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The relative roles of tectonism and eustacy in the deposition of the Urswick Limestone in south Cumbria and north Lancashire

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SUMMARY: Tectonically-controlled shoaling cycles occur in Asbian platform limestones in south Cumbria and north Lancashire. These cycles may attain 20 m in thickness, and are interpreted to represent rapid rises in relative sea level. Such rises were probably controlled by subsidence during episodes of platform downfaulting, rather than by gradual subsidence resulting from mechanisms such as thermal sag. The tectonic cycles comprise several smaller units bounded by emergent surfaces. Emergent surfaces are developed on facies representing deep subtidal to supratidal environments, and resulted from temporary glacio-eustatic regressions. The occurrence of similar facies above and below these emergent surfaces suggests that the ice cap that was responsible for the glacio-eustacy was small in size, such that it was completely ablated during interglacials. This would have resulted in similar water depths, and hence facies, before and after emergence. The small ice cap may represent a precursor to the later, major Permo-Carboniferous glaciation.

The Asbian (late Dinantian) Urswick Limestone Formation in south Cumbria and north Lancashire displays a sedimentary cyclicity. It is the purpose of this paper to demonstrate the controls on this cyclicity, and where appropriate, to refine the mechanisms proposed by other workers for cyclic carbonates of similar age elsewhere. Cyclicity in the late Dinantian of northern England was first recognised by Phillips (1836) who described the Yoredale cycles of Yorkshire. Since then many authors have described and suggested mechanisms which may account for the late Dinantian cyclicity which is developed throughout much of northern Europe and North America (reviewed in Walkden 1987). In the Asbian, the controlling mechanism of cyclicity in platform limestones has been variously attributed to eustatic processes (Ramsbottom 1973, 1979, 1981), tectonic control (Davies 1983), or interplay of tectonism, eustacy and sedimentary progradation (Somerville 1979a, b; Gray 1981; Berry 1984; Walkden 1987).

Two scales of cycles occur in the Urswick Limestone. Firstly, there are minor cycles, whose upper and lower boundaries are defined by emergent surfaces. Secondly, there are major cycles which comprise a sequence of minor cycles in which the marine sediments between emergent surfaces appear to be continuous as part of a upwards-shoaling (progradational) sequence, such that the emergent surfaces appear to merely 'punctuate' the shoaling sequence. It is important to note that these major and minor cycles do not correspond to those of Ramsbottom (1973).

In order to interpret this cyclicity it is necessary to describe the geological setting and interpret the depositional environments of the Urswick Limestone. Following this is a full description of the cyclicity, a review of possible mechanisms which may account for sedimentary cyclicity, then an interpretation of both the major and minor cycles. Finally, evolution of cycle styles during deposition of the Urswick Limestone and the relationship of the observed cyclicity to that proposed by other workers for Asbian cycles is described. The resulting depositional model uses regional controls to explain similarities with the other platforms and local factors to explain differences. For the purposes of this paper, sea level positions and changes are referred to as 'highstand', 'lowstand', 'transgression' and 'regression', whilst sedimentary trends are described as 'progradational', 'shoaling', etc.

1. GEOLOGICAL SETTING

The Urswick Limestone outcrops in south Cumbria and north Lancashire (Fig 1, 2). It is divided into a lower and upper part, corresponding to the early and late Asbian (Fig. 3). These attain a maximum thickness of 50 and 100 m respectively. The Urswick Limestone represents a shallow water carbonate platform grading laterally into platform margin and basinal environments in the vicinity of Carnforth and Lancaster respectively (Fig. 2). The platform onlaps an end-Holkerian unconformity with 25 m of relief, which represents a considerable non-sequence (Strank 1981).

The structural unit on which the Urswick Limestone was deposited is referred to as the southern part of the Lake District High (SLDH), after the terminology of Grayson and Oldham (1987). This high was essentially flat-lying during the Asbian, and is probably bounded by the Haverigg Fault to the west, the Kendal Fault and Lancaster Fells Basin to the east (Fig. 2), whilst to the

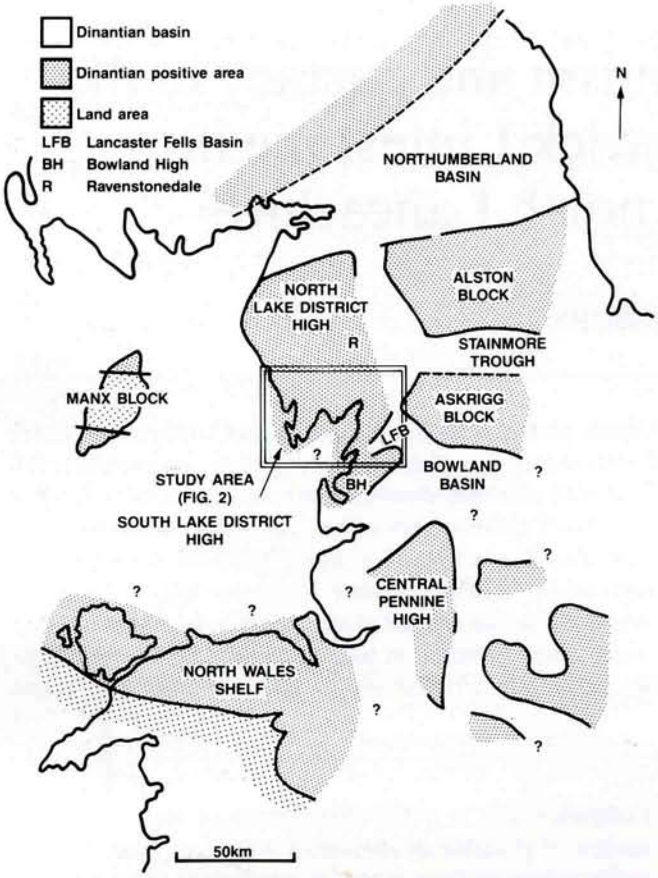

Fig. 1. Palaeogeography of northern England and Wales during the late Asbian, showing the location of the area studied. After Gawthorpe *et al.* (this volume).

north and south the boundaries are undefined because of erosion or cover by a thick Permo-Triassic sequence. The only evidence of differential tectonic movement across the high during the Asbian is suggested by the development of a thin sequence in Furness in the early part of the late Asbian, e.g. Stainton Quarry (Fig. 3). This suggests that the SLDH was structurally homogenous and relatively stable. It is probable that by the late Asbian the carbonate platform was continuous with the cyclic limestones described from north Cumbria (Shackleton 1978). To the south a westwards continuation of the structural archipelago of small half-grabens that occur between the Askrigg Block and St. George's Land is likely (Lee 1988). Asbian sediments in the Isle of Man demonstrate platform margin, lagoonal and nearshore facies, all of which are in close proximity with basement rocks which were emergent throughout the Asbian (Dickson & Barber 1976, Dickson *et al.* 1987). Relationships of sediment to basement therefore appear to be complex westwards of the SLDH. The Ravenstonedale Gulf of George (1958) probably did not continue northwards from the Lancaster Fells Basin, since platform sediments occur between the Kendal and Dent-Craven faults which separate the SLDH from the Askrigg Block (Fig. 1). The Asbian age Garsdale Limestone and Danny Bridge Limestone along the line of the Dent Fault are also both of shallow water facies (Burgess 1986). As part of a large granite-buoyed high (see Bott (1978) for a review), the SLDH occupies a central position within the belt of Manx-Cumbria-

