DEPOSITIONAL ENVIRONMENTS
IN THE
PETERSHILL FORMATION
BATHGATE, WEST LOTHIAN

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FRONTISPIECE

Areal photograph of the Bathgate Hills, at approximately 1:44,307 scale. The hills extend between Bathgate to the southwest and Linlithgow, in the northeastern corner. The line of quarries which expose the Petershill Fm. extends slightly over half the distance between these two points. Two plastic overlays (contained in the back pocket, Volume II) identify the major physiographical features of the area and provide a generalized palaeogeographical reconstruction of the area during the Carboniferous. Photograph used with permission of the Crown.

DECLARATION

The work presented in this thesis is my own. Where I have used the work of others, I have specifically stated so in the text or in the acknowledgements.

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ABSTRACT

The name "Petershill Fm." is proposed for the 30-40 m thick sedimentary sequence of Visean (V_3c) age, occurring within a thick pile of Carboniferous lavas which form the present day Bathgate Hills. These lavas were erupted in the middle of the Midland Valley graben, to form a mid-basin high. The Petershill Fm. (abbrev. Ph. Fm.) marks an exceptional interval of quiescence and sedimentation along the southern flanks of this volcanic pile. Current exposure is confined to a north-south strip, which provides a nearshore-offshore profile of the successive environments deposited across the platform.

The Ph. Fm. is roughly divisible in half, into an upper, clastic, Silvermine Mbr. and a lower, carbonate, Reservoir Mbr. The Reservoir Mbr. forms a transgressive-regressive sequence terminating in two major intervals of erosion and subaerial exposure. The first sediments to overstep the lava surface form a continuous level-bedded sequence, deposited in progressively more open-marine environments.

Differences in the faunal composition of level-bedded facies may be related to substrate properties and lithological composition. Sequences of indistinct burrowing in argillaceous biomicrosparites indicate that they formed gel substrates (capable of thixotropic behaviour), which were likely to have been unstable. Trace fossils additionally reveal that some slightly argillaceous limestone horizons underwent an increase in consolidation from a gel to plastic state. Epifauna concentrate at these horizons, suggesting that the increase in consolidation may be attributed to penecontemporaneous lithification associated with intervals of non-deposition.

The succeeding regressive facies are laterally differentiated into a mosaic of adjacent environments, consisting of a shoreward lagoon, a nearshore turbulent zone, and a biohermal build-up, passing

into fine-grained biomicrosparites further offshore. In the nearshore zone, disorientated and overturned, massive cerioid corals, winnowed lag horizons of Gigantoproductus, and current cross-stratification establish that currents were strong and destructive. The laterally equivalent build-up, which possessed topographic relief, accumulated in a distal nearshore zone of maximum biological productivity and sediment preservation potential. It shows a faunal succession which may be attributed to regional shallowing over the platform as a whole. Offshore from the build-up, fine-grained biomicrosparites accumulated in a zone of quieter and slightly deeper water, as shown by a delicate, yet undisturbed fauna.

Comparisons between these contemporaneous facies reveals that substrate consistency and mobility were key factors in controlling faunal distribution as well as the subsequent diagenetic history of a lithology. Mobile, granular substrates (characteristic of turbulent zones) supported taxa with robust growth forms, in some cases (e.g. Chaetetes) especially adapted to high-energy conditions. Firm substrates (characteristic of the build-up and further offshore facies) provided ideal surfaces for epifaunal colonization and encrustation. The open gallery systems of Thalassinoides paradoxica forma minuta (forma nov) and other structures (e.g. intraclasts and fractures) provide evidence of firmness and limited early lithification. Firm substrates preserve much of their depositional porosity and were therefore susceptible to early meteoroic diagenesis which created breccias and cavity systems that, in some cases, resemble Stromatactis.

Algae, particularly branched filamentous types (new), Girvanella, dasycladaceans and microproblematica, often regarded as algae, are widespread throughout the Reservoir Mbr. in some cases forming structures attributable to binding. Algae are widely distributed in several facies and thus not likely to have been the sole sediment stabilizing agents. A combination of factors, including rate and type of sediment influx, turbulence and the stabilizing effect of the fauna itself, probably ultimately determined the properties of the sediment surface.

Regression culminated in subaerial exposure and the formation of sandstone, tuff and plant debris infilled fissures, which provide evidence of a complex history of events not preserved elsewhere in the sequence. The overlying Silvermine Mbr. consists of a basal sandstone facies followed by a coarsening-upward (CU) facies. The basal sandstone shows a shoreline-offshore profile comparable to that in the carbonate facies underneath. Coastal bay sandstones pass via an inflection point into a system of nearshore sand bars. The CU sequence above accumulated during infilling of a coastal bay, progradation being finally terminated by renewed volcanic activity and lava outpouring.

The Ph. Fm. is unique in the Midland Valley in the diversity of its fauna and facies. Relief over the surrounding basinal areas, provided by the Bathgate volcanics, located in the middle of the graben, and the shape of the underlying platform are most likely to account for the exceptional nature of the Ph. Fm. sedimentation.

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INTRODUCTION

0.1 The Bathgate Hills

The Bathgate Hills form a belt of high ground extending between Bathgate and Linlithgow, south of the Firth of Forth (Fig. 0-1). They rise gently from the surrounding countryside to between 250-300 m (Frontispiece). The hills are formed by an exceptionally thick pile of lavas in the Dinantian Lower Limestone Group of the Midland Valley Carboniferous. The sedimentary sequence described in this thesis forms a continuous horizon through these lavas.

The thickest and best exposed sedimentary sequence in the Bathgate lavas is the Petershill Formation (formerly the Petershill Limestone). It is almost certainly continuous with the Hillhouse Limestone further north (Fig. 0-2), although lithologies and facies cannot be exactly correlated. The Wairdlaw Limestone, which is a few hundred metres above the Petershill Fm., is the only other sedimentary sequence at approximately the same stratigraphic horizon in the lava pile (Fig. 0-2).

0.2 Exposure

The Petershill Fm. is exposed in a line of old limestone quarries extending north-south along the southern flanks of the Bathgate Hills (Frontispiece). It is well exposed along strike for over 3 km north of Glenbare Quarry (Fig. 0-2; Frontispiece). Exposures are close enough so that individual beds, or horizons (metres thick), can be followed. Additional accuracy in lateral correlation, and a more complete vertical section, was provided by five boreholes sunk as part of the present study.

0.3 Structure

0.31 Overview

The large-scale geological structure of the area is comparatively simple (Fig. 0-2). The Bathgate Hills are located on the eastern

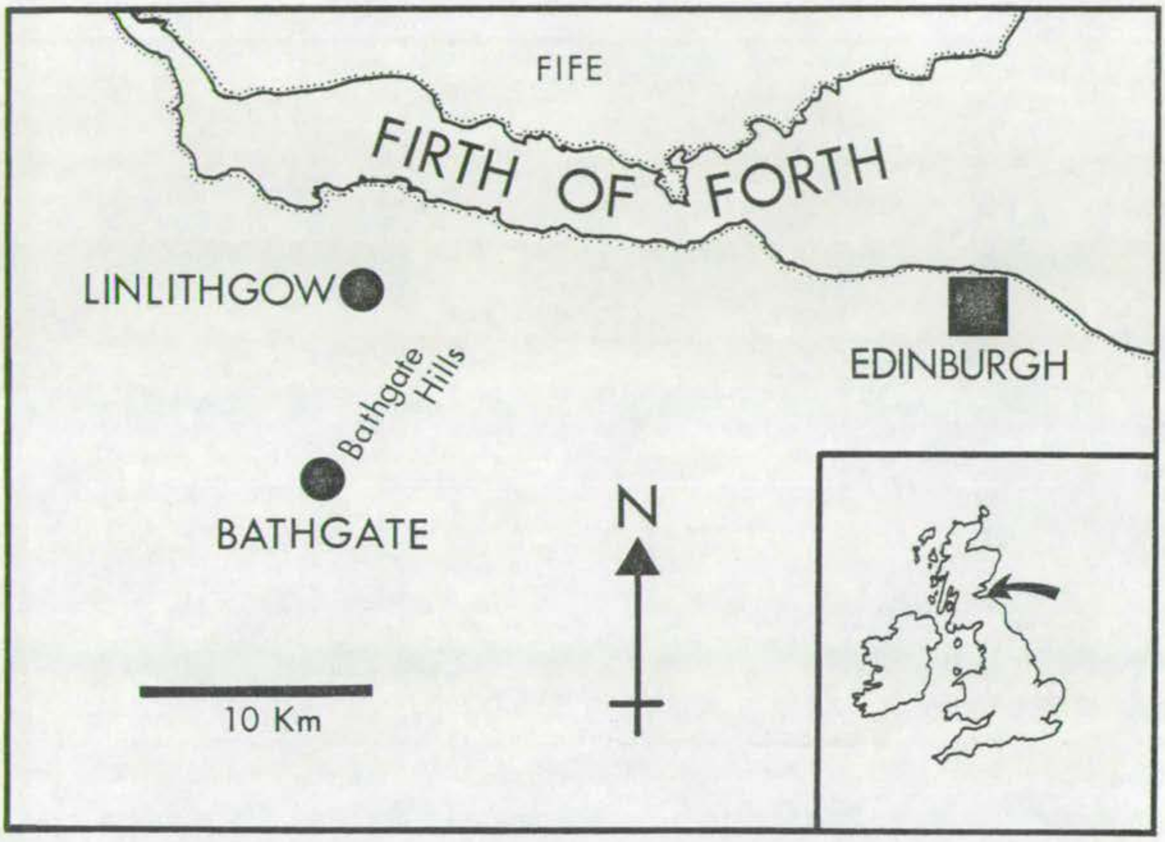


Fig. 0-1 Geographical location of the Petershill Fm. in the Bathgate Hills

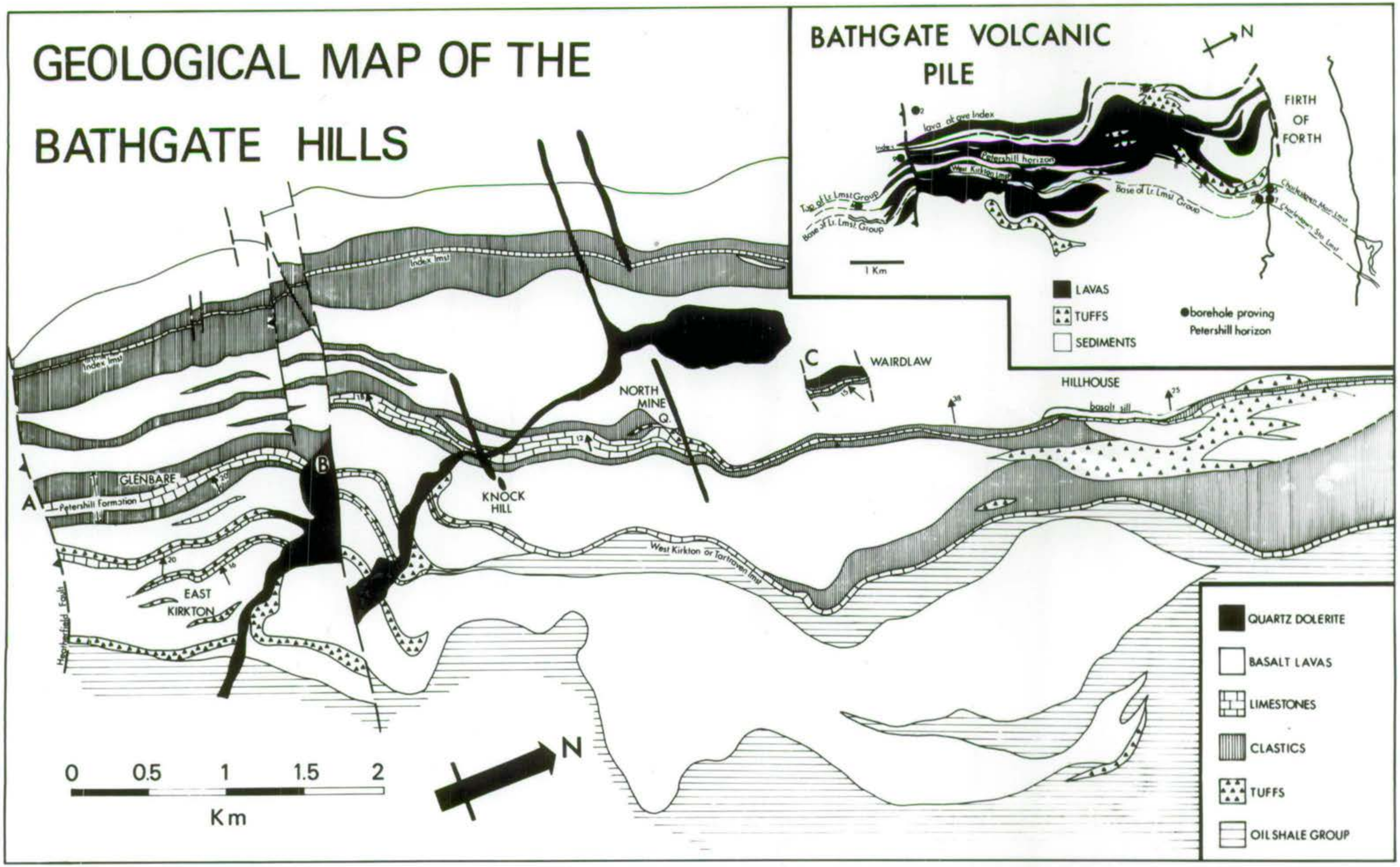
limb of a large northeast-trending syncline known as the Central Coalfield. Beds dip westward, varying slightly from a mean dip of 20°, ranging between 4-40°. The strike is fairly constant, changing only slightly due to low amplitude east-west folds which produce a slightly sinuous outcrop pattern. A few major faults offset the strike, notably the Heatherfield Fault at Bathgate and the fault at Galabraes (A and B, Fig. 0-2). On the south side of the hills, the larger faults are normal and downthrown to the south, while on the north side the downthrow is generally to the north. The sense of offset on the faults is well shown by the large eastward-dipping quartz dolerite dyke which cuts through the hills (Figs. 0-2; 0-7; pocket insert). This large dyke also cross-cuts the system of smaller east-west trending dykes common throughout the hills (Peach et al. 1910, p 284). Macgregor and MacGregor (1961, pp 72-75) concluded that these intrusives were of Permo-Carboniferous age and not directly related to the extrusive basaltic volcanism of the Bathgate lavas.

0.32 Correlation across the Bathgate Hills

Further proof of the overall structural simplicity of the Bathgate Hills is provided by traceable horizons at the top, middle and near the bottom of the Lower Limestone Group. At the top, a lava flow above the Index Limestone (Fig. 0-2) forms a traceable unit along the southern half of the hills (Howell and Geikie 1861, pp 47-62). In the middle, the Petershill-Hillhouse horizon (abbrev. Petershill horizon) forms the only major continuous sedimentary intercalation amongst the lavas. Roughly 100 m below the base of the Petershill horizon, the West Kirkton or Tartraven Limestones (west of the East Kirkton Limestone, Fig. 0-2) are discontinuously exposed in the middle, northern, and southern margins of the hills. The W. Kirkton horizon is encountered with fairly predictable regularity along strike, thus establishing

Fig. 0-2 Geological map of the Bathgate Hills (based on 6" geological map of sheets 31 and 32 and mapping carried out in the course of the present study). Borehole information establishing the presence of the Petershill horizon is based on the nine localities (shown on inset) taken from Peach et al. (1910, p 115); Howell and Geikie (1861, pp 47-62); Macgregor and Haldane (1933, pp 23, 27, 35); Forsyth (1970, p 8).

GEOLOGICAL MAP OF THE BATHGATE HILLS



that major tectonic offsets do not occur. Because the structure is so straightforward it is conveniently possible to use the plan geological map (Figs. 0-2; 0-7) as an accurate cross-section of the area; the sequence has simply been tilted on edge by roughly 20°.

