankney Type: Although there are a number of differences between the three fining-upwards rhythms at Blankney (see section IV.11.e.ii.), each essentially shows a tabular cross-bedded oolitic grainstone bed (Lithofacies B1) passing up via a mixed-grain lithology (Lithofacies B2) into a compact, fine-grained peloidal grainstone (Lithofacies B3; see sections IV.11.d.ii.

and IV.11.e.ii.). The rhythms, which are between 1-3 metres thick (Fig.4.161) each have erosive bases, although the boundaries within individual rhythms are gradational. Taken together these features suggest that the high-energy basal bed records an event which interrupts the "normal" back-barrier sedimentation, as typified by the underlying Blankney Member deposits (see section V.6.c.). As the rhythmic pattern is a gradual reversion to sediments (peloidal limestones) of broadly Blankney Member type, the remainder of the rhythm records a re-establishment of the back-barrier environment. This interpretation is supported by the sandwiching of the Blankney rhythms between the definite back-barrier sediments of the Blankney Member and the definite on-barrier sediments of the remainder of the overlying Sleaford Member (Lithofacies A2; see section V.7.c.iii), which in itself indicates a leeward barrier position for the rhythms. Bearing this in mind, it can be seen that the increasing importance of the basal cross-bedded oolite in each successively younger rhythm, reflects the approaching influence of on-barrier (high-energy) conditions, as does the increased winnowing (in successive rhythms) of the Lithofacies B3 sediments (grainstone in highest rhythm but packstone or even wackestone in lower two rhythms). Thus the fining-upwards rhythms appear to reflect oscillating environments (barrier-lagoon) on the lee-side of the barrier, which is gradually advancing across the area. Of the available possibilities it would seem that the ryhthms could reflect alternating barrier surges (Lithofacies B1, washovers ?) and lagoon re-advances (Lithofacies B2 and B3), or some kind of lee-barrier distributary channel sequence (cf. Bridges, 1976, p.354).

Although no actual channel form has been seen in any of the rhythms, Shinn (1973, p.191) pointed out that migratory tidal-channels would not necessarily leave a channel form in their lower reaches, but produce a "sheet-like" deposit similar to meandering river channels. In such a case the contrasting northward and southward cross-bedding directions seen in different rhythms (Fig.4.161) could represent opposite migratory paths, lying at an angle to the main barrier axis (assumed to be NW-SE from the predominance of north-easterly or south-westerly cross-bedding directions in the barrier sediments). However the type of cross-bedding seen (Fig.4.161) is not really consistent with such an origin, and the channel-infill might alternatively reflect bedforms, produced by flood or ebb surges, as postulated by Bridges (1976, p.354; see also Basan, 1973); the lack of channel form being due to the orientation of the exposed section.

An alternative model for these rhythms is provided by washover fans; the cross-bedded (10°-15° dips mostly), well-washed, oolitic sands in sets up to 0.86 metres thick would seem to be reasonable carbonate analogues for the clastic washover deposits described by Kraft et al., (1973, p.343). The two lower rhythms show landward-facing foresets (south-westwards dipping) and the increased importance of this level in the younger presumably reflects its greater proximity to the barrier. After each washover incursion into the back-barrier environment, calmer conditions re-establish themselves across the area and lagoonal sediments encroach over the washover deposits. Despite the attractiveness of this model, the uppermost rhythm presents a problem in that its cross-bedded unit "faces" northwards - the opposite direction to that expected in a normal washover. Such an anomaly might be explained in a number of ways: the complexity of the barrier's geography, so obvious in modern settings (for example see Evans et al., 1973) is not easily determined in the "fossil" state, and this could account for the "opposed" cross-bedding direction; secondly, the rhythms may have originated near a tidal inlet (not exposed), which would be a ready source of conflicting current directions (cf. Weide, 1968); or thirdly, a flood surge (which would give an "ebb" direction in a back-barrier situation) may have produced a "wash-on", transporting back-barrier oolites (from a lagoon shoal ?) towards the barrier. It would appear therefore, that despite the uncertainty of their precise origin, these rhythms reflect oscillatory conditions on what could broadly be classed as the lee-side of the barrier. They are overlain by the high-energy, cross-bedded units of Lithofacies A2, which presumably dissipated most of the sea's energy during the "calmer periods" represented in the upper parts of the rhythms.

Coarsening-upwardsRhythms - Haceby Type: These rhythms, which can be over 2 metres thick, are defined by an upwards increase in oncolite content; bimodal, oolitic grainstones grade gradually up into oncolitic-oolitic-packstones (see sections IV.11.d.iii. and IV.11.e.iii.), where the large oncolites (up to 50 x 20 mm.) are very densely concentrated (Fig.4.163). No sedimentary structures are normally seen (except for one rhythm at Dembleby), but the bases of the rhythms are erosive, and some have a shell-lag, rich in "Nerinea" gastropods. Only a sparse fauna of "Nerinea", *Lucina* and disarticulated *Trigonia* shells occurs within the rhythms.

In the absence of sedimentary structures, the constituent particles provide the only evidence for interpreting the conditions of deposition, and oncolites would therefore seem to be crucial.

Unfortunately they are not readily matched with the oncolites (or rhodolites) described from either modern (Logan et al., 1964; Bosellini and Ginsburg, 1971; and Gebelein, 1976) or ancient settings (Pugh, 1968; Leeder, 1975; and Tucker, 1977) because they lack any clearly defined internal lamination or certain calcareous structures. However, they appear identical to the grains from the French Bathonian figured by Purser (1975, fig. 38.6.), especially as both have similar intra-granular vugs. The Bathonian examples also occur in coarsening-upwards cycles but as the oncolites are distributed in both the sub-tidal and tidal-flat portions, no simple environmental relationships can be determined from them. Furthermore the evidence for upwards-shallowing and emergence, that typifies Purser's Bathonian cycles, has been gained from independent criteria (op.cit., pp.338-340), none of which are present in the Lincolnshire rhythms. In fact the upper part of the Haceby rhythms has what are probably early marine cements rather than the beach-rock types described by Purser (1975). Elsewhere, R.C.L. Wilson (1975) has outlined other coarsening-upwards cycles that are capped by oncolite-rich sediments but insufficient details were given to make an adequate comparison with the Haceby sections, although the oncolites were not thought to be similar (R.C.L. Wilson, personal communication, 1977). In the absence of ancient or modern anologues for either the cycles or this particular type of oncolite (rhodolite ?) only general environmental comparisons can be drawn. However, the available comparative information for oncolites is scant and very reptetitive. Practically all authors, in the absence of other evidence and presumably influenced by the early work of Logan et al. (1964), have attributed "fossil" oncolites to agitated low intertidal or shallow subtidal environments (cf. Laporte, 1971; Halley, 1975; Leeder, 1975; and Tucker, 1977). This conclusion has been based partly upon direct observation (Logan et al., 1964; and Gebelein, 1976) and on the general principal that quite high turbulence is required to produce the near-spherical "algal-balls". No refinement of this rather broad environment has been offered, although Gebelein (1976) has noted that lag concentrates of oncolites occur in tidal channels, a setting apparently favoured by rhodolites too (Bosellini and Ginsburg, 1971). The blanket acceptance of such an environment for all ancient oncolites, especially those lacking good internal lamination, has already been unfavourably commented upon (see section V.2.c.iii.) and here again it presents difficulties. Within the Haceby rhythms, it is the oncolite-rich levels that are the less well winnowed (packstone vs. grainstones) and many of the oncolites are not strictly spheroidal in shape, which by analogy with modern rhodolites would suggest reduced energy conditions (Bosellini and Ginsburg, 1971, fig. 12); however, now here are the grainstones discoidal or flat. Against this the dense concentrations of the Haceby oncolites (Fig.4.163) far exceed the figures given by Gebelein (1976) for modern Bahaman concentrations, where turbulent conditions were postulated to exist in water depths of less than one metre.

The almost complete absence of sedimentary structures from these rhythms suggests that the rhythms are products of a lee-barrier setting. The erosive bases, suggest a gradual migration of oolite shoals lagoonward away from the barrier perhaps, which implies an upward-shallowing origin for the rhythm, with the oncolites concentrated in the shallowest waters (cf. R.C.L. Wilson, 1975; and Gebelein, 1976). However this does not necessarily mean that the oncolites occurred in the most turbulent conditions (cf. rhodolite occurrences discussed by Bosellini and Ginsburg, 1971); it may well have been that the oolites, being in slightly deeper or more "exposed" water were subject to stronger agitation and that the oncolites were something of a "lag" deposit, collecting in protected shallows on the lee of the barrier - not even necessirily where they grew (cf. Wilson, 1975, p.440). Movement may have only occurred during storms and their dense concentrations may have acted as a baffle to some extent, reducing the effects of winnowing. Continued transgression resulted in their reworking and incorporation into Lithofacies A2 (see section IV.11.d.i.) while periodic storms could have jettisoned some into on-barrier drainage channels (see section V.7.c.iv.). This model is rather tentatively forwarded in the absence of firmer interpretative evidence; these, and indeed most of the ancient "subtidal" oncolites would seem to require much more detailed study before their origin (depositional environment) is satisfactorily appreciated.

Minor Rhythms: Most of the minor rhythms, described in sections IV.11.d.ii. and IV.11.d.iii. involve gradational lithological changes within individual beds. The loss or gain of sedimentary structures may be associated with the facies changes. Such rhythms are not always in repetitive sequences like the Blankney and Haceby types, but may occur within successions that expose other lithofacies. These minor rhythms can broadly be classified into two types: those with erosive bases (usually fining-upwards) and those without (usually coarsening-upwards). The former, exemplified by the basal bed of the Sleaford Member at Castle Bytham (a cross-bedded oolite; see section IV.11.d.ii.) are probable "washovers" (cf. Kraft et al., 1973), which reflect the high-energy deposition of barrier deposits upon back-barrier sediments; the erosive base indicates transportation into a "foreign" environment. The latter, which are generally peloidal limestones grading up into oolites, usually lack sedimentary structures, although cross-bedding may occur in the upper part. These rhythms most probably reflect the gradual oscillation of facies in the relatively protected, yet lithologically diverse environment, on the lee-side of the barrier. In its simplest conception, such a rhythm might be thought to result from the gradual lagoonward shift of the barrier, the gradual upward introduction of cross-bedding being a response to increased current velocities, which may have resulted from the shallowing produced by the encroachment of the barrier. Collectively therefore the minor rhythms represent fossil examples of the very complex facies distributions, that typify the lee-side of modern carbonate barrier-complexes (Purser and Evans, 1973; and Evans et al., 1973).

V.7.c.vii.Conclusions: The facies-complex composing the Sleaford Member represents a variety of environments, which can be found on modern carbonate barriers. In particular it has been possible to distinguish between barrier-inlet sequences, which provided sea-lagoon links, and on-barrier sediments, that afforded protection from the main force of the Jurassic seas. It is clear from the "lagoonal" sediments underlying the barrier sequences that some areas were better protected than others, and this has been emphasised by the localised occurrence of supratidal deposits, indicative of emergence and true barrier islands. Similarly the relative measure of "energy" provided by the presence/absence of cross-bedding has enabled leeward-barrier environments, such as the rhythmic sequences, to be differentiated from windward settings, where the major cross-bedded units probably developed. However it has not really been possible to interpret the sub-environments in such a way as to produce a palaeogeography for the barrier system, although the position of the barrier-inlets and emergent horisons are obviously accurately located. This is not really surprising in the light of the complexity of modern barriers (cf. Purser and Evans, 1973; and Evans et al., 1973) and the lack of modern and ancient models for the sedimentation patterns such barriers produce.

V.7.d. Sub-environments of the Barrier: Creeton Member.

V.7.d.i. Introduction: Although the Creeton Member can be stratigraphically differentiated from the Sleaford Member, the origins of the two units are closely related; each represents different aspects of the same barrier-complex. However, the relatively uniform sediments forming the Creeton Member reflect a less diverse array of depositional environments than those seen in the lithologically complex Sleaford Member. Furthermore, as the Creeton Member overlies the Sleaford Member (except at Clipsham), the environments represented would have formed mostly on the barrier or seaward of it, a factor that has an important bearing on the interpretation on the unit's sediments.

V.7.d.ii. Tidal Delta vs. Spillover Lobe Sediments: In broad terms, the large sets of tabular cross-bedded oolites and skeletal oolites composing the Creeton Member can be readily matched with the sediments of modern tidal deltas (Jindrich, 1969; Loreau and Purser, 1973; Evans et al., 1973; Purser and Evans, 1973; and cf. Kraft et al., 1973) and spillover (Ball, 1967) or washover lobes (cf. Kraft et al. 1973) and on purely sedimentological grounds it would be difficult, if not impossible, to separate the two. However, as the facies of these two sub-environments have different (to some extent) relationships with the associated facies in the overall barrier environment, stratigraphical relationships provide a possible method of differentiating between deltaic and spillover sediments (the term spillover is used here in the sense implied by Ball, 1967). For example tidal deltas may form at either end of the associated barrier-inlets (Dickinson et al., 1972, p.198); they might therefore rest upon "lagoonal" sediments (if a flood-tidal delta) or upon fore-barrier/barrier/barrier-inlet sediments (if an ebb-tidal delta), assuming a transgressive barrier situation, as is the case in the Lincolnshire Limestone. In contrast, spillover sediments would be expected to occur only on barrier or back-barrier sediments (cf. Ball, 1967). As the Creeton Member invariably rests upon the barrier sediments of the Sleaford Member (north of Clipsham), flood-tidal deltas are unlikely to be represented in the Creeton Member (for the problem of Clipsham see section V.7.d.v.). Indeed the recognition of only three possible barrier-inlets within the barrier system (see section V.7.c.ii.) means that even ebb-tidal delta formation is likely to have been restricted. Such ebb-tidal deltas should have a preponderance of seaward-facing sedimentary structures (Jindrich, 1969), which in this case would be approximately north-eastwards. Of the three possibilities, only the Ancaster Inlet appears to have produced a significant ebb-flow delta (and Great Ponton ?). All the other Creeton Member localities expose successions, with predominantly south-westerly dipping foresets (landward facing), that rest upon barrier rather than back-barrier sequences; they must therefore be considered as on-barrier features something akin to spillover lobes (cf. Ball, 1967) rather than flood-tidal deltas.

The Creeton Member can be tentatively divided into two major sub-environments: the ebb-tidal delta of the Ancaster-Wilsford area and the Spillover Lobe environment, which is best exemplified by the Castle Bytham sequence. Each of these sub-environments is more fully discussed below, while the more problematical sequences are compared to the "ideals" in a concluding section.

V.7.d.iii.Ebb-Tidal Delta Sediments: The Creeton Member sequences exposed in the Ancaster-Wilsford district are thought to represent an ebb-tidal delta complex which built out seawards from the mouth of the Ancaster Barrier-Inlet. At both Copper Hill and Castle Quarries, Ancaster, the member is represented by cross-bedded "clean" oolites and skeletal oolites (Lithofacies A; see sections IV.12.d. and IV.12.e.i.), which are very similar to that of the modern Persian Gulf Oolite Deltas (cf. Evans et al., 1973, p.251; and Loreau and Purser, 1973, pp.284-285), although the Lincolnshire ooliths tend to be finer grained than those described by Loreau and Purser (1973, fig. 5C). The cross-bedding, which has a strong northerly-dipping component (Fig.4.189), occurs as a tabular set of 3-5 metres amplitude (Fig.4.152); the planar foresets dip at approximately 20° (range: 12-25°). Although of a larger scale, the cross-bedding corresponds to the delta foreset beds of Jindrich (1969, p.548; see also Bridges, 1976) and represents the major outbuilding lobes of the delta. The spread of foreset dip directions (Fig.4.189) is to be expected, as the delta lobes fan out on leaving the confinement of the barrier-inlet (cf. Evans et al., 1973, fig. 10), which necessarily pre-dates the delta in the development of the barrier-complex (Purser and Evans, 1973, p.220). The superposition of the ebb-dominated tidal delta on the flood-dominated tidal-inlet deposits (Sleaford Member) at Ancaster (Fig.4.152) clearly demonstrates this temporal relationship stratigraphically; it also illustrates the transgressive nature of the barrier-complex as a whole.

At Wilsford the Creeton Member is less noticeably cross-bedded and has two distinct lithofacies (see section IV.12.d.): the purer oolite facies (Lithofacies A) is finer-grained (medium calcarenite) than those of the Ancaster sections. This, together with the lack of distinct cross-bedding and widespread micritisation of the grains suggests a less agitated regime more in keeping with the outer-delta environment of Loreau and Purser (1975, see fig. 5B). However, downcutting into this facies is the similarly poorly cross-bedded skeletal-rich Lithofacies B, which occupies a wide scour (> 500 metres) with a maximum depth of 3-2 metres. This scour appears to be aligned NE-SW and could therefore represent an axial channel within the delta complex; a proposal which is supported by its strongly scoured base and bioclastic-rich sediment infill (cf. Loreau and Purser, 1973, fig. 5D). Although it is rather wide the Wilsford "channel" is of the same order as that described by Loreau and Purser (1973, fig. 4.) and its depth was similarly comparable. (op.cit., fig. 3.).

V.7.d.iv. Spillover Lobe Sediments: The Creeton Member succession at Castle Bytham shows a sequence of cross-bedded oolites and skeletal oolites (Lithofacies A; see sections IV.12.d. and IV.12.e.i.) that have foresets dipping predominantly south-westwards, although a north-easterly component is also present (Fig.4.191).

In detail, this and similar sequences have a basal massive unit (2 metres thick at Castle Bytham) which dips south-westwards; in both size and composition, this would appear to correspond with the large spillover lobes seen in the Bahaman carbonate province (Ball, 1967, p.558), although no axial channel features have been recognised. The development of an oyster-encrusted hardground on top of this unit suggests that it was immobile for long periods, which is consistent with Ball's observation that such large structures are only "moved" or developed during storm periods (Ball, 1967, p.560), although hurricanes have also been known to erode spillovers (Perkins and Enos, 1968). Similarly the presence of interstitial micrite, which settled out from suspension during calm periods (see section IV.12.e.i.) indicates periods of immobility for the other cross-bedded units, overlying the basal spillover. The higher sets tend to be smaller ($<$ 1.25 metres) and have either south-westerly or north-easterly cross-bedding directions; they presumably represent smaller spillovers or mega-ripples, riding upon the backs of the spillover structures.

The basal units of the Castle Bytham and similar sequences, are invariably landward-facing (south-westwards) and therefore the most powerful and dominant winds (and tidal currents) must have been on-shore, a conclusion that is supported by the orientation of the sedimentary structures in the barrier-complex as a whole. This is to have been expected for during Bajocian times, Lincolnshire lay in the path of the NE Trade Winds (Smith et al., 1973). However, the bipolar current orientations of the higher cosets in these Creeton Member successions reflect a stronger tidal effect, which may have been a function of deposition in shallower water. This bipolarity is also interesting for another reason, that of the position of the spillovers on the barrier. The term spillover lobe (Ball, 1967) or washover fan (cf. Kraft et al., 1973) suggests transportation of sediments over the barrier into the back-barrier lagoon, and this is the case with many of Ball's lobes. However, the Creeton Member spillovers rest upon other barrier sediments, which by their greater diversity and relationship with "lagoonal" deposits probably represent the lee-side of the barrier proper - as exemplified by the Castle Bytham sequence, where for example back-barrier patch-reefs are seen (cf. Purser and Evans, 1973, p.218). Nowhere are the Creeton Member spillovers seen to rest on back-barrier sediments (except perhaps at Clipsham, see section V. 7.d.v.). It appears likely therefore that these spillovers are mostly on the windward side (seaward) of the barrier, where the highest energy conditions exist, and ebb as well as flood currents are able to produce significant sedimentary structures (cf. Ball, 1967, fig. 9 and p.599). The major structures probably face landwards because of the predominant storm direction would, in this wind belt, be from the north-east. Inshore from these spillovers, on the lee-side of the barrier, the Sleaford Member barrier sediments accumulated and transgressed over the back-barrier sediments. Thus, the progressive transgression of the Lincolnshire Limestone sea eventually provides a stratigraphic sequence showing, at Castle Bytham for example, back-barrier sediments (Castle Bytham Member), overlain erosively by leeward-barrier deposits (Sleaford Member) and seaward-barrier sediments (Creeton Member).

V.7.d.v. <u>Conclusions and Outstanding Problems</u>: Although the two sub-environments suggested for the Creeton Member are quite feasible in the localities discussed, it is not always so easy to relate all the other Creeton Member successions to the two models. The Castle Bytham types like Creeton, Burton Coggles, South Rauceby, North Rauceby and Little Ponton (?) are fairly readily matched, because both lithologically and sedimentologically they are relatively uniform; it is probable therefore that they represent very similar sedimentary features: spillovers. (At Creeton, additional sediments of the Sleaford Member overlie the possible inlet deposits, suggesting that the inlet was inoperative prior to the deposition of the Creeton Member.) At the Soil Fertility Quarry, Clipsham, similar lithotypes, with cross-bedding directions towards the south-east rather than the south-west, rest upon the back-barrier sediments of the Castle Bytham Member; this succession may represent an actual spillover or washover resting directly upon "lagoonal" sediments, or alternatively it might be envisaged as a flood-tidal delta (cf. Kraft et al., 1973, fig.7.), for which no inlet has been exposed or recognised. The variation in cross-bedding direction could be explained by a number of factors, not least of which could have been a more east-west alignment of the barrier at the southern end of the Lincolnshire Limestone Gulf.

The remaining, mostly mid-Lincolnshire localities tend to have, in their basal parts at least, a south-westerly dipping cross-bedded unit, which is often cut into by usually north-easterly dipping, skeletal-rich beds (e.g. Old Somerby and Haceby Lodge Quarries). Such sequences may be related to the Ancaster or possibly a Great Ponton tidal-delta complex (the two may have coalesced). The present outcrop distribution and the inherent complexity of tidal-delta systems (cf. Loreau and Purser, 1973, fig. 4) make such an idea possible, although difficult to determine.

V.7.e. The Origin of the Barrier.

At the onset of the deposition of the Lincolnshire Limestone it is possible that two of the optimal conditions for barrier development (offshore bar or barrier island) existed: a broad, low-relief coastal plain and slow regional subsidence (Weide, 1968, p.408), and that a third, longshore drift, may also have been operative, although there is no firm evidence to support such a contention. It is perhaps not surprising therefore that a barrier coastline evolved. However, even though a suitable setting for the development of a barrier may have been present, the actual mechanism for its formation is more controversial (Schwartz, 1971).

The origin of barrier islands is still considered to be something of an open question (Reineck and Singh, 1973), and Schwartz (1971) has advocated the acceptance of multiple causality, which encompasses all three of the most widely proposed mechanisms of origin:

(1) Upbuilding of offshore bars

(2) Cutting of inlets through spits

(3) Submergence of ridge-like coastal features

Although the latter two have been widely accepted (Hoyt, 1967; Weide, 1968; Schwartz, 1971; and Bridges, 1976), the emergence of offshore bars to form barrier islands has not been so favourably received (see especially Hoyt, 1967), except when a result of a fall in sea level (Hoyt, 1967; and Leontyev, 1969). Essentially Hoyt (1967) doubted the "offshore bar theory" because of the general absence in barrier island sequences, of beach and shallow neritic deposits, that should have developed shoreward of the growing, yet still submergent bar. He also pointed out that experiments have shown that waves cannot aggrade submarine bars to the point of emergence (Hoyt, 1967, p.1126), although he conceded (op.cit., p.1127) that small-scale barriers could develop by upward accretion of bars (see also Curray et al., 1969, p.70). Later Otvos (1970) outlined evidence supporting the development of barriers from offshore bars while Price (1963) had already indicated the possibility of storms playing a role in the "emergence" of bars. Certainly on general considerations there seems no major evidence to prohibit such a mechanism. Hoyt's major reservation, concerning the lack of marine sediments shoreward of the barrier, probably reflects too narrow a view of the effectiveness of "offshore bars" (cf. Price, 1951), as barriers. Firstly, it is too naive to suggest that even submergent bars cannot modify sedimentation on their leeside, as is clearly the case in the carbonate areas of southern Florida and the Bahamas (Ball, 1967; and Basan, 1973). The degree of effectiveness in producing shoreward "lagoonal deposits" will obviously depend upon a number of variables, amongst which the amount of run-off, the evaporation-precipitation balance, the size of the bar, and the number of inlets (providing lagoon-marine contact), could all be important. Although all of the features of the "Marine Sand Belt" of Ball (1967) are submerged (covered at high tide, cf. Hoyt, 1967, p.1126) many of the characteristics of his "Platform Interior Sand Blanket" are directly attributable to development in a lee-barrier environment (Ball, 1967, p.575). Secondly, on a low-relief coastal plain undergoing marine transgression, the offshore bar would develop early on in the sedimentary history (Irwin, 1965) and therefore back-bar sedimentation would probably never provide the beach and shallow neritic deposits Hoyt (1967) considered such an integral part of this sedimentary regime. The ensuing growth of the bar would only increase its effectiveness as a barrier, and the "lagoonal" nature of the back-bar sediments would be emphasised. It seems most unlikely that the difference between a "barred" and "barriered" coastline could be distinguished in the sedimentary record of the lagoon, as the deposits would reflect a protected environment, which could have resulted in either case. Perhaps only the existence of a back-barrier shoreline could resolve the issue unless the fauna was taken into consideration. Even here though, the "lagoonality" of the fauna would probably reflect the climate rather than the type of barrier, for run-off or evaporation generally determines whether the lagoon is to be hypo or hyper-saline, as is the case in unbarred estuarine settings for example. It is only restricted mixing with open marine waters that is required for the climate to affect salinity and such restriction could result regardless of whether the barrier was emergent or not.

The absence of back-barrier marine deposits poses a problem with all the models of barrier island formation, except perhaps the "coastal-ridge-submergence" hypothesis of Hoyt (1967) for even though the "spit-breaching" mechanism was adopted by Bridges (1976), he had to advocate non-deposition until the "sediment trap" (= barrier, op.cit., p.352) was developed, i.e. back-barrier marine sediments were also absent in this case. Therefore it appears that the lack of back-barrier marine sediments is probably not a crucial factor in the understanding of barrier island formation and that in all likelihood, their absence will be "normal" regardless of whichever mechanism was operative. As the available evidence does not definitely preclude any of the proposed mechanisms of barrier island formation, it would seem wiser to accept the more catholic approach of Schwartz (1971).

In the case of the Lincolnshire Limestone a combination of tidal-flat, lagoon and "quiet-water" sediments are sandwiched between the mostly non-marine deposits of the underlying Grantham Formation and the barrier sands (Sleaford Member); there is no evidence of open (unrestricted) marine deposition landward of the barrier, although the fauna of these "lagoonal" deposits contain "normal marine" elements (brachiopods and some echinoderms). This suggests that fairly free interchange existed between the "protected" area and the open sea, which tempered the effects of evaporation (cf. Persian Gulf, although there was probably a humid climate in Lincolnshire during the Middle Jurassic). Furthermore, a combination of a low-lying hinterland and the effects of the marine transgression probably meant that few rivers of any size drained into the area, so hyposaline conditions did not result. However, the barrier is known to have been emergent in places (see section V.7.c.v.) and could therefore be classed as a barrier island, so restriction cannot be denied. Indeed the existence of the tidal-flat deposits so low in the Lincolnshire Limestone succession indicates the presence of a barrier from the onset of sedimentation (cf. Purser, 1975), although the restriction of "pure" lagoonal deposits (Leadenham Member, Ropsley Beds and Little Bytham beds; see chapter IV) to higher stratigraphic levels (and specific geographical regions) indicate that the barrier's effectiveness increased with time (cf. Purser and Evans, 1973, p.226), especially in central Lincolnshire. It is interesting to note that the evidence for the barrier's emergence is in the same area as the maximum development of the Leadenham Member lagoon. These factors, would seem to favour the barrier developing as an offshore bar (submergent), which then aggraded through time eventually to become emergent in central Lincolnshire (at least), although elsewhere it may have remained submerged throughout its existence (general absence of barrier beach sediments, see section V.7.c.).

The barrier itself shows little sign of having been part of a beach-ridge system (cf. Hoyt, 1967), for since the sediments are marine carbonates, invariably showing early marine cements (see section IV.11.e.), it is unlikely that they bordered the "clastic" coastline of the Grantham Formation. There is no evidence of remnant aeolian deposition or any terrestrial sediments (or beach-rock cements), which might be expected if the Lincolnshire Limestone sea surrounded rather than reworked this nascent "barrier island" (cf. Hoyt, 1967). Furthermore no reason for the gradual establishment of restricted lagoonal conditions is provided by this mechanism either.

As for the spit-breaching mechanism, it is difficult to envisage how or where the original spit system developed, even if longshore currents were able to perpetuate it. The carbonate composition of the barrier prevents the inference of a fluviatile or deltaic source of sediment initiating the southward growth of a barrier from the Yorkshire sedimentary province (cf. Bridges, 1976). Rather, the development of a series of bars, at a significant break-of-slope offshore (cf. Ball, 1967) is envisaged, and the uneven growth of these probably provided the features now seen in both the sediments of the barrier and its protected lee-side waters. The inorganic precipitation <u>in situ</u> of most of the carbonate sediments removes the need of an external sediment supply, which is so necessary for the development of a clastic barrier system and so important to any model for the origin of clastic barriers.

V.7.f. <u>Conclusions</u>.

It would appear from the above discussions that the Sleaford and Creeton Members' deposits represent an offshore barrier-complex, in which a number of distinctive sub-environments can be recognised. In broad terms, the high-energy facies (the large cross-bedded sets of both members) probably represent prominent sedimentary features on the windward or seaward side of the barrier, where the main marine forces were expended. Except for the Ancaster ebb-tidal delta (part of Creeton Member) most of these features are thought to be large spillover structures or ridges/complex bars (cf. Ball, 1967) which predominantly "faced" landwards because of the prevailing North-Easterly Trade Winds. However, the current directions, as indicated by the cross-bedded units, are complex and it is possible that in addition to the onshore or across-barrier movements (probably south-westwards if barrier-inlets are an accurate guide), ebb-and-flood-tide currents and longshore drift (south or south-eastwards) complicate the sediment movement patterns; the other important factor governing such movements, the geography of the barrier, remains largely unknown. Occupying the area in the lee of this high-energy belt is a complex of relatively protected sub-environments, that are represented by a variety of lithofacies, some of which have been interpreted as washovers, local drainage channels and oncolite shoals. These probably migrated freely as the barrier's configuration changed under its steady progress landwards, and rhythmic sequences are common. Further inshore back-barrier sediments replace the lee-barrier rhythms; the former are differentiated from the lee-barrier deposits by their lack of cross-bedding. In central Lincolnshire, supratidal deposits, resting upon high-energy facies (Sleaford Member, Lithofacies A2) have indicated the existence of a barrier island, while elsewhere the strong tidal influence reflected in the cross-bedded deposits indicates that most of the barrier's sediments were deposited at or near sea level.

Throughout this discussion, onshore directions have invariably been referred to as south-westwards, primarily because what little evidence exists to indicate Bajocian landareas, favours a London Landmass and a possible shoreline to the west (cf. Bradshaw, 1975, fig. 1, and see section V.2.d.ii.). However, it is possible that the Lincolnshire Limestone sea occupied an East Midlands Gulf (Kent, personal communication, 1976) but even if this were the case, there can be little doubt that the western shoreline of the Lincolnshire Limestone sea was "protected" by off-shore barriers.

The rather eclectic approach to the interpretation of the sub-environments and development of the barrier model has been necessitated by the dearth of "fossil" examples of barrier sequences (Bridges, 1976) and the geomorphological bias of much of the modern research, although Kraft et al. (1973) offer a refreshing contradiction to this. The Trucial Coast work (Purser, 1973) has also offered much comparative information, but many of the "mysteries" of these barriers remain unsolved. Because of this and the inherent complexity of barriers, it is perhaps not surprising that the degree of certainty attached to the individual interpretations offered here, varies somewhat. Barriers, both ancient and modern, hold many future challenges for the sedimentologist.

V.8. CONCLUSIONS: ENVIRONMENTAL SYNTHESIS.

During earliest Bajocian times, the slowly subsiding East Midlands shelf was engulfed by a shallow epeiric sea, in which the Lincolnshire Limestone Formation was deposited to form part of the "carbonate fringe of the London Landmass" (Ziegler, 1975). It is possible that, at its southern end at least, this "East Midlands" epeiric sea may have had the morphology of a gulf (Kent, personal communication). Land or "positive areas" fringed the northern (Yorkshire Delta), western and southern sides of the nascent gulf, which probably opened out north-eastwards. Whether a south-western connection existed with the "Southern England Carbonate Province" remains unresolved.

V.8.a. Off-Shore Barrier Development.

The transgression of a shallow sea across a gently subsiding, low-gradient shelf sea provided an ideal setting for off-shore barrier development (Weide, 1968). It is possible that the barrier evolved from the coalescence and up-building of bars, which developed initially at some significant break-of-slope (Irwin, 1965; and cf. Ball, 1967), off-shore from the sea's western coastline. Present knowledge suggests that the long axis of the barrier was most probably aligned NW-SE. The development of the barrier effectively split deposition into two main provinces: back-barrier and barrier-complex, although each province contained a number of sub-environments. As "back-barrier" sedimentation is recognisable throughout the lower Lincolnshire Limestone, the barrier-complex must have evolved at or near the onset of the formation's deposition.

V.8.b. Back-barrier Environments.

Although, in broad terms, the back-barrier environment is represented by all the sediments older than the Sleaford Member, it also has a bipartite division. The discites Zone age sediments (Sproxton, Greetwell and Leadenham Members) reflect a different depositional regime to the younger (ovalis Subzone) units. For ease of discussion each will be dealt with separately and an attempt made to summarise the entire lagoonal setting in a final subsection.

V.8.b.i. Sedimentation during discites Zone times: Deposition during these times was geographically polarised by the influence of the "Lincoln High"; effectively southern and central Lincolnshire sedimentary provinces evolved. At the onset of sedimentation the "Lincoln High" persisted as a positive area in central Lincolnshire and sedimentation only proceeded in the southern province (and North Lincolnshire Basin), where a series of regressive rhythms built up. Each rhythm was initiated/terminated by a transgression that resulted from a period of accelerated subsidence; such events have been recorded by erosive levels while the actual sediments of the rhythms reflect the tidal-flat progradation out into sheltered, subtidal back-barrier waters. In central Lincolnshire during this time the "Lincoln High" gradually succumbed to the transgression and its continued, steady subsidence produced a shallow subtidal facies mosaic that eventually gave way to "true" lagoonal conditions, in which lime mud was deposited and a stable benthonic fauna thrived. The gradual subsidence (and deepening ?) of this area contrasted with the episodic subsidence "jerks" of south Lincolnshire. Stratigraphical considerations, suggest that the "High" tilted southwards and consequently the junction between the provinces was gradational rather than sharply defined.

Towards the close of this period, the central Lincolnshire lagoon (Leadenham Lagoon) graded southwards into more agitated environments, which were typified by "lagoonal" oolites. The contrasts probably reflect differences in circulation, which varied with the degree of through-and-over-barrier "mixing". Certainly the main barrier-inlets were concentrated in mid and south Lincolnshire and it is only in central Lincolnshire that evidence of barrier emergence exists. The south Lincolnshire barrier was probably always awash, at least at high water. The presence of marine stenohaline benthonic groups throughout both areas, shows that a combination of through-barrier mixing and the prevailing Bajocian climate maintained the back-barrier salinities at or close to "normal" marine.

V.8.b.ii. <u>Sedimentation during ovalis Subzone times</u>: The <u>discites</u> Zone sedimentary region was abruptly terminated at the erosive onset of these times, when all of Lincolnshire was blanketed by the basal oolite of the Lincoln Member. This "event" is thought to have resulted from a transgressive "pulse" of the barrier across the lagoon. Although no "true" barrier sediments are represented, the basal oolite of the Lincoln Member is similar to the "agitated back-barrier oolite belt" represented by the Metheringham and Castle Bytham Members (upper Lincolnshire Limestone).

More typical lagoonal conditions were soon re-established and a complex of depositional environments evolved, ranging from muddy, lagoonal areas to oolite shoals. However, oolites became increasingly important (shoreward encroachment of barrier across lagoon) and the low-energy lagoonal deposits gave way to the "agitated back-barrier oolite belt" of the Metheringham and Castle

Bytham Members. This belt is thought to represent the immediate back-barrier zone where agitation was both more intensive and more frequent because of the greater proximity to over-and-through-barrier current activity.

V.8.b.iii.Morphology of the Lagoon: In general terms the lagoon or back-barrier area, can be envisaged as a broad (minimum width = 8 kilometres), shallow-water area, fringed to the west and south-west by tidal flats, which abutt onto a low-lying hinterland, and east-wards by the offshore barrier-complex. Within the lagoon a complex sedimentary facies pattern evolved in response to varying hydro-dynamic conditions, which themselves reflect the degree of and proximity to over-and-through-barrier currents, and perhaps even depth. Such complexity is quite typical of back-barrier settings (cf. Purser and Evans, 1973; and Evans et al., 1973). Despite the complexity, two main "energy" or facies belts exist: the more inshore, low-energy zone is dominated by mud-supported lithologies, and the immediate back-barrier, high-energy belt, where grain-supported lithologies predominate (Fig. 5.9). "True" lagoonal mud areas probably developed in areas of maximum shelter, which may have resulted from greater barrier protection (emergent), deeper water, or removal from main current movements, or a combination of two or all three.

V.8.c. Barrier Environments.

The erosive base of the Sleaford Member reflects the transgressive nature of the barrier-complex, which is characterised by a multitude of facies, representing the associated sub-environments. Despite the complexity, a number of these component-environments have been recognised and a crude bipartite division can be made with what might be termed leeward and windward features. However, the barrier owes its origin to complex bars, which may occur in either zone and reflect the influence of longshore as well as ebb and flood-current activity.

V.8.c.i. Leeward Features: These are invariably found in the Sleaford Member because it rests directly upon the back-barrier sediments. The nature of the facies and their relationships suggest that the lee-side of the barrier was a wide, low-gradient area, often quite well protected by the high-energy deposits of the windward side. Essentially the leeward environment is typified by rhythmically-deposited sediments that reflect the oscillations of the barrier's "inner" margin. Lagoonward advances were mostly the result of "washover", although slowly migrating oolite shoals, capped with oncolites, might also have performed a similar role. Sedimentary structures indicate that lagoonward (towards the south-west) current movements predominate. The area was drained by "lagoonward facing" drainage channels.

This kind of environment seems to have been particularly well developed in mid and central Lincolnshire where there is evidence of barrier island formation. It could be, therefore, that such deposits are only properly developed behind the protection of an emergent barrier.

V.8.c.ii. Windward Features: These tend to be found in the higher parts of the Sleaford Member and the Creeton Member; they almost invariably rest upon lee-barrier features. The environment is characterised by large-scale, cross-bedded units that represent complex bars and large spillovers (sensu Ball, 1967). These features, which are perhaps only moved or significantly added to during storms, provide the main "protective barrier", upon which the sea's energy was dissipated. Although there is a predominance of landward-facing structures, some of the bars and spillovers and their parasitic mega-ripples faced seaward, reflecting ebb and flood current activity. Longshore currents also exerted a degree of influence on sedimentation. This complex pattern, typified by the Creeton Member sequences of south Lincolnshire, is parallelled in some modern Bahaman environments (cf. Ball, 1967, fig. 9.).

It is in this windward belt that the upward growth and emergence of the barrier probably occurred, for the supratidal "barrier island" deposits of central Lincolnshire rest upon a seaward-facing bar.

V.8.c.iii. Barrier-Lagoon Relationships: The degree of emergence and lateral continuity of a barrier control the degree of lagoonal restriction. In the case of the Lincolnshire Limestone barrier both faunal and sedimentological criteria have enabled the degree of restriction to be qualitatively assessed.

It has become apparent from this analysis that quite significant contact existed between the lagoon and the "open" epeiric sea, because stenohaline marine benthonic organisms occur even in the most "lagoonal" sediments (e.g. Leadenham Member). Although the Bajocian climate may have contributed to the maintenance of marine salinities (balance of evaporation with rainfall and run-off), it is the barrier-inlets and over-barrier current activity that is probably the primary reason for the marine or near-marine salinities. Despite this, circulation must have been restricted for "true" lagoonal sediments (lime muds with stable *in situ* benthonic faunas), like those of the Leadenham Member, to have been developed. In general, however, such sediments are concentrated in central

Lincolnshire, where there is evidence of the barrier's emergence and a general absence of barrier-inlets. In more southerly areas, where the discontinuous and submergent barrier existed, the back-barrier sediments are dominated by "lagoonal oolites", which reflect more open circulation and greater agitation.

Central Lincolnshire therefore probably had a distinctive land-sea profile, with a restricted lagoon passing seaward into emergent barrier islands. In contrast, south Lincolnshire probably had a submergent barrier with far more open sea-lagoon interchange and consequently a more agitated lagoonal environment.

V.8.c.iv. Deposition Seaward of the Barrier-complex: The upward truncation of the Lincolnshire Limestone, resulting from intra-Jurassic movements, has removed an unknown amount of Bajocian sediments from the East Midlands succession. Therefore the nature of the sediments seaward of the barrier remain unknown, except for the Ancaster region, where an ebb-tidal delta (Creeton Member) developed at the seaward mouth of the Ancaster barrier-inlet. This may have been a complex delta fed by the Great Ponton inlet as well.

V.8.d. Environmental Model.

The facies of the Lincolnshire Limestone represent a barrier shoreline, the low-lying hinterland (to the west), fringed by tidal flats, passed out into a broad, lagoonal area that was bordered on its seaward (east) side by a partly emergent barrier-complex. The barrier was transversed by inlets, at least one of which (Ancaster) developed a significant ebb-tidal delta at its seaward mouth. A reconstruction of this environmental setting is shown in figure 5.9. As the Lincolnshire Limestone succession shows the barrier-complex facies superpositioned upon the lagoonal and tidal-flat deposits the formation as a whole records a marine transgression.

V.8.e. Discussion.

The complexity of the lagoonal facies, especially with the erosive event at the base of the Lincolnshire Member destroying one regime and initiating another, raises the problem of whether this model (i.e. one barrier and its lagoon) is sufficient to explain the depositional conditions throughout the whole of the Lincolnshire times. Alternative models might have the erosive base of the Lincoln Mamber representing:

(1) the breakdown of an initial barrier; the erosive base and basal oolite of the Lincoln Member reflect marine reworking before the evolution of another barrier, or

(2) the landward migration of the early barrier right across the lagoon; no barrier sediments are represented in this case but the erosive base of the Lincoln Member marks the barrier's migration.

In each case a subsequent barrier evolved to "protect" the later lagoons (ovalis Subzone age sediments). The evidence discussed earlier (see especially section V.4.b.ii.) suggests that neither of these alternatives really fit the evidence and that a one barrier/ lagoon system probably did persist throughout the entire Lincolnshire Limestone period of deposition.

CHAPTER VI

CONCLUSIONS.

VI.1. RESUME OF AIMS.

The principal objectives of this research project have been to develop a coherent, formalised lithostratigraphy for the Lincolnshire Limestone Formation, and to determine the nature of the environments in which it was deposited. During the course of this work, significant new ammonite discoveries were made which prompted the revision of all the ammonites known to have been recovered from the Lincolnshire Limestone. In the light of this revision, their stratigraphical significance has been re-assessed. Three main lines of research have therefore been pursued: biostratigraphy, lithostratigraphy and facies analysis. The principal conclusions derived from each of these fields have been pinpointed in the following sections, and a brief comment has been made on the areas that are most likely to be profitable for future research.

VI.2. BIOSTRATIGRAPHY: CONCLUSIONS.

New ammonite discoveries made during the course of this research stimulated a review of the ammonite faunas of the Lincolnshire Limestone. In addition to re-examining all the recorded specimens (determined from an exhaustive literature search), which were still available, the identification of other museum specimens, not previously included in the literature, has also been revised. (The taxonomic part of this work was mostly carried out by Dr.C.F. Parsons). Finally all the specimens have been assigned to their respective unit of the newly proposed lithostratigraphy in order better to assess their significance in dating the formation. The major results of this work have been itemised below.

(1) The prevailing belief that most of the Lincolnshire Limestone was of *discites* Zone age (Kent, 1966; and Senior and Earland-Bennett, 1973) has been repudiated. There are at least three distinct ammonite faunas in the formation that are indicative of the *discites* Zone, and both the *ovalis* and *laeviuscula* Subzones of the *laeviuscula* Zone.

(2) As no ammonites have been recovered from the lowest lithostratigraphic subdivision (Sproxton Member), the maximum age of the formation is not certainly known. However, ammonites, indicative of a *discites* Zone age, have been collected from horizons immediately above the Sproxton Member right up to the base of the Lincoln Member; this range encompasses the Greetwell and Leadenham Members. The *discites* Zone therefore has a far more restricted range than has previously been considered to be the case. Species of the subgenera *Sonninia* (*Euhoploceras*) and *Hyperlioceras* (*Hyperlioceras*) typify this level.

(3) The basal oolite of the Lincoln Member has yielded a number of ammonites belonging to the subgenera Sonninia (Fissilobiceras), which is indicative of the ovalis Subzone of the laeviuscula Zone. The widespread development of this lithostratigraphically important level raises the possibility that it may also form a significant biostratigraphic divide, separating discites and laeviuscula Zone age rocks.

(4) The occurrence of other Sonninia (Fissilobiceras) specimens at higher levels, notably near the top of the Castle Bytham Member (upper Lincolnshire Limestone), suggests that the ovalis Subzone of the laeviuscula Zone may range up to the base of the Sleaford Member; this would encompass all the members lying between the bases of the Lincoln and Sleaford Members (Fig. 2.2.).

(5) Only one ammonite has been recorded from horizons higher than the Castle Bytham Member: the Shirbuirnia cf. fastigata, which was recorded from the lower part of the Sleaford Member at Castle Bytham. This ammonite is indicative of the laeviuscula Subzone of the laeviuscula Zone. The occurrence in the Castle Bytham succession of two ammonites, indicative of the two subzones of the laeviuscula Zone, approximately two metres apart and astride the base of the Sleaford Member, suggests that this horizon marks an important biostratigraphical level. Further evidence is obviously needed in order to verify or refute this suggestion. However, if correct, it would mean that both major stratigraphical divides are also important biostratigraphical divisions.

(6) The upper part of the Sleaford Member and the whole of the Creeton Member have so far failed to yield any ammonites. The minimum age of the formation therefore remains in doubt.

For the first time it has been conclusively demonstrated that the Lincolnshire Limestone Formation can be subdivided on the basis of its ammonite faunas. It is also now known to span not only the discites Zone but both of the subzones of the laeviuscula Zone too. On present evidence it appears that the major biostratigraphical divides may coincide with important lithostratigraphical boundaries.

VI.3. LITHOSTRATIGRAPHY: CONCLUSIONS.

Detailed logging of all the available Lincolnshire Limestone sections within Lincolnshire (and neighbouring Leicestershire) has shown that the stratigraphy proposed by Kent (1966) is untenable. It has therefore been replaced with the revised lithostratigraphic scheme detailed in chapter four. The principal characteristics of the new scheme, which has been erected along the guidelines suggested by Hedberg (1976), have been outlined below:

(1) In Lincolnshire it has been possible to subdivide the Lincolnshire Limestone Formation into eleven members. A number of these (Greetwell, Leadenham and Lincoln) also have distinct sub-divisions of their own, which have either been designated formally or informally depending on the criteria upon which they have been established. Apart from the Lindsey Shale Member (= Kirton Cement Shale) none of the new units correspond precisely to any of the sub-divisions suggested by Kent (1966), and therefore a new terminology has also been introduced to denote the new stratigraphic units.

(2) The six oldest members (Sproxton, Greetwell, Leadenham, Lincoln, Scottlethorpe and Lindsey Shale) constitute the lower Lincolnshire Limestone, while the younger five (Castle Bytham, Metheringham, Blankney, Sleaford and Creeton) compose the upper Lincolnshire Limestone. The upper/lower divisions broadly correspond

to the Upper/Lower Lincolnshire Limestone subdivisions of earlier terminologies.

(3) In South Humberside the lower part of the formation has a different stratigraphical succession to that seen further south. The details of this northern sequence have already been reported (Ashton, 1975). The Northamptonshire area awaits detailed examination.

Although many new interpretations have been forwarded in the revised lithostratigraphic scheme, the most notable new discoveries have been:

(1) The recognition of two distinct levels that permit county-wide correlation. These are the erosive bases of the Lincoln and Sleaford Members.

(2) The base of the Lincoln Member is considered to be of fundamental importance in the understanding of the internal relationships of the formation, and it has been adopted as the datum level for all lithostratigraphic correlations. The recognition of its probable biostratigraphic significance has compounded its importance. Neither this specific horizon nor the Lincoln Member as a whole, have been recognised previously.

(3) In addition to its correlative value, it is now realised that the base of the Sleaford Member is responsible for the major down-cutting seen within the Lincolnshire Limestone. There has rarely been any significant erosion at the lower/upper Lincolnshire Limestone contact.

(4) The Sproxton Member which is the basal unit of the formation in south Lincolnshire was found not to have been developed over much of central Lincolnshire. The lowest part of the formation becomes progressively attenuated towards Lincoln, where a "condensed"

Greetwell Member sequence is seen, There is no uniformly developed basal unit in the Lincolnshire Limestone, as was previously thought (the old "Blue Beds", cf. Kent, 1966, fig.1).

The major differences between the new stratigraphic scheme and that proposed by Kent (1966, fig.1) are (this list excludes differences attributable solely to the adoption of a formalised approach to litho-stratigraphy):

(1) The "Blue Beds", which were thought to have been a ubiquitously developed basal unit, have been shown to belong to two separate stratigraphic levels. In south Lincolnshire, where they do form the base of the formation, they have been included in the Sproxton Member, while in central Lincolnshire they constitute an internal subdivision of the Greetwell Member, the Wragby Bed. This does not occur at the base of the formation.

(2) The recognition of the fundamentally important Lincoln Member has enabled the following stratigraphic re-alignments to be made:

a) The "Cementstones" are now known not to form a single unit across the whole county; the "Cementstones-facies" rocks have been shown to belong in two separate stratigraphic units that are always divided by the basal oolite of the Lincoln Member. The Leadenham Member constitutes the older "Cementstones-facies" unit, while the younger forms the Ropsley Beds, which are part of the Lincoln Member.

b) The "Crossi Beds" do not form a coherent unit. In south Lincolnshire they have been shown to form part of the Scottlethorpe Member, while in central Lincolnshire the "Lower Crossi Bed" has been demonstrated to be an integral part of the Lincoln Member. The "Upper Crossi Bed" has been incorporated in the Metheringham Member.

c) The Scottlethorpe and Lindsey Shale Members are now understood to be lateral equivalents, as they have been shown to interdigitate at Harmston. This shows that the Kirton Cement Shale should have been included in the "Lower" rather than the "Upper Lincolnshire Limestone".

(3) The Cathedral Beds, which form a distinctive and laterally traceable subdivision of the Leadenham Member, have not previously been recognised.

(4) The "Upper Lincolnshire Limestone" can be subdivided to a far greater extent than has previously been recognised. The erosive base of the Sleaford Member forms a natural bipartite division, the lower part of which is made up of the Metheringham, Blankney and Castle Bytham Members. None of these has previously been recognised as separate member The Sleaford and Creeton Members compose the upper part.

(5) The Sleaford Member encompasses the "Ancaster Freestone" of Ancaster and the "Great Ponton Gastropod Beds". The re-alignment of the "Gastropod Beds" with the "Ancaster Freestone" contradicts the theory recently proposed by Kent (in Swinnerton and Kent, 1976), suggesting that the "Ancaster Rag" was equivalent to the "Great Ponton Gastropod Beds".

(6) The Sleaford Member is responsible for the major erosive downcutting seen in the formation. The degree of downcutting is far greater than previously thought because the more precise subdivision of the upper Lincolnshire Limestone has shown that at Ancaster, for example, the Metheringham and Blankney Members have been removed as well as all the lower Lincolnshire Limestone as far down as mid-Lincoln Member. A similar degree of downcutting is seen at Great Ponton (Fig.2.2.).

(7) The topmost part of the formation, the Creeton Member, encompasses the "Ancaster Rag" of Ancaster, the "Great Ponton *Terebratula* Beds" (this contradicts Kent's suggestion, see point 5 above) and the "Clipsham Stone". No sound evidence is thought to exist for suggesting that the "Great Ponton *Terebratula* Beds" are younger than the rest of the Lincolnshire Limestone.

VI.4. CARBONATE ENVIRONMENTS: CONCLUSIONS.

The analysis of the Lincolnshire Limestone facies presented in the previous chapter represents the first real attempt at interpreting the depositional environments of the formation. Although palaeogeographic interpretations have been hampered by the compressed E-W distribution of outcrops, the nature of the facies in vertical sequence has enabled many sub-environments to be recognised, and an overall environmental model to be proposed. The main results of the environmental interpretation have been itemised below:

(1) The Lincolnshire Limestone Formation as a whole represents a transgressive sequence with off-shore barrier-complex sediments resting upon near-shore "lagoonal" and tidal-flat deposits.

(2) The basic environmental model involves an inferred western shore, bordered by tidal flats, which passed out into a broad "lagoonal" area that was protected by an off-shore barrier-complex. Inlets through the barrier provided open connections with the East Midlands epeiric sea (see Fig. 5.9.).

(3) Environmentally, the base of the formation was split into southern and central Lincolnshire provinces:

a) The southern province: a sequence of regressive rhythms are represented in the Sproxton and Greetwell Members' sequences. Each rhythm reflects tidal-flat progradation into a shallow, subtidal, protected "lagoonal" area. The rhythms are thought to have been initiated/terminated by a transgression, which resulted from a period of accelerated subsidence. In this area therefore, subsidence proceeded inaa series of episodic "jerks". Changes in the nature of successive rhythms suggest that the transgressions were increasingly successful.

b) The central province: this area is stratigraphically condensed in its lower part; the Sproxton Member and part of the Greetwell Member are completely absent. This is thought to be due to the effects of the "Lincoln High", that acted as a positive area during this period. After finally being overwhelmed by the Lincolnshire Limestone transgression, the gradual subsidence of the "High" produced a mosaic of relatively low-energy, but agitated facies (Greetwell Member), which finally gave way to "true" lagoonal (lime mud) deposition (Leadenham Member).

(4) The "polarised" sedimentation pattern was subsequently destroyed at the onset of Lincoln Member times. The erosive base of this unit is thought to represent a shoreward advance (storm induced ?) of the barrier-complex across the lagoon (the member's basal oolite is similar to the "high-energy back-barrier oolites" of the Metheringham and Castle Bytham Members).

(5) Lagoonal sedimentation soon became re-established, and the facies of the Lincoln Member reflect deposition in a variety of back-barrier settings, ranging from muddy lagoonal areas to agitated oolite shoals. This kind of low-energy sedimentation persisted throughout the ensuing period when the Scottlethorpe Member was deposited. The Lindsey Shale probably reflected an influx of fine

clastics southwards into this back-barrier setting.

(6) The "better-washed" oolites of the Metheringham and Castle Bytham Members reflect the more agitated conditions immediately behind the barrier.

(7) The overlying Sleaford and Creeton Members represent the barrier-complex itself. It has been possible, to some extent, to distinguish between the sub-environments of the lee and windward sides of the barrier.

(8) The principal sub-environments of the barrier-complex recognised in the Sleaford Member are: barrier-inlets, barrier-island sediments (evidence of emergence), complex on-barrier bars, lee-barrier rhythms and on-barrier drainage channels.

(9) The principal sub-environments of the barrier-complex recognised in the Creeton Member are: an ebb-tidal delta in the Ancaster region and large spillover lobe structures.

In the most general terms therefore three major environments have been recognised: tidal flats, lagoonal (in which the energy conditions were very variable), and off-shore barrier-complex. In addition, the recognition of the "Lincoln High" (mini-swell) and its effect on sedimentation during earliest Lincolnshire Limestone times is considered an important " spin-off" discovery of this work.

VI.5. FUTURE WORK.

During the course of this work a number of possible areas, in which future research would prove profitable, have recommended themselves. These can be summarised as:

(1) The taxonomy of all the benthonic faunal groups is in urgent need of revision.

(2) With such revision, faunal analysis would provide greater insight into Jurassic faunal associations in general and the environmental interpretation of the Lincolnshire Limestone facies in particular. The presence of in situ faunas in some members and the general absence of large-scale transportation in many units makes many of the formation's faunas ideal for such studies, especially now a lithostratigraphic framework and environmental model have been devised.

(3) Although significant advances have been made in the biostratigraphy of the formation, the search for ammonites is still considered to be of paramount importance. The minimum and maximum ages of the formation are still to be resolved, and confirmation of many lithostratigraphic correlations are still needed.

(4) The Northamptonshire area requires detailed revision to establish its lithostratigraphic and environmental relationships with the more northerly sequences.

As with all research projects scope remains for further work in certain aspects uncovered during the main study. In the case of the Lincolnshire Limestone the "low-energy oncolites" provides one such field. Above all however, the Lincolnshire Limestone provides an excellent fossil example of a carbonate barrier shoreline. The detailing of the characteristics of the actual barrier-complex would perhaps be more valuable than any other single item of research undertaken in this project.

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THE UNIVERSITY OF HULL

The Stratigraphy and Carbonate Environments of
the Lincolnshire Limestone Formation (Bajocian)
in Lincolnshire and parts of Leicestershire.

VOLUME 2

being a Thesis submitted for the Degree of

Doctor of Philosophy

in the University of Hull

by

Michael Ashton, M.A. (Oxon.)

November, 1977.

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CONTAINS

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CONTENTS (VOLUME 2)

CHAPTER I

INTRODUCTION

TEXT-FIGURES

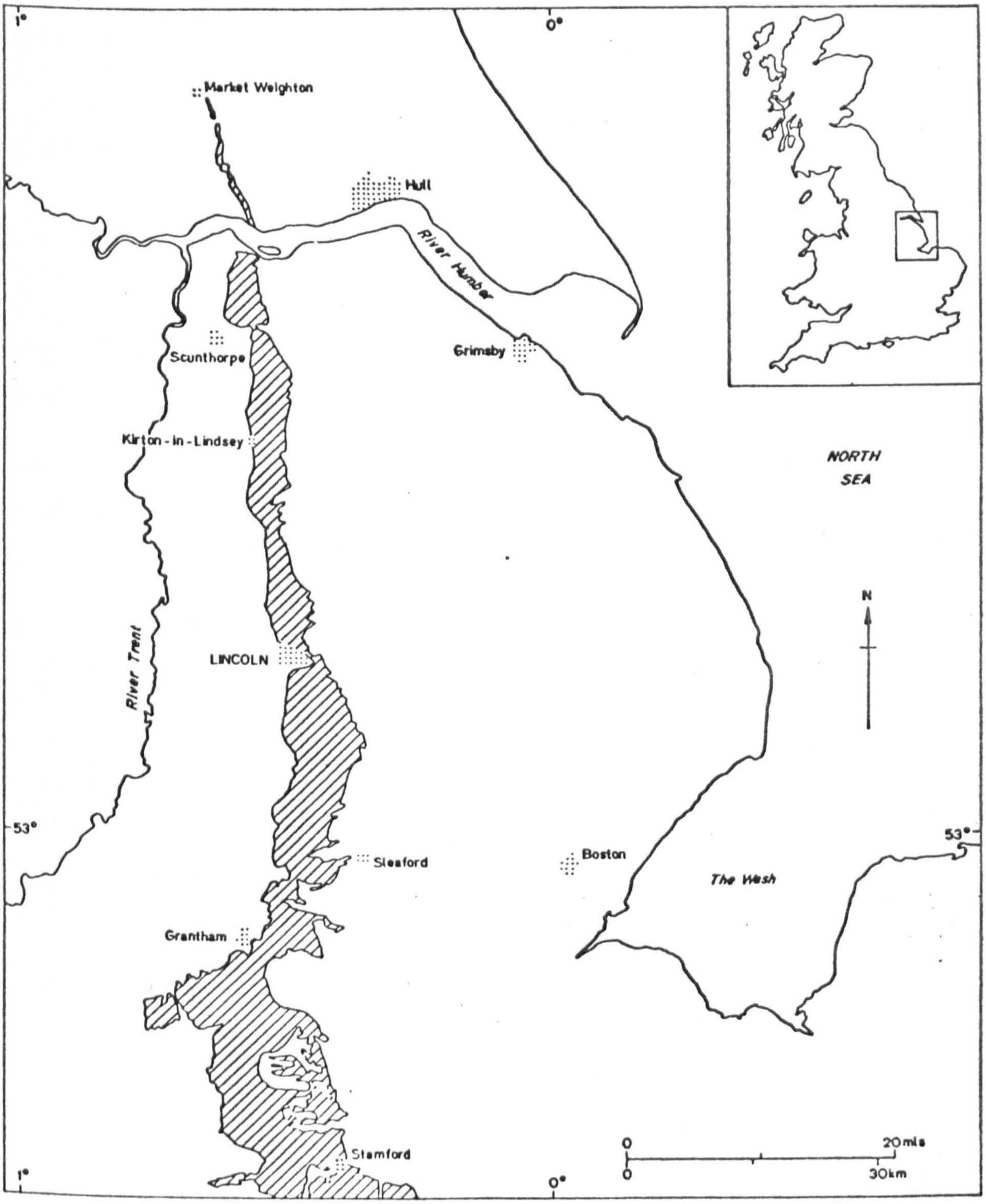
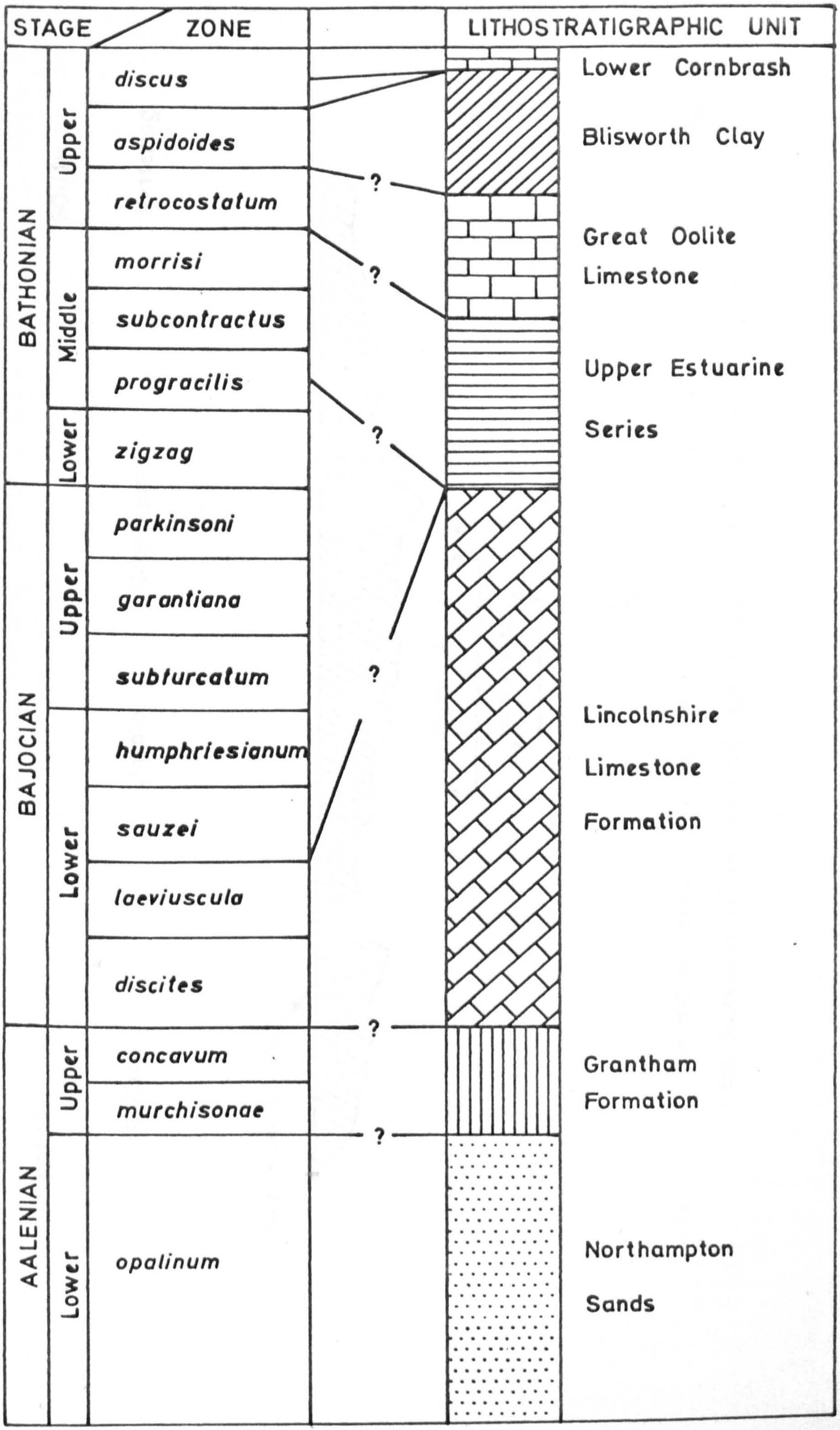


Fig. 1.1. The distribution of the Aalenian/Bajocian rocks (cross-hatched) in eastern England.

Fig. 1.2. The generalised Middle Jurassic succession of the East Midlands. (compiled from Ashton, 1976; Ashton and Parsons, in prep.; Kent, 1975b; Parsons, 1974a, 1976a, 1976b, and personal communication; Sylvester-Bradley, 1968; and Torrens, 1968.)


STAGE
ZONE
LITHOSTRATIGRAPHIC UNIT
BATHONIAN
Upper
discus
aspidoides
retrocostatum
Middle
morrisi
subcontractus
progracilis
Lower
zigzag
BAJOCIAN
Upper
parkinsoni
garantiana
subfurcatum
Lower
humphriesianum
sauzei
laeviuscula
discites
AALENIAN
Upper
concavum
murchisonae
Lower
opalinum
?
?
?
?
?
?
Lower Cornbrash
Blisworth Clay
Great Oolite Limestone
Upper Estuarine Series
Lincolnshire Limestone Formation
Grantham Formation
Northampton Sands

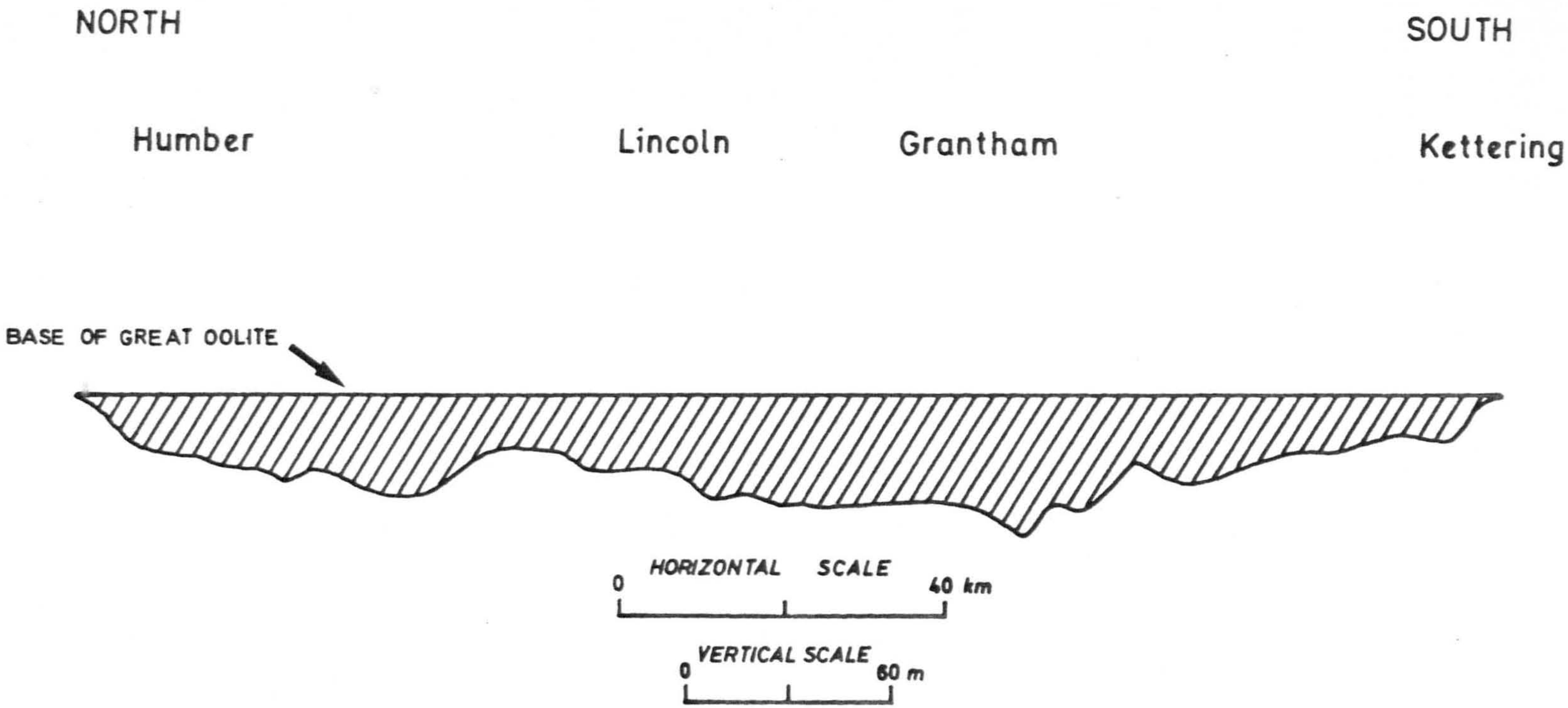


Fig. 1.3. A generalised cross-section through the Lincolnshire Limestone Formation, illustrating its lenticular nature (amended from Swinnerton and Kent, 1976, fig. 9).

Fig. 1.4. Map showing the major thinning trends of the Lincolnshire Limestone Formation. (Principal sources of information : Woodward, 1904, Woodward and Thompson, 1909; Whitaker, 1922; and Evans, 1952.)

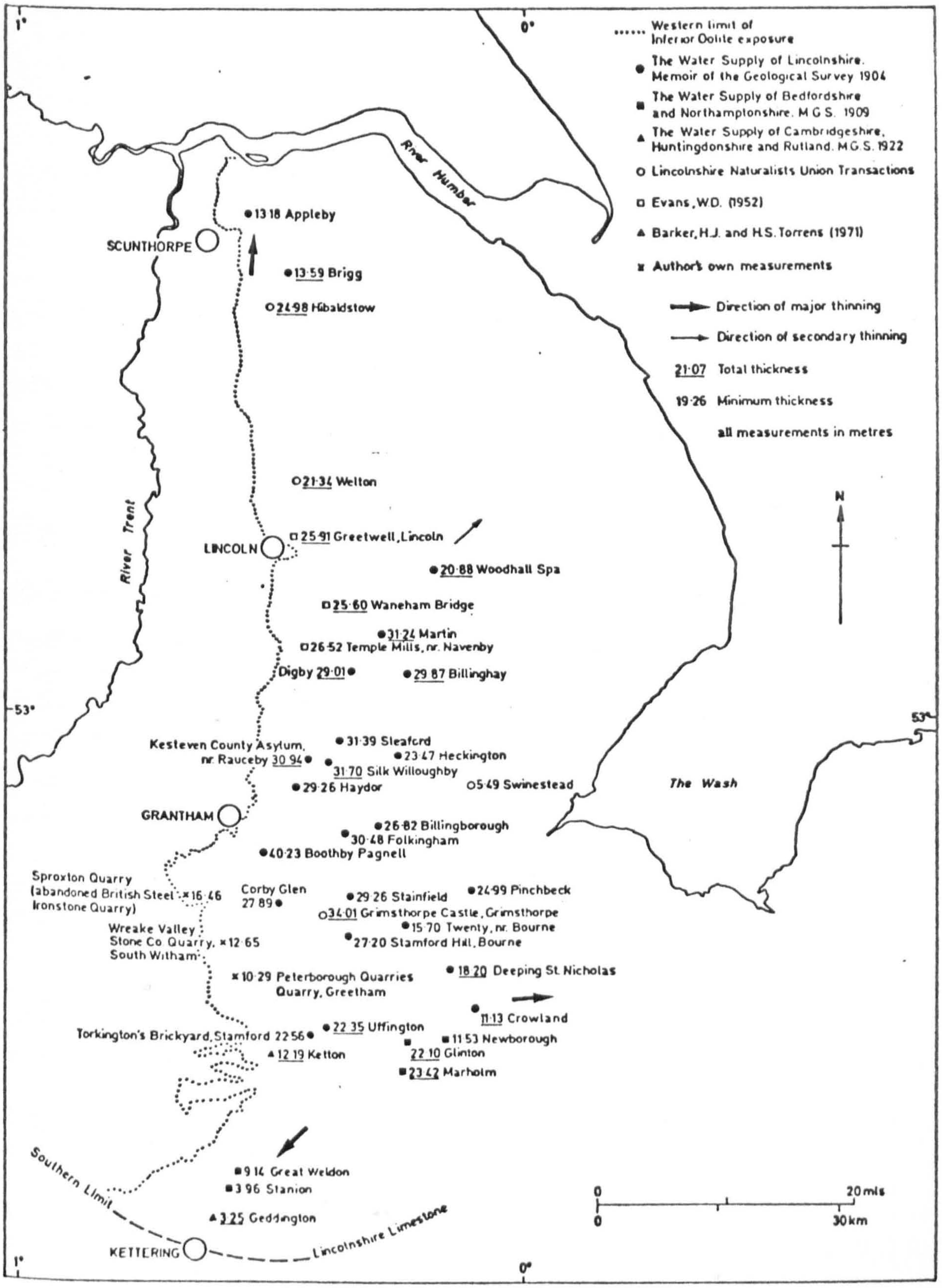

Western limit of Inferior Oolite exposure
The Water Supply of Lincolnshire. Memoir of the Geological Survey 1904
The Water Supply of Bedfordshire and Northamptonshire. M.G.S. 1909
The Water Supply of Cambridgeshire, Huntingdonshire and Rutland. M.G.S. 1922
Lincolnshire Naturalists Union Transactions
Evans, W.D. (1952)
Barker, H.J. and H.S. Torrens (1971)
Author's own measurements
Direction of major thinning
Direction of secondary thinning
21·07 Total thickness
19·26 Minimum thickness
all measurements in metres
River Humber
River Trent
SCUNTHORPE
LINCOLN
GRANTHAM
KETTERING
The Wash
13·18 Appleby
13·59 Brigg
24·98 Hibaldstow
21·34 Welton
25·91 Greetwell, Lincoln
20·88 Woodhall Spa
25·60 Waneham Bridge
31·24 Martin
26·52 Temple Mills, nr. Navenby
Digby 29·01
29·87 Billinghay
31·39 Sleaford
Kesteven County Asylum, nr. Rauceby 30·94
23·47 Heckington
31·70 Silk Willoughby
29·26 Haydor
5·49 Swinestead
26·82 Billingborough
30·48 Folkingham
40·23 Boothby Pagnell
Sproxton Quarry (abandoned British Steel Ironstone Quarry) 16·46
Corby Glen 27·89
29·26 Stainfield
24·99 Pinchbeck
34·01 Grimsthorpe Castle, Grimsthorpe
15·70 Twenty, nr. Bourne
27·20 Stamford Hill, Bourne
Wreake Valley Stone Co Quarry, South Witham 12·65
10·29 Peterborough Quarries Quarry, Greetham
18·20 Deeping St. Nicholas
11·13 Crowland
Torkington's Brickyard, Stamford 22·56
22·35 Uffington
11·53 Newborough
12·19 Ketton
22·10 Glinton
23·42 Marholm
9·14 Great Weldon
3·96 Stanion
3·25 Geddington
Southern Limit Lincolnshire Limestone
N
1°
0°
53°
0
20 mls
30 km

Fig. 1.5. Correlation chart for the Aalenian and Bajocian successions of the Cotswolds, East Midlands and Yorkshire Basins, and the "Oxford Shallows". (compiled from Kent, 1975b; Knox, 1973a; Parsons, 1976a and 1977; and Sylvester-Bradley, 1968.)