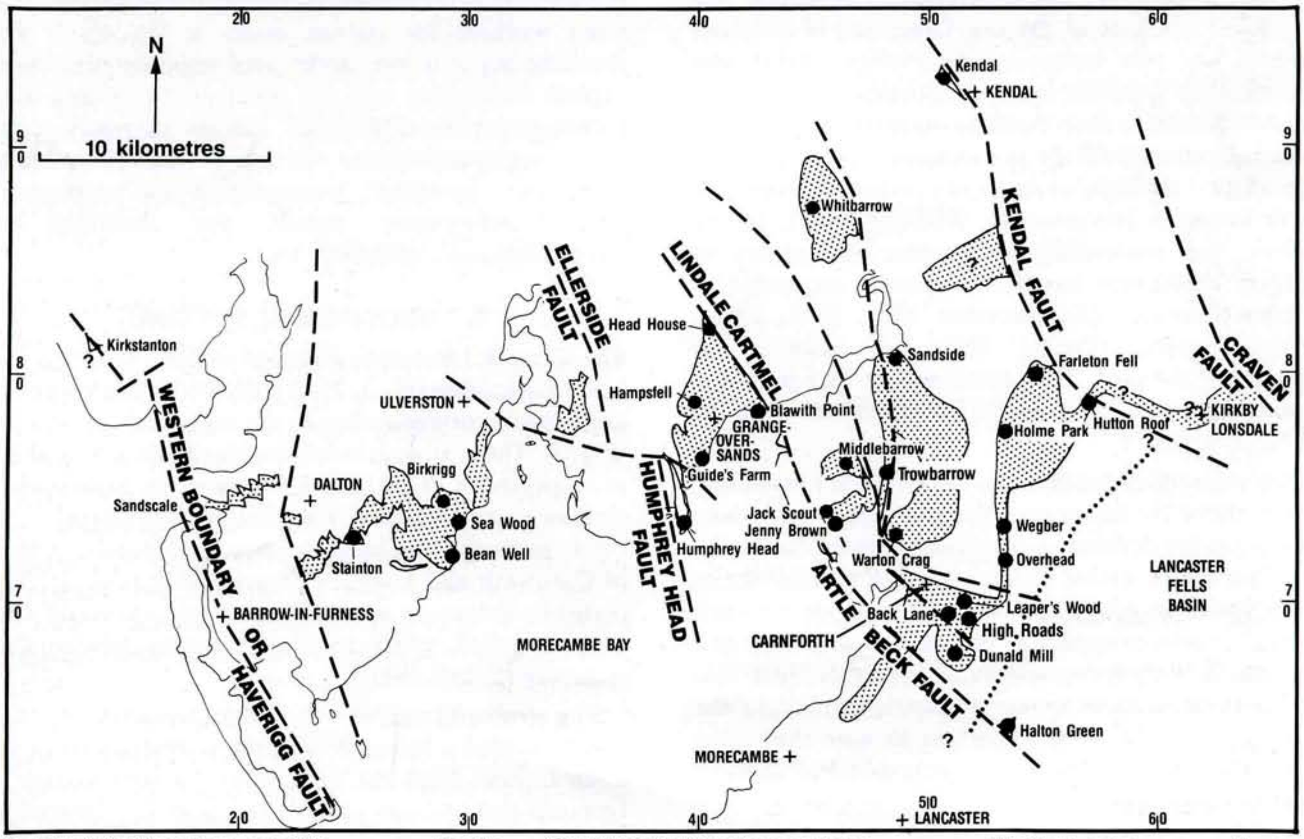

Fig. 2. Location map, showing the outcrop of Urswick Limestone, major faults and the position of the platform edge. Data from field observations, Garwood (1913), Moseley (1972), Rose & Dunham (1977) and Soper & Moseley (1978).

Alston-Askrigg 'highs' which contrast markedly with the smaller structural units immediately to the south, and the much larger landmasses of St. George's Land and the Southern Uplands.

Larger-scale palaeogeographical and tectonic settings of the British Carboniferous stages are the subject of continued debate. Dinantian carbonate platform sequences were interpreted by Ramsbottom (1973) as representing a series of eustatically-controlled transgressions. However, Ramsbottom considered that these transgressions affected an essentially pre-existing topography (1981, p.476), and that tectonic effects were of only local importance. Many of these conclusions were questioned by George (1978), who stressed the role of tectonism, such as demonstrated since by Miller & Grayson (1982), Gawthorpe & Clemmey (1985), Gawthorpe (1986, 1987), Gutteridge (1987) and Gawthorpe *et al.* (this volume). A long-term series of eustatic transgressions could only have developed in response to changes in the volumes of ocean basins, essentially a function of variation in the volume of ocean ridges (Donovan and Jones 1979). Such changes produce a theoretical maximum rate of transgression of 10 m sea level rise per million years (Pitman 1978). Assuming Leeder & McMahon's (1988) figure of 9 Ma for the Asbian and Brigantian, this would result in a maximum sea level rise of 90 m, an insufficient rise to account for the deposition of all 150 m of the Urswick Limestone and the 80 m thick Gleaston Formation. Since Ramsbottom's work, large scale palaeogeographical reconstructions have suggested that regional syn-sedimentary subsidence controlled by plate tectonic processes was responsible for the Carboniferous 'transgressions'. The mechanism of plate tectonic control is controversial, e.g. dextral megashear (Dewey 1982), north-south extension associated with slab pull (Johnson 1982; Bott 1987), or rift-to-sag as a consequence to subduction (Leeder 1982, 1987) and east-west rifting in response to the opening of the proto-Atlantic (Haszeldine 1984) have all been proposed. It is therefore likely that the Urswick Limestone accumulated in response to active subsidence and, to a lesser degree, sediment loading and compaction.

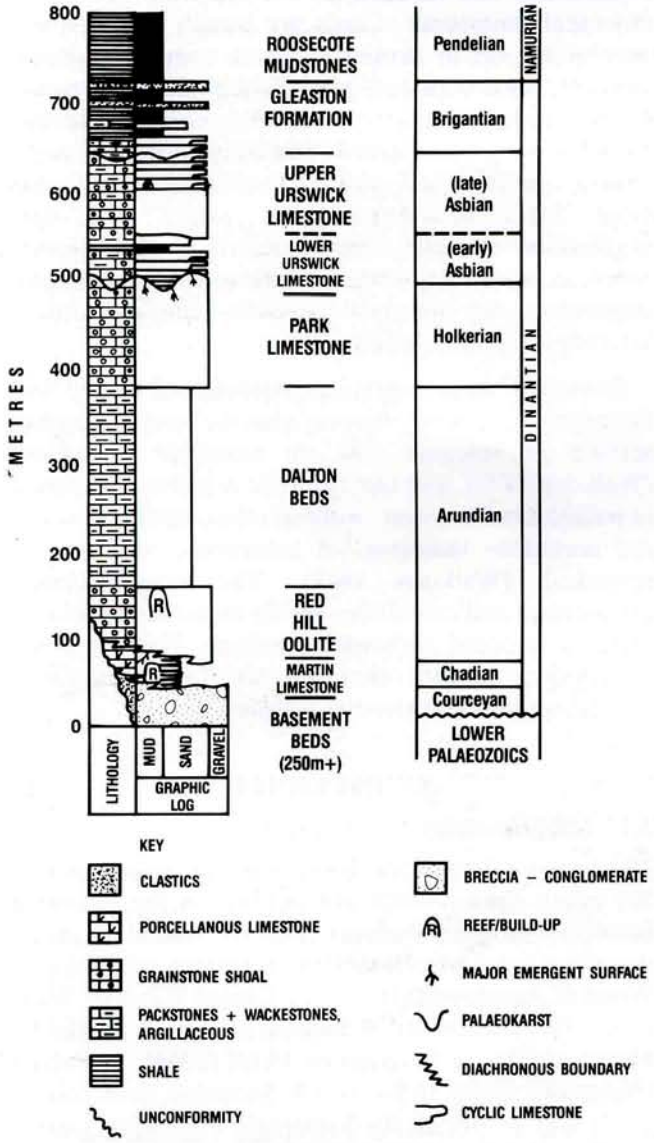

Fig. 3. Lower Carboniferous stratigraphy in South Cumbria. Data from field observations, Rose & Dunham (1977) and Vaughan & Adams (1984).

2. FACIES AND ENVIRONMENTS OF DEPOSITION

The Urswick Limestone comprises four facies:

1. Sub-fair weather wavebase mudstones-packstones
2. Shoal grainstones
3. Intertidal/supratidal mudstones-wackestones
4. Terrigenous siliciclastic and carbonate clastics

2.1. Facies 1 — Sub-fair weather wavebase mudstones-packstones

This facies ('sub-wavebase facies') is characterised by a high detrital clay content and a packstone to mudstone fabric, in which the original lime mud is now preserved mostly as microsparry-pseudosparry calcite with crystals up to 100 μm in diameter. A combination of dark coloured detrital clays, a relatively high organic content and dark grey microsparry calcite infilling *Thalassinoides* burrows results in a dark colour in fresh exposures (Fig. 4a). Beds are typically 0.1 to 1 m thick. The *Thalassinoides* burrows often impart a rubbly appearance. Macrofossils in growth position are common (Fig. 4a) and include *Lithostrotion, Syringopora,* rugose corals, articulated and unabraded productoids, *Straparollus*, and occasional trilobites. Characteristic microfossils include sponge spicules, *Saccamminopsis,* bryozoans, and the algae *Coelosporella, Stacheoides* and *Kamaena* (Fig. 4b).

The presence of carbonate and siliciclastic fines, diverse open marine faunas and floras often in growth position and abundant bioturbation indicate sub-wavebase environments. Water depths were probably in the order of tens of metres by analogy with modern sediments in the Persian Gulf (Wagner & Togt 1973).

However, in protected settings water depths may have been no more than 1 or 2 m. Occasional restriction is indicated by a decrease in the abundance of foraminifera, calcispheres and macrofossils.