0.4 The Bathgate volcanics

From the preceeding description (and Fig. 0-2) it can be seen that the Petershill Fm. represents a rare interval of sedimentation in an area of extensive volcanism. A brief description of the volcanics is thus necessary to an understanding both of sedimentation and the regional facies relationships of the Petershill Fm. In this section relevant aspects of the Bathgate volcanics are described and discussed. The significance of some of these observations is explained in subsequent chapters.

0.41 Distribution and geometry

Basaltic lavas and tuffs occupy most of the Dinantian sequence between Bathgate and Linlithgow, particularly within the Lower Limestone and Limestone Coal Groups. In cross-section (Fig. 0-2), the volcanics form a large, somewhat asymmetric pile occupying the position of sediments between the Upper Oil Shale Group and the middle of the Upper Limestone Group (Fig. 0-4). Two of the reasons for the asymmetry of the pile are apparent from the regional cross-section: the lavas do not thin uniformly in all directions and, also, the centre of volcanism appears to have shifted to the north and west through time Macgregor and Haldane 1933, pp 96-97). The Bathgate volcanics reach a maximum thickness of approximately 900 m a little over half way between Bathgate and Linlithgow. The Petershill horizon is approximately 300 m stratigraphically above the base of the volcanic pile.

From the area of greatest thickness, the lavas thin to the southwest, extending 8 km south and 14 km west*[1]. In this region, above

*[1] the lavas are absent from the Skolie Burn section, south of Bathgate (Macgregor and Anderson 1923, plate V) and are known to extend under the Central Coalfield as far west as Slammanan (Anderson 1963).

and below the Petershill Fm., the lavas thin gradually, forming a broad shelf-like area over which sediments onlap, change composition and usually pinch-out. Less often, thin sedimentary sequences appear discontinuously along a particular lava horizon, as seen in the Wandering Coal Seam. On the northern margin of the Bathgate volcanic pile, the lavas thin abruptly and lateral facies differentiation does not take place among the interbedded sediments. North and south of the Bathgate Hills the Lower Limestone Group consists of repeated, Yoredale-type cyclothems roughly 10 m thick (Francis 1965, p 309).

0.42 Petrology and interbedded sediments

The Bathgate volcanics consist of basaltic lavas and tuffs. Lavas are porphyritic and microporphyritic olivine basalts, heavily altered at outcrop, with phenocrysts commonly pseudomorphed by calcite, quartz or chlorite. Their petrology has been described in detail by several authors; Francis (1967) provides a comprehensive reference list. Upper surfaces are commonly reddened and kaolinitized, being capped by "lava boles" or eroded subaerial exposure surfaces (Anderson 1963; Francis 1965, p 371). Francis (ibid) concluded that the Bathgate lavas represented subaerial flows or their remnants after periods of subaerial exposure and planation.

Thin sandstones, shales, fireclays, marine sediments and sediments originally described as "ashes", interbed with the lavas or infill hollows on their surface (q.v. Howell and Geikie 1861, pp 47-62; Macgregor and Haldane 1933, pp 79-88; Peach et al. 1910, pp 145-149; Fig. 0-7, Appdx). Many of the sediments formerly described as ashes would currently be classed as tuffs. They are composed of variable proportions of angular fragments of basaltic debris, volcanogenic clay, sedimentary rock fragments, quartz sand, plant fragments and mica. Many show bedding or lamination. Their petrology and field occurrence suggests they are mostly detrital accumulations of material derived from the erosion of nearby volcanics, wind-blown material, and allochthonous sand. The presence of rootlet horizons, plant debris, and reddened horizons additionally indicates a terrestrial, marginal-marine or intermittently-marine origin, although their detailed interpretations await further research.

0.43 Flow morphology and its significance

A fairly detailed picture of the size and geometry of the volcanics has emerged from boreholes, my own mapping and previous survey work (Howell and Geikie 1861, pp 47-62; Peach et al. 1910, pp 144-150; Macgregor and Haldane 1933, pp 79-88; Anderson 1963). Uniform layers of lava, which are likely to have been single flows or their remnants, are 1-15 m thick (usually near 8 m in thickness) and seldom extend for more than 0.5 km. Several flows usually appear in close succession, followed by a variable thickness of sediment.

If the present exposure of volcanics may be used as an indication of their former extent, then it appears that most flows and flow sequences originally spread from numerous small centres consisting of one or more vents, eventually coalescing to form a continuous volcanic pile. This suggestion agrees well with the general style or pattern of volcanism observed throughout the British Carboniferous. Francis (1967) and MacGregor (1948) recognized that the Midland Valley volcanics occurred along faults and basement lines of weakness that were active during the Carboniferous. Francis (ibid) listed several examples strongly suggesting that the systems of small fractures extending along these lines of weakness provided avenues to the surface for rising magmas. Similarly, in the Bathgate Hills, it is likely that the lavas issued from many minor fractures to form small vents and cones, rather than from a single large cauldron.

Rapid changes in the thickness of sediments immediately overlying the lavas and the presence of discontinuous sedimentary sequences suggest that the upper surfaces of the lavas were relatively uneven (Figs. 0-2; 0-7). Although it is difficult to generalize, it thus appears likely that the surface onto which most transgressions took place consisted of hollows and ridges of lava. Thus the topography of the sedimentation surface and shelf shape are likely to have been strongly influenced by the underlying lavas.

0.5 Tectonic setting

0.51 Overview

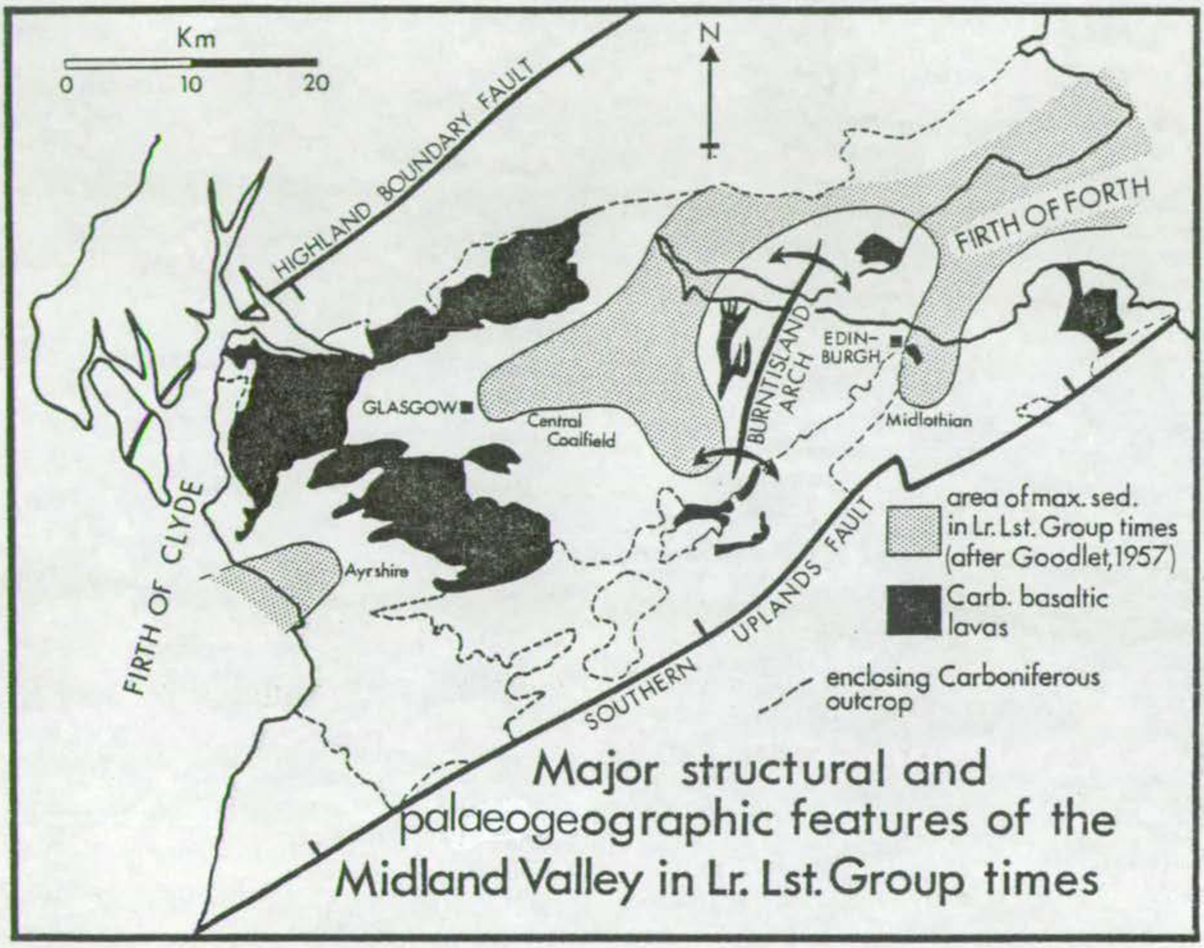
During the Carboniferous the Midland Valley of Scotland formed an intracratonic basin, downfaulted between northeast-southwest trending boundary faults and widening to the northeast (George 1958; Kennedy 1960). Positive areas bounded the basin to the north and south of these boundary faults (Fig. 0-3). The former boundaries of the basin coincide roughly with the present physiographic region known as the Midland Valley. Within the basin, contemporaneous faulting, volcanism and folding produced a complex sedimentation pattern (Kennedy ibid).

0.52 Basinal areas

Isopach and isolith maps for the Carboniferous, in particular of the Lower Limestone Group (Goodlet 1957; Kennedy 1960), depict three major basinal areas in the Midland Valley: the Ayrshire Coalfield; the Central-West Lothian Coalfield; and the Midlothian Coalfield (q.v. Fig. 0-3). During the Carboniferous the former two basinal areas were separated by massive outpourings forming the Clyde Plateau lavas (Francis 1967).

Isopach analysis has shown that greater thicknesses of clastic sediments were deposited in the basinal areas, while reduced sedimentation

Fig. 0-3



Major structural and palaeogeographic features of the Midland Valley in Lr. Lst. Group times and carbonate deposition characterized topographic highs (Goodlet 1957).

0.53 The Burntisland Anticline

The Central-West Lothian and Midlothian Coalfields are separated by an antiformal flexure known as the Burntisland Anticline or arch (Fig. 0-3). This palaeogeographic feature is poorly understood, as it is not well exposed. Goodlet (1959, pp 225-228) described it an an antiformal flexure extending northeast from the Bathgate Hills to the Burntisland District of Fife. Both Goodlet (ibid) and later Francis (1967) noted that the Carboniferous lavas of these districts parallel its trend. Goodlet's isopach analysis shows that the arch was an area of little or no relative subsidence. Both Francis (1965, pp 370-373) and Goodlet (ibid) concluded that the anticline formed a positive area during parts of the lower Carboniferous. Thus it appears that the Bathgate lavas were extruded on the side of a tectonic arch, which acted at least as an impediment and, at times, as a barrier to sedimentation between different parts of the Midland Valley basin.

0.6 Stratigraphy

A lithostratigraphical system for correlation is in use in the Midland Valley of Scotland (q.v. Macgregor 1930). Because the geology is well known, this system provides an extremely accurate means of correlation, particularly in the middle Carboniferous, where individual beds or horizons can be equated. Recently George et al. (1976) have erected a comprehensive new chronostratigraphic system for the Dinantian of Great Britain and provided correlations with the local stratigraphy (shown in Fig. 0-4). The stratigraphical position of the Petershill Fm. within this system was determined by two methods: a) the biostratigraphical position of the Petershill Fm. was established

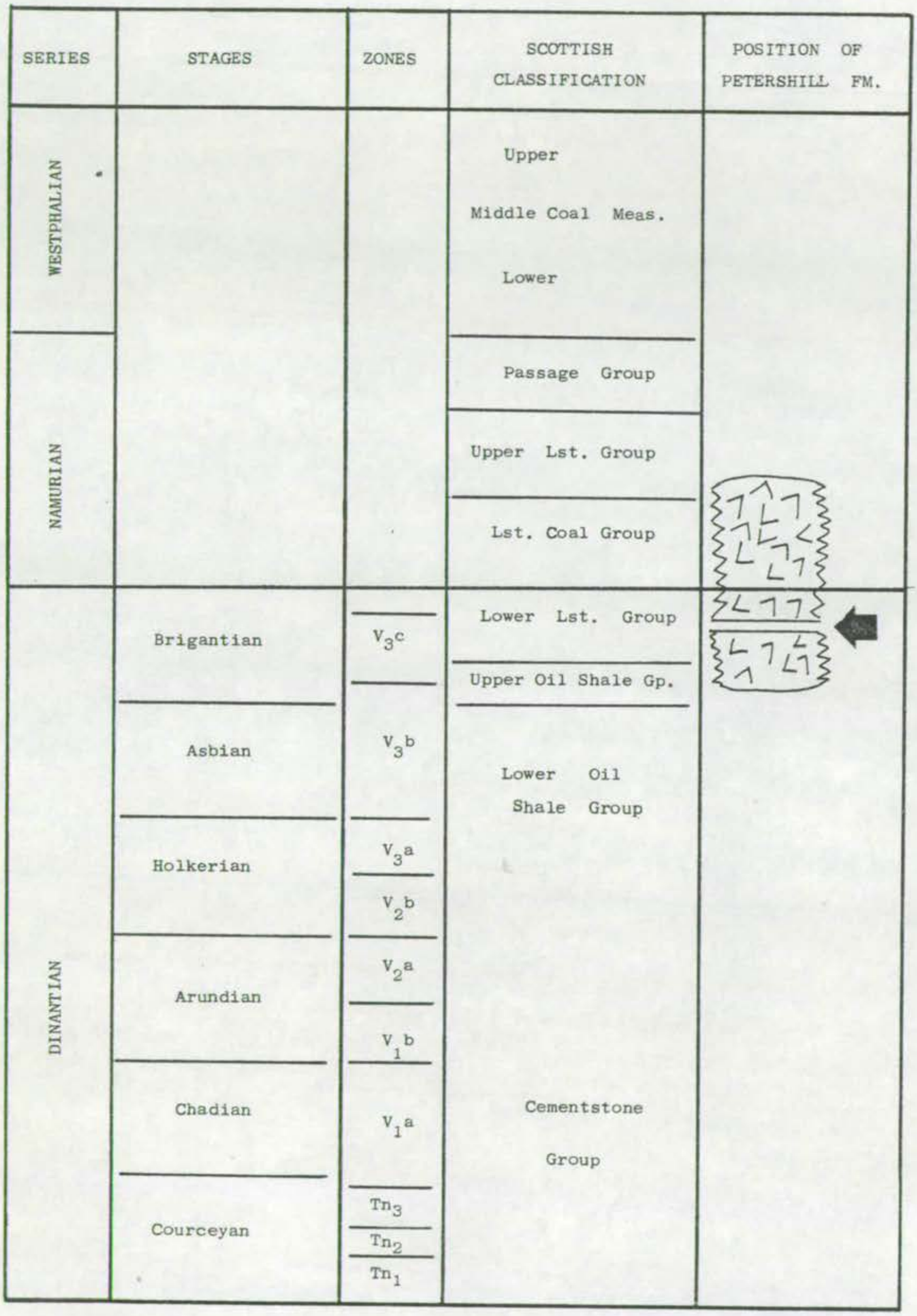


Fig. 0-4 Stratigraphical location of the Petershill Fm.
Foraminiferan zones shown.

by Professor R. C. L. Conil from the foraminiferan fauna in my own thin sections; b) by analysis of previously published data on the local stratigraphy. The evidence from these two methods agreed, confirming the correlation described by Macgregor (1930, p 518).

0.61 Regional correlation

The Petershill Fm. is one of seven to eight named limestone horizons in the Lower Limestone Group. In the Midland Valley, the names of the limestones, as well as their number, change over fairly short distances (a few km). Several workers, notably Macgregor (1930) have correlated the limestones across the Midland Valley, but not always with the same degree of certainty. In the Lower Limestone Group, correlation has relied on the use of marker bands, together with lithological and palaeontological similarities between sequences.