Stage	Substage	ZONES	LITHOLOGICAL UNITS: COTSWOLDS	OXFORDSHIRE	EAST MIDLANDS	YORKSHIRE
BAJOCIAN	UPPER	*parkinsoni*	*Clypeus* Grit Upper Coral Bed	*Clypeus* Grit		? Scalby Formation
		garantiana	Upper *Trigonia* Grit			
		subfurcatum				
	LOWER	*humphriesianum*				Scarborough Formation
		sauzei	*Heimia phillipsiana* and *Bourguetia* Beds		?	Cloughton ? Formation
		laeviuscula	*Witchellia* Grit Notgrove – Freestone Gryphite & *L. buckmani*-Grit		Lincolnshire Limestone Formation	
		discites	Lower *Trigonia* Grit			? Eller Beck Formation
AALENIAN		*concavum*	Tilestone ? Snowshill Clay Harford Sands		? Grantham Formation	? Saltwick Formation ?
		murchisonae	Upper-Freestone ? Oolite – Marl	?		Dogger Formation
		opalinum	Scissum Beds		? Northampton Sands	

STAGE	North of Market Weighton	South of Market Weighton	North Lincolnshire
BATHONIAN	Upper Deltaic Series	Upper Estuarine Series	Upper Estuarine Series
BAJOCIAN	Grey Limestone Series		*missing*
	Upper Middle Deltaic Series		
	Yons Nab Beds/Upper Limestone Millepore Oolite/Whitwell Oolite	Cave Oolite	Hibaldstow Oolite Kirton Shale & *Acanthothyris crossi*
	Lower Middle Deltaic Series	Basement Beds	Kirton Cementstone Series
	Hydraulic Limestone/Eller Beck Bed	Hydraulic Limestone	Blue & Silver Beds
	Lower Deltaic Series	Lower Estuarine Series	Lower Estuarine Series
	Dogger	*missing*	Northampton Sand

Fig. 1.6. Correlation of the "Bajocian" (including Aalenian) successions of Yorkshire and North Lincolnshire proposed by Bate (1967, table 3).

Fig. 1.7. The subdivisions of the "Inferior Oolite" of North Lincolnshire and the Lincoln district proposed by Ussher (compiled from Ussher *et al.*, 1888 and Ussher, 1890).

Fig. 1.8. The broad groupings of the lithostratigraphical subdivisions of the Lincolnshire Limestone proposed by Woodward (1894, p.174).

<table>
<tr><th colspan="4">USSHER 1888</th><th colspan="3">USSHER 1890</th></tr>
<tr><td rowspan="7">INFERIOR OOLITE</td><td rowspan="4">Lincolnshire Limestone</td><td rowspan="2">Equivalents of the Ponton Series</td><td>Grey Limestone</td><td rowspan="2">Hibaldstow Beds</td><td rowspan="4">Lincolnshire Limestone</td><td rowspan="7">INFERIOR OOLITE</td></tr>
<tr><td rowspan="2">Semi - oolitic Beds</td></tr>
<tr><td rowspan="2">Equivalents of the Kirton Beds</td><td rowspan="2">Kirton Beds</td></tr>
<tr><td>Hydraulic Limestone Series</td></tr>
<tr><td rowspan="3">Basement Beds</td><td colspan="2">? missing</td><td>Hydraulic Limestone</td><td rowspan="3">Basement Beds</td></tr>
<tr><td colspan="2">Lower Estuarine Series</td><td>Lower Estuarine Sand and Clay</td></tr>
<tr><td colspan="2">Northampton Sands</td><td>Dogger</td></tr>
<tr><td colspan="4">LINCOLN DISTRICT</td><td colspan="3">NORTH LINCOLNSHIRE</td></tr>
</table>

<table>
<tr><td rowspan="4">LINCOLNSHIRE LIMESTONE</td><td>Ponton Upper Shelly beds; Wansford, Ketton, Stamford, Casterton, Clipsham, Castle Bytham, and Ancaster Freestones; Hibaldstow Beds</td></tr>
<tr><td>Ponton oolite and gasteropod-bed; Houghton freestone; Stamford Marble; Weldon freestone & shell beds; Kirton clay-bed</td></tr>
<tr><td>Barnack Rag; Lincoln silver-bed; Kirton Beds</td></tr>
<tr><td>Collyweston Slate; Whittering Pendle</td></tr>
</table>

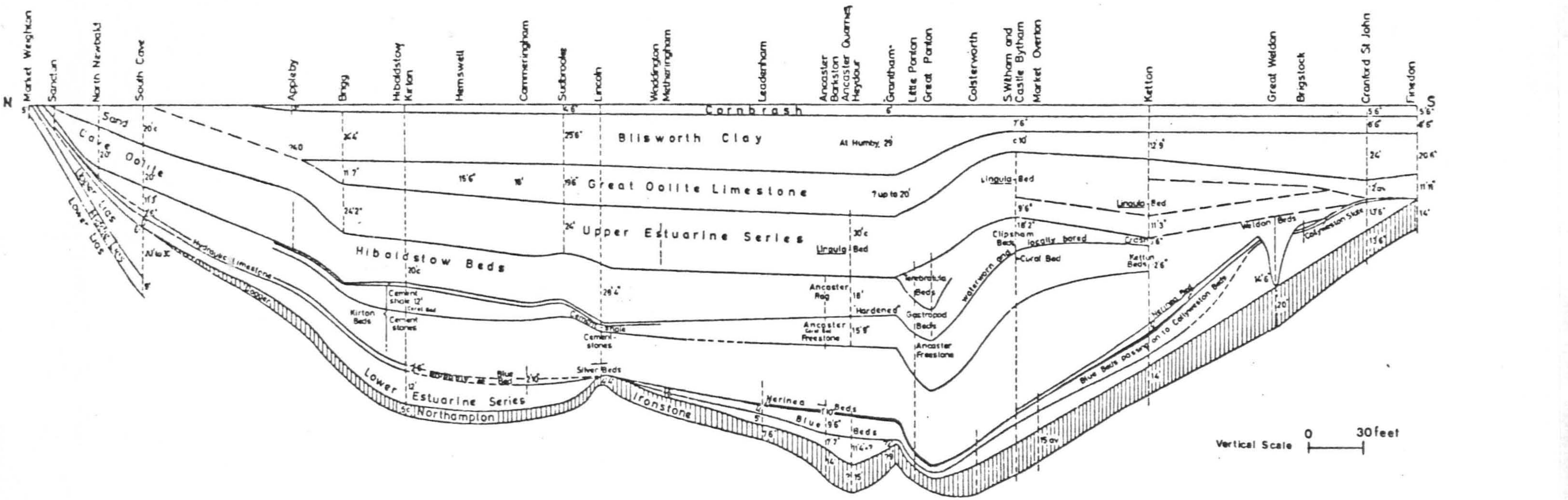


Fig. 1.9. Correlation of the Middle Jurassic of the Midlands according to the late L. Richardson. Although originally drafted in 1939, the diagram was not published until 1968, after Richardson's death (am ended from Sylvester-Bradley, 1968, fig. 42).

CHAPTER II

THE STRATIGRAPHY OF THE LINCOLNSHIRE LIMESTONE FORMATION : GENERAL CONSIDERATIONS

TEXT-FIGURES

Fig. 2.1. Location map for the Lincolnshire Limestone sections measured during this study (the code for each quarry is shown in brackets).

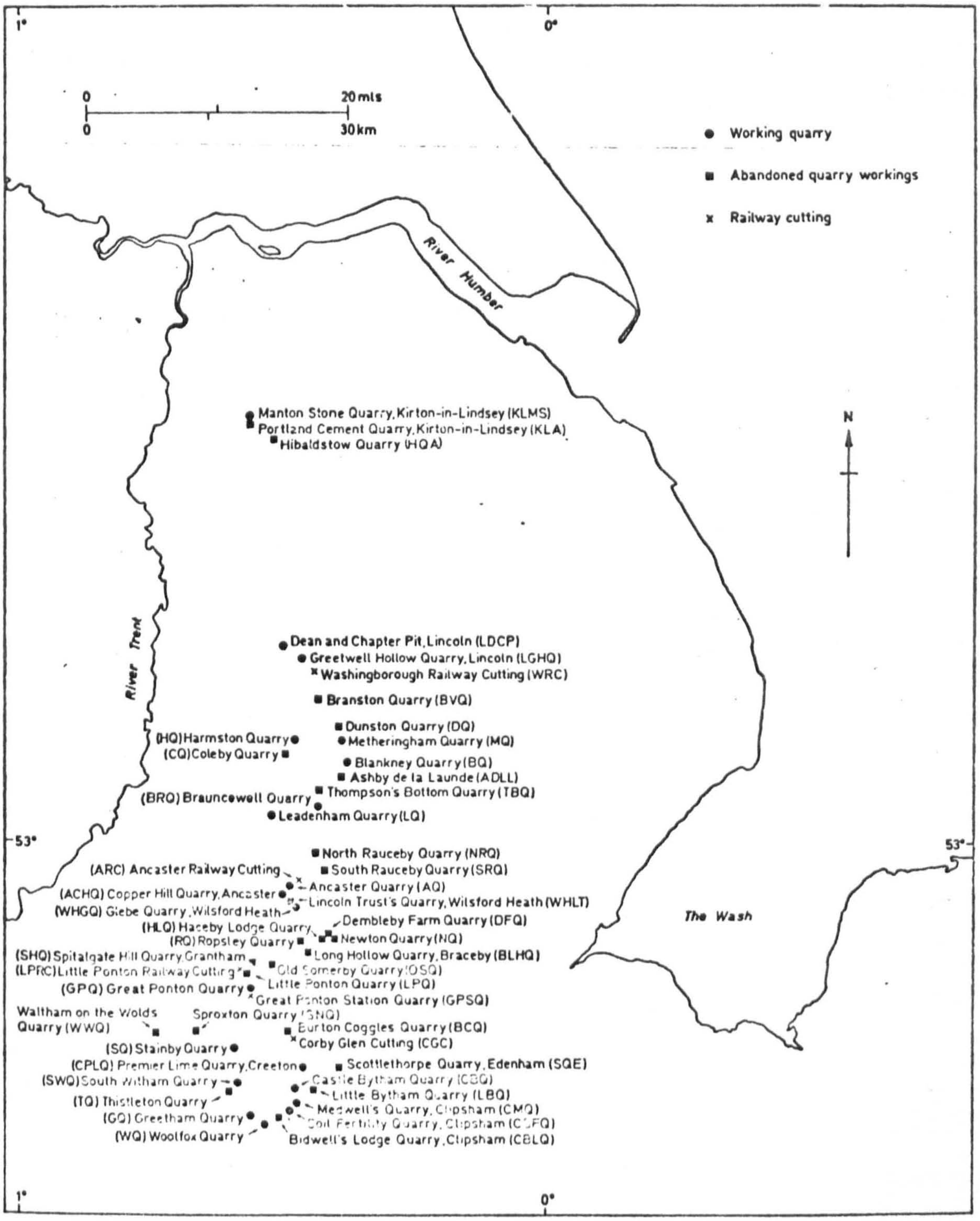

1°
0°
0
20 mls
0
30 km
Working quarry
Abandoned quarry workings
Railway cutting
River Humber
N
Manton Stone Quarry, Kirton-in-Lindsey (KLMS)
Portland Cement Quarry, Kirton-in-Lindsey (KLA)
Hibaldstow Quarry (HQA)
River Trent
Dean and Chapter Pit, Lincoln (LDCP)
Greetwell Hollow Quarry, Lincoln (LGHQ)
Washingborough Railway Cutting (WRC)
Branston Quarry (BVQ)
Dunston Quarry (DQ)
(HQ) Harmston Quarry
Metheringham Quarry (MQ)
(CQ) Coleby Quarry
Blankney Quarry (BQ)
Ashby de la Launde (ADLL)
Thompson's Bottom Quarry (TBQ)
(BRQ) Brauncewell Quarry
Leadenham Quarry (LQ)
53°
53°
North Rauceby Quarry (NRQ)
South Rauceby Quarry (SRQ)
(ARC) Ancaster Railway Cutting
Ancaster Quarry (AQ)
(ACHQ) Copper Hill Quarry, Ancaster
Lincoln Trust's Quarry, Wilsford Heath (WHLT)
(WHGQ) Glebe Quarry, Wilsford Heath
The Wash
(HLQ) Haceby Lodge Quarry
Dembleby Farm Quarry (DFQ)
(RQ) Ropsley Quarry
Newton Quarry (NQ)
(SHQ) Spitalgate Hill Quarry, Grantham
Long Hollow Quarry, Braceby (BLHQ)
(LPRC) Little Ponton Railway Cutting
Old Somerby Quarry (OSQ)
Little Ponton Quarry (LPQ)
(GPQ) Great Ponton Quarry
Great Ponton Station Quarry (GPSQ)
Waltham on the Wolds
Quarry (WWQ)
Sproxton Quarry (SNQ)
Burton Coggles Quarry (BCQ)
Corby Glen Cutting (CGC)
(SQ) Stainby Quarry
(CPLQ) Premier Lime Quarry, Creeton
Scottlethorpe Quarry, Edenham (SQE)
(SWQ) South Witham Quarry
Castle Bytham Quarry (CBQ)
Little Bytham Quarry (LBQ)
(TQ) Thistleton Quarry
Medwell's Quarry, Clipsham (CMQ)
(GQ) Greetham Quarry
Soil Fertility Quarry, Clipsham (CSFQ)
(WQ) Woolfox Quarry
Bidwell's Lodge Quarry, Clipsham (CBLQ)
1°
0°

Fig. 2.2. Schematic representation of the subdivisions proposed for the Lincolnshire Limestone Formation. (In Figs. 2.2. to 2.8. inclusive, "cross-hatching" indicates "gaps" in the succession.)

L.B.b. = Little Bytham beds (Lincoln Member)

G.F.b. = Greetham Fossil beds (Greetwell Member)

R.B. = Ropsley Beds (Lincoln Member)

B.H.L.M. = Basal Hydraulic Limestone Member

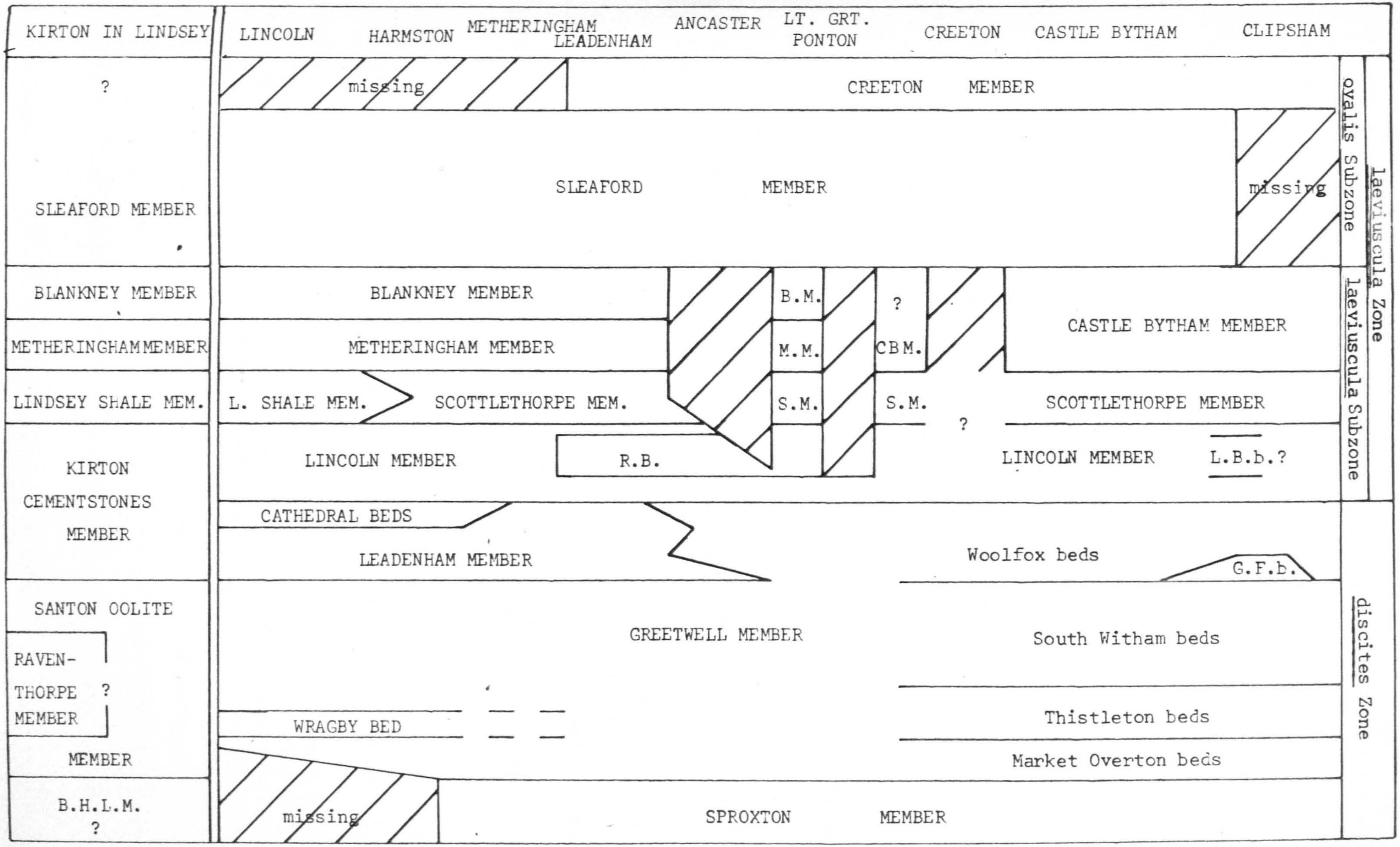
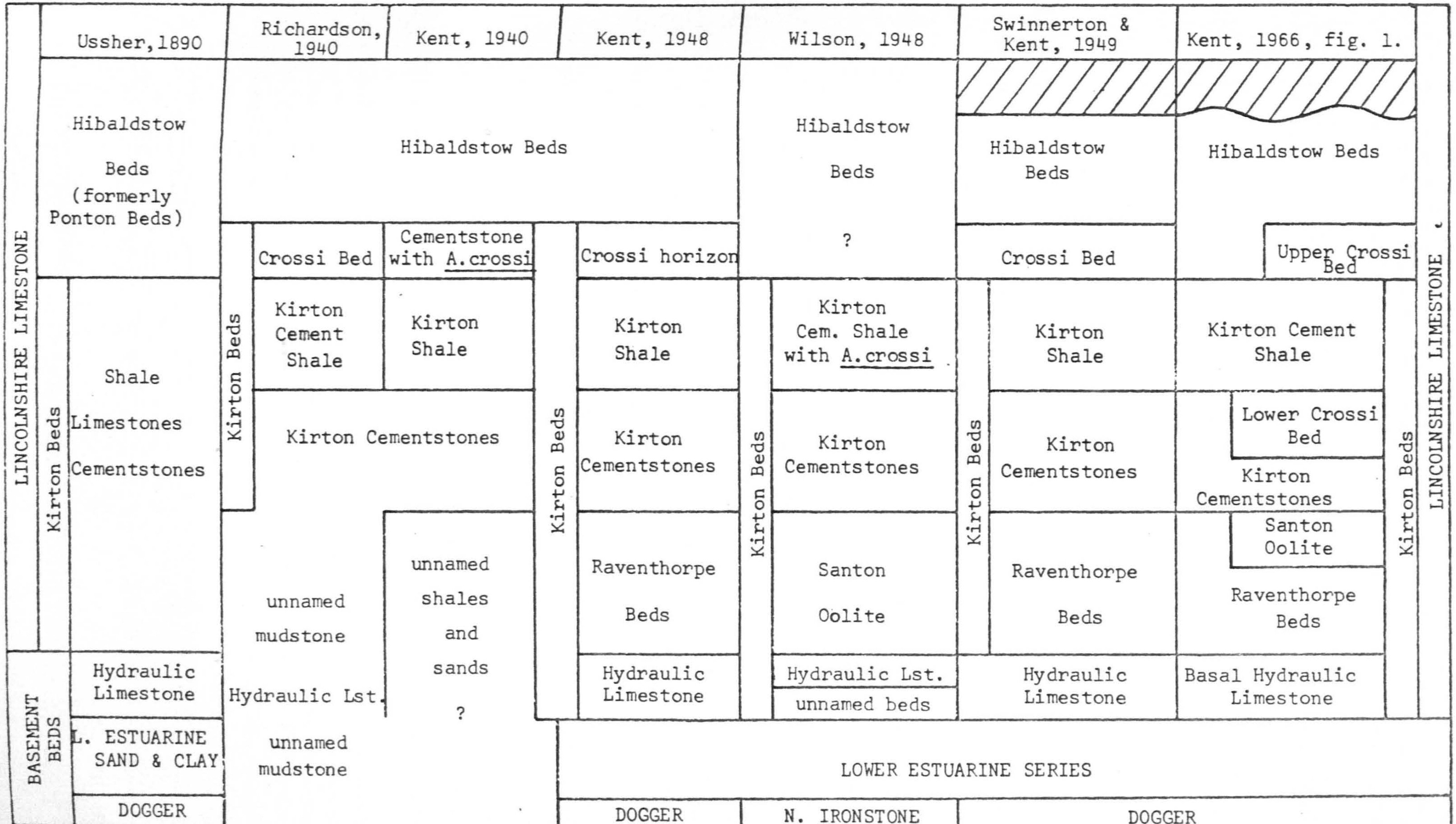

KIRTON IN LINDSEY
LINCOLN
HARMSTON
METHERINGHAM
LEADENHAM
ANCASTER
LT. GRT. PONTON
CREETON
CASTLE BYTHAM
CLIPSHAM
?
missing
CREETON MEMBER
SLEAFORD MEMBER
SLEAFORD MEMBER
missing
oxalis Subzone
laeviuscula Zone
BLANKNEY MEMBER
BLANKNEY MEMBER
B.M.
?
METHERINGHAM MEMBER
METHERINGHAM MEMBER
M.M.
CBM.
CASTLE BYTHAM MEMBER
laeviuscula Subzone
LINDSEY SHALE MEM.
L. SHALE MEM.
SCOTTLETHORPE MEM.
S.M.
S.M.
SCOTTLETHORPE MEMBER
?
KIRTON CEMENTSTONES MEMBER
LINCOLN MEMBER
R.B.
LINCOLN MEMBER
L.B.b.?
CATHEDRAL BEDS
LEADENHAM MEMBER
Woolfox beds
G.F.b.
SANTON OOLITE
RAVEN-THORPE MEMBER
?
GREETWELL MEMBER
South Witham beds
discites Zone
WRAGBY BED
Thistleton beds
MEMBER
Market Overton beds
B.H.L.M.
?
missing
SPROXTON MEMBER

Fig. 2.3. The stratigraphic terminologies formerly proposed for the Lincolnshire Limestone in the South Humberside region.


Ussher, 1890
Richardson, 1940
Kent, 1940
Kent, 1948
Wilson, 1948
Swinnerton & Kent, 1949
Kent, 1966, fig. 1.
LINCOLNSHIRE LIMESTONE
Hibaldstow Beds (formerly Ponton Beds)
Kirton Beds
Shale Limestones Cementstones
BASEMENT BEDS
Hydraulic Limestone
L. ESTUARINE SAND & CLAY
DOGGER
Hibaldstow Beds
Kirton Beds
Crossi Bed
Kirton Cement Shale
Kirton Cementstones
unnamed mudstone
Hydraulic Lst.
unnamed mudstone
Cementstone with A.crossi
Kirton Shale
unnamed shales and sands
?
Kirton Beds
Crossi horizon
Kirton Shale
Kirton Cementstones
Raventhorpe Beds
Hydraulic Limestone
DOGGER
Hibaldstow Beds
?
Kirton Beds
Kirton Cem. Shale with A.crossi
Kirton Cementstones
Santon Oolite
Hydraulic Lst.
unnamed beds
N. IRONSTONE
Hibaldstow Beds
Crossi Bed
Kirton Beds
Kirton Shale
Kirton Cementstones
Raventhorpe Beds
Hydraulic Limestone
Hibaldstow Beds
Upper Crossi Bed
Kirton Cement Shale
Lower Crossi Bed
Kirton Cementstones
Santon Oolite
Raventhorpe Beds
Basal Hydraulic Limestone
Kirton Beds
LINCOLNSHIRE LIMESTONE
LOWER ESTUARINE SERIES
DOGGER

020

Fig. 2.4. The stratigraphic terminologies formerly proposed for the Lincolnshire Limestone in the Spital district.

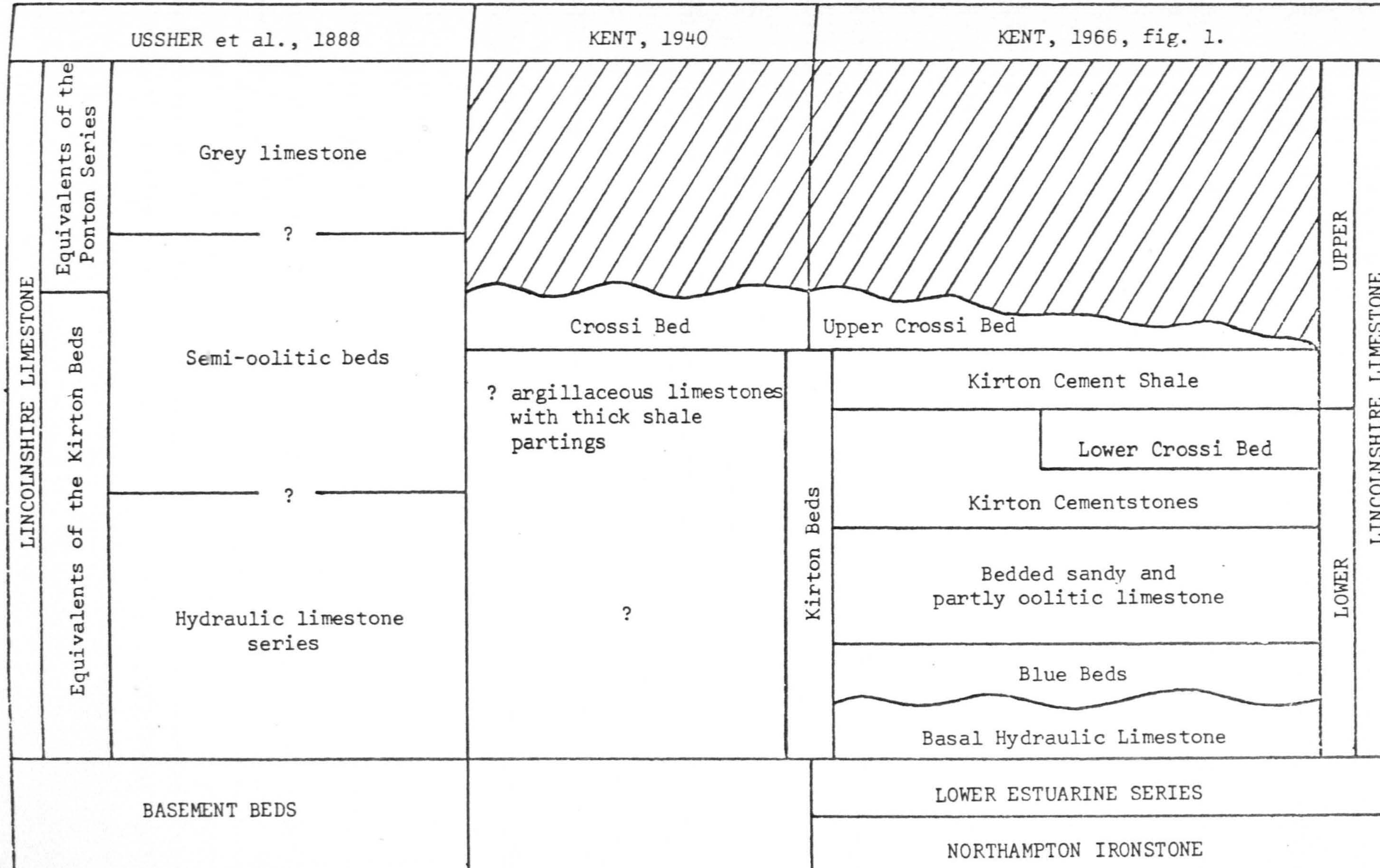
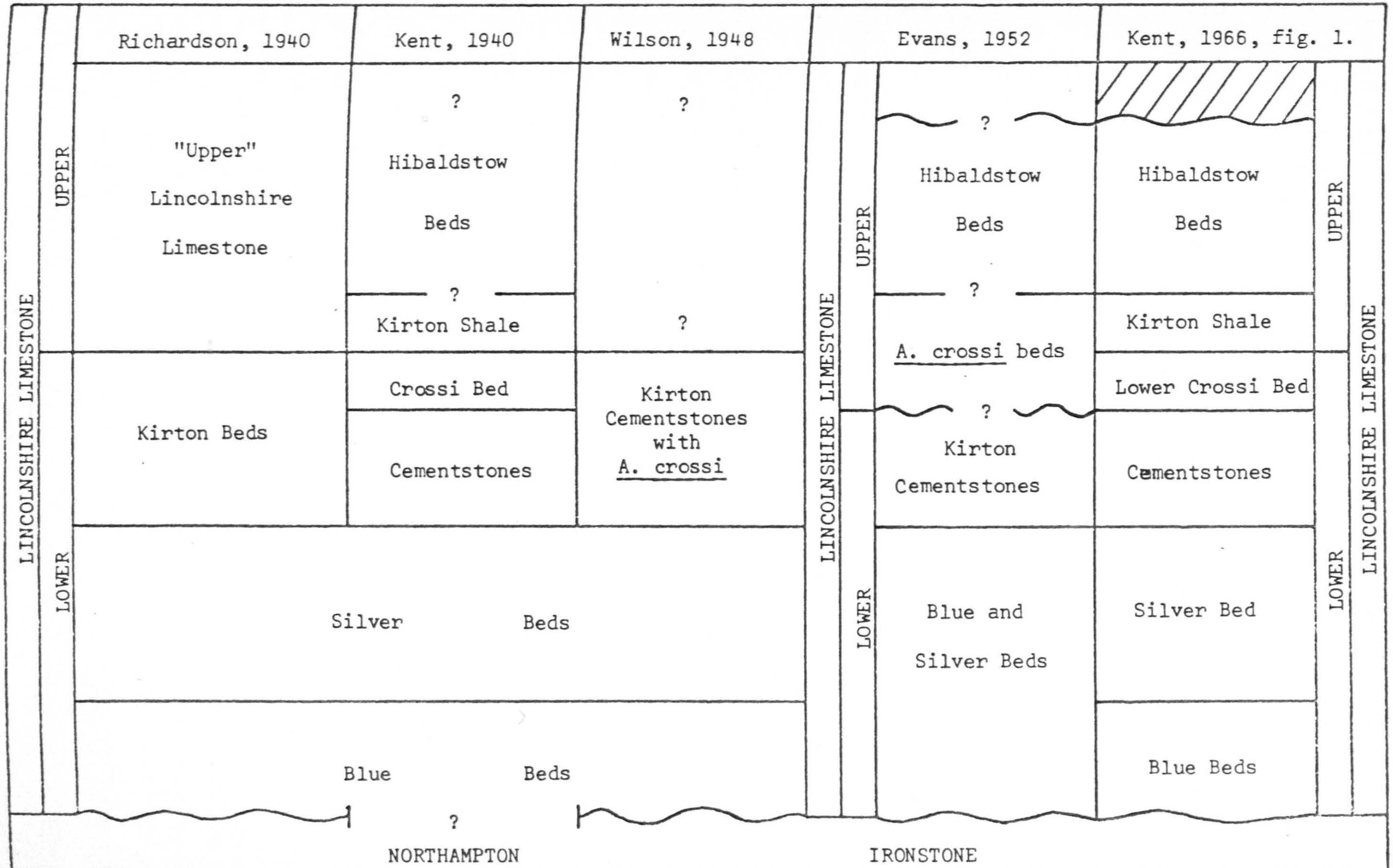

USSHER et al., 1888
KENT, 1940
KENT, 1966, fig. 1.
LINCOLNSHIRE LIMESTONE
Equivalents of the Ponton Series
Equivalents of the Kirton Beds
Grey limestone
?
Semi-oolitic beds
?
Hydraulic limestone series
Crossi Bed
? argillaceous limestones with thick shale partings
?
Upper Crossi Bed
Kirton Beds
Kirton Cement Shale
Lower Crossi Bed
Kirton Cementstones
Bedded sandy and partly oolitic limestone
Blue Beds
Basal Hydraulic Limestone
UPPER
LOWER
LINCOLNSHIRE LIMESTONE
BASEMENT BEDS
LOWER ESTUARINE SERIES
NORTHAMPTON IRONSTONE

Fig. 2.5. The stratigraphic terminologies formerly proposed for the Lincolnshire Limestone in the Lincoln district.


Richardson, 1940
Kent, 1940
Wilson, 1948
Evans, 1952
Kent, 1966, fig. 1.
LINCOLNSHIRE LIMESTONE
UPPER
LOWER
"Upper" Lincolnshire Limestone
Kirton Beds
?
Hibaldstow Beds
?
Kirton Shale
Crossi Bed
Cementstones
?
?
Kirton Cementstones with A. crossi
Silver Beds
Blue Beds
?
LINCOLNSHIRE LIMESTONE
UPPER
LOWER
?
Hibaldstow Beds
?
A. crossi beds
?
Kirton Cementstones
Blue and Silver Beds
Hibaldstow Beds
Kirton Shale
Lower Crossi Bed
Cementstones
Silver Bed
Blue Beds
UPPER
LOWER
LINCOLNSHIRE LIMESTONE
NORTHAMPTON IRONSTONE

024

Fig. 2.6. The stratigraphic terminologies formerly proposed for the Lincolnshire Limestone in the Ancaster district.

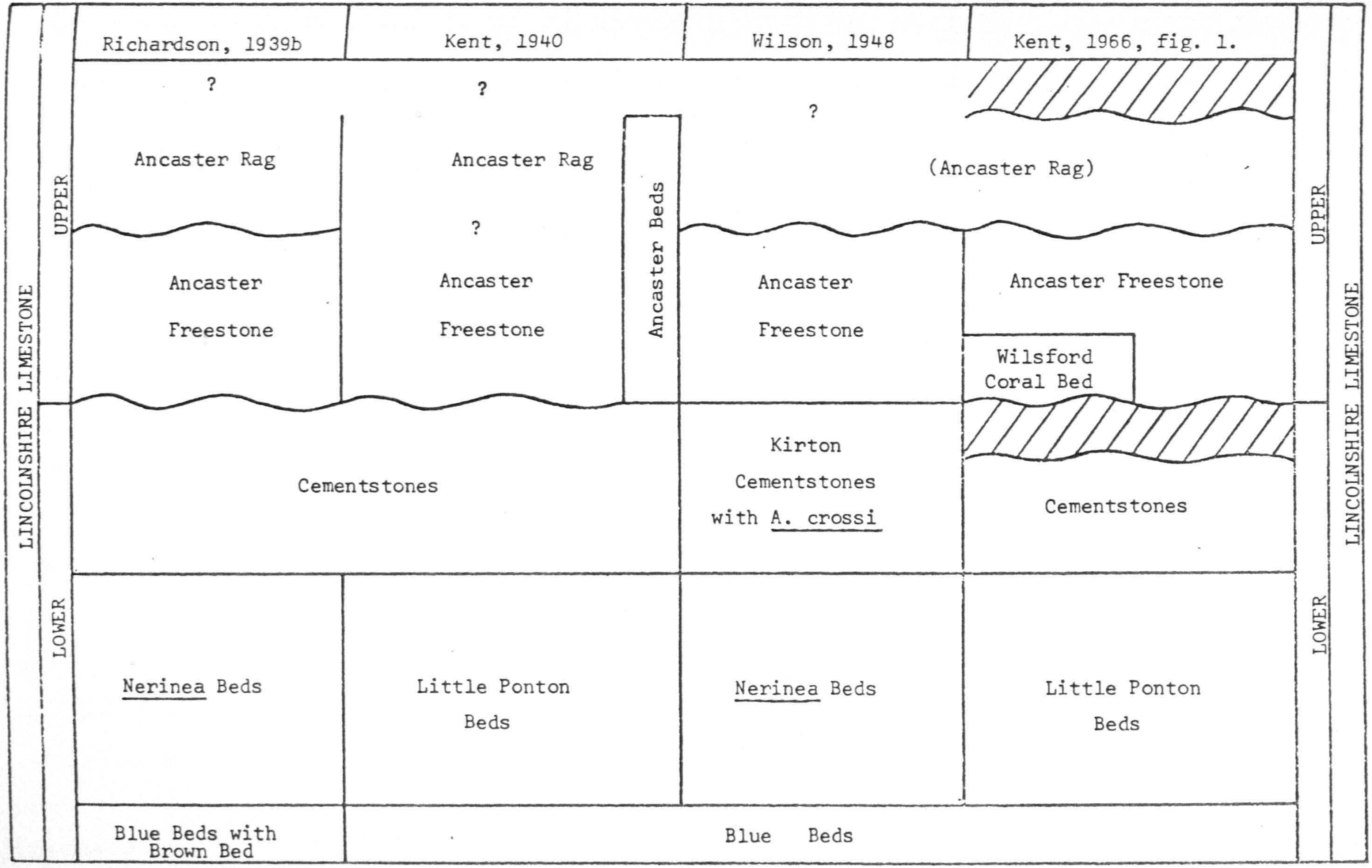

Richardson, 1939b
Kent, 1940
Wilson, 1948
Kent, 1966, fig. 1.
LINCOLNSHIRE LIMESTONE
UPPER
LOWER
?
Ancaster Rag
Ancaster Freestone
Ancaster Beds
(Ancaster Rag)
Wilsford Coral Bed
Cementstones
Kirton Cementstones with A. crossi
Nerinea Beds
Little Ponton Beds
Blue Beds with Brown Bed
Blue Beds

Fig. 2.7. The stratigraphic terminologies formerly proposed for the Lincolnshire Limestone in the Grantham district.

<table>
<tr><th></th><th></th><th>Richardson, 1939b</th><th>Kent, 1940</th><th>Swinnerton & Kent, 1949</th><th>Hollingworth & Taylor, 1951</th><th>Kent, 1966, fig. 1.</th><th></th><th></th></tr>
<tr><td rowspan="9">LINCOLNSHIRE LIMESTONE</td><td rowspan="3">UPPER</td><td><u>Terebratula</u> Beds</td><td>Great Ponton <u>Terebratula</u> Beds</td><td rowspan="3">Great Ponton Beds</td><td rowspan="3">Coarse, shelly oolites and pisolites of Great Ponton</td><td>Great Ponton <u>Terebratula</u> Beds</td><td rowspan="4">UPPER</td><td rowspan="9">LINCOLNSHIRE LIMESTONE</td></tr>
<tr><td><u>Amberlya</u> Bed</td><td rowspan="2">Great Ponton Gastropod Beds</td><td rowspan="2">Great Ponton Gastropod Beds</td></tr>
<tr><td>Gastropod Beds</td></tr>
<tr><td rowspan="6">LOWER</td><td>Ancaster Freestone</td><td colspan="2">Ancaster Beds</td><td colspan="2">Ancaster Freestone</td></tr>
<tr><td rowspan="2">Cementstones</td><td colspan="4">Crossi Bed</td><td rowspan="5">LOWER</td></tr>
<tr><td colspan="2">Cementstones</td><td>unnamed beds with <u>Pholadomya</u> Bed 10 feet above Pisolite Group</td><td>Cementstones</td></tr>
<tr><td rowspan="2"><u>Nerinea</u> Beds</td><td rowspan="2">Little Ponton Beds</td><td rowspan="2">Oolites</td><td>Pisolite Group</td><td rowspan="2">Little Ponton Beds</td></tr>
<tr><td rowspan="2">Sandy Limestone Group</td></tr>
<tr><td colspan="3">Blue Beds</td><td>Blue Beds</td></tr>
</table>

Fig. 2.8. The stratigraphic terminologies formerly proposed for the Lincolnshire Limestone in the Stamford district.

Judd, 1875	Richardson, 1939a	Kent, 1940	Swinnerton & Kent, 1949	Hollingworth & Taylor, 1951	Kent, 1966, fig. 1.		
"coralline" facies" and "shelly facies"" having no constant relationship	Barnack Rag Weldon Rag (Weldon Beds)	? Weldon and Clipsham Beds ?	?	Coarse, shelly oolites and pisolites of Clipsham	Barnack Rag and Weldon Stone	LOWER	LINCOLNSHIRE LIMESTONE
	Freestone Bed of "Lings"	Ketton Freestones and Freestone of the Lings	Clipsham Stone	Ketton Freestone	Ketton Stone ("Freestone of the Lings")		
	Crossi Bed					UPPER	
	? *Nerinea* Beds	? Cementstones	Oolites	unnamed beds with *Pholadomya* Bed 10 feet above Pisolite Group	Cementstones		
		Little Ponton Beds		Pisolite Group	*Nerinea* (Pisolite) Beds		
				Sandy Limestone Group			
Collyweston Slate	? "Collyweston Beds" Collyweston Slate	Collyweston Slate	Blue Beds/ Collyw. Slate	Collyweston Slate	Blue Beds/ Collyweston Slate		

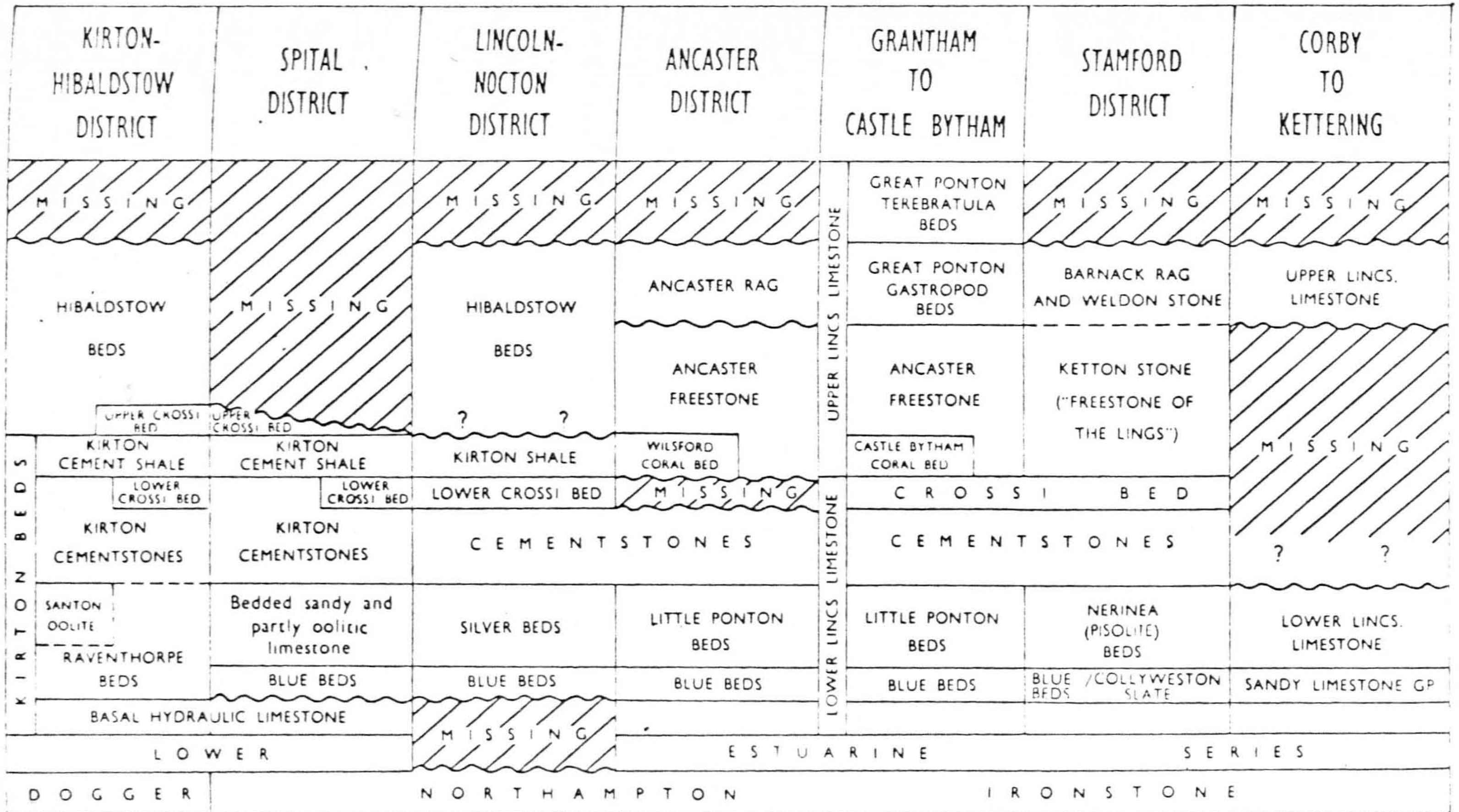


Fig. 2.9. The correlation of the "Inferior Oolite" subdivisions between the Humber and Kettering, proposed by Kent (1966, fig. 1).

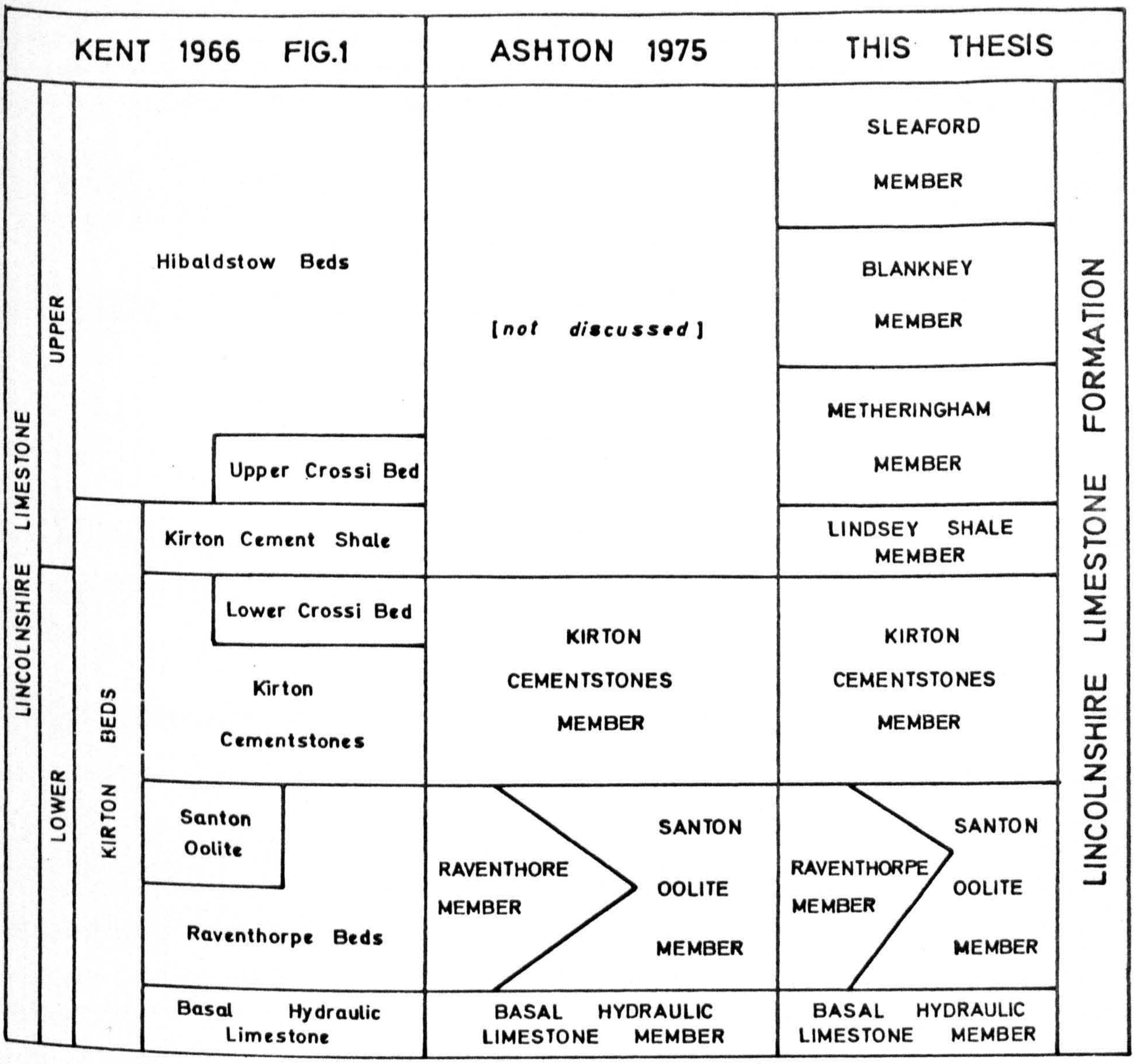


Fig. 2.10 The contrasting stratigraphies of the Lincolnshire Limestone Formation, proposed for the South Humberside region.

Fig. 2.11. The distribution of *Acanthothiris crossi* (J.F. Walker) in the newly proposed subdivisions of the Lincolnshire Limestone Formation.

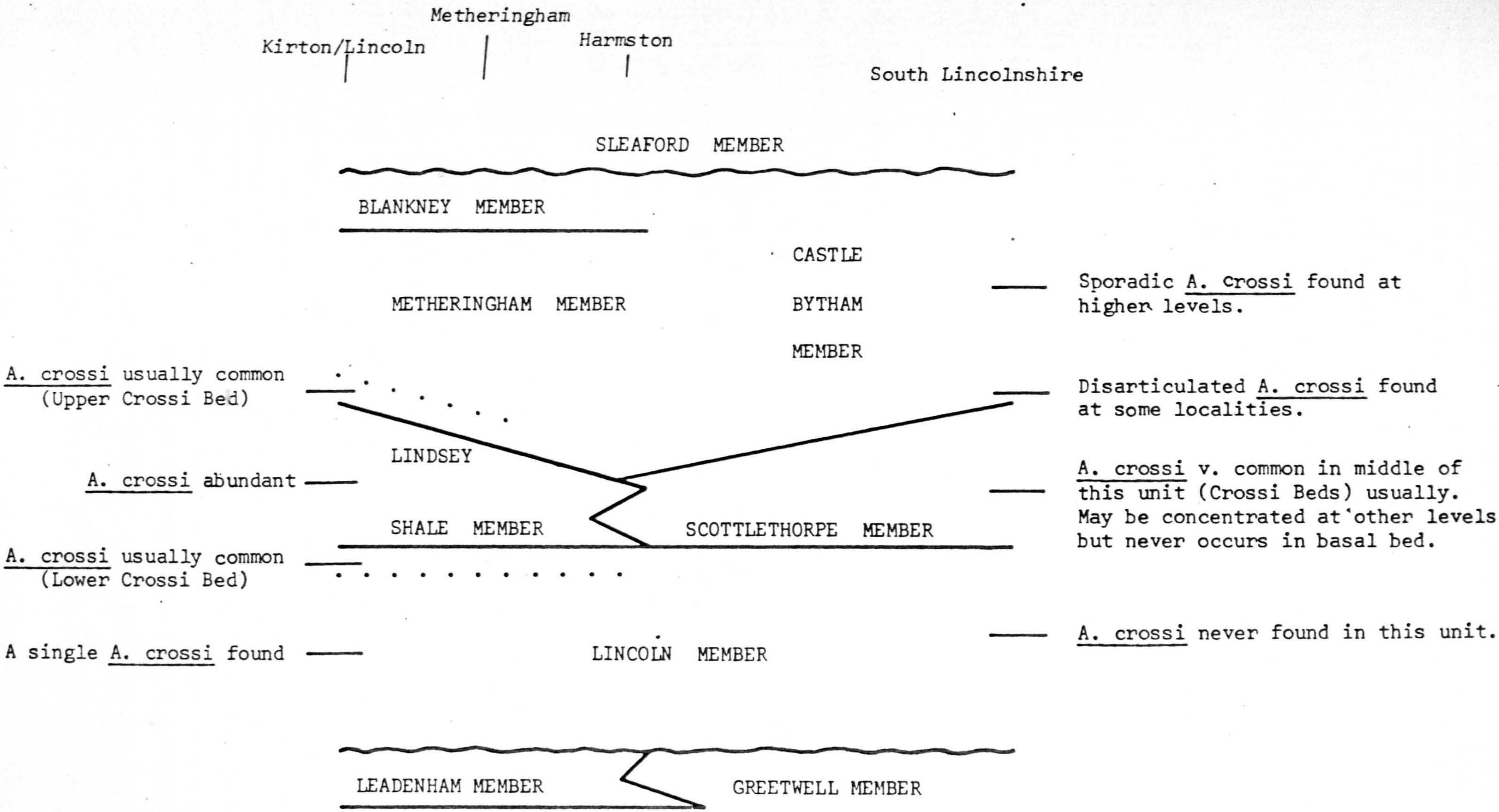

Kirton/Lincoln
Metheringham
Harmston
South Lincolnshire
SLEAFORD MEMBER
BLANKNEY MEMBER
METHERINGHAM MEMBER
CASTLE
BYTHAM
MEMBER
Sporadic A. crossi found at higher levels.
A. crossi usually common (Upper Crossi Bed)
Disarticulated A. crossi found at some localities.
LINDSEY
A. crossi abundant
A. crossi v. common in middle of this unit (Crossi Beds) usually. May be concentrated at other levels but never occurs in basal bed.
SHALE MEMBER
SCOTTLETHORPE MEMBER
A. crossi usually common (Lower Crossi Bed)
A. crossi never found in this unit.
A single A. crossi found
LINCOLN MEMBER
LEADENHAM MEMBER
GREETWELL MEMBER

Fig. 2.12. The contrasting stratigraphies proposed for the lower part of the Lincolnshire Limestone succession, exposed at Greetwell Hollow Quarry, Lincoln (TF 003721).

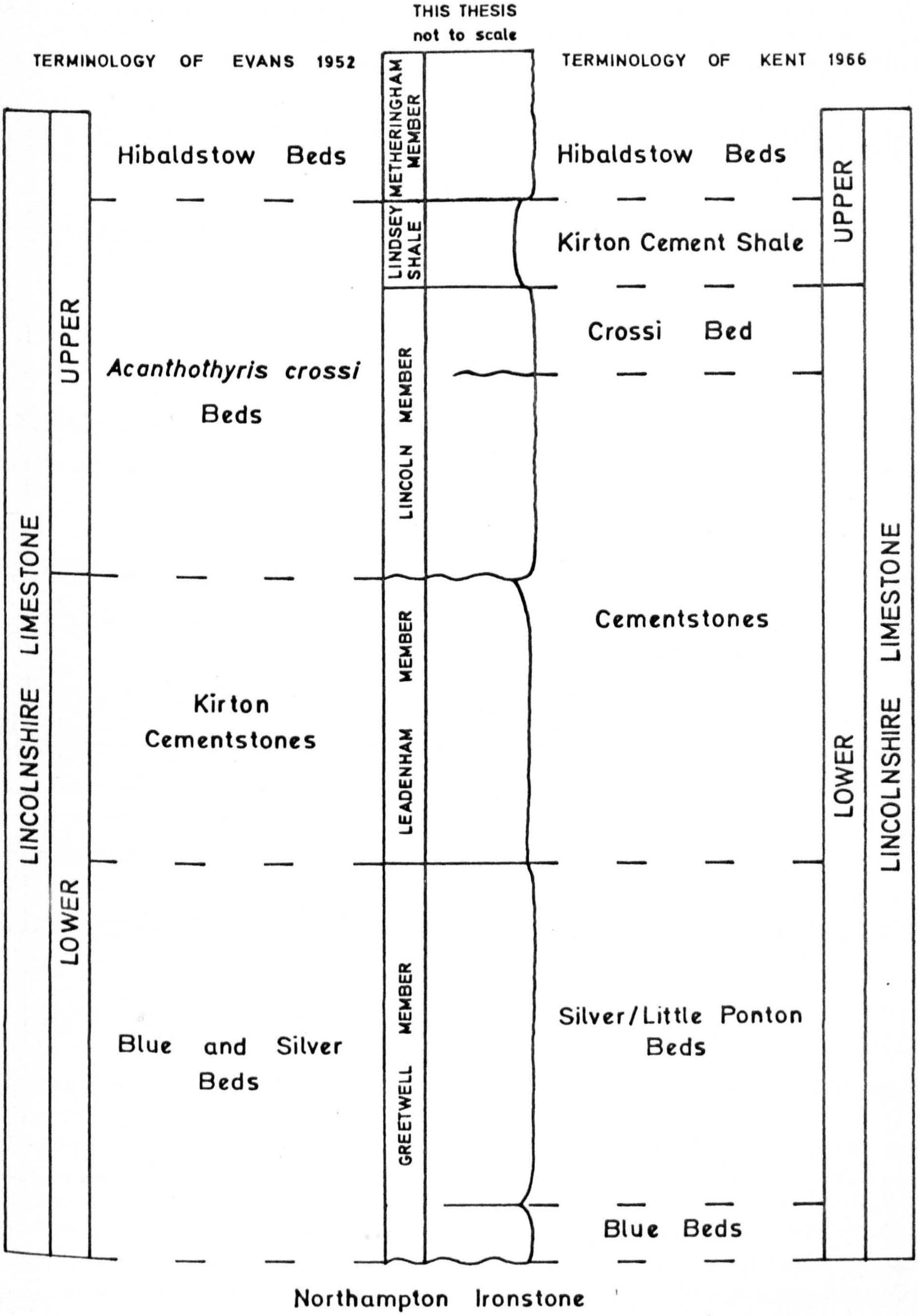
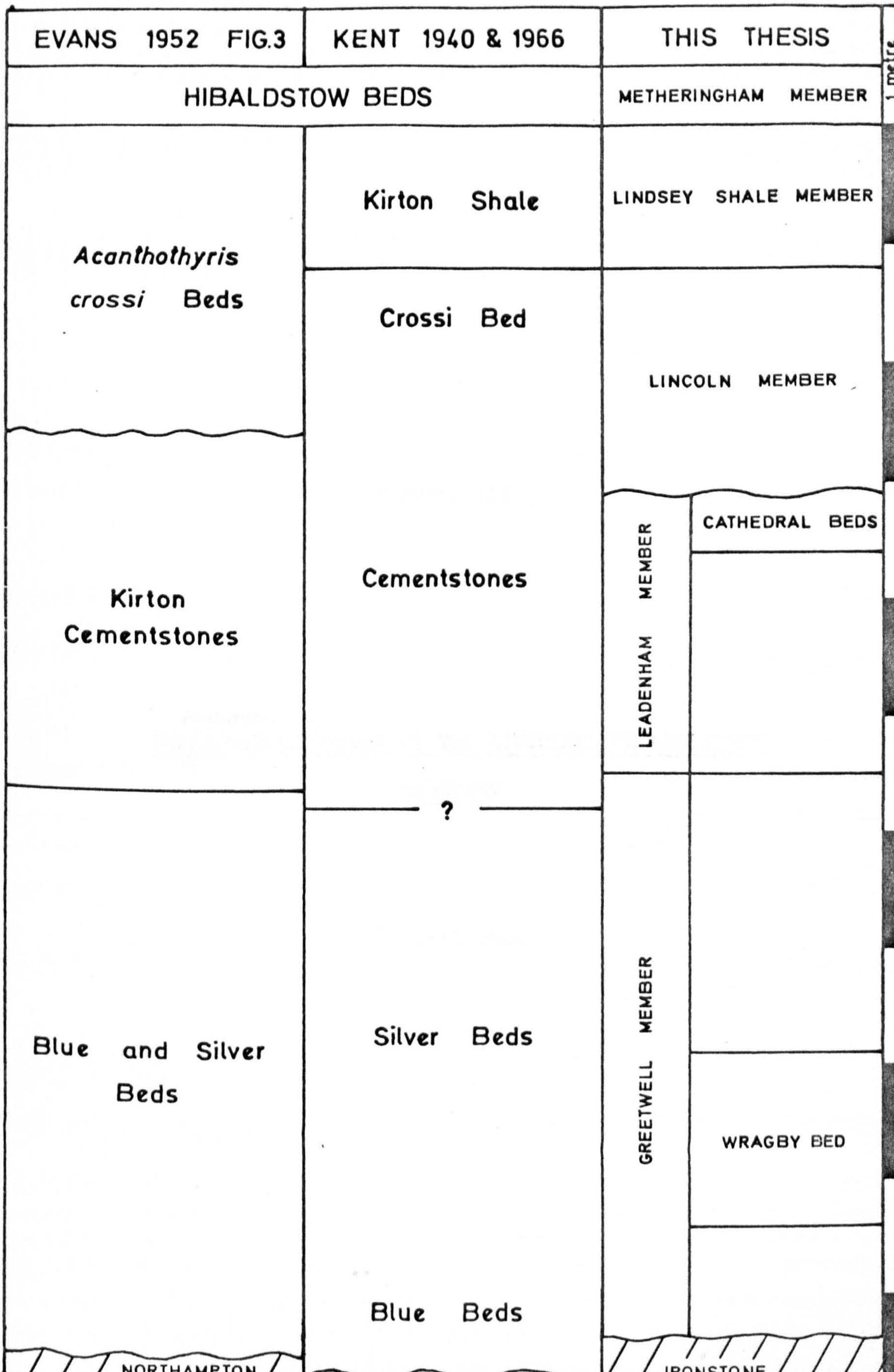

THIS THESIS
not to scale
TERMINOLOGY OF EVANS 1952
TERMINOLOGY OF KENT 1966
LINCOLNSHIRE LIMESTONE
UPPER
LOWER
Hibaldstow Beds
Acanthothyris crossi Beds
Kirton Cementstones
Blue and Silver Beds
METHERINGHAM MEMBER
LINDSEY SHALE
LINCOLN MEMBER
LEADENHAM MEMBER
GREETWELL MEMBER
Hibaldstow Beds
Kirton Cement Shale
Crossi Bed
Cementstones
Silver/Little Ponton Beds
Blue Beds
UPPER
LOWER
LINCOLNSHIRE LIMESTONE
Northampton Ironstone

Fig. 2.13 The contrasting terminologies proposed for the generalised Lincolnshire Limestone succession of central Lincolnshire.


EVANS 1952 FIG.3
KENT 1940 & 1966
THIS THESIS
1 metre
HIBALDSTOW BEDS
METHERINGHAM MEMBER
Acanthothyris crossi Beds
Kirton Shale
LINDSEY SHALE MEMBER
Crossi Bed
LINCOLN MEMBER
CATHEDRAL BEDS
LEADENHAM MEMBER
Kirton Cementstones
Cementstones
?
GREETWELL MEMBER
Blue and Silver Beds
Silver Beds
WRAGBY BED
Blue Beds
NORTHAMPTON
IRONSTONE

CHAPTER III

THE AMMONITE BIOSTRATIGRAPHY OF THE LINCOLNSHIRE LIMESTONE FORMATION

TEXT-FIGURES

Fig. 3.1. Details of all the ammonite discoveries from the Lincolnshire Limestone that have been recorded in the literature. (Errata: S. (Fissilobiceras) fissilobatum should read S. (Fissilobiceras) fissilobata.)

IDENTIFICATION		LOCALITY	RECORDED HORIZON	PRESENT LOCATION		ORIGINAL RECORD
THIS PAPER	ORIGINAL			COLLECTION AND ACCESSION No		
	Ammonites Blagdeni (?) Sowerby (juvenile)	Barnack, near stamford	Barnack Rag	Lost ?		Sharp, 1873
	A Murchisonae (?) Sowerby (juvenile)					
	A Murchisonae Sowerby	Tinkler's and neighbouring quarries, Stamford	Below *crossi* bed			
	A subradiatus Sowerby					
	A terebratus Phillips					
Sonninia (Euhoplоceras) cf *polyacantha* (Waagen)	*A polyacanthus* Waagen	Little Bytham, Lincolnshire	?	IGS	GSM25604	Judd, 1875
	One specimen of the family *A Truellei* d'Orbigny"	North-west Lincolnshire	Marly bed that is the lower of the two beds forming the Santon Oolite	Lost ?		Cross, 1875
	Ammonite of *Humphriesianus* type		Lincolnshire Lst above Santon Oolite			
	A "Sowerbyi"	Dunston	?	Lost ?		Ussher, 1888
Hyperlioceras (Hyperlioceras) aff *rudidiscites* S Buckman	*A laeviusculus* Sowerby	Dean and Chapter Pit, Lincoln		IGS	JR 108	
S (E) cf *polyacanthe* (Waagen)	*A polyacanthus* Waagen	North Lincoln, ? Dean and Chapter Pit	Lincolnshire Limestone	IGS	GSM114114	Woodward, 1894
S (E) cf *marginata* S Buckman	*A polyacanthus* Waagen				GSM114115	
	A "Sowerbyi"	Saxby-Bourn railway cutting, SW of South Witham, Lincolnshire	?	Lost ?		
Darellia (Darellia) polita S Buckman	*Ludwigella (Darellia) polita* S Buckman	Quarry near the "Bowling Green" on Wragby Road, Lincoln	6-8 ft above base of Lincolnshire Limestone	LCCM	1634 34	Batters, 1933
Graphoceras (Ludwigella) aff *stigmosum* S Buckman	*L (D) alta* S Buckman	Quarry NE of Greetwell Hollow Farm, Lincoln	?		43.34	Baker, 1934
H (H) aff *rudidiscites* S Buckman	*Hyperlioceras* aff *rudidiscites* S Buckman	Quarry near the "Bowling Green" on Wragby Road, Lincoln	10-12 ft above base of Lincolnshire Limestone (Silver Beds)	IGS	ZK 772	Kent and Baker, 1938
H (H) subsectum (S Buckman)	*Deltotoceras subsectum* S Buckman				ZK 773	
H (H) cf *subdiscoideum* S Buckman	*Deltoidoceras subdiscoideum* S Buckman				ZK 770	
H (H) aff *rudidiscites* S Buckman	*H* aff *discites* (Waagen) 3 specimens	Quarry NE of Greetwell Hollow Farm, Lincoln	?	LCCM	355 37	
H (H) subsectum (S Buckman)					355 37A	
H (H) subsectum (S Buckman)				? BMNH	C 38091	
S (E) cf *marginata* S Buckman	*Sonninia (Euhoplоceras)* sp of *acanthodes* group		10 ft 8 ins above the base of the Lincolnshire Limestone	LCCM	356 37	
	Fontannesia sp	Spittlegate Hill Reservoir, Grantham	? 5 ft above base of Lincolnshire Lst, immediately post Blue Beds	Lost ?		
S (E) cf *densicostata* S Buckman	*Euhoplоceras* sp [of *regularis-costigera* group]	Barnstone Cement Quarry, Waltham Station, Leicestershire	8 ft above base of Lincolnshire Limestone (Silver Beds)	IGS	ZK 774	
Sonninia (Fissilobiceras) cf *ovalis* (Buckman ex Qu)	*Sonninia* sp	Castle Bytham Quarry, Lincolnshire	Near top of "Bastard Freestone"	BMNH	C 39337	Richardson, 1939 a
Shirburnia cf *S fastigata* S Buckman	*Hyperlioceras* sp		approx 15 ft above the *crossi* bed		C 47900	Kent, 1966
D (D) cf *coela* S Buckman	*H* aff *discites* (Waagen)	Greetwell Hollow Quarry, Lincoln	Cementstones		C 47901	
	Hyperlioceras sp	Clipsham, Leicestershire	Short distance beneath Upper Estuarine Series (but derived)	Lost ?		Kent, 1970
S (E) acanthodes S Buckman	*S (E) acanthodes* S Buckman	Botany Pit, near Geddington, Northamptonshire	From bed 1 35 m above base of Lincolnshire Limestone	IGS	Zr 7339	Barker and Torrens, 1971
S (F) fissilobatum (Waagen)	*H rudidiscites* S Buckman	Woolfox Quarry, Leicestershire	4 2 metres above the *crossi* bed	RCM	1969/279	Senior & Earland-Bennett, 1973
S (F) aff *fissilobatum* (Waagen)	*Fissilobiceras* aff *fissilobatum* (Waagen)	Greetham Quarry, Leicestershire	Below *crossi* beds	RCM	1976/32	Ashton, 1977
S (Euhoplоceras) sp	*Euhoplоceras* sp	Leadenham Quarry, Lincolnshire	Cementstones	In private collection of Mr Nicholas Osborne, 47, East Road, Navenby, nr Lincoln	NDO 1	
S (F) aff *fissilobatum* (Waagen)	*F* aff *fissilobatum* (Waagen)		Below *crossi* beds		NDO 2	
S (F) aff *fissilobatum* (Waagen)	*Fissilobiceras* sp				NDO 3	
S (E) cf *dominans* S Buckman	*E* cf *dominans* S Buckman	Harmston Quarry, Lincolnshire	up to 5 m above the Cementstones		NDO 4	

Fig. 3.2. Details of all the ammonite discoveries from the Lincolnshire Limestone, that have not previously been recorded in the literature. (Errata: *S*. (*Fissilobiceras*) *fissilobatum* should read *S*. (*Fissilobiceras*) *fissilobata*.)