2.2 Facies 2 — Shoal grainstones

The shoal grainstone facies is characterised by the absence of depositional lime and terrigenous mud and is typically pale brown in colour, thickly (<10m) bedded and massive with a blocky fracture (Fig. 4c). Macrofossils in growth position are uncommon, but include occasional *Lithostrotion* and *Syringopora,* encrustations of *Chaetetes,* locally developed concentrations of *Davidsonina septosa* and other productoids. The grainstones rarely possess sedimentary structures and little bioturbation is apparent; this may reflect the well sorted nature of the sediment. Allochems include abundant peloids, occasional intraclasts and ooids (Fig. 4d), whilst the alga *Kamaenella* dominates the bioclastic component (Fig. 4e). Other characteristic algae are *Koninckopora, Ungdarella, Polymorphocodium* fragments and *Girvanella,* which binds and encrusts sediment. Isopachous prismatic, microsparry and micritic cements (Fig. 4d) of probable marine origin lithify grainstones locally, as around Carnforth and at Stainton (Fig. 2).

The absence of depositional fines, scarcity of macrofossils in growth position, abrasion of allochems, presence of early marine cements binding the sediment and lithifying intraclasts, all suggest an intertidal to shallow subtidal high energy, probably wave dominated (Horbury 1987) grainstone shoal complex. Similar modern shoal sediments in the Persian Gulf were described by Purser (1973a). It is possible to differentiate this facies into:

i) Platform-edge and nearshore shoals with abundant large peloids, intraclasts, oids and early marine cements (Fig. 4d),
ii) Medium to fine grained peloid-bioclastic grainstones more characteristic of lower energy shallow lagoonal environments (Fig. 4e).

2.3 Facies 3 — Intertidal/supratidal mudstones-wackestones

Mudstones and wackestones of this facies ('intertidal-supratidal facies') possess a characteristic conchoidal fracture, and occur as single beds up to 0.4 m thick. Bed colour varies from pale to dark brown. Macrofossils in growth position are uncommon, and comprise thick-shelled gastropods and large articulated bivalves. *Chaetetes,* productoids and corals are found as rolled, abraded and micritised fragments. Thin stromatolites (Fig. 4f) and oncoids represent the indigenous flora. Fenestrae, desiccation fractures and root moulds are occasionally developed (Fig. 5a), and are sometimes filled with internal sediments. Microfossils are scarce, and microfabrics are commonly faintly peloidal (Fig. 5a).

The restricted fauna and flora, low diversities of allochems in growth position, sedimentary structures such as fenestrae, desiccation fractures and intraclasts, all suggest an intertidal low energy to supratidal environment. Similar modern intertidal and supratidal sediments have been described from Florida and the Bahamas by Shinn (1983).

2.4 Facies 4 — Terrigenous siliciclastic and carbonate clastics

A great variety of terrigenous deposits occur, and fall into two broad sub-facies: i. Siliciclastic mudstones and ii. Carbonates.

The siliciclastic mudstone subfacies consist of multicoloured K-bentonite clays overlying mammilated palaeokarstic surfaces (Fig. 4c), below which rhizocretions, laminar calcrete and alveolar textures occur (Figs. 5b,c).

The carbonate subfacies consist of conglomerates, calcarenites and calcisilitites derived from erosion of emergent limestones. Clasts are usually rounded and may attain 4m in diameter. These comprise laminar calcrete, clasts with pedogenic fabrics, abraded marine fossils, reworked fragments of *Thalassinoides* burrows from sub-wavebase facies 1, and clasts of facies 2 and 3 shoal grainstones and intertidal/supratidal porcellanites (Fig. 5d). Finely-comminuted calcite and dark argillaceous material occur as matrix or as a discrete lithology. These deposits preferentially fill topographic depressions on emergent surfaces, and are usually laterally discontinuous (Fig. 5e).

Bentonite clays overlying palaeokarsts in the late Dinantian have been interpreted as the result of gradual settling of volcanic dust on emergent limestones (Walkden 1972), and represent the regolith component of palaeosols. However, without other criteria the clays are unreliable indicators of emergence and may be reworked (Walkden 1987). The conglomerates, calcarenites and calcisiltites testify to surficial drainage over the exposed carbonate platform. These deposits always associate with other evidence of emergence such as rhizocretions and alveolar textures.

3. CYCLICITY

3.1 Minor cyclicity

The Urswick Limestone is divided into numerous (20-30) minor cycles which are defined as the sediment between emergent surfaces (Fig. 6), similar to cycles described from late Dinantian sediments in Alaska by Wood & Armstrong (1975), the United States by Walls *et al.* (1975), Harrison & Steinen (1977), in France by Hoyez (1971), in Belgium by Pirlet (1964), in Poland (Skompski, 1984), in Siberia (R. Swennen, pers. comm. 1987) and in Britain by Somerville (1979a,b), Davies (1984), Walkden (1987) and Ramsay (this volume). Within any given locality the majority of emergent surfaces demonstrate an undulose mammilated relief of

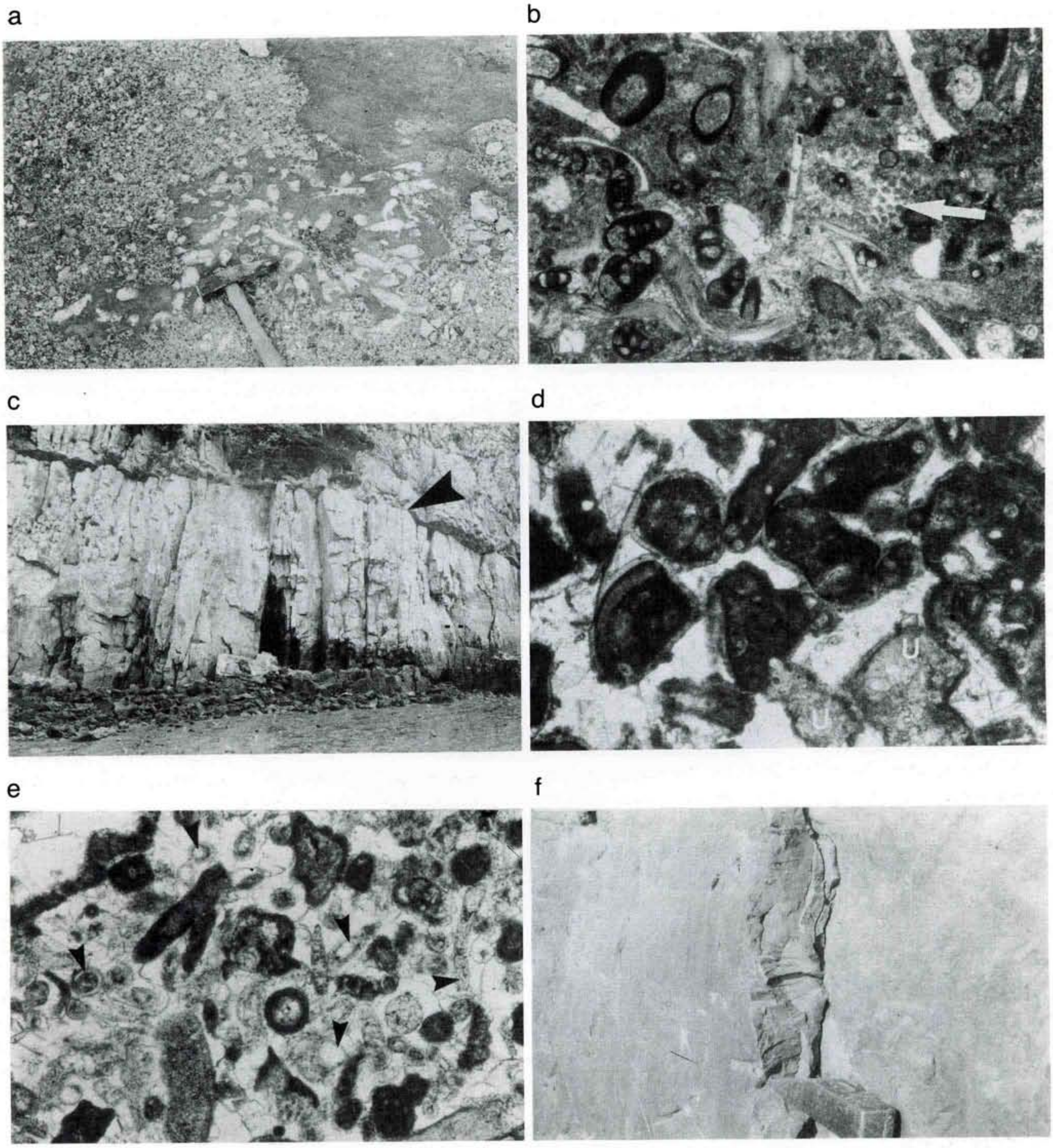

Fig. 4. a. Dark packstones and wackestones of facies 1 and a rugose coral colony in growth position. Hammer for scale. Lower Urswick Limestone, Holme Park Quarry. b. Facies 1 displaying a diverse biota of foraminifera, bivalve moulds, bryozoans, ostracods, calcispheres and the alga *Coelosporella* (arrowed) in a packstone texture. Field of view is 6.5 mm. Specimen from the upper Urswick Limestone, Back Lane Quarry. c. Blocky weathering, pale massive grainstones of facies 2. A prominent emergent surface occurs below the vegetation (arrowed); the massive bed below is 11 m thick. Upper Urswick Limestone, Jack Scout Cove. d. Medium grained grainstone facies 2. Most allochems are micritised foraminifera, peloids or intraclasts. Some robust algae (*Ungdarella*, u) occur. An isopachous marine cement is developed around each grain. Field of view 6.5 mm. Specimen from the upper Urswick Limestone, Dunald Mill Quarry. e. Medium-fine grained grainstone of facies 2. The dominant bioclast is the alga *Kamaenella* (arrowed), other grains are crinoid ossicles, foraminifera and occasional peloids. Note the preservation of *Kamaenella* and the lack of micritisation compared with 4e. Field of view is 1.25 mm. Specimen from the lower Urswick Limestone, Kendal. f. Stromatolite of facies 3 to the left of the hammer, which thickens and thins according to the topography on which it grew and the style of algal accretion. The overlying bed is an oolitic grainstone; this sequence represents a rare transgressive deposit. Upper Urswick Limestone, Trowbarrow Quarry.