The Neilson Shell Bed (NSB), roughly in the middle of the Lower Limestone Group, has proven to be a particularly useful marker horizon. Wilson (1966, 1974) used the NSB to correlate many of the limestones of the Midland Valley in the middle of the Lower Limestone Group. Once equivalence had been established at the NSB level, correlation of other horizons, particularly those below the NSB, was feasible with confidence.

0.62 The Petershill Fm.: a history of correlation

In the past opinions have differed over the exact correlation of the Petershill Fm. and the position of the base of the Lower Limestone Group in the Bathgate Hills. In the first Survey Memoir, Howell and Geikie (1861, pp 52-55) placed the Petershill Limestone in the middle of the Lower Limestone Group, and the West Kirkton Limestone (stratigraphically underneath) at the base. Later, Geikie (1879, p 18) altered the position of the base of the Lower Limestone Group, moving it to the base of the Petershill Limestone.

Peach et al. (1910, p 110), Cadell (1925, Ch 15), Macgregor and Anderson (1923) and Macgregor (1930) regarded the original correlation as correct, and equated the Petershill Limestone with the Foul Hosie and Carriden No. 5 limestones south and north. By far the most comprehensive recent stratigraphical analysis of the Lower Limestone Group on the eastern limb of the Central Coalfield (Macgregor and Haldane, 1933, pp 21-32) arrived at the same conclusion regarding the stratigraphical position of the Petershill Fm. They stated that:

> "There can be no doubt that the (Carriden) No. 5 Limestone is the equivalent to the Charlestown Main Seam and that the latter, at one time regarded as the base of the Lower Limestone Group in West Fife, must be placed on the same horizon as the Petershill or Silvermine Limestones of the Bathgate Hills".

Wilson (1966) correlated these limestones with others across the Midland Valley, but did not include the Petershill Fm. because he did not find the Neilson Shell Bed above the limestone. Referring to these correlations, he (ibid, p 114) stated that "faunal evidence neither confirmed nor denied these correlations". In a subsequent borehole study, Forsyth (1970) correlated the Lower Carboniferous sequence north and south of the Bathgate Hills, but omitted the Petershill Fm., presumably because of lack of information in the region of the volcanics. Thus the earlier surveys have correlated the Petershill Fm. with little hesitation, while faunal and borehole studies have been less commital.

0.7 Lithostratigraphical position of the Petershill Fm.

In my opinion, Geikie's original correlation, given in Howell and Geikie (1861), and later expanded by Macgregor (1930), is correct. The Petershill horizon should be regarded as equivalent to the limestones found elsewhere at the horizon of the Neilson Shell Bed. The reasons for this assumption are: a) the absence of the NSB does not deny equivalence; b) there is a marked sedimentological similarity in all sequences; c) borehole data suggests that a continuous sedimentary sequence is actually present at the Petershill stratigraphical horizon.

0.71 Facies specificity of the Neilson Shell Bed

The absence of the NSB at the horizon of the Petershill Fm. could be construed as negative evidence for correlation. Wilson (1966), however, pointed out that the NSB fauna is specific to a shale facies occurring immediately above the limestone of a cycle. In the Petershill Fm., and in the limestones in the Kinghorn district (also near volcanic centres) the NSB facies is absent, and sandstones occupy the shale horizon. In these cases the absence of the fauna is almost certainly related to the environmental difference between the Petershill-Kinghorn limestones and the "normal" NSB shale facies. The absence does not thus necessarily imply miscorrelation.

0.72 Sedimentological similarity of the limestones beneath the NSB

Wilson (1966, p 113) noted that the NSB occurred above the first major marine development in the Lower Limestone Group (with the exception of a minor marine band east of Glasgow). A comparison of the limestones at this horizon, namely the Foul Hosie Limestone (Macgregor and Anderson 1923, plate IV), the Carriden No. 5 Limestone (Macgregor and Haldane 1933, pp 23-25), the Charlestown Main Limestone of Fife (Geikie 1900, pp 87-97) and the Petershill Fm., shows that they are remarkably similar. Peach et al. (1910, p116), Cadell (1925, pp 85, 143) and Macgregor and Haldane (ibid, pp 22-26) observed several striking similarities in the lithological and faunal features of these sequences, drawing a particularly strong correlation between the sequence in West Fife and the Petershill Fm. The sedimentological resemblance between these sequences provides the most reliable evidence for equivalence. These sections have in common: a) an unusual thickness of limestone (2-10 times thicker than average for the Lower Limestone Group);

b) a sequence consisting of bedded argillaceous limestones overlain by purer, fossiliferous limestones (containing Lithostrotion and productoids), capped by bioclastic crinoidal limestones. This lithological similarity suggests that a common environmental succession took place in these areas, manifested by changes in the proportion of detritus, a diversification of the fauna during carbonate sedimentation and a final high energy phase. Such sedimentological similarities provide the most compelling evidence that these horizons were contemporaneous.

0.73 Lateral persistence of the Petershill Fm.

It is possible that the Petershill Fm. represents an isolated horizon among the lavas without equivalents elsewhere. This seems unlikely, however. All the boreholes drilled north and south of the Bathgate Hills have found limestones at the appropriate level (borehole locations 1-9, shown on Fig. 0-2). Their distribution strongly suggests that the Petershill sequence is part of a horizon which is continuous with the widely-accepted correlative limestones.

0.8 Biostratigraphy

As previously stated, a lithostratigraphical correlation scheme is in use in the Midland Valley (q.v. George et al. 1976). However, within some lithostratigraphical groups, index fossils and marker assemblages (e.g. the NSB) have been used to further corroborate or refine correlations. Difficulties have arisen in trying to correlate the internal stratigraphy of the Midland Valley with the more widely recognized goniatite and microfossil zonational schemes used in Britain and elsewhere. Currie (1954), for instance, was only able to recognize half the goniatite stages found elsewhere in Britain because of the paucity of Scottish specimens. A comprehensive foraminiferan-based zonation has yet to be applied to the Carboniferous of Scotland.

As part of this study, Professor R. C. L. Conil kindly identified the Foraminifera in my thin sections of the Petershill Fm. (Table 0-5). The foraminiferan "date" furnished by Professor Conil provides the basis on which to begin to correlate the Scottish Dinantian succession with the internationally recognized biozones. A preliminary international correlation scheme for the British Carboniferous is already in existence (George et al. 1976). The purpose here is to provide the first confirmation of a small part of the scheme which George et al. (ibid) have proposed.

The foraminiferan fauna indicates that the Petershill Fm. is equivalent to, or perhaps above the uppermost Viséan zone found in Belgium, the V_3c. The sequence in Belgium is not as complete as that of Britain, where another Viséan zone may yet be present (George et al. 1976). The Petershill Fm. foraminiferan fauna as a whole, and several taxa in particular, indicate an upper V_3c date (P. Langerstaey, pers. comm.). Particularly significant V_3c taxa are: a) cribrate palaeotextularids such as *Cribrostomum*, *Janiskewskina*, *Climmacamina simplex* and *Palaeotextularia*; b) *Bradyina* and *Howchinia bradyiana*; c) advanced forms of *Eostafella* with 4-5 whorls and 15-20 chambers in the outer whorl. If the lithostratigraphical correlation presented in this thesis is correct, then the V_3c foraminiferan stage date of the Petershill Fm. may also be applied to its correlatives (q.v. Macgregor 1930).

0.9 History and previous research

Virtually all previous research on the Bathgate Hills has been carried out by the officers of the Geological Survey in the course of mapping the area. No previous sedimentological or palaeoecological research has been done at the horizon of the Petershill Fm., nor has any attempt been made to synthesize the geological information known about the Bathgate Hills.

Table O-5 . Foraminiferan fauna of the Petershill Formation.[*1]

Age	$V_3b\gamma$	V_3b-V_3c-N	$\sim V_3c$	V_3c	V_3c-Nam		Abundance[*2]
Eostafella	x	x	x	x	x		Ab
Pseudoendothyra sp.	x						R
Endothyranopsis crassus	x	x	x	x	x		Ab
Endothyra sp.	x	x	x	x	x		Ab
Endothyra similis crustata		x	x	x	x		R
Endothyra ex gr. bowmani		x			x		R
Endothyra apposita	x						VR
Endothyra acantha	x						VR
Archaediscus convexus	x						R
Archaediscus stilus	x				x		VR
Archaediscus sp.	x	x	x		x		R
Archaediscus chernoussovensis	x		x	x			R
Pachysphaerina pachysphaerica	x						VR
Bradyina sp.	x			x			VR
Valvulinella sp.	x	x		x			R
Valvulinella tchotchiai		x					VR
Palaeotexlularia sp	x	x	x	x	x		Ab
Tournayellidae sp	x						VR
Earlandia vulgaris	x	x	x	x			C
Earlandia minor	x	x	x	x	x		Ab
Earlandia elegans				x			VR
Pseudoammodiscus sp	x	x	x	x	x		C
Nodosoarchaediscus incertus		cf					VR
Koskinotextularia sp	x		x	x			R
Asperodiscus sp					x		VR
Climacammina simplex	x		x				VR
Paradainella nibelis	x						VR
Koskinobigenerina sp.	x		x	x			R
Mikhailovella sp				x			VR
Janispheoskina sp				x			VR
Cribrostomun sp				x			VR
Pseudolituotubella gravata		x	x	x	x		Ab
Archaesphaera inequalis		x	x	x	x		Ab
Bisphaera sp							
Draffnia triloba sp							
Eotubertina sp							
Archaeospheara sp							
Lituotubella sp							

[*1] identified by Prof. R.C.L. Conil

[*2] Relative abundance: ab = abundant, c = common, r = rare, vr = very rare

This thesis is the first attempt at detailed mapping, recognizing facies within the Petershill Fm. and describing the geological history of the area. To my knowledge it is the first work which combines palaeontological and sedimentological data in an attempt to find environmentally useful criteria for analyzing Scottish Carboniferous limestones. Previous Carboniferous environmental studies have largely been restricted to mudstone sequences. Both the analytical procedures and the facies classification scheme employed in this study are likely to be valuable in future Carboniferous research in the Midland Valley.

0.91 History of mapping

The Bathgate Hills fall on the boundary between sheets 31 and 32 although they have traditionally been described in the Memoir for sheet 32. The first map of the hills was published in 1847 by C. Forsyth, a survey officer (q.v. Forsyth, 1847). During 1856-57 the area was surveyed by A. Geikie in connection with the publication of sheet 32 in 1859. Geikie's first description, in the historical first edition of the Geology in the Neighbourhood of Edinburgh, (Howell and Geikie 1861) still provides the most comprehensive account of the geology of the Bathgate Hills. In subsequent memoirs Geikie's work has either been referred to, or simply quoted verbatim.

The Lower Limestone Group of the Bathgate Hills has not been surveyed in detail since it was first mapped (R. B. Wilson, pers. comm.), although a great deal of work has been done on the Carboniferous sequence above and below it, and on the igneous rocks of the area. During the latter 19th century H. M. Cadell surveyed the oil shales stratigraphically underneath. A revision of the geology of the Central Coalfield was carried out at about the same time by C. T. Clough and G. W. Gabham. The igneous geology was surveyed by C. T. Clough, E. B. Bailey, J. Falconer, and the petrology described by J. Fleet. The results from this period of detailed mapping appeared in a second edition of sheet 32 in 1859, in the second edition of the Memoir, (Peach et al. 1910), in numerous individual publications: Cadell (1901, 1920, 1923) and Falconer (1905-1906), and in a series of large scale (1:10560) geological maps.

Since the early period of ground mapping, geological work has been concentrated on the economic geology of the coals, and on regional stratigraphic correlations, both based largely on borehole and mining information (Macgregor and Anderson 1923; Macgregor and Haldane 1933; and Forsyth 1970).

0.92 Palaeontological research

Most previous research on the sediments at the Petershill horizon has been documentary in its approach. The early memoirs (Howell and Geikie 1861, pp 146-148; Geikie 1879, localities 10-25) include fairly complete faunal lists. For reasons unknown to me, however, Bathgate does not appear in the later editions. Several previous taxonomic works, listed in Table 0-6 have recorded individual elements of the fauna.

The Petershill Fm. is best known for its coral fauna. Smith (1913) and Hill (1938) have described *Aulophyllum fungites* (Fleming), *Lonsdaleia floriformis floriformis* (M'Coy), and *Lithostrotion junceum* (Fleming) from the Petershill Fm. More recently Parks (1966) described phenotypic variation in *Aulophyllum fungites* from the Reservoir Quarry.

0.10 Summary of geological setting

The Petershill Fm. and its equivalents form an almost certainly continuous horizon through a sequence of Lower Carboniferous lavas forming the present day Bathgate Hills. These lavas replace the Lower Limestone Group sediments along 10 km of section on the eastern limb of

TABLE 0-6

TAXA	LOCALITY	AUTHOR
brachiopods, various	Petershill Fm. and Hillhouse Lst	Davidson 1858
Spirorbis caperatus	Petershill Fm.	Etheridge 1880
sponges - *Hyalostelia* sp.	Petershill Fm. and Hillhouse Lst	Hinde 1896
ostracods	Petershill Fm.	Latham 1933
corals	Petershill Fm.	Hill 1938
conodonts	Petershill Fm.	Clarke 1960

the Central Coalfield, between the town of Bathgate and Linlithgow. They were erupted along an antiformal flexure known as the Burntisland Arch, which separated the Central Coalfield basin from the Midlothian Coalfield basin.

The present lava distribution pattern suggests the volcanics on the south side of the pile created a broad platform area, or shelf, extending tens of kilometres southwest from the area of their greatest thickness. Changes in the thickness of interbedded sediments suggest that the south and westerly directions may be regarded as "basinward", whereas the area of greatest lava thickness is likely to have been emergent or intermittently covered in very shallow waters.

Erosional discontinuities at the top surfaces of lavas indicate they were subaerially erupted and subsequently weathered. During periods of quiescence, when the lava pile was inundated, the accumulated thickness of lava provided substantial relief over the surrounding basinal floor of the Midland Valley graben. Evidence for topographic influence on sedimentation of the entire volcanic sequence is seen in the atypically thick carbonate part of the Petershill Fm. and changes in the thickness of the sequence as a whole. The Petershill Fm. was thus deposited on a platform flanking a volcanic topographic high.

