PETROGRAPHIC VARIATION ASSOCIATED WITH HUMMOCKY CROSS STRATIFICATION IN THE PERMIAN OF NOTTINGHAMSHIRE, ENGLAND

by

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Summary

The Cadeby Formation of Nottinghamshire accumulated on a shallow shelf at the margin of the Zechstein Sea and is predominantly composed of dolomitised pelloidal carbonates with dispersed siliciclastic material. Hummocky cross-stratified units exposed in quarry sections through the formation contain high proportions of siliciclastic fine sands together with concentrations of shell debris and are interpreted as storm beds. The non-carbonate materials are interpreted as being derived from erosion of littoral sediments which were transported offshore during storms. These clastic grains are not uniformly distributed through the beds with hummocky upper surfaces but rather are concentrated in the lowest divisions of the units. This petrographic variation therefore appears to indicate that the major basinward flux of shore-derived material preceded the development of hummocky relief upon the sea bed during the deposition of these beds.

Introduction

Hummocky cross-stratification (HCS) (Harms et al., 1975) has been described from both carbonate and siliciclastic shallow marine sediments, although the mechanisms by which it may be generated are still controversial particularly with regard to the relative timing of sediment input and hummock formation. Walker *et al.* (1983) have proposed a turbidity current mechanism to emplace sediments which may *subsequently* be reworked by storm waves thereby producing 'turbidite-HCS beds', whilst Swift *et al.* (1983) favour formation of hummocky cross-stratification concomitant with deposition of sediment in a combined flow regime. Part of this controversy no doubt arises from the wide variety of bedding styles which have been described as 'hummocky stratification' and, as Walker *et al.* (1983) suggest, different hydrodynamic models may be appropriate for each of these different varieties. It is the purpose of this paper to document evidence provided by petrographic variation within hummocky cross-stratified dolostones of the Cadeby Formation of Nottinghamshire, which indicates that, in this instance, the major influx of sediment preceded the development of hummocky relief on the sea bed.

The Cadeby Formation (Smith *et al.* 1986) (formerly the Lower Magnesian Limestone) of Nottinghamshire is of Upper Permian age and represents part of the first Zechstein cycle (Taylor and Colter, 1975). The sediments discussed herein accumulated in an embayment of the Zechstein Sea termed the Nottingham Bight (Smith, 1970). In this area the Cadeby Formation consists predominantly of dolomitised carbonates which grade into dolomitic sandstones at the western margin of the Bight. The presence of dispersed siliciclastic and plant materials within the dolostones at the westernmost outcrops of the formation suggest that the shoreline of the contemporary Zechstein Sea lay only a little further west than the present outcrop limit (Taylor, 1968). From this limit the Cadeby Formation extends eastwards across the gently sloping East Midlands Platform for some 40 km to the contemporary shelf edge where it passes beneath a thick evaporite sequence (Smith, 1974). Sedimentary facies varied across the shelf from nearshore pelloidal and shelly carbonates with dispersed siliciclastic grains to oolitic limestones with a low siliciclastic content at the shelf edge (Taylor and Colter, 1975). In the study area (Fig. 1) most of these carbonate sediments have been strongly altered to coarse euhedral dolomite crystals in which the primary carbonate grains are only discernable as ghost textures.

Hummocky cross-stratification has been reported from the Cadeby Formation of Yorkshire by Kaldi (1986) and is exposed in two working quarries at Bulwell (Grid ref. SK538438), north Nottinghamshire (Fig. 1). These quarries lie approximately 8 km east of the western outcrop limit of the formation and expose successions

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dominated by evenly bedded dolostones separated by thin muddy interbeds. However, several beds are characterised by hummocky bedding surfaces (Fig. 2) which are associated with variation in the composition of the carbonates and it is this variation in bedding style and petrography which provides information regarding the mechanism of hummock development.