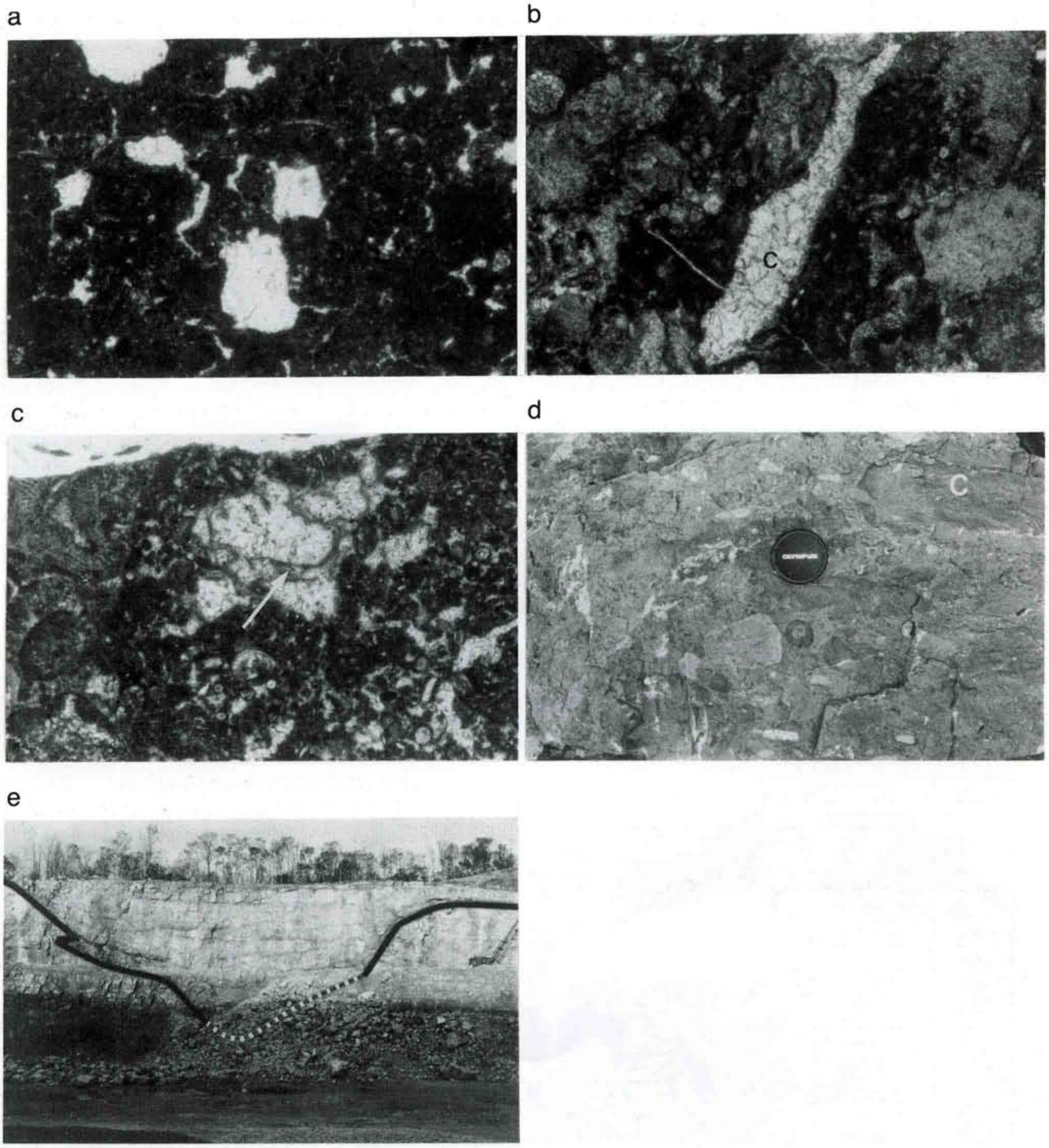

Fig. 5. a. Fenestrae, desiccation cracks and faintly peloidal textures in facies 3 porcellanous mudstone. Field of view 6.5 mm. Specimen from the upper Urswick Limestone, Stainton Quarry. b. Rhizocretion with a central sparry calcite-filled cavity (c) and micritic walls in a sub-wavebase packstone-wackestone of facies 1. Field of view is 6.5 mm. Specimen from 19 m below top of the lower Urswick Limestone at Leaper's Wood Quarry. c. Alveolar texture (arrowed) filling a cavity in sub-wavebase wackestone of facies 1. Same specimen and scale as 5b. d. The conglomerate forms the base of the section at Dunald Mill Quarry, and probably represents a fan deposit associated with multiple emergence and erosion at the end of the early Asbian. The dark clasts are reworked *Thalassinoides* facies 1 whilst the paler clasts are derived from facies 2 and 3. A large clast (c) is a reworked fragment of laminar calcrete. Lens cap for scale. e. Large valley (outlined) incised down from an emergent surface 11 m below the top of the lower Urswick Limestone at Leaper's Wood Quarry. The valley is 26 m deep, and contains an infill of sediments which were not developed on the emergent surface from which it incised.

up to 2 m. This amplitude and the cycle thicknesses remain relatively constant within the locality. Minor cycle thicknesses are typically in the order of 4-5 m, although this varies through the succession such that the total range is 0.2-15 m. Cycles vary in thickness gradually between localities, and for this reason individual cycles cannot reliably be correlated. These thickness variations are thought to reflect only minor erosion and dissolution of a subaerially exposed but already undulose sea-bed, since the karst morphology, scarcity of solution cavities on a micro and macro scale, and the presence of rhizocretions and laminar calcrete suggest that the depth of karstification was probably limited to the 1-2m relief on the surfaces (Horbury 1987). Within minor cycles, facies usually demonstrate an upwards shoaling. Emergent surfaces may be developed on all the marine facies (1 to 3), (Figs 5b,c, 6, 7). The emergent surfaces that bound and define the minor cycles sometimes display evidence of deep, localised incisions, which may cut down through several minor cycles. The best developed of these is the valley that attains a maximum depth of 26 m in Leaper's Wood Quarry (Fig. 5e). Shallower valleys up to 8 m in depth occur at other stratigraphical levels (Fig. 7). These valleys represent localised deep karstification down from the low relief mammilated palaeokarst, and appear to have developed where pre-emergence slopes were locally steep, such as in the vicinity of the platform margin.

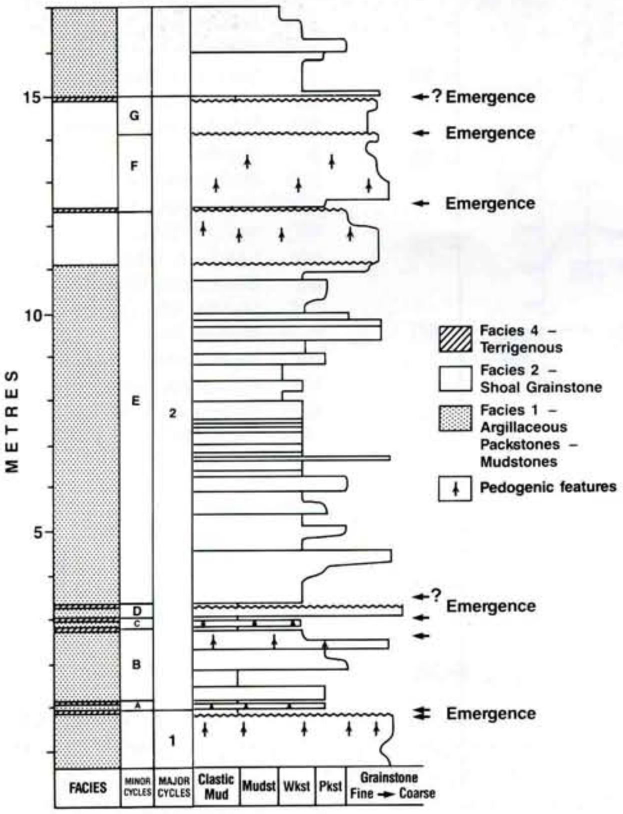

Fig. 6. An example of a major cycle in the lower Urswick Limestone at Stainton Quarry, from 13 to 28 m below the lower-upper Urswick Limestone boundary. This major cycle illustrates the upwards shoaling and constituent minor cycles, with emergent surfaces underlain and overlain by similar facies types.