0.11 Methods

0.11.1 Mapping

The Petershill Fm., the Hillhouse Lst., the Wairdlaw Lst., and the area between them was mapped on a scale of 1:2500. Part of this map (Fig. 0-7) is enclosed in the back pocket at the end of this thesis. As part of mapping, the major quarry faces (Table 0-8) were described and logged. Field relationships between quarries were further clarified by sinking boreholes. Although this thesis deals with the Petershill Fm., the nearby limestones were mapped for

Table 0-8 Location of major sequences sampled

Petershill Lime Works NS 985 692	vertical section borehole	50 cm interval
South Quarry NS 985 693	vertical sections at north, middle and south of quarry	every bed
Petershill Reservoir NS 985 695	3 vertical sections along N-S exposures	
	3 vertical sections along E-W exposures	20 cm interval
	2 boreholes	
Galabraes Quarry NS 986 699	1 section along N bank of Reservoir 2	1m interval
	2 vertical sections in quarry	50 cm interval
Sunnyside Reservoir NS 983 702	1 vertical section 1 borehole	50 cm interval
Rifle Range NS 988 709	3 vertical sections	50 cm interval
S. Mine Lime Works NS 990 714	3 vertical sections at north, middle and south of quarry	50 cm interval
North Mine Quarry NS 994 721	2 vertical sections	50 cm interval
Wairdlaw Limestone NS 995 732	2 vertical sections	50 cm interval
Hillhouse Limestone NS 005 070	2 vertical sections north and south of road	50 cm interval

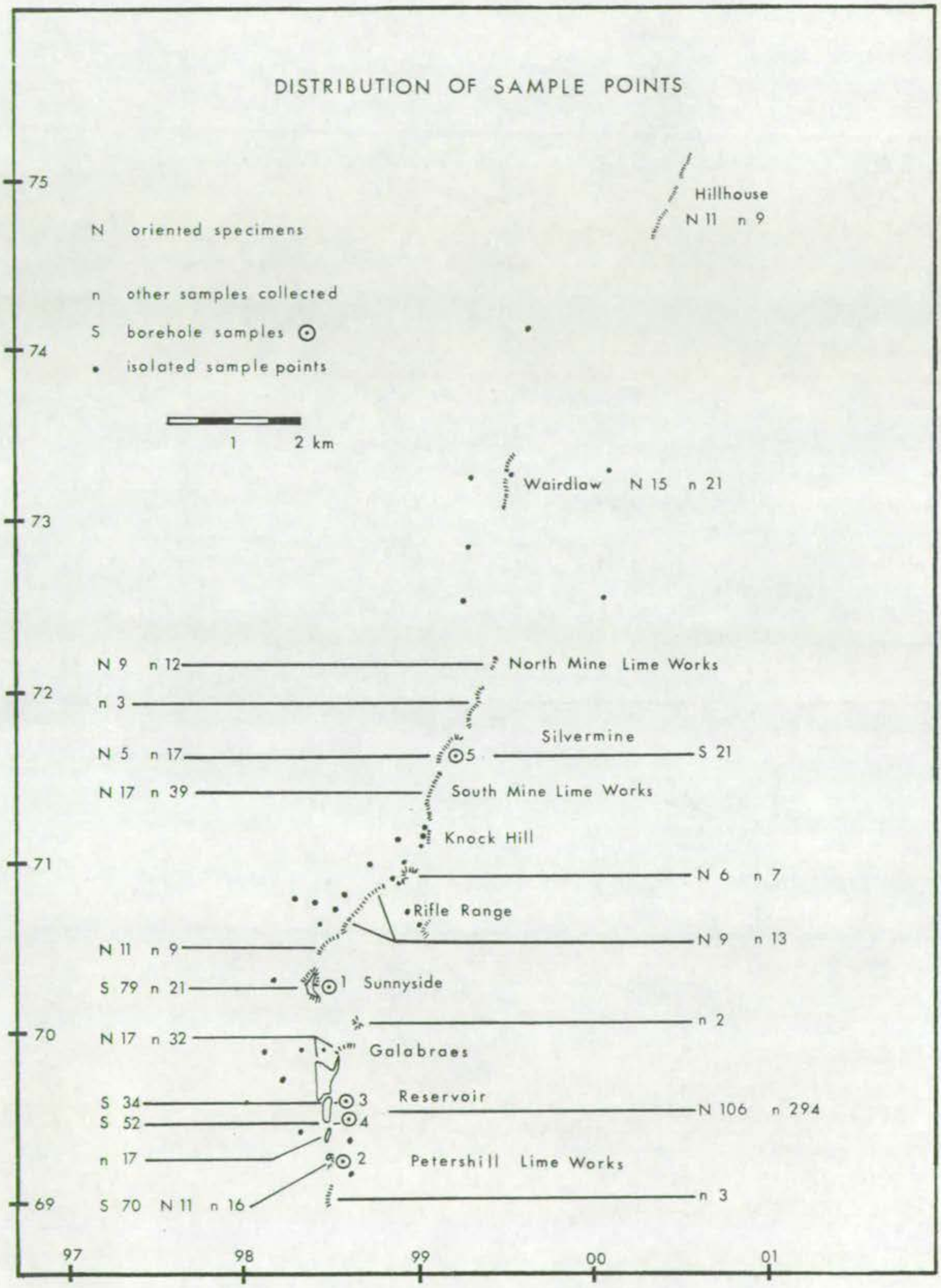


Fig. 0-9 Location of sampling points. Marginal divisions are National Grid numbers.

comparative purposes, and to establish the stratigraphy.

0.11.2 Sampling

In the course of the present study, a variety of sampling plans were used, depending on the purpose for sampling and the type of exposure. During mapping, all major outcrops were sampled for correlation purposes. A list of these appears in Table 0-8. Sample locations were recorded on photographs. Where possible samples were orientated with respect to north, "up" and dip; otherwise only "up" was recorded.

A plan based on sampling all exposures equally and at random was initially attempted and found impractical. Differences in accessibility, type of sampling point (quarry face, grassy slope, or borehole) precluded a uniform approach to sampling. More importantly, the value of hand specimens as a source of data differed significantly between facies. Sandy sequences, for instance, did not have to be sampled as extensively as limestones, because their major depositional processes could be deduced more easily from the study of larger scale sedimentary structures. Likewise, biohermal lithologies were sampled more extensively than unfossiliferous mudstones because of the greater diversity of fauna they contained.

0.11.3 Sampling strategies

0.11.31 Correlation and facies distinction

200 orientated samples   200 unorientated samples

At each locality described in Table 0-8 and shown in Fig. 0-9, vertical sections were compiled during mapping. With one exception, samples were taken at a minimum interval of 50 cm. Where facies changed rapidly, or where a diverse number of lithologies were encountered, one or more samples were taken from every bed, and along beds at roughly 1.0 m intervals.

0.11.32 Boreholes 250 specimens

In addition, five boreholes of 2.5 cm diameter core were sunk at the most easily accessible N-S limits of the Petershill Fm., and at intervals in between in order to complete the sequence. Core descriptions appear in Appendix B; their features are summarized in Fig. 2-12. Boreholes were found to be especially useful as they provided continuous sections, unweathered material, and information on the base of the Petershill Fm.

0.11.33 Faunal sampling and ecological analysis

Basic data on the fauna and palaeoecology was gathered by recording the fossils at each exposure and from large blocks. These large blocks (approximately 80 blocks between 30-100 cm^3) were taken from each lithology at major outcrops, broken up in the field and their fauna recorded. More detailed information was obtained from carefully orientated blocks which were broken up in the laboratory.

Fossils exposed on quarry faces were also recorded. Parts of overgrown and lichen-covered faces were cleared by washing down with hydrochloric acid. In the Reservoir Quarry, the southern face was cleared of a thick film of algae and mud (which had accumulated while the Reservoir was full) using a commercial sandblaster, through the courtesy of the Nature Conservancy Council. This was found to be an excellent tool for clearing off all the surface coatings and bringing out the contrast between fossils and matrix as well as sedimentary textures (dolomitic lamination, clastic and fossiliferous partings).

0.11.4 Analytical procedure

Fig. 0-10 shows how samples were processed, as well as illustrating the practical aspects of the integrated approach to analysis adopted here. Orientated specimens, the first source of information,

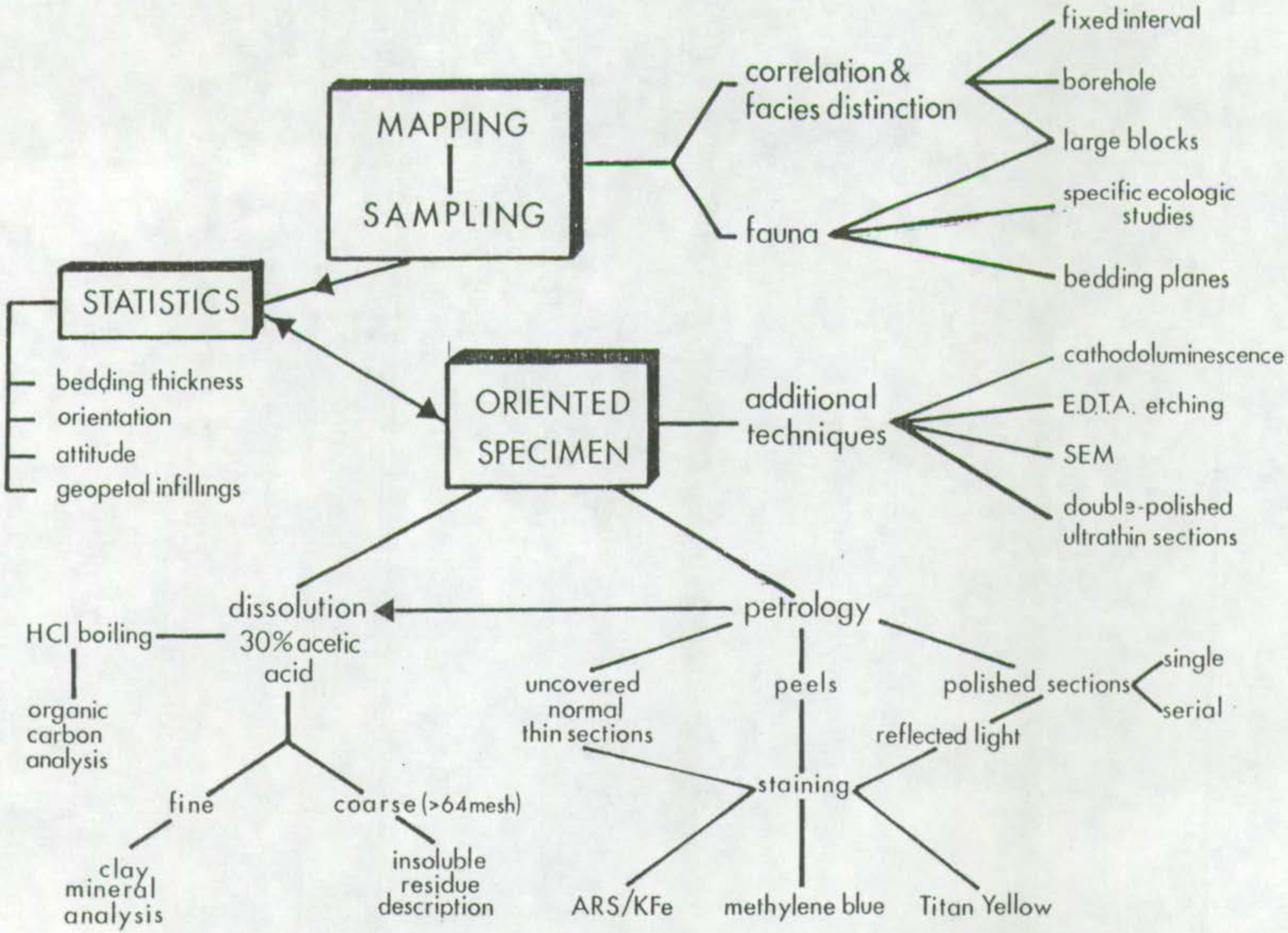


Fig. 0-10 Methods Flow Chart

were examined by a wide range of techniques (Fig. 0-10). Petrographic data from the orientated specimens was considered in conjunction with a spectrum of observations, ranging from field occurrence to Scanning Electron Microscopy. The final environmental interpretation was based on the examination of as many sources of data as possible, after a rigorous study of diagenesis (Ch 6).

0.11.41 Notes on techniques

A. Insoluble residue analysis and clay mineralogy - 38 specimens from the Petershill Fm., the Hillhouse Limestone and the Wairdlaw Limestone were analyzed. Samples were coarsely broken up (± 1 cm), weighed, dissolved in 30% (by volume) acetic acid, size fractioned, and the residue weighed (Fig. 0-10). The coarse size fractions were picked for microfossils and detrital grains, while the <64µ fraction was further separated for clay mineral analysis (Appdx C). Mineralogic analysis of the <5µ clay fraction was carried out; the details of this procedure are outlined in Appdx C.

B. Double-polished ultra-thin sections - 10-20µ thick, uncovered thin sections, polished on both sides with 0.35µ Aloxite were found essential in interpreting diagenetic textures and algal fabrics. Grain relationships, normally obscured by the thickness of standard slides became clear, as did subtle textures in fine-grained limestone fabrics. Uncovered sections also have the advantage of being usable in the Luminoscope.

C. Acetate peels and staining - A few modifications to the techniques described by Dickson (1966) were helpful in producing peels containing as much petrographic detail as double-polished thin sections:

a) the sample was polished with 0.35µ Aloxite

b) very thin 0.17 mm (0.003 inch) acetate sheet was used

c) the concentration of hydrochloric acid was varied to allow 5-15 minute etching times and approximately 1 minute staining time

d) the specimens were only stained once in a combined Alizarin Red S and potassium ferricyanide solution.

D. Scanning Electron Microscopy (SEM) - Scanning microscopy was carried out on a Cambridge Mark 4 Stereoscan at operating voltages between 20-30 Kv. Insoluble residues, EDTA-etched limestone surfaces and un-etched, broken fossil and limestone surfaces were examined by this method.

E. Cathodoluminescence - Electron-excited luminescence, or cathodoluminescence, relies on the principle that an electron beam, when focused onto an uncovered thin section, will cause traces of an activator such as Mn^{++} in the calcite or dolomite lattice to luminesce orange/red. The presence of Fe^{++} or Fe^{+++} quenches luminescence. This principle makes it possible to examine the results of changes in the composition of pore water during diagenesis (Meyers 1978). Fluctuations in activator-quencher composition, usually of iron, appear as very fine zones in cements, similar to, but much more detailed than those revealed by staining. Sipple and Glover (1965) and Nickel (1978) provide a comprehensive explanation of luminescence.

Previous research on carbonates using cathodoluminescence has tended to concentrate on diagenesis, focusing on dating cement sequences (q.v. Nickel 1978). The present study, however, also shows that cathodoluminescence is an invaluable aid to textural studies.

The advantages of cathodoluminescence in textural studies lie in its ability to resolve the shape of crystals, while revealing their composition and often showing up internal structure unrecognizable in plane polarized light (q.v. Ch 6). In revealing the outline of a crystal clearly it becomes possible to identify fossil fragments.

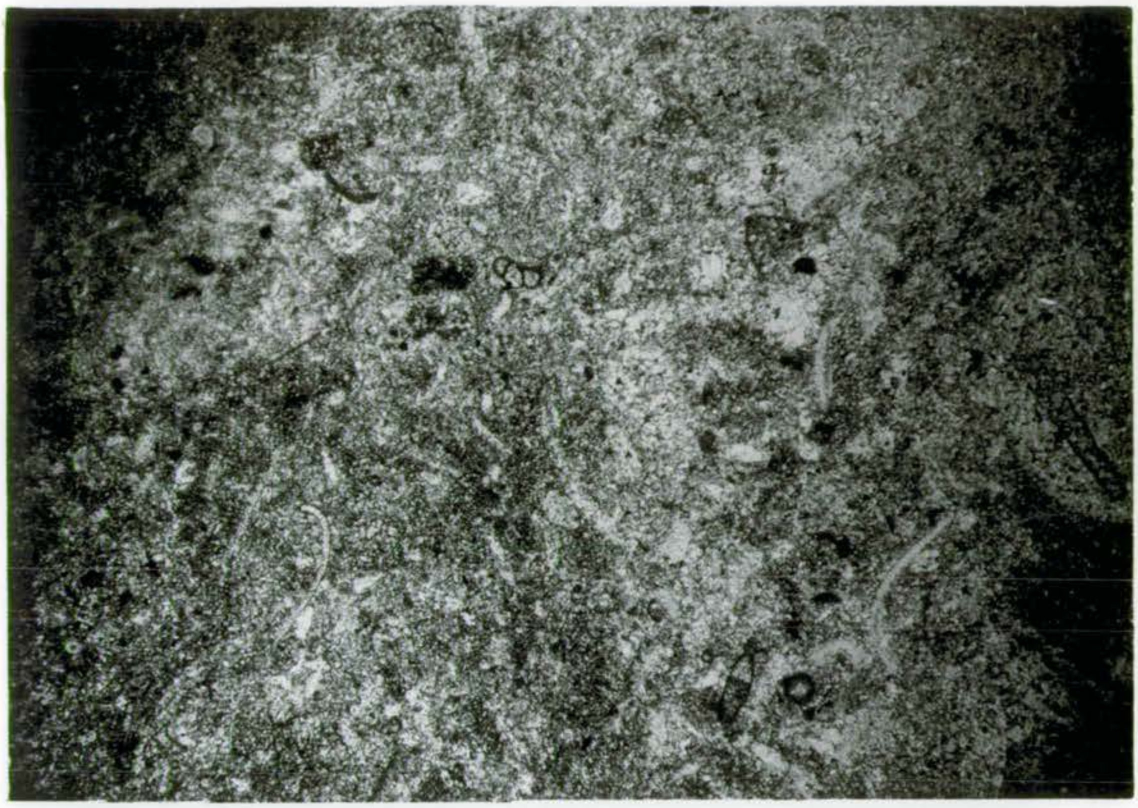
Cathodoluminescence additionally resolves zones in cements not detectable by staining or by microprobe analysis. Where being able to distinguish matrix and cement is a problem (e.g. Figs. 0-11; 0-12), cathodoluminescence becomes an invaluable tool.