Field observations

In the summer of 1983 the Bulwell quarries exposed a thickness of approximately 5 m of dolostones of the Cadeby Formation. Bedding within the sequence was clearly defined by thin (5 to 30 mm) clay and sandy clay partings between thicker (typically 10 to 30 cm) dolostones which showed a tendency to thin upwards (Fig. 2). In the lowermost 1.3 m of section the beds exhibited localised disturbance resulting in a series of "folds" which were truncated by overlying beds (horizon A; Fig. 2). This relationship indicates a synsedimentary origin for the structures, possibly associated with rapid dewatering. The overlying strata were not deformed in this way and consisted predominantly of sub-horizontally disposed parallel bedded dolostones. However, at several prominent horizons, (horizons B to E; Fig. 2) anomalously thick beds were marked by flat lower contacts but undulose upper contacts. In sections parallel to bedding these upper surfaces were seen to consist of a series of domes and basins with a spacing of approximately 1 m. Shell moulds of bivalves which were scarce within the sequence as a whole, were concentrated at the bases of horizons B (Plate 14A) and C. These beds rich in shell moulds have been found elsewhere in the local area (Taylor, 1968; Nutting, 1980). No lamination was discernable in this lowest, shelly part of the hummocky units although faint parallel lamination characterised the sediments immediately superimposed upon them. Lamination of a 'scour and drape' type (cf. Dott and Bourgeois, 1982), was, however preserved in dolostone of the overlying hummocky division. These relationships, based on observations of all four hummocky horizons (B to E; Fig. 2), are summarised schematically in Fig. 3.