IDENTIFICATION: THIS PAPER	IDENTIFICATION: MUSEUM CATALOGUE	LOCALITY	HORIZON	PRESENT LOCATION: Collection	PRESENT LOCATION: Accession No.	REMARKS
Sonninia (Fissilobiceras) cf. *ovalis* (Buckman ex. Qu.)	*Sonninia* sp.	Castle Lime Quarry Castle Bytham, Lincolnshire	10 feet above the base of the quarry (ie. coral-bivalve bed)	BMNH	C 48800	C.G. Adams Collection, 1956
S. (F.) cf. *ovalis* (Buckman ex. Qu.)	*Sonninia* sp.				C 48801	
Hyperlioceras (Hyperlioceras) cf. *discoideum* (Buckman ex. Qu.)	*Hyperlioceras* sp.	Grantham, Lincolnshire	?		C 73373	Ex. Grantham Museum
S. (F.) aff. *fissilobatum* (Waagen)	(as this paper)	Leadenham Quarry, Lincolnshire	Unit D Bed 1 (See Fig. 2 of this paper)		C 80403	Found by Mr. D. Theaker and recovered by MA in August, 1976
S. (Fissilobiceras) sp.					C 80404	
S. (Fissilobiceras) sp.					C 80405	
S. (F.) aff. *fissilobatum* (Waagen)			Unit D Bed 1b (See Fig. 2 of this paper)		C 80406	Discovered "in situ" on G.A. Field Exc., Sept. 1976
H. (Hyperlioceras) sp. Indet.	*Hyperlioceras* sp.	Wragby Road Quarry, Lincoln	?	IGS	ZK 771	Curated with specimens cited by Kent & Baker ('38)
S. (Fissilobiceras) sp.		Ropsley Quarry, Lincolnshire			TNN 212	Collected by Dr. J.A. Dickson in 1973
S. (E.) aff. *marginata* S. Buckman	*Sonninia (Euhoploceras)* sp.	Greetwell Quarry, Lincoln		LCCM	41.38	
H. (H.) subsectum (S. Buckman)	*Hyperlioceras subsectum* (S. Buckman)	Kirton Lime Quarry, near Kirton-in-Lindsey, S. Humberside		SM	352	Found by the Rev. Cutts, 1942
indet. Graphoceratid fragment	No identifications recorded	Sproxton Quarry, Leicestershire	Bed 4 (equivalent to Bed 7 of Richardson, 1939b, Fig. 40)	LM	18' 1975/3	Found by museum staff
impression of *Graphoceras (Ludwigella)* sp.					18' 1975/4	
S. (Fissilobiceras) sp.		Leadenham Quarry, Lincolnshire	Unit D Bed 1. (See Fig. 2 of this paper)	In private collection of Mr. Marsh, 13, Dryden Av, Lincoln		Not available for detailed examination

Fig. 3.3. Location map showing the principal localitites in the Lincolnshire Limestone, from which ammonites have been collected.

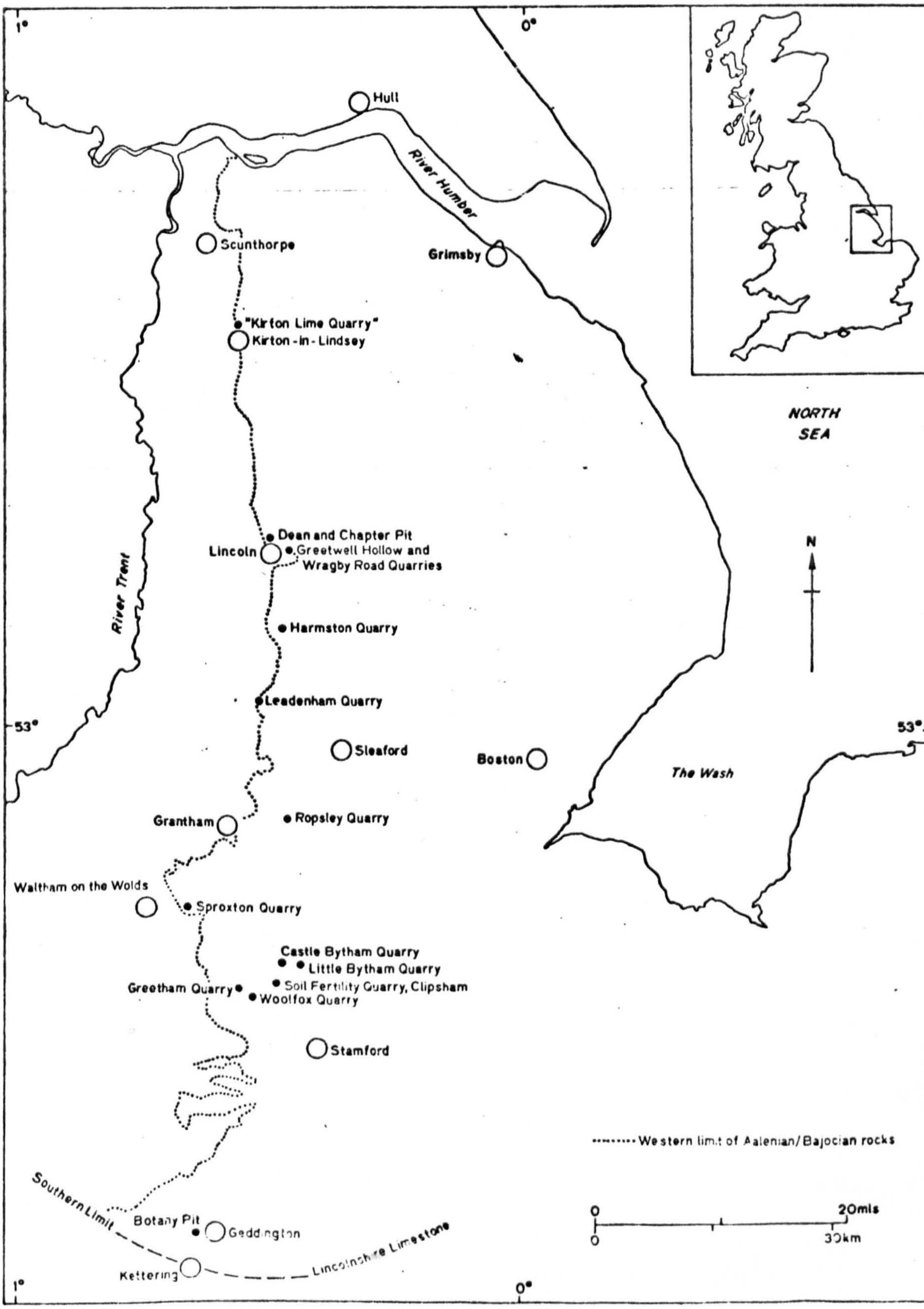

1°
0°
Hull
River Humber
Scunthorpe
Grimsby
"Kirton Lime Quarry"
Kirton-in-Lindsey
NORTH SEA
Dean and Chapter Pit
Lincoln
Greetwell Hollow and Wragby Road Quarries
N
River Trent
Harmston Quarry
Leadenham Quarry
53°
53°
Sleaford
Boston
The Wash
Grantham
Ropsley Quarry
Waltham on the Wolds
Sproxton Quarry
Castle Bytham Quarry
Little Bytham Quarry
Greetham Quarry
Soil Fertility Quarry, Clipsham
Woolfox Quarry
Stamford
Western limit of Aalenian/Bajocian rocks
Southern Limit
Botany Pit
Geddington
Kettering
Lincolnshire Limestone
0
20mls
0
30km
1°
0°

Fig. 3.4. Correlation chart for the Lincolnshire Limestone sequences, from which the majority of ammonite discoveries have been made.

Key to lithostratigraphic units:

K = Creeton Member

J = Sleaford Member

H = Metheringham Member

G = Castle Bytham Member

F = Scottlethorpe Member

E = Lindsey Shale Member

D′ = Ropsley Beds

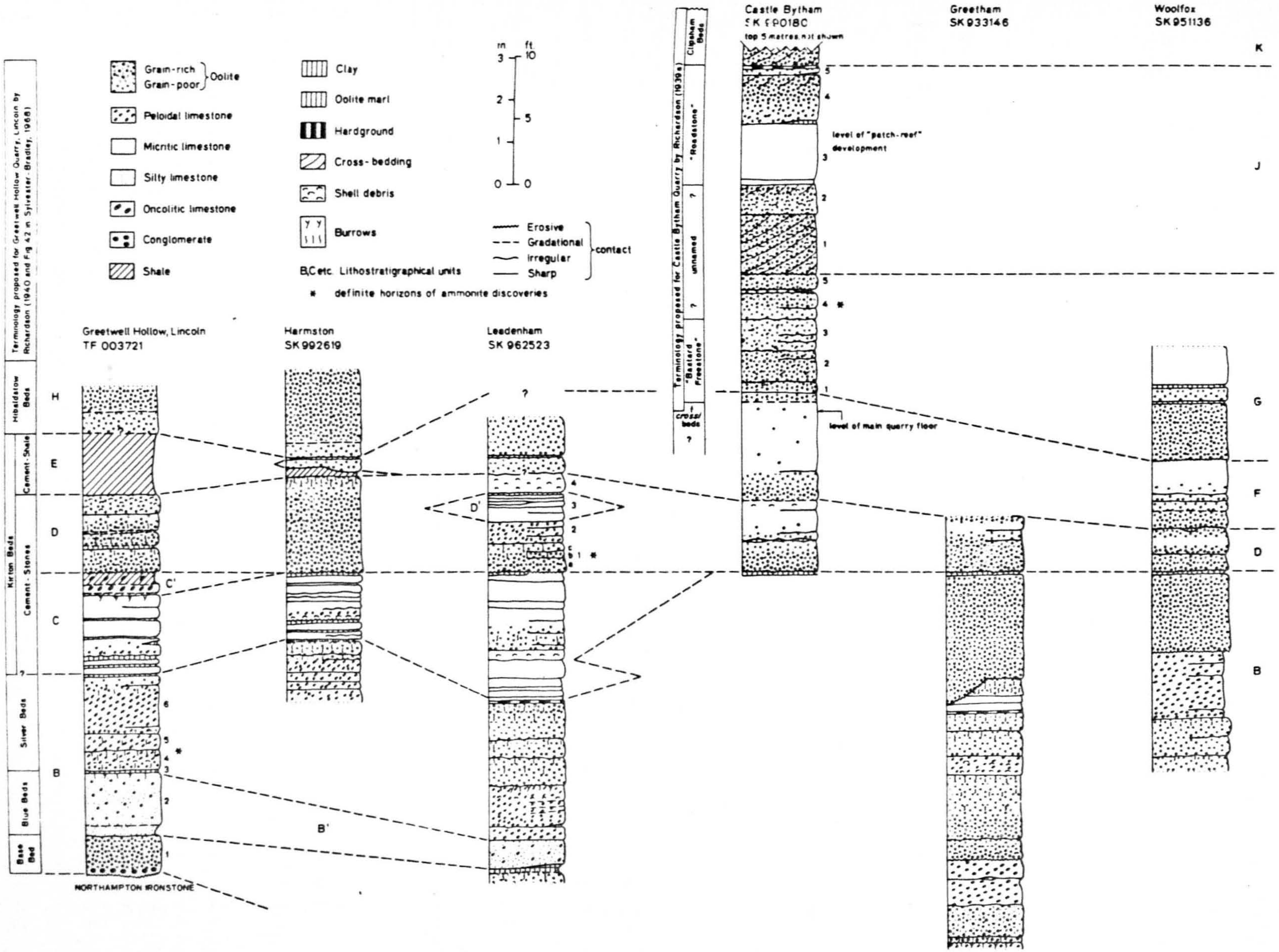
D = Lincoln Member

C′ = Cathedral Beds

C = Leadenham Member

B′ = Wragby Bed

B = Greetwell Member



Terminology proposed for Greetwell Hollow Quarry, Lincoln by Richardson (1940 and Fig 42 in Sylvester-Bradley, 1968)
Hibaldstow Beds
Cement-Shale
Cement-Stones
Kirton Beds
Silver Beds
Blue Beds
Base Bed
Grain-rich
Grain-poor
Oolite
Peloidal limestone
Micritic limestone
Silty limestone
Oncolitic limestone
Conglomerate
Shale
Clay
Oolite marl
Hardground
Cross-bedding
Shell debris
Burrows
B,C etc. Lithostratigraphical units
* definite horizons of ammonite discoveries
m
ft
Erosive
Gradational
Irregular
Sharp
contact
Greetwell Hollow, Lincoln
TF 003721
Harmston
SK992619
Leadenham
SK 962523
NORTHAMPTON IRONSTONE
Terminology proposed for Castle Bytham Quarry by Richardson (1939a)
Clipsham Beds
"Roadstone"
unnamed
"Bastard Freestone"
cross/ beds
Castle Bytham
SK 990180
top 5 metres not shown
level of "patch-reef" development
level of main quarry floor
Greetham
SK933146
Woolfox
SK951136
H
E
D
C
C'
B
B'
D'
K
J
G
F

Fig. 3.5. The stratigraphic distribution of the main ammonite groups in the Lincolnshire Limestone Formation (courtesy of C.F. Parsons).

B	C	D	E-F	G	H-I	J	LITHOLOGICAL UNITS / AMMONITE SPECIES
●	?						Hyperlioceras subsectum
●							H. cf. subdiscoideum
●							H. aff. rudidiscites
●							G.(Ludwigella) aff. stigmosum
●							Darellia (D.) polita
	?						? D.(? D.) cf. coela
●	●						Sonninia (Euhoploceras) marginata group
●							S.(E.) cf. densicostata
		●					S.(E.) cf. dominans
		●					S.(Fissilobiceras) aff. fissilobata
				?			S.(F.) fissilobata
				● – ●			S.(F.) cf. ovalis
						●	Shirbuirnia cf. fastigata
		OVALIS			LAEVIUS.		SUBZONE
DISCITES		LAEVIUSCULA					ZONE

CHAPTER IV

THE LITHOSTRATIGRAPHY OF THE LINCOLNSHIRE LIMESTONE FORMATION

TEXT-FIGURES

SCALES

On the text-figures, which are photographs, the following "scales" have true values of:

hammer	=	330mm
lens cap	=	approximately 50 mm
pencil	=	approximately 160 mm
felt-tip marker	=	140mm
man	=	1.8 metres

On the photomicrographs the "bar" scale is equal to 0.2 mm.

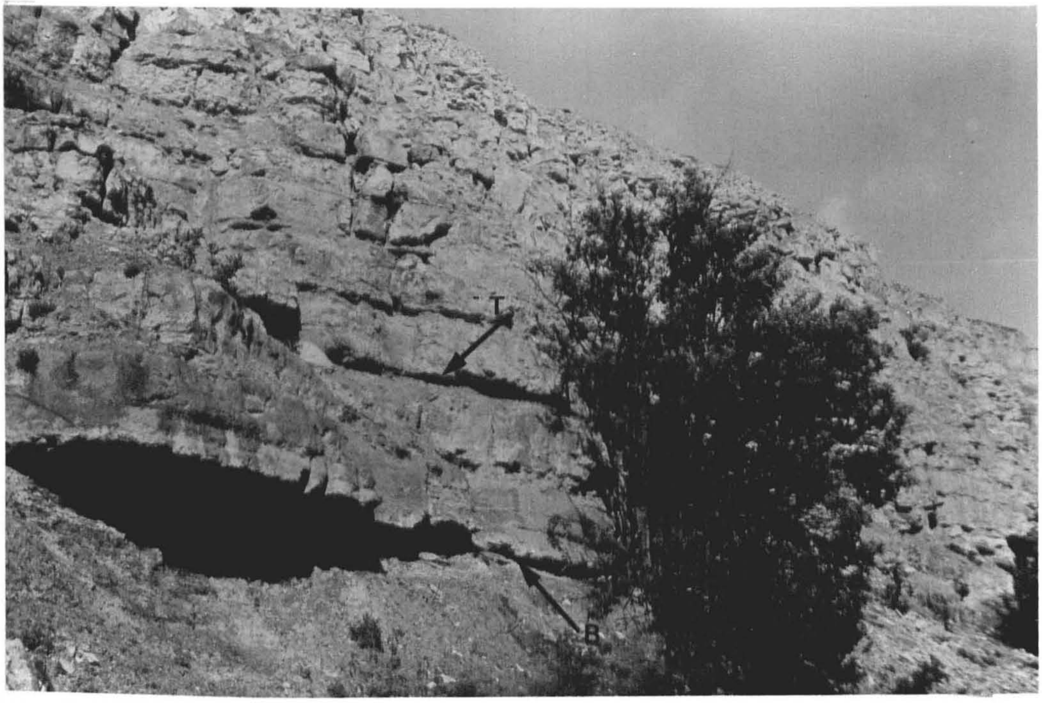
These scales apply to Chapters IV and V.

Fig. 4.1. Lithostratigraphic correlation chart for the lower Lincolnshire Limestone. The base of the Lincoln Member has been taken as the datum level. Each member is denoted by a capital letter in addition to its name: Greetwell Member is B. Formalised subdivisions of members are characterised by a "dash": the Wragby Bed is B'. Informal subdivisions of members are usually denoted by a secondary letter: the Market Overton beds are BA. Within each unit individual beds are numbered and sub-beds lettered (in low case). The diagram is in the back pocket of Volume 2.

Fig. 4.2. Lithostratigraphic correlation chart for the upper Lincolnshire Limestone. The base of the Lincoln Member has been taken as the datum level. Individual beds (and sub-beds) and lithostratigraphic units are denoted in the same manner as for the lower Lincolnshire Limestone.

Fig. 4.3. The type section of the Sproxton Member exposed at Sproxton Quarry (SK 866253). The top (arrowed T) and base (arrowed B) are indicated.

Fig. 4.4. Trace fossils seen on the base of the Sproxton Member at Stainby Quarry (SK 910233).


T
B

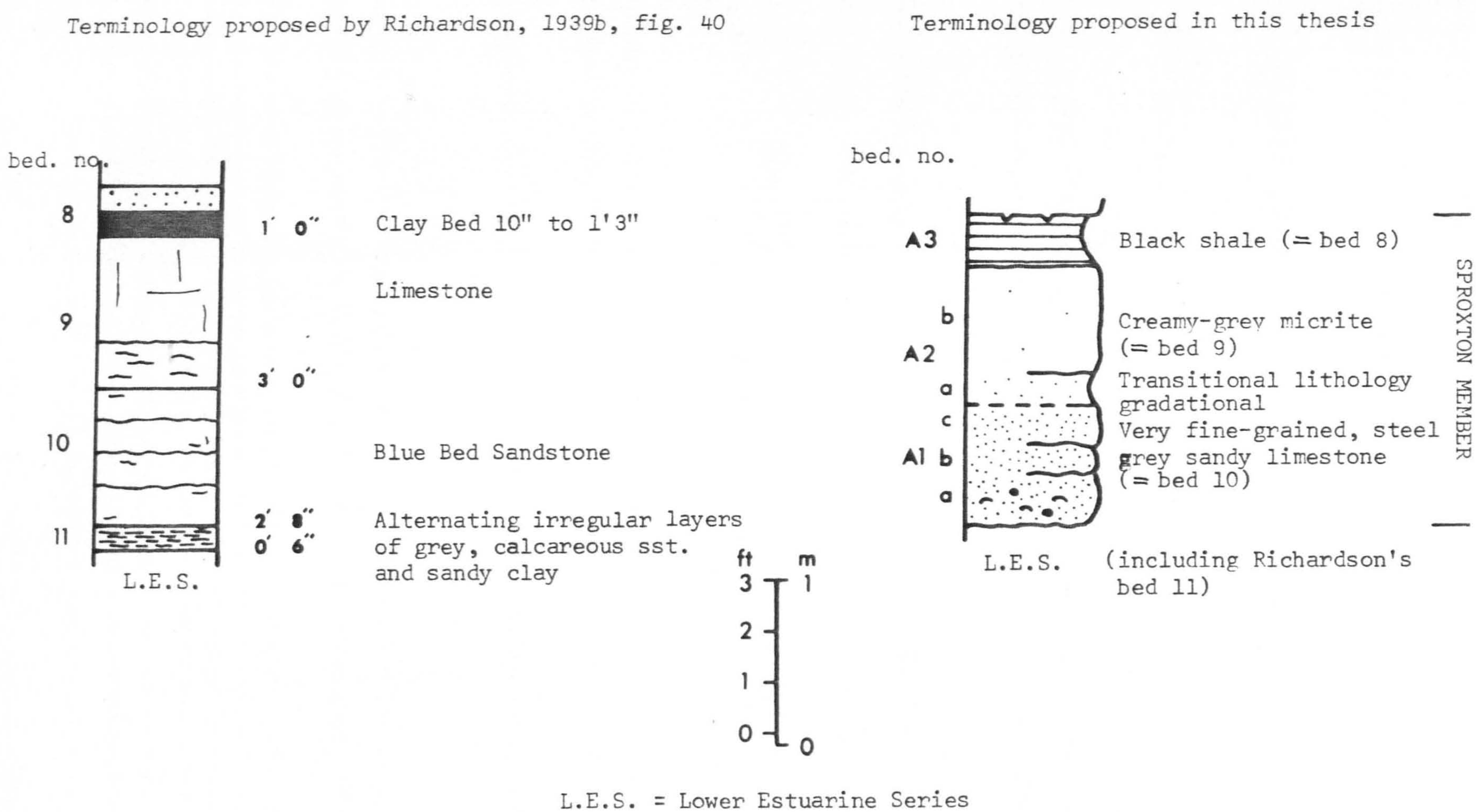
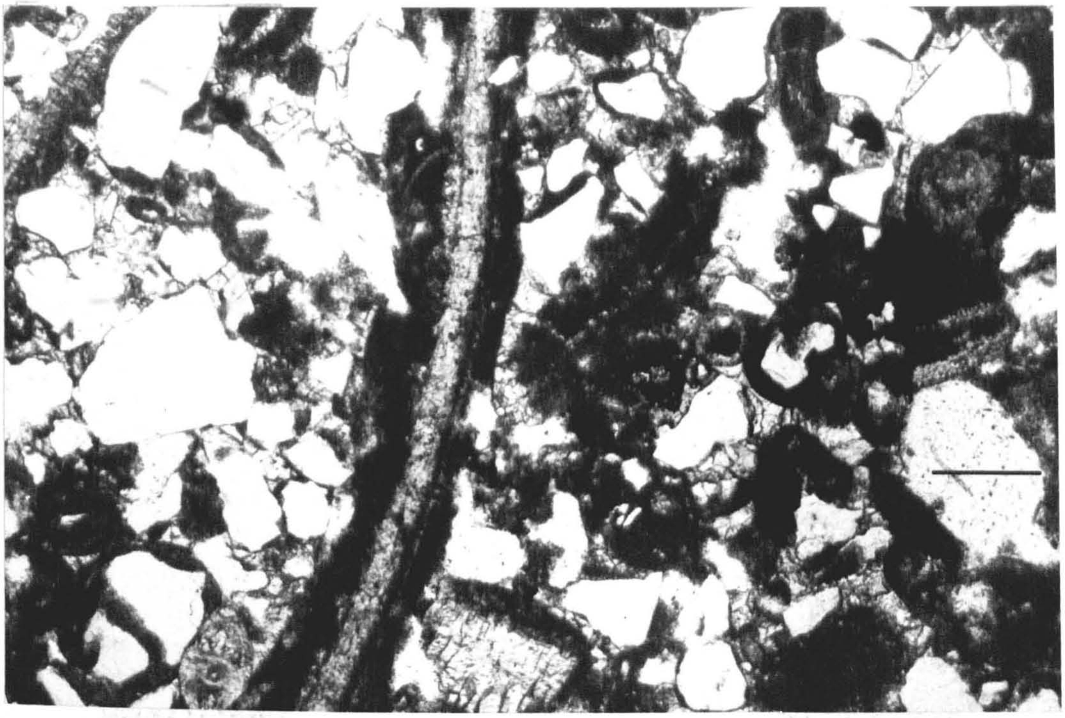
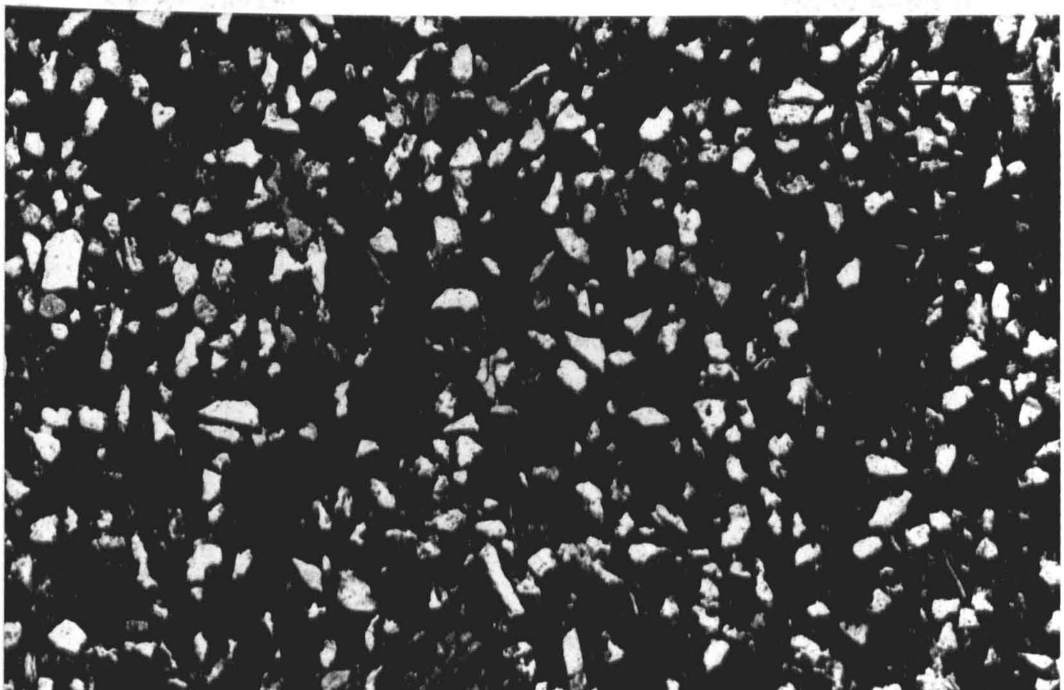


Fig. 4.5. The contrasting interpretations and terminologies applied to the lowest part of the Lincolnshire Limestone Formation in the Sproxton district.

Fig. 4.6. Photomicrograph of a quartzose oosparite (bed SNQ Ala), typical of Lithology A of the Sproxton Member.

Fig. 4.7. Photomicrograph of a quartzose biomicrite (bed SNQ Alc), typical of Lithology B of the Sproxton Member.





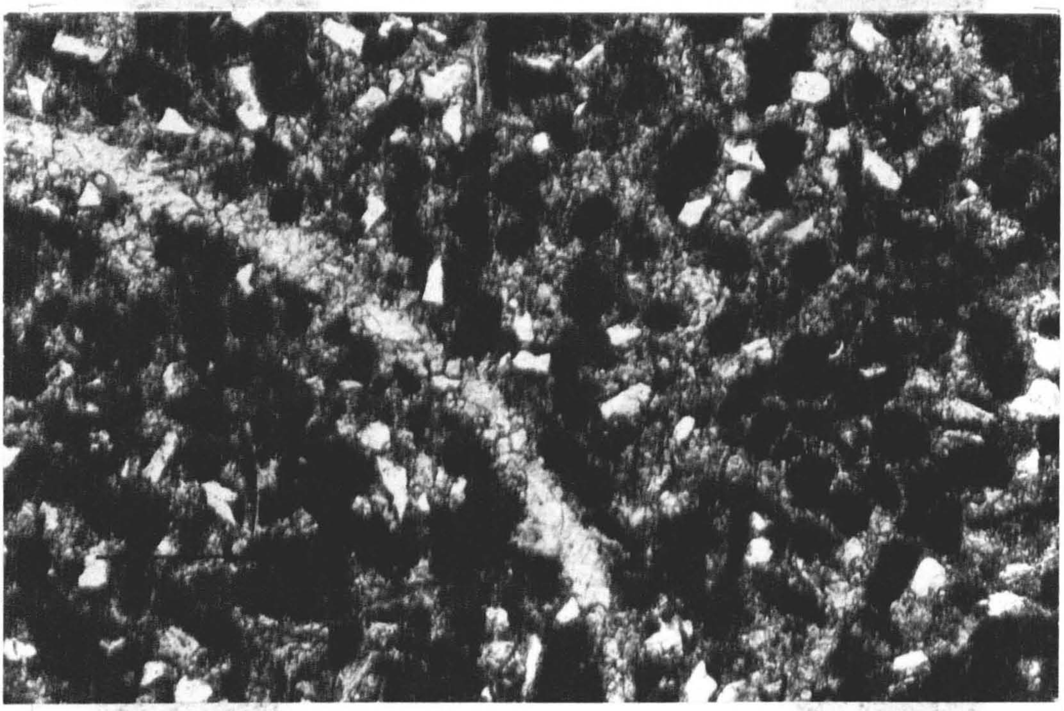


Fig. 4.8. Photomicrograph of a quartzose biopelsparite (bed SNQ A2b), typical of Lithology C of the Sproxton Member.

LITHOLOGY	GRAINS			MATRIX	TEXTURE
	% OF TOTAL ROCK	TYPE	SIZE		
C Quartzose biopelsparite	37%	peloids	mostly < 0.062	Sparite > Micrite	Packstone
	6%	bioclasts	0.4 to 3.0 mm		
	2%	intraclasts	0.35 to 0.7 mm		
	13%	quartz	silt to v. fine sand		
B Quartzose biomicrite	4%	bioclasts	0.2 to 2.3 mm	Ferroan dolomite	Wackestone
	36%	quartz	silt to v. fine sand	Microspar after micrite	
A Quartzose oosparite	30%	ooliths	mostly 0.25 mm	Sparite > Micrite	Packstone
	2%	intraclasts	0.6 to 2.0 mm		
	7%	bioclasts	0.19 to 1.3 mm		
	9%	peloids	0.09 to 0.14 mm		
	19%	quartz	fine to medium sand		

Fig. 4.9. The principal lithological characteristics of the Sproxton Member.

Fig. 4.10. Correlation of the lowest part of the Lincolnshire Limestone Formation between Greetwell (Lincoln), Metheringham and Sproxton. Note particularly how the evidence from the Metheringham sequence enables the "Lincoln Blue Beds" (= B́2 of this diagram, see also Fig. 4.32) to be distinguished from the "South Lincolnshire Blue Beds" (= Sproxton Member at Sproxton). The former are a distinctly different, higher stratigraphic unit, which has here been termed the Wragby Bed.

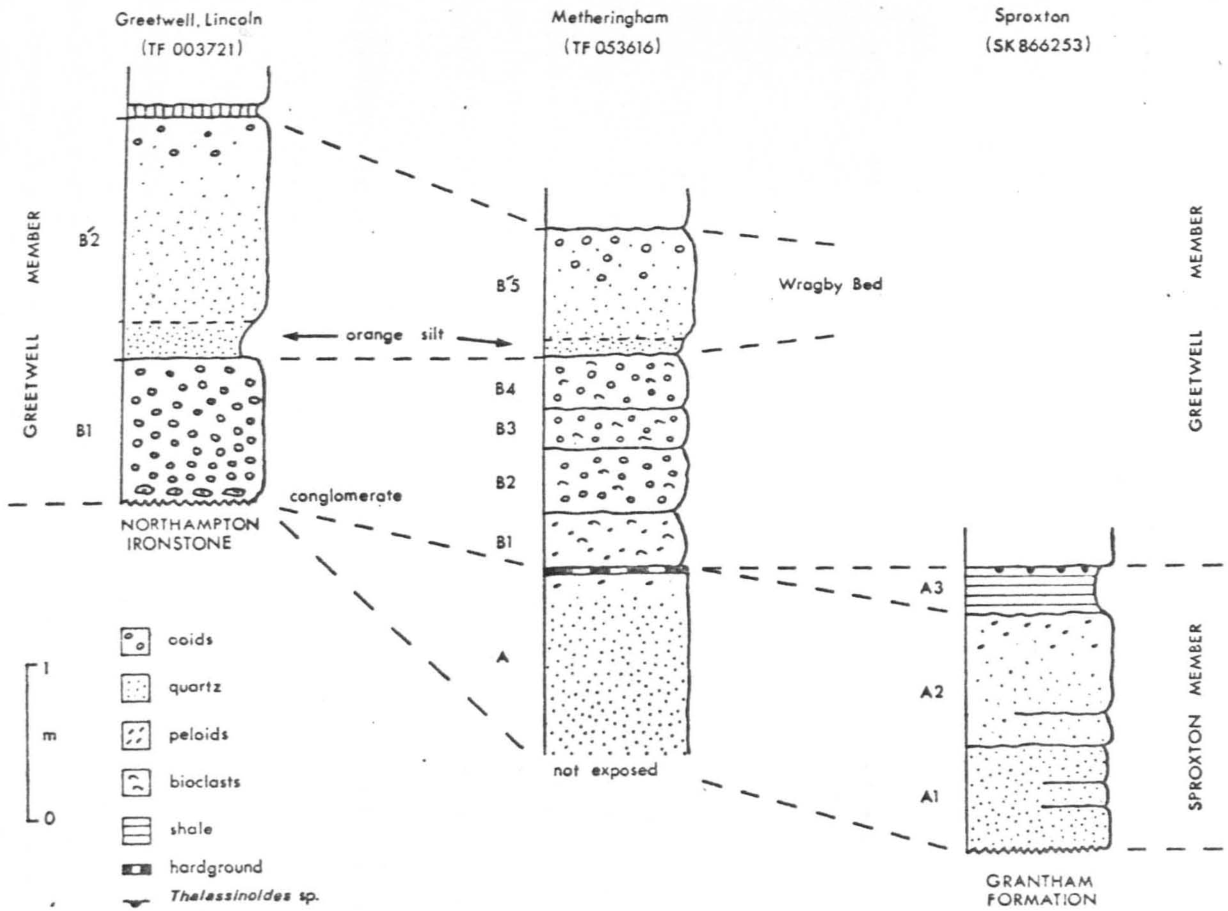

Greetwell, Lincoln
(TF 003721)
Metheringham
(TF 053616)
Sproxton
(SK 866253)
GREETWELL MEMBER
B2
B1
B5
B4
B3
B2
B1
A
Wragby Bed
orange silt
conglomerate
NORTHAMPTON IRONSTONE
not exposed
A3
A2
A1
GREETWELL MEMBER
SPROXTON MEMBER
GRANTHAM FORMATION
ooids
quartz
peloids
bioclasts
shale
hardground
Thalassinoides sp.
1
m
0

Fig. 4.11. The basal conglomerate of the Lincolnshire Limestone seen at Greetwell Hollow Quarry, Lincoln (TF 003721). The conglomerate occurs at the base of the Greetwell Member.

Fig. 4.12. Location map showing the main sedimentary provinces of the Greetwell Member and some important localities.

LGHQ	=	Greetwell Hollow Quarry, Lincoln
MQ	=	Metheringham Quarry
LQ	=	Leadenham Quarry
RQ	=	Ropsley Quarry
LPRC	=	Little Ponton Railway Cutting
WWQ	=	Waltham on the Wolds Quarry
SQ	=	Stainby Quarry
SWQ	=	South Witham Quarry
TQ	=	Thistleton Quarry
GQ	=	Greetham Quarry
WQ	=	Woolfox Quarry

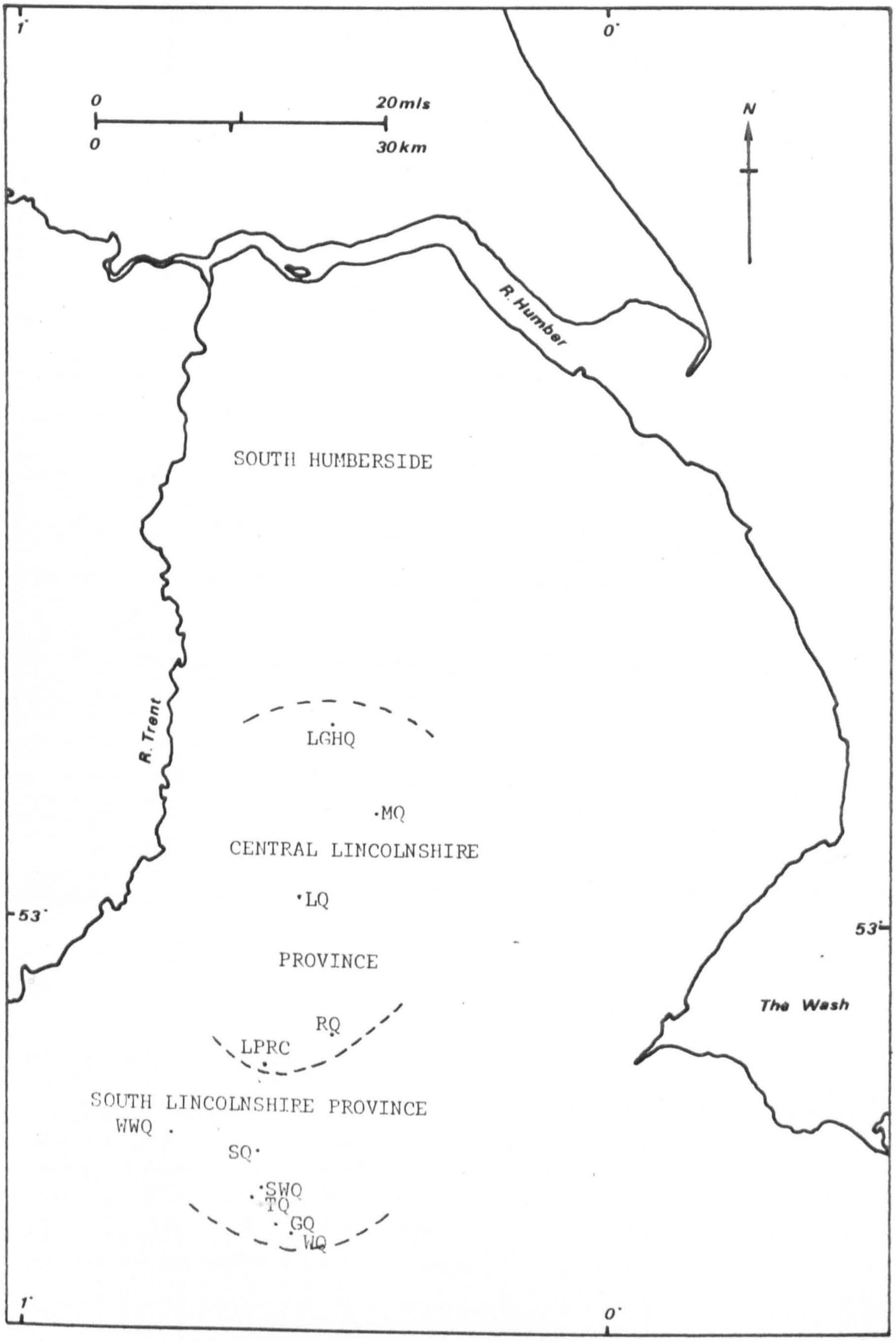

1°
0°
0
20 mls
0
30 km
N
R. Humber
SOUTH HUMBERSIDE
R. Trent
LGHQ
MQ
CENTRAL LINCOLNSHIRE
LQ
PROVINCE
53°
53°
The Wash
RQ
LPRC
SOUTH LINCOLNSHIRE PROVINCE
WWQ
SQ
SWQ
TQ
GQ
WQ
1°
0°

Fig. 4.13. The type section of the Greetwell Member exposed at Greetwell Hollow Quarry, Lincoln (TF 003721). The top (arrowed T) and base (arrowed B) are indicated.

Fig. 4.14. The hypostratotype of the Greetwell Member exposed at Sproxton Quarry (SK 866253). The top (arrowed T) and base (arrowed B) are indicated.

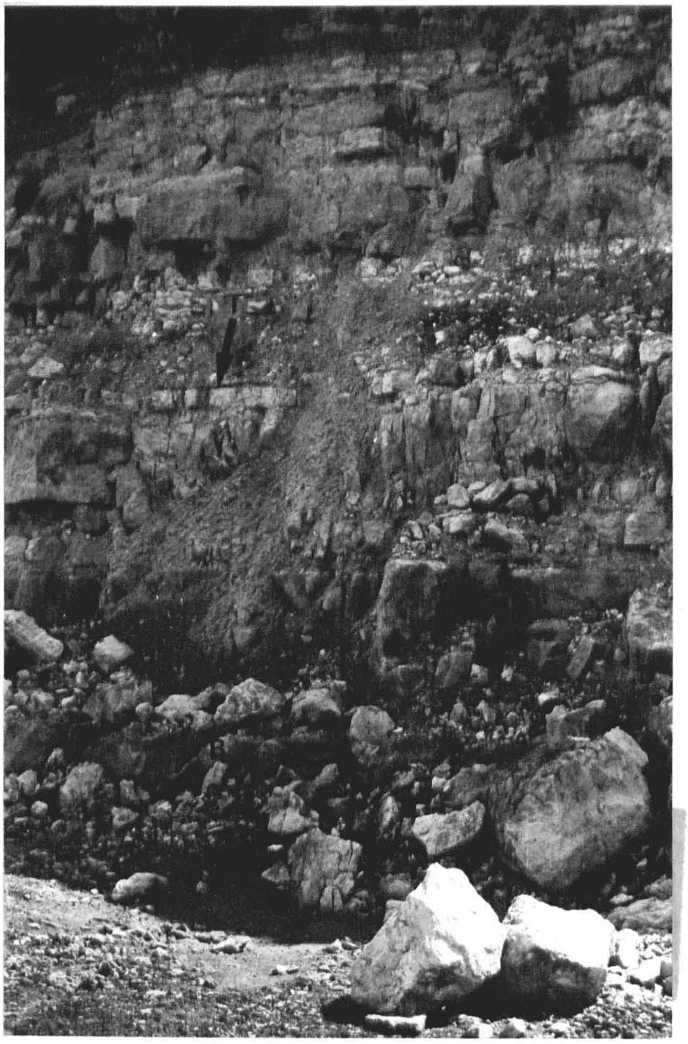


Fig. 4.15. Isopachyte map for the whole of the Greetwell Member. Isopachs are in metres. Basic data is taken from Fig. 4.1.

lg = Greetwell Hollow Quarry, Lincoln

m = Metheringham Quarry

l = Leadenham Quarry

a = Ancaster Railway Cutting

lp = Little Ponton Railway Cutting

ww = Waltham on the Wolds Quarry

sn = Sproxton Quarry

s = Stainby Quarry

sw = South Witham Quarry

t = Thistleton Quarry

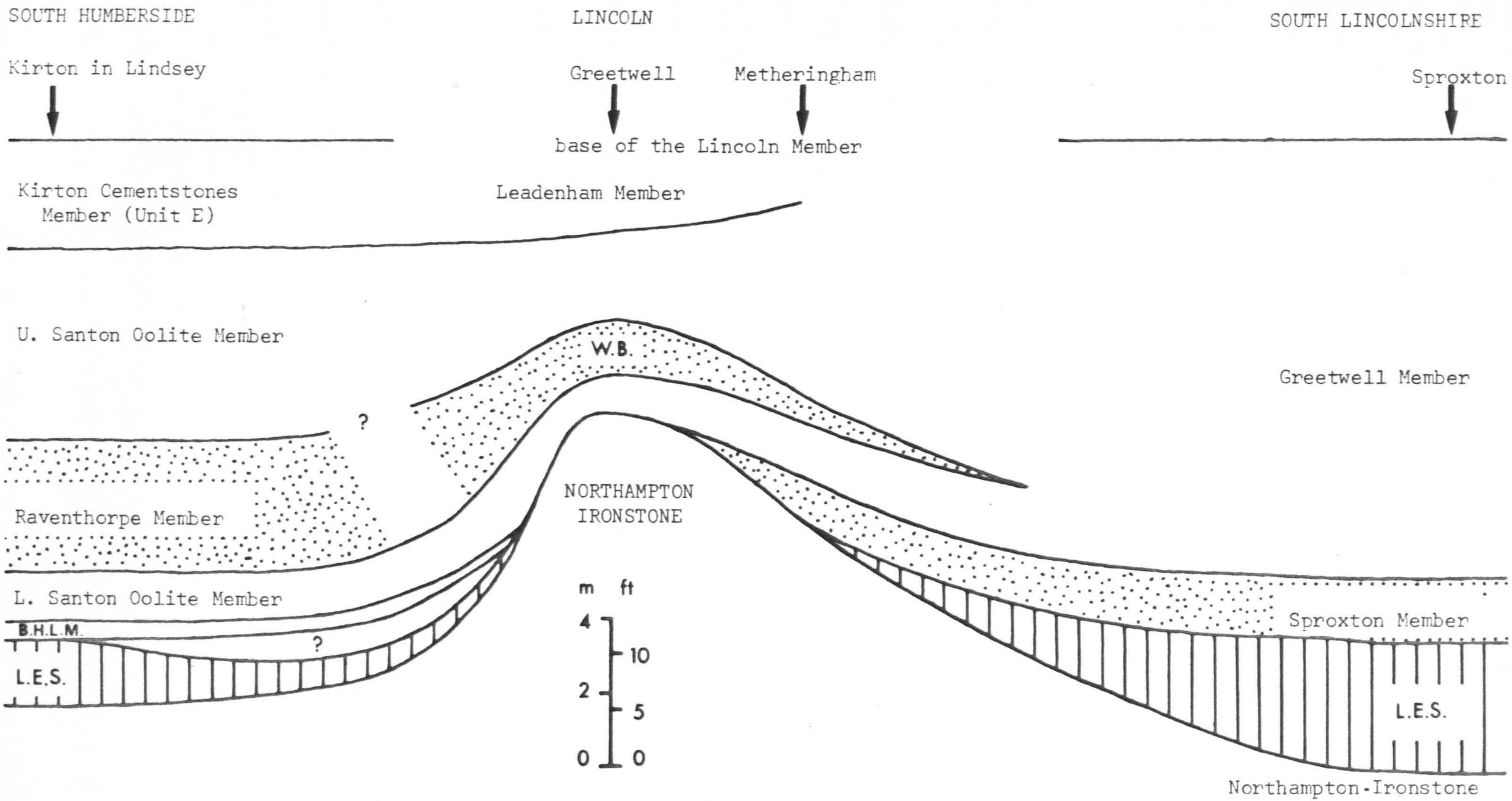
g = Greetham Quarry

w = Woolfox Quarry

lb = Little Bytham Quarry


1°
0°
0
20 mls
0
30 km
N
R. Humber
R. Trent
lg
5
6
7
m
l
53°
53°
a
7
8
9
lp
10
11
ww
sn
s
11·5
t
sw
lb
g
w
The Wash
1°
0°

Fig. 4.16. Semi-schematic correlation scheme proposed for the lower part of the Lincolnshire Limestone Formation between South Humberside and South Lincolnshire. The sections given for specific quarries in the Lincs. Lst. are to scale, with the base of the Lincoln Member (or its equivalent) being taken as the datum level. The Grantham Formation and Northampton Ironstone are not drawn to scale.

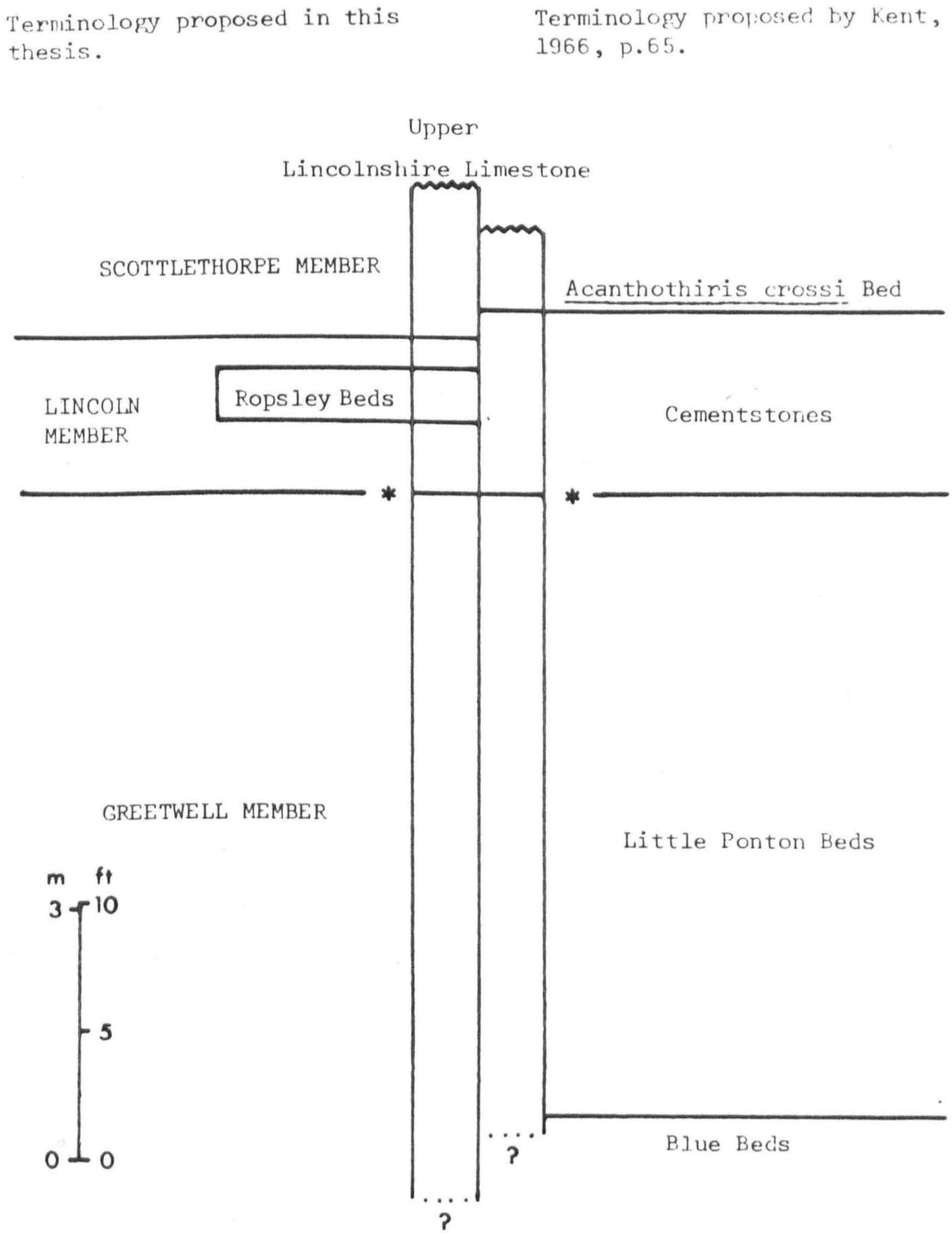


W.B. = Wragby Bed (of Greetwell Member)

B.H.L.M. = Basal Hydraulic Limestone Member

L.E.S. = Lower Estuarine Series = Grantham Formation

? Lowest Lincolnshire Limestone

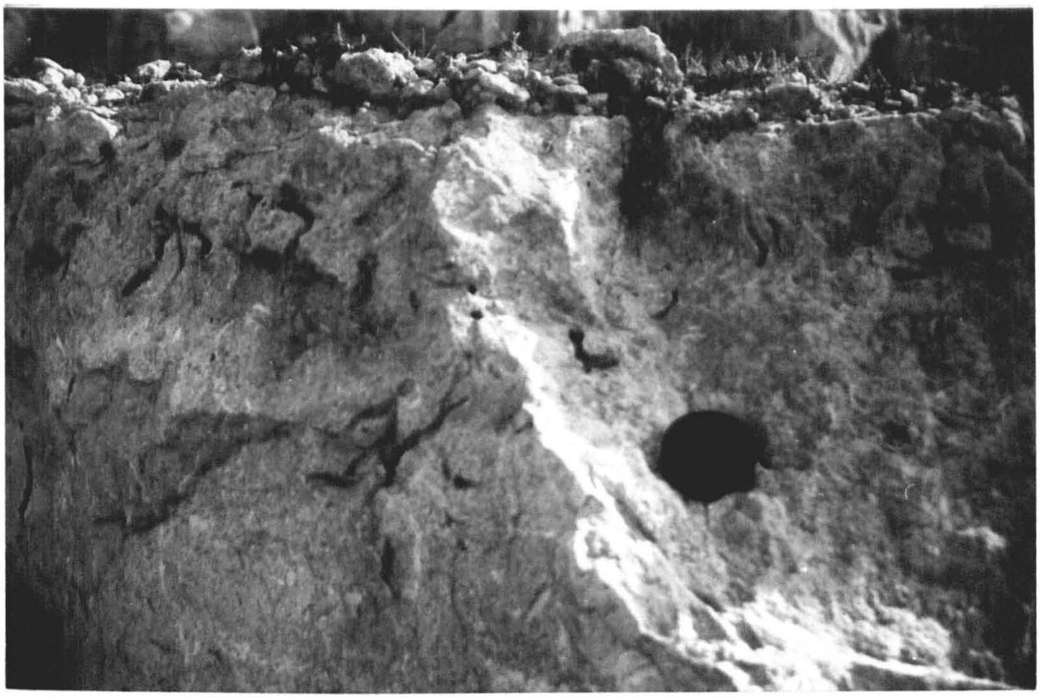


* level at which correlation between Kent's and the author's own section was made.

Fig. 4.17. The contrasting terminologies proposed for the lower part of the Lincolnshire Limestone at the Little Ponton Railway Cutting (SK 930320).

Fig. 4.18. Complex "open" burrow systems, typical of Lithofacies A of the Greetwell Member, seen in Leadenham Quarry (SK 962523).

Fig. 4.19. Complex "micrite-infilled" burrow systems, typical of Lithofacies A of the Greetwell Member, seen in Dunston Quarry (TF 053634).



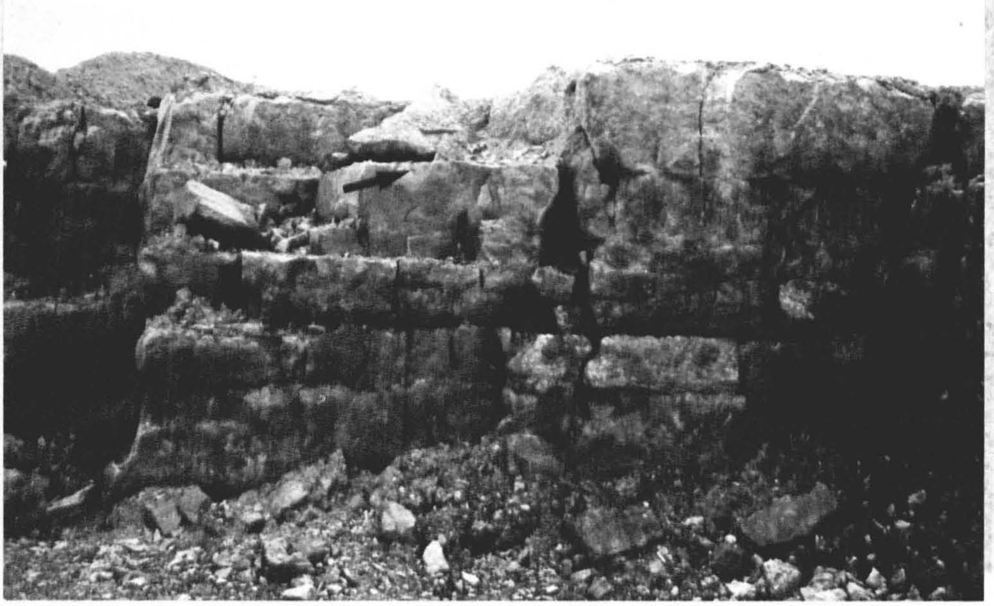
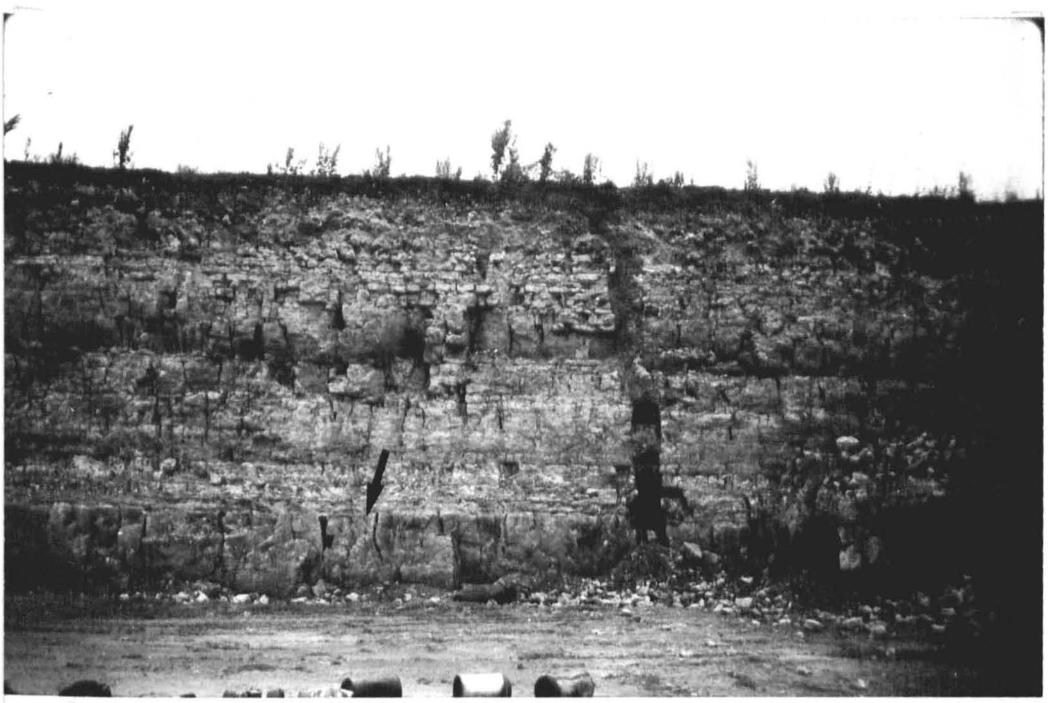


Fig. 4.20. Coral head (arrowed) seen in Lithofacies A of the Greetwell Member at Leadenham Quarry (SK 962523).

Fig. 4.21. Complex burrow systems, typical of Lithofacies A of the Greetwell Member, seen in Lithofacies B of that member at Leadenham Quarry (SK 962523).

Fig. 4.22. The hardground junction (arrowed) separating the Leadenham and Greetwell Members at Leadenham Quarry (SK 962523).



BED	LITHOFACIES	TYPICAL LITHOLOGY	GRAINS % OF TOTAL ROCK	GRAINS TYPE	GRAINS SIZE	MATRIX	TEXTURE
LQ B6	A	Oncolitic biomicrite	44% 13% 4% 4% traces	oncolites bioclasts ooliths peloids intraclasts	0.7 to 2.5 mm 0.3 to 2.7 mm 0.36 to 0.84 mm 0.09 to 0.22 mm -	Micrite ≫ Sparite	Wackestone
LDCP B3	A	Oncolitic oomicrite	20% 32% 5%	oncolites ooliths bioclasts	0.66 to 2.0 mm 0.07 to 0.7 mm 0.14 to 1.8 mm	Micrite > Sparite	Wackestone (bimodal)
RQ B2	A	Oncolitic pelsparite	57% 10% 6% 4%	oncolites peloids bioclasts ooliths	0.7 to 2.0 mm 0.062 to 0.19 mm 0.2 to 6.0 mm ≃ 0.4 mm	Sparite ≫ Micrite	Wackestone (bimodal)
RQ B1	A	Skeletal oosparite	63% 9% 4%	ooliths bioclasts intraclasts	0.8 to 0.48 mm rarely larger (1.1mm) 0.16 to 2.8 mm 0.4 to 0.7 mm	Sparite > Micrite	Packstone

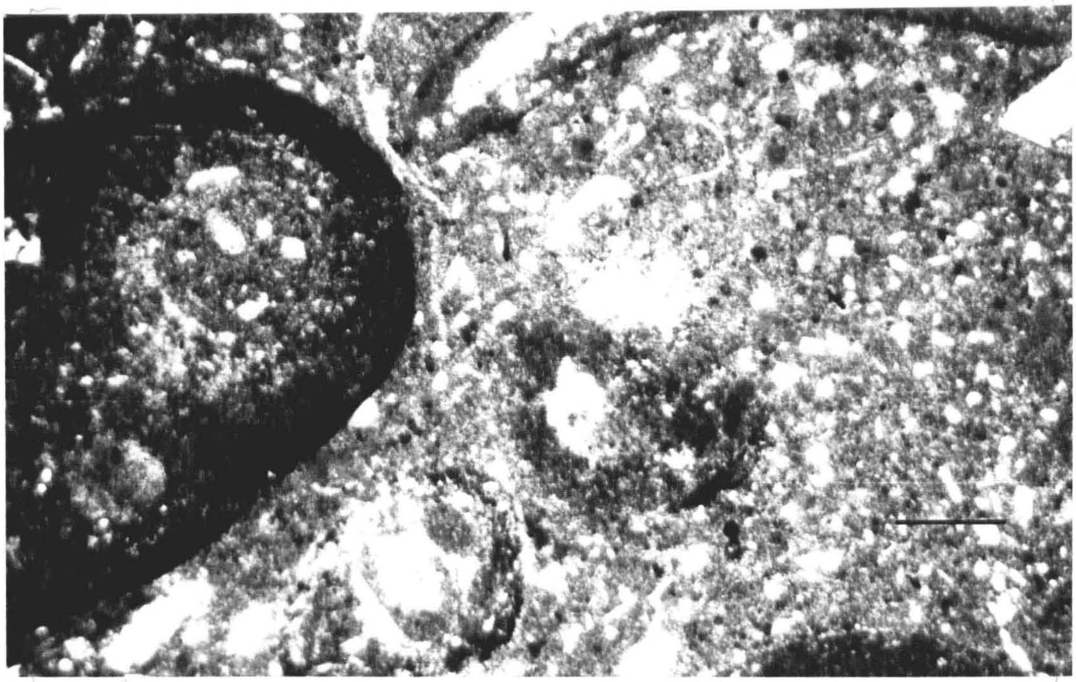
Fig. 4.23. The principal characteristics of Lithofacies A of the Greetwell Member in central Lincolnshire.

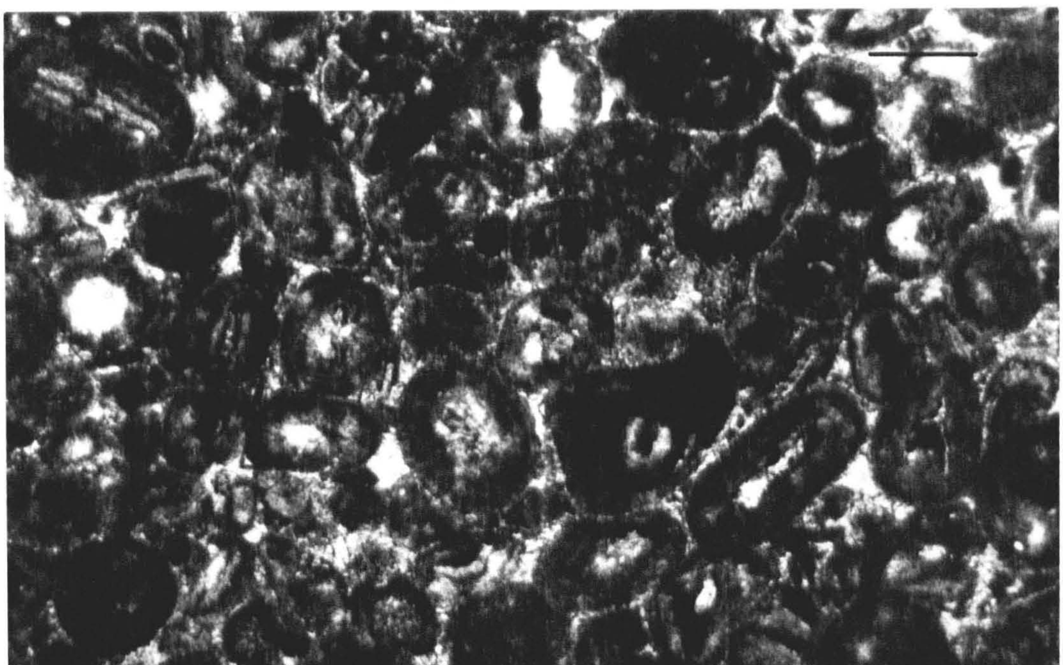
BED	LITHOFACIES	TYPICAL LITHOLOGY	GRAINS: % OF TOTAL ROCK	GRAINS: TYPE	GRAINS: SIZE	MATRIX	TEXTURE
LDCP B2	B	Bio-pelsparites	36%	peloids	practically all $<$ 0.125	Sparite $\gg$ Micrite	Packstone/ Grainstone (bimodal)
			22%	bioclasts	0.062 to 5.6 mm		
			1%	oncolites	0.35 to 1.5 mm		
			traces	ooliths	0.19 to 0.6 mm		
LGHQ B5b	B	Oncolitic bio-pelsparite	55%	peloids	practically all $<$ 0.125	Sparite $>$ Micrite	Packstone (bimodal)
			12%	bioclasts	0.062 to 4.4 mm		
			3%	oncolites	0.4 to 1.5 mm		
			3%	ooliths	0.19 to 0.6 mm		

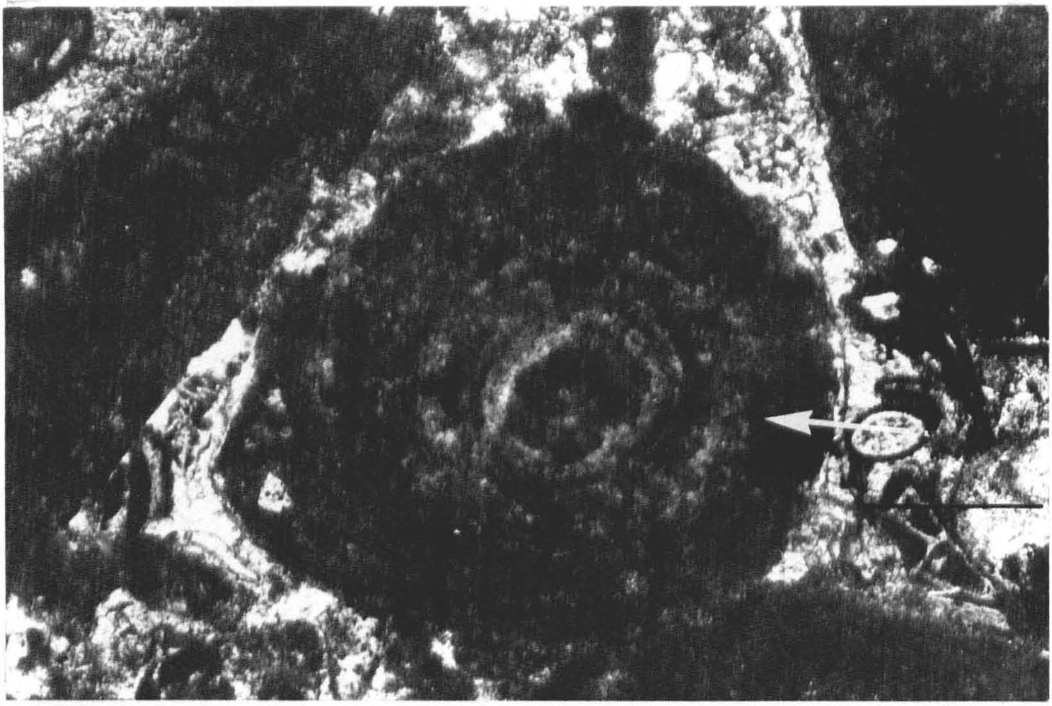
Fig. 4.24. The principal characteristics of Lithofacies B of the Greetwell Member in central Lincolnshire.

Fig. 4.25. Photomicrograph of an oncolitic biomicrite (bed LQ B6), typical of Lithofacies A of the Greetwell Member, seen in central Lincolnshire.

Fig. 4.26. Photomicrograph of a skeletal oosparite (bed RQ B1), typical of Lithofacies A of the Greetwell Member, seen in central Lincolnshire.







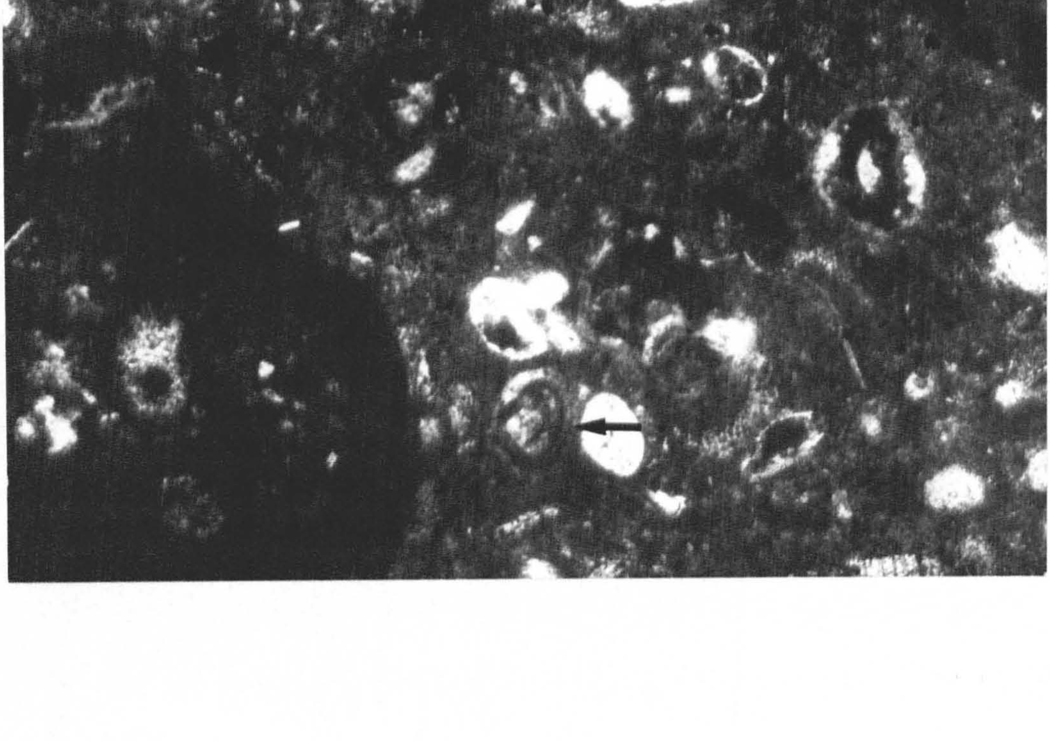
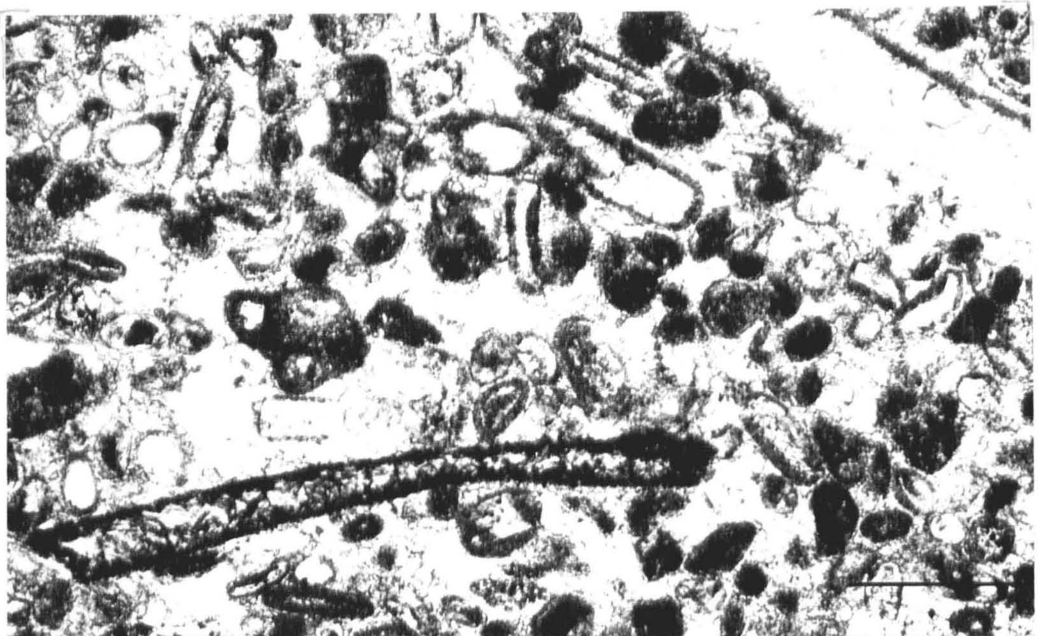


Fig. 4.27. Photomicrograph of an oncolitic pelsparite (bed RQ B2), typical of Lithofacies A of the Greetwell Member, seen in central Lincolnshire. Note particularly the oolith cores of the oncolites (arrowed).

Fig. 4.28. Photomicrograph of an oncolitic oomicrite (bed LDCP B3), typical of Lithofacies A of the Greetwell Member, seen in central Lincolnshire. Note particularly the interstitial incipient ooliths (arrowed).

Fig. 4.29. Photomicrograph of a biopelsparite (bed LDCP B2), typical of Lithofacies B of the Greetwell Member, seen in central Lincolnshire.

Fig. 4.30. Photomicrograph of a biopelsparite (bed LQ B4c) typical of Lithofacies B of the Greetwell Member, seen in central Lincolnshire.