Luminescence may additionally reveal that apparently abraded particles are actually unworn, a sign of textural immaturity. Codiacean algae, mollusc, sponge and other fragments that are preserved as skeletal moulds are particularly likely to appear in significantly higher proportions with cathodoluminescence. Estimates of sorting and packing (grain support) are also markedly different in transmitted light and under cathodoluminescence, the latter method recovering information usually obscured by diagenesis.

Figures 0-11 and 0-12 illustrate many of the points made above. In the transmitted light images it is difficult to determine the origin of much of the pseudospar-sized matrix crystals. Moreover, the few identifiable foraminiferans and ostracods (arrow, Fig. 0-11) lead to an impression that they are the dominant allochems in a moderately-sorted assemblage of broken skeletal debris. The luminescent image resolves many of the unrecognizable sparry blebs as moulds of siliceous sponges, gastropods, the dasycladacean alga *Sphinctoporella*, and trilobites. Point counts of the percentage fossils from six probable wackestones similar to those illustrated yielded an average of 20% (range 12-44%, 400 points/section) more fossils with cathodoluminescence than transmitted light counts. More sponge spicules were counted in the cathodoluminescent image than foraminiferans and ostracods combined, indicating that both the absolute and relative percentages of grains may be different. The increase in detail also extends to the relationships between grains: with cathodoluminescence, evidence suggesting grain support is much greater. Moreover, the presence of delicate

Fig. 0-11 Petrographic value of cathodoluminescence: Photomicrographs of a slightly argillaceous biomicrosparite in transmitted light (top) and with cathodoluminescence (bottom). g.I. 46,340.

Comparison of the two figures reveals striking differences in composition, grain size, and packing. With cathodoluminescence, the indistinct sparry areas of transmitted light image are revealed to be skeletal moulds, infilled with non-luminescent (black) cement. Fossils include: sponge spicules (s); gastropods (g); and trilobite thoracic segments (t). Fossils presumed to have recrystallized early (q.v. Ch 6) such as the ostracod (o) and foraminiferans, have similar luminescent characteristics to the matrix and thus do not contrast. Delicate structures such as the spines on fossil fragments (del) which are only apparent with cathodoluminescence, reveal that many grains are immature, and therefore only slightly reworked. Galabraes Quarry, scale bar = 1 mm.




del
s
s
g
o
t
b

Fig. 0-12 Petrographic value of cathodoluminescence: transmitted light (top) and cathodoluminescent (bottom) photomicrographs of a slightly argillaceous biomicrosparite. g.T. 46, 341.

Comparison of the two images illustrates the value of cathodoluminescence in petrographic interpretation. Dasycladacean alga (*Sphinctoporella*, d) and a perforate-walled foraminiferan (*Bradyina*, B) become readily apparent with cathodoluminescence, as do differences in skeletal preservation. Selective dissolution within a productoid spine (sp) is shown by non-luminescent (black) laminae. Differences in the degree of neomorphism only affect luminescent characteristics slightly, shown by differentially recrystallized but still uniformly luminescent, matrix, and the sparry and micritic areas of benthonic sessile foraminiferan, *Earlandia vulgaris* (e). Reservoir Quarry, scale bar = 205µ.


a


b
e
B
sp
d

structures and poorer sorting shown by cathodoluminescence indicates that the allochems are less mature than the impression from transmitted light would suggest. Thus cathodoluminescence may provide so much more petrological data as to radically change a sedimentological interpretation.

Operating conditions - Vacuum - 0.05 Torr. Operating voltages - 13-18 Kv; 39 mA in a Nuclide Corporation Luminoscope mounted on a Leitz binocular microscope. Images recorded on FP4, 35 mm film uprated to 200 ASA. Fluctuations in the operating voltage account for differences in the intensity of the luminescent images shown throughout the text. Higher operating voltages yielded better images and resolved a greater number of compositional zones, but often burned thin sections, making them unusable for subsequent work.

0.12 Statistical analysis

Wherever possible the observations made in this thesis were confirmed statistically. This approach ensured that a more consistent method of data collection was adopted towards each lithology. Specific studies were carried out on the following:

A) geopetal infillings;
B) large and small-scale sedimentary structure orientation;
C) bedding thicknesses;
D) the attitude and orientation of productoids and solitary corals.

0.13 Curation

The majority of the specimens collected as part of this thesis, are housed in a permanent thesis collection in the Royal Scottish Museum. Photographs showing the exact location of each sample are included as part of that collection. A smaller collection, together with the borehole cores, is housed in the Grant Institute of Geology.

0.14 Presentation

This thesis is presented in two volumes. The first contains the Table of Contents for both volumes and the main body of text. The second contains the references, appendices, and the unbound figures in a back pocket.

Throughout the text new terms have been underlined as they have been introduced or defined. Underlining has also been used sparingly as a means of emphasis. The usage of well-accepted terms with somewhat ambiguous meanings is clearly defined in Appendix D, a glossary.

Various symbols and abbreviations have been employed in the figures and the lithological descriptions in some chapters. A key to these is provided in Figures 0-13, 0-14, 0-15 which follow. Specimens housed in the Grant are labelled with the preface G.I., those in the Royal Scottish Museum, with RSM.

Fig. 0-13 Key to common lithological symbols

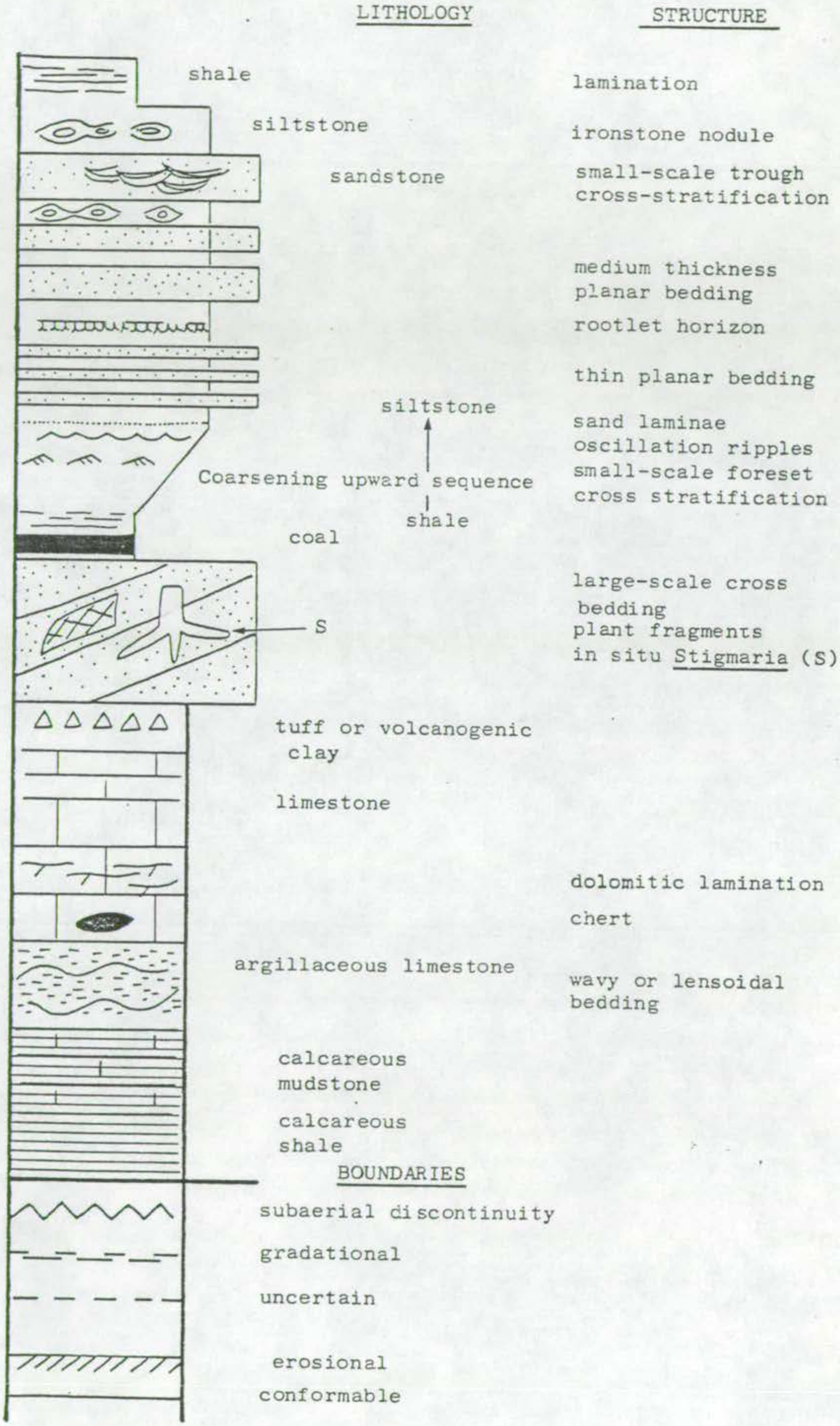


Fig. 0-14 Key to common fossil symbols

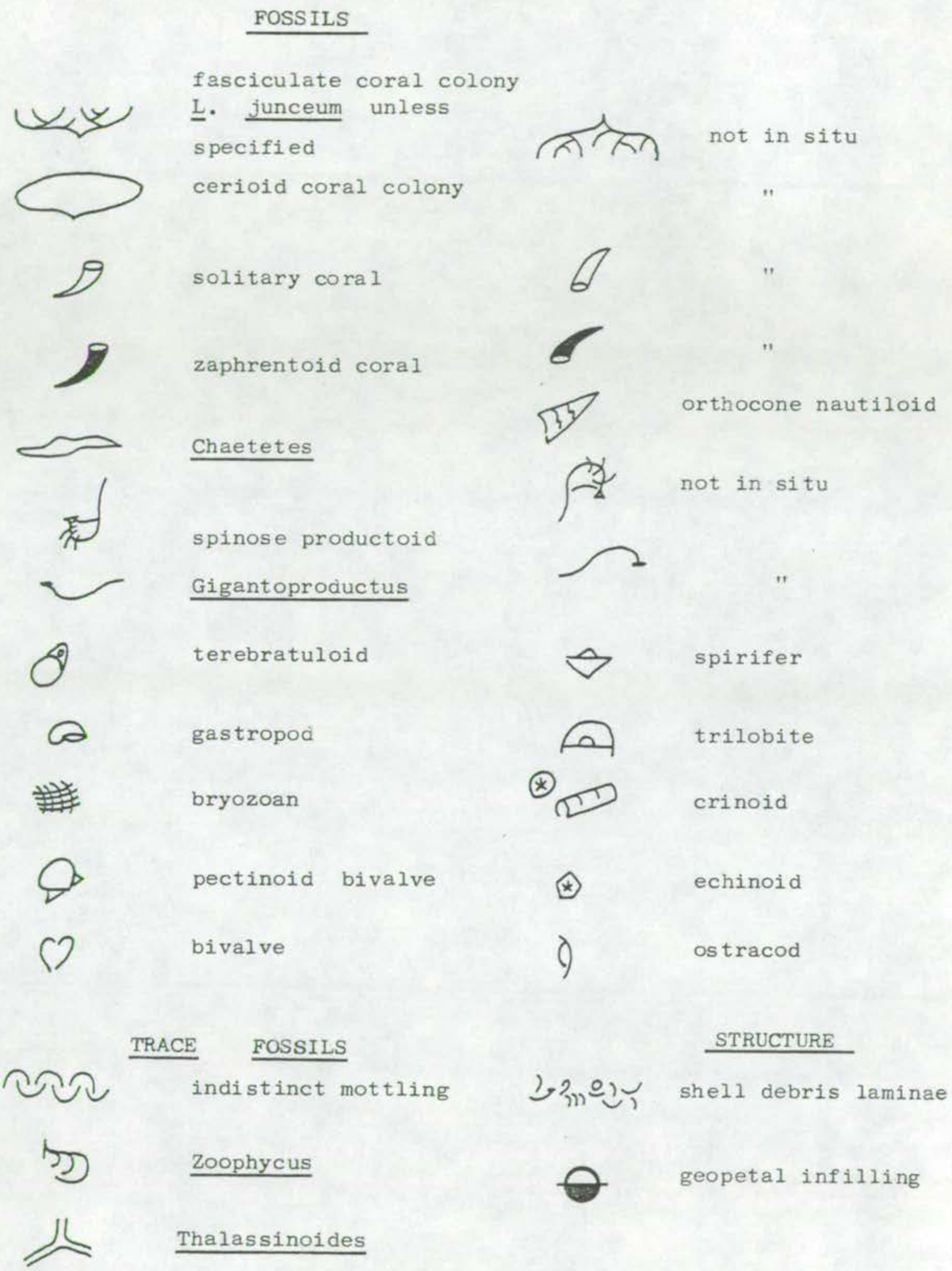


Fig. O-15

Key to commonly used abbreviations

Lithologies:

grnst-	grainstone	bmsp/biomsp-	biomicrosparite
pkst-	packstone	lst/lmst-	limestone
wkst-	wackestone	mdst-	mudstone
sh-	shale	slst-	siltstone
sst-	sandstone	argill-	argillaceous
calc-	calcareous	dolo-	dolomitic

Modifying terms:

lg-	large	th-	thick
med-	medium	x-strat-	cross-stratified
sm-	small	mod-	moderate
brach-	brachiopod	crin-	crinoidal
bryz-	bryozoan	sol-	solitary
qtz-	quartz	biot/biot'd-	bioturbated
carb-	carbonaceous	sfce-	surface

THE PETERSHILL FORMATION

CHAPTER 1

TYPE DESCRIPTION

1.0 Introduction

It is proposed that the Petershill Fm. be adopted as a formal lithostratigraphical unit in Scottish Carboniferous stratigraphy. "Petershill Formation" is proposed in preference to "Petershill Limestone Formation" because the latter mistakenly implies that the sequence is predominantly carbonate. It includes the sequence previously referred to as the Petershill Limestone by various authors including Wilson (1966); Parks (1966); Latham (1933); Macgregor (1930); Macgregor and Anderson (1923); Cadell (1925); and Smith (1913). It also replaces other confusing names given to the same sequence in the past, namely: Main Limestone (Cadell 1925, p 141); Hurlet Limestone and Great Limestone (Howell and Geikie 1861; as well as several other authors); Silvermine Limestone (Macgregor and Anderson ibid). The name is taken from Petershill Farm on which the limestones were probably first quarried (located on Fig. 0-7, Appdx, back pocket).