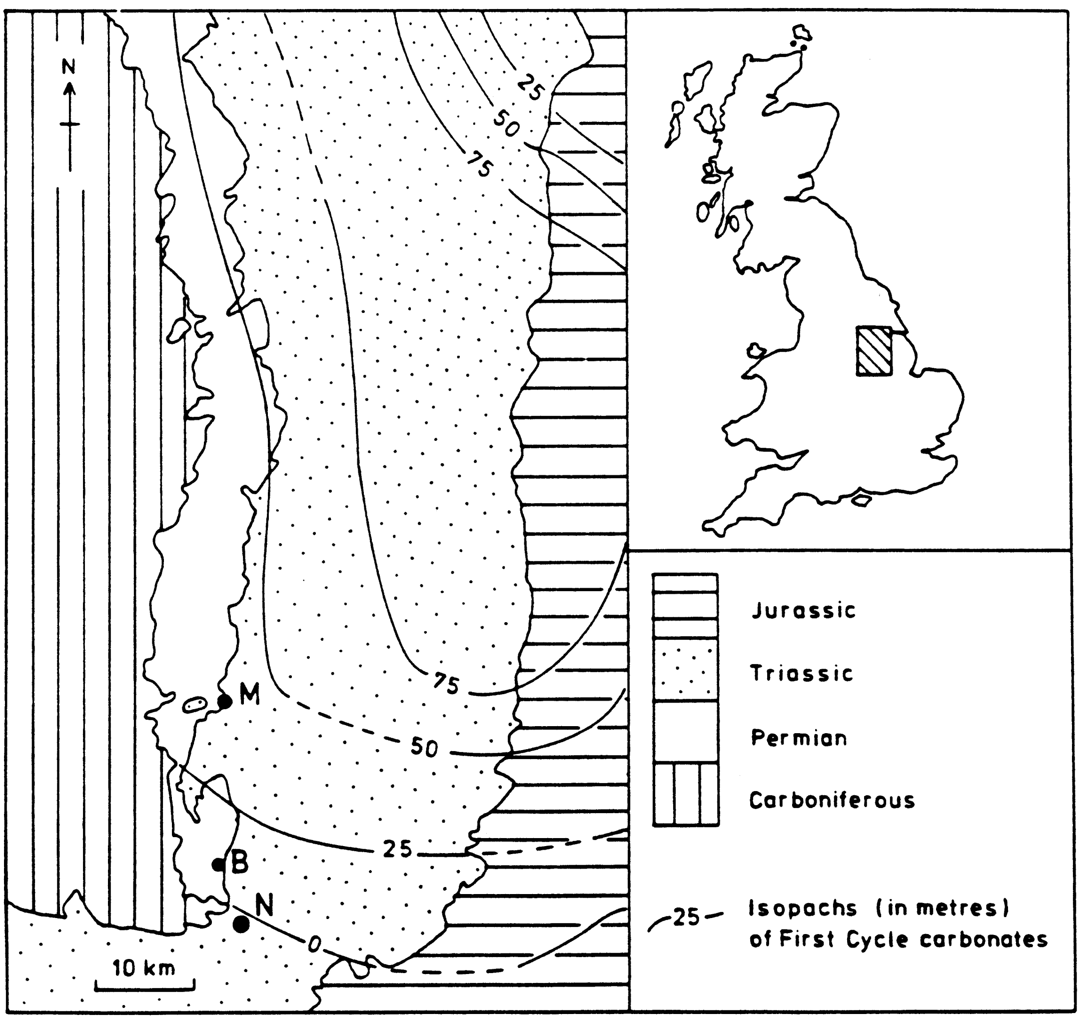

Fig. 1. Map to show the regional setting of the Permian rocks of Nottinghamshire. Inset map shows location of large scale map in eastern England. N = Nottingham, M = Mansfield, B = Bulwell. Isopachs of First Cycle carbonates after Taylor and Colter (1975).

The amplitude of the hummocks had in some cases been reduced by ripple reworking of material from the crests into the trough areas (Plate 14A) which were also sites of increased shell concentration. The ripple-reworked dolostones contained thin laminae of micaceous muds similar to the sandy clays which draped the hummocky unit as a whole. Commonly these drapes thickened into the swales between hummocks where they exceptionally attained thicknesses of 0.2 m.

The concentration of shelly material in the swales between the hummocks and the well preserved ripple lamination (distinguished by the thin mud drapes between adjacent ripple sets) which draped the upper surfaces of some hummocks provide evidence that the beds genuinely had primary hummocky relief rather than resulting from a modification of primary bedding by diagenetic processes.

Field examination of the hummocky units and intervening parallel bedded horizons suggested that significant variation in the proportion of shell and clastic material occurred both: (i) between the hummocky and parallel-bedded units, and (ii) between the various divisions of the hummocky strata. This contention was further investigated by laboratory analyses.

Laboratory analyses

Oriented thin sections were produced from samples collected in the field and examined using conventional light microscopy and cathodoluminesence techniques. Acid insoluble residues of the dolostones and untreated samples of the muddy drapes were examined by X-ray diffraction and scanning electron microscopy. The grain size of the clastic material was determined by sieve and settling tube analyses.