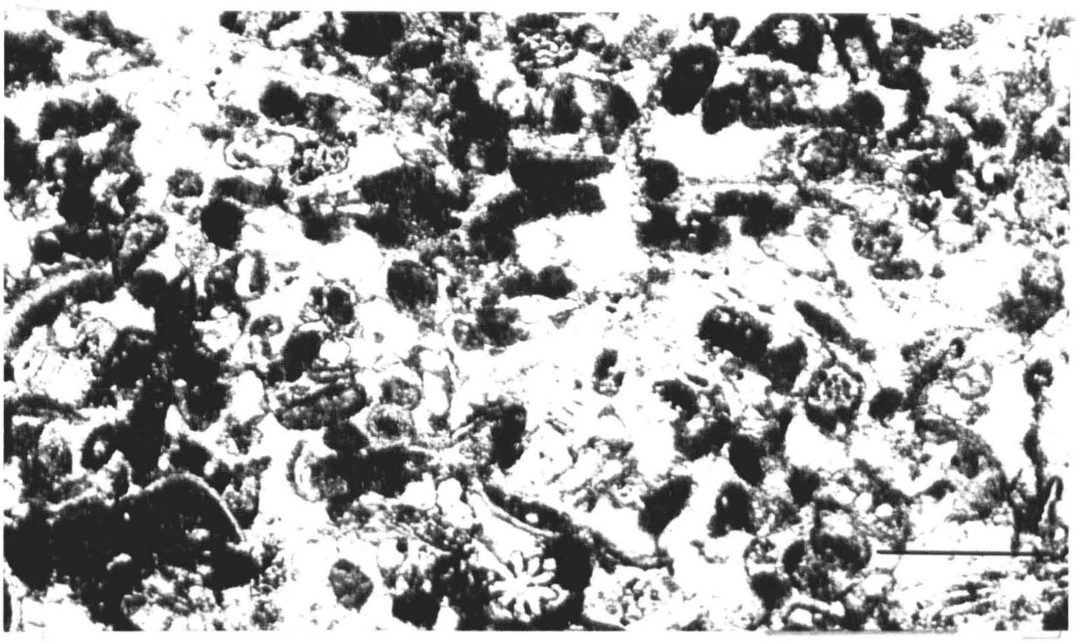
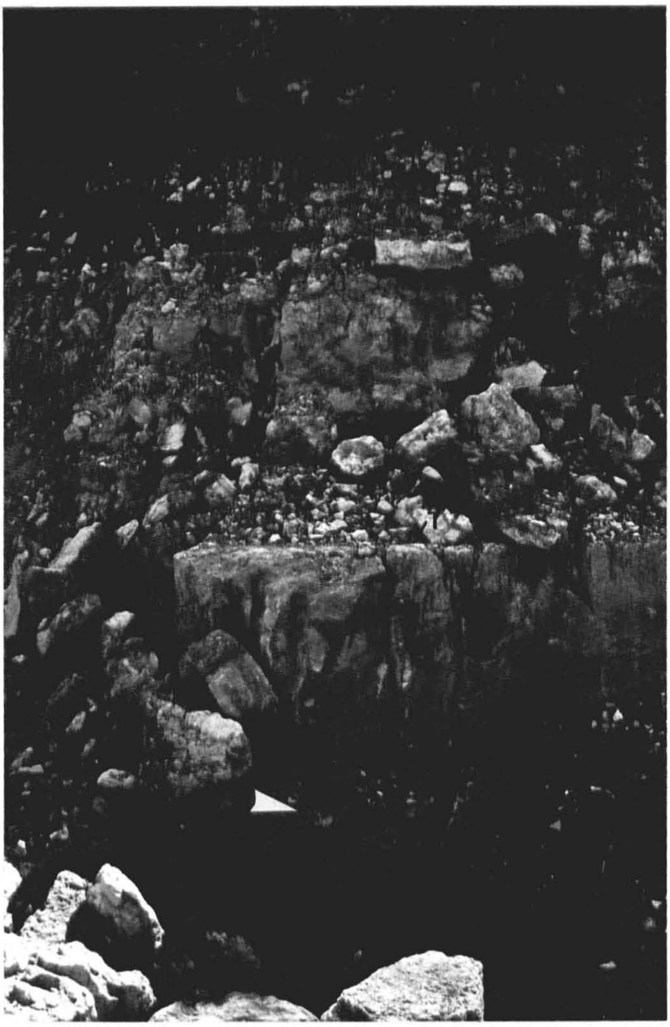


Fig. 4.31. The type section of the Wragby Bed of the Greetwell Member exposed at Greetwell Hollow Quarry, Lincoln (TF 003721). The top (arrowed T) and base (arrowed B) are indicated.



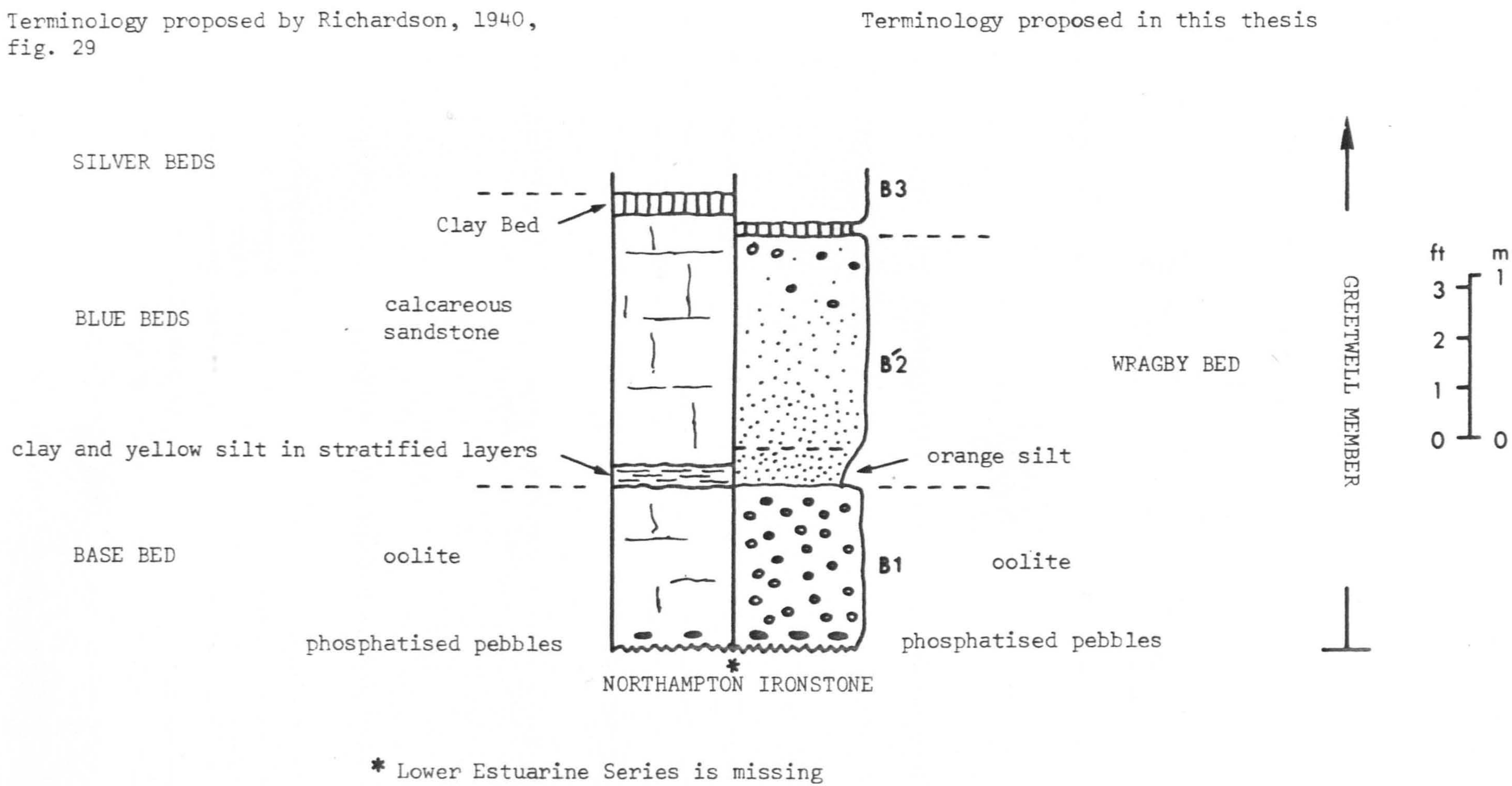


Fig. 4.32. The contrasting interpretations and terminologies applied to the lowest part of the Lincolnshire Limestone Formation at Greetwell Hollow, Lincoln (TF 003721).

Fig. 4.33. The Metheringham Quarry sequence (TF 053616) showing the Wragby Bed (arrowed WB) and the Sproxton Member (arrowed SM).

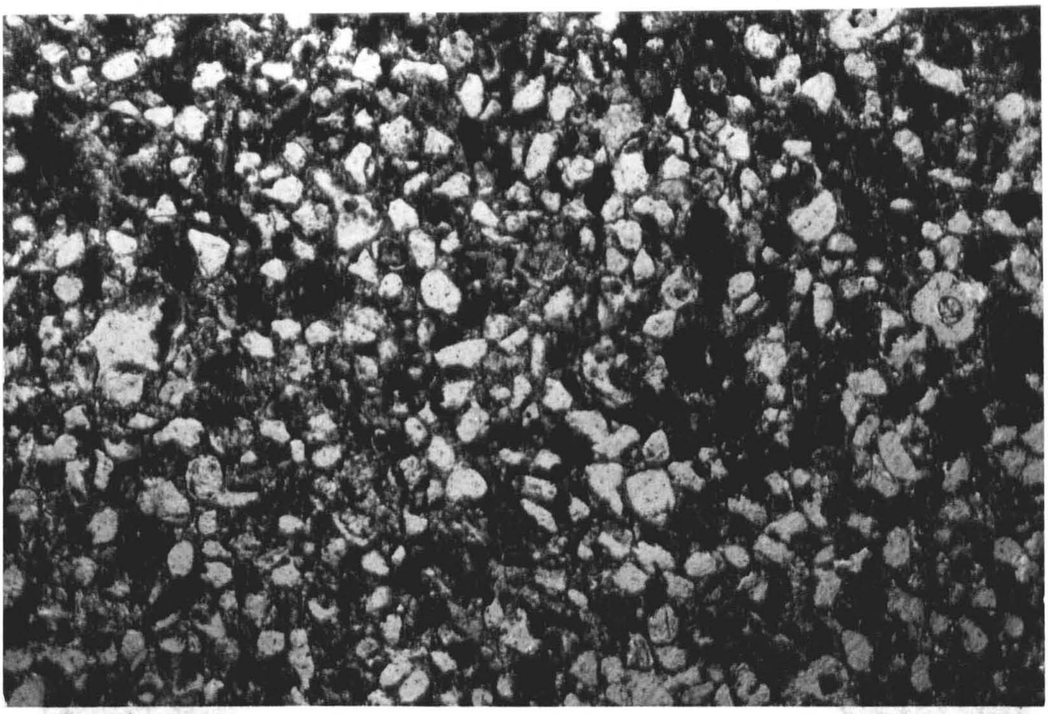

VB
SM

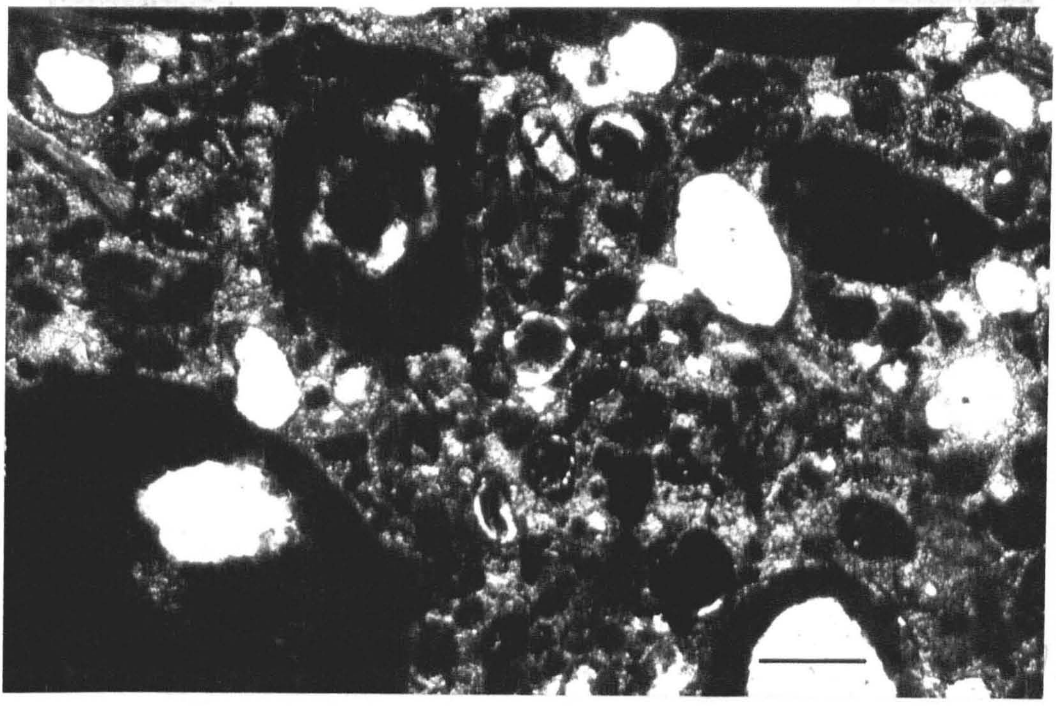
BED	LITHOFACIES	TYPICAL LITHOLOGY	GRAINS			MATRIX	TEXTURE
			% OF TOTAL ROCK	TYPE	SIZE		
MQ B́5b	–	3. Oncolitic biopelsparite	5%	oncolites	0.8 to 2.2 mm	Sparite > Micrite	Packstone (bimodal)
			8%	bioclasts	0.3 to 2.4 mm		
			37%	peloids	below 0.15 mm		
			6%	ooliths	0.5 to 1.1 mm		
			3%	quartz	silt to v. fine sand		
LGHQ B́2b	–	2. Quartzose pelsparite	23%	quartz	silt to v. fine sand	Sparite > Micrite	Packstone
			21%	peloids	usually $<$ 0.125 mm		
			9%	bioclasts	0.125 to 1.6 mm		

Fig. 4.34. The principal lithological characteristics of the Wragby Bed.

Fig. 4.35. Photomicrograph of a quartzose pelsparite (bed LGHQ B′2b), typical of Lithology 2 of the Wragby Bed (Greetwell Member).

Fig. 4.36. Photomicrograph of an oncolitic biopelsparite (bed MQ B′5b), typical of Lithology 3 of the Wragby Bed (Greetwell Member).





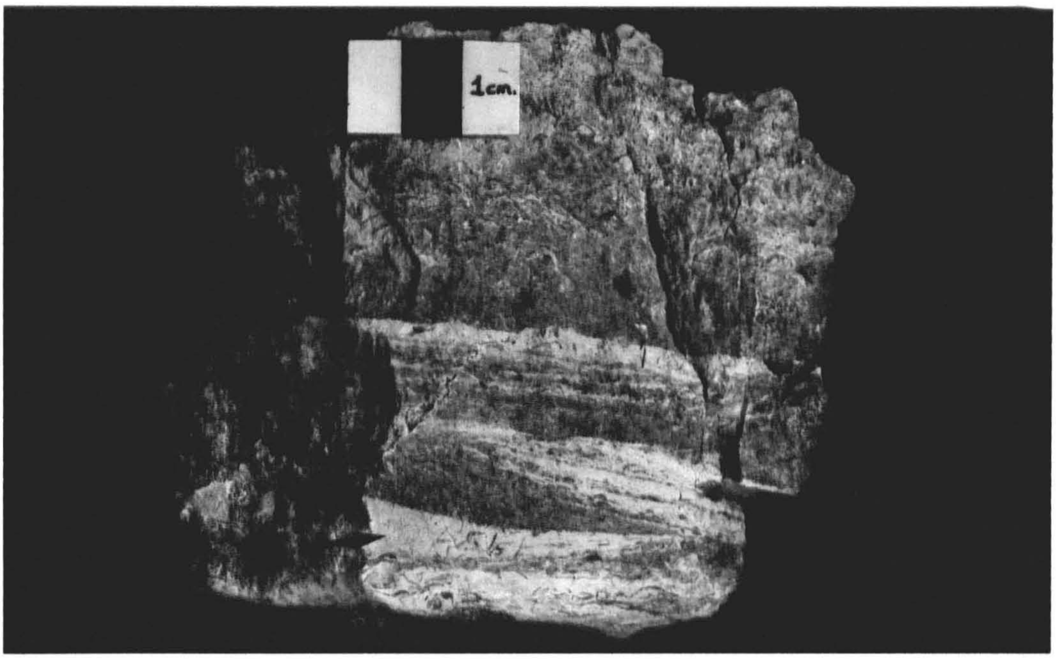

B

Fig. 4.37. The type section of the Market Overton beds (Greetwell Member of south Lincolnshire) exposed at Thistleton Quarry (SK 903180). The top (arrowed T) and base (arrowed B) are indicated.

Fig. 4.38. Laminations seen in Subfacies B1 of the Market Overton beds (Greetwell Member) at Stainby (SK 910233). Fine peloid-rich/peloid poor laminae with "single fossil stringers" (arrowed 1) and coarser, parallel or cross laminations of alternating bioclastic-rich/bioclastic-poor laminae (arrowed 2) are indicated.

Fig. 4.39. Alternating bioclastic/micritic laminae seen in Subfacies B1 of the Market Overton beds (Greetwell Member) at Sproxton (SK 866253). Both parallel and cross-laminated sequences can be seen. (Block from bed SNQ BA 5b). Note particularly the irregular bases and flat tops of the micritic micro-beds (arrowed), which have suffered later scour in some cases.


1
2
1cm.


1cm.

BED	LITHOFACIES	TYPICAL LITHOLOGY	GRAINS			MATRIX	TEXTURE
			% OF TOTAL ROCK	TYPE	SIZE		
TQ BA3	A	Silty biomicrite	19% 3%	quartz bioclasts	silt to v. fine sand 0.2 to 3.0 mm mostly > 0.5 mm	Micrite	Mudstone (without silt) Wackestone
TQ BA1	A	Biomicrite	7% 2% 1%	bioclasts peloids quartz	0.2 to 4.8 mm 0.031 to 0.46 mm silt to v. fine sand	Micrite	Wackestone

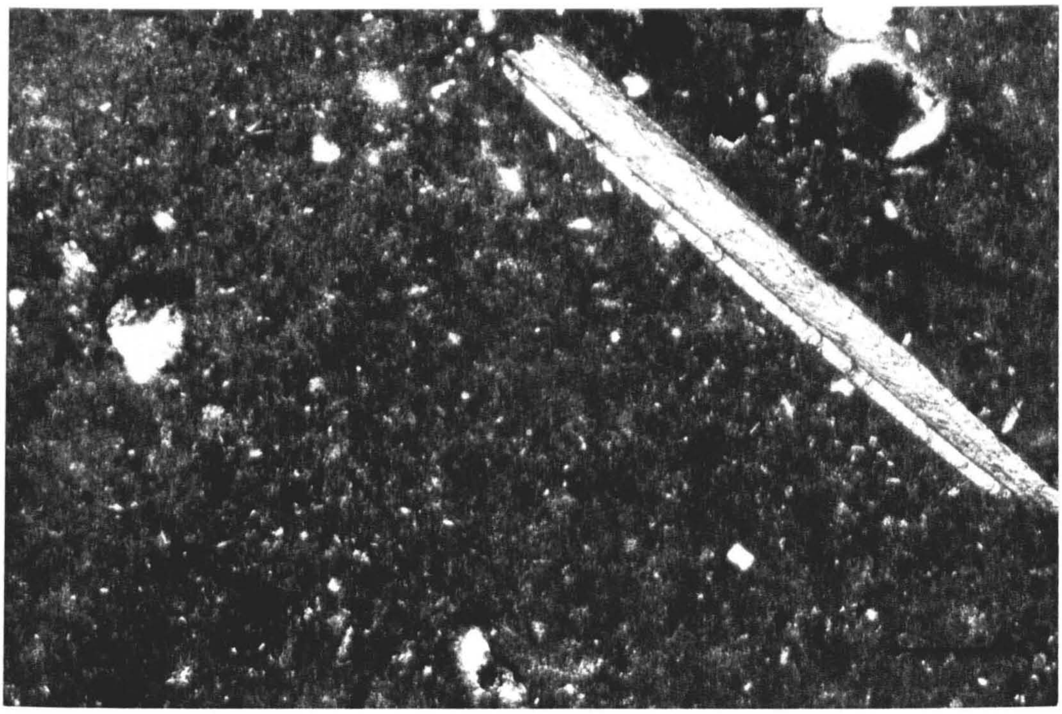
Fig. 4.40. The principal characteristics of Lithofacies A of the Market Overton beds (Greetwell Member of south Lincolnshire).

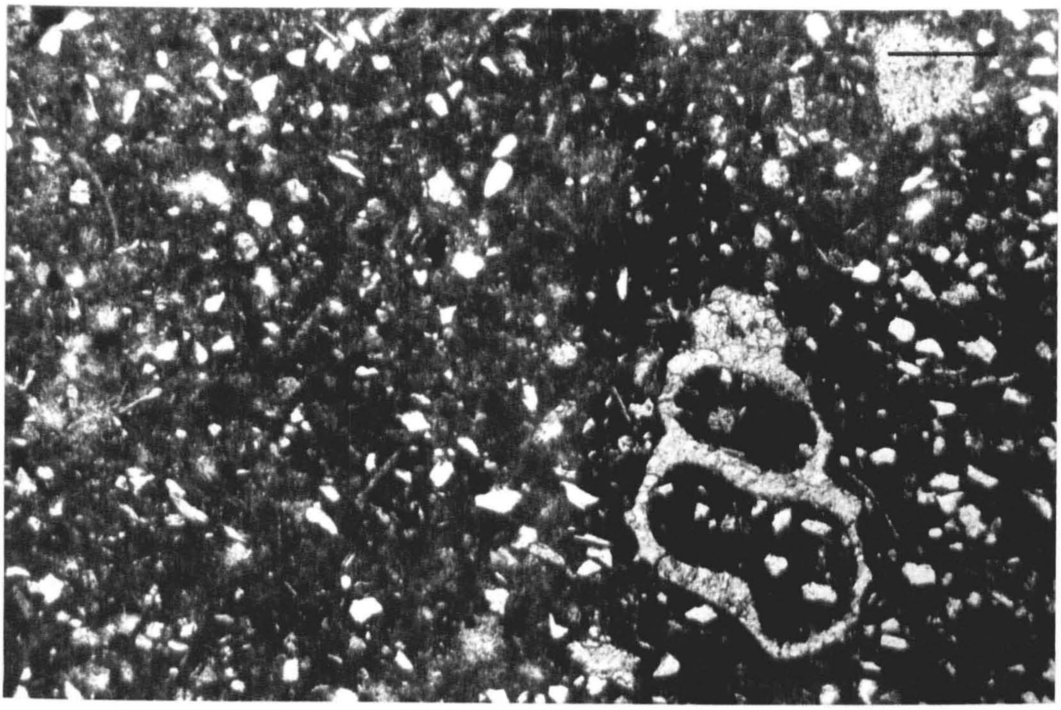
BED	LITHOFACIES	TYPICAL LITHOLOGY	GRAINS			MATRIX	TEXTURE
			% OF TOTAL ROCK	TYPE	SIZE		
TQ BA5c	B	Pelsparite	41%	peloids	mostly < 0.125 mm max. seen 0.3 mm	Sparite ≏ Micrite	Packstone
			7%	bioclasts	0.09 to 1.6 mm		
			2%	intraclasts	0.6 to 2.2 mm		
			13%	ooliths	0.4 to 1.05 mm		
			1%	oncolites	0.9 to 2.6 mm		
			2%	quartz	silt to v. fine sand		
SNQ BA2	B	Silty biopelsparite	13%	bioclasts	0.15 to 4.1 mm	Sparite > Micrite	Packstone
			35%	peloids	mostly 0.025 to 0.031 max. seen 0.3 mm		
			traces	intraclasts	≏ 0.4 mm		
			17%	quartz	silt to v. fine sand		

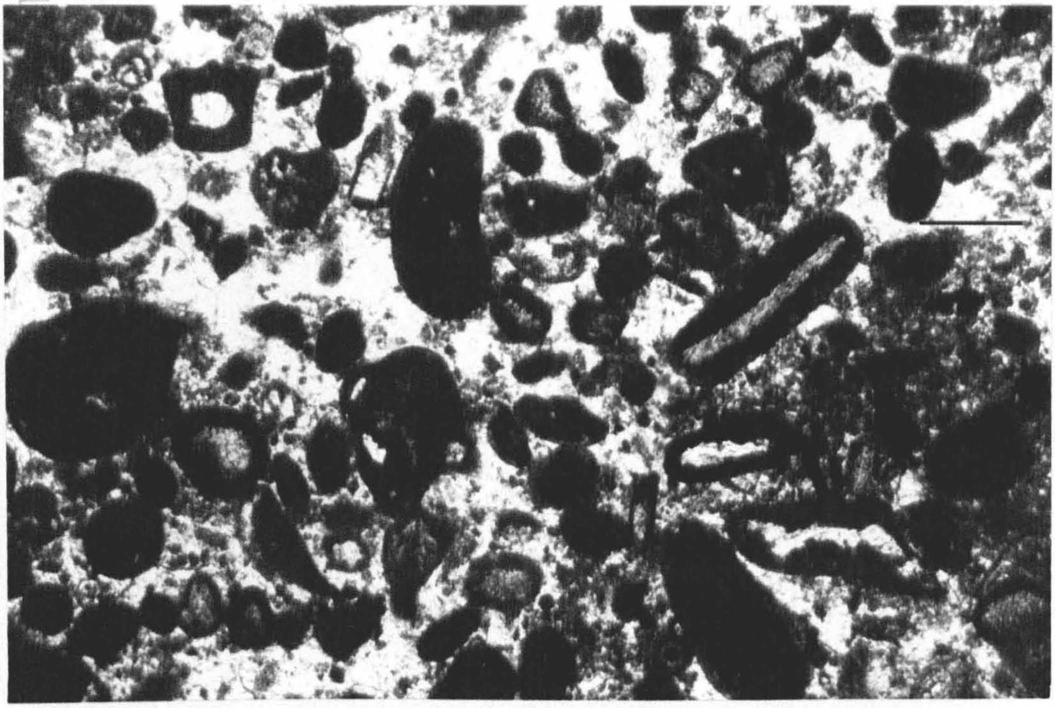
Fig. 4.41. The principal characteristics of Lithofacies B of the Market Overton beds (Greetwell Member of south Lincolnshire).

Fig. 4.42. Photomicrograph of a biomicrite (bed TQ BA 1), typical of Lithofacies A of the Market Overton beds (Greetwell Member of south Lincolnshire).

Fig. 4.43. Photomicrograph of a silty biomicrite (bed TQ BA 3), typical of Lithofacies A of the Market Overton beds (Greetwell Member of south Lincolnshire).





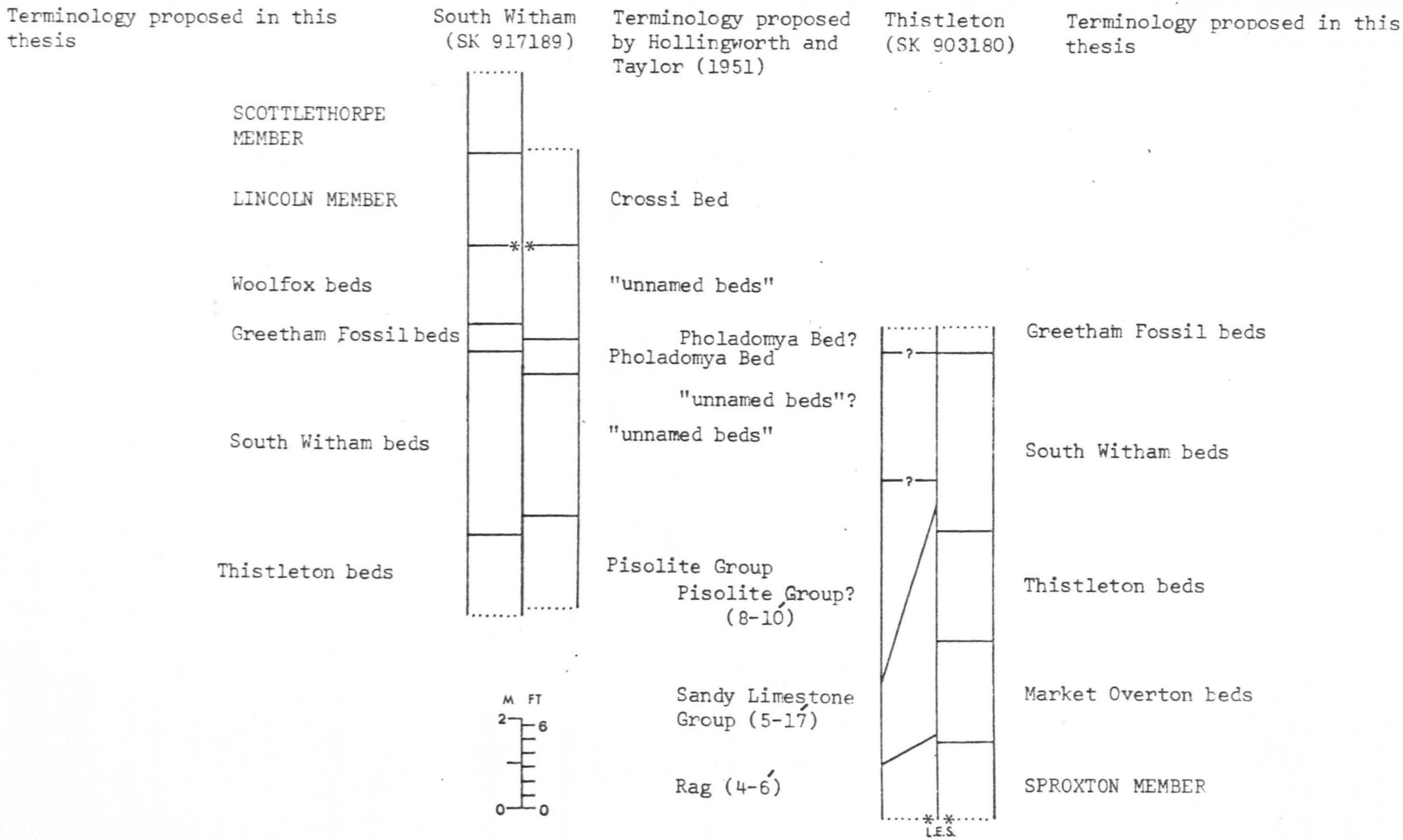



T
B

Fig. 4.44. Photomicrograph of a pelsparite (bed TQ BA 5c), typical of Lithofacies B of the Market Overton beds (Greetwell Member of south Lincolnshire).

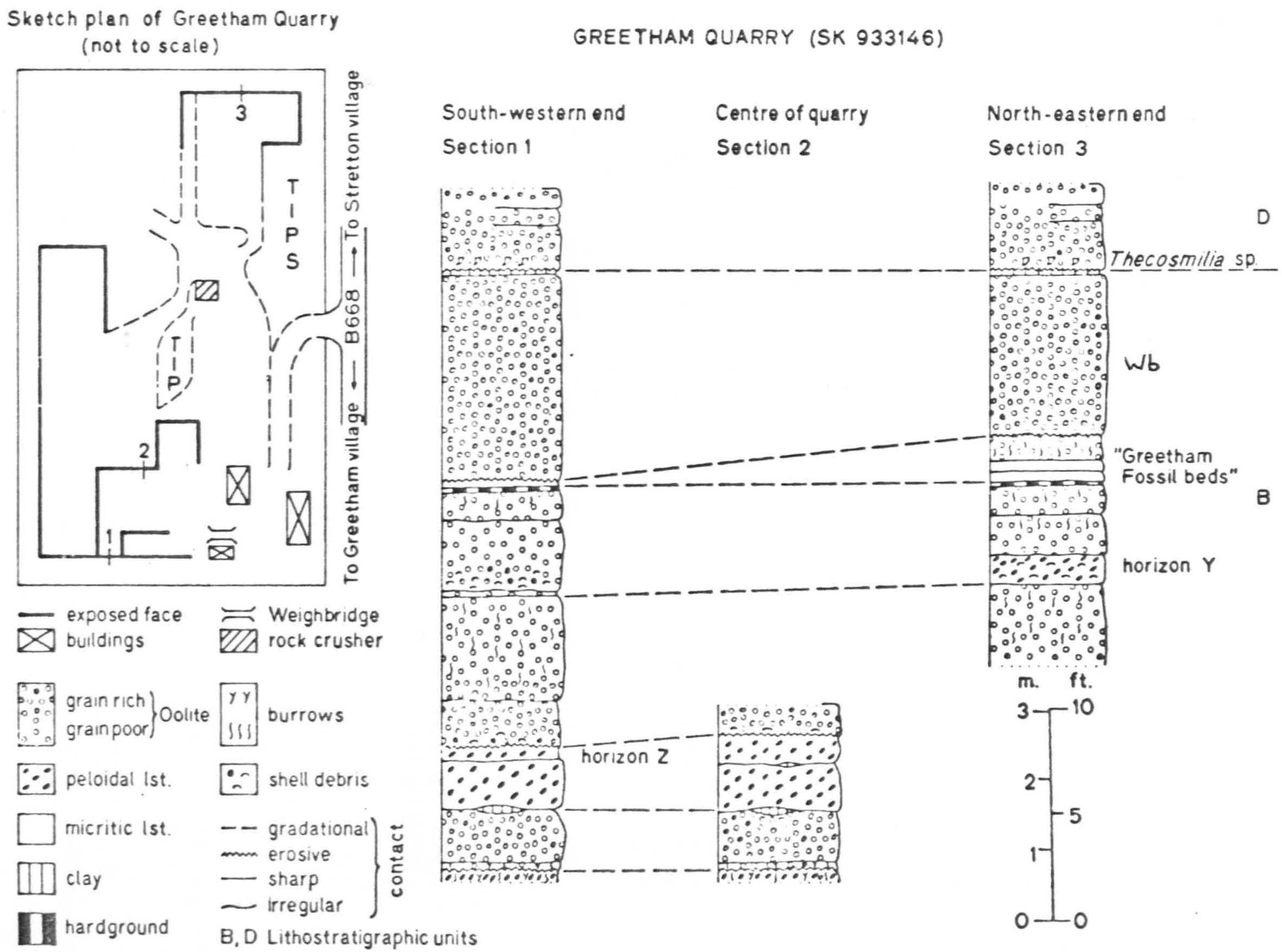
Fig. 4.45. The type section of the Thistleton beds (Greetwell Member of south Lincolnshire) exposed at Thistleton Quarry (SK 903180). The top (arrowed T) and base (arrowed B) are indicated.

Fig. 4.46. The contrasting terminologies and stratigraphic interpretations, which have been applied to the lower part of the Lincolnshire Limestone at Thistleton (SK 903180) and south Witham (SK 917189) quarries.



* Correlation level between author's own section and that of Hollingworth and Taylor (1951)

Fig. 4.47. The erosive downcutting of the Woolfox beds (Greetwell Member) into the Greetham Fossil beds (Greetwell Member) seen in Greetham Quarry (SK 933146).



Sketch plan of Greetham Quarry
(not to scale)
T I P S
T I P
1
2
3
To Stretton village
B668
To Greetham village
exposed face
buildings
Weighbridge
rock crusher
grain rich
grain poor
Oolite
burrows
peloidal lst.
shell debris
micritic lst.
clay
hardground
gradational
erosive
sharp
irregular
contact
B, D Lithostratigraphic units
GREETHAM QUARRY (SK 933146)
South-western end
Section 1
Centre of quarry
Section 2
North-eastern end
Section 3
D
Thecosmilia sp.
Wb
"Greetham
Fossil beds"
B
horizon Y
horizon Z
m.
ft.
3
10
2
5
1
0
0

Fig. 4.48. Finely laminated (arrowed), peloidal calcarenites typical of Subfacies C1 of the Thistleton beds (Greetwell Member) pictured at Thistleton Quarry (SK 903180). Bed TQ BB3 is pictured.

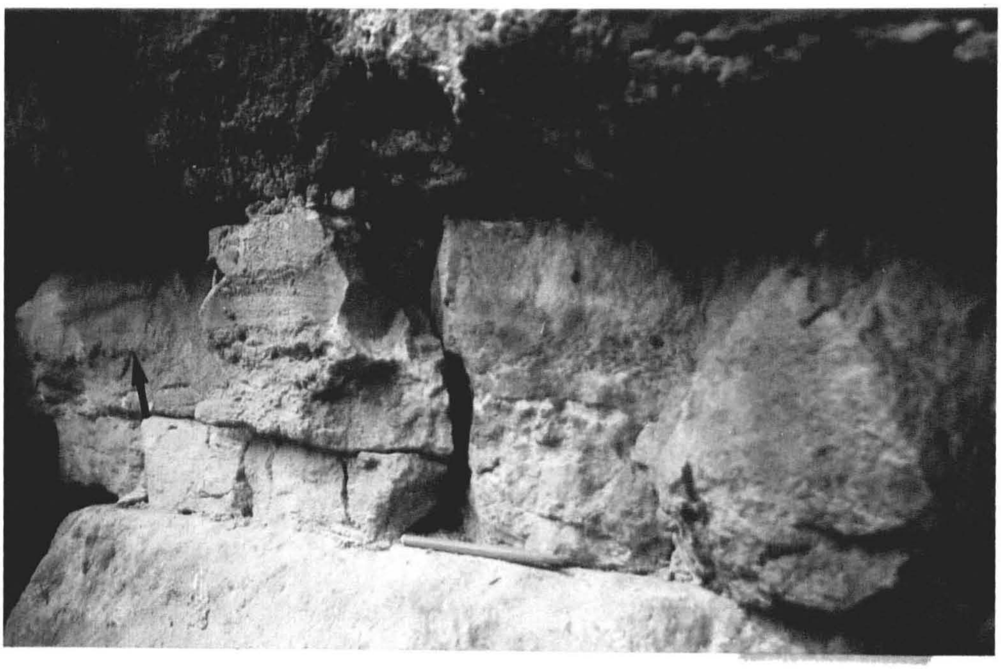
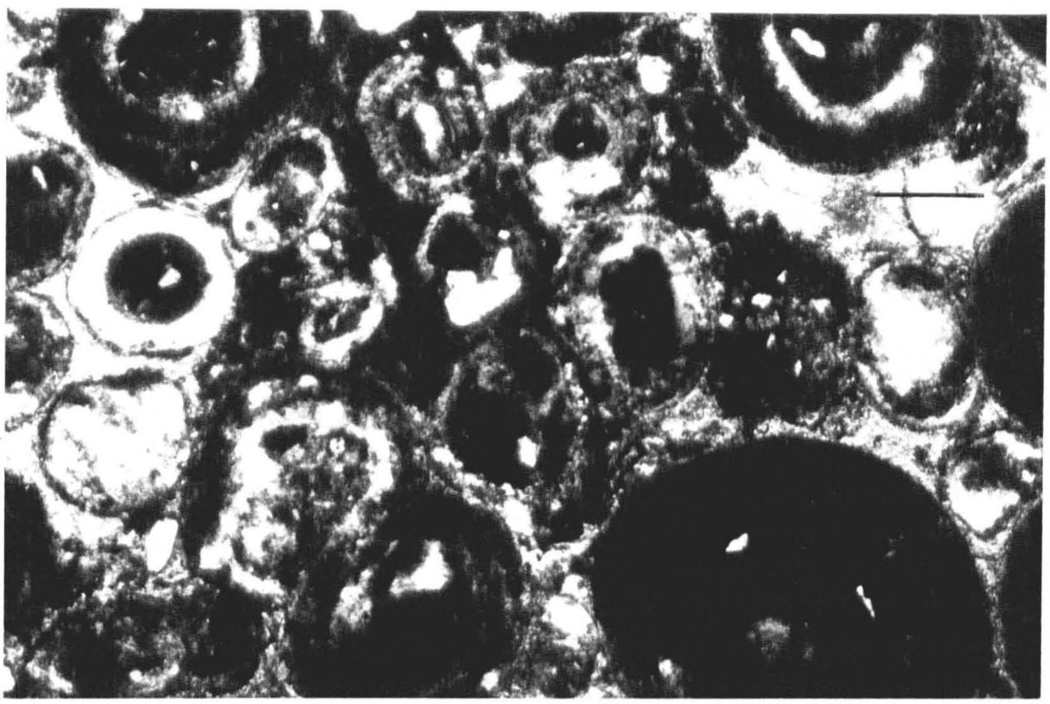


Fig. 4.49. The principal characteristics of the lithofacies of the Thistleton beds (Greetwell Member of south Lincolnshire).

BED	LITHOFACIES	TYPICAL LITHOLOGY	GRAINS: % OF TOTAL ROCK	GRAINS: TYPE	GRAINS: SIZE	MATRIX	TEXTURE
TQ BBS	C	Skeletal pelsparite	47% 17% 2% traces 3%	peloids bioclasts ooliths oncolites quartz	0.062 to 0.125 mm 0.062 to 2.7 mm 0.3 to 1.1 mm 0.7 to 1.8 mm silt to v. fine sand	Sparite ≫ Micrite	Packstone
TQ BB4	C	Skeletal pelsparite	45% 8% 1% 3%	peloids bioclasts ooliths quartz	mostly 0.04 to 0.125 mm max. seen 0.3 mm 0.05 to 2.8 mm 0.3 mm silt to v. fine sand	Sparite ≫ Micrite	Packstone
TQ BB3	C	Skeletal pelsparite	55% 4% traces 1% 5%	peloids bioclasts ooliths intraclasts quartz	0.062 to 0.19 mm 0.065 to 1.6 mm 0.09 to 0.3 mm ≃ 1.8 mm silt to v. fine sand	Sparite ≫ Micrite	Packstone
TQ BB2	B	Oosparite	54% 2% 2% 10% 7%	ooliths bioclasts oncolites intraclasts peloids	0.2 to 0.7 mm 0.18 to 2.6 mm 0.6 to 1.6 mm 2.2 mm 0.031 to 0.125 mm	Sparite > Micrite	Packstone
TQ BB1	A	Oolitic biosparite	50% 6% 7% 3%	bioclasts ooliths intraclasts peloids	0.2 to 3.8 mm mostly 0.2 to 0.6 mm max. seen 1.1 mm 0.8 to 2.1 mm < 0.2 mm	Sparite	Grainstone

Fig. 4.50. Photomicrograph of an oolitic biosparite (bed TQ BB 1), typical of Lithofacies A of the Thistleton beds (Greetwell Member of south Lincolnshire).

Fig. 4.51. Photomicrograph of an oosparite (bed TQ BB 2), typical of Lithofacies B of the Thistleton beds (Greetwell Member of south Lincolnshire).



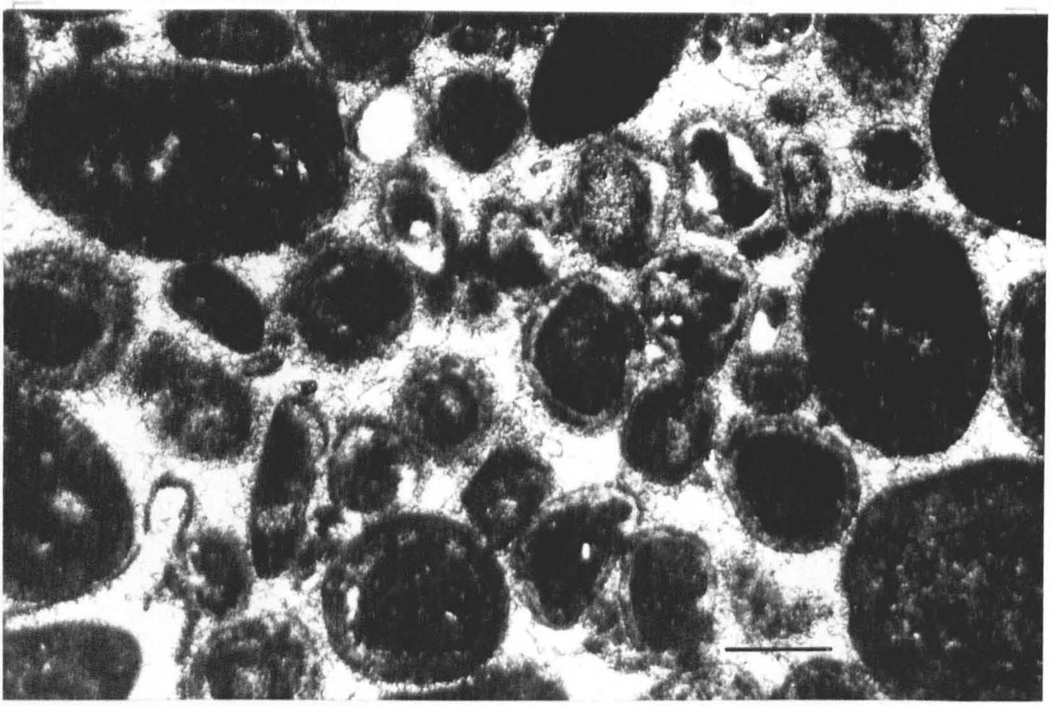
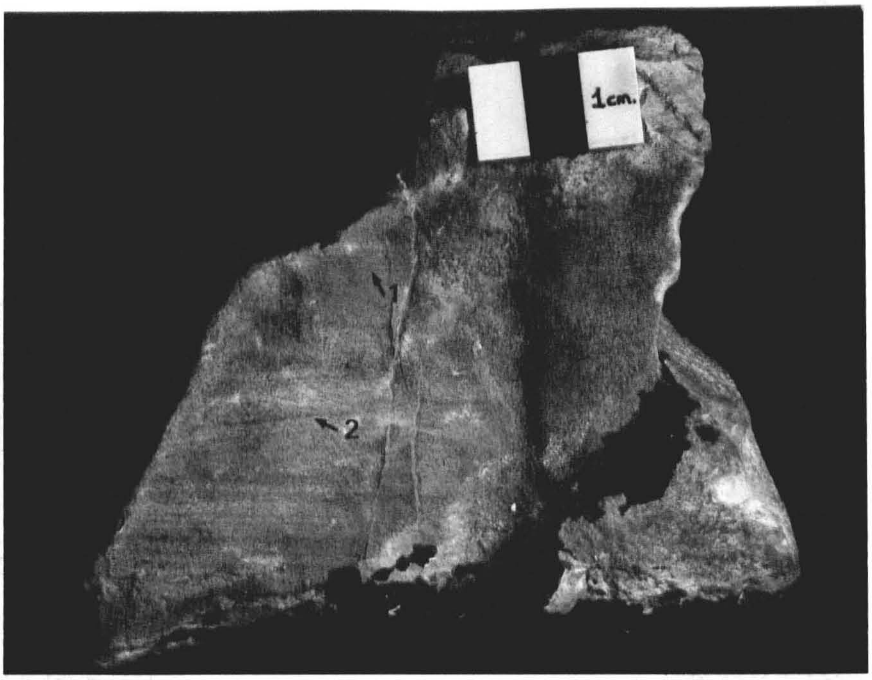


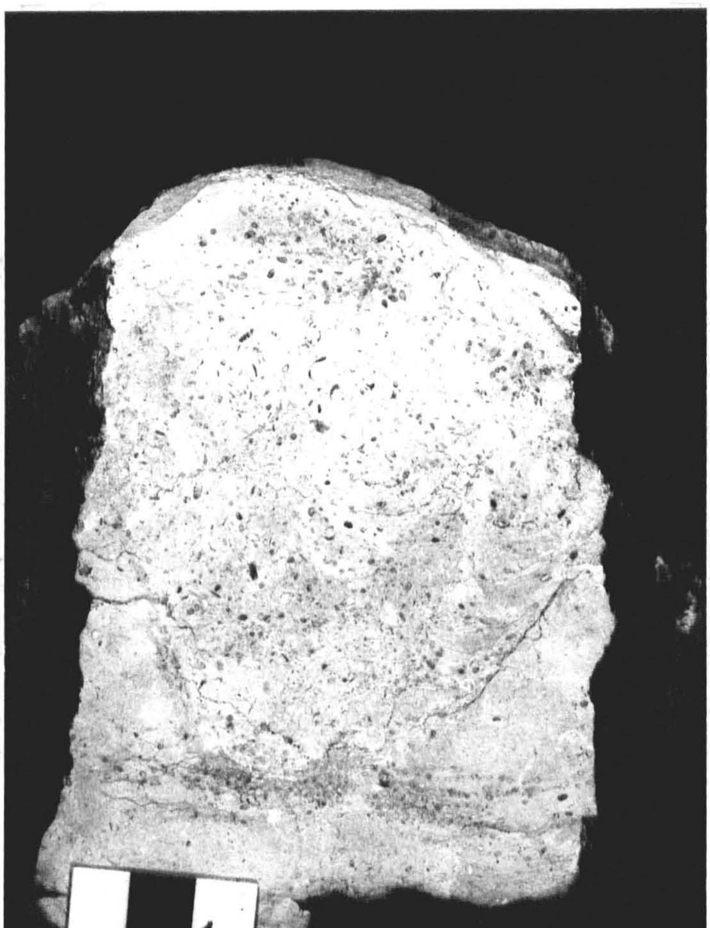
Fig. 4.52. Photomicrograph of an oosparite (bed SWQ BB 1), typical of Lithofacies B1 of the Thistleton beds (Greetwell Member of south Lincolnshire).

Fig. 4.53. Photomicrograph of a skeletal pelsparite (bed TQ BB 3), typical of Lithofacies C of the Thistleton beds (Greetwell Member of south Lincolnshire).

Fig. 4.54. Very fine parallel (arrowed 1) and cross laminations (arrowed 2) seen in peloidal calcarenites, typical of Subfacies C1 of the Thistleton beds (Greetwell Member). A weathered face of a block from bed TQ BB3 is pictured.

Fig. 4.55. Laminations typical of Subfacies C1 of the Thistleton beds (Greetwell Member) cut by bioturbation. (Bed TQ BB5 is pictured).


1cm.
1
2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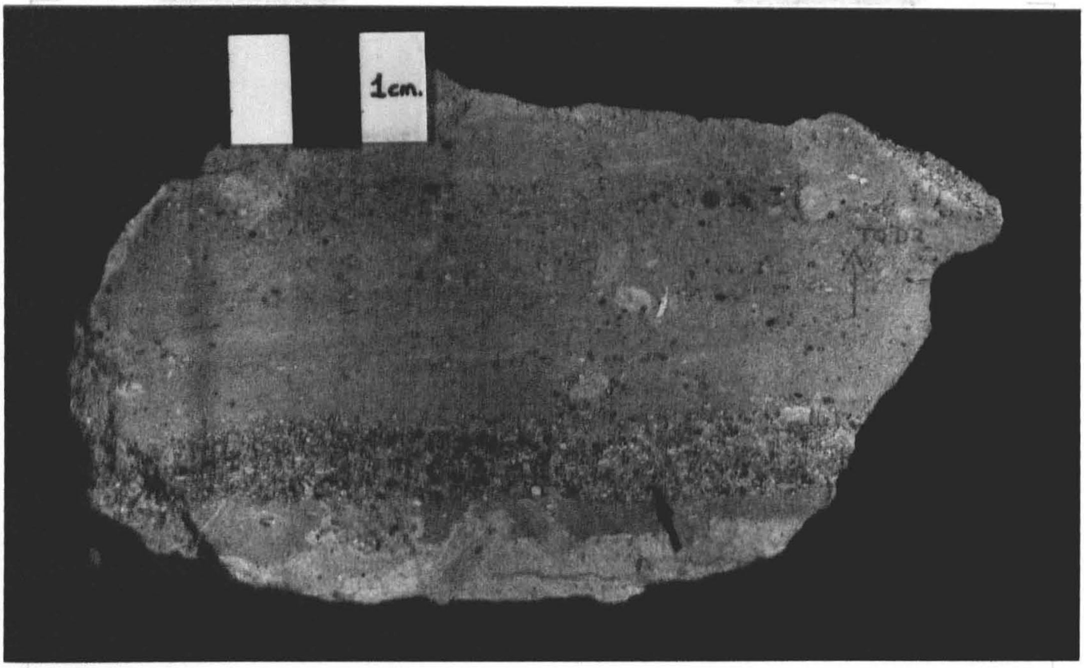

1cm.


1cm.

Fig. 4.56. Storm layer (arrowed) seen in a laminated sequence of the Thistleton beds (Greetwell Member). The storm layer is typical of Subfacies C2 of the Thistleton beds. (Bed TQ BB5 is pictured).

Fig. 4.57. Single vertical burrow (Skolithos?) cutting through both laminated and storm layers of Lithofacies C of the Thistleton beds (Greetwell Member). The weathered side of the block (bed TQ BB5) figured in Fig. 4.56. is pictured.

Fig. 4.58. The type section of the South Witham beds (Greetwell Member of south Lincolnshire) exposed at South Witham Quarry (SK 917189). The top (arrowed T) and base (arrowed B) are indicated.


T
B

Fig. 4.59. Isopachyte map for the South Witham beds of the Greetwell Member. Isopachs are in metres. Basic data is taken from Fig. 4.1.

lp = Little Ponton Railway Cutting

ww = Waltham on the Wolds Quarry

sn = Sproxton Quarry

s = Stainby Quarry

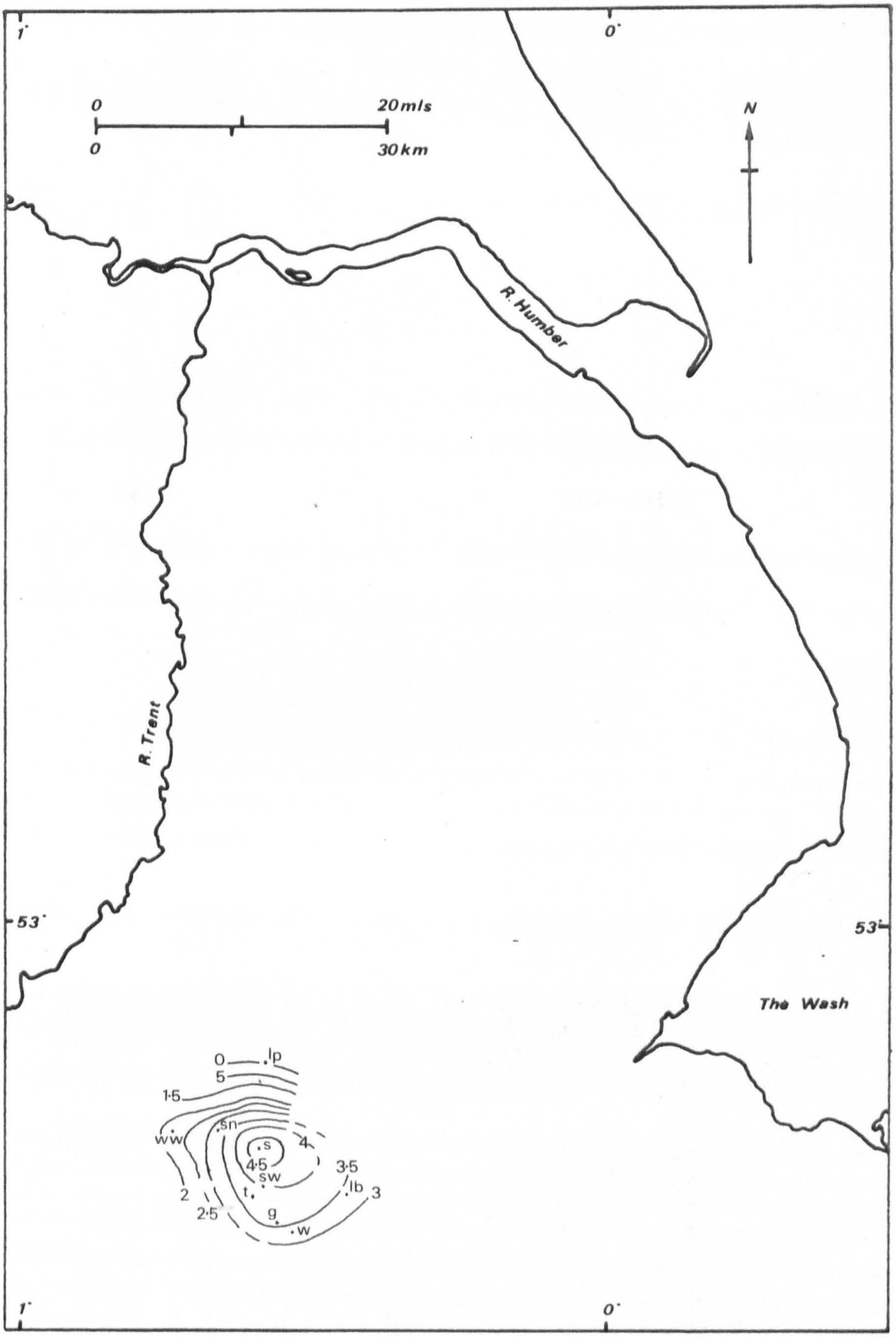
sw = South Witham Quarry

t = Thistleton Quarry

g = Greetham Quarry

w = Woolfox Quarry

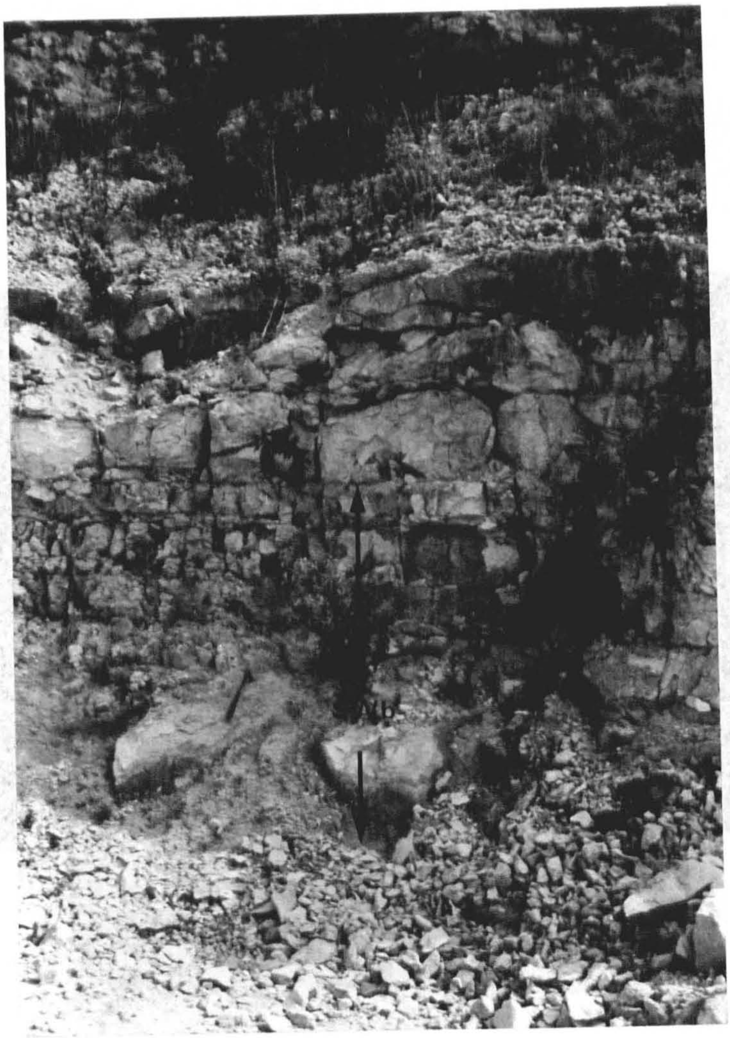
lb = Little Bytham Quarry

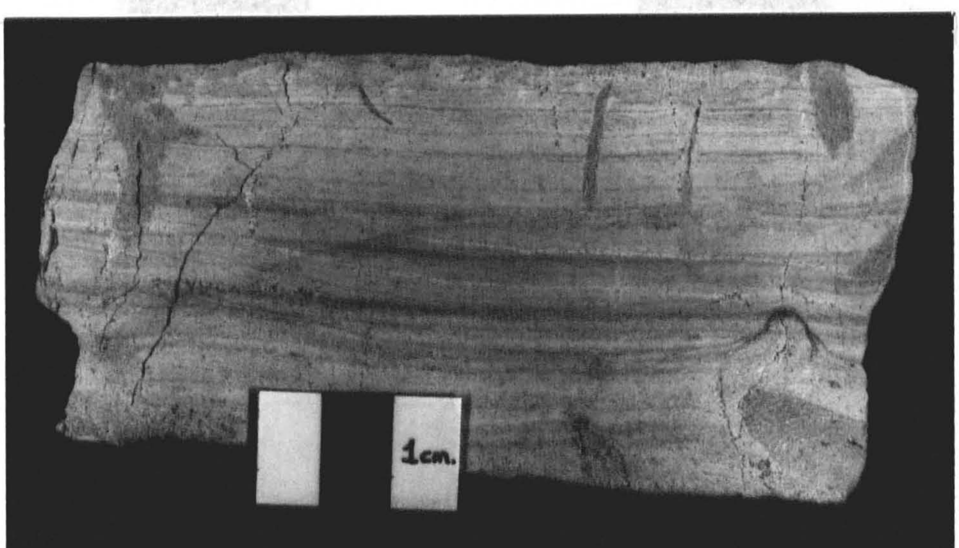


1°
0°
0
20 mls
0
30 km
N
R. Humber
R. Trent
53°
53°
The Wash
0
lp
5
1·5
ww
sn
s
4
4·5
sw
3·5
lb
3
t
2
2·5
g
w
1°
0°

Fig. 4.60. The South Witham beds (marked SWb) exposed at Little Bytham Quarry (TF 013178).

Fig. 4.61. "Skolithos"-like burrows cutting the laminations, typical of Subfacies B1 of the South Witham beds (Greetwell Member). Block pictured comes from bed SQ BC 8.

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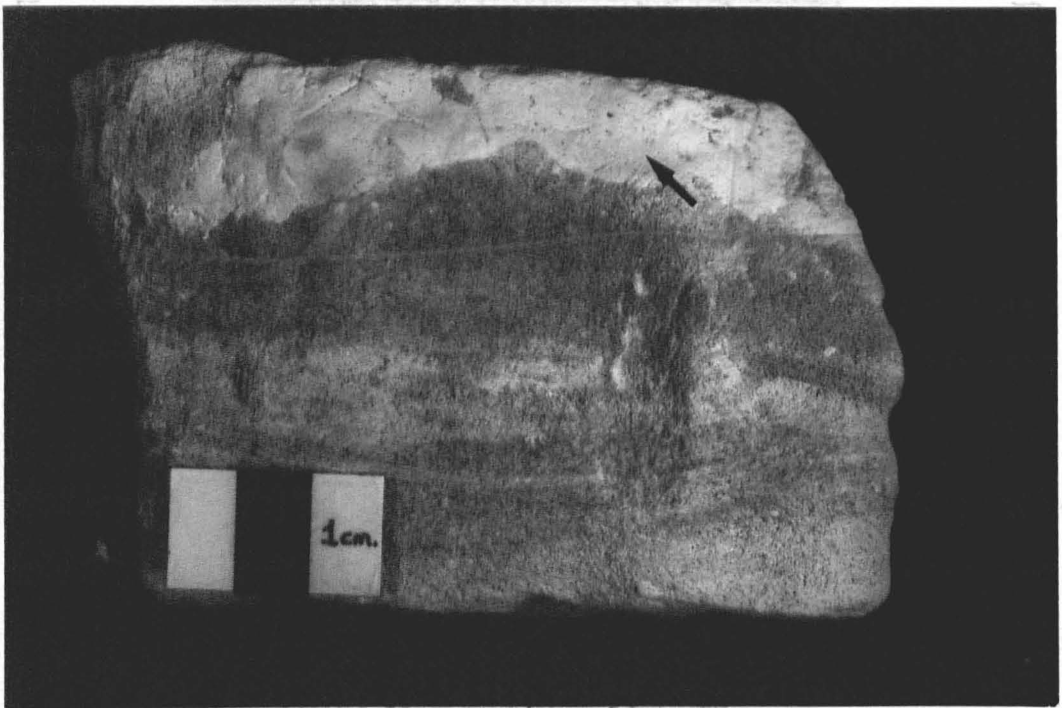

1cm.


2

Fig. 4.62. Micritic "micro-beds" (arrowed), typical of Subfacies B1 of the South Witham beds (Greetwell Member). The block pictured comes from bed WQ BC 3d.

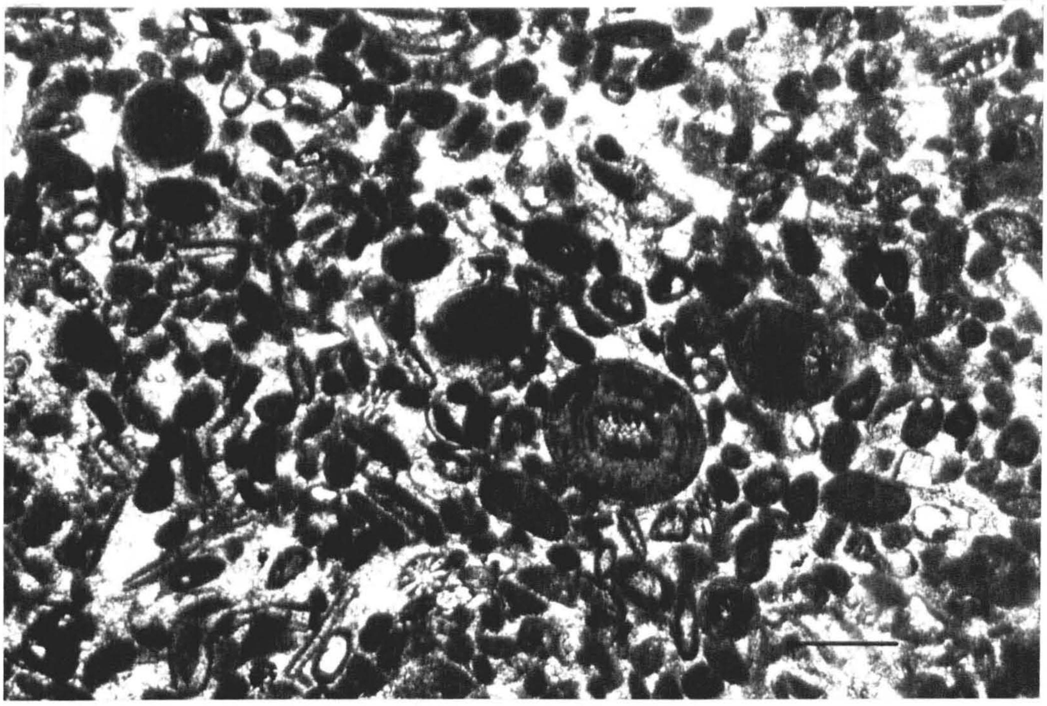
Fig. 63. Vertical burrows (arrowed) cutting through the micritic "micro-beds" of Subfacies B1 of the South Witham beds (Greetwell Member). Faint laminations within the micritic "micro-beds" are arrowed (2). This is the polished reverse side of the block (bed WQ BC 3d.) shown in Fig. 4.62.

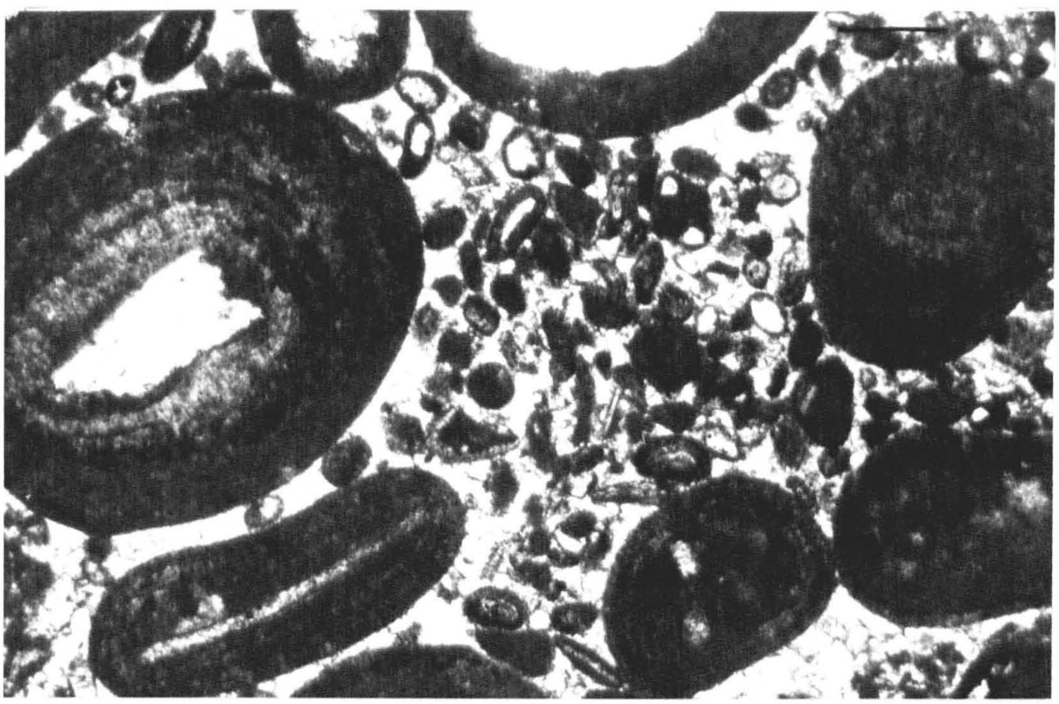
BED	LITHOFACIES	TYPICAL LITHOLOGY	GRAINS			MATRIX	TEXTURE
			% OF TOTAL ROCK	TYPE	SIZE		
SNQ BC4	B	Skeletal pelsparite	50%	peloids	0.031 to 0.19 mm	Sparite > Micrite	Packstone
			12%	bioclasts	0.3 to 3.6 mm		
			3%	oncolites	0.5 to 1.5 mm		
			3%	quartz	silt		
SWQ BCla	A	Skeletal oolitic pelsparite	54%	peloids	0.045 to 0.22 mm	Sparite > Micrite	Packstone (bimodal)
			5%	ooliths	0.2 to 1.4 mm		
			1%	intraclasts	1.2 to 2.8 mm		
			10%	bioclasts	0.125 to 8.3 mm		
SNQ BCl	A	Peloidal oosparite	40%	ooliths	0.2 to 1.1 mm	Sparite > Micrite	Packstone (bimodal)
			18%	peloids	0.062 to 0.15 mm		
			10%	intraclasts	1.2 to 3.3 mm		
			4%	bioclasts	0.1 to 3.2 mm		
			9%	oncolites	1.0 to 1.3 mm		
TQ BCla	A	Peloidal oosparite	57%	ooliths	0.15 to 1.1 mm	Sparite > Micrite	Packstone (bimodal)
			12%	peloids	usually 0.062 to 0.125 max. 0.125 mm		
			15%	intraclasts	1.1 to 1.9 mm		
			1%	bioclasts	0.19 to 2.9 mm		

Fig. 4.64. The principal characteristics of the lithofacies of the South Witham beds (Greetwell Member of south Lincolnshire).

Fig. 4.65. Photomicrograph of a skeletal oolitic pelsparite (bed SWQ BC 1a), typical of Lithofacies A of the South Witham beds (Greetwell Member of south Lincolnshire).

Fig. 4.66. Photomicrograph of a peloidal oosparite (bed SNQ BC 1), typical of Lithofacies A of the South Witham beds (Greetwell Member of south Lincolnshire).





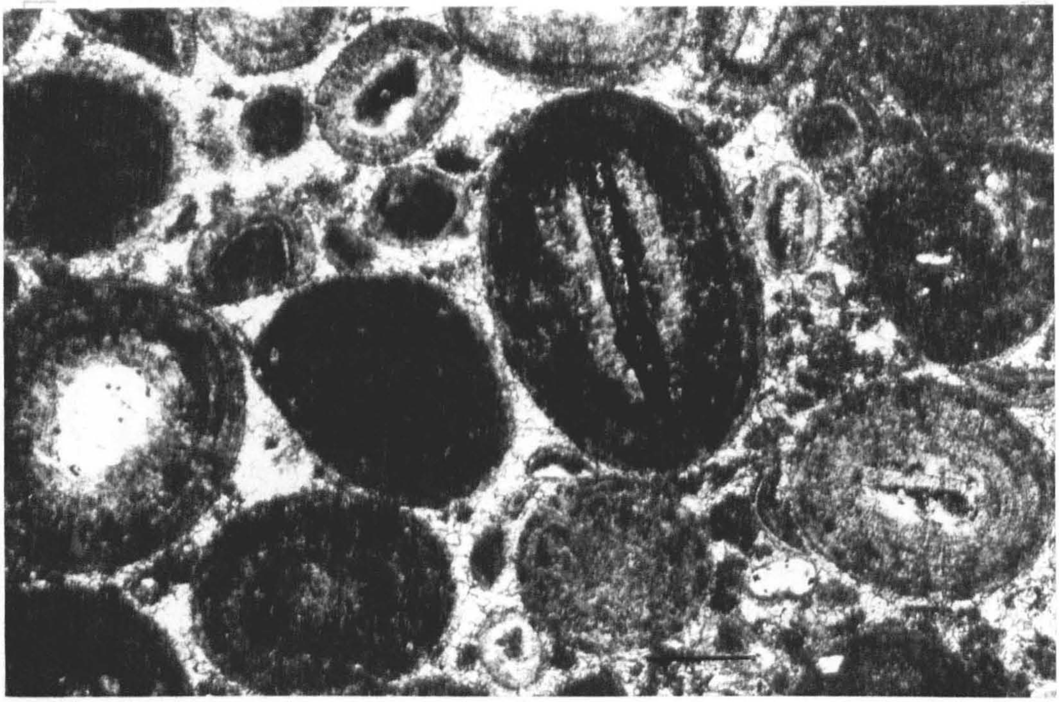
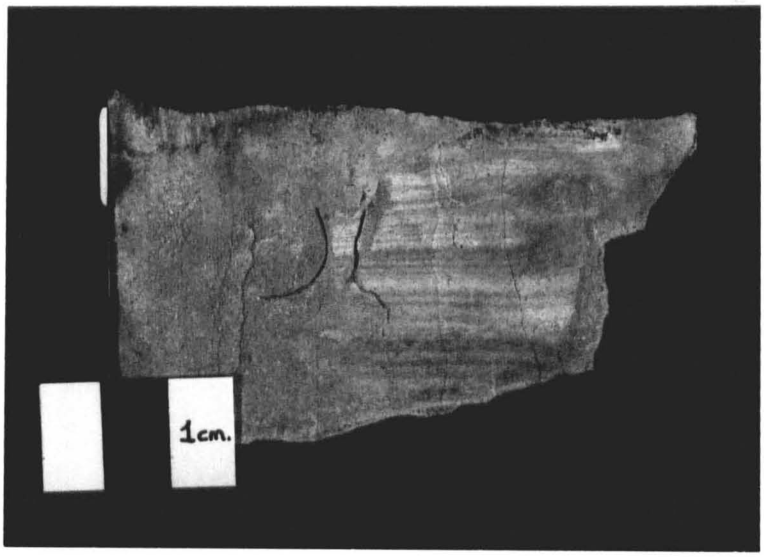


Fig. 4.67. Photomicrograph of a peloidal oosparite (bed TQ BC 1a), typical of Lithofacies A of the South Witham beds (Greetwell Member of south Lincolnshire).