3.2 Major cyclicity

It is notable that in the upper parts of the lower Urswick Limestone and the upper Urswick Limestone (Fig. 7) several, or parts of several, minor cycles build up into 10-20 m thick 'shoaling' major cycles, which may or may not be capped by an emergent surface (Fig 6, 7). These cycles have sub-wavebase facies 1 bases which grade subtly up into shoal facies 2 at their tops. The emergent surfaces that occur within these major cycles appear to punctuate a particular facies with inferred water depths prior to and post emergence being similar (Fig 6, 7, 8). It is important to note that the development of major cycles has only been recorded from parts of the Urswick Limestone to date. Because of this, the mechanism which accounts for major cycle development must also explain the relevant differences between the Urswick Limestone and sedimentary sequences on other Asbian platforms. In the parts of the Urswick Limestone where major cycles are not developed, thick sequences of minor cycles comprising shoal facies 2 and intertidal/supratidal facies 3 are developed.

3.3 Possible controls on cyclicity

In purely carbonate environments sedimentary cyclicities may develop in response to different types of change in sea level. These include:

1. Gradual relative rise in sea level due to long-term eustatic processes, e.g. due to increases in mid ocean ridge volumes (Donovan & Jones 1979). Cyclicity should comprise diachronous progradational units that climb in a piggy-back fashion in the direction of progradation as described from the modern Bahamas by Strasser & Davaud (1986). Such cycles may be developed globally under ideal conditions.
2. Gradual relative rise in sea level due to slow platform subsidence. Cyclicity would be developed as in 1, but it would be confined to the parts of plates that were subsiding, probably in relatively localised belts. Examples of cycles attributed to this mechanism have been described by Berry (1984) and Skompski (1984).
3. Rapid fluctuations in sea level, due to eustatic processes. Such sea level changes are usually glacially controlled (Donovan & Jones 1979, Read *et al.* 1986) with rapid transgressions during ice cap ablation and somewhat slower regressions during ice cap growth (Hays *et al.* 1976, Evans 1979). Carbonate cycles are typically terminated by well-developed palaeokarst with evidence of an actual fall in sea-level (Read *et al.* 1986). Cycle thicknesses are determined by the amplitude of the sea level fluctuations (Read *et al.* 1986), and the duration of sea level high stands. If transgressions are rapid and amplitudes are large incipient platform drowning

may occur (Schlager 1981, Read *et al.* 1986). This is because there is a lag time during transgression when carbonate sedimentation rates cannot keep pace with the rate of relative sea-level rise (Schlager 1981), and the initial sediments reflect the rapidly established deep water environment (Evans 1979, Read *et al.* 1986). Low amplitude fluctuations and those with slower transgressions produce shallower water cycles in which sedimentation rates either keep up with relative sea level rise or the sediment/water interface is always above wavebase (Read *et al.* 1986).

If sea level fluctuations are frequent, and regressions are rapid, sediment may not build up to the intertidal-supratidal zone before regressions expose the sediment (Read *et al.* 1986). This may result in exposure surfaces developed on sub-wavebase facies, as demonstrated by Hardie *et al.*

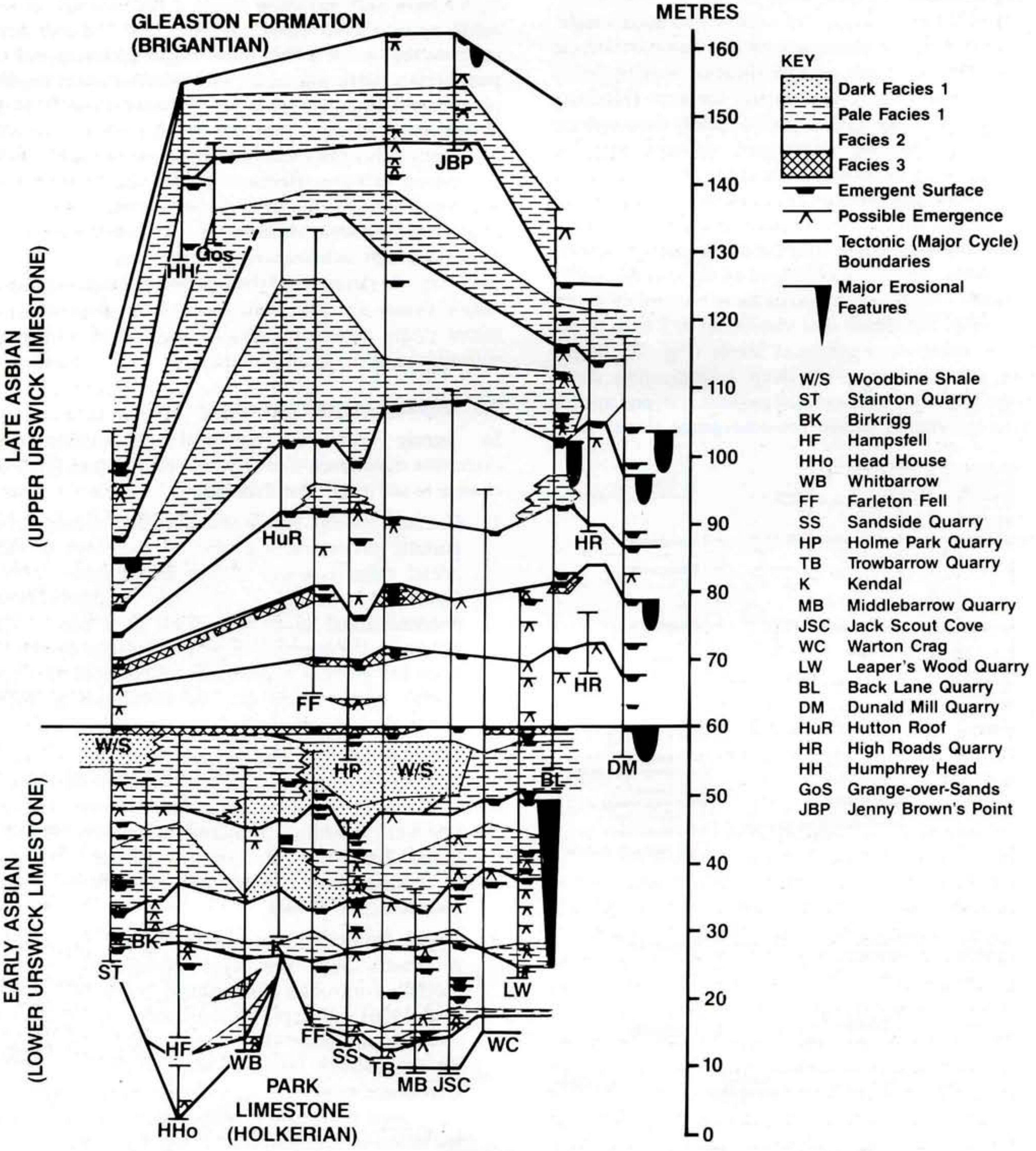

Fig. 7. Cross-section through the Urswick Limestone. The occurrence of numerous emergent surfaces developed on all facies types, the presence of platform-wide major cycles and the development of localised major erosional features are all evident. Also note the onlap and relief on the basal unconformity, and the thinning of the Urswick Limestone towards Stainton Quarry.

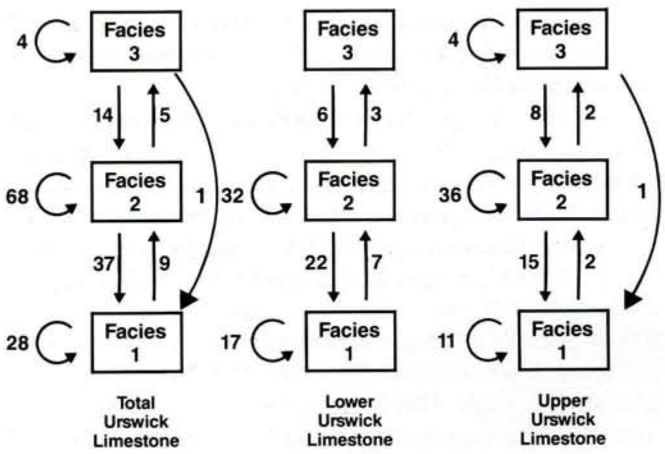

Fig. 8. Flow diagram of facies changes over emergent surfaces. Of the 166 recorded emergent surfaces, 100 were underlain and overlain by the same facies. Fourteen were overlain by shallower water facies, whilst 52 were overlain by deeper water facies; the latter are usually tectonic cycle boundaries. A lower percentage of exposure surfaces are developed on facies 1 in the upper compared with the lower Urswick Limestone (16 percent versus 27).