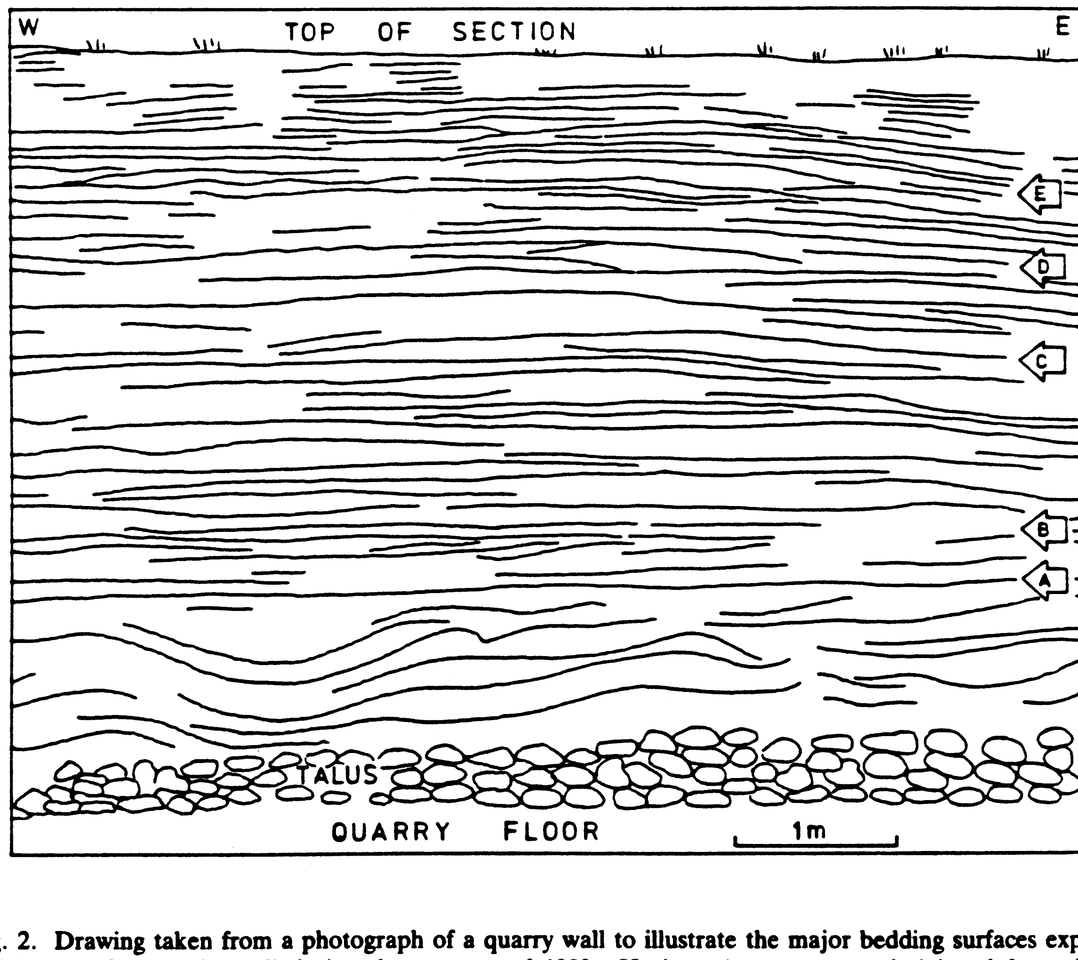

Fig. 2. Drawing taken from a photograph of a quarry wall to illustrate the major bedding surfaces exposed in Wilkinson's Quarry, Bulwell during the summer of 1983. Horizon A truncates underlying deformed strata; horizons B to E show development of hummocky bedding.

Composition of the Parallel Bedded Strata

The parallel bedded rocks between the hummocky units consisted of coarse dolomite with dispersed siliciclastic material. In thin section, ghost textures preserved within the dolomite crystals indicated that pelloidal carbonate grains made up a significant proportion of the rock prior to dolomitisation. Up to 12% of these dolostones was non-carbonate material of which 46% was of fine siliciclastic sand. The mud-grade sediments were dominated by a kaolinite-illite clay mineral assemblage together with some muscovite. These non-carbonate materials were indistinguishable from the material which constituted the thin muddy layers between the dolostone beds.

Composition of the Hummocky Strata

Bulk dissolution of samples from the hummocky strata resulted in a similar proportion of non-carbonate material (9 to 12%) to that found in the parallel bedded units. However, unlike the latter this material was not uniformly dispersed within the beds but could be seen to be differentially distributed between the divisions shown in Figure 3 when examined in oriented thin sections.

Basal Division—Coarse dolomite crystals and dolomitised shell fragments occurred in roughly equal proportion with quartz and feldspar medium to very fine sand grains (Plate 14B). Diagenetic ovegrowths occurred on many of the detrital grains but the well rounded outlines visible beneath the overgrowths testify to the detrital origin of the grains. The shell fragments occurred both in convex-up and concave-up orientations; in accordance with observations of shell moulds made in the field.

Parallel Laminated Division—Coarse dolomite crystals and medium to fine siliciclastic sand also occurred in this division although the sand proportion increased to over 60% and included lithic fragments in addition to quartz and feldspar grains (Plate 14C).

Hummocky Cross-stratified Division—This division possessed a lower siliciclastic sand content than the underlying divisions (10–20%). The sand was predominantly of fine to very fine grade and was evenly dispersed within the dolomite rhombs.

Flat Laminated Division—This division was petrographically indistinguishable from the underlying division.