Fig. 4.68. Photomicrograph of a skeletal pelsparite (bed SNQ BC4), typical of Lithofacies B of the South Witham beds (Greetwell Member of south Lincolnshire).

Fig.4.69. Parallel lamination, typical of Subfacies B1 of the South Witham beds (Greetwell Member), destroyed by bioturbation. The block pictured comes from bed SQ BC 8.

Fig. 4. 70. Photomicrograph of a stained peel of a laminated calcarenite (bed SQ BC 8), typical of Subfacies B1 of the South Witham beds (Greetwell Member).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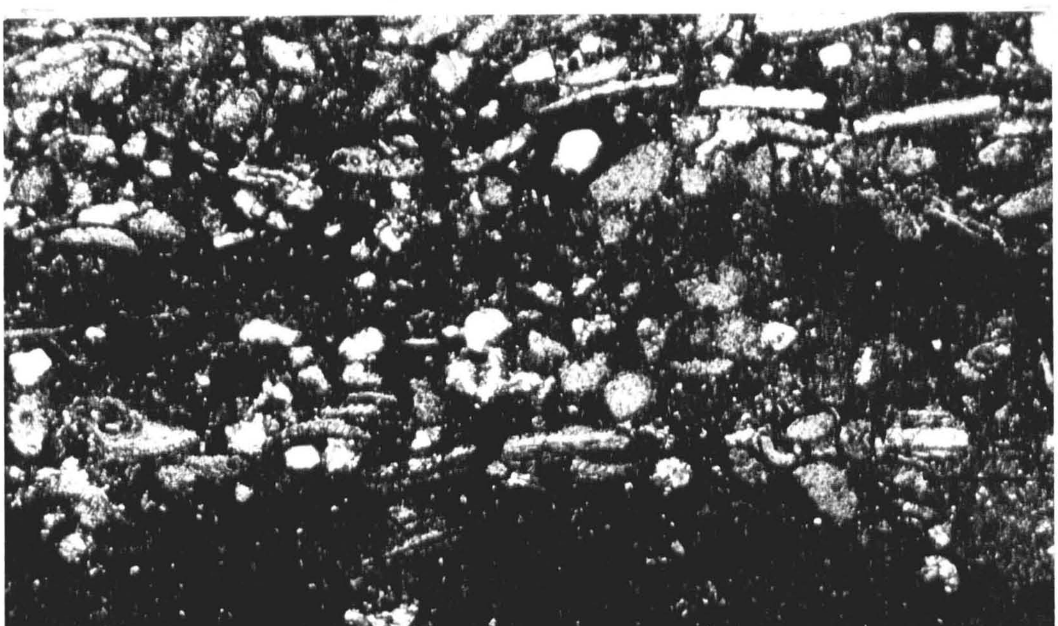


Fig. 4.71. Trophic-Substrate niche chart for the Greetham Fossil beds (Greetwell Member) fauna from Greetham Quarry (SK 933146).

S = Suspension feeder

D = Deposit feeder

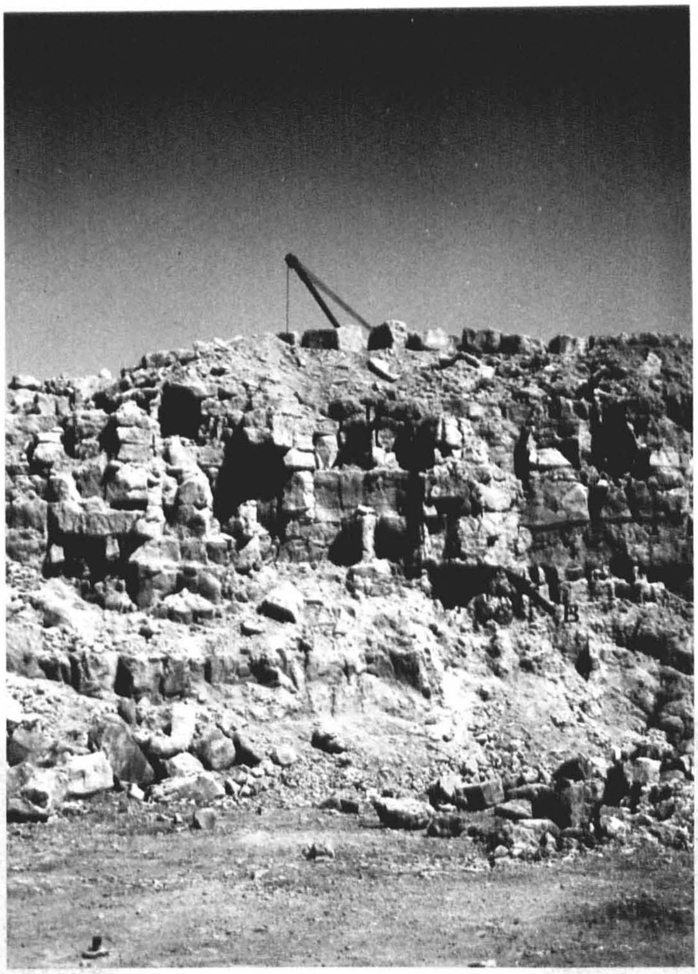
G = Grazer (herbivorous)

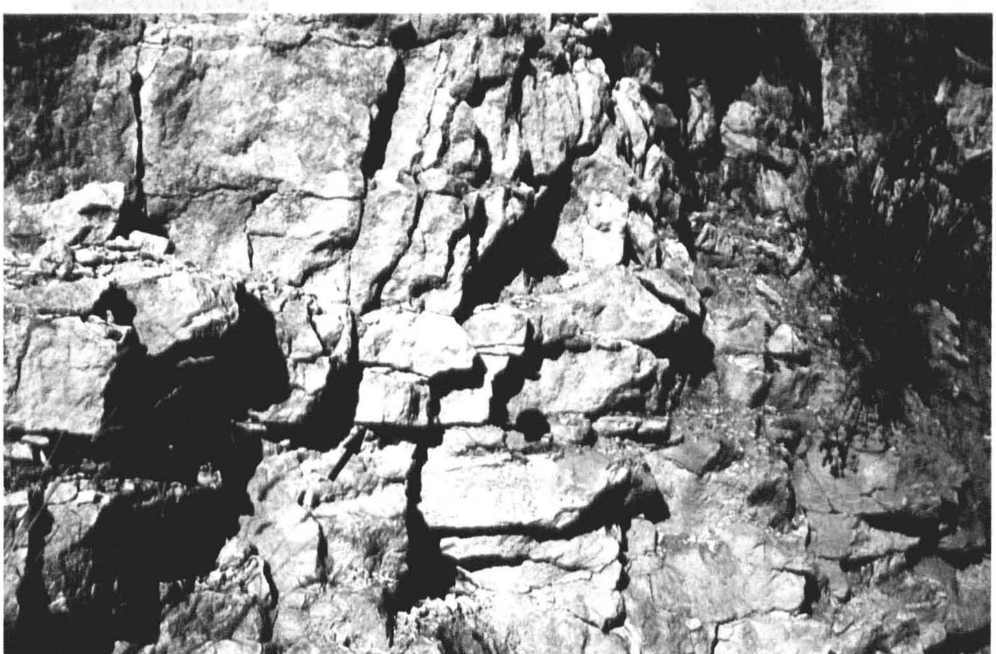
F = Filter feeder

BED		SPECIES	TAXON	Feeding type	EPIFAUNAL			SEMI-INFAUNAL		INFAUNAL		
											SHALLOW	
GQ BD1	GQ BD2				Byssate/ Pedunc.	Cemented	Free	Byssate	Free	Deep	mobile	immobile
	x	Astarte minima Phillips	Bivalve	S							x	
x	x	Camptonectes sp. 1	"	S	x							
	x	Ctenostreon cf. rugosum (W. Smith)	"	S		x						
x		Gresslya sp. indet.	"	S						x		
x		Inoceramus sp. 1.	"	S	x							
x	x	Lima (Regallima) oolitica Lycett	"	S	x							
x	x	Linsdallia quadrata (J. de C. Sowerby)	"	S	x							
	x	Lithophaga sp. 1.	"	S								borer
x	x	Lopha sp. 1.	"	S		x						
x	x	Modiolus imbricatus (J. Sowerby)	"	S	x			x				
x	x	M. plicatus (J. Sowerby)	"	S	x			x				
x		Osteomya dilata (Phillips)	"	S								
	x	Parallelodon hirsonensis (d'Archiac)	"	S	x							
	x	Pholadomya gigantea (J. Sowerby)	"	S								x
x	x	P. lirata (J. Sowerby)	"	S								x
x	x	Pinna cuneata Phillips	"	S				x				
	x	P. cf. (Stegoconcha) ampla (J. Sowerby)	"	S				x				
x		Protocardia sp. 3.	"	S							x	
	x	"Nerinea" spp.	Gastropod	D?					x			
	x	Isastrea sp. 1.	Coral	S		x						
x	x	?Montlivaltia (? sp. nov)	"	S		x						
	x	Pseudodiadema cf. depressum Agassiz	Echinoderm	G			x					
x		"Terebratula" sp.	Brachiopod	F	x							

Fig. 4.72. The type section of the Woolfox beds (Greetwell Member of south Lincolnshire) exposed at Woolfox Quarry (SK 951136). The top (arrowed T) and base (arrowed B) are indicated.

Fig. 4.73. Truncation of the South Witham beds by the Woolfox beds, seen at Stainby Quarry (SK 910233). The contact is arrowed.





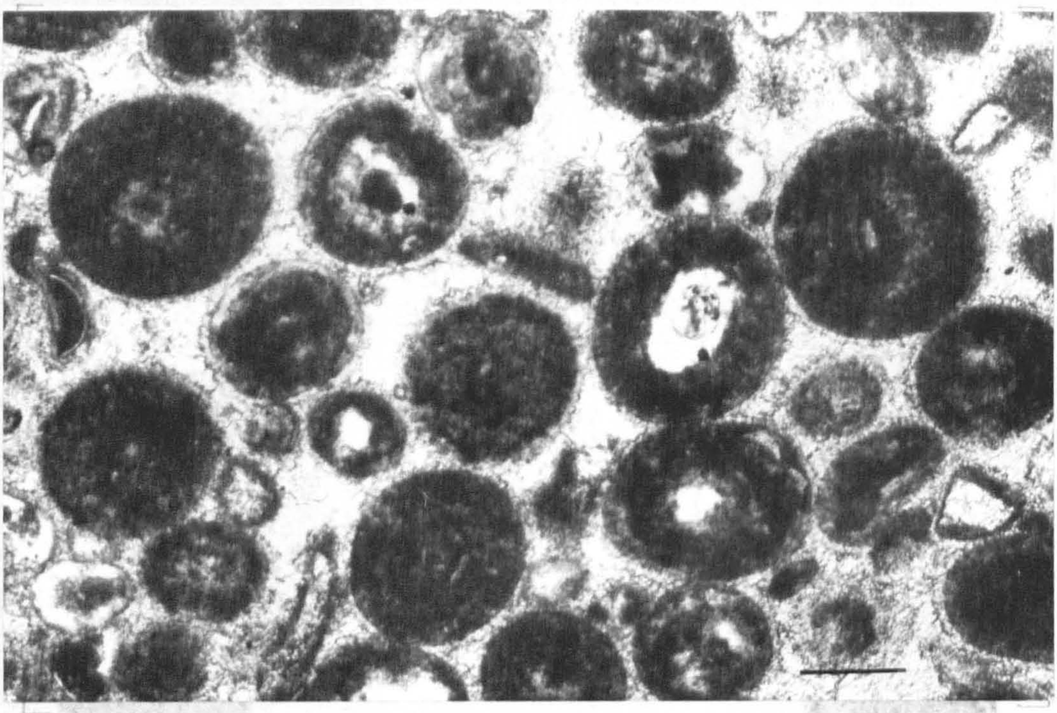


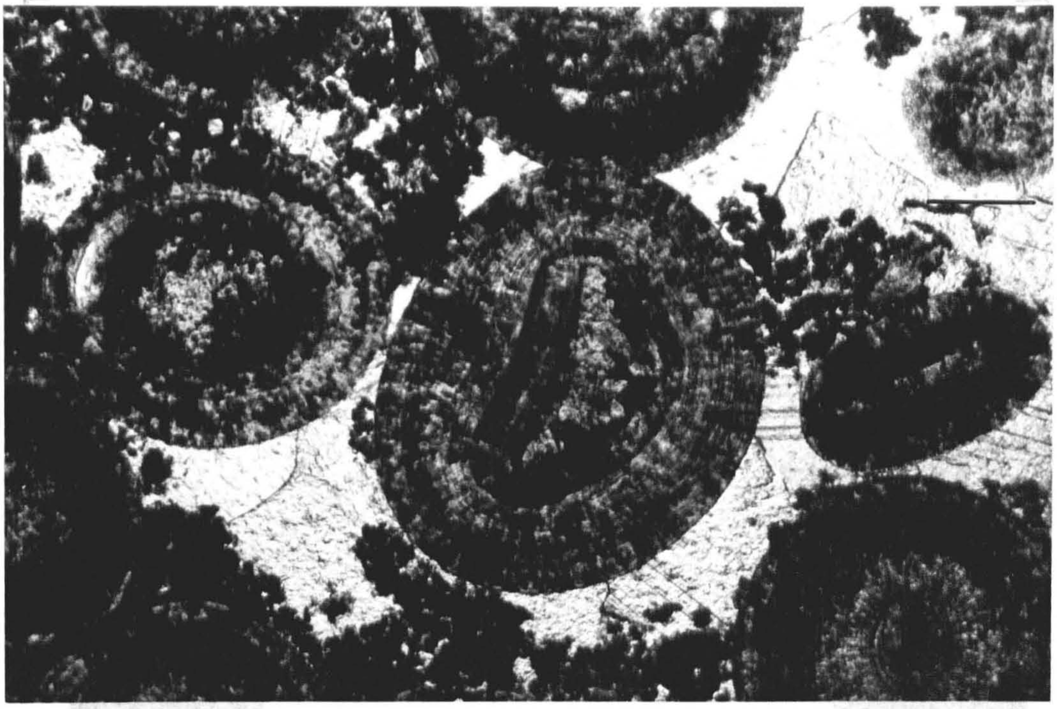
Fig. 4.74. Photomicrograph of an oosparite (bed WQ BE), typical of Lithofacies A of the Woolfox beds (Greetwell Member of south Lincolnshire).

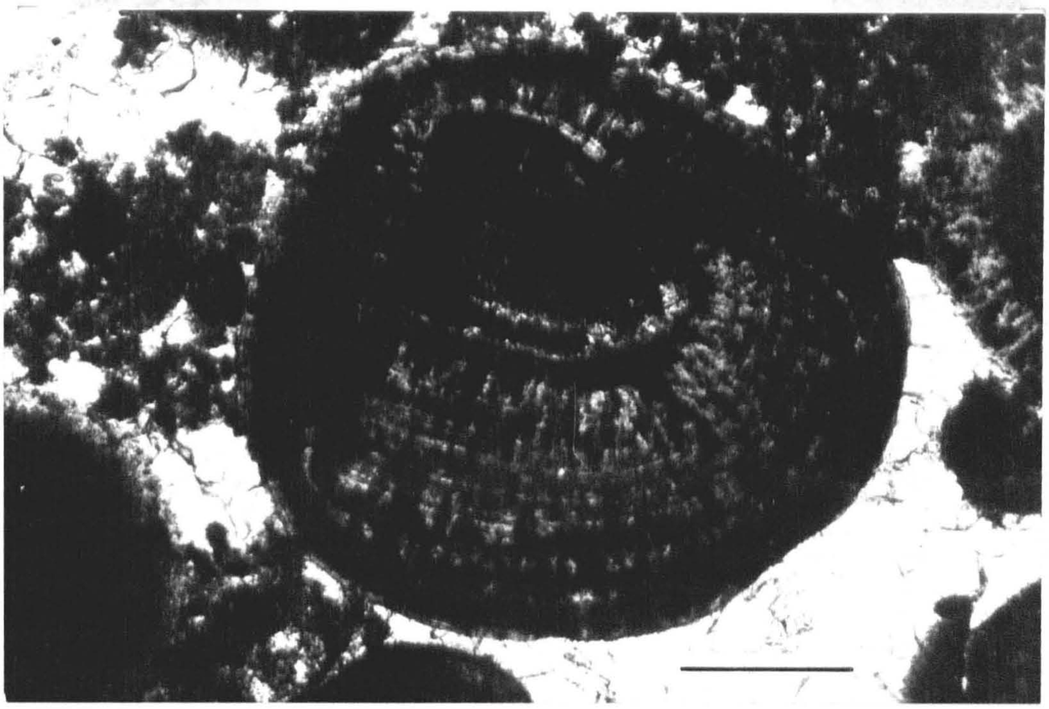
BED	LITHOFACIES	TYPICAL LITHOLOGY	GRAINS % OF TOTAL ROCK	GRAINS TYPE	GRAINS SIZE	MATRIX	TEXTURE
WQ BE	A	Oosparite	70% 1% 2%	ooliths bioclasts intraclasts	0.15 to 0.6 mm 0.19 to 5.0 mm 0.7 to 0.75 mm	Sparite	Grainstone
GQ BE	A	Oosparite	79% 3% traces	ooliths bioclasts intraclasts	0.2 to 1.0 mm 0.5 to 2.4 mm ≃ 0.7 mm	Sparite	Grainstone

Fig. 4.75. The principal characteristics of Lithofacies A of the Woolfox beds (Greetwell Member of south Lincolnshire).

Fig. 4.76. Photomicrograph of a skeletal oosparite (bed WWQ BE), typical of Lithofacies A of the Woolfox beds, showing ooliths with radial fabric, which is picked out by "columns" of included-micrite.

Fig. 4.77. Photomicrograph of a skeletal oosparite (bed WWQ BE), typical of Lithofacies A of the Woolfox beds, showing a broken oolith incorporated within a "secondary" oolitic coating.






T
B

Fig. 4.78. The type section of the Leadenham Member exposed at Leadenham Quarry (SK 962523). The top (arrowed T) and base (arrowed B) are indicated.

Fig. 4.79. The contrasting terminologies and stratigraphic interpretations, which have been applied to the lower Lincolnshire Limestone at Greetwell, Lincoln (TF 003721) and Leadenham (SK 962523).

L.S.M.	=	Lindsey Shale Member
R.B.	=	Ropsley Beds
C.B.	=	Cathedral Beds
N.I.	=	Northampton Ironstone
*	=	Levels at which correlation between the author's own sequence and that of Evans (1952) were made

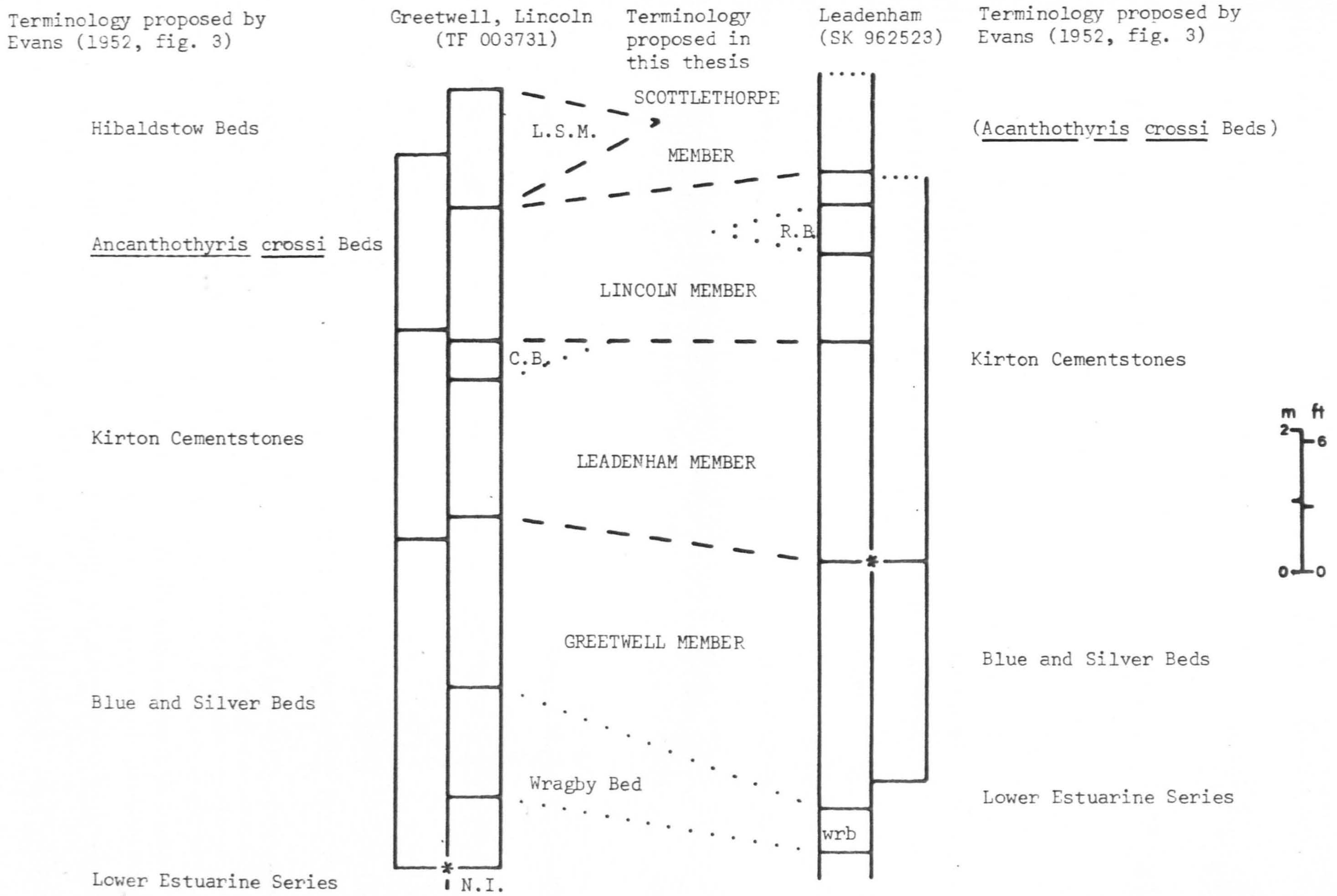

Terminology proposed by Evans (1952, fig. 3)
Greetwell, Lincoln (TF 003731)
Terminology proposed in this thesis
Leadenham (SK 962523)
Terminology proposed by Evans (1952, fig. 3)
Hibaldstow Beds
Ancanthothyris crossi Beds
Kirton Cementstones
Blue and Silver Beds
Lower Estuarine Series
SCOTTLETHORPE MEMBER
L.S.M.
R.B.
LINCOLN MEMBER
C.B.
LEADENHAM MEMBER
GREETWELL MEMBER
Wragby Bed
wrb
N.I.
(Acanthothyris crossi Beds)
Kirton Cementstones
Blue and Silver Beds
Lower Estuarine Series
m ft
2 6
0 0

Fig. 4.80. Isopachyte map for the Leadenham Member (including Cathedral Beds). Isopachs are in metres. Basic data is taken from Fig. 4.1.

LDCP = Dean and Chapter Pit, Lincoln

BVQ = Branston Quarry

DQ = Dunston Quarry

MQ = Metheringham Quarry

HQ = Harmston Quarry

CQ = Coleby Quarry

LQ = Leadenham Quarry

ARC = Ancaster Railway Cutting

LPRC = Little Ponton Railway Cutting

RQ = Ropsley Quarry

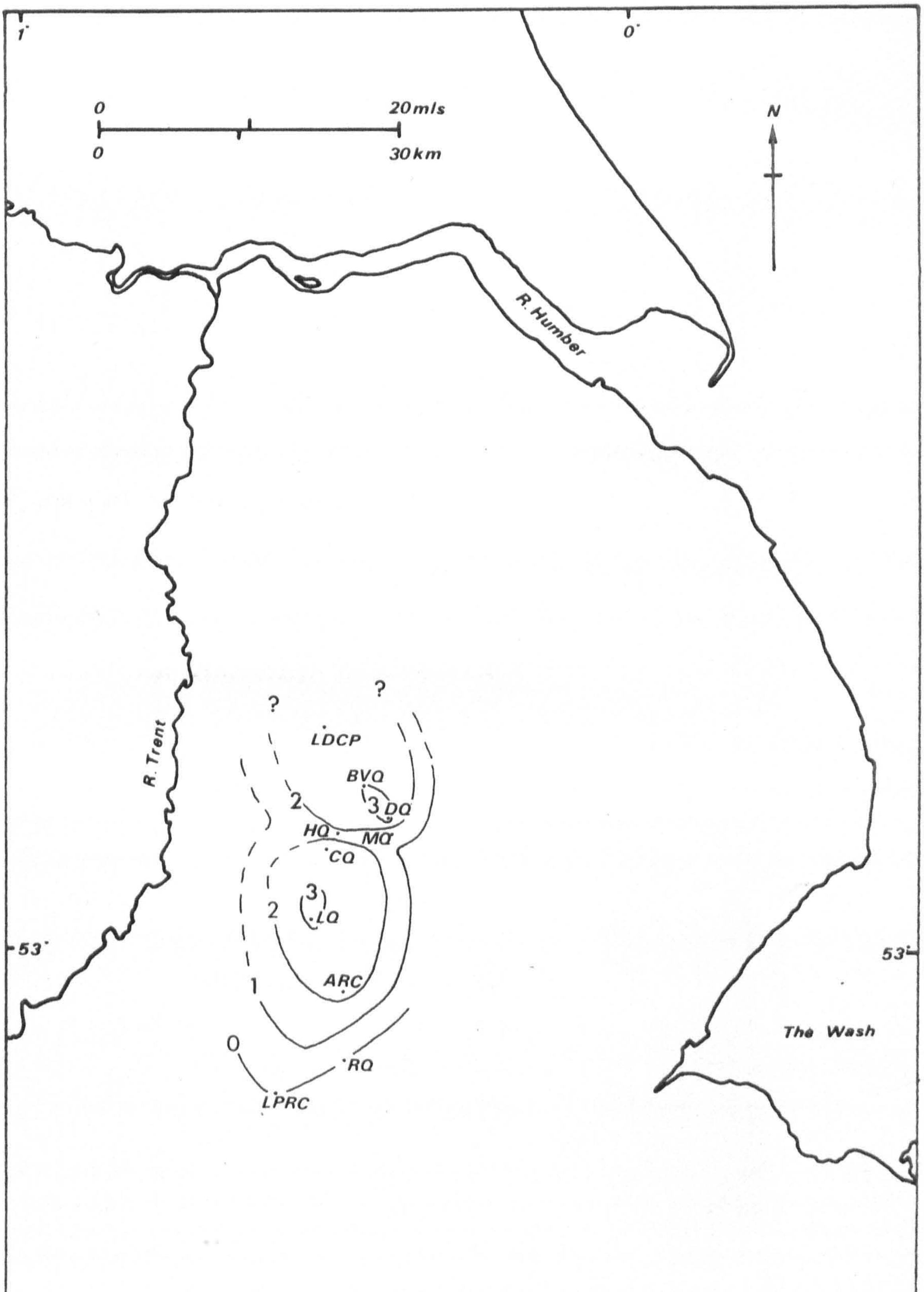
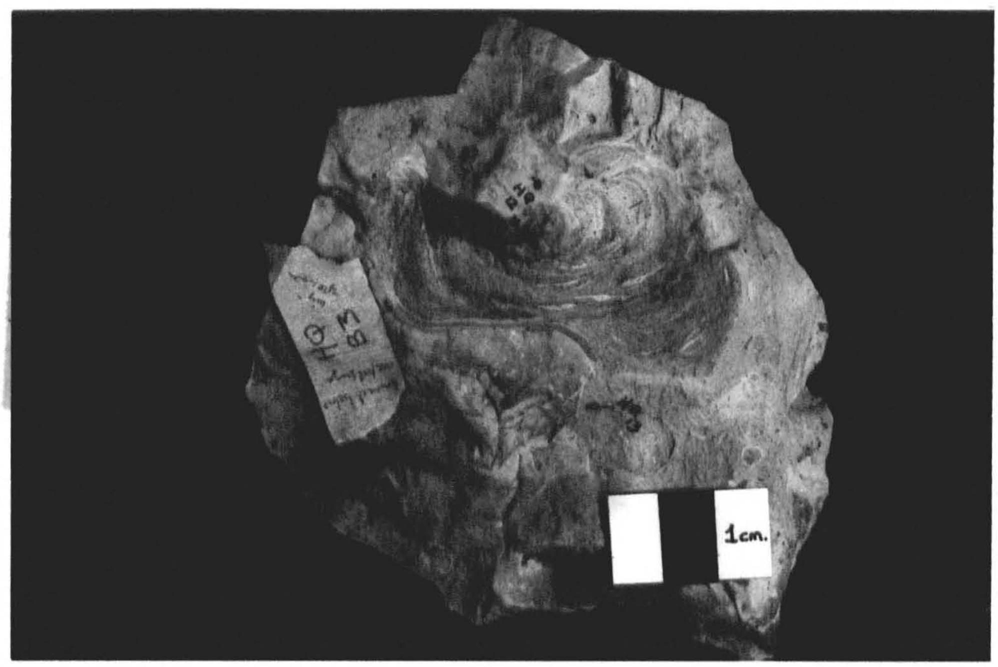

1°
0°
0
20mls
0
30km
N
R. Humber
R. Trent
?
?
LDCP
BVQ
2
3
DQ
HQ
MQ
CQ
3
2
LQ
53°
53°
ARC
1
The Wash
0
RQ
LPRC
1°
0°

Fig. 4.81. A *Pholadomya lirata* (J. Sowerby) seen in "life position" in the Leadenham Member at Leadenham Quarry (SK 962523).

Fig. 4.82. Plan view of a block (bed HQ C3) from the Leadenham Member of Harmston Quarry (SK 992619), showing *Zoophycos* sp. (arrowed HQ 12) and *Chrondrites* sp. (arrowed HQ 13).

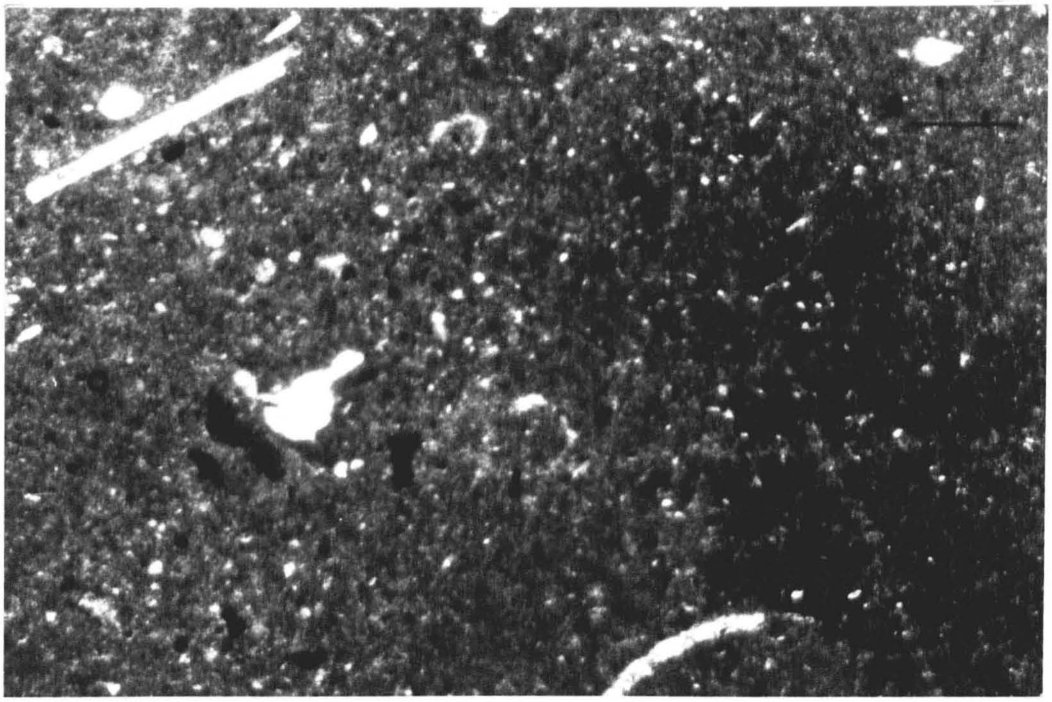

1cm.

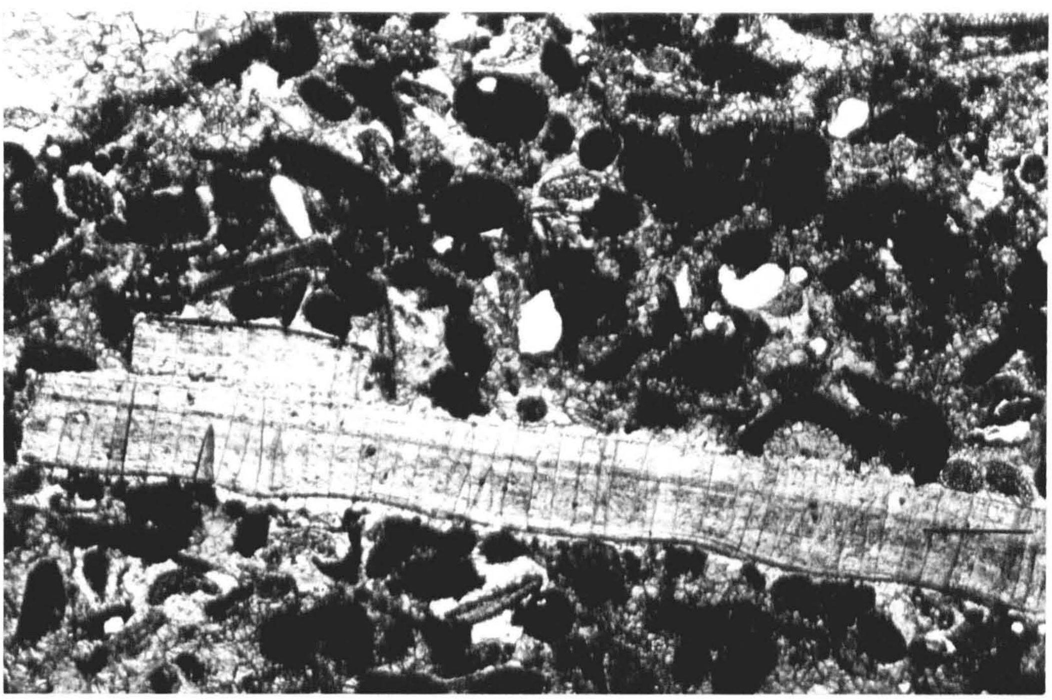
BED	LITHOFACIES	TYPICAL LITHOLOGY	GRAINS			MATRIX	TEXTURE
			% OF TOTAL ROCK	TYPE	SIZE		
LQ C5	A	Biomicrite	16% 9% 1%	bioclasts peloids quartz	0.3 to 8.0 mm 0.062 to 0.28 mm silt	Micrite	Wackestone (grain poor)
LDCP C6	A	Quartzose biomicrite	6% 8%	bioclasts quartz	0.25 to 1.3 mm silt	Micrite	Mudstone
CQ C3a	B	Oncolitic biomicrite	7% 36% 4% 3%	oncolites bioclasts peloids quartz	0.6 to 1.6 mm 0.4 to 4.5 mm mostly 0.125 mm silt	Micrite	Wackestone
CQ C3a base	B	Biosparite	34% 28% 6%	bioclasts oncolites peloids	0.5 to 4.2 mm 1.1 to 3.2 mm usually 0.2 to 0.8 mm	Sparite $\simeq$ Micrite	Packstone

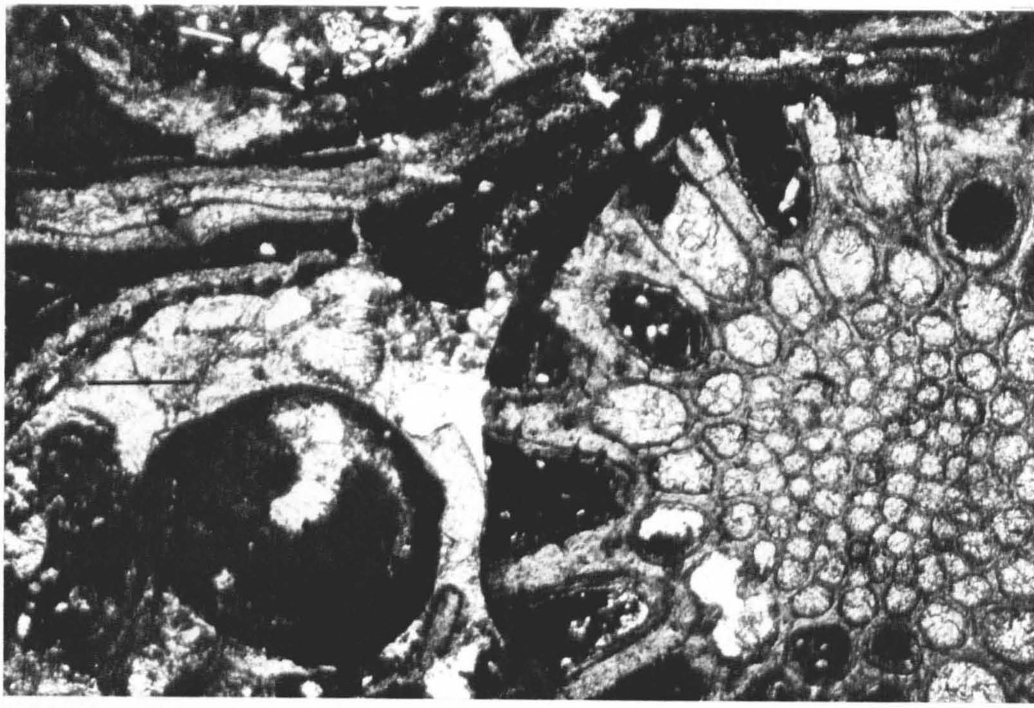
Fig. 4.83. The principal characteristics of the Lithofacies of the Leadenham Member.

Fig. 4.84. Photomicrograph of a biomicrite (bed LQ C5), typical of Lithofacies A of the Leadenham Member.

Fig. 4.85. Photomicrograph of a biopelsparite lens (bed LQ C9c), typical of Lithofacies A of the Leadenham Member.







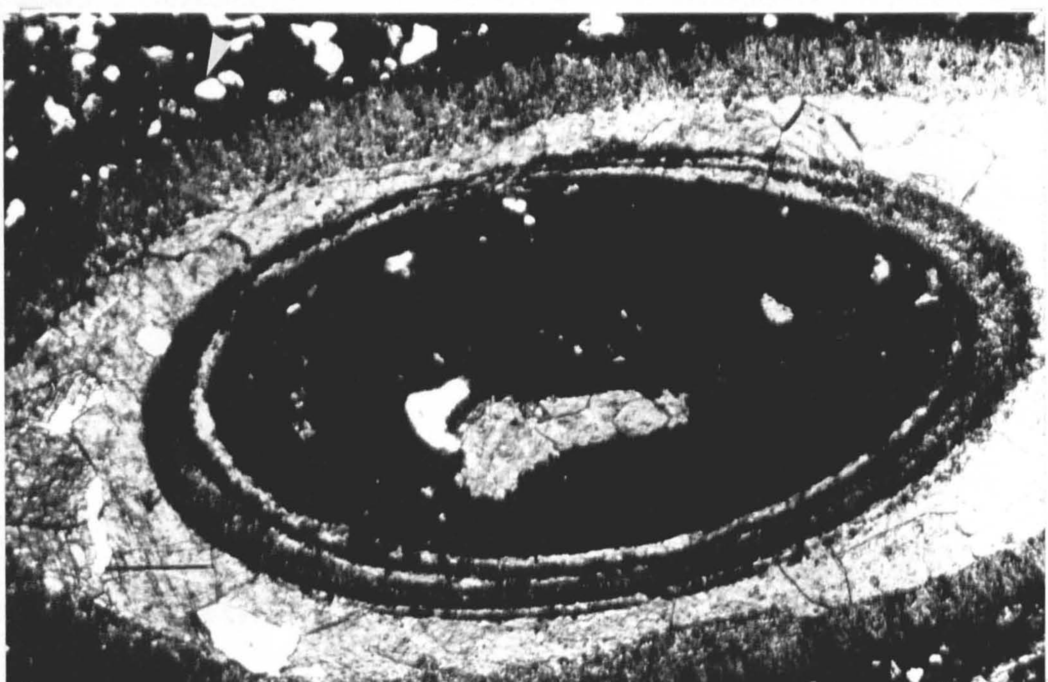


Fig. 4.86. Photomicrograph of a biosparite (base of bed CQ C3a), typical of Lithofacies B of the Leadenham Member.

Fig. 4.87. Photomicrograph of an oncolite biomicrite (bed CQ C3a), typical of Lithofacies B of the Leadenham Member, showing an oncolite with silt included in its amorphous micrite-rim (arrowed).

Fig. 4.88. Species distribution chart for the commoner forms present in the Leadenham Member (Lithofacies A). Species with the wider geographical range also tend to be the commonest forms. (Some "absences" may be due to collection failure as sample sizes are variable).

SPECIES \ LOCALITY	LINCOLN		Harmston	Coleby	Dunston	Metheringham	Leadenham
	Greetwell	LDCP					
Bivalves							
Astarte minima Phillips		x	x	x	x	x	x
Camptomectes laminatus (J. Sowerby)	x		x				
Camptonectes sp. 1.							x
Grammatodon sp. 1.					x		x
Gresslya abducta (Phillips)	x					x	
Lopha marshii							x
Modiolus (Inoperna) plicatus (J. Sowerby)							x
Ostrea (Catinula) ampulla d'Archiac			x				
Oxytoma sp. 1.							x
Oxytoma sp. 2.	x						
Parallelodon hirsonensis (d'Archiac)							x
Pholadomya lirata (J. Sowerby)	x		x	x	x	x	x
Pinna cuneata Phillips	x		x	x	x	x	x
Plagiostoma pontonis (Lycett)							x
Plagiostoma oolitica (Lycett)							x
Pleuromya uniformis (J. Sowerby)	x			x	x		x
Protocardia sp. 1.	x						x
Protocardia sp. 2.					x		x
Gastropods							
Cylindrabullina cf. *glabra* (Phillips							x
Natica adducta Phillips			x		x		x
"*Nerinea*" sp.			x				
Echinoids							
Pseudodiadema cf. *depressum* Agassiz	x			x			x
Pentacrinus sp.	x		x				
Cidaris sp.			x				
Trace Fossils							
Chondrites sp.	x	x	x	x	x		
Thalassinoides sp.	x				x		
Zoophycos sp.		x	x	x			x
Corals							
Horn-shaped solitary		x	x	x	x	x	x

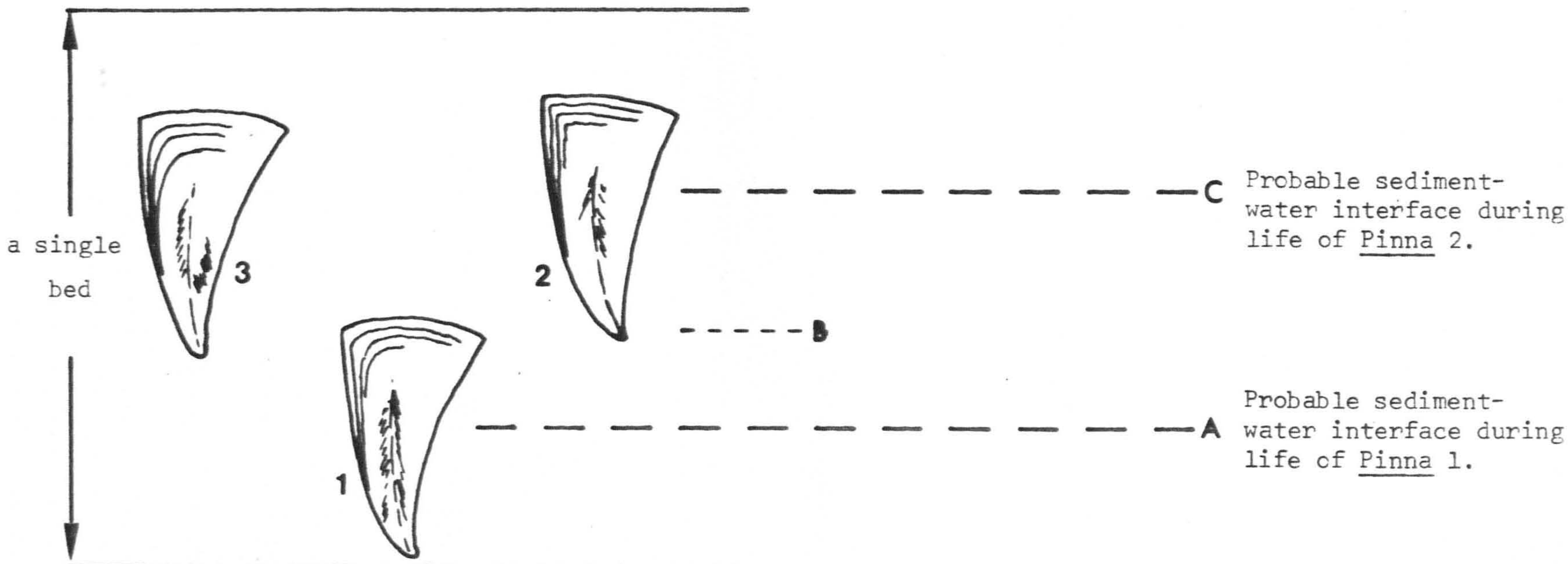


Fig. 4.89. Schematic representation of Pinna colonies in the Leadenham Member. At the hypothetical sediment-water interface level B, it is apparent that Pinnae 1 and 2 could not have co-existed because Pinna 2 would have insufficient anchorage and the sediment would be too close to the posterior margin of Pinna 1. The bed's colony must therefore represent a number of distinct generations of Pinna that existed at separate times during the bed's deposition.

Fig. 4.90. Trophic-Substrate niche chart for the fauna from Lithofacies A of the Leadenham Member at Leadenham Quarry (SK 962523).

S = Suspension feeder

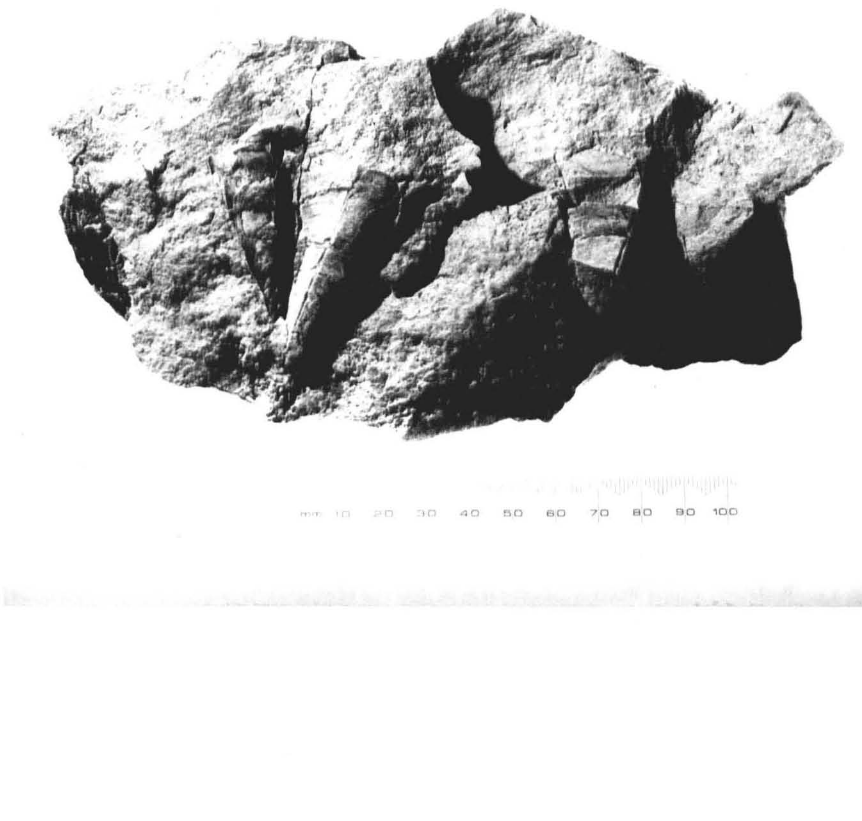
C = Carnivore

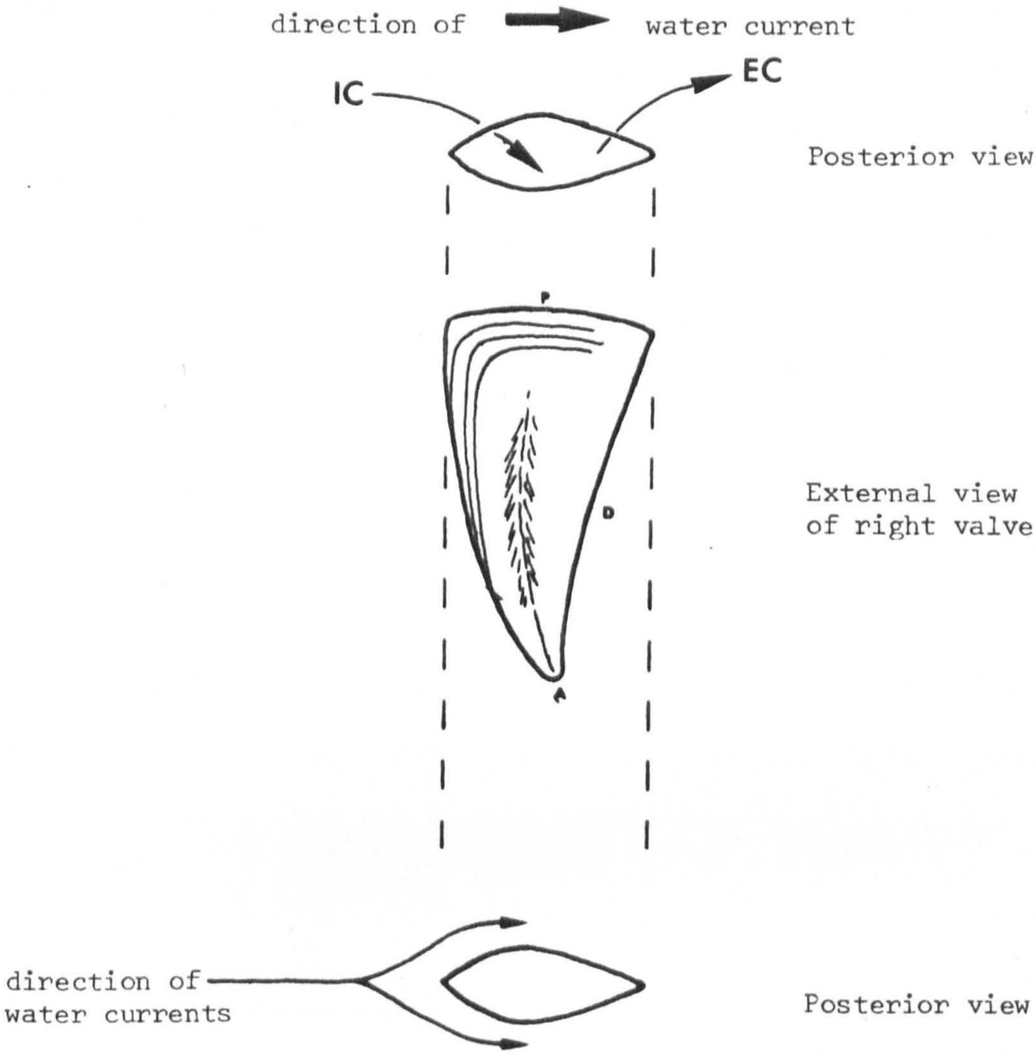
G = Grazer (herbivorous)

* = Common element of the fauna

SPECIES	TAXON	Feeding Type	EPIFAUNAL			SEMI-INFAUNAL		INFAUNAL		
			Byssate/ Pedunculate	Cemented	Free	Byssate	Free	Deep	Shallow Mobile	Shallow Immobile
*Astarte minima (Phillips)	Bivalve	S								
Camptonectes sp. 1.	"	S	x							
Grammatodon sp. 1.	"	S	x							
*Lopha marshii	"	S		x						
Modiolus (Inoperna) plicatus (d'Archiac)	"	S				x				
Oxytoma sp. 1.	"	S	x							
Parallelodon hirsonensis (d'Archiac)	"	S	x							
*Pholadomya lirata (J. Sowerby)	"	S						x		x?
*Pinna cuneata (Phillips)	"	S				x				
Plagiostoma pontonis (Lycett)	"	S	x							
P. oolitica (Lycett)	"	S	x							
*Pleuromya uniformis (J. Sowerby)	"	S						x		
Protocardia sp. 1.	"	S							x	
Protocardia sp. 2.	"	S							x	
Cylindrobullina cf. glabra (Phillips)	Gastropod	?			x?					
*Natica adducta (Phillips)	"	C			x					
Solitary coral	Coral	S		x						
Pseudodiadema cf. depressum (Agassiz)	Echinoid	G			x					

Fig. 4.91. Pinna cuneata Phillips colonies from the Leadenham Member of Dunston Quarry (TF 053634). Note the near-parallel alignment of the dorso-ventral axes of the bivalves. The block pictured comes from bed DQ C7a.


mm 10 20 30 40 50 60 70 80 90 100



A = Anterior

D = Dorsal

P = Posterior

EC = Exhalent current

IC = Inhalent current

Fig. 4.92. Diagrammatic representation of "advantage" gained from current alignment by Pinna cuneata Phillips.

Fig. 4.93. Palaeocurrent directions derived from <u>Pinna cuneata</u> Phillips related to the isopachyte map of the Leadenham Member. (Isopachs are given in metres. The palaeocurrent directions given are "lineations" and therefore are "symmetrical". (See Appendix 4).

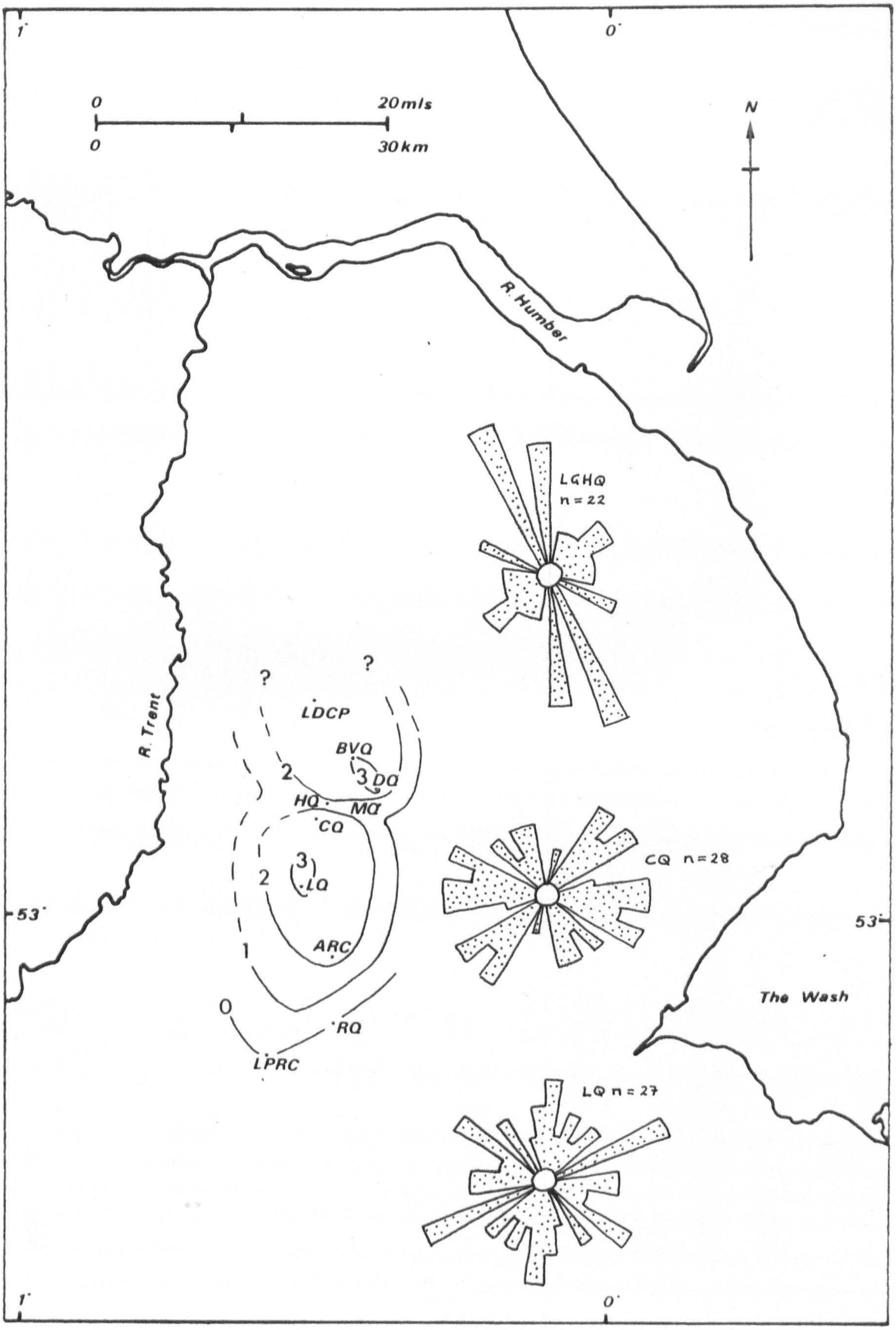
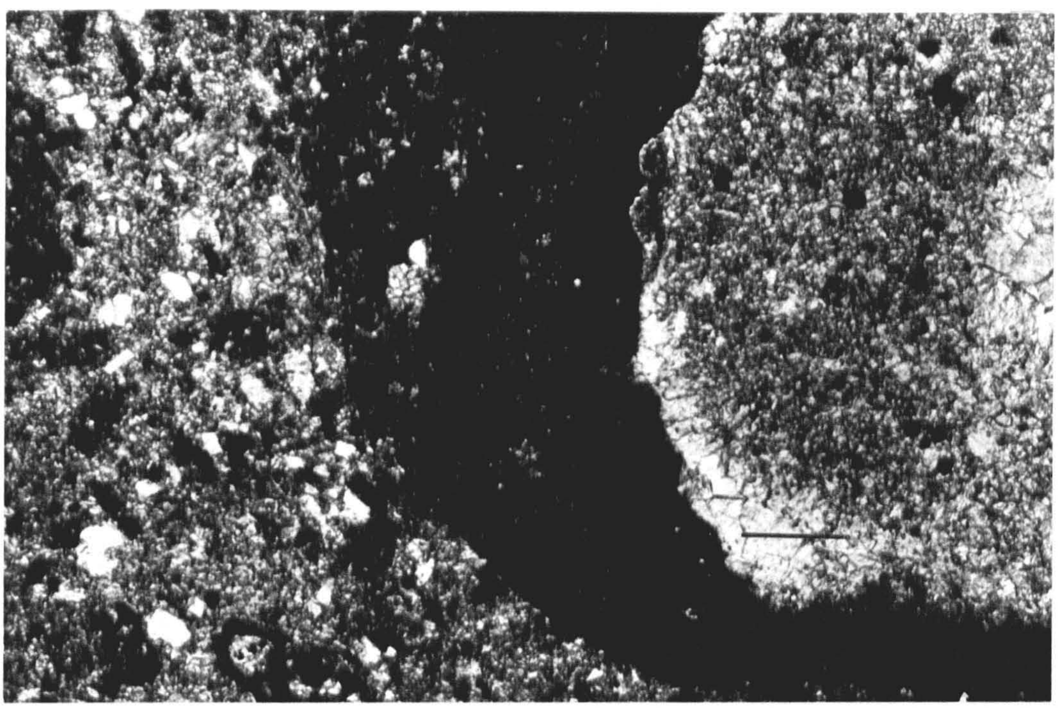
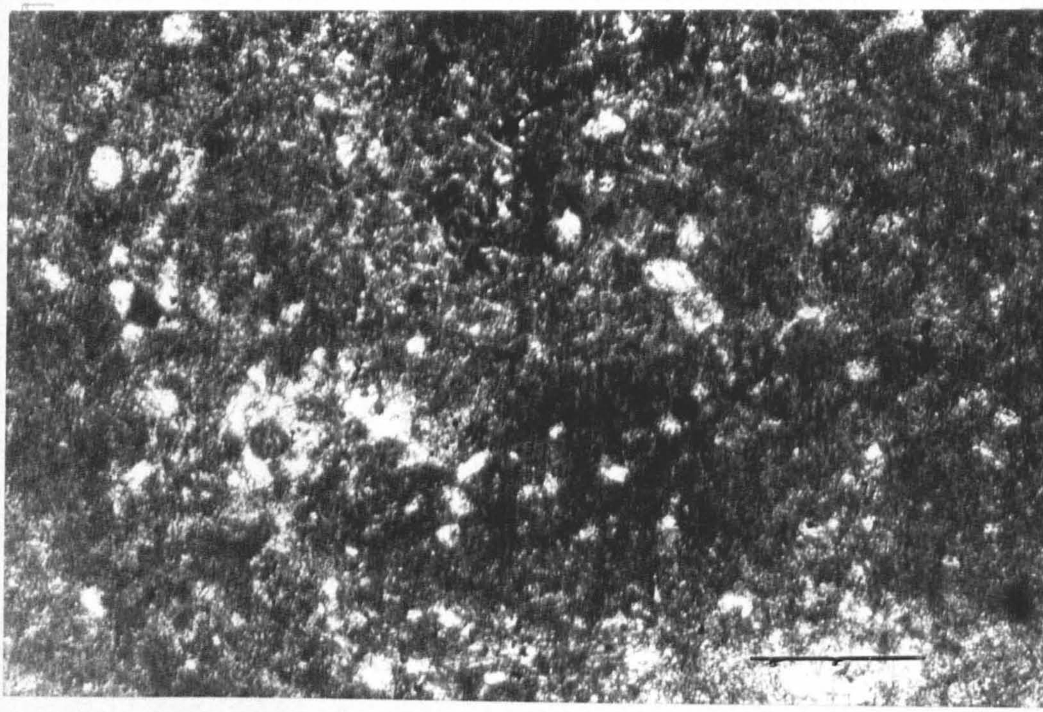

1°
0°
0
20mls
0
30km
N
R. Humber
R. Trent
LGHQ
n = 22
?
?
LDCP
BVQ
2
3
DQ
HQ
MQ
CQ
3
2
LQ
ARC
1
0
RQ
LPRC
CQ n=28
53°
53°
The Wash
LQ n = 27
1°
0°

Fig. 4.94. The type section of the Cathedral Beds (Leadenham Member) exposed at the Dean and Chapter Pit, Lincoln (SK 977734). The top (arrowed T) and base (arrowed B) are indicated.

Fig. 4.95. Photomicrograph of a skeletal-oncolite bearing quartzose biomicrite (bed LDCP C´4), the typical limestone lithology of the Cathedral Beds (Leadenham Member).


B





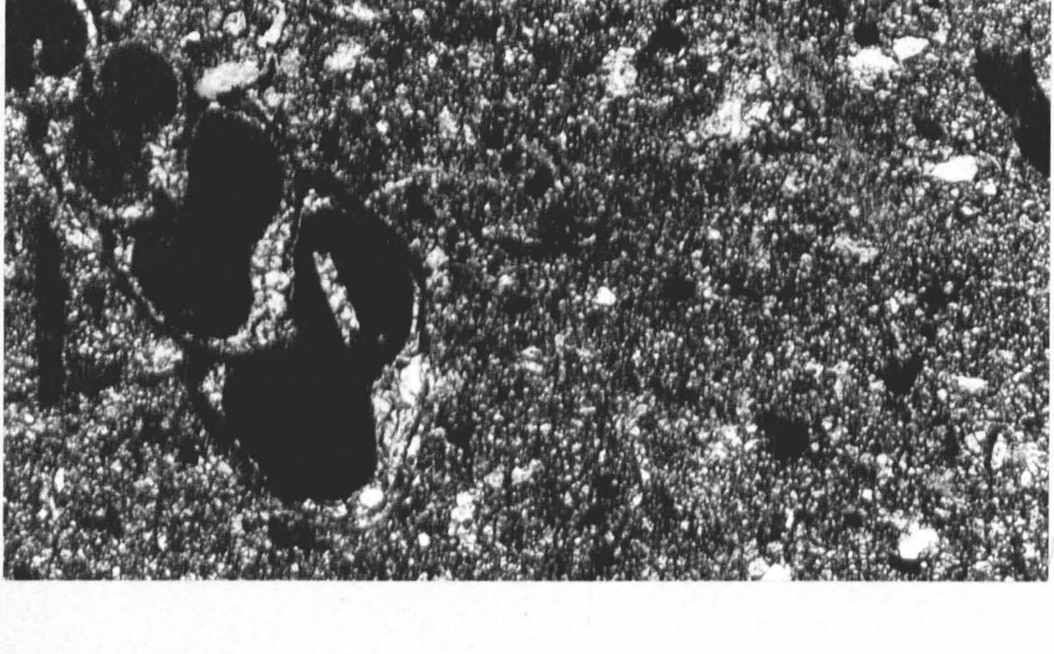


Fig. 4.96. Photomicrograph of a skeletal-oncolite quartzose biomicrite (bed LDCP C´4) of the Cathedral Beds (Leadenham Member), showing the intertwined algal filaments (arrowed) present within a skeletal-oncolite.

Fig. 4.97. Photomicrograph of a skeletal-oncolite bearing quartzose biomicrite (bed LGHQ C´2) of the Cathedral Beds, showing neomorphic spar.

Fig. 4.98. The type section of the Lincoln Member exposed at Greetwell Hollow Quarry, Lincoln (TF 003721). The top (arrowed T) and base (arrowed B) are indicated.

Fig. 4.99. The hypostratotype of the Lincoln Member exposed at Stainby Quarry (SK 910233). The top (arrowed T) and base (arrowed B) are indicated.

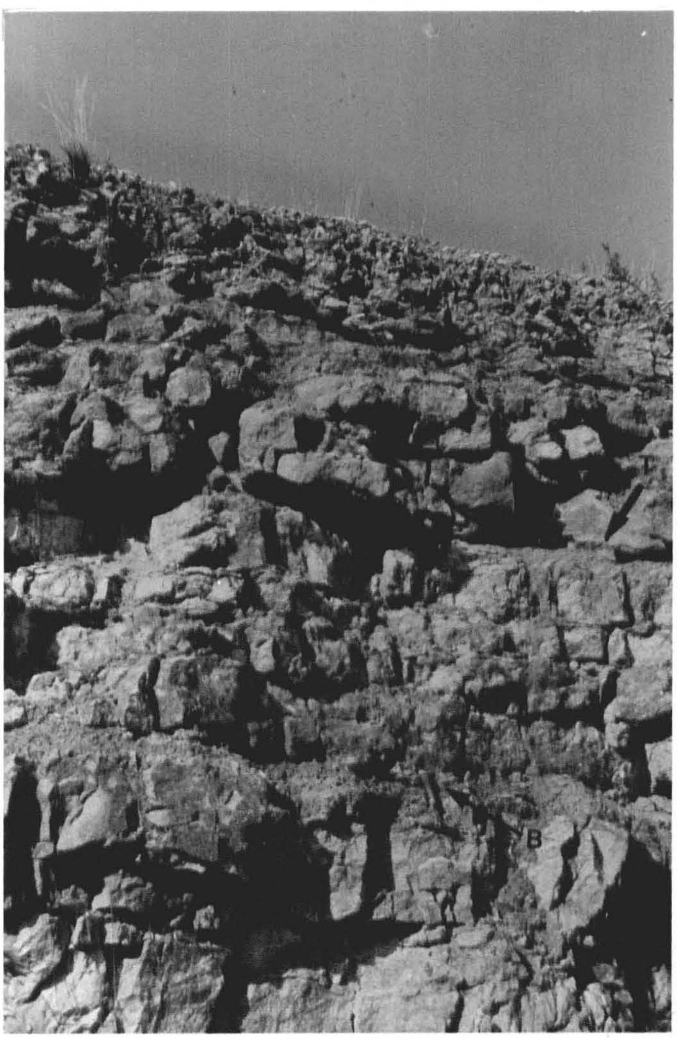
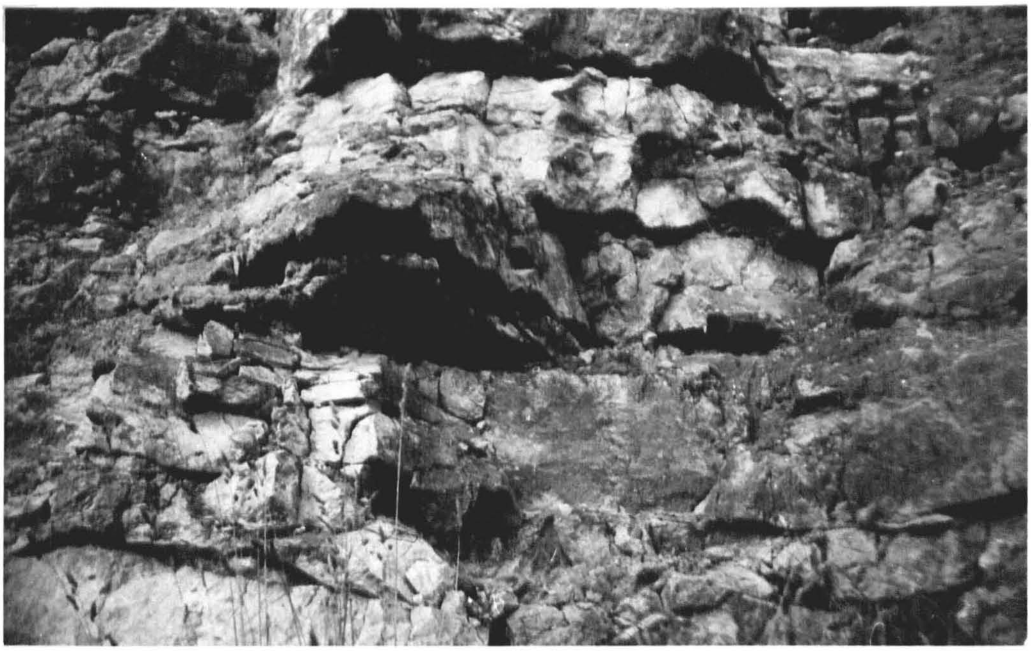

B

Fig. 4.100. Massive oolite (arrowed), forming base of the Lincoln Member, overlying "Cementstones-facies" rocks at Metheringham Quarry (TF 053616).

Fig. 4.101. The heavily weathered base (arrowed) of the Lincoln Member seen at Stainby Quarry (SK 910233).

Fig. 4.102 Close-up of the weathered base of the Lincoln Member at Stainby Quarry (SK 910233), showing decalcified, iron-stained moulds of Thecosmilia sp.