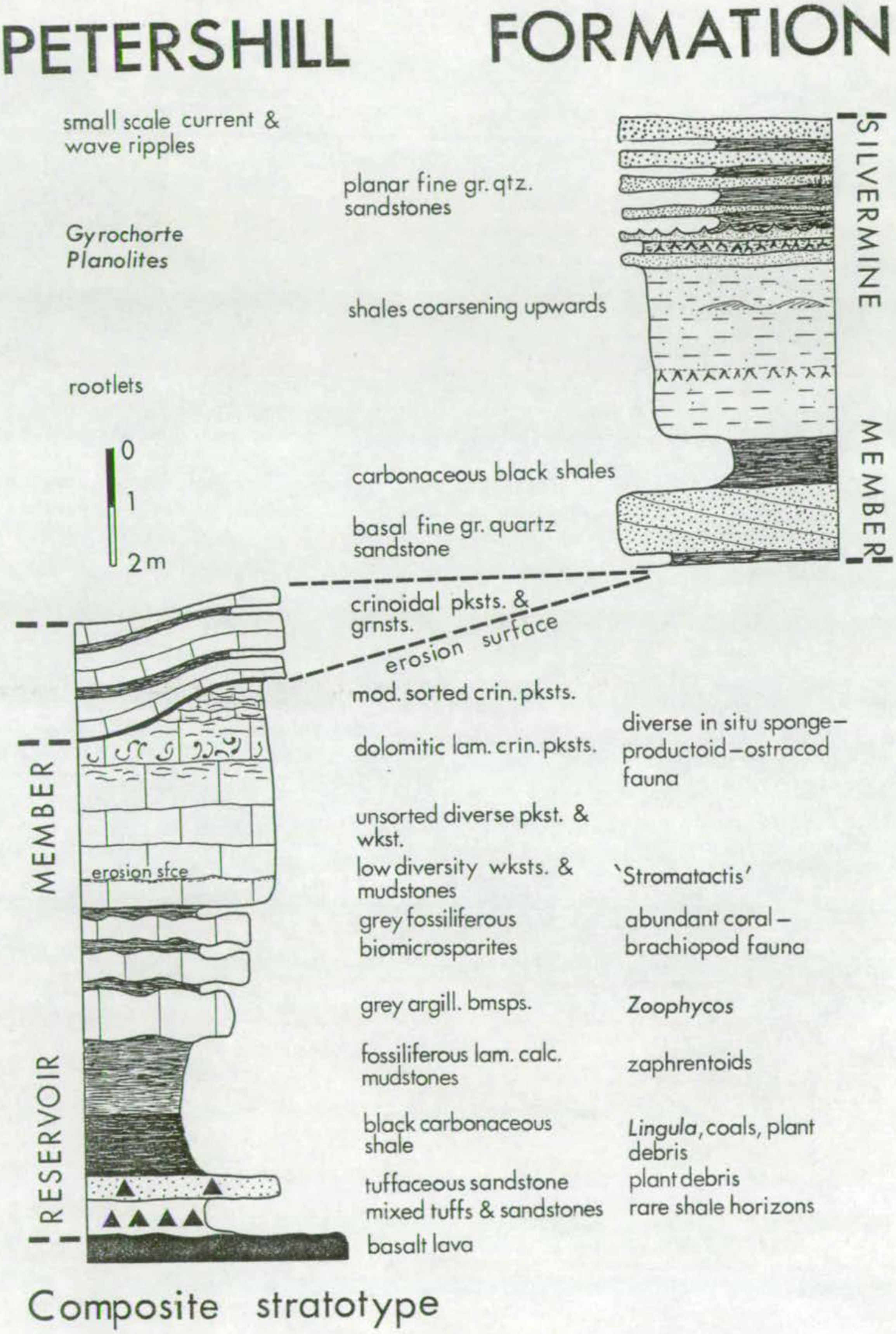
1.1 Limits of outcrop of the Petershill Formation

The Petershill Fm. extends 4.2 km along strike from the town of Bathgate to North Mine Quarry (grid refs. NS 983 692 - NS 996 722), bounded by the Heatherfield fault at Bathgate, (Figs. 1-2; 0-2; 0-7) and a quartz dolerite dyke at North Mine Quarry. North and south of these limits, the typical succession can no longer be recognized due to facies changes and poor exposure. Stratigraphically, the Petershill Fm. includes all the sedimentary rocks between two major lava flow sequences in the Lower Limestone Group.

1.2 Type localities

A composite stratotype has been chosen for the Petershill Fm. based on the sequences at the Petershill Reservoir and South Mine Lime

Fig. 1-1 Composite stratotype of the Petershill Fm.



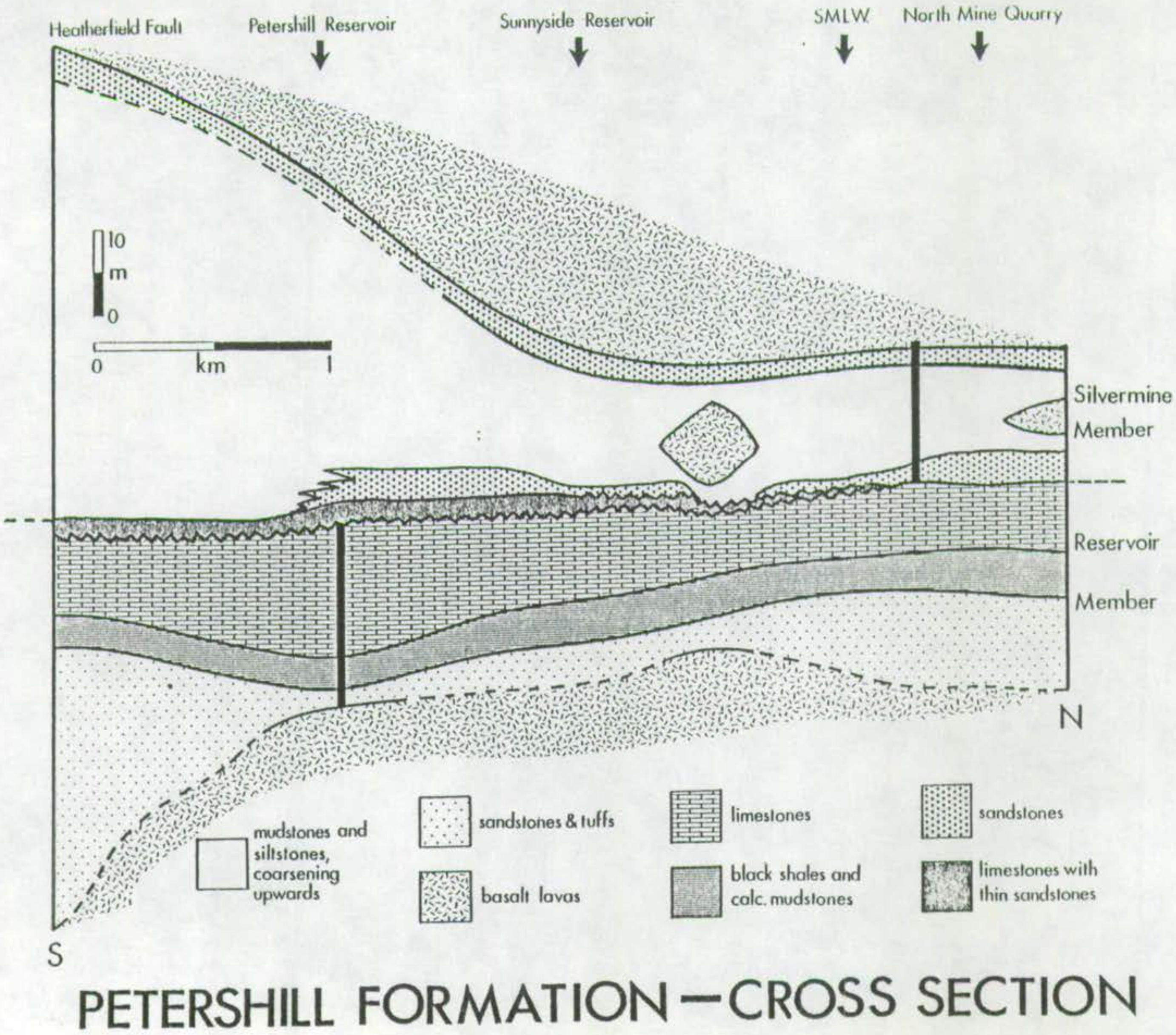
Works. The two exposures provide a complete, but not entirely representative section through the Petershill Fm., because of lateral facies changes (Figs. 1-2, A-1, Appdx). Two members are recognized within the Petershill Fm.; the lower, which is predominantly carbonate, is termed the Reservoir Member, above which is a predominantly clastic sequence termed the Silvermine Member. Over most of the Petershill Fm. outcrop the two are separated by an unconformity, occurring roughly in the middle of the sequence (Figs. 1-1; A-1).

1.3 The Reservoir Member

The base of the Reservoir Member (and of the Petershill Fm.) is drawn at the top of an approximately 80 m thick sequence of basalt lavas with thin sedimentary horizons. Overlying the lavas is a variable thickness (2-25 m) of tuffs, sandy tuffs, and finally sandstones. The sandstones and tuffs are succeeded by a fairly uniform thickness of carbonaceous shales with one or more coals, Lingula, and marine bands containing bivalves, productoids, and serpulids. The shales are followed by rather unfossiliferous, calcareous mudstones grading upward into argillaceous limestones. Up to the stratigraphic level of the argillaceous limestones, the type section is similar to that found elsewhere in the Petershill Fm. Above this horizon, there is considerable lateral facies variation (Fig. A-1, back pocket Appdx) such that the sequence elsewhere in the Petershill Fm. outcrop may not be identical to that of the type locality.

At the type locality argillaceous limestones gradually become more calcareous and fossiliferous, giving way to 2-3 m of grey, wavy-bedded biomicrosparites with an abundant fasciculate and solitary coral fauna (q.v. Fig. 2-9). The slightly argillaceous limestones inturn pass upward into cream-coloured, high-carbonate biomicrosparites with a diverse productoid-sponge-fenestellid fauna. An erosional

Fig. 1-2 Generalized cross-section, solid vertical bars show location of stratotypes.



surface (surface A), interpreted as a subaerial discontinuity separates the high-carbonate biomicrosparites from a 6-10 m thick sequence of poorly bedded, often laminated high-carbonate biomicrosparites above. These form a biohermal facies characterized by an association of productoids, sponges, rostroconchs, bryozoans, crinoids, and echinoids. A second erosion surface (surface B), also interpreted as originating during subaerial exposure, marks the top of the biohermal facies (Figs. 1-1; 2-9). It forms a prominent break in quarry faces which may be traced between quarries along most of the Reservoir (surface B, Fig. A-1). This erosion surface passes laterally into an apparently conformable limestone sequence at South Mine Lime Works and further north.

The erosion surface is overlain by 2-3 m of crinoidal packstones, usually moderately- to well-sorted. These packstones constitute the top limestones of the Reservoir Mbr. The boundary between the Reservoir and Silvermine members has been drawn at the top limestone of this sequence, usually a distinctive thick to massive crinoidal packstone. The top limestone surface of the Reservoir Mbr. is also a subaerial discontinuity over most of its lateral extent (surface C, Fig. A-1).

1.4 The Silvermine Member

The Silvermine Member is named after the Silvermine at Hilderstone Farm, located at the north end of South Mine Lime Works (Figs. 1-2; A-1).

At the type locality and over most of its lateral extent, the Silvermine Mbr. basal unit consists of a 2-3 m thick, fine-grained quartz sandstone. South of the Petershill Reservoir this basal sandstone passes into carbonaceous shales with a sparse marine fauna. The sequence above coarsens upward from carbonaceous shales through siltstones, into sand laminated siltstones, giving way to thin- and eventually medium-bedded sandstones. The upper boundary of the Silvermine Member and the Petershill Fm. is drawn at the base of the lava flow succeeding the coarsening-upward sequence.

1.5 Stratigraphy

The Petershill Fm. may be locally correlated with the Hillhouse Limestone further north and regionally correlated with the un-named limestone at St. Magdalene's Distillery, Linlithgow (q.v. Macgregor and Haldane 1933), the Carriden No. 5 Limestone and the Foul Hosie Limestones. The foraminiferan fauna of the Petershill Fm. place it in the V_3c zone, of the uppermost Viséan, in the newly-erected Brigantian stage.

CHAPTER 2

INTERNAL STRATIGRAPHY OF THE PETERSHILL FORMATION

2.0 Introduction

A pre-requisite to the delineation of facies and the interpretation of depositional environments is an understanding of the lithological and stratigraphical relationships between the various exposures in the Petershill Fm. In this chapter the sequences at the major exposures in the Petershill Fm. are described and correlated for the first time. The stratigraphical relationships described here form the basis for the facies described in subsequent chapters. The following description follows a traverse from north to south along the exposures of the Petershill Fm., with a later description of the boreholes.

A key to the commonly used symbols and abbreviations is presented in Figs. 0-13, 0-14, 0-15. Symbols which are not listed in these figures are otherwise labelled. The symbol conventions presented in these figures have been altered in a few places in subsequent chapters where greater detail was necessary.

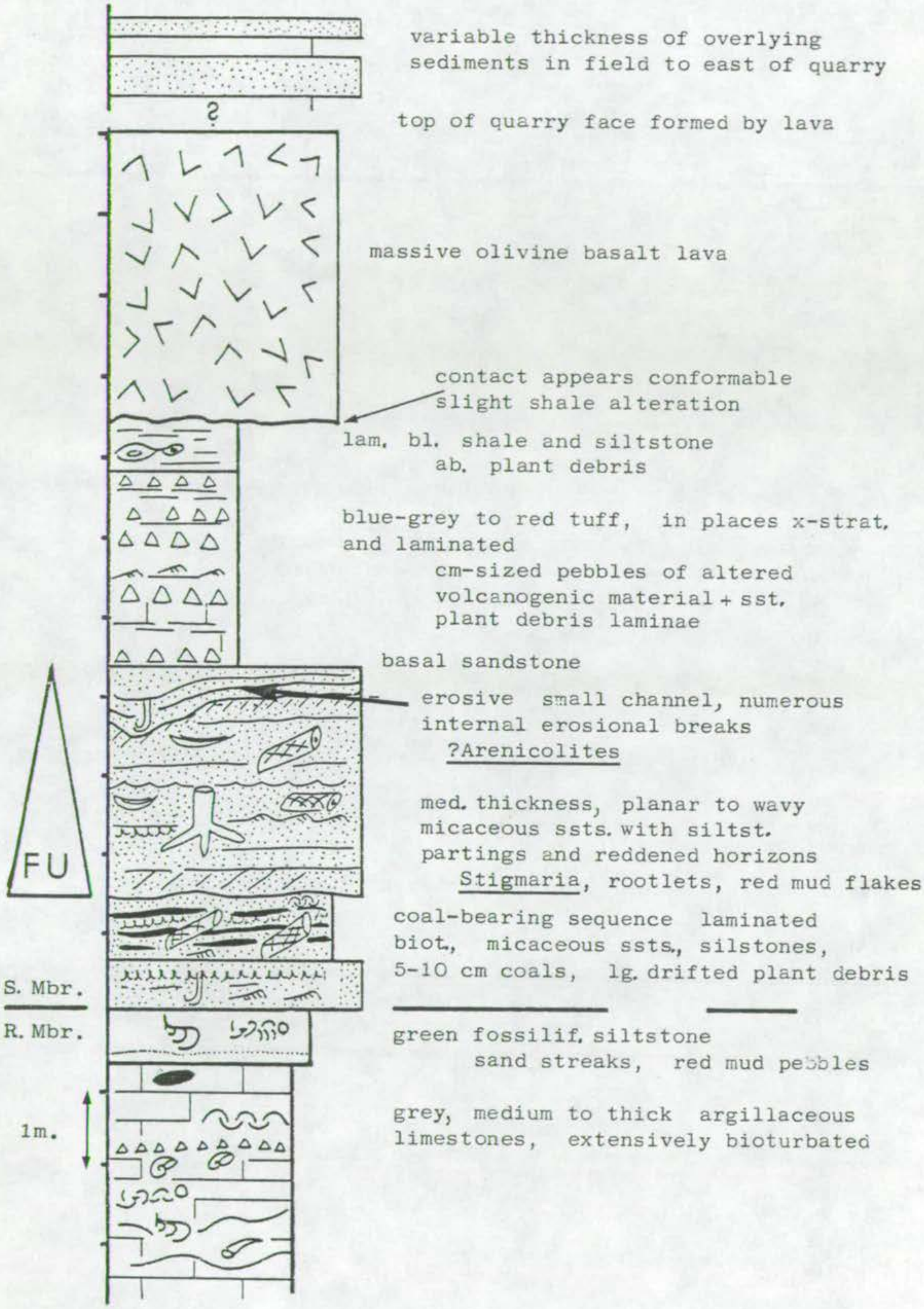
2.1 North Mine Quarry Fig. 2-1

2.11 Field relationships

This is the northernmost exposure of undoubted Petershill Fm.; further north outcrops are too scattered and poor for lithological correlation.

An E-W dyke transects the Petershill Fm. immediately north of the quarry (Figs. 0-7; 0-2). Further north previous workers have recorded two exposures between the Petershill Fm. and the Hillhouse Limestone: Geikie's 10,560:1 Geological Survey map (1897) shows a limestone quarry occurring 200 m north of North Mine Quarry, and Cadell (1925, p 140) reported 23 metres of sediments in a borehole 2 km north at Balmorvie Farm.