Cross Laminated Division—The dolomite spar and dispersed sand of this interval were interbedded with thin mud laminae containing abundant muscovite mica flakes aligned parallel to the bedding. The clay mineral assemblage was predominantly kaolinite-illite and was indistinguishable from that of the overlying division.

Muddy Division—The clays and sands which draped the hummocky units were of similar composition to those occurring between the parallel bedded units and within the hummocky units.

Discussion

Clastic material, probably derived from the nearby shoreline, occurs dispersed within the dolostones of the Cadeby Formation and declines in abundance eastwards (Taylor and Colter, 1975; Nutting, 1980). Muddy laminae between dolostone beds possess similar mineral assemblages to the dispersed siliciclastic material and hence seem likely to have a similar provenance. The dispersed clastic sediment would therefore seem to indicate a steady input of shorederived sediment onto the shelf ('facies mixing *sensu* Mount 1984). If the muddy interbeds are of primary origin they would seem to indicate a periodic increase in the rate of the clastic flux relative to the rate of carbonate sedimentation: however, it is possible in some cases that these interbeds are of diagenetic origin.

The preservation of primary bedding structures and the differentiation of the constituent minerals between divisions precludes a diagenetic origin for the hummocky strata recognised at Bulwell. Since these hummocky strata are distinguishable from the majority of the sediments exposed at the quarries they seem likely to represent anomalous sedimentation events which are inferred to be associated with storms (cf. Harms, 1979; Tucker, 1982; Duke, 1985) and represent 'punctuated mixing' (*sensu* Mount 1984). Furthermore the sequence of primary sedimentary structures and variation in the petrography of the various divisions indicate a sequence of processes operating within each storm event which are summarised below.

1. The sharp base of each hummocky division represents an initial phase of erosion. No directional sole structures are present on the base of the overlying B division and consequently it is not possible to determine whether unidirectional or oscillatory flows caused this erosion. Erosion by lowering of wave base or bottom return currents (cf. Allen, 1982; Aigner and Reineck 1982) associated with the storm are possible causative mechanisms.
2. The earliest phase of deposition above each erosion surface incorporates shell debris and increased concentration of siliciclastic material. It is suggested that these sediments indicate a flux of material from the shore onto the shelf since the shoreward sediments have a higher siliciclastic component and shells are not usually found within the parallel bedded strata.
3. Increased erosion of shoreface sediments and shelfward transport by unidirectional flow appears to be indicated by the parallel laminated division. The highest proportion of siliciclastic sediment occurs within this division and therefore, by interference, the highest rate of shelfward sediment flux appears to have preceded the development of hummocky relief on the seabed indicated by the overlying hummocky cross-stratified division.
4. Scour and drape structures within the hummocky cross-stratified division are taken as indicators of dominantly oscillatory flows (cf. Walker *et al.*, 1983). The lower proportion of siliciclastic material in this division by comparison with the underlying divisions also suggests that the unidirectional flux of clastic sediment was waning at the time of hummock development. The carbonate material in this division seems unlikely to have been derived by wave scour of the underlying sediment since this is rich in clastic grains and it is suggested therefore that the bulk of the hummocky cross-stratified sediments were supplied by settling from suspension as the intensity of the storm decreased.
5. Ripple reworking of the tops of the hummocks appear to indicate that the hummocks came into disequilibrium with the flow and this seems likely to be a result of either further reduction in wave energy and or a reduced rate of sediment deposition. Certainly the occurrence of micaceous clay drapes between adjacent ripple sets appears to indicate reduced energy conditions.
6. The final phase of deposition of the hummocks is represented by sedimentation of very fine sands and muds, presumably from suspension, in the waning stages of the storm.