BED	LITHOFACIES	TYPICAL LITHOLOGY	GRAINS % OF TOTAL ROCK	GRAINS TYPE	GRAINS SIZE	MATRIX	TEXTURE
MQ D3	B′	Oncolitic oomicrite	9%	oncolites	0.28 to 1.7 mm	Micrite (much microspar)	Wackestone
			10%	bioclasts	0.2 to 2.8 mm		
			12%	ooliths	0.4 to 0.7 mm		
			10%	peloids	0.09 to 0.3 mm		
MQ D2a	B	Oncolitic biopelmicrite	41%	oncolites	0.4 to 2.4 mm	Micrite	Wackestone
			3%	bioclasts	0.15 to 1.4 mm		
			12%	peloids	0.1 to 0.4 mm		
MQ D1	A	Oncolitic oosparite	20%	oncolites	0.8 to 2.2 mm	Sparite ≫ Micrite	Packstone (/Grainstone)
			28%	ooliths	0.18 to 0.9 mm		
			5%	bioclasts	0.2 to 3.2 mm		
			7%	peloids	0.2 to 0.8 mm		

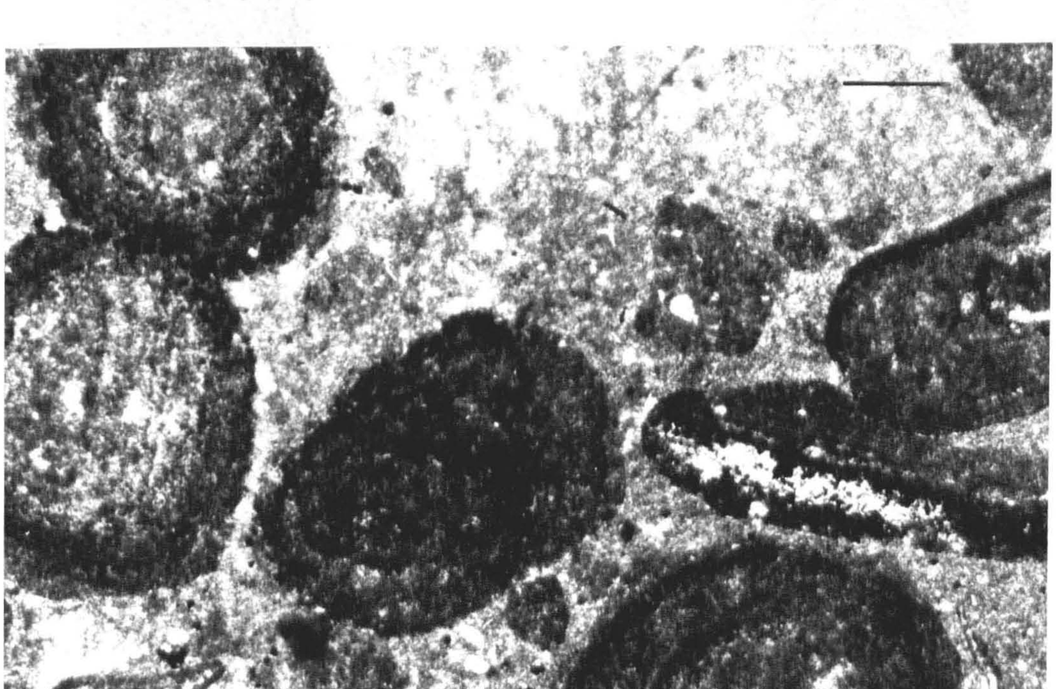
Fig. 4.103. The principal characteristics of the lithofacies of the Lincoln Member in central Lincolnshire.

BED	LITHOFACIES	TYPICAL LITHOLOGY	GRAINS			MATRIX	TEXTURE
			% OF TOTAL ROCK	TYPE	SIZE		
SQ Dlc	B	Oncolitic biopelmicrite	7%	oncolites	0.6 to 3.6 mm	Micrite	Wackestone
			14%	bioclasts	0.4 to 6.2 mm		
			2%	ooliths	0.6 to 1.2 mm		
			12%	peloids	0.062 to 0.2 mm		
WQ Dl	A	Skeletal oosparite	55%	ooliths	0.3 to 0.8 mm	Sparite > Micrite	Grainstone
			11%	intraclasts	0.8 to 2.9 mm		
			6%	bioclasts	0.5 to 2.2 mm		
			2%	peloids	mostly $<$ 0.125 mm		

Fig. 4.104. The principal characteristics of the lithofacies of the Lincoln Member in south Lincolnshire.

Fig. 4.105. Photomicrograph of a skeletal oosparite (bed WQ D1), typical of Lithofacies A of the Lincoln Member.

Fig. 4.106. Photomicrograph of an oncolitic biopelmicrite (bed MQ D2a), typical of Lithofacies B of the Lincoln Member.



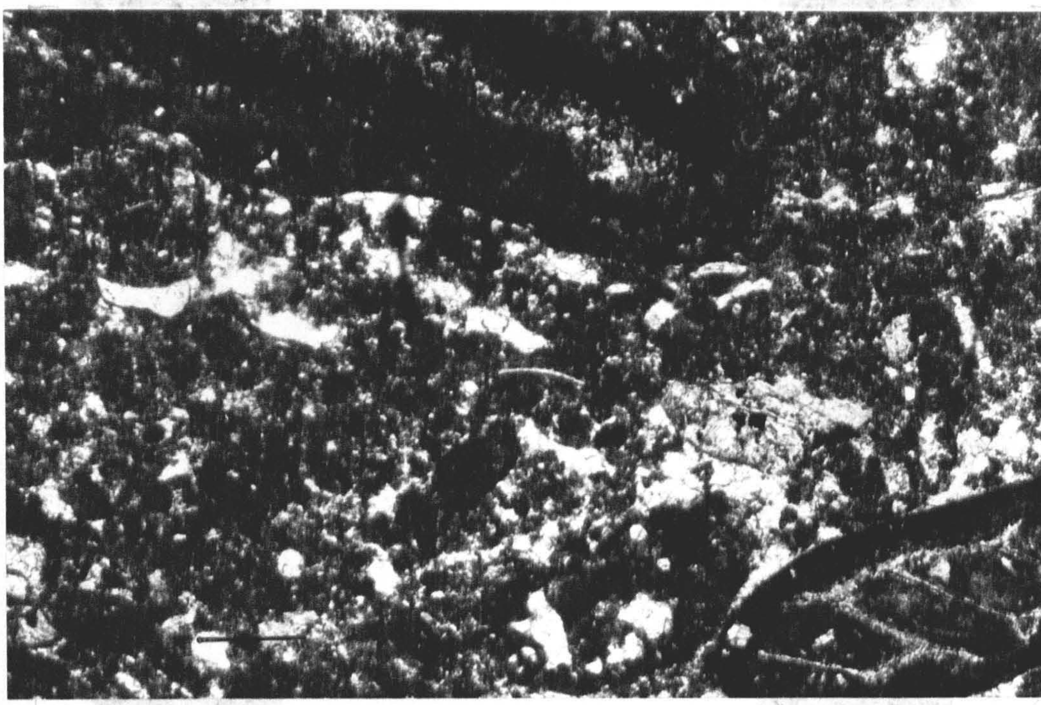


Fig. 4.107. Photomicrograph of an oncolitic biopelmicrite (bed SQ Dlc), typical of Lithofacies B of the Lincoln Member.

Fig. 4.108. Taxonomic composition chart for the fauna of the Lincoln Member (excluding the Ropsley Beds).

MAJOR TAXON		SPECIES
MOLLUSCA	BIVALVIA	*Astarte* sp., *Camptonectes laminatus* (J. Sowerby), *Ctenostreon* sp., ?*Gervillia* sp., *Gresslya abducta* (Phillips), ?*Limatula* sp., *Lithophaga* sp., *Lopha* sp., *Lucina bellona* d'Orbigny, *Modiolus* sp., ?*Perna* sp., *Pholadomya lirata* (J. Sowerby), *Pinna* sp., *Plagiostoma rodburgensis* (Whidborne), *Plagiostoma* sp., *Pleuromya uniformis* (J. Sowerby), *Protocardia* sp. a. Oysters
MOLLUSCA	CEPHALOPODA	*Fissilobiceras* aff. *fissilobatum*, *Fissilobiceras* sp.
MOLLUSCA	GASTROPODA	?*Natica* sp., *Symmetrocapulus* sp., Abundant other types
BRACHIOPODA		*Acanthothiris crossi* (J.F. Walker), "*Rhynchonella*" sp., Terebratulids - abundant, small
CNIDARIA		Solitary coral, Colonial corals (largely sparite replaced), *Thecosmilia* sp.
BRYZOA		*Haploecia straminea* (Phillips)
ECHINODERMATA		*Pseudodiadema* cf. *depressum* Agassiz, *Cidaris* spine, *Pentacrinus* ossicles
ANNELIDA		Serpulids
ARTHOPODA		*Eolepas aalensis*
VERTEBRATA		Fish Tooth
"TRACE FOSSILS"		*Thalassinoides* sp.

Fig. 4.109. Trophic-Substrate niche chart for the Lincoln Member fauna from the Greetwell Hollow Quarry, Lincoln (TF 003721).

S = Suspension feeder

F = Filter feeder

C = Carnivore

G = Grazer (herbivorous)

D = Deposit feeder

SPECIES	TAXON	Feeding Type	EPIFAUNAL			SEMI-INFAUNAL		INFAUNAL		
			Byssate/ Pedunculate	Cemented	Free	Byssate	Free	Deep	Shallow Mobile	Shallow Immobile
Camptonectes laminatus (J. Sowerby)	Bivalve	S	x							
Pholadomya lirata (J. Sowerby)	"	S						x		x?
Pleuromya uniformis (J. Sowerby)	"	S						x		
Protocardia sp. a.	"	S							x	
Plagiostoma rodburgensis (Whidborne)	"	S	x		x?					
Gresslya abducta (Phillips)	"	S						x		
Lucina bellona (d'Orbigny)	"	S							x	
?*Limatula* sp.	"	S	x							
?*Natica* sp.	Gastropod	C			x					
'*Rhynchonella*' sp.	Brachiopod	F	x							
Pseudodiadema cf. *depressum* (Agassiz)	Echinoid	G			x					
Burrows	?	D						(x)		

Fig. 4.110. Trophic-Substrate niche chart for the fauna of the Lincoln Member biostrome seen at the Dean and Chapter Pit, Lincoln (SK 977734).

S = Suspension feeder

F = Filter feeder

G = Grazer (herbivorous)

SPECIES	TAXON	Feeding Type	EPIFAUNAL			SEMI-INFAUNAL		INFAUNAL		
			Byssate/ Pedunculate	Cemented	Free	Byssate	Free	Deep	Shallow	
									Mobile	Immobile
Plagiostoma spp.	Bivalve	S	x		x?					
Modiolus sp.	"	S	x							
Ctenostreon sp.	"	S		x						
Lopha sp.	"	S		x						
'*Terebratula*' sp.	Brachiopod	F	x							
Symmetrocapulus sp.	Gastropod	G			x					
Colonial corals	Coral	S		x						

Fig. 4.111. The type section of the Ropsley Beds (Lincoln Member) exposed at Ropsley Quarry (TF 002364). The top (arrowed T) and base (arrowed B) are indicated.


T
B

Fig. 4.112. Isopachyte map for the Ropsley Beds of the Lincoln Member. Isopachs are in metres. Basic data is taken from Fig. 4.1.

HQ = Harmston Quarry

MQ = Metheringham Quarry

LQ = Leadenham Quarry

ARC = Ancaster Railway Cutting

RQ = Ropsley Quarry

LPRC = Little Ponton Railway Cutting

SNQ = Sproxton Quarry

SQ = Stainby Quarry

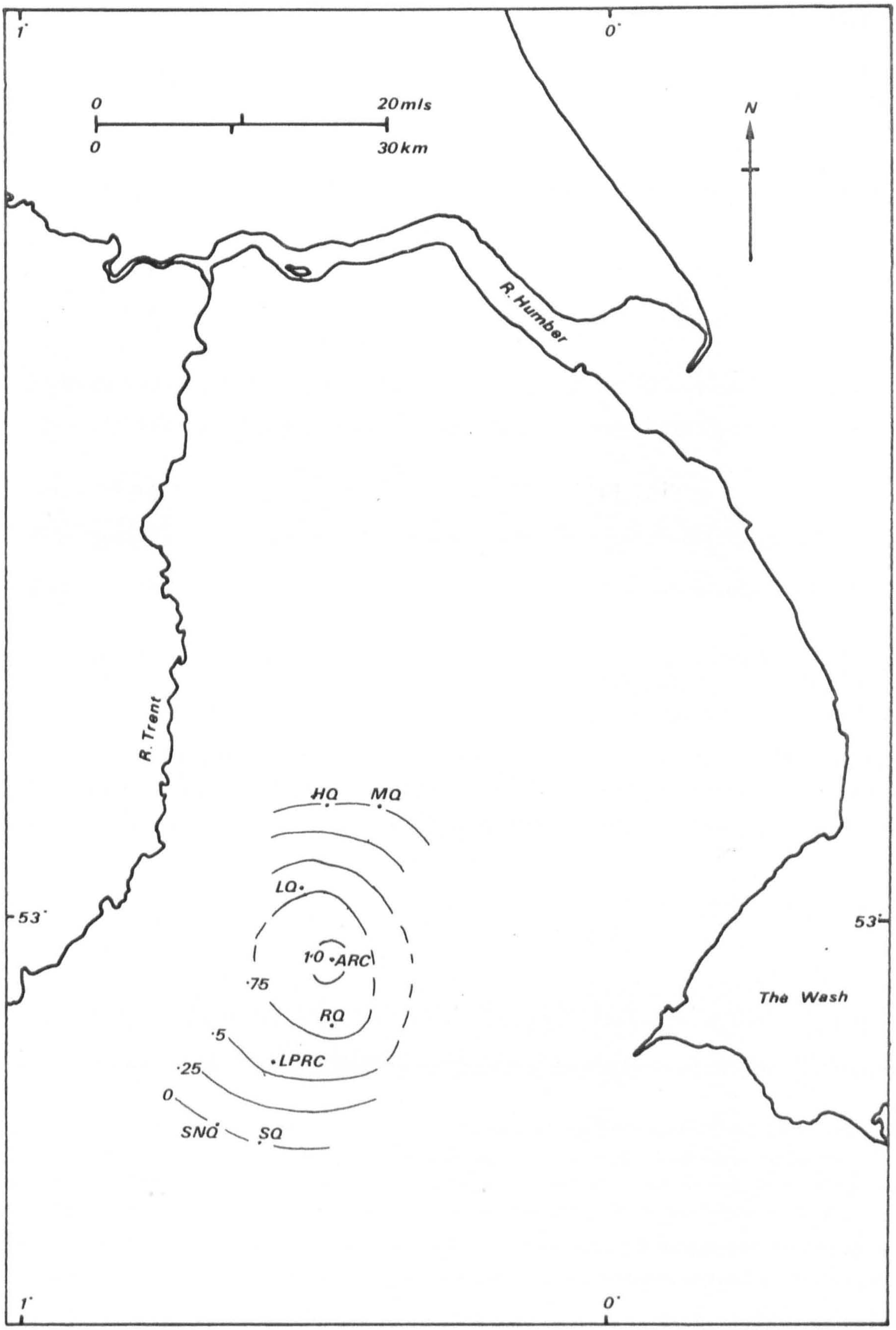

1°
0°
0
20 mls
0
30 km
N
R. Humber
R. Trent
HQ
MQ
LQ
1·0
ARC
·75
RQ
·5
LPRC
·25
0
SNQ
SQ
53°
53°
The Wash
1°
0°

Fig. 4.113. Downcutting of the Sleaford Member into the Ropsley Beds (Lincoln Member) at Copper Hill Quarry, Ancaster (SK 979427). The erosive contact is arrowed.

Fig. 4.114. "Lithophaga" type borings penetrating the top of the Ropsley Beds (Lincoln Member) at Copper Hill Quarry, Ancaster (SK 979427). The borings occur at the erosive contact between the Sleaford Member and Ropsley Beds, and are infilled with ooliths from the Sleaford Member.


mm 10 20 30 40 50 60 70 80 90 100

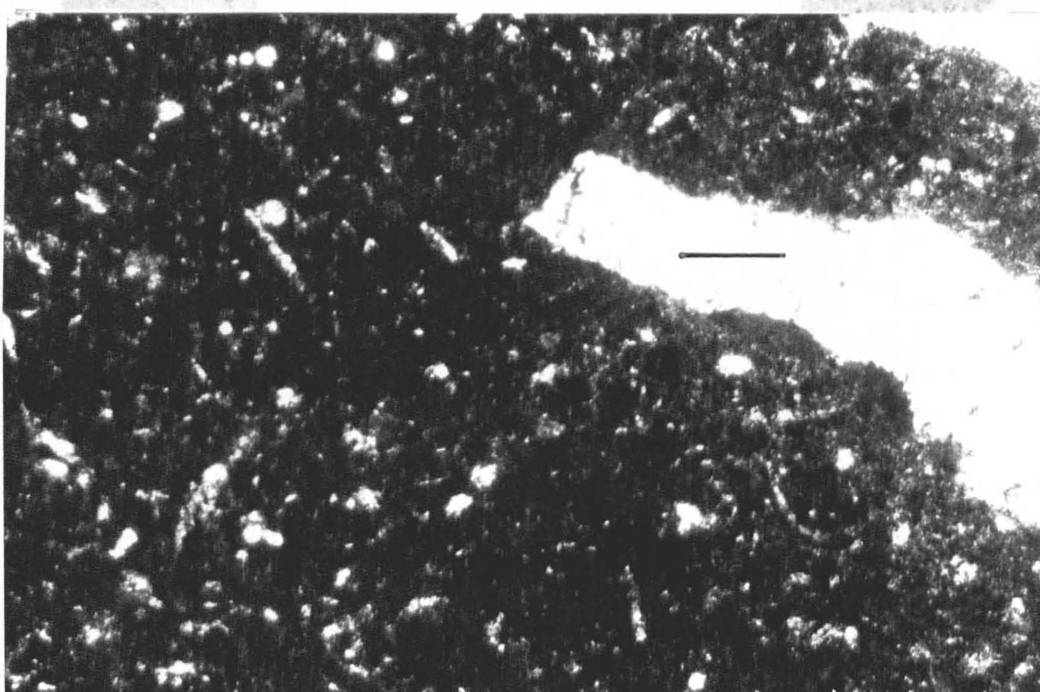


Fig. 4.115. Photomicrograph of a biomicrite (bed RQ D´1), the typical lithology of the Ropsley Beds (Lincoln Member).

Fig. 4.116. Trophic-Substrate niche chart for the Ropsley Beds fauna from Ropsley Quarry (TF 002364).

S = Suspension feeder

C = Carnivore

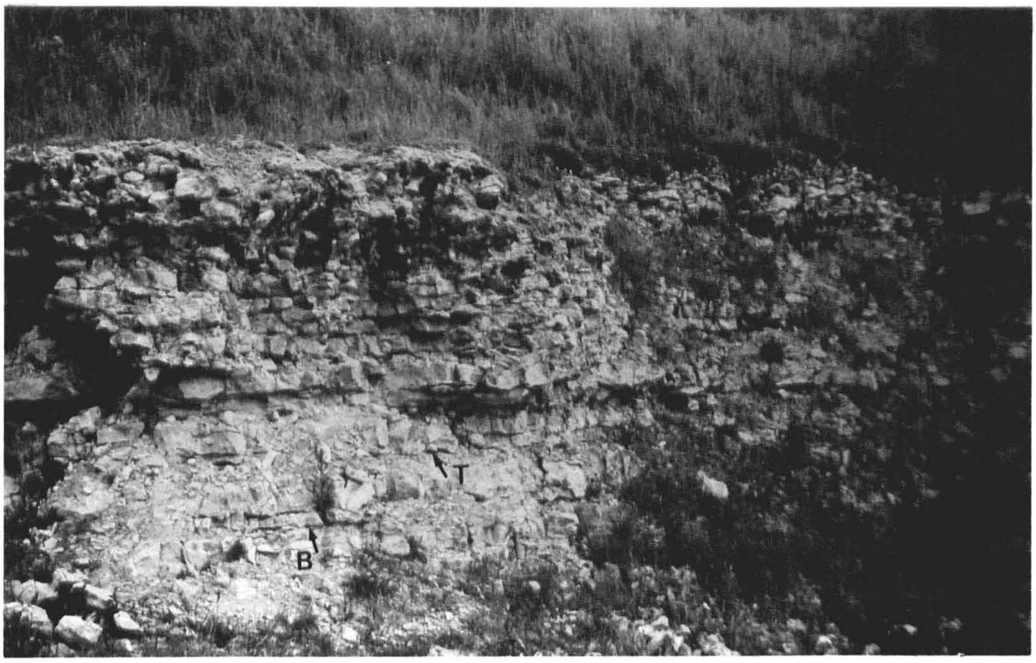
G = Grazer (herbivorous)

F = Filter feeder

SPECIES	TAXON	Feeding Type	EPIFAUNAL			SEMI-INFAUNAL		INFAUNAL		
			Byssate/ Pedunculate	Cemented	Free	Byssate	Free	Deep	Shallow Mobile	Shallow Immobile
Gervillella acuta (J. de C. Sowerby)	Bivalve	S	x							
Lucina bellona (d'Orbigny)	"	S							x	
Mactromya sp.	"	S							x?	
Modiolus imbricatus (J. Sowerby)	"	S				x				
Pteroperna sp. a.	"	S	x							
Plagiostoma sp.	"	S	x?		x					
Natica adducta (Phillips)	Gastropod	C			x?					
Pseudomelania (Oonia) subglobosa (Morris & Lycett)	"	S?							x	
Procerithium minchinhamptonense (Arkell & Cox)	"	G			x					
'Terebratula' sp.	Brachiopod	F	x							
Montlivaltia trochoides (Edwards & Haime)	Coral	S		x						

Fig. 4.117. The type section of the Little Bytham beds (Lincoln Member) exposed at Little Bytham Quarry (TF 013178). The top (arrowed T) and base (arrowed B) are indicated.

Fig. 4.118. The type section of the Scottlethorpe Member exposed at Scottlethorpe Quarry, Edenham (TF 046204). The top (arrowed T) and base (arrowed B) are indicated.


T
B


B

Fig. 4.119. Isopachyte map for the Scottlethorpe Member. Isopachs are in metres. Basic data is taken from Fig. 4.1.

HQ = Harmston Quarry

MQ = Metheringham Quarry

LQ = Leadenham Quarry

AQ = Ancaster (Castle) Quarry

RQ = Ropsley Quarry

LPRC = Little Ponton Railway Cutting

SNQ = Sproxton Quarry

SQ = Stainby Quarry

SWQ = South Witham Quarry

WQ = Woolfox Quarry

CSFQ = Soil Fertility Quarry, Clipsham

CBQ = Castle Bytham Quarry

LBQ = Little Bytham Quarry

SQE = Scottlethorpe Quarry, Edenham

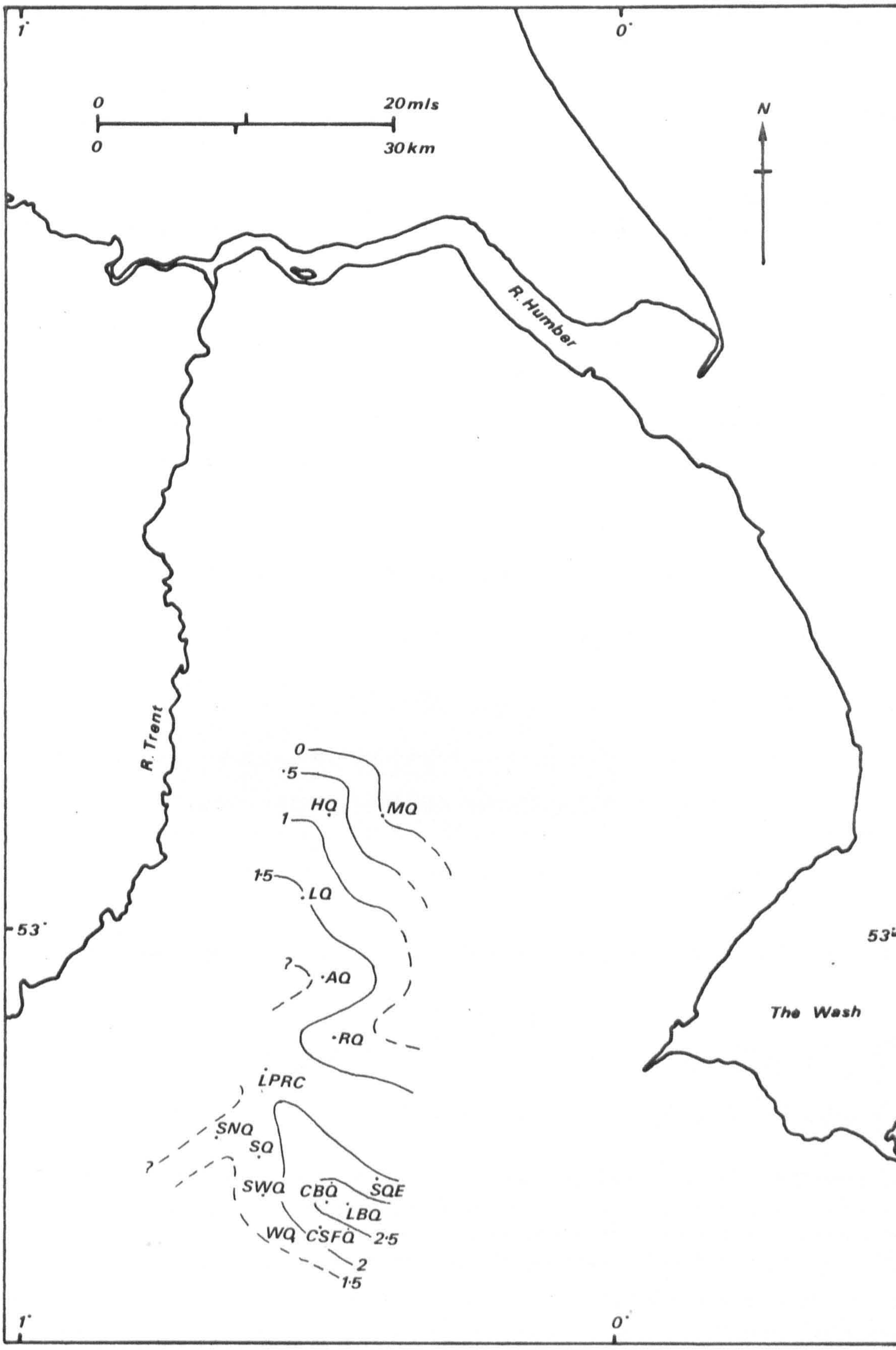
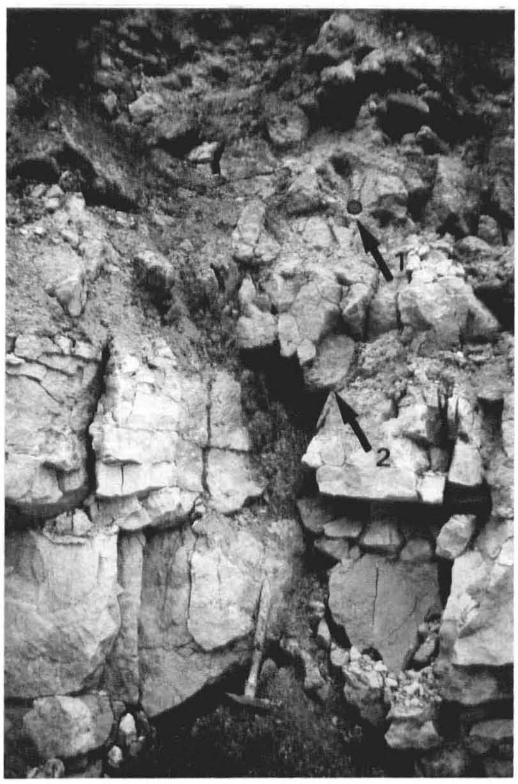

1°
0°
0
20 mls
0
30 km
N
R. Humber
R. Trent
53°
53°
The Wash
0
·5
1
1·5
HQ
MQ
LQ
?
AQ
RQ
LPRC
SNQ
SQ
?
SWQ
CBQ
SQE
LBQ
WQ
CSFQ
2·5
2
1·5
1°
0°

Fig. 4.120. Downcutting of the Sleaford Member into the Lincoln Member at Great Ponton Quarry (SK 935303). The Sleaford Member/Lincoln Member contact is arrowed 1; the Lincoln Member/Greetwell Member contact is arrowed 2.

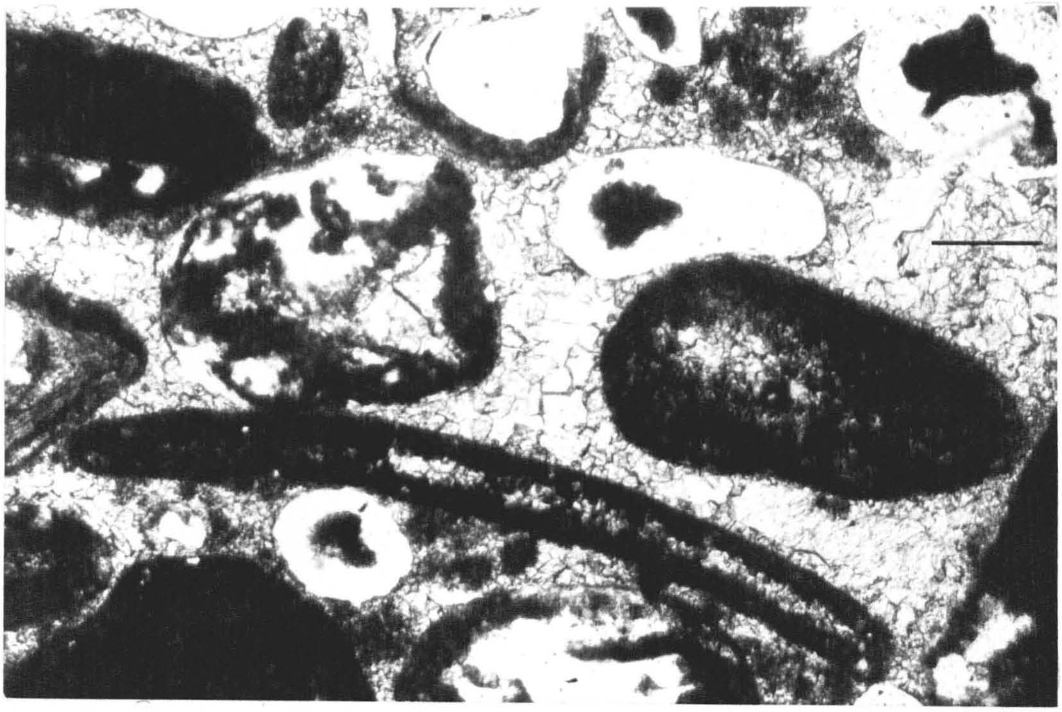

1
2

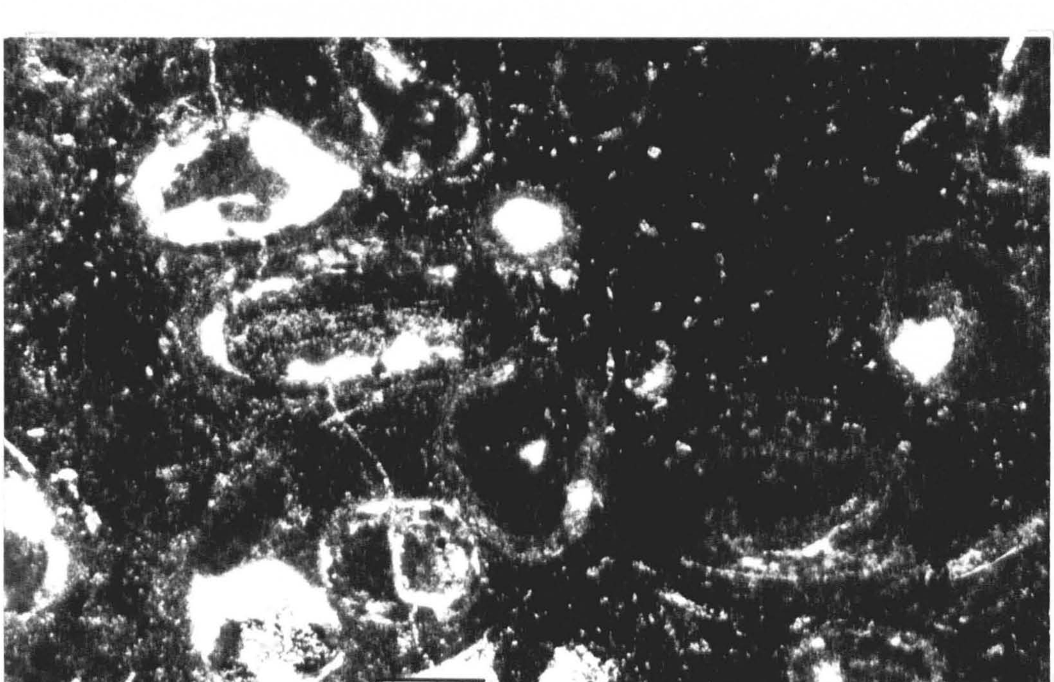
BED	LITHOFACIES	TYPICAL LITHOLOGY	GRAINS: % OF TOTAL ROCK	GRAINS: TYPE	GRAINS: SIZE	MATRIX	TEXTURE
CSFQ E3a	C	Biomicrite	14%	bioclasts	up to 8 mm	Micrite	Wackestone (grain poor)
			5%	peloids	0.02 to 0.6 mm		
			2%	oncolites	1.3 to 2.2 mm		
RQ E4	B	Skeletal oomicrite	29%	ooliths	usually 0.2 to 0.8 mm max. 1.5 mm	Micrite (some sparite)	Wackestone (grain rich)
			6%	bioclasts	0.2 to 3.6 mm		
			4%	intraclasts	1.5 to 2.1 mm		
			15%	oncolites	around 0.8 mm		
LPRC E1a	A	Skeletal oosparite	51%	ooliths	0.3 to 1.5 mm usually 0.4 to 1.0 mm	Sparite ≫ Micrite	Packstone
			5%	bioclasts	0.5 to 2.3 mm		
			7%	intraclasts	1.1 to 1.8 mm		
			4%	peloids	$<$ 0.2 mm		

Fig. 4.12i. The principal characteristics of the lithofacies of the Scottlethorpe Member.

Fig. 4.122. Photomicrograph of a skeletal oosparite (bed LPRC Ela), typical of Lithofacies A of the Scottlethorpe Member.

Fig. 4.123. Photomicrograph of a skeletal oomicrite (bed RQ E4), typical of Lithofacies B of the Scottlethorpe Member.





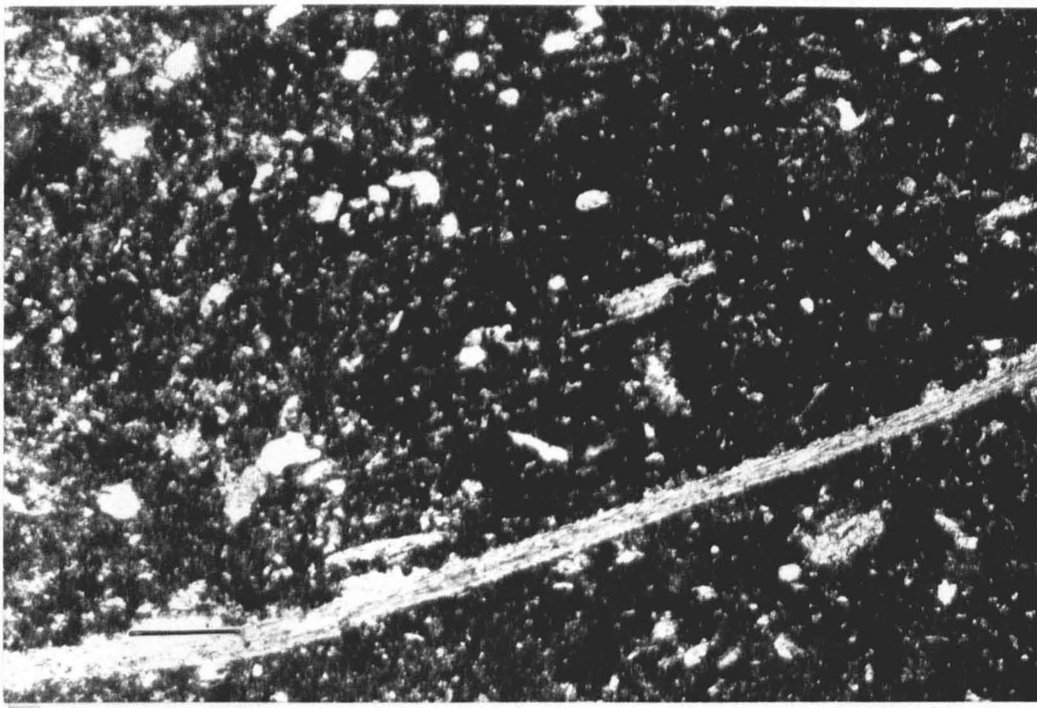


Fig. 4.124. Photomicrograph of a biomicrite (bed CSFQ E3a), typical of Lithofacies C of the Scottlethorpe Member.

Fig. 4.125. Biohermal domes of Thecosmilia sp. (?) corals seen in the Scottlethorpe Member of the Soil Fertility Quarry, Clipsham (SK 978154).

Fig. 4.126. The type section of the Lindsey Shale Member exposed near Kirton in Lindsey (SE 940014). The top (arrowed T) and base (arrowed B) are indicated.

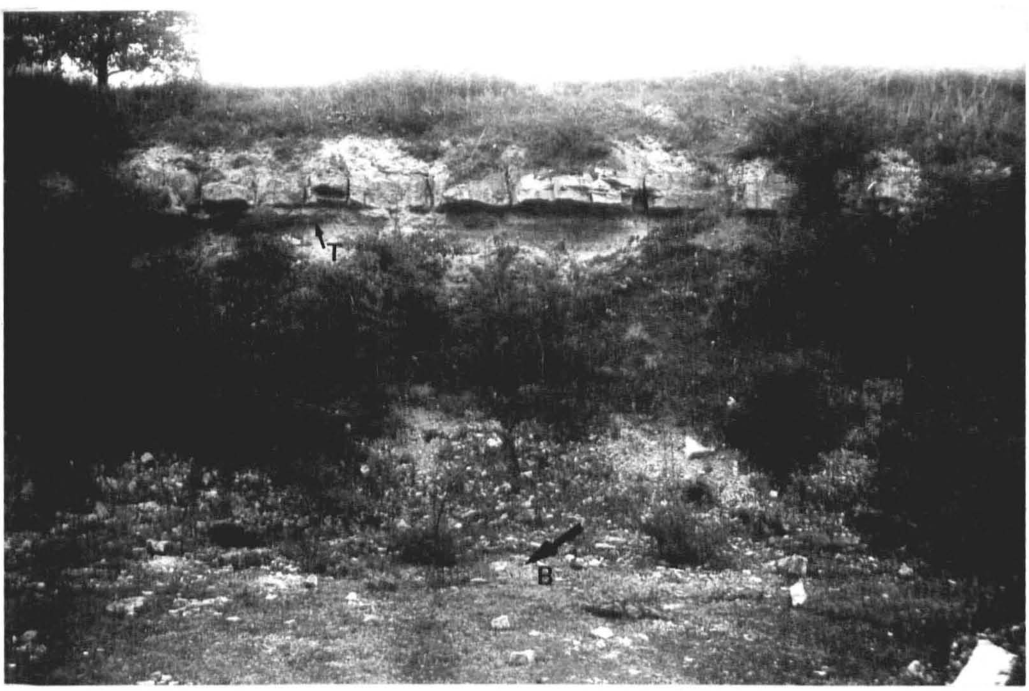
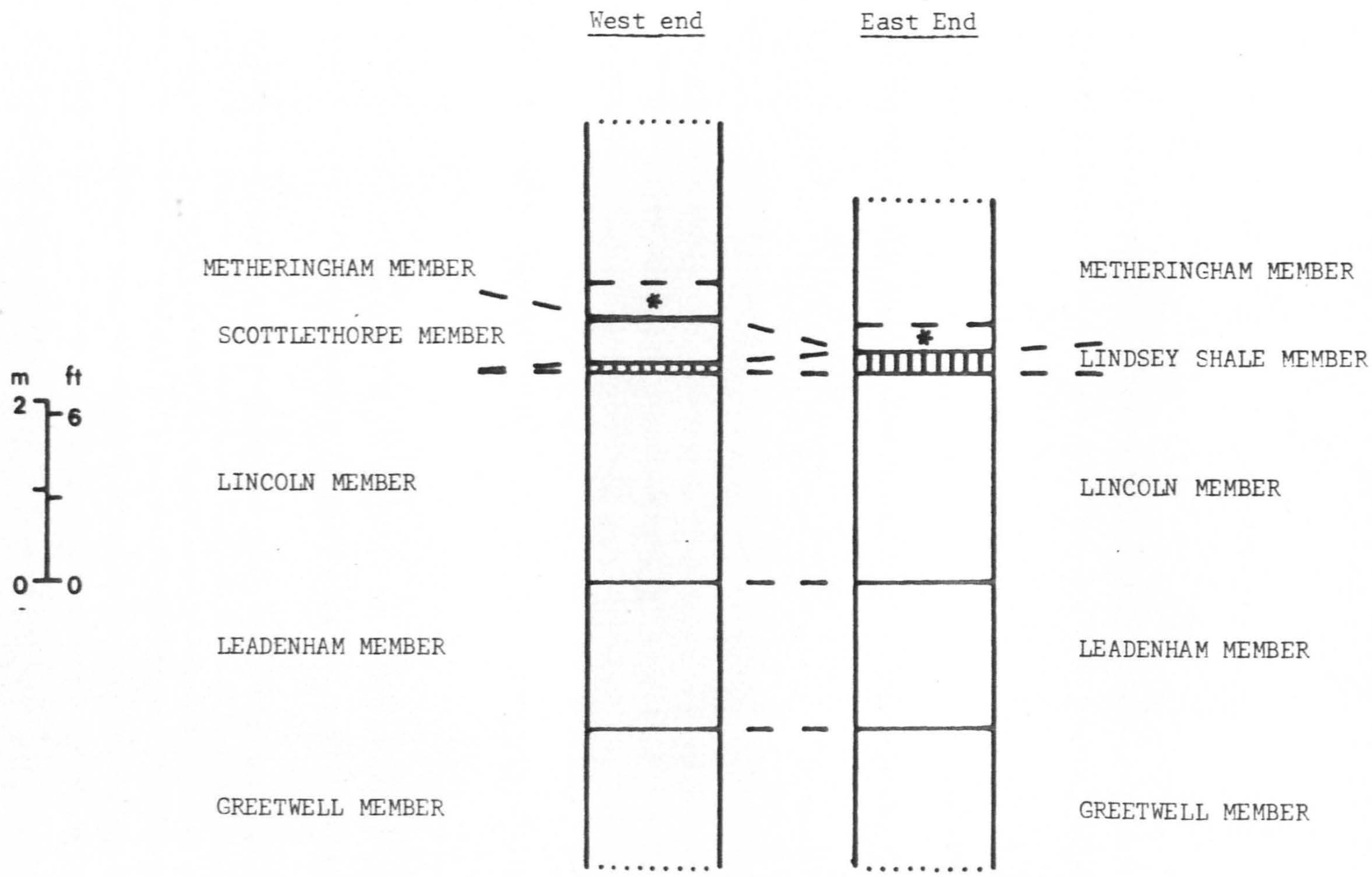

T
B

Fig. 4.127. The stratigraphical interpretation proposed for Harmston Quarry (SK 992619). Note in particular that the Lindsey Shale Member (formerly Kirton Shale) and Scottlethorpe Member (including former Crossi Beds) are considered to interdigitate.

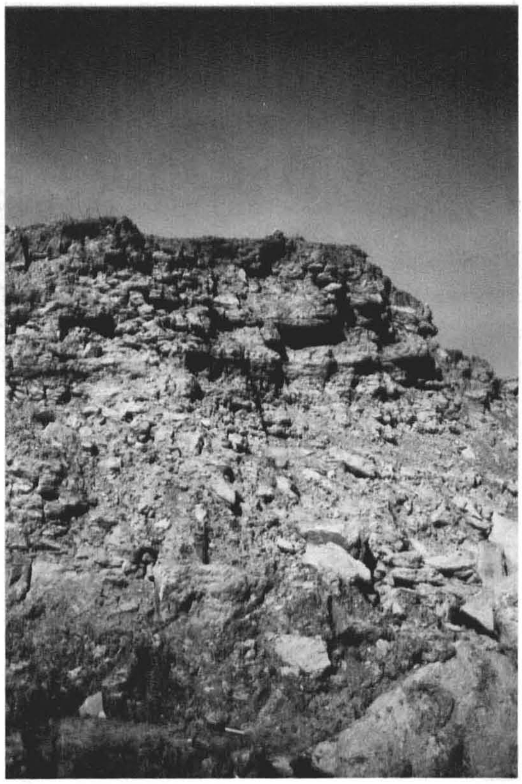
Harmston (SK 992619)



* probable "Upper Crossi Bed" of previous workers.

Fig. 4.128. A "False Formation" exposed in the Lindsey Shale Member of the Manton Stone Company Quarry near Kirton in Lindsey (SE 940024).

Fig. 4.129. The type section of the Metheringham Member exposed in Metheringham Quarry (TF 053616). The top (arrowed T) and base (arrowed B) are indicated.



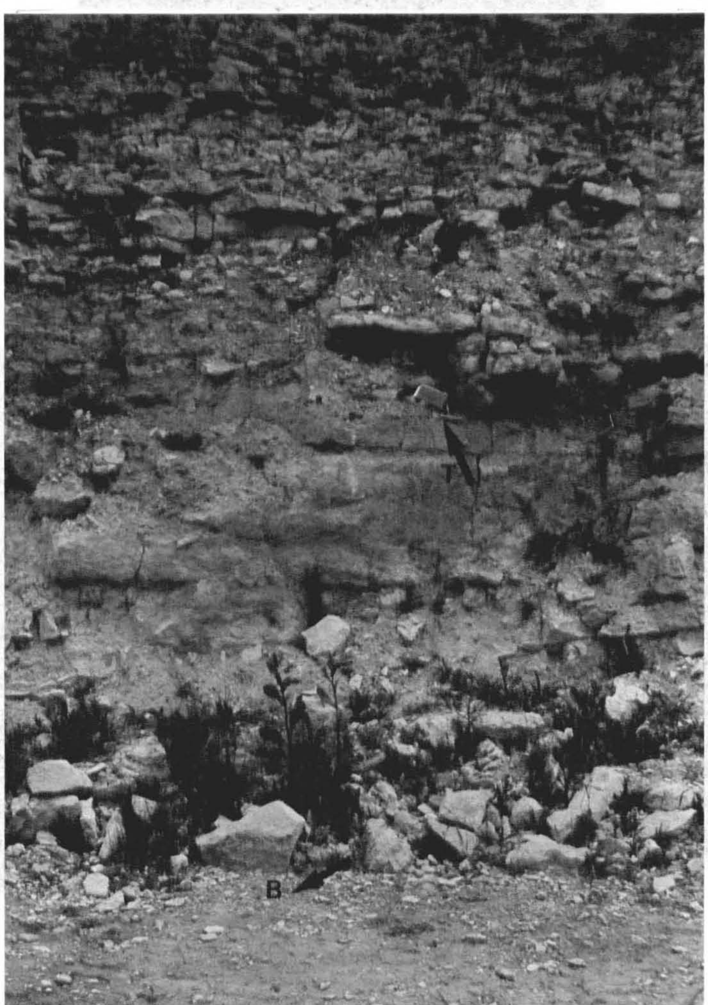

B

Fig. 4.130. The gradational contact between the Metheringham and Lindsey Shale Members seen at Greetwell Hollow Quarry, Lincoln (TF 003721).

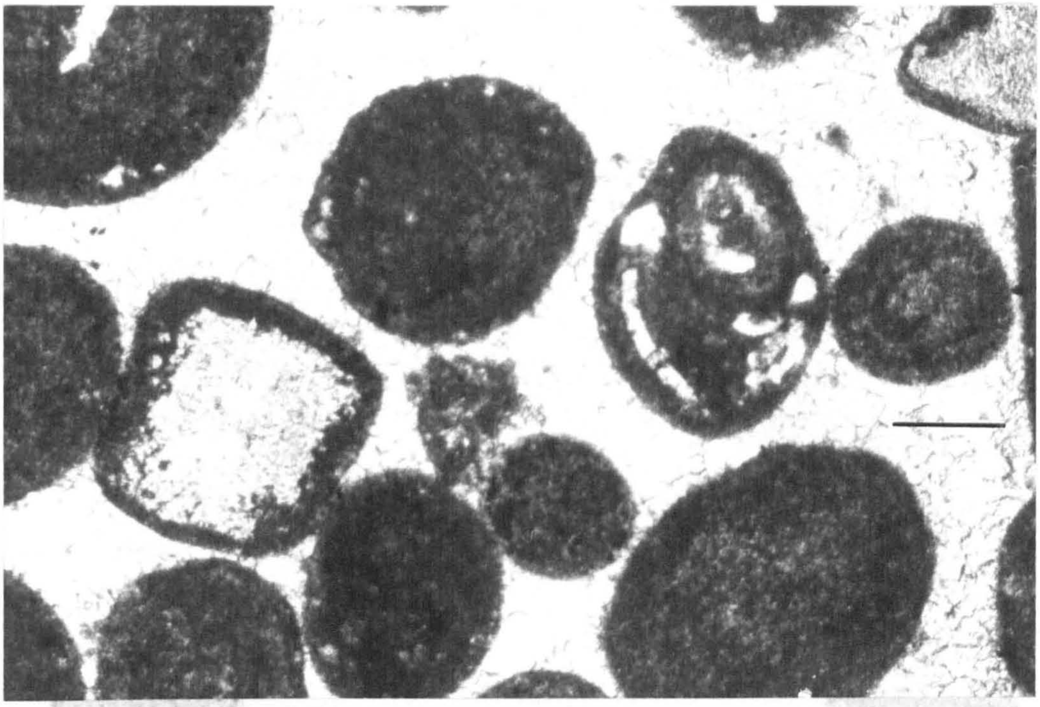
Fig. 4.131. Thalassinoides sp. (arrowed) and other horizontal traces seen on the base of the Metheringham Member at Metheringham Quarry (TF 053616).

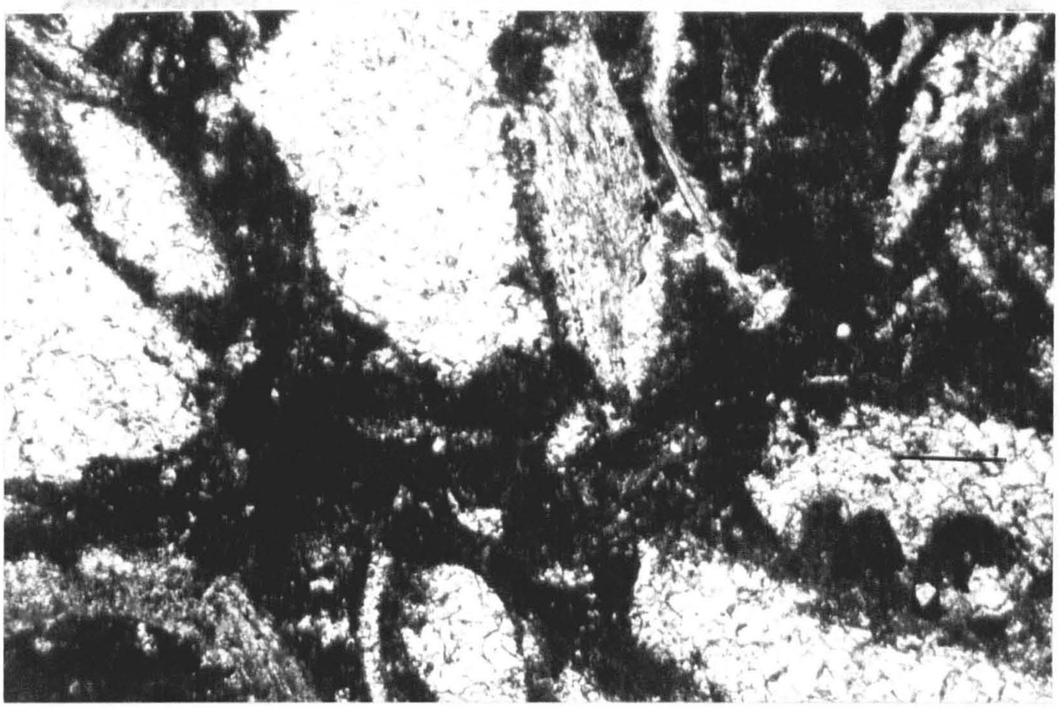
BED	LITHOFACIES	TYPICAL LITHOLOGY	GRAINS			MATRIX	TEXTURE
			% OF TOTAL ROCK	TYPE	SIZE		
MQ H6	–	Silty oncolitic pelsparite	48% 13% 7% 2%	"oncolites" peloids bioclasts quartz	0.75 to 2.1 mm 0.062 to 0.125 mm 0.15 to 1.3 mm silt to v. fine sand	Sparite > Micrite	Packstone
MQ H3	–	Oncolitic oosparite	43% 21% 10% 2%	ooliths oncolites peloids bioclasts	0.4 to 1.3 mm 1.1 to 2.1 mm 0.2 to 0.4 mm 0.3 to 2.0 mm	Sparite ≫ Micrite	Grainstone
MQ H1	–	Oosparite	55% 18% 5%	ooliths intraclasts bioclasts	0.2 to 1.3 mm mostly 0.4 to 0.8 mm 0.6 to 1.4 mm 0.3 to 2.6 mm	Sparite	Grainstone

Fig. 4.132. The principal characteristics of the lithofacies of the Metheringham Member.

Fig. 4.133. Photomicrograph of an oosparite (bed MQ H1), the typical lithology of the Metheringham Member.

Fig. 4.134. Photomicrograph of a biomicrite (bed KLA H1), which forms the basal bed (= former Upper Crossi Bed) of the Metheringham Member in South Humberside.





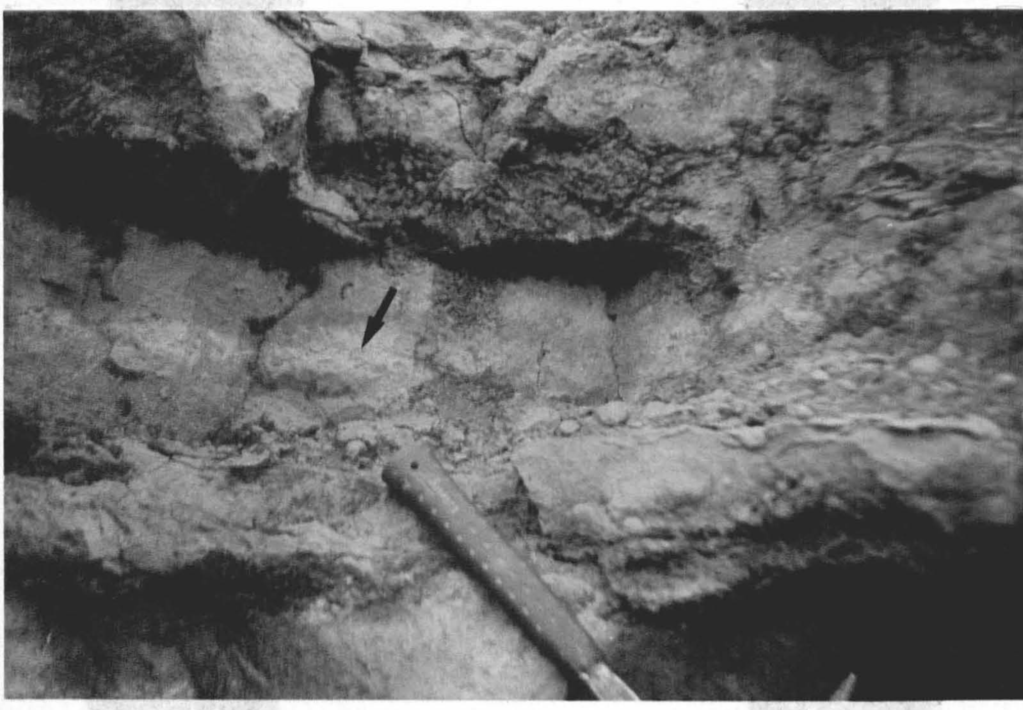


Fig. 4.135. Abundant "<u>Nerinea</u>" spp. (arrowed) gastropods, which are the characteristic faunal element of the Blankney Member, seen in the Metheringham Quarry (TF 053616) sequence.

Fig. 4.136. The type section of the Blankney Member exposed in Metheringham Quarry (TF 053616). The top (arrowed T) and base (arrowed B) are indicated.

Fig. 4.137. The hypostratotype of the Blankney Member exposed at Long Hollow Quarry, Braceby (TF 010351). The top (arrowed T) and base (arrowed B) are indicated.


B


T
B

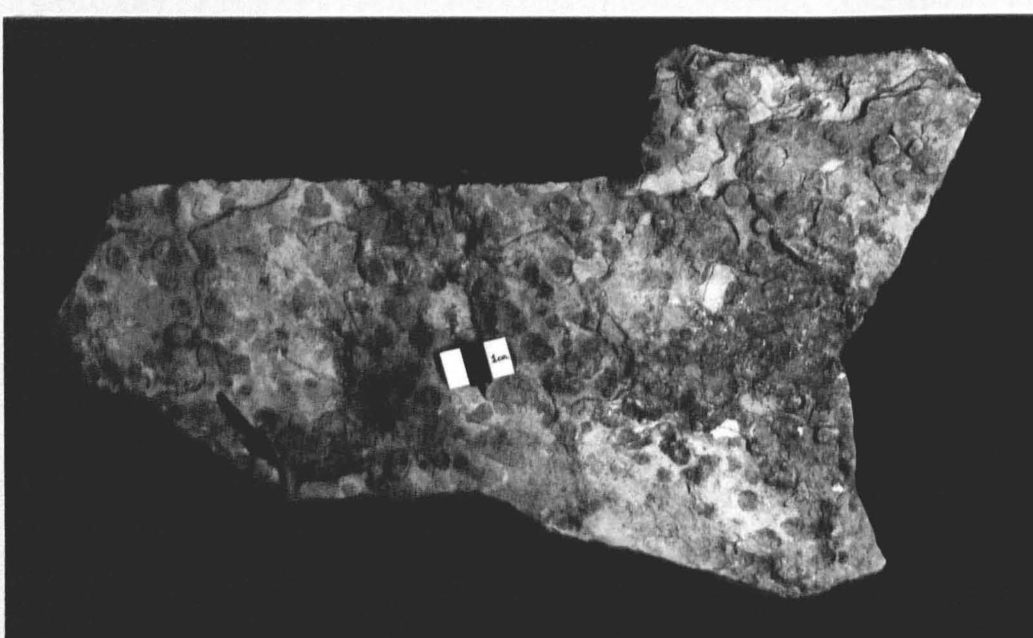


Fig. 4.138. "Dogger-like" concretions (arrowed) seen in the Blankney Member at Metheringham Quarry (TF 053616).

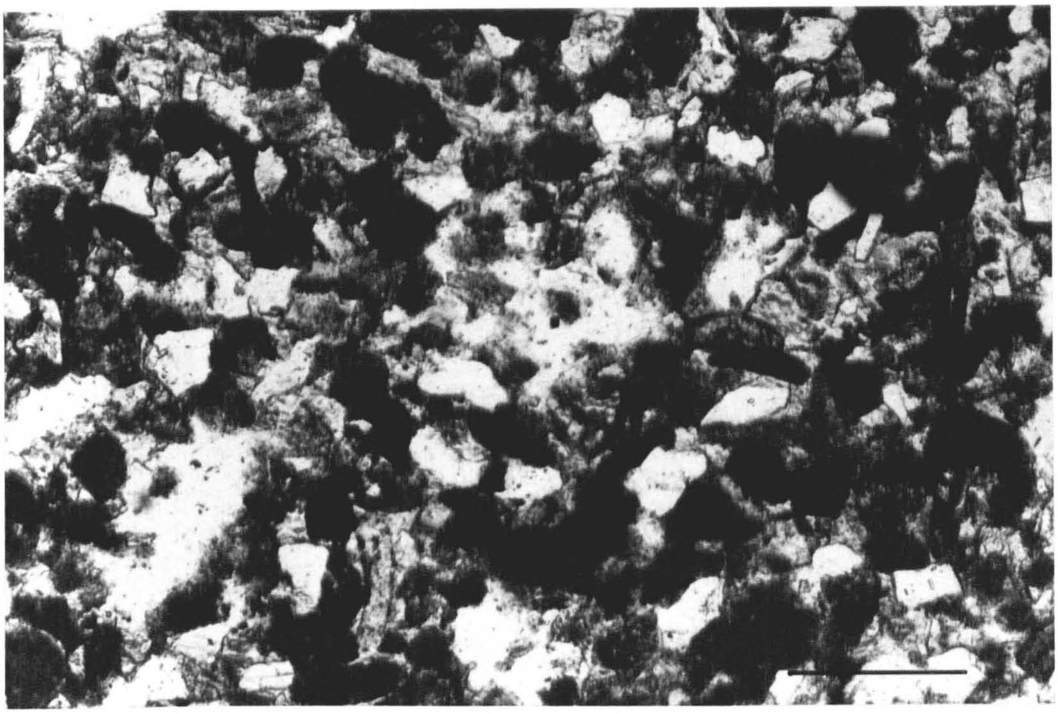
Fig. 4.139. Plan view of dense Skolithos sp. burrows from the Blankney Member of Metheringham Quarry (TF 053616). Possible connections between adjacent pipes, which may form vertical, U-shaped burrows, are arrowed.

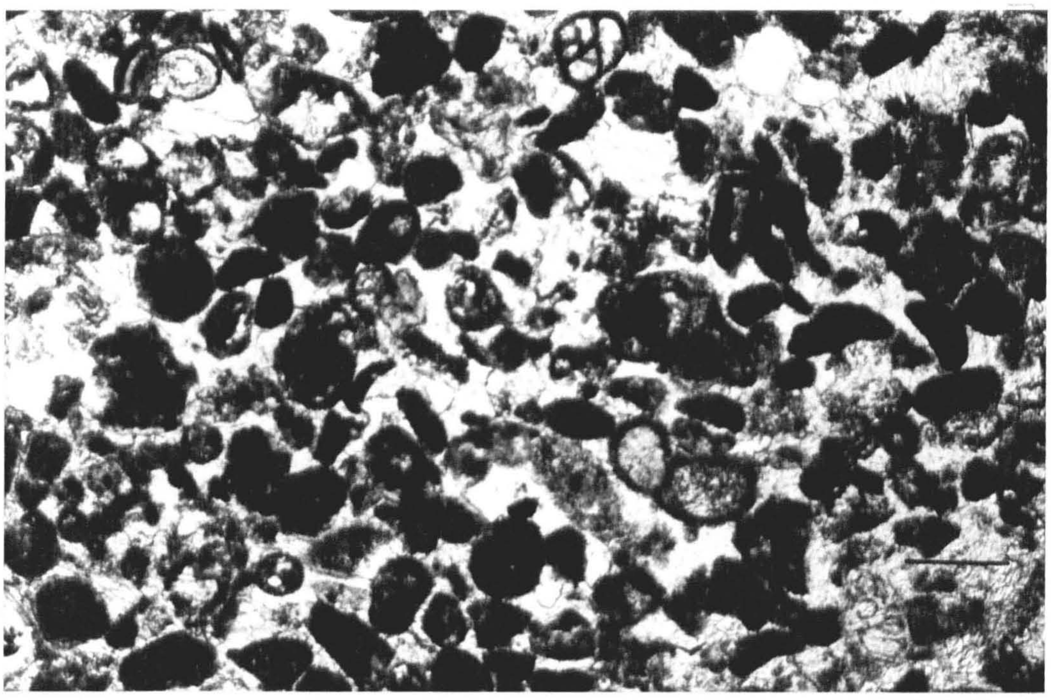
BED	LITHOFACIES	TYPICAL LITHOLOGY	GRAINS: % OF TOTAL ROCK	GRAINS: TYPE	GRAINS: SIZE	MATRIX	TEXTURE
MQ I	A	Quartzose pelsparite	53%	peloids	0.062 to 0.125 mm	Sparite > Micrite	Packstone
			3%	bioclasts	0.062 to 0.187 mm		
			13%	quartz	silt to v. fine sand		
BLHQ I1	A′	Skeletal pelsparite	51%	peloids	0.031 to 0.37 mm mostly 0.062 to 0.19 mm	Sparite ≫ Micrite	Grainstone
			9%	bioclasts	0.125 to 1.6 mm mostly 0.125 to 0.25 mm		
			3%	ooliths	0.15 to 0.37 mm		
			2%	quartz	silt to v. fine sand		
BLHQ I2d	B	Peloidal oosparite	23%	ooliths	0.2 to 0.85 mm mostly 0.25 to 0.4 mm	Sparite	Grainstone
			42%	peloids	<0.2 mm		
			9%	bioclasts	0.15 to 4.4 mm		
			4%	intraclasts	0.8 to 1.8 mm		
SHQ I6	C	Skeletal oosparite	51%	ooliths	0.2 to 1.4 mm	Sparite > Micrite	Packstone
			9%	bioclasts	0.2 to 5.8 mm		
			7%	intraclasts	1.2 to 3.7 mm		
			8%	peloids	0.15 to 0.25 mm		

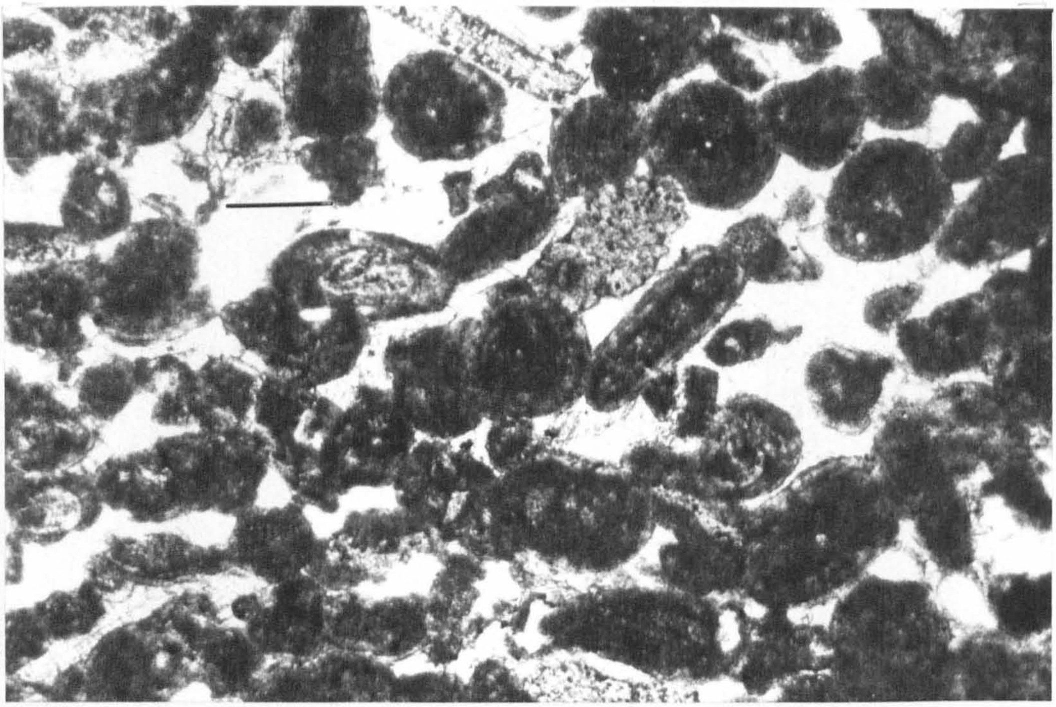
Fig. 4.140. The principal characteristics of the lithofacies of the Blankney Member.

Fig. 4.141. Photomicrograph of a quartzose pelsparite (bed MQ I), typical of Lithofacies A of the Blankney Member.

Fig. 4.142. Photomicrograph of a skeletal pelsparite (bed BLHQ I1), typical of Lithofacies A′ of the Blankney Member.







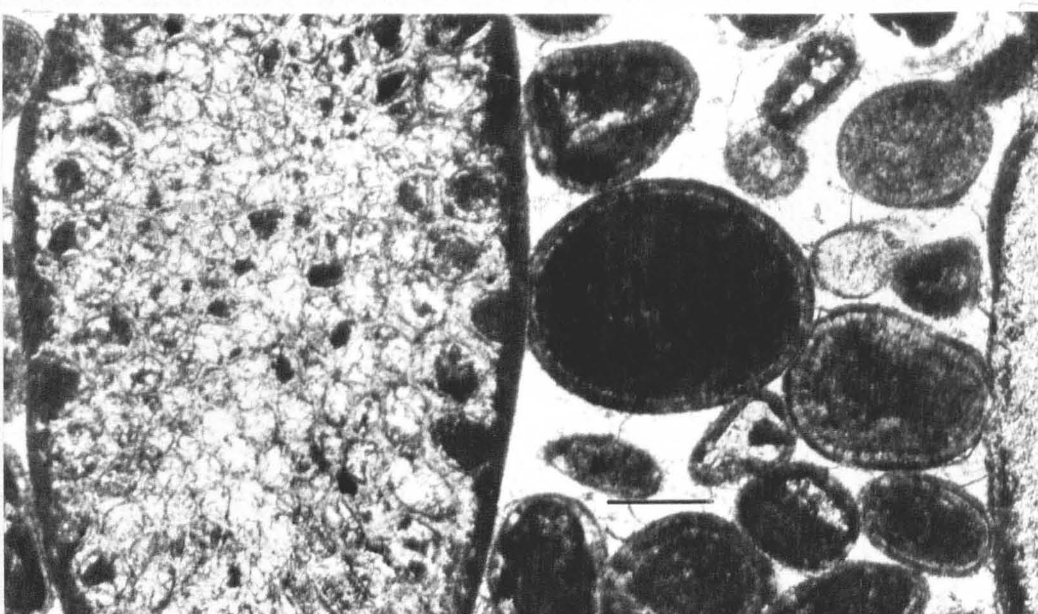
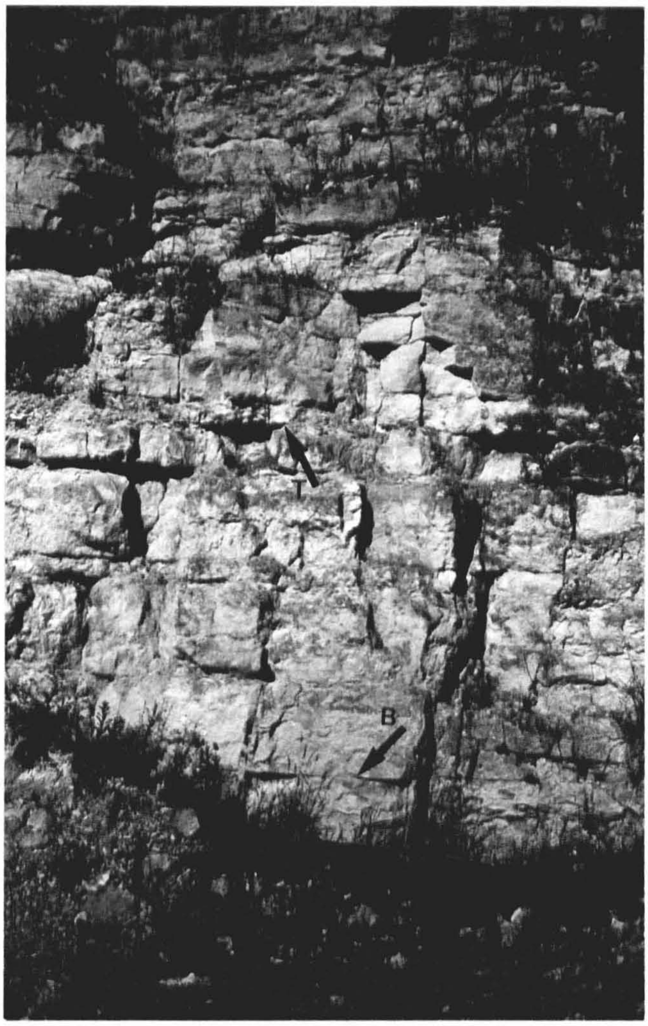


Fig. 4.143. Photomicrograph of a peloidal oosparite (bed BLHQ I 2d), typical of Lithofacies B of the Blankney Member.

Fig. 4.144. Photomicrograph of a skeletal oosparite (bed SHQ I6), typical of Lithofacies C of the Blankney Member.

Fig. 4.145. The type section of the Castle Bytham Member exposed at Castle Bytham Quarry (SK 990180). The top (arrowed T) and base (arrowed B) are indicated.