(1986). The eustatic control on these cycles dictates that they should occur over very large areas.

4. Rapid sea level fluctuations caused by tectonic effects. Four types of tectonic control on cyclicity have been described, although only mechanism i) has actually been tested in neotectonic areas.

i) The first type occurs where isostatic unloading of fault footwall blocks during extension causes uplift of the footwall block (Jackson & McKenzie 1983; Cisne 1986; Barr 1987) on which platform margins frequently develop (Leeder & Gawthorpe 1987). These rises of the footwall (rapid shallowing of the water) are interspersed with periods of subsidence during which there is no movement on the controlling fault, when sedimentation rates may or may not keep pace with subsidence. These cycles may therefore be deepening — upwards (rapid subsidence) or shoal dominated (slow subsidence), both with obvious emergent surfaces as a consequence of footwall uplift. Cisne (1986) accounted for Fischer's (1964) deepening-up Lofer cycles by footwall uplift, and Leeder & Gawthorpe (1987) proposed that periodic footwall uplift may produce a sedimentary cyclicity. Such cycles are localised to the vicinity of the controlling fault.

ii) The second type of cycle may develop where the whole platform is undergoing pulsed subsidence controlled by episodic movement on faults that bound the platform, as reviewed in Schlager (1981). During quiescent periods following faulting, these cycles may develop basal sub-wavebase facies if the subsidence was fast, and will demonstrate upwards-shoaling sequences as the sedimentation rates increase. The thicknesses of these cycles and thicknesses of sub-wavebase facies will depend on the magnitude of downfaulting. Their lateral extent will depend on the size of the structural unit being downfaulted. Because these cycles develop only in response to relative rises in sea level, evidence of sea-level fall will be lacking and these cycles will not necessarily be terminated by well developed emergent surfaces.

iii) The third mechanism is slab-pull controlled subsidence, which has been suggested to account for Yoredale-type cyclicity (Bott 1987). Such subsidence would only be developed in a setting where the carbonate platform was on the subducting lithospheric plate, and is of large scale in terms of amplitude, frequency and areal extent. Like the pulsed, boundary-fault controlled subsidence described above, slab-pull cycles would probably shoal upwards and well developed emergent surfaces would not necessarily occur on their tops.

iv) Lastly, Officer & Drake (1986) suggested that epeirogenic uplift and subsidence of continental cratons could account for many ancient sedimentary cycles. However, their conclusions were based on measuring rapid recent rates of subsidence and comparing these to slower rates during the Quaternary, and extrapolating these data into a cyclic pattern. As pointed out by Sahagian (1987), recent rates of subsidence cannot be used as a guide to epeirogeny where the rates are determined from passive continental margin coastal settings, as Officer & Drake's (1986) data were, principally because nearsurface sediment compaction overprints epeirogenic effects. This suggests that epeirogenic effects as a control on cyclic sea level changes cannot reliably be detected. Epeirogenic subsidence is a feature of continental cratons, and is therefore unlikely to be of significance in less stable, tectonically active and structurally heterogenous areas such as the British Dinantian.

5. Both isostacy and sediment compaction may account for relative rises in sea level where the sediment pile is already thick. However, these settings are unlikely to occur in Dinantian platform carbonates because these carbonate platforms are rarely more than a few hundred metres thick (Grayson & Oldham 1987). Any cycles developed by this mechanism would probably be sedimentary in origin, comprising diachronous progradational units as in long-term eustatic processes (Section 3.3.1).

3.4 Interpretation of the cyclicity

3.4.1 Minor cyclicity

Control on cyclicity. Rapid rises and falls in sea level are suggested by emergent features developed on the sub-wavebase facies 1, the presence of deeply incised emergent surfaces that developed during regressive phases, and by the paucity of sediments deposited during transgressions or regressions. The development of emergent surfaces of a similar type worldwide also suggests that controls on emergence were related to global events, the only suitable mechanism being glacio-eustatic fluctuations in sea level. Early Carboniferous glacial sediments are known from central South America (Crowell 1978), and were interpreted by Smith *et al.* (1973) to represent small 'Alpine' glacier systems.

Sea levels after a transgression were at approximately the same height as before the preceding regression (Fig. 9), suggested by the similarity of facies below and above emergent surfaces (Figs 6-8). Such a regular datum for sea-level during marine deposition would not be expected if the amplitudes of eustatic events were similar to the glacio-eustatic sea level changes observed in the Pleistocene, were both transgressions and regressions were irregular in magnitude (Vail *et al.* 1977, Imbrie *et al.* 1984, Meischner *et al.* 1986). This may be because the Dinantian ice caps were small, which limited the maximum amount of ice available for melting during interglacials and hence maximum sea levels were constant relative to datum assuming that the ice cap melted completely. A small Dinantian 'Alpine' ice cap accords closely with the conclusions of Smith *et al.* (1973), and Walkden's (1987) comments that the magnitude of Dinantian glacio-eustatic sea level changes were in the order of tens of metres, approximately one order of magnitude less than those of the Pleistocene. The maximum size of such an ice cap might have been approximately the same as the ice caps developed over Antarctica and Greenland today, which if melted would result in 40-55 m rise in sea level (Donovan & Jones 1979, Sahagian 1987). Small ice caps may precede and follow periods of major continental glaciations such as the Late Carboniferous/Permian and the Pleistocene glaciations. Ingle (1981) recorded such a 3 Ma long 'cool-down' phase during the early to middle Miocene, whilst the Antarctic ice-cap built up. Mathematical modelling suggests that such small ice-caps can exist, although they are inherently unstable (North & Crowley 1985).

Mechanisms controlling glaciation. Periods of major glaciations such as during the Permo-Carboniferous and Pleistocene are thought to be initiated principally by positioning of continental masses over the poles, and by continents encircling polar seas (Crowell & Frakes 1970, Frakes 1979, Donovan & Jones 1979, Crowell 1982,