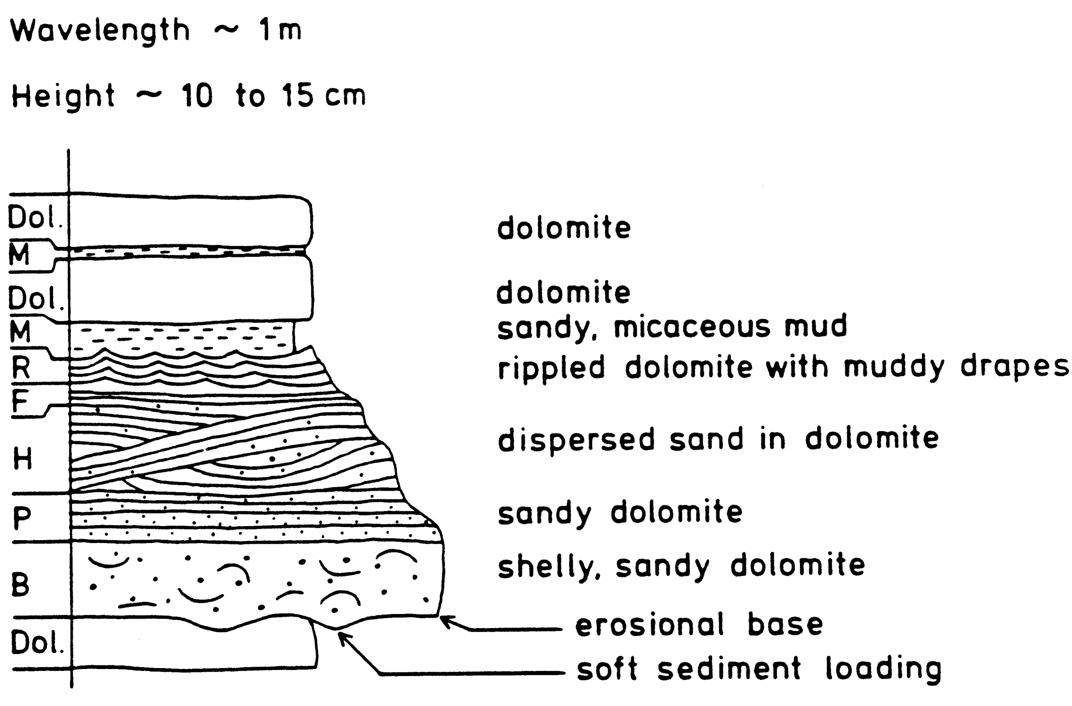

Fig. 3. Schematic representation of a hummocky cross-stratified unit. Dol. = parallel bedded dolostone, B = basal division, P = parallel laminated division, H = hummocky cross-stratified division, F = flat laminated division, X = ripple laminated division, M = muddy division.