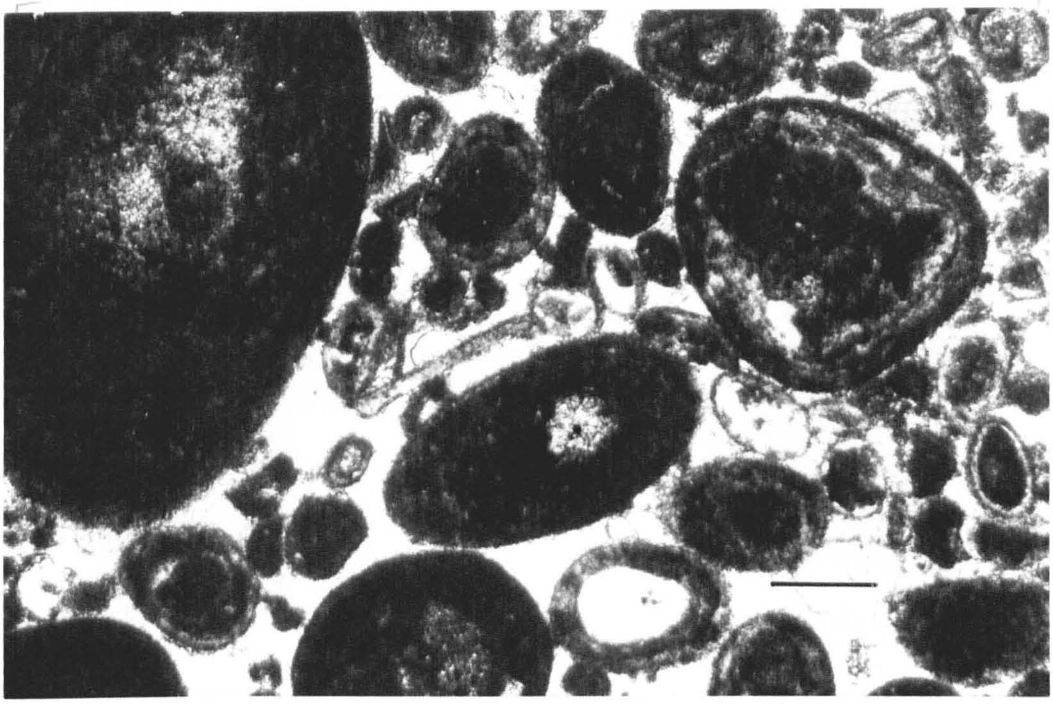

T
B

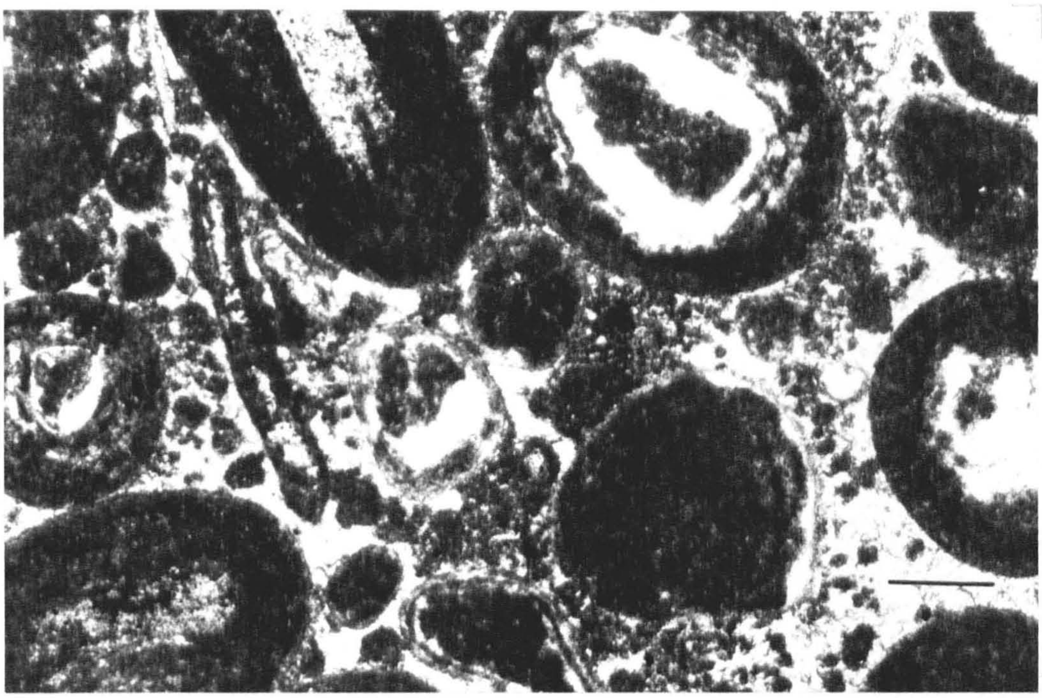
BED	LITHOFACIES	TYPICAL LITHOLOGY	GRAINS: % OF TOTAL ROCK	GRAINS: TYPE	GRAINS: SIZE	MATRIX	TEXTURE
LBQ G4	C	Oncolitic biomicrite	20%	oncolites	0.9 to 3.4 mm mostly 0.9 to 1.8 mm	Micrite	Wackestone
			23%	bioclasts	0.2 to 9.6 mm		
			8%	peloids	0.1 to 0.45 mm		
			2%	ooliths	0.45 to 0.8 mm		
CBQ G4b	B	Peloidal oosparite	61%	ooliths	0.3 to 1.4 mm	Sparite > Micrite	Grainstone/ Packstone
			11%	peloids	0.062 to 0.15 mm		
			4%	bioclasts	0.3 to 0.85 mm		
CBQ G1	A	Oosparite	57%	ooliths	0.3 to 1.0 mm	Sparite	Grainstone
			8%	bioclasts	0.4 to 3.0 mm		
			12%	intraclasts	2.1 to 3.2 mm		

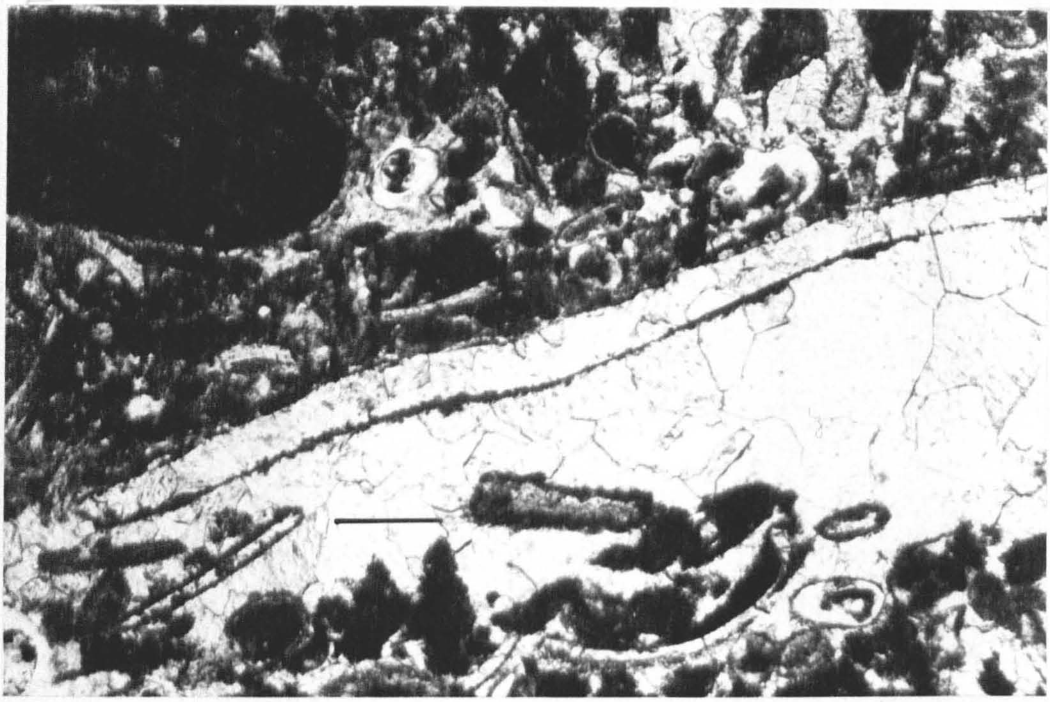
Fig. 4.146. The principal characteristics of the lithofacies of the Castle Bytham Member.

Fig. 4.147. Photomicrograph of an oosparite (bed CBQ G5), typical of Lithofacies A of the Castle Bytham Member.

Fig. 4.148. Photomicrograph of a peloidal oosparite (bed CBQ G4b), typical of Lithofacies B of the Castle Bytham Member.







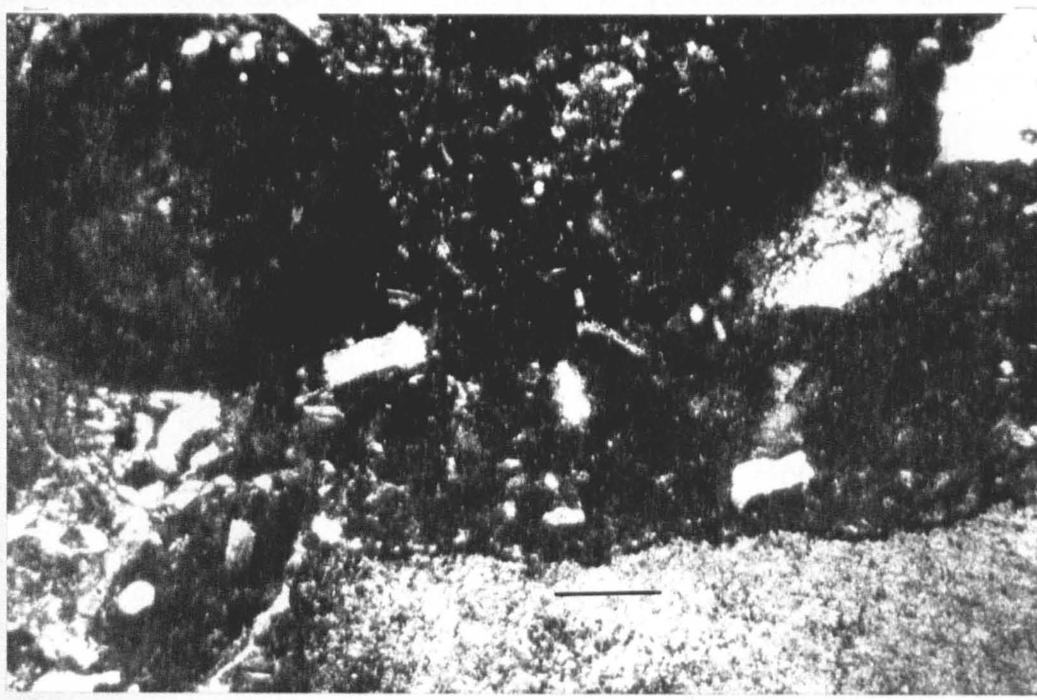


Fig. 4.149. Photomicrograph of a biopelsparite (bed CBQ G3b), typical of Lithofacies B of the Castle Bytham Member.

Fig. 4.150. Photomicrograph of an oncolitic biomicrite (bed LBQ G4), typical of Lithofacies C of the Castle Bytham Member.

Fig. 4.151. Trophic-Substrate niche chart for the Castle Bytham Member fauna from Castle Bytham Quarry (SK 990180).

S = Suspension feeder

C = Carnivore

D = Deposit feeder

F = Filter feeder

SPECIES	TAXON	Feeding Type	EPIFAUNAL			SEMI-INFAUNAL		INFAUNAL		
			Byssate/ Pedunculate	Cemented	Free	Byssate	Free	Deep	Shallow	
									Mobile	Immobile
Lucina bellona (d'Orbigny) (Abundant)	Bivalve	S							x	
Ctenostreon sp.	"	S	x							
Pholadomya lirata (J. Sowerby)	"	S						x		x
Pectinids	"	S	x							
Plagiostomids	"	S	x							
Natica adducta (Phillips)	Gastropod	C			x					
'Nerinea' spp.	"	D			x					
'Terebratula' spp.	Brachiopod	F	x							
'Montlivaltia' sp.	Coral	S		x						
Colonial corals	"	S		x						

Fig. 4.152. The type section of the Sleaford Member exposed at Copper Hill Quarry, Ancaster (SK 979427). The base (arrowed B) and top (arrowed T) are indicated.

Fig. 4.153. Oyster-encrusted hardground capping the Sleaford Member at Castle Bytham Quarry (SK 990180).


T
B

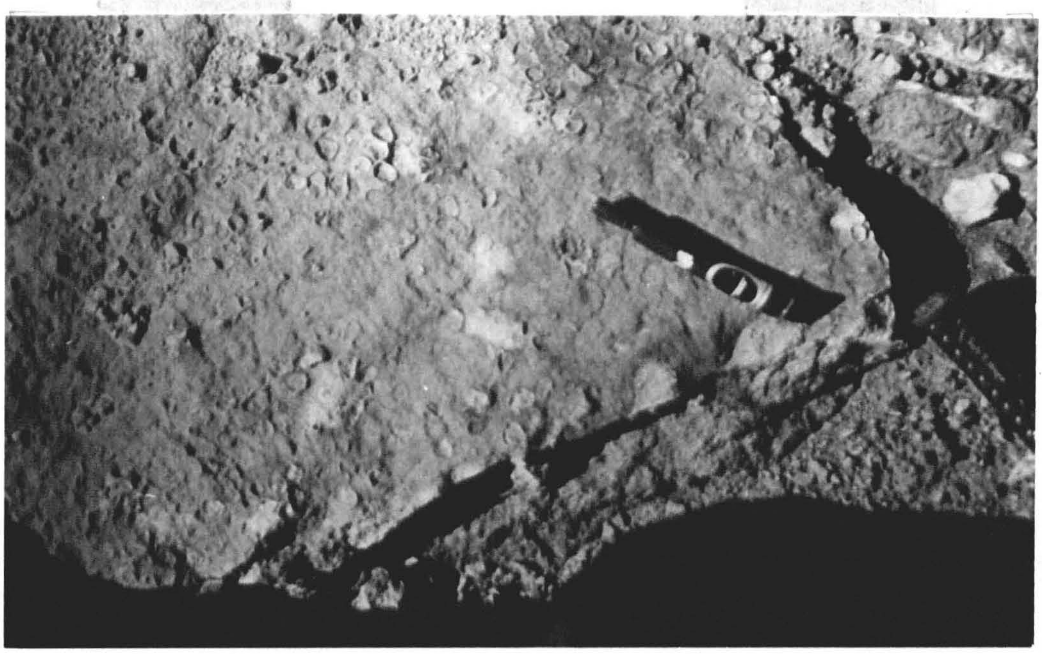


Fig. 4.154. Large-scale cross-bedding seen in the Sleaford Member at Brauncewell Quarry (TF 028518). Such cross-bedded oolites are typical of Lithofacies-group A of the Sleaford Member. The south-east face is pictured.

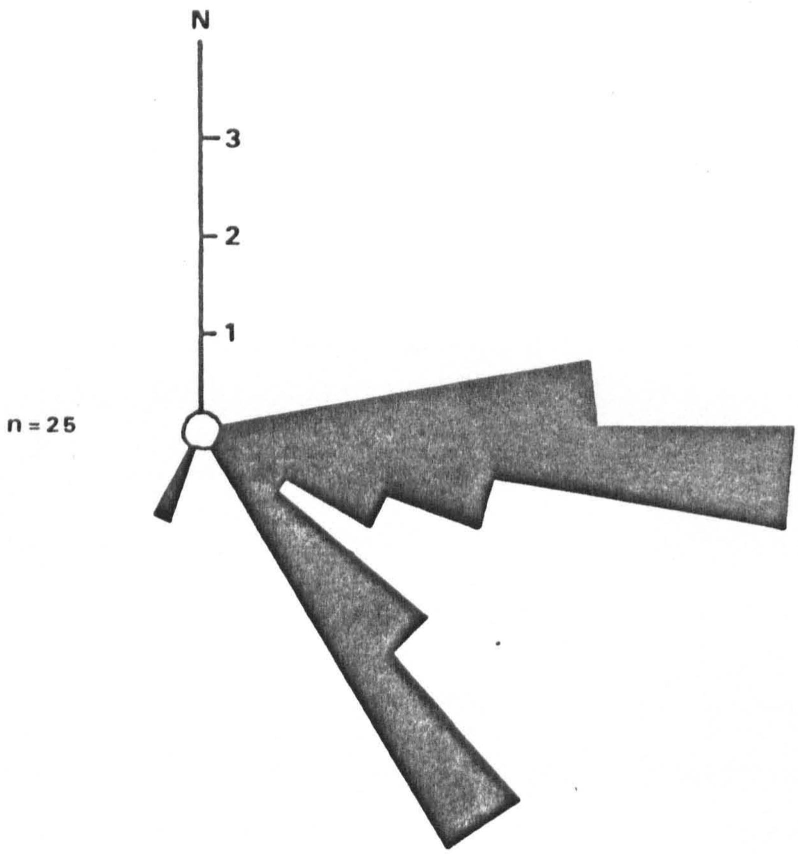
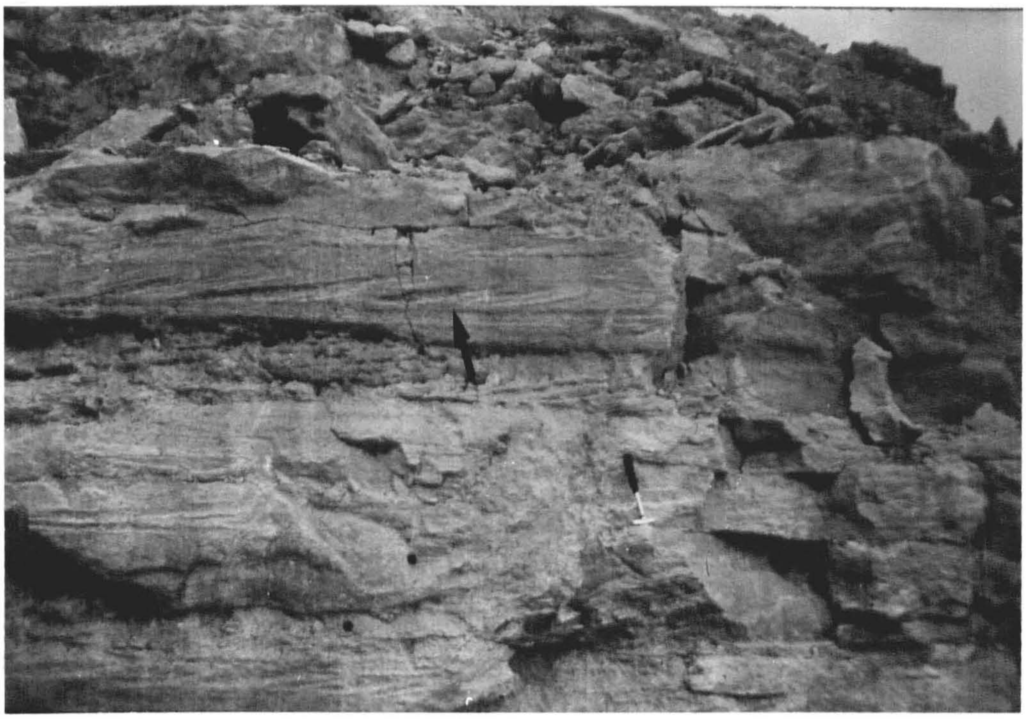


Fig. 4.155. Palaeocurrent directions indicated by "foreset dips" measured in the Sleaford Member (J1) of Brauncewell Quarry (TF 028518).

Fig. 4.156. Smaller-scale, low-angle, cross-bedded oolites seen in the Sleaford Member at the Premier Lime Company Quarry, Creeton (SK 999205). The concave foresets are "drawn-out" into bottom sets (arrowed). The north-east face is pictured.



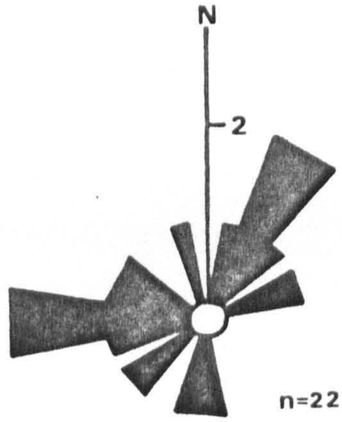
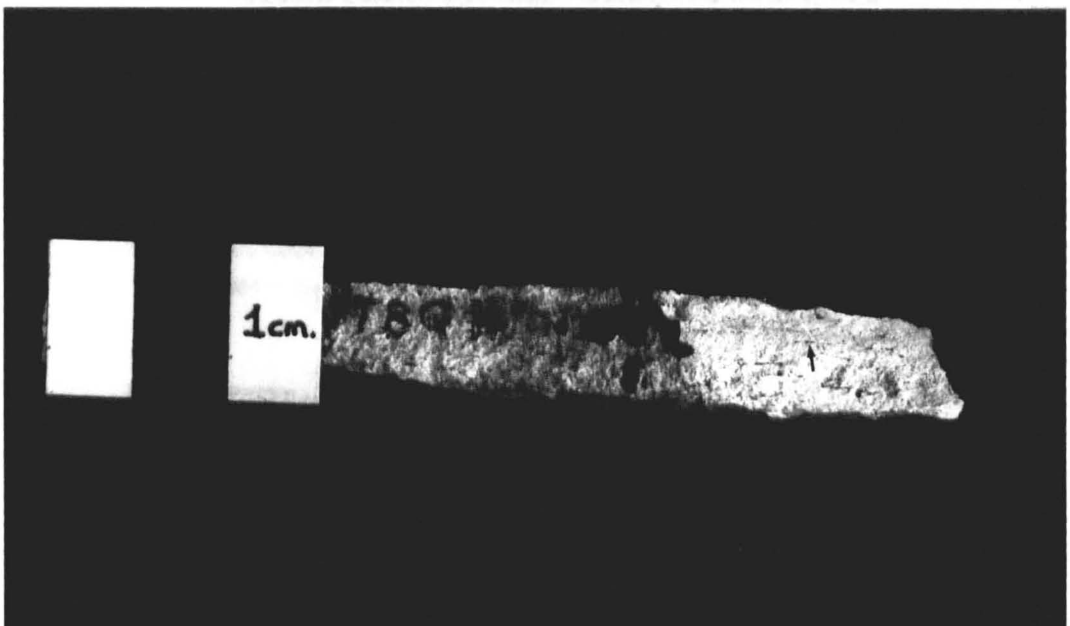


Fig. 4.157. Palaeocurrent directions indicated by "foreset dips" measured in the Sleaford Member (J4) of Blankney Quarry (TF 062592).

Fig. 4.158. "Wafers" of white micrite (arrowed) occurring in the parallel-bedded, "pisolitic" ooid-calcirudites of the Sleaford Member at Thompson's Bottom Quarry (TF 026555), central Lincolnshire.

Fig. 4.159. "Birdseyes" (arrowed) seen in the micritic "wafers" of the Sleaford Member at Thompson's Bottom Quarry (TF 026555).


1cm.

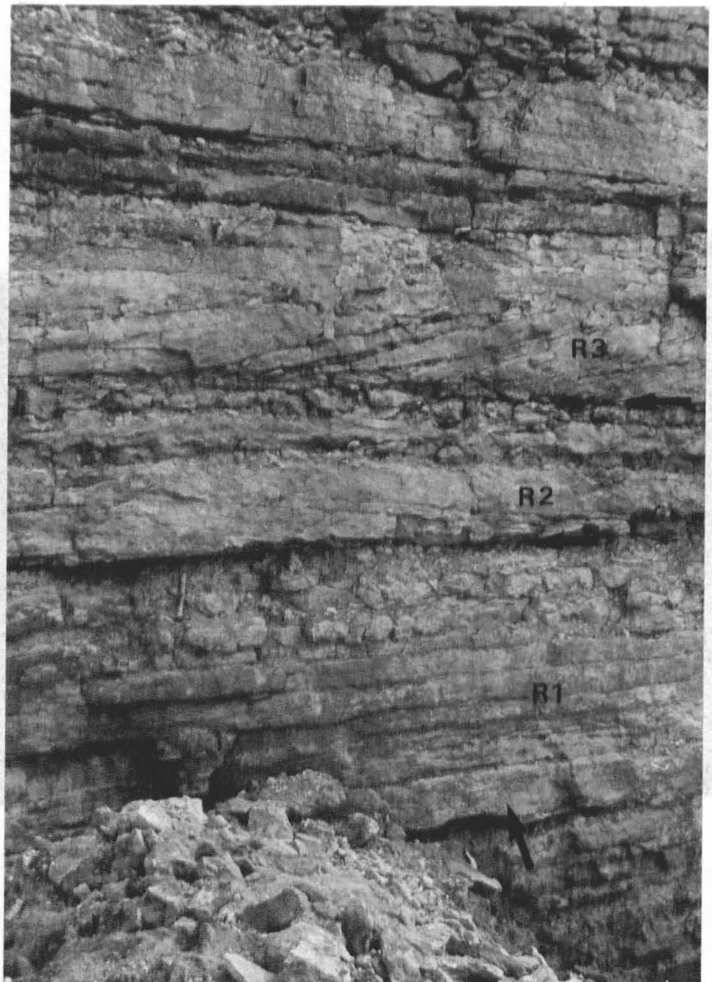
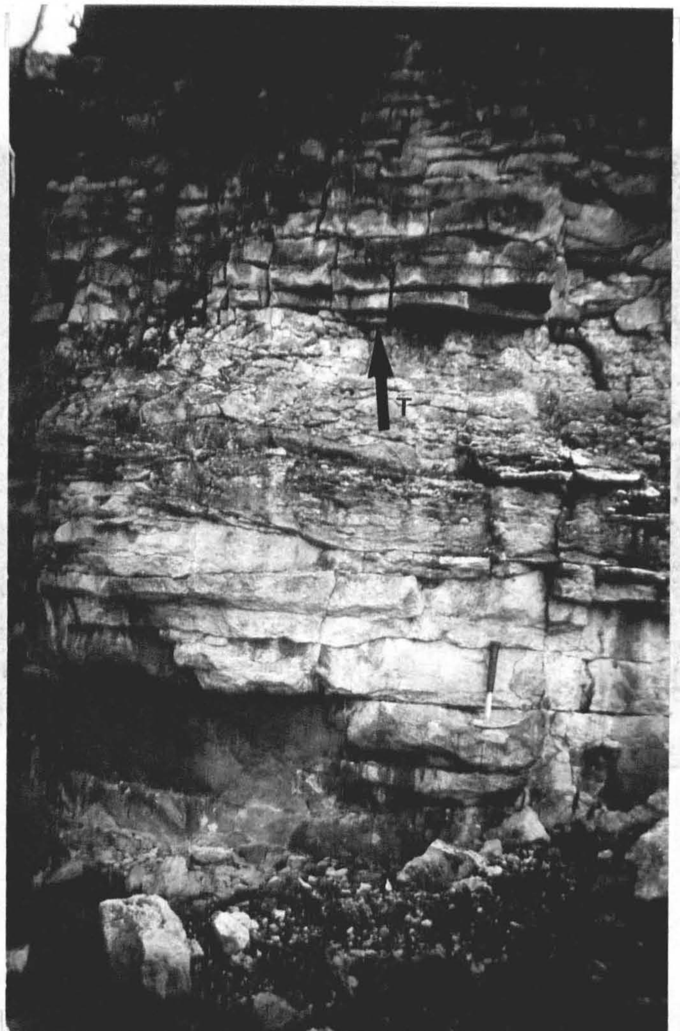

R3
R2
R1

Fig. 4.160. "Wafers" of white micrite (arrowed) occurring in oolites of the Sleaford Member at North Rauceby Quarry (TF 021474).

Fig. 4.161. Fining-upwards rhythms seen in the Sleaford Member at Blankney Quarry (TF 062592). The boundaries between rhythms (denoted R1, R2 and R3) are indicated. Note particularly the contrasting cross-bedding directions seen in these rhythms; the east face of the quarry is pictured.

Fig. 4.162. Complex burrow systems (arrowed) penetrating down from a hardground (?) within the Sleaford Member at Ashby de la Launde (TF 052570).

Fig. 4.163. Dense concentrations of "pisoliths" (arrowed) at the top of a coarsening-upwards rhythm (Sleaford Member) exposed at Haceby Lodge Quarry (TF 028369).


T

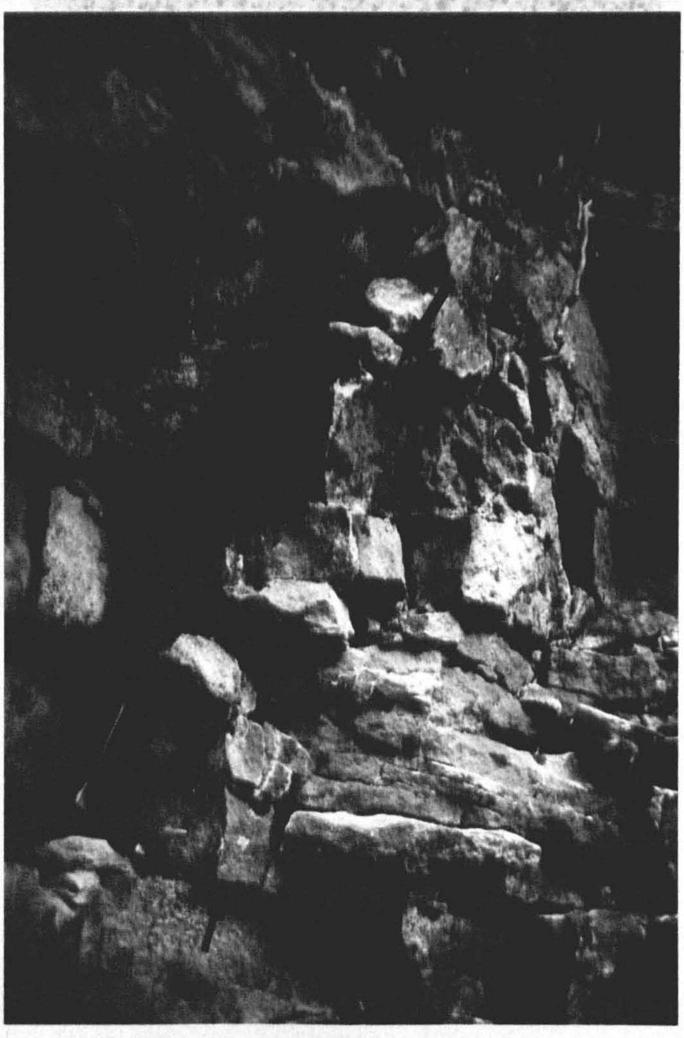


Fig. 4.164. Coarsening-upwards rhythm seen in the Sleaford Member at Haceby Lodge Quarry (TF 028369). The top of the rhythm is arrowed (T) but the base is not exposed. Note particularly the increase in pisolith content up the rhythm.

Fig. 4.165. Coarsening-upwards rhythm seen in the Sleaford Member at Dembleby Farm Quarry (TF 034371). Note particularly the cross-bedded lower portion of the rhythm. The boundaries of the rhythm are indicated.

Fig. 4.166. Schematic representation of the variations seen in the coarsening-upwards rhythms (Lithofacies-group C) of the Sleaford Member.

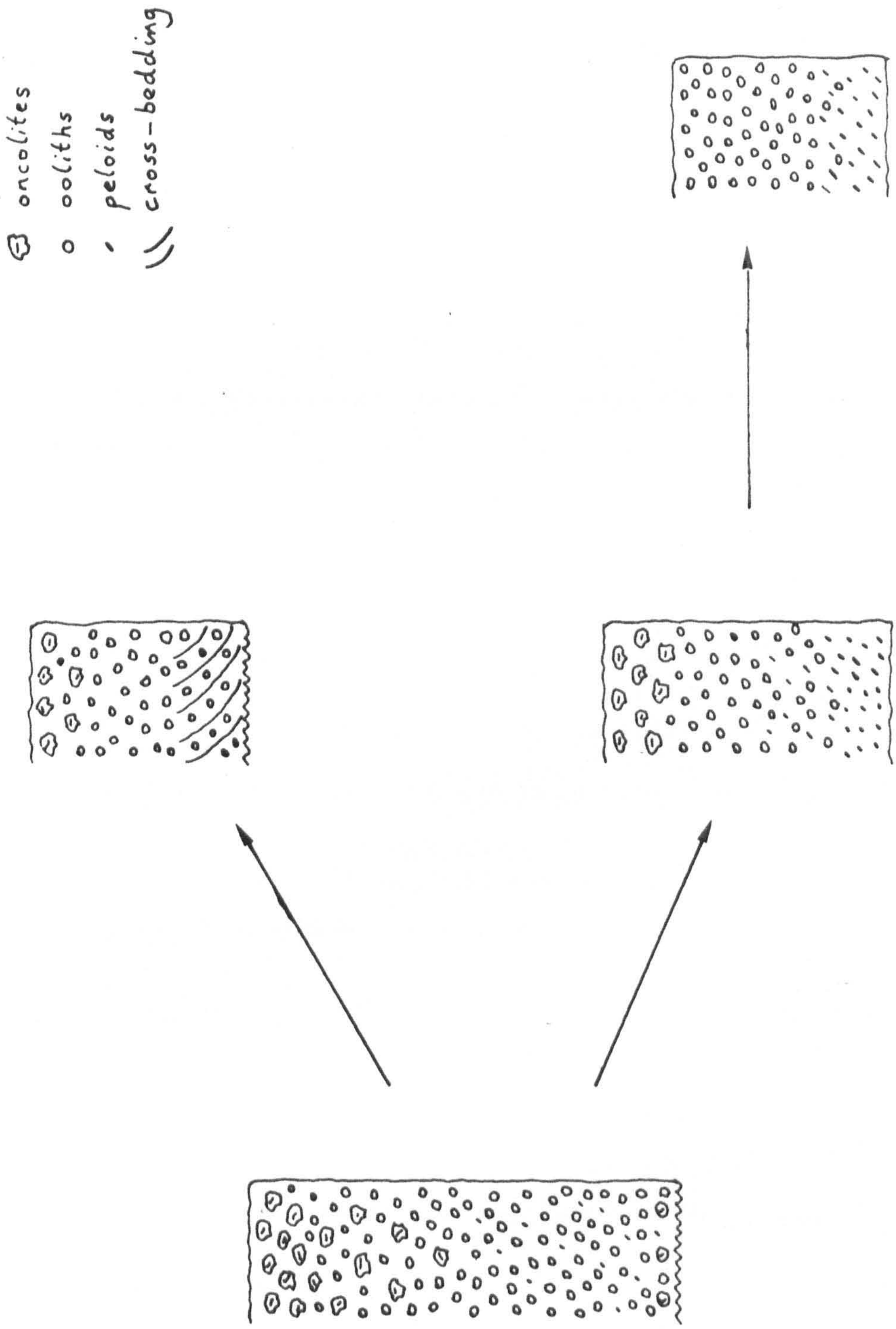

oncolites
ooliths
peloids
cross-bedding

Fig. 4.167. Herring-bone cross-bedding (arrowed) seen in the Sleaford Member at Copper Hill Quarry, Ancaster (SK 979427).

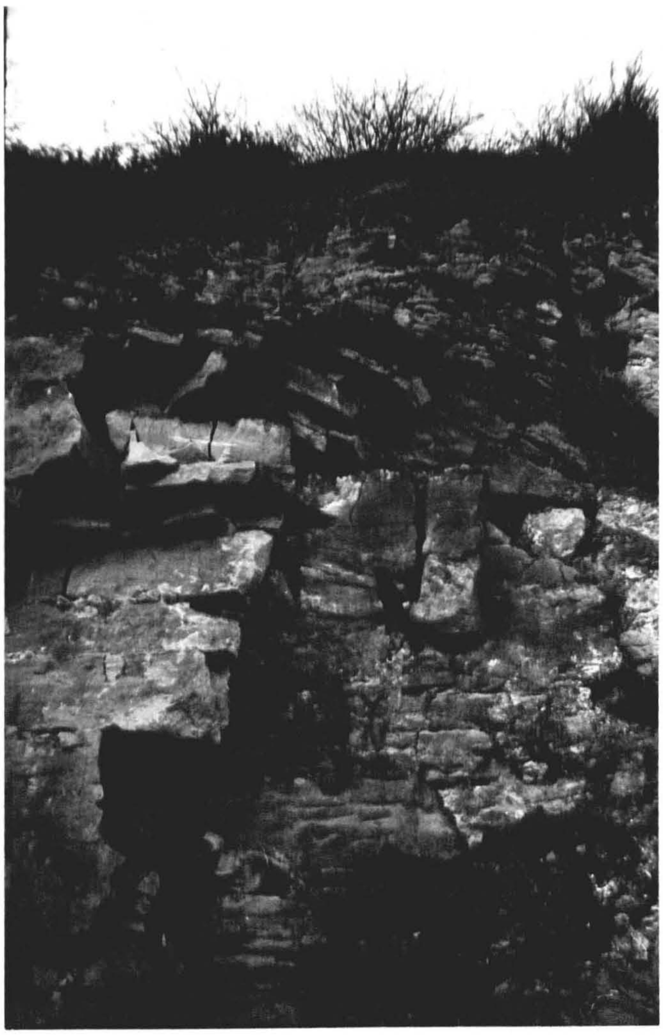
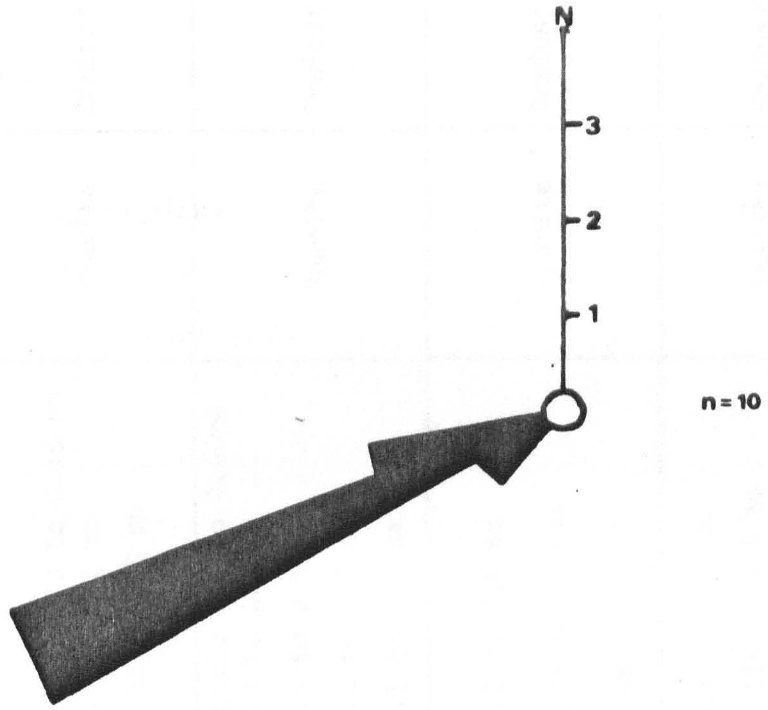
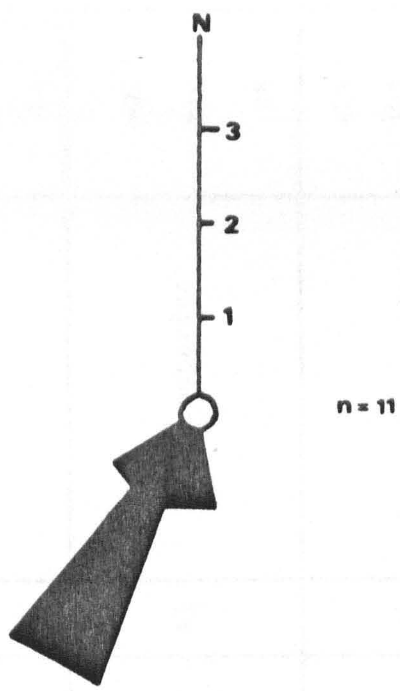


Fig. 4.168. Palaeocurrent directions indicated by "foreset dips" measured in the Sleaford Member (J2) of Copper Hill Quarry, Ancaster (SK 979427).

Fig. 4.169. Palaeocurrent directions indicated by "foreset dips" measured in the Sleaford Member at Spittlegate Hill Quarry (SK 937342), near Grantham.


N
3
2
1
n=10

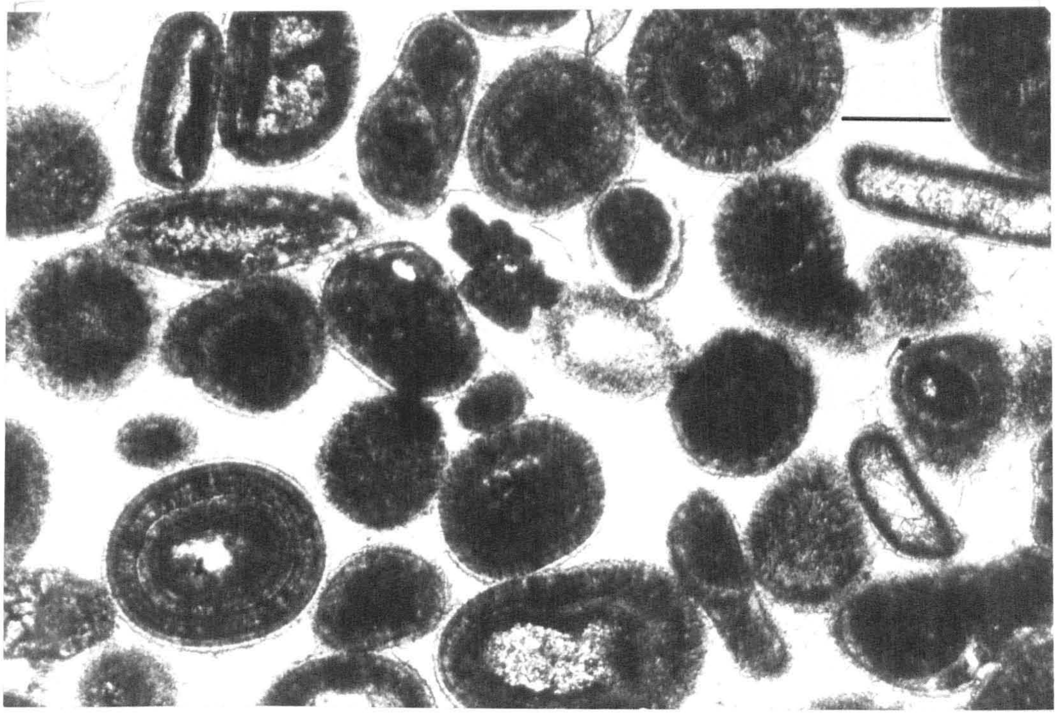

N
3
2
1
n=11

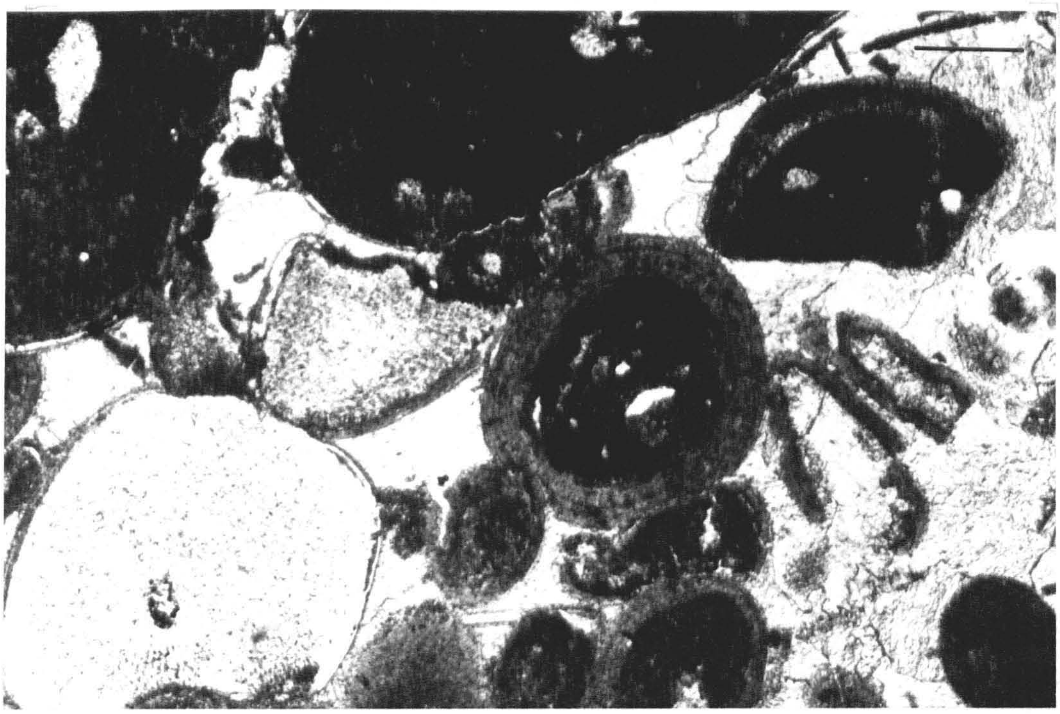
BED	LITHOFACIES	TYPICAL LITHOLOGY	GRAINS: % OF TOTAL ROCK	GRAINS: TYPE	GRAINS: SIZE	MATRIX	TEXTURE
ACHQ J2 top	A1	Oosparite	72% 1%	ooliths bioclasts	mostly 0.3 to 0.45 mm 0.2 to 1.2 mm 0.25 to 1.0 mm	Sparite	Grainstone
ACHQ J5	A1	Skeletal oosparite	40% 12% 19% 6%	ooliths bioclasts intraclasts oncolites	mostly 0.4 to 0.8 mm 0.3 to 1.2 mm 0.3 to 2.5 mm 1.1 to 3.2 mm 1.1 to 1.4 mm	Sparite	Grainstone
ACHQ J1	A1	Bio-oosparite	40% 28% 6%	bioclasts ooliths intraclasts	0.2 to 5.4 mm 0.25 to 1.3 mm ≃ 1.6 mm	Sparite	Grainstone
BQ J4	A2	Skeletal oncolitic oosparite	47% 16% 2% 5% 4%	oncolites ooliths bioclasts peloids intraclasts	0.8 to 6.4 mm 0.125 to 0.5 mm 0.3 to 4.6 mm < 0.2 mm ≃ 3.4 mm	Sparite	Grainstone

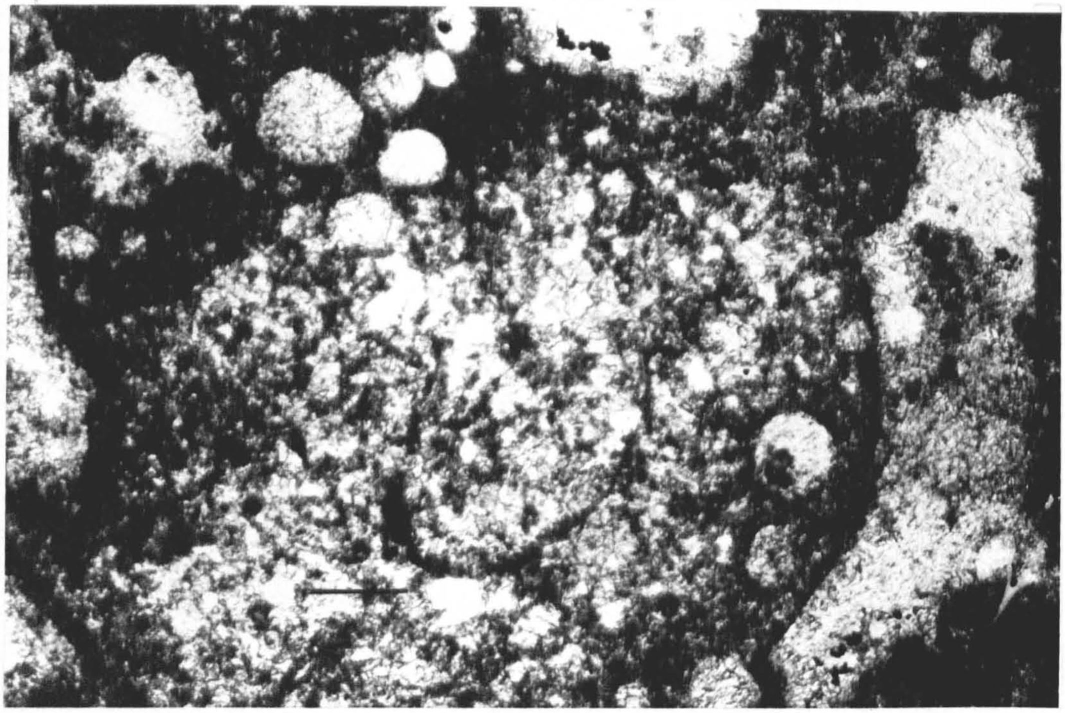
Fig. 4.170. The principal characteristics of Lithofacies-group A of the Sleaford Member.

Fig. 4.171. Photomicrograph of an oosparite (bed ACHQ J2 top), typical of Lithofacies A1 of the Sleaford Member.

Fig. 4.172. Photomicrograph of a bio-oosparite (bed ACHQ J1), typical of Lithofacies A1 of the Sleaford Member.







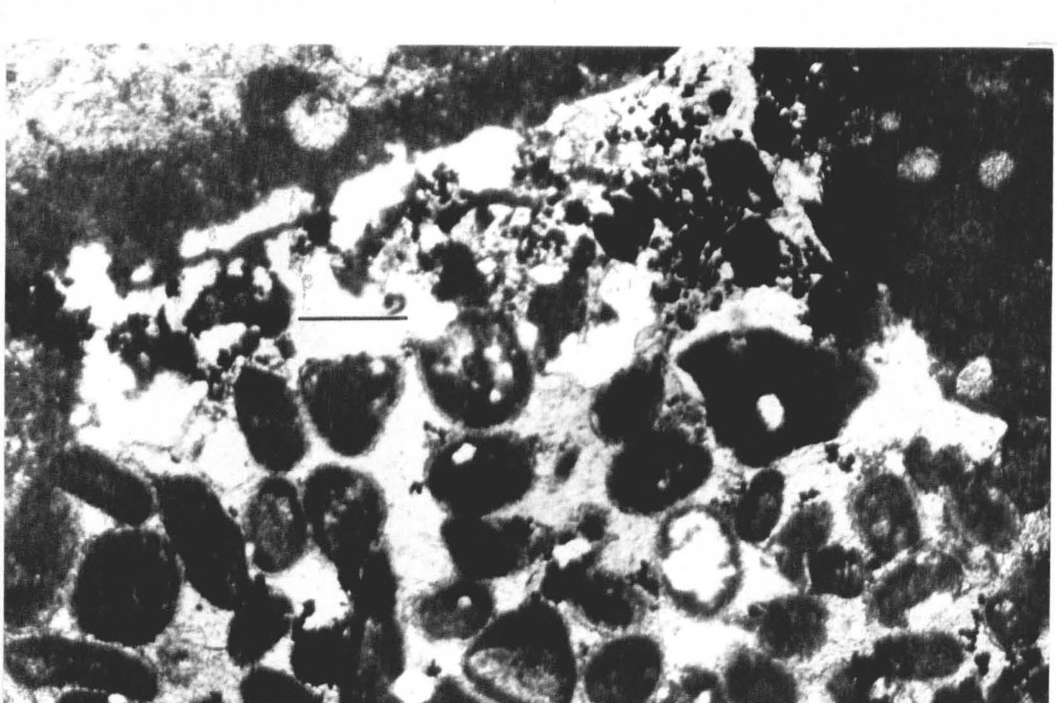


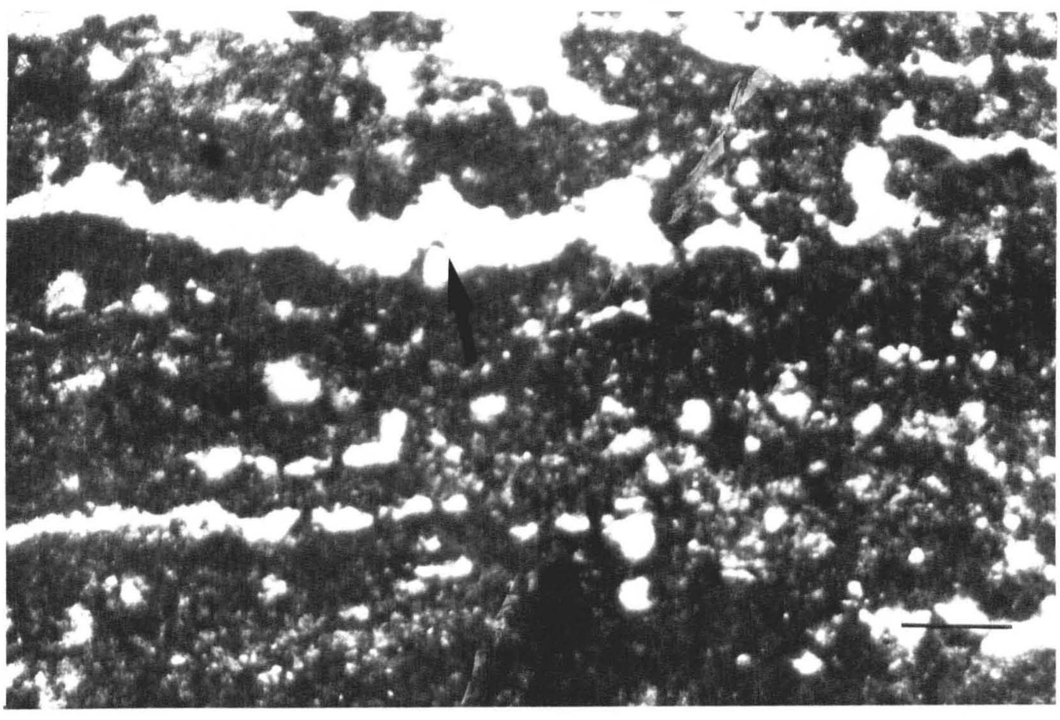
Fig. 4.173. Photomicrograph showing an oncolite, typical of Lithofacies A2 of the Sleaford Member. The oncolite occurs in a skeletal oncolitic oosparite (bed BQ J4).

Fig. 4.174. Photomicrograph of a skeletal oncolitic oosparite (bed BQ J4), typical of Lithofacies A2 of the Sleaford Member.

Fig. 4.175. Fenestral micro-mound (arrowed) in the algal stromatolite "wafers" of the Sleaford Member (J2) seen in Thompson's Bottom Quarry (TF 026555), Central Lincolnshire.

Fig. 4.176. Photomicrograph of "birdeyes" (arrowed) in bed J2 of the Sleaford Member at Thompson's Bottom Quarry (TF 026555), Central Lincolnshire.


1cm.

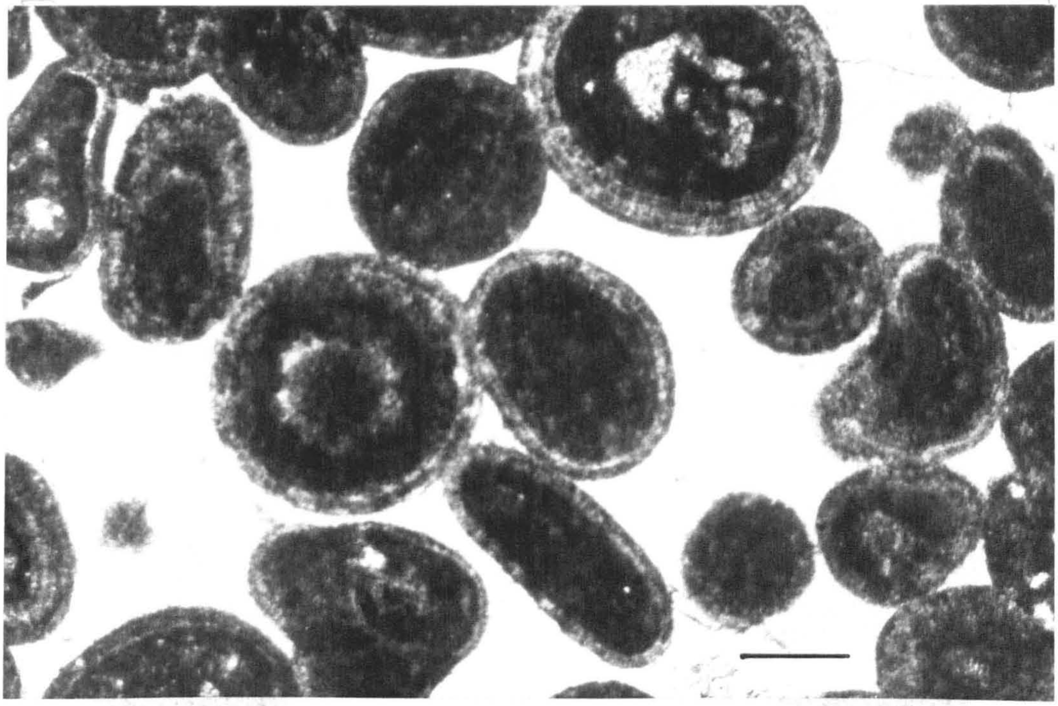


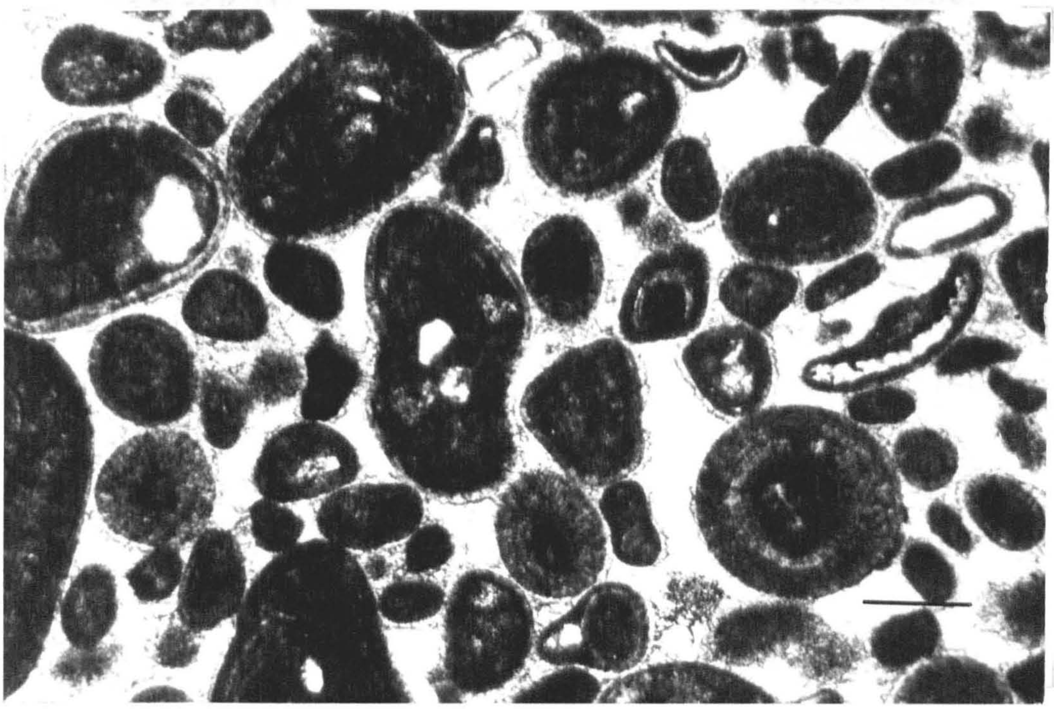
BED	LITHOFACIES	TYPICAL LITHOLOGY	GRAINS			MATRIX	TEXTURE
			% OF TOTAL ROCK	TYPE	SIZE		
BQ J3c	B3	Pelsparite	67%	peloids	0.062 to 0.28 mm mostly 0.062 to 0.2 mm	Sparite	Grainstone
			7%	bioclasts	0.125 to 0.43 mm		
			1%	quartz	silt to v. fine sand		
BQ J3b	B2	Peloidal oosparite	46%	ooliths	0.2 to 0.85 mm	Sparite	Grainstone
			14%	peloids	0.062 to 0.4 mm mostly 0.062 to 0.25 mm		
			10%	intraclasts	0.9 to 3.8 mm		
			3%	bioclasts	0.3 to 1.6 mm		
BQ J3a	B1	Oosparite	63%	ooliths	0.25 to 0.75 mm mostly 0.3 to 0.6 mm	Sparite	Grainstone
			10%	intraclasts	0.8 to 1.5 mm		
			4%	peloids	0.062 to 0.125 mm		

Fig. 4.177. The principal characteristics of Lithofacies-group B of the Sleaford Member.

Fig. 4.178. Photomicrograph of an oosparite (bed BQ J3a), typical of Lithofacies B1 of the Sleaford Member.

Fig. 4.179. Photomicrograph of a peloidal oosparite (bed BQ J3b), typical of Lithofacies B2 of the Sleaford Member.





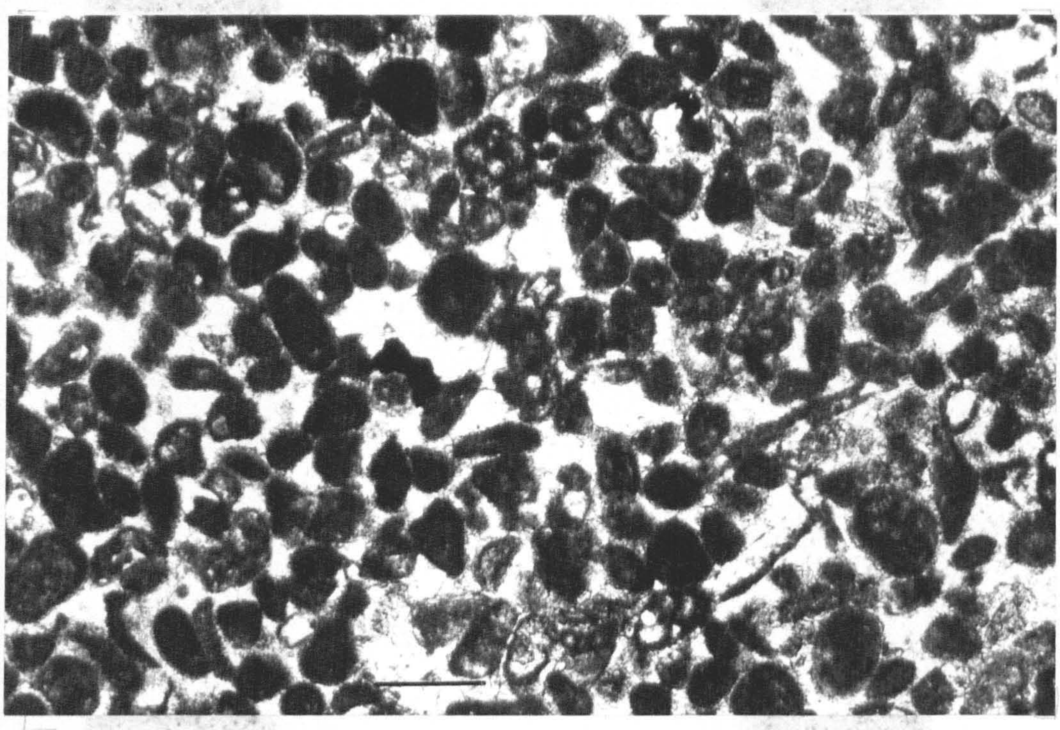


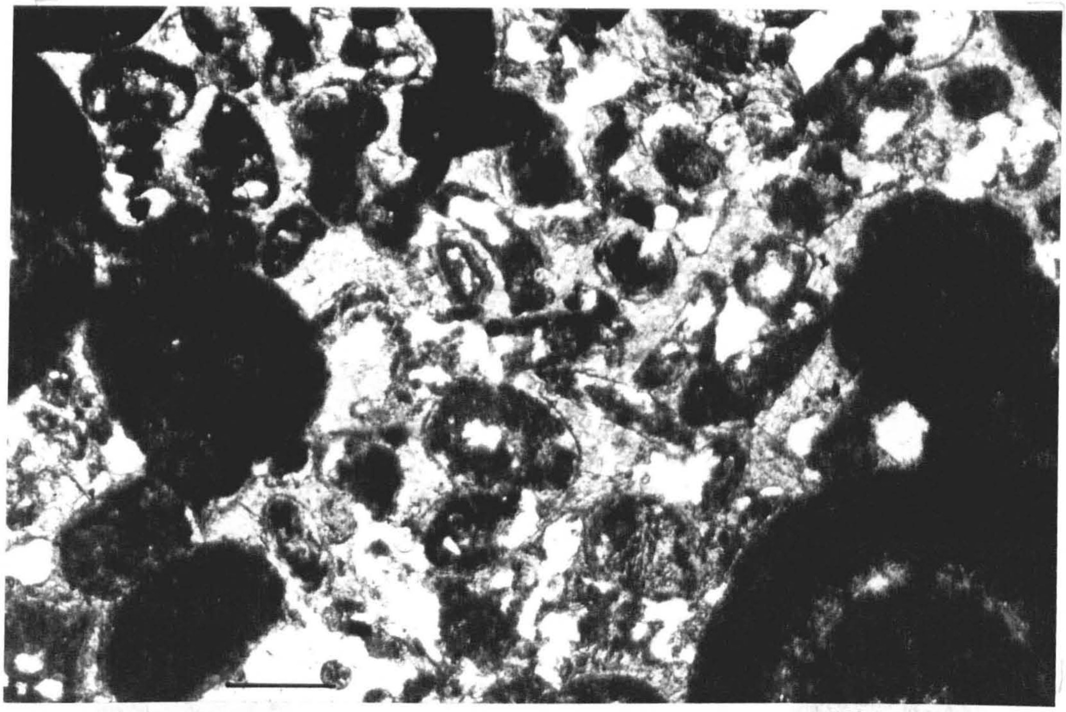
Fig. 4.180. Photomicrograph of a pelsparite (bed BQ J3c), typical of Lithofacies B3 of the Sleaford Member.

BED	LITHOFACIES	TYPICAL LITHOLOGY	GRAINS			MATRIX	TEXTURE
			% OF TOTAL ROCK	TYPE	SIZE		
HLQ J1c	C3	Oncolitic oosparite	31%	oncolites	2.7 to 20 mm	Micrite > Sparite	Packstone
			15%	ooliths	0.3 to 1.2 mm		
			3%	bioclasts	0.4 to 2.2 mm		
			6%	intraclasts	$\simeq$ 1.9 mm		
HLQ J1b	C2	Oncolitic oosparite	44%	ooliths	0.2 to 0.9 mm	Sparite	Grainstone
			23%	oncolites	1.0 to 4.1 mm		
			9%	bioclasts	0.125 to 3.4 mm		
HLQ J1a	C1	Oosparite	74%	"ooliths" (bimodal)	0.125 to 1.25 mm	Sparite	Grainstone
			4%	bioclasts	0.25 to 2.2 mm		

Fig. 4.181. The principal characteristics of Lithofacies-group C of the Sleaford Member.

Fig. 4.182. Photomicrograph of an oosparite (bed HLQ J1a), typical of Lithofacies C1 of the Sleaford Member.

Fig. 4.183. Photomicrograph of an oncolitic oosparite (bed HLQ J1c), typical of Lithofacies C3 of the Sleaford Member. Oncolites are arrowed.



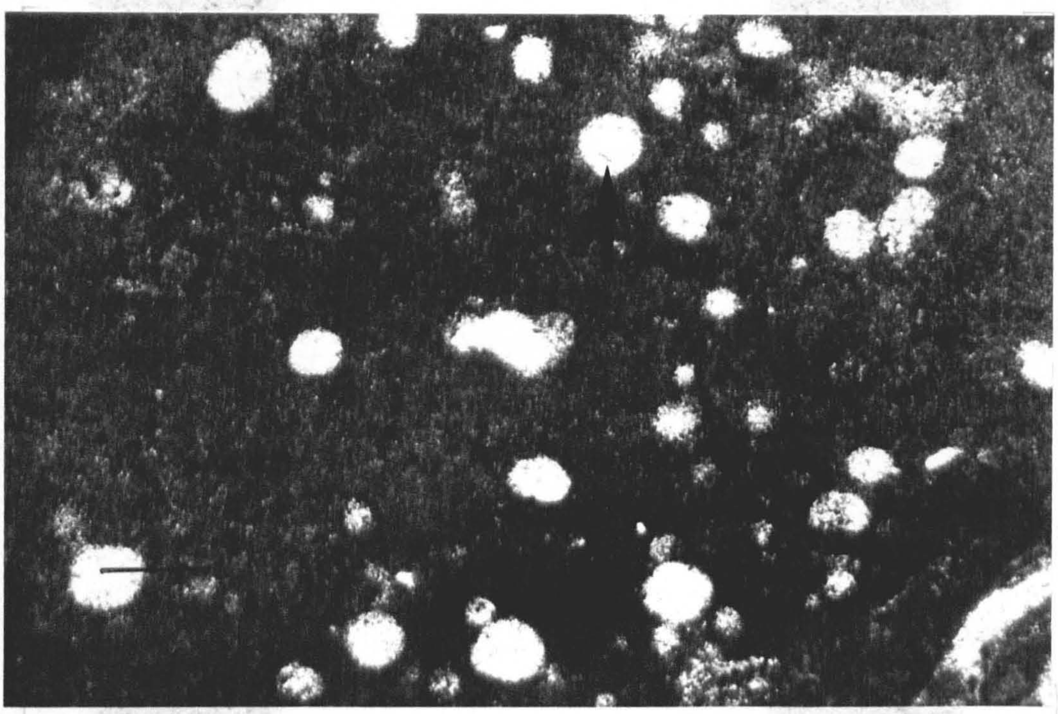


Fig. 4.184. Photomicrograph of an oncolite, typical of Lithofacies C3 of the Sleaford Member. Intra-oncolite "vugs" are arrowed. The oncolite occurs in an oncolitic oosparite (bed HLQ J1c).

Fig. 4.185. The type section of the Creeton Member exposed at Castle Bytham Quarry (SK 990180). The base (arrowed B) is indicated.

Fig. 4.186. The upper boundary-stratotype of the Creeton Member exposed at the Premier Lime Company Quarry, Creeton (SK 999205). The contact with the overlying Upper Estuarine Series is arrowed. Note also the cross-bedding direction in bed K2 (arrowed CB). The north-east face is pictured.


B


CB

Fig. 4.187. Thickness variations seen in Lithofacies A and B of the Creeton Member, and Sleaford Member in the Ancaster and Wilsford Heath quarries. The author's own sections are compared with that measured by Brodie (1853). The terminologies previously associated with these beds are illustrated in Fig. 4.188.

B = Lithofacies B, Creeton Member

A = Lithofacies A, Creeton Member

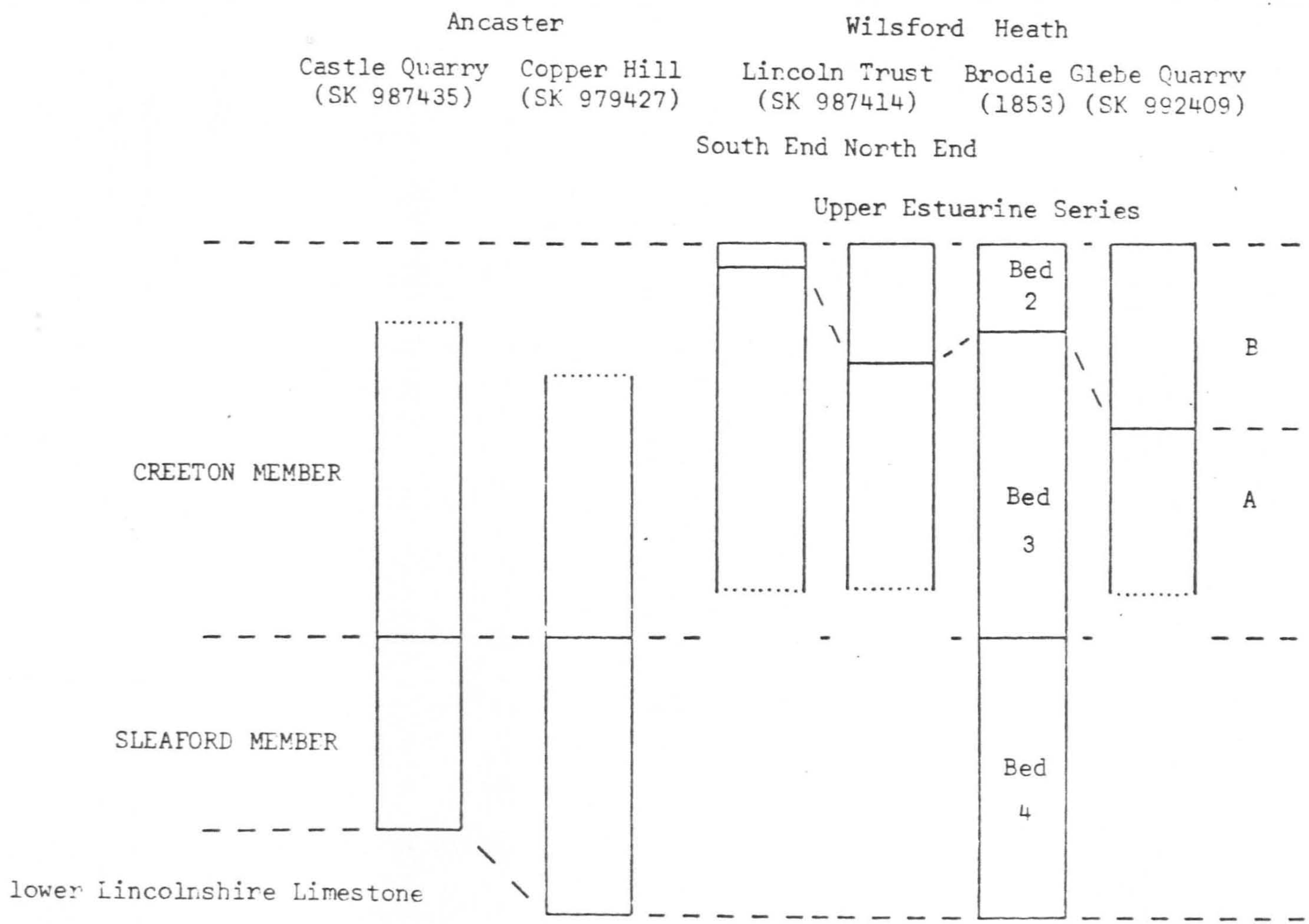
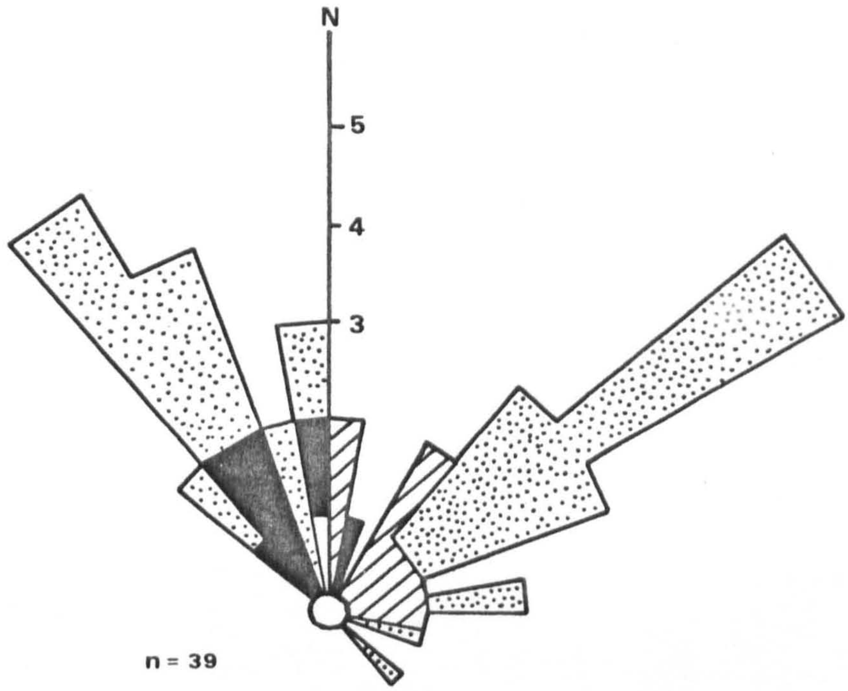

Ancaster
Wilsford Heath
Castle Quarry (SK 987435)
Copper Hill (SK 979427)
Lincoln Trust (SK 987414)
Brodie Glebe Quarry (1853) (SK 992409)
South End North End
Upper Estuarine Series
Bed 2
B
CREETON MEMBER
Bed 3
A
SLEAFORD MEMBER
Bed 4
lower Lincolnshire Limestone

Fig. 4.188. The contrasting terminologies and stratigraphic interpretations, which have been applied to the uppermost Lincolnshire Limestone of the Ancaster and Wilsford Heath Quarries.