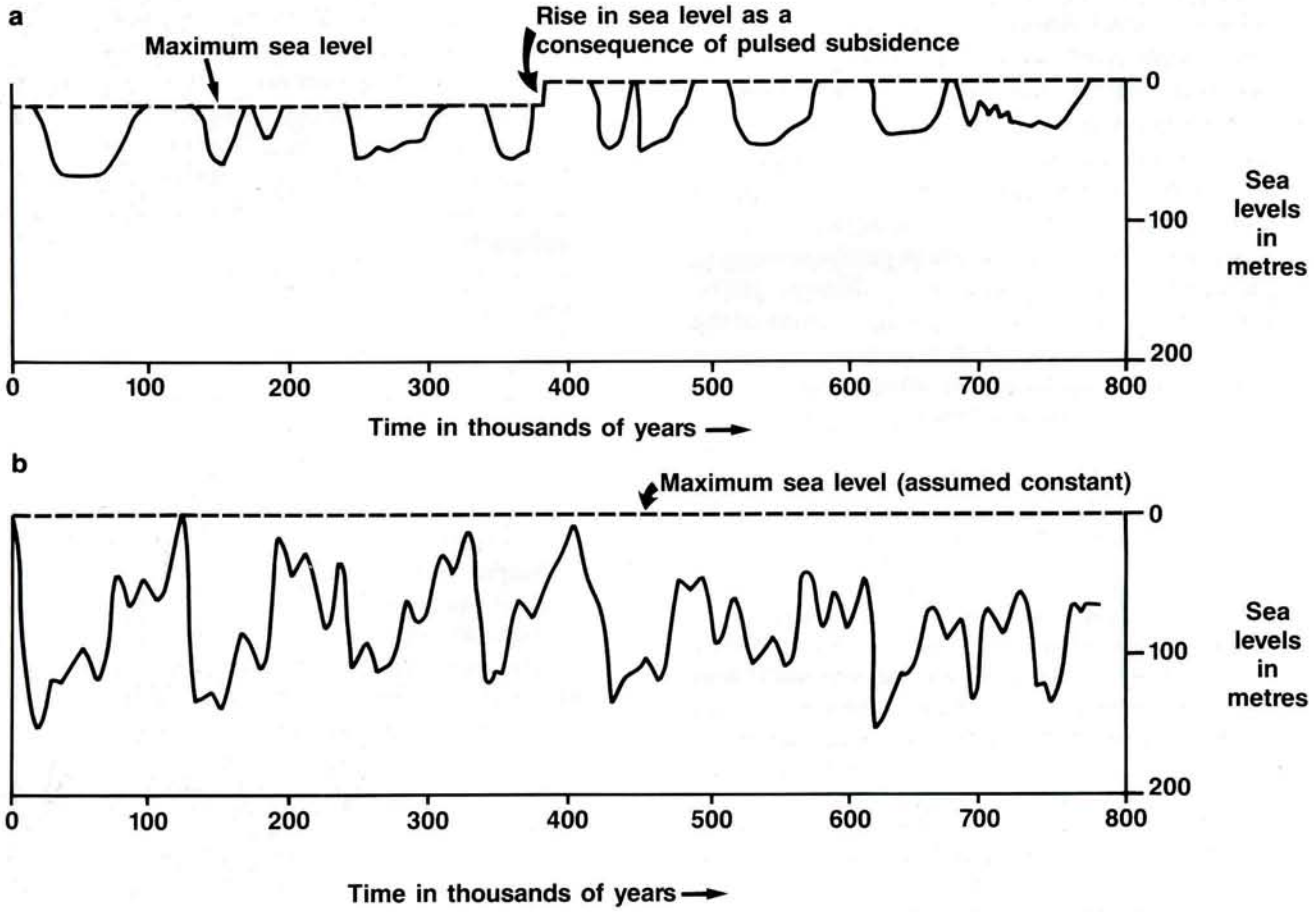

Fig. 9. a. Schematic sea level changes in the Asbian, as suggested by the Urswick Limestone. Note the low amplitude (30-50 m) and the similar maxima of all major transgressions. Pulsed subsidence results in a permanent rise in the maxima of major transgressions. b. Pleistocene sea level changes, after Imbrie *et al.* 1984. Note the greater amplitude of sea level changes (up to 150 m) than in the Asbian, and also that the maximum sea level is rarely attained by transgressions.

Imbrie 1985). Land was present over the South Pole throughout the Carboniferous (Fig. 10), during which time there was a steady southwards drift of Gondwanaland such that by the Permian much of the globe's surface within 60°S was continental. Crowell & Frakes (1970) and Hallam (1985) listed objections to a purely continent-positioning mechanism for initiating major periods of glaciation, because the Mesozoic record suggests that the south pole was over Gondwanaland during both the Permian and Triassic, although major continental glaciations are only known from the Permian. Therefore other glacial forcing factors are probably important, such as north-south continent alignment forcing ocean water and atmospheric circulation patterns to rotate in a meridional fashion (Crowell & Frakes 1970), increases in the land areas over the tropics and falls in global sea level (Barron *et al.* 1980), cooling of saline ocean bottom waters (Brass *et al.* 1982), volcanic fluxes associated with plate movement patterns (Imbrie 1985), and variations in atmospheric CO_2, the 'greenhouse effect' (Hallam 1985). Presumably when many of these subtly inter-related factors are combined favourably an ice cap develops over the continent. The size and rate of initial growth of the ice cap was probably dependant on the net glacial forcing influence of all the factors listed above, and it would be reasonable to expect an increase in the effectiveness of this forcing prior to periods of major continental glaciation, as suggested by Ingle (1981). It is also possible that periods of non-major 'Alpine' continental glaciations could have occurred in isolation from major continental glaciations, for example during the early Carboniferous (Smith *et al.* 1973), and in the mid Triassic (Hardie *et al.* 1986).

In conclusion, the minor cycles represent shoaling-upwards of platform sediments. Shoaling was rapidly terminated, frequently prior to sediment building up into the intertidal-supratidal environment, by emergence as a consequence of the growth of small ice

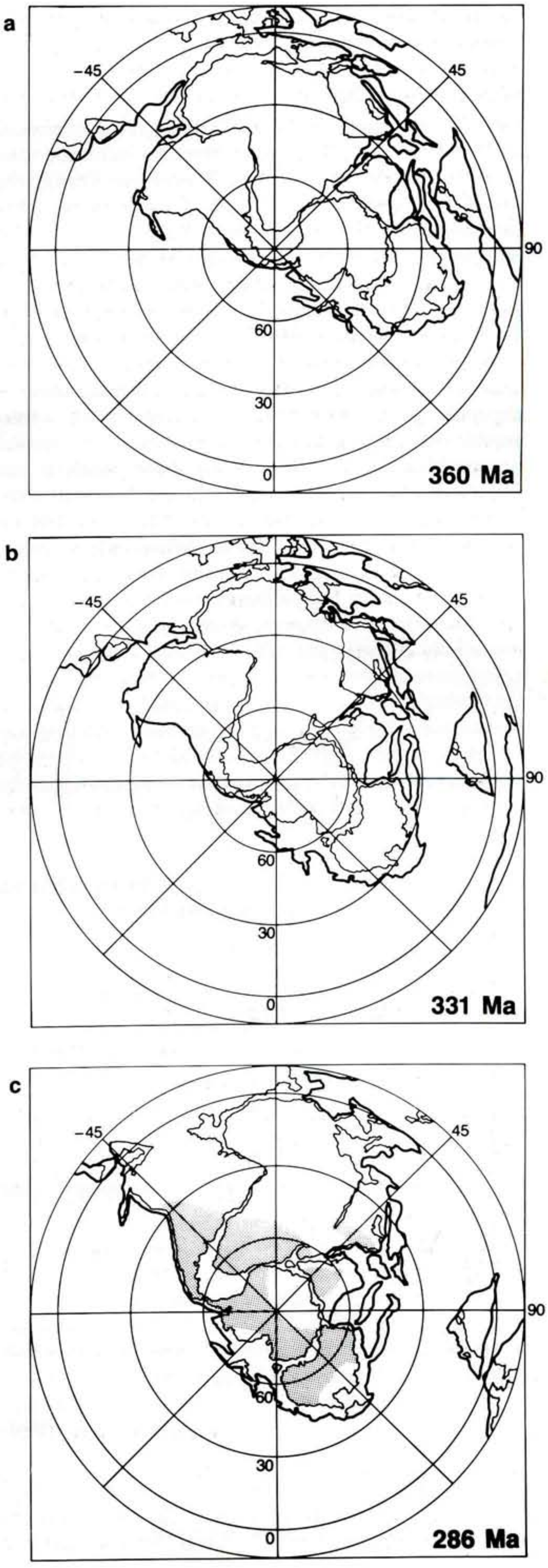

Fig. 10. a. Southern hemisphere continent positions at 360 Ma (Devonian-Carboniferous boundary). Note that there is a considerable area of continent (outlined by the heavy lines) over the south pole, although there are no known glacial sediments or indirect evidence of glaciation from this time. b. Same projection as a, at 331 Ma (Asbian). There is an obvious drift of Gondwanaland over and towards the south pole, with less ocean within 60°S than at 360 Ma. This positioning of the continent would probably fulfil the requirements for ice-cap growth, providing other factors were correct. c. Same projection as a & b, 286 Ma (Carboniferous/Permian boundary). Areas covered by continental ice sheets are stippled. Note that the polewards drift has continued, although the differences between a, b and c are slight. This suggests that continent positioning alone may not be the sole factor in the initiation of the Permo-Carboniferous glaciation.

cap(s) on Gondwanaland prior to the major Permo-Carboniferous glaciation.

3.4.2 Major cyclicity

Major cycles demonstrate an initial rapid transgression, after which rates of sedimentation increased and exceeded the rate of relative sea level rise. During the early Asbian these major cycle transgressions were localised to the SLDH (Southern Lake District High), and possibly extended northwards to North Cumbria. This suggests that the controlling mechanism was localised and hence probably tectonic in origin, the most likely mechanism being pulsed platform downfaulting. Bott's (1987) slab-pull effects offer a possible explanation, but if the Yoredale cycles are an example of slab-pull cycles, then perhaps Asbian 'major' cycles would be expected elsewhere over a similar geographical area to the 'Yoredales', which is not observed. Also, the presence of the necessary southerly-dipping subduction zone as suggested by Bott (1987) is debatable (Leeder 1982, 1987). Where major cycles develop in the Urswick Limestone they demonstrate that subsidence of the platform was being achieved by episodic movement of up to 20 m along the faults that bound the SLDH, perhaps similar to the postulated synsedimentary movement along the Dent Fault during the Carboniferous (Underhill *et al.* 1988). At other times subsidence must have been more gradual, such that sub-wavebase facies were never deposited. The Urswick Limestone therefore represents an example of tectonic control on platform carbonate cycles.

4. EVOLUTION OF TECTONIC CYCLE STYLES IN THE URSWICK LIMESTONE

4.1 Lower Urswick Limestone

The base of the lower Urswick Limestone onlaps the end-Holkerian emergent surface which had at least 25 m of relief. Basal cycles are coarse grained grainstones with early marine cements, and are interpreted as strandline/shoal deposits associated with transgression over the undulose topography. Subsidence occurred in small pulses of 2-6 m and only occasionally did the depositional surface drop sufficiently to allow deposition of sub-wavebase packstones and wackestones.