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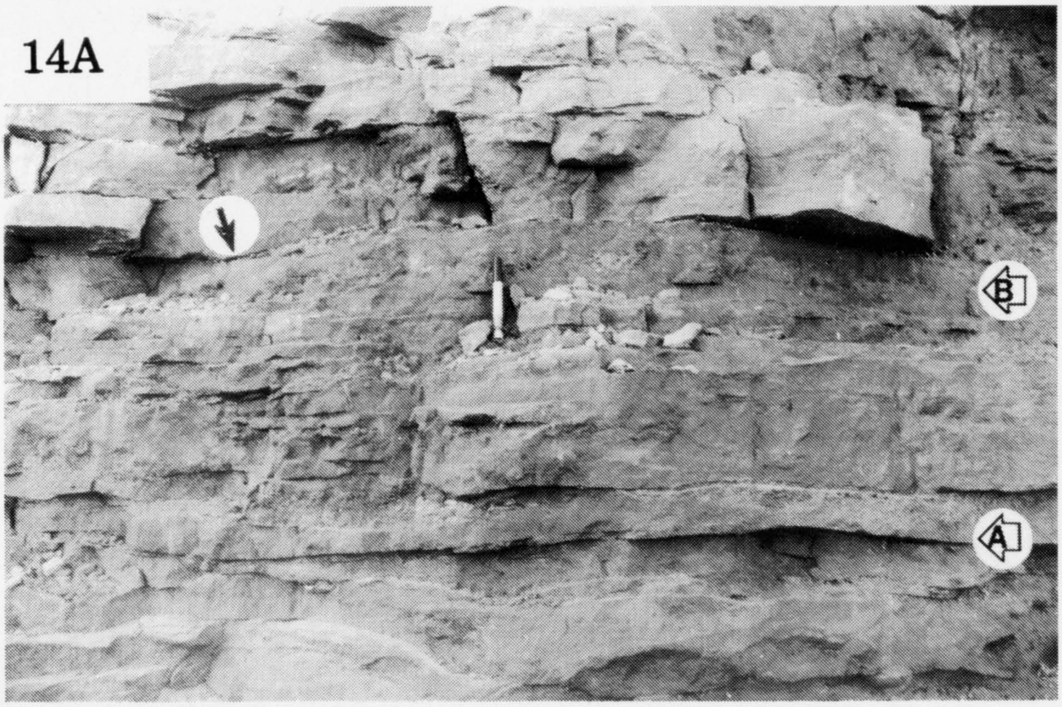
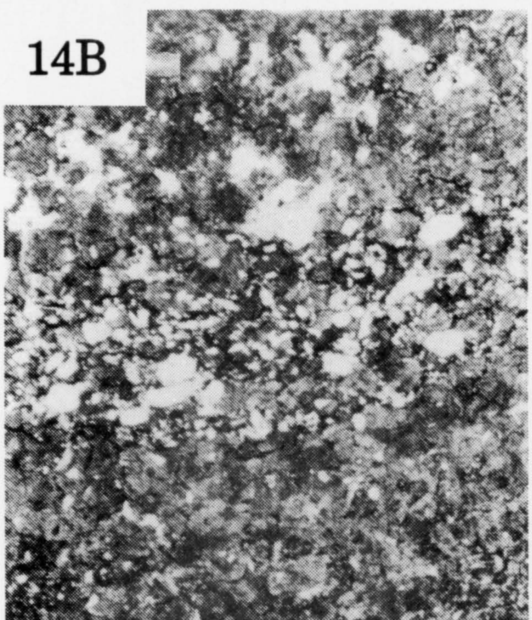


Plate 14A. Photograph of horizon B (Fig. 2) illustrating a well developed hummock at the level of the marker pen (length 145 mm). Note shell debris in the lower part of the hummock and reworking of material from the crest of the hummock into the swale (arrowed).



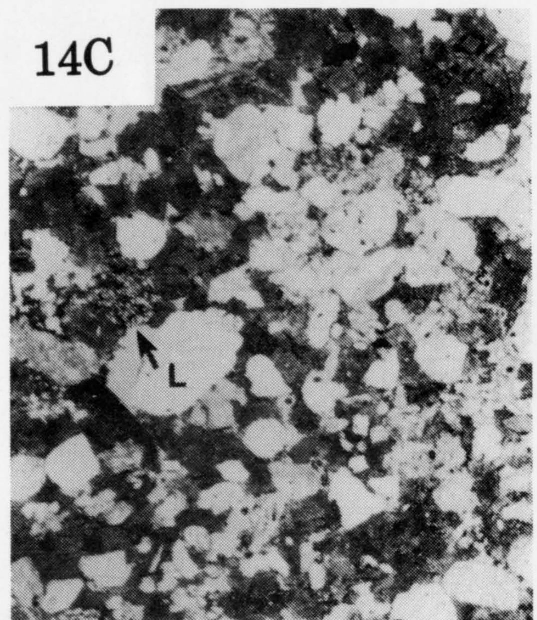


Plate 14B. Photogicrograph of an oriented thin section prepared from the junction between the basal (B) and parallel laminated (P) divisions of a hummocky cross-stratified unit. Note the dolomitised shell fragments (arrowed) within the dolomite-rich B division (lower half of photograph) and increase in the proportion of quartz present in the overlying P division. Plane polarised light.

Plate 14C. Photomicrograph of an oriented thin section prepared from the parallel laminated division (P) of a hummocky cross-stratified unit. Note the abundant siliciclastic grains, including a lithic fragment (L), some of which possess quartz overgrowths. Dolomitised pelloidal carbonate grains (G) are also discernable as 'ghost' textures.