Figure 2-1 The sequence at North Mine Quarry NS 9960 7206



This unusual thickness of sediments between the lavas may suggest that the sequence is continuous at the Petershill horizon through the area of greatest lava thickness. The limestones, however, are unlikely to be continuous between the Petershill Fm. and the Hillhouse Limestone. Limestone was, at one time, a valuable resource in the Bathgate Hills which has been exploited at every possible surface outcrop, to the extent of being mined at depth underground. Even the poorest quality limestone outcrops have been extensively quarried. The absence of any such quarries along the strike section between the northernmost Petershill Fm. exposure and Hillhouse thus strongly suggests that the limestone part of the sequence is laterally discontinuous. The sediments in this northern area appear to be atypical of either the Petershill Fm. or the Hillhouse Limestone, and are best regarded as being transitional between the two.

2.12 The sequence Fig. 2-1

The quarry is partly infilled and heavily overgrown. Most of the present exposure is in the Silvermine Mbr., although a few metres of the Reservoir Mbr. are seen in the northern extremities of the quarry. Cadell (1925, p 140) recorded a further 11 m of limestones (almost certainly underlain by mudstones and tuffs) below the base of the present exposure.

The sequence begins with 2 m of argillaceous biomicrosparites, probably lensoidally bedded (q.v. Ch 3). Nearly 1 m of bioturbated fossiliferous siltstones containing reddened and slightly rounded mud pebbles overlie the limestones. The limestone-siltstone boundary, which is well exposed for over 20 m laterally, appears to be conformable. The siltstones pass upwards first into thin-bedded, micaceous sandstones with rootlets and Arenicolites, then into a coal-bearing sequence, followed by a thick basal sandstone (Fig. 2-1). This sequence is described in greater detail in Ch 15. The size of sedimentary structures and (to a lesser extent) grain size decrease upwards within the basal sandstone, while the number of horizons indicating exposure (e.g. rootlets) progressively increase in number upwards.

The sandstones at base of the Silvermine Mbr. are overlain by a blue-grey to buff or red laminated tuff with numerous horizons of plant debris, pebbles of altered coarse volcanogenic material, and sandstone. A laminated micaceous or sandy black shale, very similar to that found at the equivalent horizon elsewhere (Figs. 0-7; A-1), overlies the tuff. The whole sequence is then capped by a slightly vesicular, olivine basalt. There are no indications of intrusion, and the basalt sheet is considered to be a lava flow. Although it cannot definitely be established, it is almost certain that clastic sediments overly the lava, as indicated by the shaly soil and abundant sandstones in the field immediately to the east (Fig. 0-7 back pocket).

2.2 North Mine Quarry to South Mine Lime Works (SMLW)

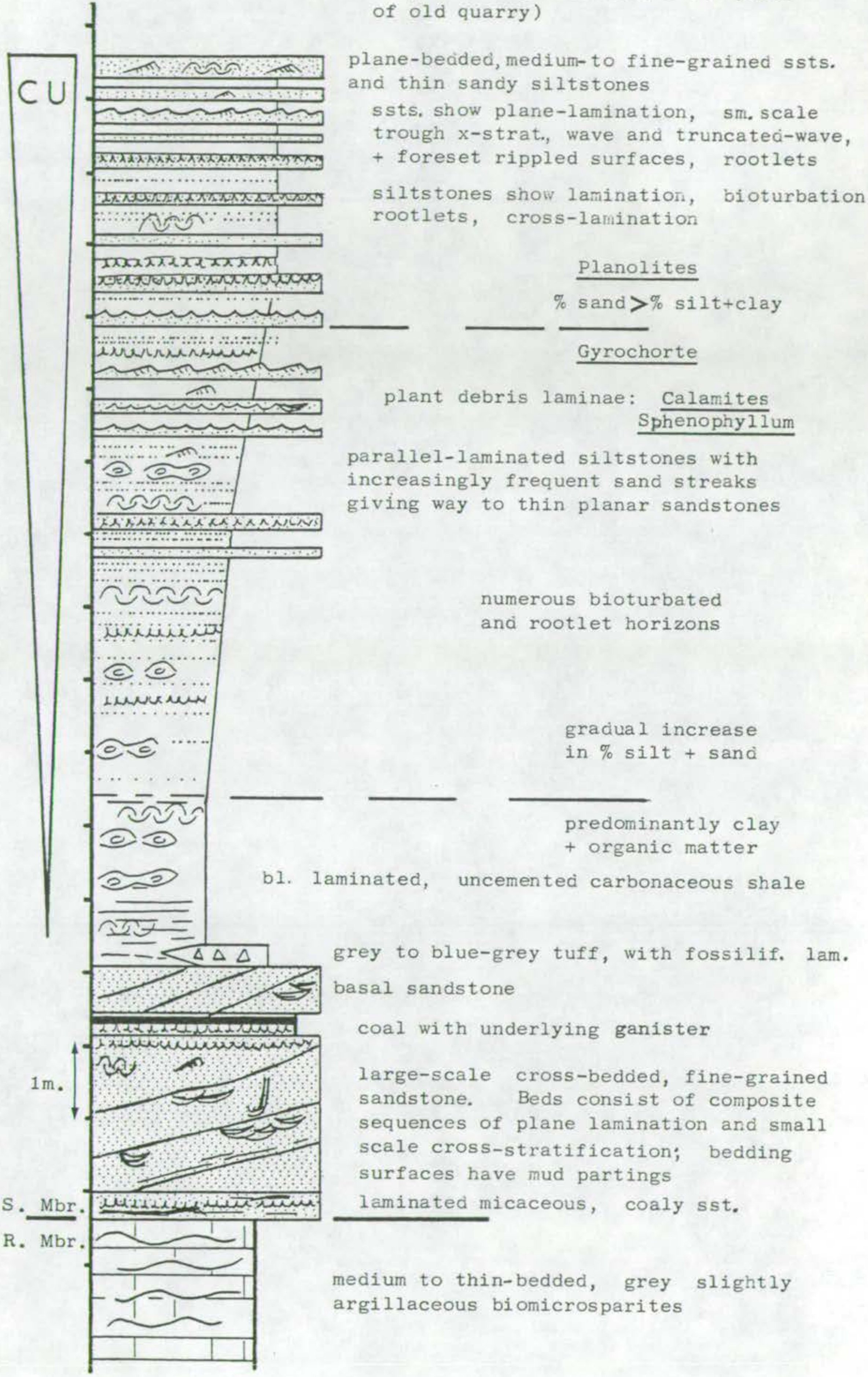
The old quarries between N. Mine Quarry and the north end of SMLW (commonly known as the Silvermine) are almost completely overgrown. Several significant lateral lithological changes take place along this interval (shown in Fig. A-1) which can be traced in these discontinuous outcrops. In traversing from north to south, the limestones become less argillaceous, while the overlying basal sandstone and tuff become progressively thinner. The lava which forms the top of the sequence at N. Mine Quarry pinches out within a few hundred yards south of the sequence illustrated in Fig. 2-1 (see Figs. 0-7; A-1).

2.3 South Mine Lime Works (SMLW) Fig. 2-2

2.31 Field relationships

The Silvermine Mbr. (abbreviated S. Mbr.; Fig. 2-2) is exposed continuously for over 500 m in this, the type and best exposed section.

Fig 2-2 The sequence at South Mine Lime Works NS 990 714 (composite sequence from N + S parts of old quarry)



A few metres of the underlying limestones, cross-cut by a dyke, are exposed at the southern end of the quarry (Fig. 15-5), thus establishing the relationship between the limestone and sandstone sequences. A complete section through the limestones was obtained by drilling a borehole at Silvermine (Fig. 2-12; described in Appdx B).

2.32 The sequence Fig. 2-2

The sequence, which appears to be conformable, consists of limestones, overlain by the basal sandstone, passing up into a tuff (which pinches out over the length of the quarry) and finally a coarsening-upward (CU) sequence. The coal-bearing sequence is largely absent from the basal sandstone, being supplanted by large-scale cross-bedded sandstones (described in detail in Ch 15). The beds above coarsen upward from black shale, through sand-laminated (streaked) siltstones, into discrete sandstones (Fig. 2-2).

2.4 South Mine Lime Works to the Rifle Range

To the south of SMLW, in the vicinity of Knock Hill (Fig. 2-3), the geology at the horizon of the Petershill Fm. is complicated slightly by intrusive igneous rocks, and a lava flow within the Petershill Fm. Previous geological interpretations of Knock Hill (Peach et al. 1910, p 285) have failed to recognize the lava flow in the Petershill Fm. and have, instead, postulated a steeply-dipping fold. A much simpler interpretation is put forward here, which is felt to be in closer agreement with the field data.

2.41 Knock Hill Figs. 0-2; 0-7; 2-3

The prominence of Knock Hill is formed by a tabular dyke of quartz dolerite dipping steeply eastward. On the western side, basalt lavas are in contact with the dyke; the contact between the two is seen clearly in a roadside quarry (Q, Fig. 2-3) and may be traced for 40 m to the south. On the eastern side of the hill, the country rock is not exposed, but it seems likely that the dyke abuts against limestone, as there are limestone xenoliths in the exposed lower dyke surface. South of Knock Hill the Knock Hill dyke transects the Petershill Fm. and another smaller E-W trending dyke at the northernmost Rifle Range quarry (Peach et al., ibid; see also Fig. 2-3).

Neither period of intrusion shows any signs of having been accompanied by folding or significant structural deformation. The dip and dip directions of the limestones north and south of Knock Hill, and those of the sandstones stratigraphically underneath (exposed 150 m east, Fig. 0-7) vary only slightly, as they do all along strike. It is thus very difficult to find any evidence for Peach's (ibid) postulated fold. On the contrary, (as shown in Fig. 0-7) it is more likely that the sequence is only slightly disturbed, changing strike direction to west-southwestward, while dipping uniformly west.

2.42 The lava flow in the Petershill Formation

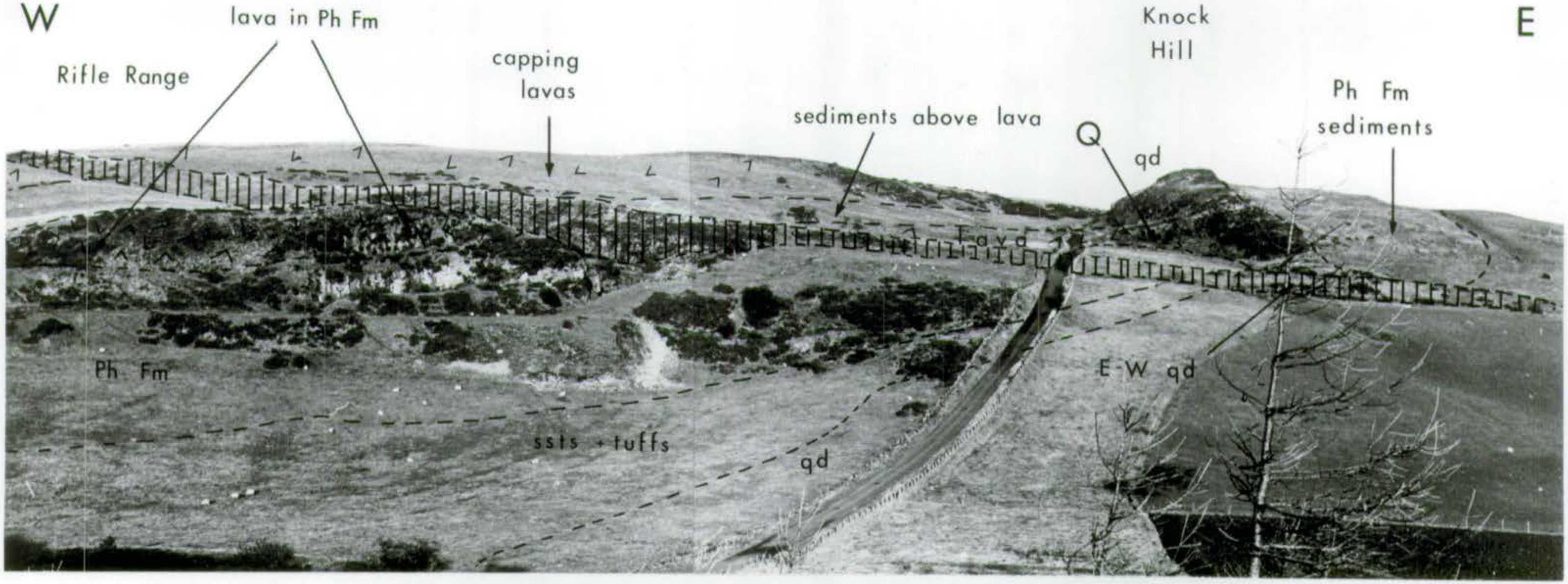
A lenticular body of olivine basalt occurs within the upper Petershill Fm. between Knock Hill and the upper (northern) Rifle Range quarries (as shown in Figs. 2-3; 2-4; 0-7). Field relationships suggest that it is a lava flow, occurring at an equivalent stratigraphic level to that at North Mine Quarry, and therefore probably related to it (Fig. A-1, back pocket).

The lava extends from the western side of Knock Hill to the northernmost Rifle Range Quarry (Figs. 2-3; 2-4). In the northern Rifle Range the shape of the lava, its stratigraphic position, and its lower contact are particularly clear (drawn out in Fig. 2-4). The overall impression is of a single sheet, or perhaps two overlying sheets, a total of 10 m thick, extending laterally for as much as 400 m at a horizon 3 m above the top limestone bed.

Structures typically associated with an intrusive igneous body

Fig. 2-3 Knock Hill

A southwestward-looking view from Raven Crag (located on Fig. 0-7) shows relationships between intrusives (Knock Hill dyke and the smaller E-W dyke, lined), the lava flow within the Petershill Fm. and the lavas capping the Petershill Fm., on the brow of the hill.


W
lava in Ph Fm
Rifle Range
capping lavas
Knock Hill
E
Ph Fm sediments
sediments above lava
Q
qd
lava
Ph Fm
E-W qd
ssts + tuffs
qd

(e.g. injection structures, xenoliths, contact alteration/baking, mineralization, columnar jointing) are absent. Moreover, the shale underneath is uniform in thickness and appears undisturbed. These data strongly suggest the basalt is a flow and not intrusive.

A broad, shoulder-like break in hillslope above the lava (Fig. 2-3) further suggests that several metres of clastic sediments overlie the flow. The clastic sequence typically forms a similar break in slope further south, where the sequence is uninterrupted.

2.5 The Rifle Range quarries

2.51 Exposure

The line of quarries which were once part of a rifle range provide discontinuous, but closely-spaced exposures at the horizon of the Silvermine-Reservoir Mbr. boundary. The Reservoir Mbr. is best exposed in north Rifle Range (Fig. 2-4) and along the eastern banks further south, while the Silvermine Mbr. is exposed along the western banks of the old quarries. The top limestone bed (the intermember boundary, see Figs. referred to) provides a readily recognizable datum for correlation between the various exposures.