Each of the three subsequent major cycles is of uniform thickness, and overall these cycles thicken upwards reflecting greater subsidence over time. The cycle top shoal facies 2 become thinner in younger cycles, with intertidal/supratidal facies 3 occasionally resting directly on thick sub-wavebase facies 1 in the upper cycle. Lobes of dark clastic silt and mud occasionally flooded the platform from a northerly source, resulting in the dark variant of sub-wavebase facies 1, and the Woodbine Shale. The platform interior became progressively more protected and locally restricted in the later cycles, suggesting that platform margin shoals had developed.

These features may be accounted for by an expansion of the platform in a landwards direction, which would enable siliclastic sediments derived from the Lake District islands (Kimber & Johnson 1986) to be transported to the south, similar to the prodeltaic advances in Leeder & Strudwick's (1987) tectonically-generated cycle. Increasing protection of the platform centre by the progressive development of platform margin shoals may have allowed packstones and wackestones of facies 1 to build up to the intertidal zone, after which they were overlain directly by low energy peritidal porcellanites of facies 3. It is only in the upper cycle that this relationship is observed, which is interpreted as the culmination of a sedimentary 'trend' in which successive cycle top grainstones become thinner and finer grained, rather than as the product of an active fall in sea level.

The complex emergent surfaces which occur at the level of the lower-upper Urswick Limestone boundary (equivalent to the early/late Asbian boundary) represent a series of regressions and transgressions that resulted in multiple karstification and deposition of terrigenous sediments of facies 4 (Horbury 1987). During this interval there was no net deposition of marine limestones, suggesting that subsidence had temporarily halted although eustacy continued.

4.2 Upper Urswick Limestone

A profound change in depositional style occurred after the end of the early Asbian. The lower part of the upper Urswick Limestone comprises shoal facies 2 with thin beds of intertidal/supratidal facies 3 over the whole platform. These shoal to supratidal deposits are thickest in the vicinity of Arnside and Carnforth, where minor cycles of grainstones may attain a thickness of 11 m, and thin in a northeasterly and westerly direction. Well exposed quarry sections reveal that emergent surfaces are more closely spaced on average (3.3 m versus 6.25 m) in those sections with thin upper Urswick Limestone than those with thick upper Urswick Limestone (Fig. 6). Numbers of emergent surfaces are similar in all relatively complete upper Urswick Limestone sequences. Platform-edge shoal facies 2 with well developed early marine cements (Figs 2, 4d) and intraclasts occur southeast of Carnforth on the margin of the Lancaster Fells Basin. Basinal sediments are represented near Halton Green, 3 km to the SE of Carnforth (Fig. 2), by an exposure of debris flow breccias overlying limestone turbidites. These are similar to the proximal slope facies in the nearby Bowland Basin (Gawthorpe 1986).

Maximum thicknesses of upper Urswick Limestone run NW-SE through Arnside and Carnforth, and together with differential spacing of palaeokarsts over the platform this suggests that the upper Urswick Limestone demonstrates differential subsidence running along the axis of major subsidence responsible for the end-Holkerian topography. Subsidence style was characterised by gradual subsidence alternating with periods of non-subsidence, rather than being of the rapid pulsed type. Sedimentation was therefore maintained above fairweather wavebase, such that 11 m thick sequences of facies 3 could develop at Jack Scout Cove (Fig. 4c), whilst during the halts in subsidence multiple emergent surfaces developed from 'stacked' emergent events, c.f. Ramsay (this volume).

The upper part of the upper Urswick Limestone is not well-exposed. However, it appears that four shoaling-upwards tectonically generated cycles developed over the platform. Like the major cycles in the lower Urswick Limestone, the basal sub-wavebase facies 1 locally demonstrate evidence of restriction. At the platform-edge localities spillover lobes from grainstone shoals can be observed building towards the platform interior, engulfing *Kamaenella* framestone/bafflestone reefs (Horbury 1987). The Asbian/Brigantian boundary is represented by a major emergent surface recorded at several localities (Rose & Dunham 1977; Strank 1981), which developed on an end-Asbian peloid - *Davidsonina septosa*-productoid grainstone shoal with 10 m of depositional relief.

The change in style of cyclicity suggests that, as in the early Asbian, the style of subsidence switched from being relatively gradual to pulsed. Development of platform-edge shoals and reef(s) effected increasing restriction of sub-wavebase lower energy platform interior sediments, although nowhere do intertidal/supratidal facies 3 overlie sub-wavebase facies 1.

The development of emergent surfaces towards the tops of major cycles in the platform centre area of the upper Urswick Limestone suggets that during each eustatic cycle marine conditions prevailed for longer than during deposition of the lower Urswick Limestone. However, the emergent surfaces near the platform margin are located throughout the tectonically generated (major) cycles, suggesting that much material was eroded and transported into the Lancaster Fells Basin during the late Asbian. This could have been achieved during both marine deposition and emergence.

5. DISCUSSION

The Urswick Limestone demonstrates two features atypical of other British Asbian platforms (reviewed in Walkden 1987). These are that the 'secular trends' of Walkden, namely i) a shift from proximal lagoon to open platform and ii) the increase in siliciclastics through the Asbian, are not apparent in the Urswick Limestone. The lower Urswick Limestone represents an open marine platform which becomes progressively deeper water in character, with an increased input of siliciclastics. The upper Urswick Limestone also demonstrates an open marine setting with later deeper water phases, but beds of low energy intertidal/supratidal facies frequently occur within shoal grainstones, and there are only minor amounts of fine siliciclastics, probably derived from atmospheric sources. Minor cycle thicknesses do increase from early to late Asbian, as noted by Walkden (1987) for the other platforms, and their numbers are also similar.

There are two mechanisms proposed by Walkden (1987) to account for changes in cycle patterns. These are a), an increase in amplitude and a decrease in frequency of the eustatic oscillations with time superimposed on a steady rate of background subsidence, and b) an increase in the rate of background subsidence through the late Dinantian with constant eustatic amplitudes and frequencies. These mechanisms cannot have operated because they have regional implications not borne out by observations on the Urswick Limestone. Both mechanisms a) and b) should have produced thin peritidal cycles in the early Asbian throughout Britain, these are not observed in the lower Urswick Limestone.

The Urswick Limestone demonstrates that the style of subsidence, rather than the overall magnitude or average rate of subsidence, controlled the development of facies sequences. The restriction of tectonically-controlled cyclicity to the SLDH indicates that generalised subsidence rates and styles applied to interpretations of Dinantian positive areas in Britain (Ramsbottom 1981; Walkden 1987) must be treated with caution, since individual structural units will respond to subsidence in slightly different ways. Controls on subsidence styles may relate to:

1. Size of structural units.
2. The presence of earlier structures within the structural unit that may be re-activated, e.g. Caledonian structural grain.
3. Fault geometries and timing of movements on those faults that bound the structural units.
4. The presence of syn- and antithetic faults within the structural unit.
5. The presence of granites.

With such variables it is perhaps not surprising that on each Dinantian structural high, carbonate ramps and platforms developed differently.

It is proposed that development of emergent surfaces in the Asbian related principally to eustatically-controlled regressions, which operated globally. Styles of subsidence are reflected by trends in water depths inferred from marine facies sequences. Where subsidence was steady and gradual, only thin 'cycles' of shallow water type developed, each of which had probably built up into the intertidal zone prior to eustatically controlled emergence. Examples of such cycles are the peritidal porcellanous limestones of the early Asbian in North Wales, and the grainstones in the lower parts of the lower and upper Urswick Limestone. Rapid subsidence with which sedimentation could not initially keep pace is indicated by the development of thick sequences of sub-wavebase facies directly above shallow water sediments of the previous cycle top. Halts in subsidence resulted in sedimentation rates exceeding subsidence rates, and produced thick shoaling cycles. It is in these long-lived cycles that the shorter frequency eustatic regressions could expose sub-wavebase sediments. Examples of such cycles are found in the upper parts of the lower and upper Urswick Limestone.

6. CONCLUSIONS

The Urswick Limestone demonstrates the interaction of eustatic, tectonic and sedimentological processes on a 30+ km - wide carbonate platform as follows:

1. Emergent surfaces, valleys and a range of infilling fluvial-deltaic-tidal facies represent temporary regressions in an otherwise marine sequence, a consequence of glacio-eustatic cyclicity driven by growth and ablation of small polar ice caps. Transgressions usually resulted in sea levels returning to similar heights as before the regression.
2. Tectonically generated cyclicity is reflected by shoaling-upwards sequences comprising several eustatic cycles in the upper parts of both the lower and upper Urswick Limestone. Periodic movement of the Southern Lake District High along major boundary faults probably accounts for the tectonic cycles.
3. The Urswick Limestone demonstrates a change from shoal grainstones to restricted, deeper water environments through both its upper and lower part. This is a consequence of subsidence changing from a gradual sag to a pulsed, more rift-like type, possibly representing the onset of two periods of fault-controlled subsidence of the Southern Lake District Block with respect to neighbouring blocks.

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