<table>
<tr><th colspan="2">Brodie (1853)</th><th>Richardson (1939b, pl.29A)</th><th>Richardson (1939b, pl.29B)</th><th colspan="3">This thesis</th></tr>
<tr><td colspan="2">"Wilsford Heath"</td><td>Thompson's Quarry
(=Glebe Quarry, Wilsford)</td><td>Newton and Scott's Quarry
(=Copper Hill, Ancaster)</td><td>Ancaster Quarries</td><td colspan="2">Wilsford Quarries</td></tr>
<tr><td>Bed 1</td><td>Blue Clay</td><td>Upper Estuarine Series</td><td>not seen</td><td>not seen</td><td colspan="2">U.E.S.</td></tr>
<tr><td>Bed 2</td><td>"Ragstone"</td><td>Ancaster Rag</td><td>(not developed)</td><td rowspan="2">CREETON MEMBER
(Lithofacies A)</td><td>Litho-facies B</td><td rowspan="2">CREETON MEMBER</td></tr>
<tr><td>Bed 3</td><td>Soft oolitic Freestone</td><td>Ancaster Freestone</td><td>Ancaster Rag</td><td>Litho-facies A</td></tr>
<tr><td>Bed 4</td><td>Hard, shelly oolite</td><td>not recorded</td><td>Ancaster Freestone</td><td>SLEAFORD MEMBER</td><td colspan="2">not seen</td></tr>
<tr><td>Bed 5</td><td>Soft, white stone</td><td>not recorded</td><td>Kirton Cementstones</td><td>Ropsley Beds
(LINCOLN MEMBER)</td><td colspan="2">not seen</td></tr>
</table>



= Castle Quarry, Ancaster (SK 987435; = "Ancaster Rag"). n = 10

= Copper Hill Quarry, Ancaster (SK 979427; = "Ancaster Rag"). n = 21

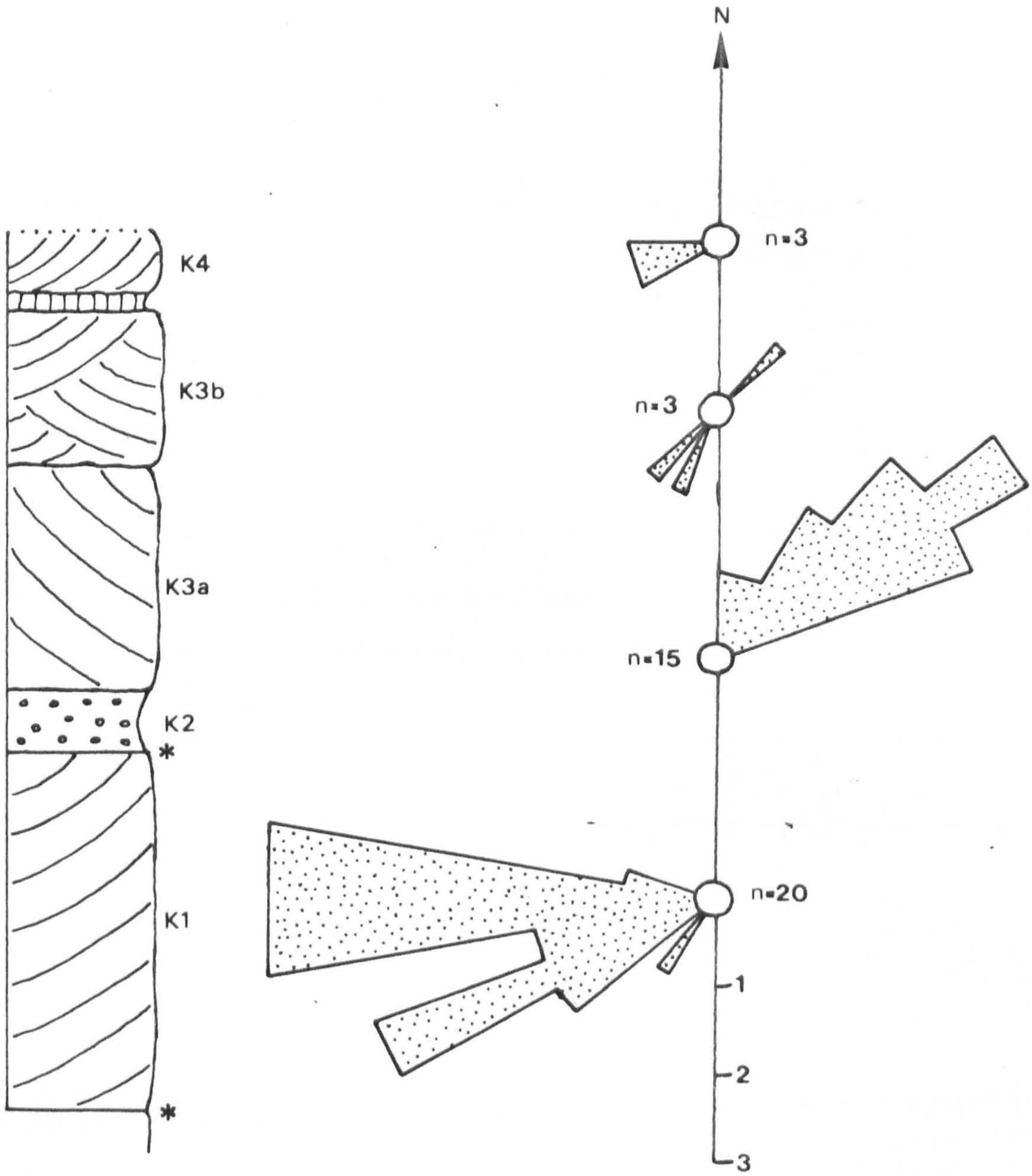
= Lithofacies B, Wilsford Heath quarries. n = 7

= Lithofacies A, Wilsford Heath quarries. n = 1

Fig. 4.189. Palaeocurrent directions indicated by "foreset dips" measured in the Creeton Member of the Ancaster and Wilsford Heath quarries.

Fig. 4.190. The downcutting of the Creeton Member into the Castle Bytham Member seen at the Soil Fertility Quarry, Clipsham (SK 978154). The erosive contact between the two units is marked.

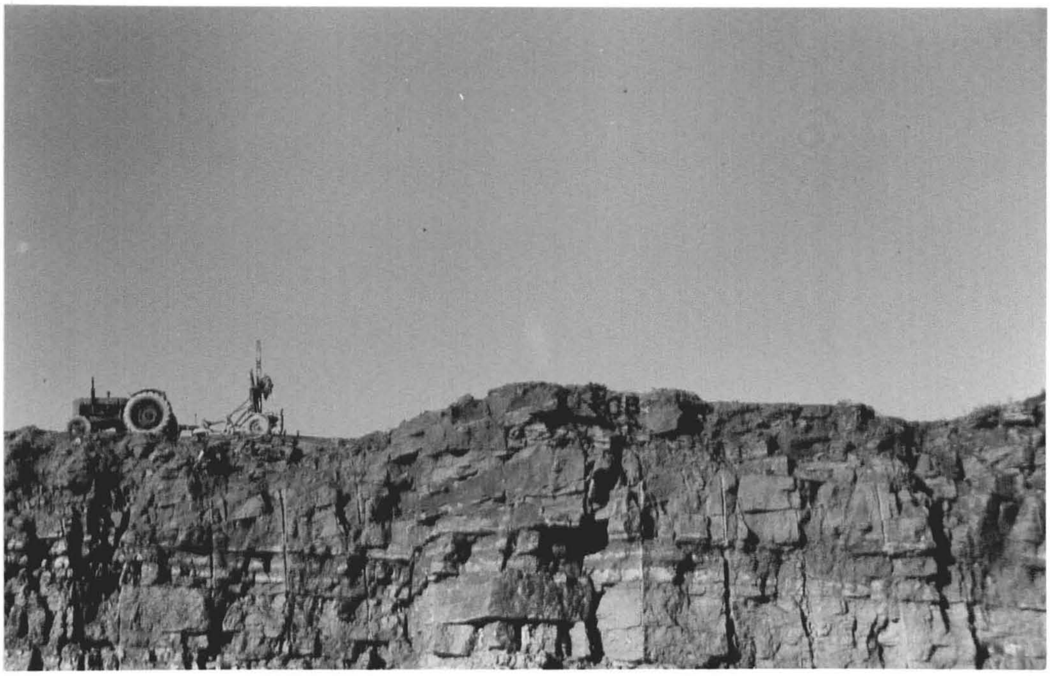
Fig. 4.191. The Creeton Member succession at Castle Bytham Quarry (SK 990180) showing the variations in palaeocurrent directions, which occur at various levels.

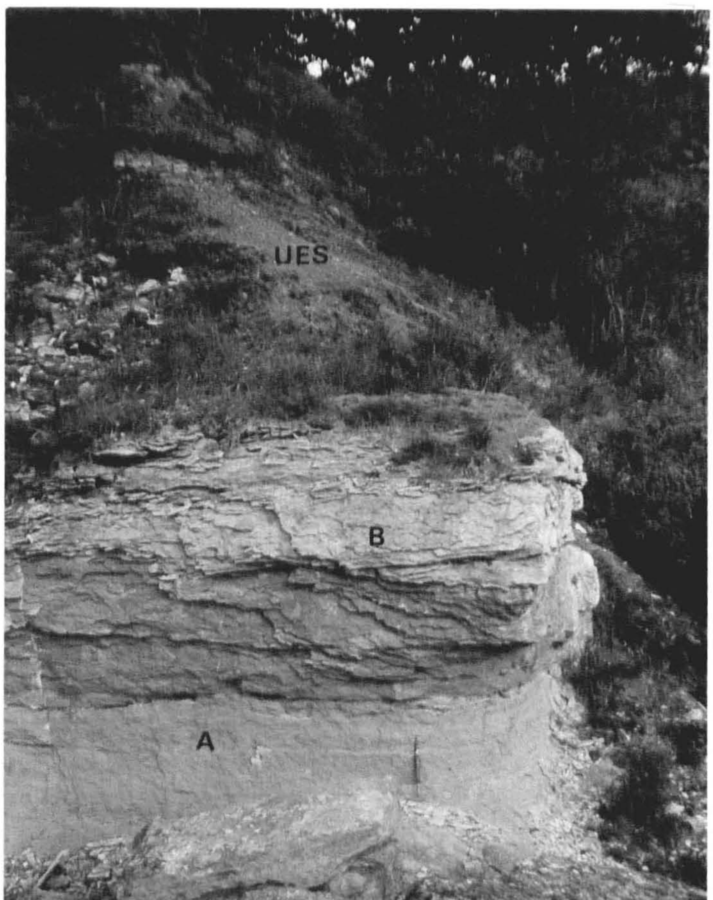


* hardground.

Fig. 4.192. Cross-bedding in bed K2 of the Creeton Member exposed at the Premier Lime Company Quarry, Creeton (SK 999205). Note the cross-bedding direction (arrowed CB), which contrasts with that of the same bed shown in Fig. 4.186. The north-east face is pictured in both figures.

Fig. 4.193. The Creeton Member exposed at the "Lincoln Trust Quarry", Wilsford Heath. Lithofacies A and B are indicated. The Creeton Member is overlain by the Upper Estuarine Series (U.E.S.).




UES
B
A

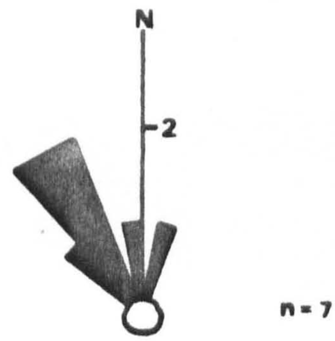


Fig. 4.194. Palaeocurrent directions indicated by "foreset dips" measured in Lithofacies B of the Creeton Member at the Lincoln Trust (SK 987414) and Glebe (SK 992409) quarries, Wilsford Heath.

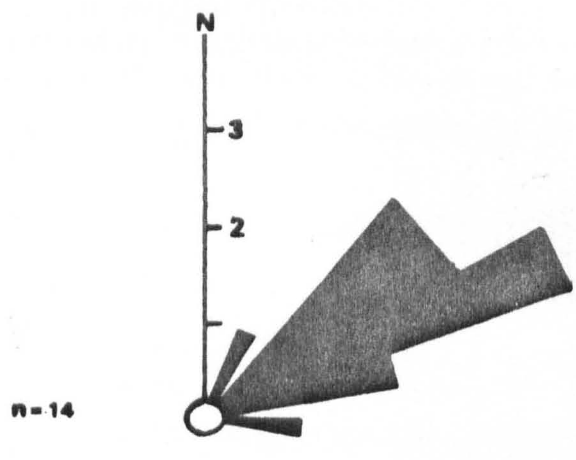
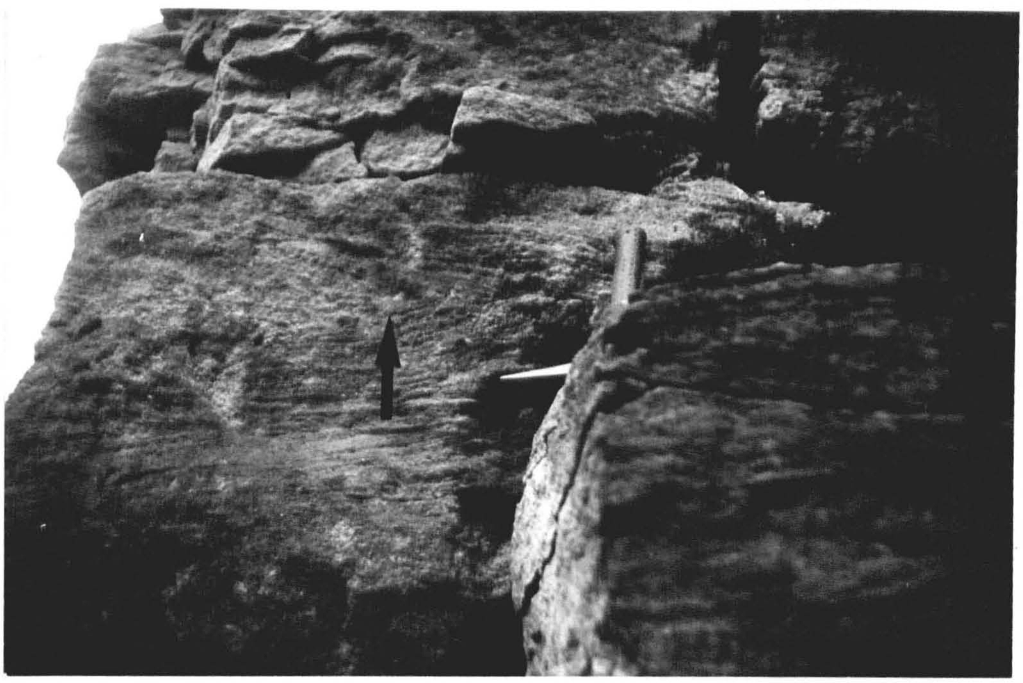


Fig. 4.195. Palaeocurrent directions indicated by "foreset dips" measured in Lithofacies B of the Creeton Member at Old Somerby Quarry (SK 959337), Medwell's (SK 988160) and Bidewell Lodge (SK 968145) quarries, Clipsham.

Fig. 4.196. Conflicting cross-bedding directions seen in the Creeton Member at Haceby Lodge Quarry (TF 028369). The cross-bedding in the lower unit (Lithofacies A; arrowed A) dips south-westwards while that of the upper unit (Lithofacies B; arrowed B) dips north-eastwards.

Fig. 4.197. Herring-bone cross-bedding (arrowed) seen in the Creeton Member at Little Ponton Quarry (SK 931325).


B
A

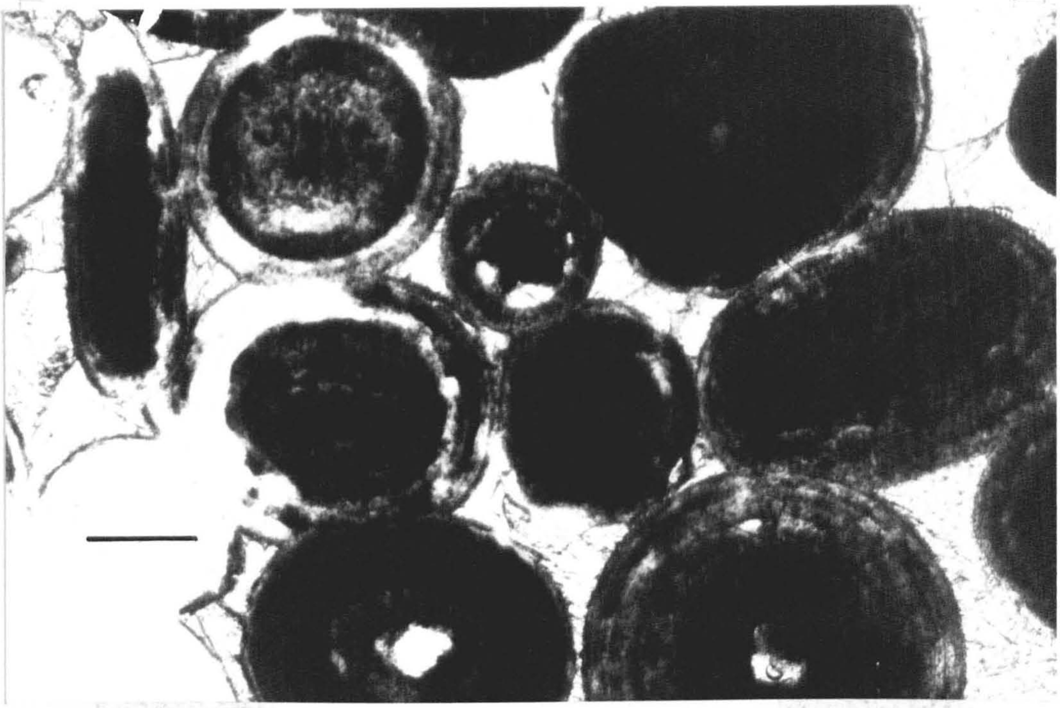


BED	LITHOFACIES	TYPICAL LITHOLOGY	GRAINS			MATRIX	TEXTURE
			% OF TOTAL ROCK	TYPE	SIZE		
HLQ K2	B	Biosparite	31% 11%	bioclasts ooliths	0.4 to 7.2 mm 0.3 to 1.6 mm mostly 0.3 to 0.5 mm	Sparite	Grainstone
ACHQ K	A/B	Skeletal oosparite	33% 18% 5%	ooliths bioclasts intraclasts	0.2 to 0.8 mm 0.2 to 6.8 mm 0.5 to 2.2 mm	Sparite (some Micrite)	Grainstone
CBQ K1	A	Oosparite	71% 1% 1%	ooliths bioclasts intraclasts	0.2 to 1.0 mm mostly 0.4 to 0.8 mm 0.7 to 1.4 mm 1.2 to 1.7 mm	Sparite	Grainstone

Fig. 4.198. The principal characteristics of the lithofacies of the Creeton Member.

Fig. 4.199. Photomicrograph of an oosparite (bed CBQ K1) typical of Lithofacies A of the Creeton Member.

Fig. 4.200. Photomicrograph of a skeletal oosparite (bed ACHQ K), a transitional lithology between Lithofacies A and B of the Creeton Member.



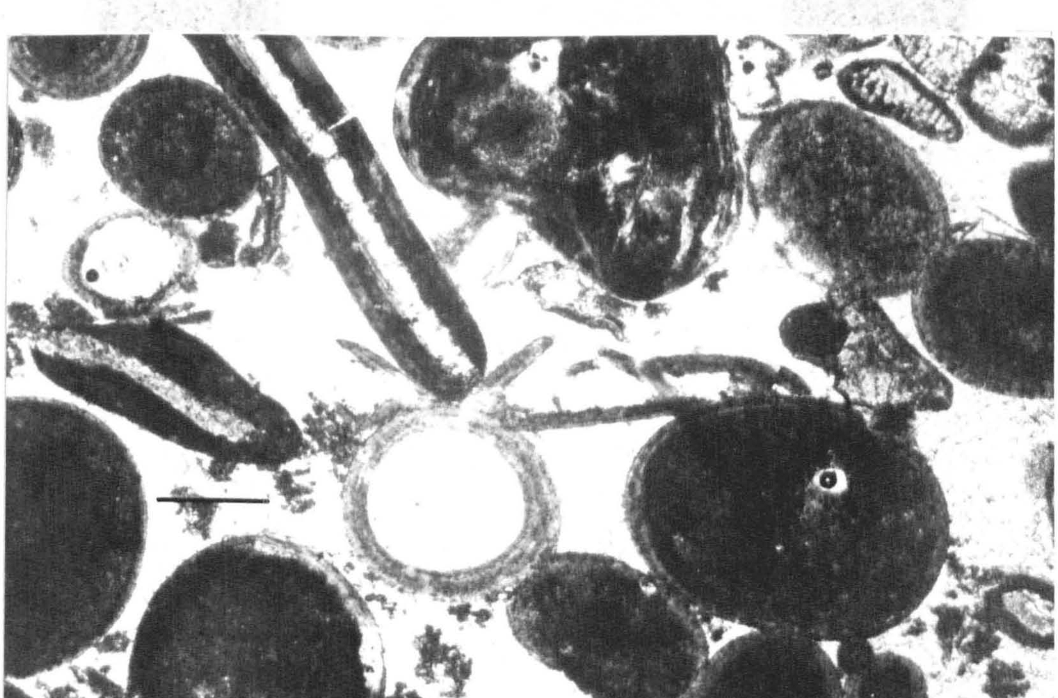


Fig. 4.201. Photomicrograph of a biosparite (bed HLQ K2), typical of Lithofacies B of the Creeton Member.

Richardson			Kent			This thesis			
Ancaster	Great Ponton	Clipsham	Ancaster	Great Ponton	Clipsham				
missing?	Great Ponton Terebratula Beds	missing?	missing?	Great Ponton Terebratula Beds	missing?	Ancaster Rag	Great Ponton Terebratula Beds	Clipsham Beds	CREETON MEMBER
Ancaster Rag	Great Ponton Gastropod Beds	Clipsham Beds	Ancaster Rag	Great Ponton Gastropod Beds	missing?	Ancaster Freestone	Great Ponton Gastropod Beds	missing due to erosion	SLEAFORD MEMBER
Ancaster Freestone	Ancaster Freestone	Ketton Beds?	Ancaster Freestone	Ancaster Freestone	Clipsham Stone?				

Fig. 202. Stratigraphic correlations proposed for the uppermost Lincolnshire Limestone by Richardson and Kent, and their re-alignment in the stratigraphic scheme proposed in this thesis.

Fig. 4.203. A simplified correlation of the litho-stratigraphies proposed by Kent (1966), Richardson and the present author. The newly proposed biostratigraphic subdivisions are also shown.

Zone	Subzone	This thesis	This thesis	Kent, 1966, fig. 1.	Kent, 1966, fig. 1.	Richardson (fig.42 of Sylvester-Bradley, 1968)	Richardson (fig.42 of Sylvester-Bradley, 1968)
Caeviuscula Zone	laeviuscula Subzone	CREETON MEMBER		Ancaster Rag/ Great Ponton Terebratula Beds		Ancaster Rag/Great Ponton Terebratula Beds/Clipsham Beds	
Caeviuscula Zone	laeviuscula Subzone	SLEAFORD MEMBER		Hibaldstow Beds/ Ancaster Freestone/ Great Ponton Gastropod Beds		Hibaldstow Beds/ Ancaster Rag/ Great Ponton Gastropod Beds	
Caeviuscula Zone	ovalis Subzone	BLANKNEY MEMBER	CASTLE BYTHAM MEMBER	Hibaldstow Beds/ Ancaster Freestone/ Great Ponton Gastropod Beds		Hibaldstow Beds/ Ancaster Rag/ Great Ponton Gastropod Beds	
Caeviuscula Zone	ovalis Subzone	METHERINGHAM MEMBER	CASTLE BYTHAM MEMBER	Hibaldstow Beds/ Ancaster Freestone/ Great Ponton Gastropod Beds		Hibaldstow Beds/ Ancaster Rag/ Great Ponton Gastropod Beds	
Caeviuscula Zone	ovalis Subzone	LINDSEY SHALE MEMBER	SCOTTLETHORPE MEMBER	Kirton Shale	Crossi Bed	Kirton Cement-Shale	not recognised?
Caeviuscula Zone	ovalis Subzone	LINCOLN MEMBER		Lower Crossi Bed		Cementstones	
discites Zone		LEADENHAM MEMBER		Cementstones		Cementstones	
discites Zone		GREETWELL MEMBER		Silver/Little Ponton/Nerinea (Pisolite) Beds		Silver Beds/beds with Nerinea Bed	
discites Zone		SPROXTON MEMBER		Blue Beds		Blue Beds	

CHAPTER V

THE CARBONATE ENVIRONMENTS OF THE LINCOLNSHIRE LIMESTONE FORMATION

TEXT-FIGURES

Fig. 5.1. Diagrammatic representation of the principal characteristics of the "ideal rhythm" of the Greetwell Member.

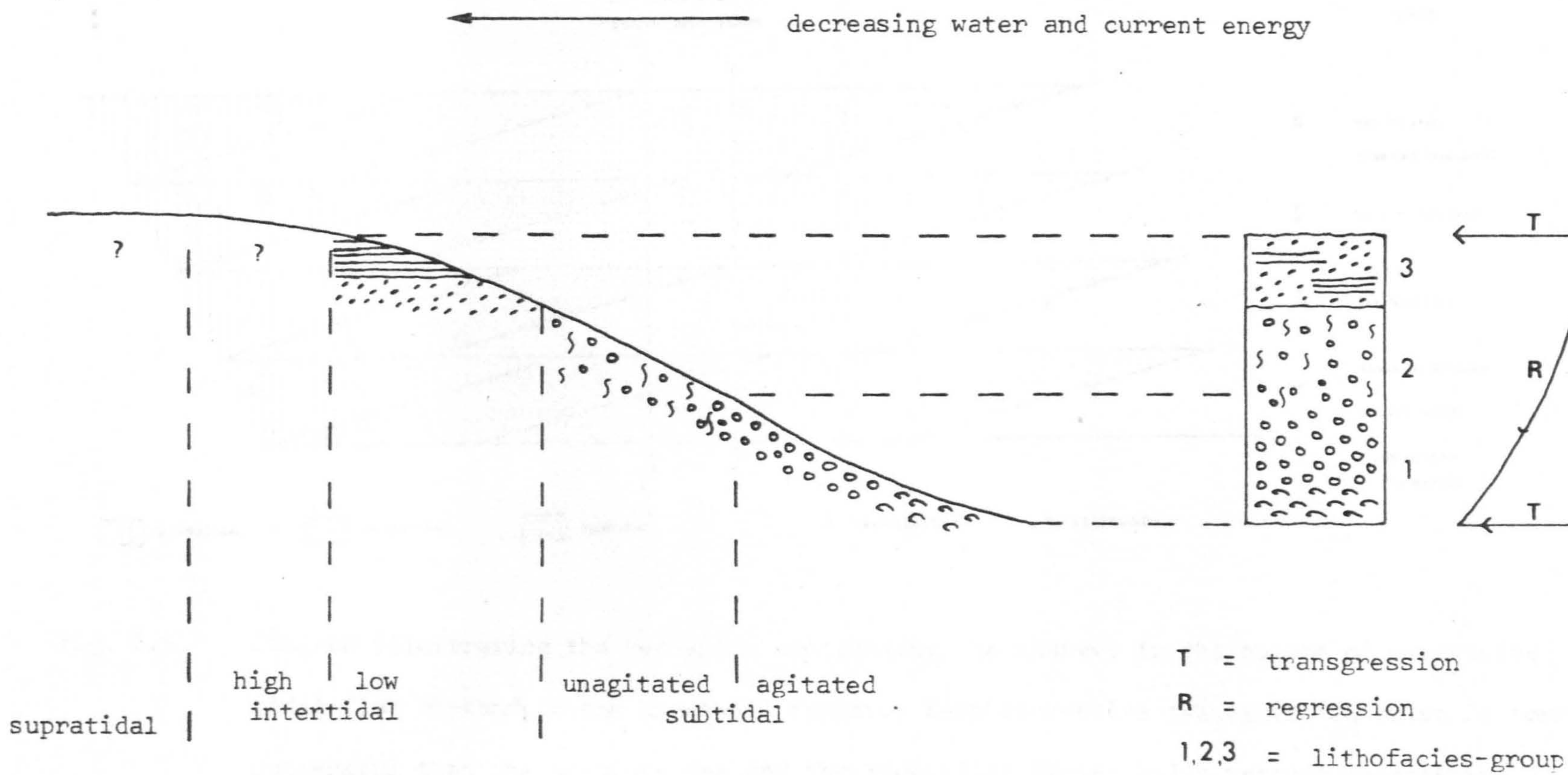
Lithofacies-group	Characteristic lithology	Texture	Sedimentary Structures	Biogenic Structures	Interpretation
3	pelsparite	Packstones	parallel lamination cross lamination micritic "micro-beds" peloidal flakes round-pebble congl. scour-and-fill	vertical burrows of "Skolithos" type. Bioturbation	Low-intertidal to high subtidal
2	oomicrite or "dirty" oosparite	Wackestones or Packstones	-	diverse burrows and bioturbation	unagitated shallow subtidal
1	oosparite or biosparite	Grainstones	current alignment of grains or good sorting may occur	-	agitated shallow subtidal

RHYTHM / Lithofacies Group of the ideal Rhythm	Δ	γ	β	α	
	Woolfox beds	South Witham beds	Thistleton beds	Market Overton beds	Sproxton Member
3		B	C	B	
2		A	B (B2)	A	*
1	A		A (B1)		

Fig. 5.2. Chart showing the principal lithofacies of each stratigraphical unit corresponding to each lithofacies group of the "ideal rhythm". The actual rhythms are also depicted.

Fig. 5.3. Bored hardground surface separating the Thistleton and South Witham beds rhythms at Waltham on the Wolds (SK 815253). "Lithophaga" bores are arrowed.

Fig. 5.4. Diagrammatic model for the deposition of the "ideal" Greetwell Member. Prograding tidal-flat rhythm of the Greetwell Member.



decreasing water and current energy
?
?
3
2
1
T
R
T
supratidal
high
low
intertidal
unagitated
agitated
subtidal
T = transgression
R = regression
1,2,3 = lithofacies-group

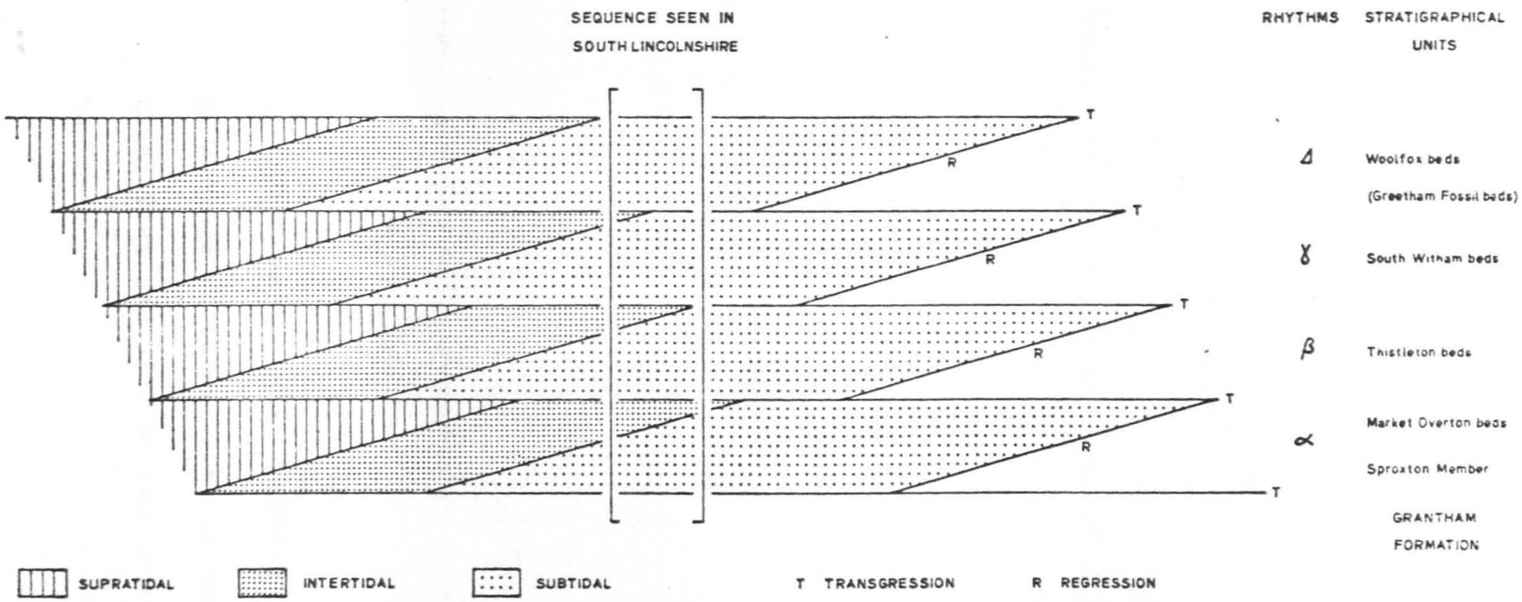


Fig. 5.5. Diagram illustrating the mechanism controlling the changes in the nature of successive tidal-flat rhythms in the Greetwell Member. Each successive transgressive pulse is more successful than the previous one and the tidal-flat facies belts retreat progressively landwards.

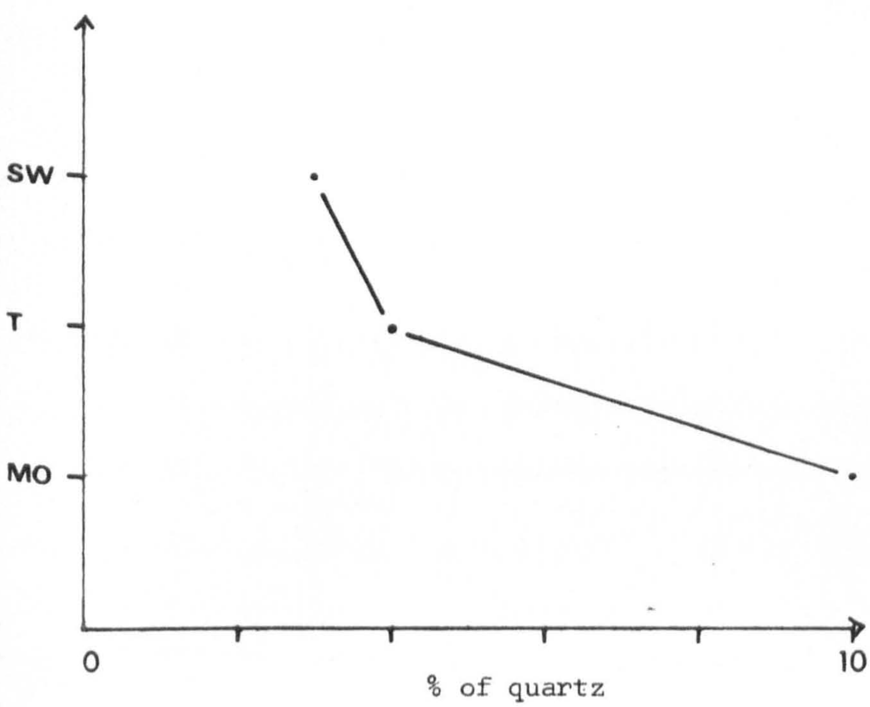


Fig. 5.6. Variation in the quartz content (as percentage of total rock) in the tidal flat deposits of the Greetwell Member.

SW = South Witham beds

T. = Thistleton beds

MO = Market Overton beds

Fig. 5.7. Schematic representation of the thinning of the Lincolnshire Limestone and Grantham Formations from south Lincolnshire towards Lincoln.

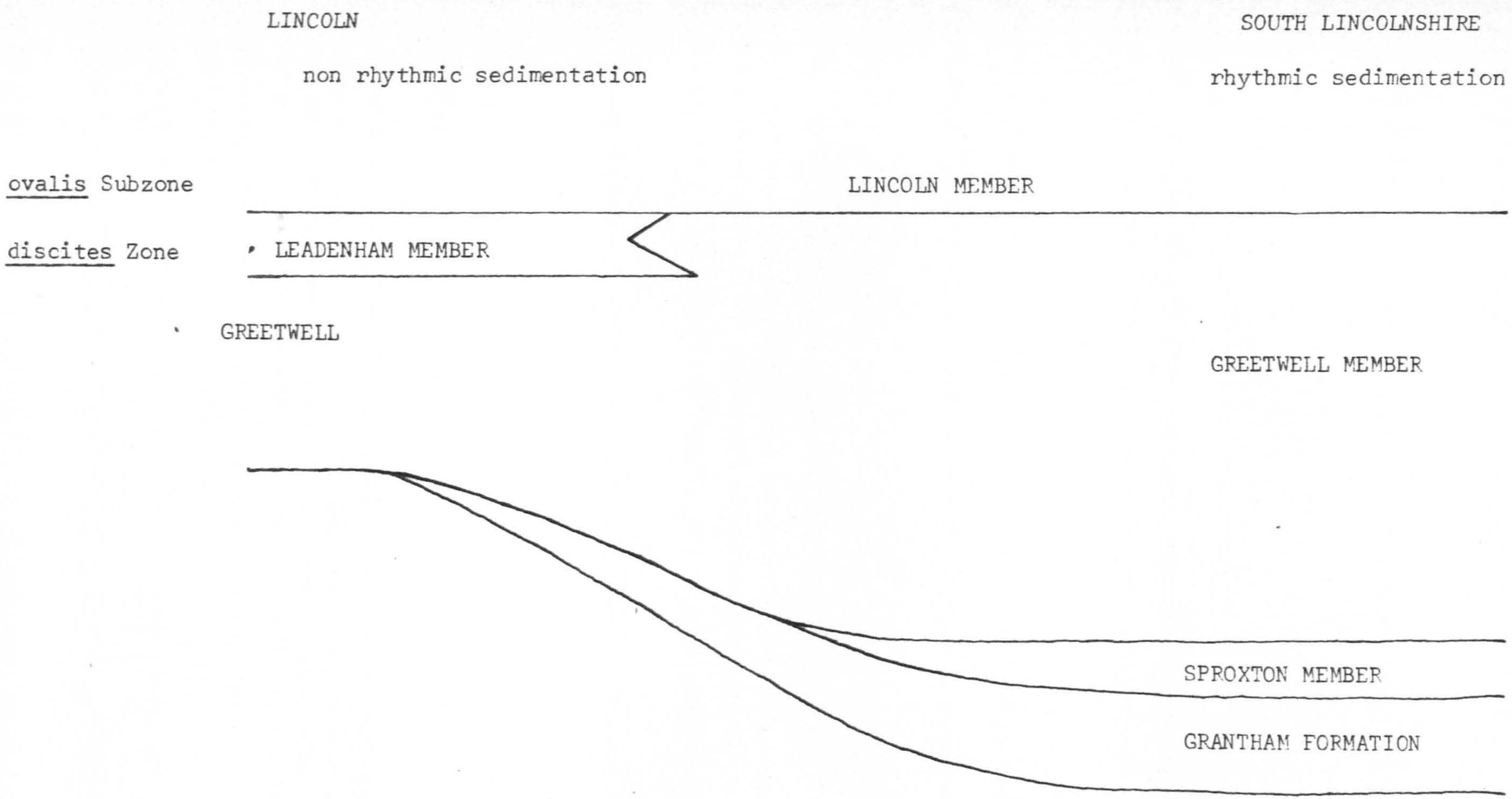
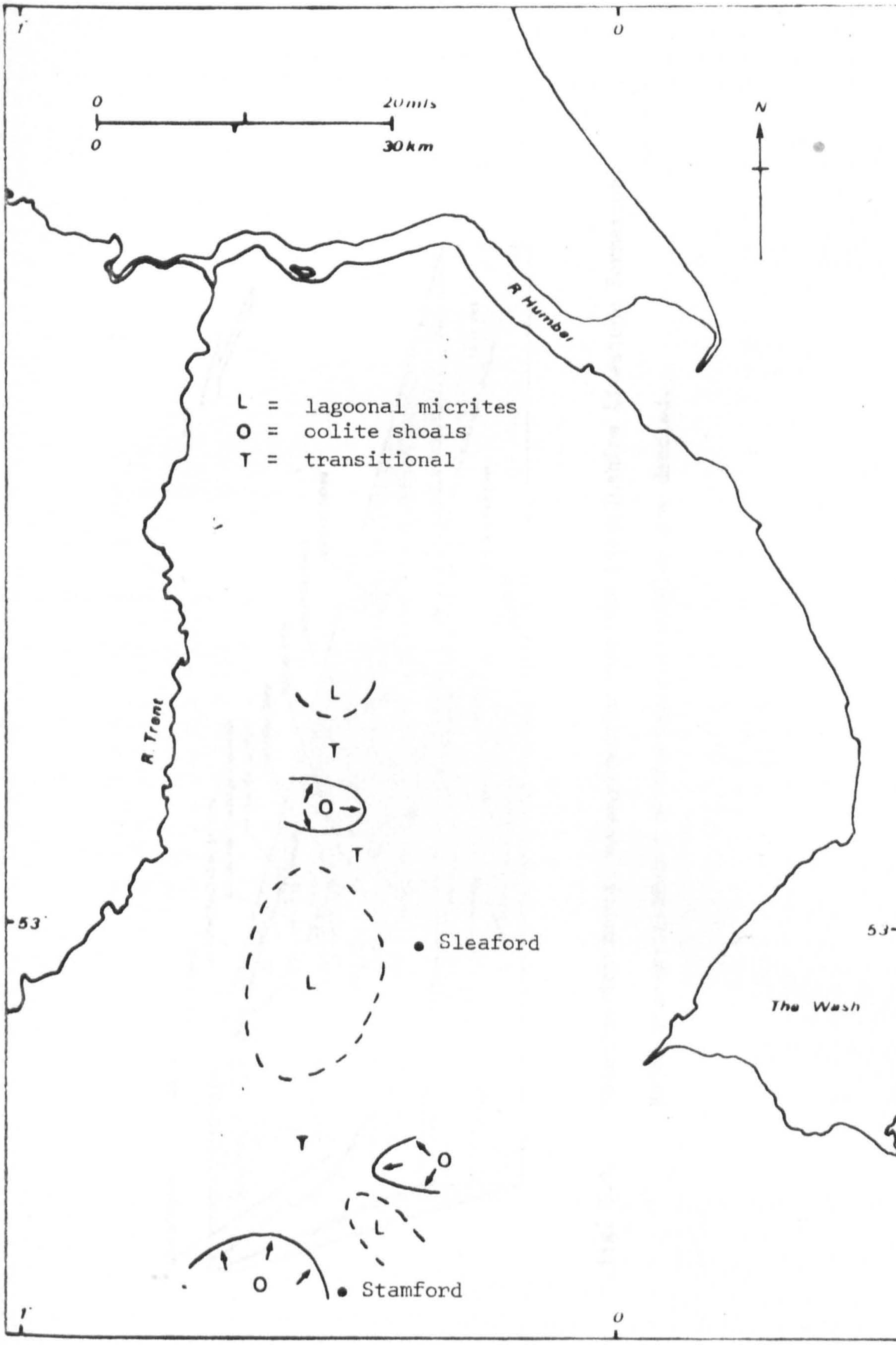

LINCOLN
non rhythmic sedimentation
SOUTH LINCOLNSHIRE
rhythmic sedimentation
ovalis Subzone
LINCOLN MEMBER
discites Zone
LEADENHAM MEMBER
GREETWELL
GREETWELL MEMBER
SPROXTON MEMBER
GRANTHAM FORMATION

Fig. 5.8. Schematic representation of the distribution of the main facies types, present in the Lincoln Member.


1°
0
0
20 mls
0
30 km
N
R Humber
L = lagoonal micrites
O = oolite shoals
T = transitional
R Trent
L
T
O
T
53°
Sleaford
L
The Wash
T
O
L
O
Stamford
1°
0

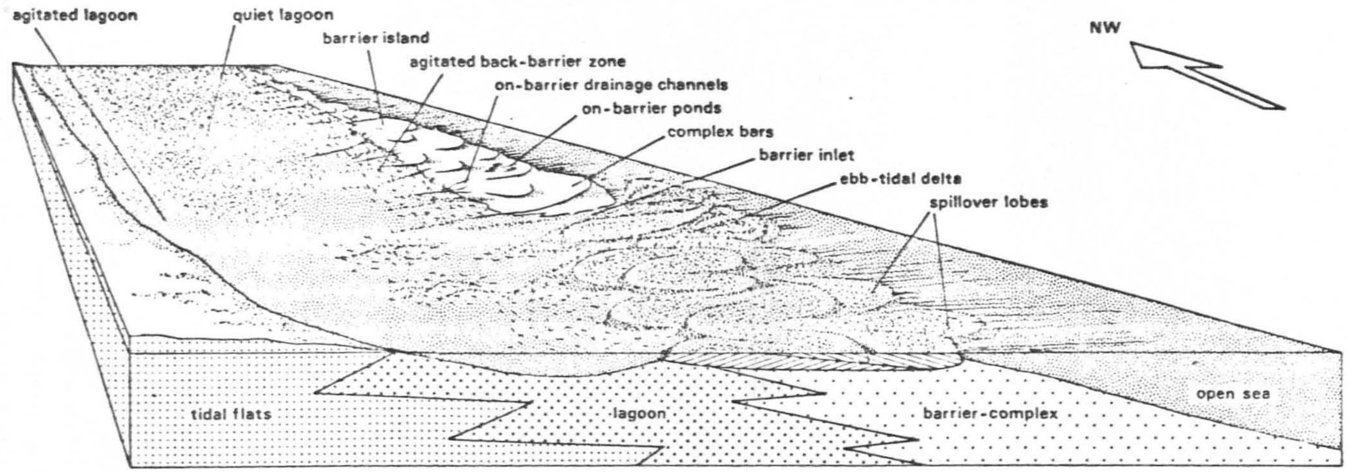


Fig. 5.9. Palaeoenvironmental reconstruction for the Lincolnshire Limestone Formation. Major sub-environments of the barrier complex are denoted.

APPENDICES

APPENDIX 1

MODAL ANALYSES - METHOD

Representatives of the main lithofacies of each lithostratigraphic unit have been "point-counted". A minimum of 200 "points" per slide have been counted using a "jump" interval of 0.20 mm. Although the detailed results of this work are shown in appendix 2, certain of the allochem (and quartz) figures have been re-calculated as percentages of the whole rock (including matrix and/or cement) and incorporated in the lithofacies charts, which constitute certain of the text-figures in the main body of the thesis. These percentages represent a "guide" to the proportional make-up of a "typical" lithology of the particular lithofacies in question; they are not meant to convey any rigorous, statistically valid compositional "average" for either that particular kind of lithology or the "parent" lithofacies. However, they can be seen to substantiate the generalised Folkian terminology used in the limestone terminology, although slight variations exist because of the terminological modifications preferred here; these have been discussed in Chapter II.

APPENDIX 2

MODAL ANALYSES - DATA

LITHOSTRATIGRAPHIC UNIT	BED		OOLITHS	BIOCLASTS	PELOIDS	ONCOLITES	INTRACLASTS	QUARTZ	MICRITE	SPARITE	TOTAL
SPROXTON MEMBER	SNQ	A1a	60	14	18	-	4	38	23	46	203
	SNQ	A1c	-	8	-	1	-	72	119	-	200
	SNQ	A2b	-	18	111	-	6	40	33	94	302
GREETWELL MEMBER	LQ	B6	12	39	11	131	-	-	100	7	300
	LDCP	B3	95	16	-	61	-	-	126	2	300
	RQ	B2	11	17	29	171	-	-	26	46	300
	RQ	B1	190	28	8	-	13	-	12	60	311
	LDCP	B2	1	65	109	2	-	-	6	117	300
	LGHQ	B5b	8	35	164	9	2	-	12	72	302
Wragby Bed	MQ	B5b	19	25	111	16	-	10	25	98	304
	LGHQ	B2b	-	17	42	-	-	45	39	57	200
Market Overton beds	SNQ	BA2	-	25	69	-	-	34	23	50	201
	TQ	BA5c	39	20	122	3	5	6	64	41	300
	TQ	BA3	-	10	-	-	-	57	233	-	300
	TQ	BA1	-	26	6	-	-	4	365	-	401
Thistleton beds	TQ	BB5	4	34	94	-	-	6	14	48	200
	TQ	BB4	2	23	136	-	-	10	42	93	306
	TQ	BB3	-	8	109	-	1	9	26	47	200
	TQ	BB2	161	6	22	7	30	-	25	54	305
	TQ	BB1	18	151	10	-	21	-	-	100	300
South Witham beds	SNQ	BC4	1	36	150	10	-	5	24	77	303
	SNQ	BC1a	16	31	161	-	3	-	12	79	302
	SNQ	BC1	119	13	54	28	29	-	9	48	300
	TQ	BC1a	170	4	37	-	45	-	9	36	301

LITHOSTRATIGRAPHIC UNIT	BED		OOLITHS	BIOCLASTS	PELOIDS	ONCOLITES	INTRACLASTS	QUARTZ	MICRITE	SPARITE	TOTAL
GREETWELL MEMBER Woolfox beds	WQ	BE	210	3	5	-	5	-	-	77	300
	GQ	BE	238	8	6	-	-	-	-	50	302
LEADENHAM MEMBER	LQ	C5	-	48	26	-	-	3	223	-	300
	LDCP	C6	-	18	1	-	-	23	258	-	300
	CQ	C3a	-	108	12	22	-	10	150	-	302
	CQ (base)	C3a	-	102	19	85	-	-	41	53	300
LINCOLN MEMBER	SQ	D1c	6	43	37	21	-	-	193	-	300
	WQ	D1	165	19	5	-	34	-	-	77	300
	MQ	D3	49	39	39	36	-	-	237	-	400
	MQ	D2a	2	10	36	124	-	-	128	-	300
	MQ	D1	79	15	20	60	-	-	12	114	300
SCOTTLETHORPE MEMBER	CSFQ	E3a	-	43	16	6	-	-	235	-	300
	RQ	E4	87	17	1	46	13	-	139	6	309
	LPRC	E1a	154	16	12	-	22	-	30	69	303
METHERINGHAM MEMBER	MQ	H6	4	21	39	144	-	5	21	70	304
	MQ	H3	173	9	39	82	-	-	-	97	400
	MQ	H1	164	14	4	-	53	-	-	65	300
BLANKNEY MEMBER	MQ	I1	-	10	158	-	-	38	24	73	303
	BLHQ	I1	9	28	154	-	-	7	7	95	300
	BLHQ	I2d	68	26	126	-	11	-	-	70	301
	SHQ	I6	152	26	23	-	21	-	26	52	300
CASTLE BYTHAM MEMBER	LBQ	G4	5	68	23	59	-	-	152	-	307
	CBQ	G4b	183	12	32	-	-	-	19	54	300
	CBQ	G1	171	25	5	-	36	-	-	63	300
SLEAFORD MEMBER	HLQ	J1c	46	10	-	92	18	-	115	19	300
	HLQ	J1b	133	26	15	69	-	-	-	57	300
	HLQ	J1a	148	7	-	-	-	-	-	45	200
	BQ	J3c	-	14	134	-	-	1	-	51	200

LITHOSTRATIGRAPHIC UNIT	BED	OOLITHS	BIOCLASTS	PELOIDS	ONCOLITES	INTRACLASTS	QUARTZ	MICRITE	SPARITE	TOTAL
SLEAFORD MEMBER	ACHQ J2 (top)	216	3	4	-	3	-	-	77	303
	ACHQ J5	119	36	-	18	58	-	4	65	300
	ACHQ J1	84	120	-	-	18	-	-	78	300
	BQ J4	49	7	15	140	13	-	-	38	302
CREETON MEMBER	HLQ K2	45	122	1	-	14	-	-	218	400
	ACHQ K	100	53	21	-	16	-	35	75	300
	CBQ K1	354	3	4	-	4	-	-	135	500

APPENDIX 3

Palaeocurrent Data - Cross-bedding

Locality	Dip direction (in degrees) magnetic	corrected	Amount of dip (degrees)
Copper Hill, Ancaster (SK 979427)			
Bed ACHQ J2	240	248	17
	245	253	21
	240	248	12
	240	248	26
	235	243	10
	235	243	9
	210	228	17
	230	238	14
	245	253	15
	232	240	11
Bed K	060	068	20
	048	056	22
	056	064	23
	304	312	19
	330	338	20
	319	327	15
	045	053	23
	035	043	19
	050	058	18
	035	043	16
	050	058	24
	350	358	18
	328	336	25
	320	328	21
	334	342	15
	340	348	17

Locality	Dip direction (in degrees) magnetic	corrected	Amount of dip (degrees)
	312	320	18
	055	063	16
	095	103	16
	076	084	21
	125	133	20
Castle Quarry Ancaster			
(SK 987435)			
Bed K	022	030	22
	000	008	22
	354	002	12
	055	063	24
	082	090	17
	039	047	22
	068	076	15
	045	053	16
	078	086	20
	022	030	25
Wilsford Heath Glebe Quarry			
(SK 992409)			
Bed K2	323	331	17
	323	331	18
	321	329	15
	306	314	16
	345	353	20
Bed K1	345	353	shallow
Lincoln Trust Quarry (SK 987414)			
Bed K2	010	018	20
	320	328	20
Brauncewell Quarry (TF 028518)			
Bed J1	095	103	15

Locality	Dip direction (in degrees) magnetic	corrected	Amount of dip (degrees)
	085	093	16
	090	098	19
	080	088	16
	082	090	18
	075	083	20
	083	091	15
	135	143	18
	090	098	14
	080	088	10
	105	113	15
	132	140	22
	132	140	24
	130	138	23
	128	136	22
	193	201	20
	090	098	22
	100	108	30
	110	118	26
	100	108	17
	080	088	15
	135	143	20
	140	148	19
	115	123	17
	130	138	26
Spittlegate Hill Quarry, Grantham			
(SK 937342)			
Bed J	201	209	27
	200	208	17
	200	208	31
	212	220	28
	175	183	15
	170	178	12
	228	236	22

Locality	Dip direction (in degrees) magnetic	corrected	Amount of dip (degrees)
	208	216	19
	208	216	29
	210	218	27
	185	193	12
Blankney Quarry (TF 062592)			
Bed J4	170	178	12
	215	223	14
	180	188	25
	285	293	8
	244	252	15
	258	266	20
	265	273	21
	037	045	10
	052	060	12
	020	028	18
	015	023	15
	030	038	25
	190	198	10
	063	071	15
	255	263	18
	298	306	18
	335	343	10
	030	038	9
	010	018	13
	270	278	21
	275	283	14
	230	238	12
Old Somerby Quarry (SK 959337)			
Bed K2	036	044	21
	021	029	26
	058	066	17

Locality	Dip direction (in degrees) magnetic	corrected	Amount of dip (degrees)
Bidewell Lodge Quarry, Clipsham			
(SK 968145)			
Bed K	064	072	19
	062	070	18
	047	055	21
	061	069	21
	058	066	23
	037	045	21
	058	066	21
	051	059	23
Medwell's Quarry, Clipsham			
(SK 988160)			
Bed K2	085	093	24
	034	042	17
	047	055	10
Castle Bytham Quarry (SK 990180)			
Bed K1	230	238	21
	252	260	14
	246	254	16
	240	248	21
	240	248	20
	245	253	17
	280	288	19
	262	270	15
	270	278	16
	262	270	18
	232	240	22
	260	268	19
	255	263	23
	260	268	11
	232	240	19

Locality	Dip direction (in degrees) magnetic	corrected	Amount of dip (degrees)
	204	212	20
	230	238	14
	252	260	19
	265	273	21
	270	278	20
Bed K3a	030	038	10
	017	025	9
	050	058	12
	045	053	24
	042	050	16
	053	061	15
	050	058	18
	035	043	22
	040	048	19
	030	038	14
	035	043	23
	010	018	10
	000	008	15
	060	068	14
	060	068	21
Bed K3b	195	203	10
	215	223	16
	040	048	17
Bed K4	245	253	21
	252	260	32
	238	246	13

APPENDIX 4

Pinna cuneata Phillips - Palaeocurrent Readings - Method

The dorso-ventral axis of the protruding posterior margin of Pinna cuneata Phillips was measured in each case. The measurement taken was a "lineation", so that, for example, $090^{\circ} = 270^{\circ}$, and unlike the conventional vector rose diagram, a lineation rose diagram has been constructed for the readings from each bed; such a diagram is completely symmetrical as each reading has in effect 2 values (the diametrically opposed vectors). The lineations therefore reflect the alignment of the bivalve's dorso-ventral axis i.e. NE-SW. All specimens were in situ and in their position of life.

In an effort to avoid bias produced by sampling, measurements were taken from as many quarry faces as possible. This effectively avoided producing "face alignments" as specimens with the dorso-ventral axes aligned parallel to the face are more likely to be seen than those perpendicular to the face.

As the data displayed in the rose diagrams was inconclusive, the data was statistically tested to see if there was a preferred orientation displayed by the bivalves. Dr P. Diggle of the Statistics Department at Newcastle performed this work and his results and comments are shown overleaf. Essentially the results are inconclusive but further work (bigger collections) may prove to be profitable.

Rayleigh's test of uniformity, and estimates of mean direction

Data	Faces	n	R	approx. P.	mean direction
LQ C7d	all	27	0.053	0.93	32°
"	S,SE,SSE	26	0.093	0.80	29°
"	SE,SSE	24	0.118	0.72	15°
"	SE	21	0.158	0.60	39°
LQ C9b	all	19	0.288	0.21	46°
"	S,SE	12	0.369	0.20	47°
"	SE	8	0.713	0.02	26°
LQ C9c	all	31	0.252	0.14	58°
"	S,SE	14	0.383	0.13	50°
"	SE	12	0.563	0.02	48°
DQ C7a	all	68	0.151	0.21	75°
"	NW	47	0.243	0.06	68°
"	SW	21	0.148	0.64	128°
CQ C3b	all	28	0.218	0.27	79°
"	E	15	0.093	0.88	90°
"	S	10	0.403	0.20	60°
LGHQ C6	all	22	0.193	0.44	2°
"	E,W	20	0.190	0.49	2°
"	E	13	0.427	0.09	151°
"	W	7	0.714	0.03	40°

Notes

1. Conventionally, p-values less than 0.05 would be regarded as significant. This may be misleading, as we have conducted a considerable number of related tests, and the results will not be independent. Thus, I prefer to regard the p-values as summary statistics, with low values suggesting that further investigation might be profitable.

APPENDIX 5

Pinna cuneata Phillips - Palaeocurrent Data

	magnetic reading (in degrees)	corrected reading (in degrees)	quarry face
LEADENHAM QUARRY (SK 962523)			
Bed LQ C7d	132	140	SE
	015	023	SE
	115	123	SE
	120	128	SE
	005	013	SE
	166	174	SE
	083	091	SE
	110	118	SE
	055	063	SE
	032	040	SE
	088	096	SE
	172	000	SE
	166	174	SE
	037	045	SE
	055	063	SE
	014	022	SE
	060	068	SE
	030	038	SE
	080	088	SE
	075	083	SE
	179	007	SE
	140	148	SSE
	152	160	SSE
	000	008	SSE
	116	124	N
	052	060	S
	100	106	S

	magnetic reading (in degrees)	corrected reading (in degrees)	quarry face
Bed LQ C9b	089	097	NC
	059	067	NC
	010	018	NC
	027	035	NC
	155	163	NC
	066	074	NC
	078	086	SE
	030	038	SE
	000	008	SE
	041	049	SE
	007	015	SE
	028	036	SE
	039	047	SE
	007	015	SE
	135	143	N
	087	095	S
	109	117	S
	081	089	S
	088	096	S
Bed LQ C9c	116	124	NC
	085	093	NC
	084	094	NC
	096	104	NC
	005	013	NC
	172	000	NC
	003	011	NC
	112	120	NC
	039	047	NC
	040	048	NC
	104	112	NC
	120	128	NC
	060	068	NC
	066	074	NC
	017	025	NC
	066	074	NC

	magnetic reading (in degrees)	corrected reading (in degrees)	quarry face
	090	098	SE
	050	058	SE
	172	000	SE
	060	068	SE
	052	060	SE
	046	054	SE
	053	061	SE
	054	062	SE
	036	044	SE
	014	022	SE
	064	072	SE
	145	153	SE
	165	173	N
	108	116	S
	150	158	S
DUNSTON QUARRY (TF 053634)			
Bed DQ C7a	116	124	NW
	014	022	NW
	161	169	NW
	063	071	NW
	083	091	NW
	072	080	NW
	058	066	NW
	078	086	NW
	092	100	NW
	026	034	NW
	093	101	NW
	095	103	NW
	154	162	NW
	138	146	NW
	060	068	NW
	123	131	NW
	088	096	NW
	160	168	NW
	031	039	NW

magnetic reading (in degrees)	corrected reading (in degrees)	quarry face
026	034	NW
093	101	NW
069	077	NW
054	062	NW
062	070	NW
072	080	NW
051	059	NW
069	077	NW
014	022	NW
169	177	NW
170	178	NW
120	128	NW
142	150	NW
065	073	NW
160	168	NW
013	021	NW
123	131	NW
090	098	NW
157	165	NW
076	084	SW
156	164	SW
010	018	SW
137	145	SW
140	148	SW
007	015	SW
113	121	SW
132	140	SW
108	116	SW
032	040	SW
082	090	SW
089	097	SW
042	050	SW
005	013	SW
121	129	SW
167	175	SW
120	128	SW

	magnetic reading (in degrees)	corrected reading (in degrees)	quarry face
	100	108	SW
	029	037	SW
	024	032	SW
	104	112	SW
	098	106	NW
	011	019	NW
	076	084	NW
	047	055	NW
	064	072	NW
	034	042	NW
	160	168	NW
	041	049	NW
	051	059	NW

COLEBY QUARRY (SK 981600)

Bed CQ C3b	073	081	S
	072	080	S
	051	059	S
	083	091	S
	078	086	S
	103	111	S
	153	161	S
	033	041	S
	008	016	S
	025	033	S
	148	156	E
	126	134	E
	022	030	E
	104	112	E
	105	113	E
	138	146	E
	029	037	E
	086	094	E
	065	073	E
	046	054	E

	magnetic reading (in degrees)	corrected reading (in degrees)	quarry face
	093	101	E
	038	046	E
	149	157	E
	161	169	E
	044	052	E
	090	098	NC
	129	137	NC
	094	102	NC

GREETWELL HOLLOW QUARRY, LINCOLN

(TF 003721)

Bed LGHQ C6	110	118	E
	145	153	E
	150	158	E
	163	171	E
	027	035	E
	055	063	E
	105	113	E
	090	098	E
	170	178	E
	147	155	E
	164	172	E
	171	179	E
	042	050	N
	145	153	N
	080	088	W
	047	055	W
	015	023	W
	039	047	W
	032	040	W
	011	019	W
	062	070	W
	150	158	E

N	=	north
S	=	south
W	=	west
E	=	east
NC	=	not recorded
SE etc.	=	south-east etc.

FIG. 4.1.

LINCOLN
ANCASTER
Dean & Chapter
SK 977734
LDCP
Greetwell
TF 003721
LGHQ
Washingborough
TF 019702
WRC
Branston
TF 023671
BVQ
Dunston
TF 053634
DQ
Metheringham
TF 053616
MQ
Harmston
SK 992619
HQ
Coleby
SK 981600
CQ
Leadenham
SK 962523
LQ
Railway Cutting
SK 997444
ARC
Copper Hill
SK 979427
ACHQ
Castle Qu.
SK 987435
AQ
Ropsley
TF 002364
RQ
Little Ponton
SK 930320
LPRC
Waltham on the Wolds
SK 815253
WWQ
upper Lincolnshire Limestone
R.B.
Lindsey Shale Member (F)
Lincoln Member (D)
Cathedral Beds (C')
Leadenham Member (C)
Greetwell Member (B)
Wragby Bed (B')
NORTHAMPTON IRONSTONE
G
FT 0
0 M
15
4
Grain-rich
Grain-poor
oolite
peloidal limestone
micritic limestone
silty limestone
oncolitic limestone
conglomerate
shale
clay
oolite marl
parallel or cross lamination
shell debris
corals
burrows
"Thalassinoides"
erosive
gradational
irregular
sharp
hardground
contact
limit of exposure
G gap in succession
G.F.b. Greetham Fossil beds (BD)
L.B.b. Little Bytham beds
R.B. Ropsley Beds (D')

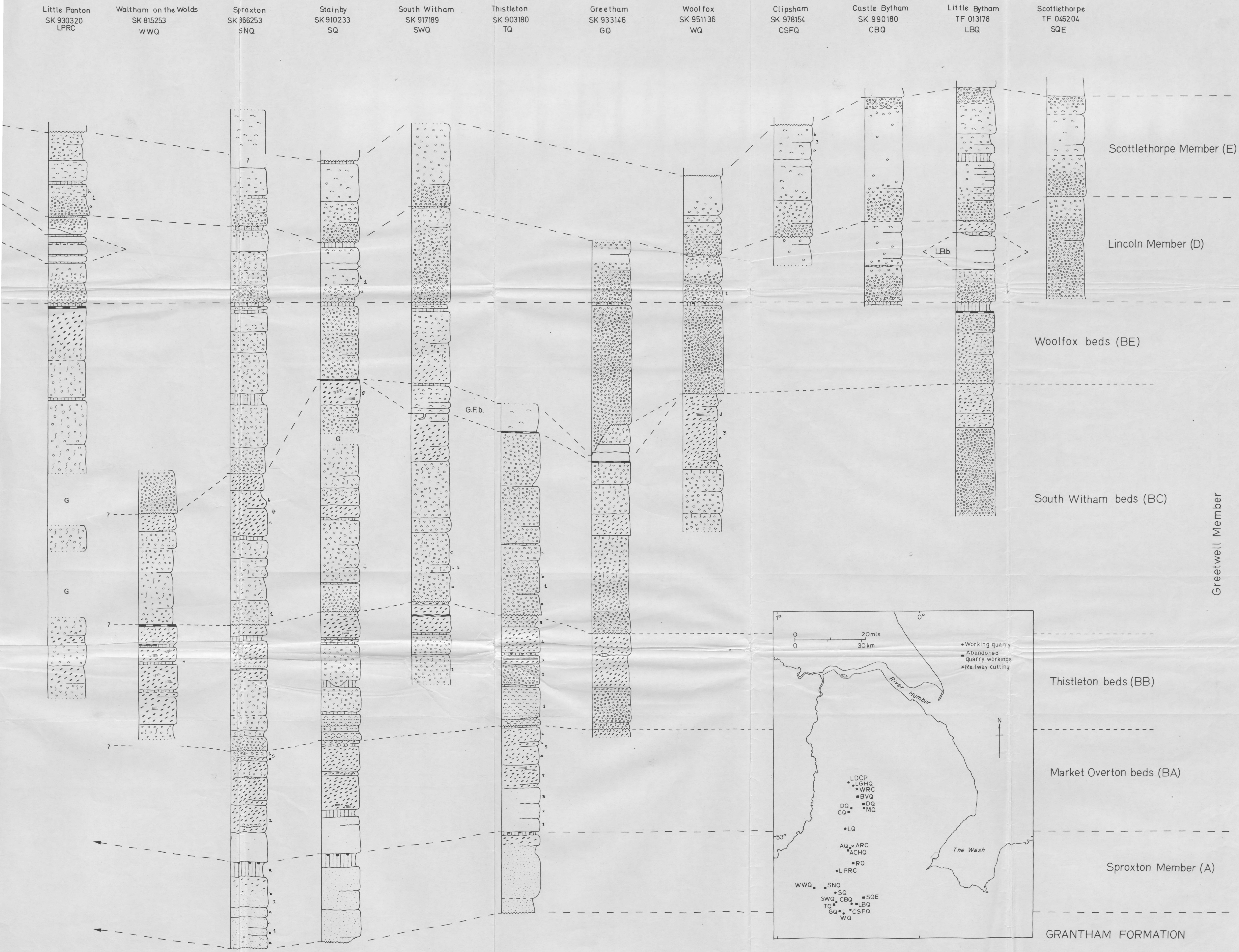

Little Ponton
SK 930320
LPRC
Waltham on the Wolds
SK 815253
WWQ
Sproxton
SK 866253
SNQ
Stainby
SK 910233
SQ
South Witham
SK 917189
SWQ
Thistleton
SK 903180
TQ
Greetham
SK 933146
GQ
Woolfox
SK 951136
WQ
Clipsham
SK 978154
CSFQ
Castle Bytham
SK 990180
CBQ
Little Bytham
TF 013178
LBQ
Scottlethorpe
TF 046204
SQE
Scottlethorpe Member (E)
Lincoln Member (D)
LBb.
Woolfox beds (BE)
G.F.b.
South Witham beds (BC)
Greetwell Member
Thistleton beds (BB)
Market Overton beds (BA)
Sproxton Member (A)
GRANTHAM FORMATION
G
1°
0°
0
20mls
0
30km
• Working quarry
▪ Abandoned quarry workings
× Railway cutting
River Humber
N
53°
The Wash
LDCP
LGHQ
WRC
BVQ
DQ
DQ
CQ
MQ
LQ
AQ
ARC
ACHQ
RQ
LPRC
WWQ
SNQ
SQ
SWQ
CBQ
SQE
TQ
LBQ
GQ
WQ
CSFQ

FIG. 4.2.

Hibaldstow SE 973008 HQA
Greetwell TF 003721 LGHQ
Metheringham TF 053616 MQ
Blankney TF 062592 BQ
Ashby TF 052570 ADLL
Thompsons B TF 026555 TBQ
Brauncewell TF 028518 BRQ
N. RAUCEBY TF 021474 NRQ
S. Rauceby TF 029452 SRQ
ANCASTER
Castle Qu. SK 987435 AQ
Copper Hill SK 979427 ACHQ
WILSFORD
Lincoln Trust SK 987414 WHLT
Glebe Qu. SK 992409 WHGQ
Newton TF 041369 NQ
Dembleby Farm TF 034371 DFQ
Haceby TF 028369 HLQ
Ropsley TF 002364 RQ
Braceby TF 010351 BLHQ
15
4
FT. 0 0 M.
UPPER ESTUARINE SERIES
Sleaford Member (J)
Blankney Member (I)
Metheringham Member (H)
lower Lincolnshire Limestone
base of Lincoln Member (datum level)
Blankney Mem.
Meth. Mem.
G
skeletal-rich
oncole-rich
cross-bedded oolites & skeletal oolites
"herring-bone" cross bedding
"patch reef"
"doggs"
gastropods
terebratulids
for rest of legend see Fig. 4.1.


LITTLE PONTON
CLIPSHAM
Ropsley TF 002364 RQ
Braceby TF 010351 BLHQ
Old Somerby SK 959337 OSQ
Spittlegate Hill SK 937342 SHQ
Railway Cutting SK 930320 LPRC
Quarry SQ 931325 LPQ
Great Ponton SK 935303 GPQ/GPSQ
Burton Coggles SK 982254 BCQ
Corby Glen SK 987244 CGC
Creeton SK 999205 CPLQ
Castle Bytham SK 990180 CBQ
Little Bytham TF 013178 LBQ
Scottlethorpe TF 046204 SQE
Medwell's SK 988160 CMQ
Soil Fertility SK 978154 CSFQ
Bidwell SK 968145 CBLQ
Woolfox SK 951136 WQ
HQA
LGHQ
The Wash
N
UPPER ESTUARINE SERIES
Creeton Member(K)
Castle Bytham Member (G)
lower Lincolnshire Limestone
base of Lincoln Member
G
em.
m.
see Fig. 41.