2.52 The Reservoir Mbr.

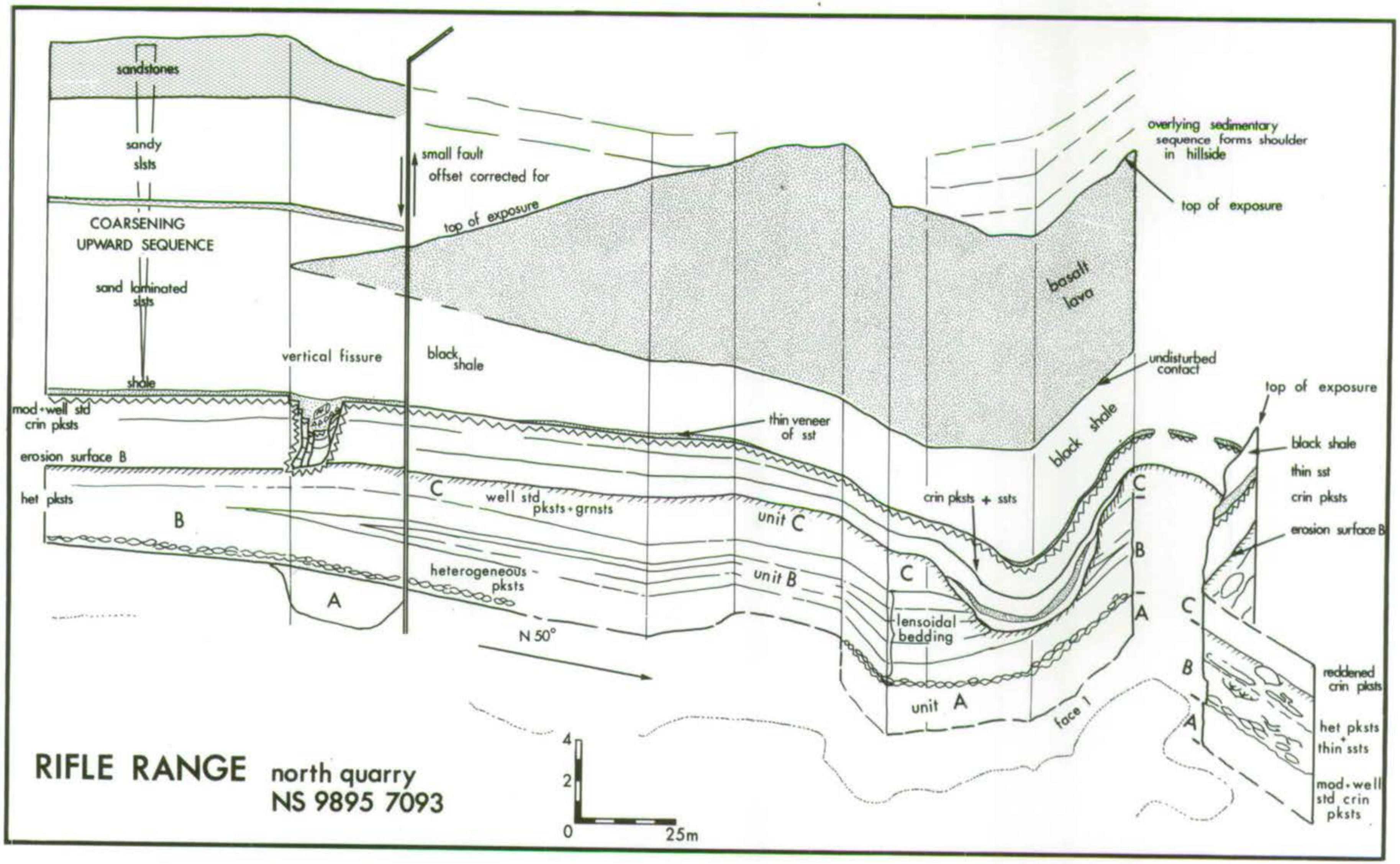
Three major lithologic units (A, B, C, Fig. 2-4; see also Ch 10) are continuous along the Rifle Range quarries and further south:

Unit A: moderate to well-sorted crinoidal packstones - This, the lowest unit, is composed of crinoidal packstones with a sparse fauna of *Lonsdaleia floriformis*, *Gigantoproductus*, sp. and *Chaetetes* sp. It is typically poorly-bedded and fairly massive.

Unit B: heterogeneous packstones - This unit consists of medium to thin, wavy, or lensoidally-bedded limestones (see Sect 3.26; Fig. 2-4) separated by thin calcareous mudstones. The limestones are characterized by a petrographic heterogeneity in grain composition and

Fig. 2-4 Northernmost Rifle Range Quarry.

A generalized drawing of the relationship between quarry faces. The sequence consists of limestones belonging to the Reservoir Mbr. up to the top of the moderate and well-sorted crinoidal packstones. A fissured discontinuity surface overlain by a thin sandstone veneer occurs at this top limestone horizon, followed by a black shale and the basalt lava flow. A photograph of part of the sequence illustrated here is shown in Fig. 13-2 (Ch 13).


sandstones
sandy
slsts
COARSENING
UPWARD SEQUENCE
sand laminated
slsts
shale
small fault
offset corrected for
top of exposure
vertical fissure
black
shale
basalt
lava
overlying sedimentary
sequence forms shoulder
in hillside
top of exposure
undisturbed
contact
mod + well std
crin pksts
erosion surface B
het pksts
B
A
C
well std
pksts + grnsts
heterogeneous
pksts
thin veneer
of sst
unit C
unit B
N 50°
black shale
crin pksts + ssts
C
C
B
A
lensoidal
bedding
unit A
face 1
top of exposure
black shale
thin sst
crin pksts
erosion surface B
C
B
A
reddened
crin pksts
het pksts
+
thin ssts
mod + well
std crin
pksts
4
2
0
25m
RIFLE RANGE
north quarry
NS 9895 7093

textural maturity. The fauna of unit B is abundant, dominated by cerioid corals, Lithostrotion colonies, and Chaetetes. Beds containing a high proportion of fauna in life-position alternate with others in which the fauna is in intermediate or fairly complete stages of breakage and transportation. The lowest 70 cm form a distinctive nodular horizon of equally-thick limestones and calcareous mudstones which weather to form a re-entrant in quarry faces (Figs. 2-4; 13-2).

Unit C: moderately sorted crinoidal packstones - The lower boundary of this unit is marked by a thin planar break formed by a blue-grey volcanogenic clay parting or wayboard (Fig. 13-2). Unit B is composed of medium to thick crinoidal packstones with fairly rare horizons of in situ fossils, predominantly cerioid corals, Gigantoproductus, and Chaetetes. A considerably higher number of in situ fossiliferous horizons and poorer degree of sorting readily distinguish units A and C.

Units A, B, and C are separated from the overlying 2-3 m of crinoidal packstones by a widespread erosional unconformity (surface B, Figs. 2-4; A-1; 13-2) interpreted as originating by subaerial exposure (q.v. Ch 13). This erosional surface (described in detail in Ch 13) truncates as much as 4 m of the underlying beds, often removing the top of unit C. Variation in the thickness of unit C is often likely to be accounted for by differences in the amount of erosion that has occurred along surface B.

Erosion surface B is one of three erosional unconformities in the Petershill Fm. (q.v. Fig. A-1). The lowest of these (surface A, Figs. 2-7; 2-11; 11-1) occurs approximately 10 m below the intermember boundary, taken at the top limestone bed in the sequence. The top surface (C), is developed along the topmost limestone bed itself and is marked by large fissures infilled with sandstones, tuffs, and plant debris.

All three surfaces have been interpreted as originating by subaerial erosion, although A and B are here described simply as erosion surfaces because the evidence for their origin is not unequivocable (q.v. Ch 13).

2.53 Lateral lithological variation in units A, B, C.

All three units described above intergrade to the north with wavy-bedded, argillaceous and slightly argillaceous limestones (Fig. A-1). To the south, lateral changes are more complex:

Unit A: the well-sorted crinoidal packstones become progressively finer grained and more argillaceous in the southern half of the Rifle Range quarries.

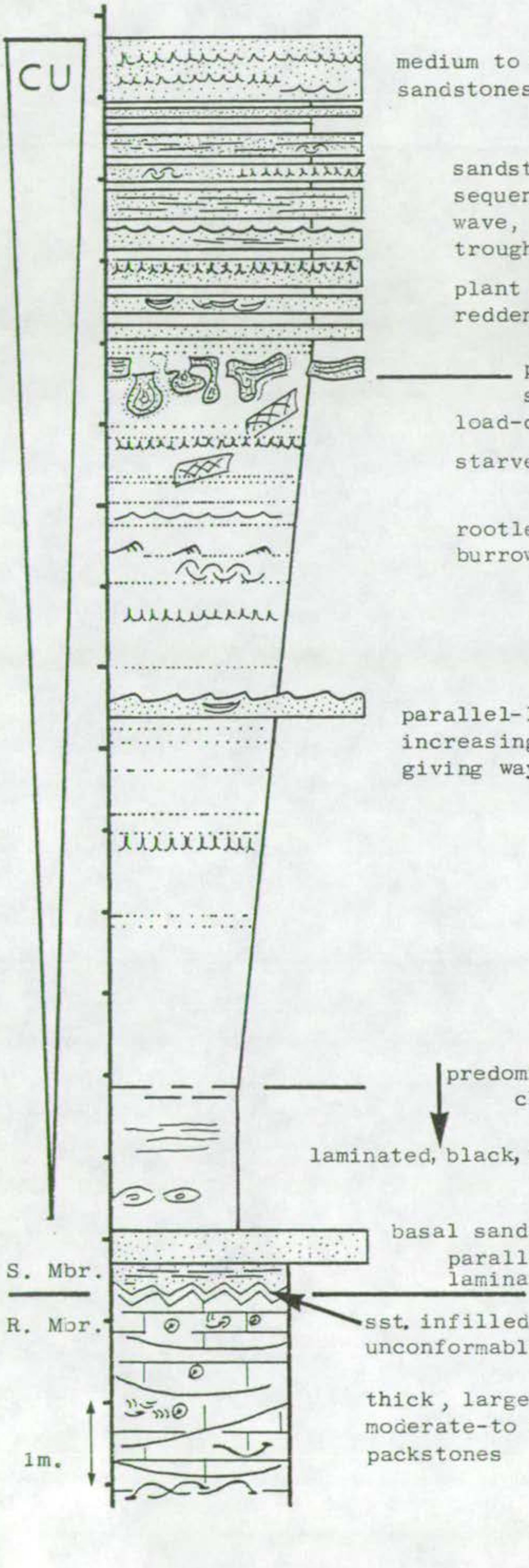
Unit B: the heterogeneous packstones extend further south as far as Sunnyside, where the three units pass into a transitional area (Fig. A-1). The overall faunal abundance of unit B decreases before reaching this transition area with Gigantoproductus and spinose productoids becoming relatively more important.

Unit C: the top unit, consisting of crinoidal packstones, may also be traced southward to Sunnyside where it becomes more fine-grained in the transition area (Fig. A-1). Crinoidal packstones similar to those in unit C are, however, also present at a laterally equivalent horizon in the facies south of the transition area.

2.54 The Silvermine Member (abbreviated S. Mbr. in Figures)

The Silvermine Mbr. sequence here is remarkably similar to that at South Mine Lime Works (compare Figs. 2-2 and 2-5). It begins with a reduced thickness of basal sandstone lying above a fissured limestone surface (fissure localities are shown in Fig. 0-7; A-1). The sandstone is overlain by a laminated, black shale which passes gradually upward into sand-streaked siltstones, discrete thin sandstones, and finally medium thickness planar sandstones. Small-scale symmetrical

Fig 2-5 The sequence along Rifle Range NS 985 708



medium to thick, planar-bedded, fine-grained sandstones and thin laminated siltstones

sandstones contain laminated to rippled sequences, symmetrical-wave, truncated-wave, interference, foreset, and trough x-stratification

plant debris laminae, rootlets, mudcracks reddened mud-flake laminae

predominantly sandstones

load-casted sandstone beds

starved ripples

rootlet horizons and indistinctly burrowed laminae

Planolites
Gyrochorte

parallel-laminated siltstones with increasingly frequent sand streaks, giving way to thin, planar sandstones

predominantly clay

laminated, black, uncemented, carbonaceous shale

basal sandstone

parallel-laminated fine-gr. sst.
laminated, pyritic sst.

sst. infilled fissures developed along unconformable, reddened, top lst. surface

thick, large-scale trough x-bedded moderate-to well-sorted crinoidal packstones and asymmetrical wave ripples, truncated wave ripples, interfering ripple sets, rootlets, as well as rare mudcracks and reddened mud flakes, provide evidence of very shallow water deposition and intermittent exposure. The sequence here is comparable to the Silvermine Mbr. further north in that it is divisible into a basal sandstone and an overlying coarsening-upward sequence, which is in turn divisible into three sub-units (c.f. Figs. 2-2; 2-5). The sedimentary structures and thicknesses of the minor units in the coarsening-upwards sequence are so similar at SMLW and Rifle Range as to suggest that sedimentation patterns were uniform over this relatively large area.

2.6 Sunnyside

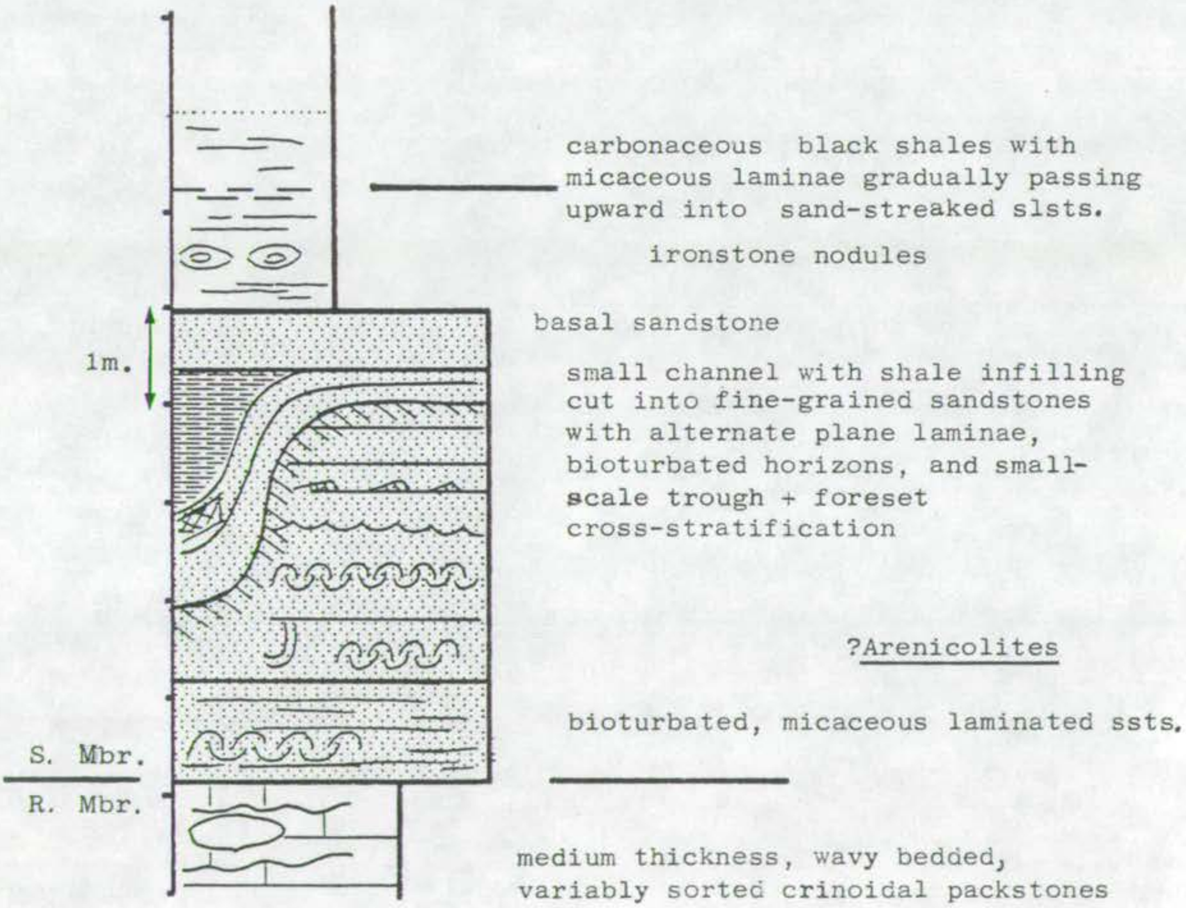
2.61 Exposure

A grassed-over causeway interrupts the once continuous line of quarries between Sunnyside Reservoir and the Rifle Range quarries. South of the causeway a line of overgrown quarries (Sunnyside quarries) lead to Sunnyside Reservoir where the sequence is well exposed at low water.

2.62 The sequence Fig. 2-6

The upper part of the Reservoir Mbr. outcrops in all the quarries leading to Sunnyside Reservoir. All three units, A, B and C, show the lateral lithological changes referred to previously. Erosion along surface B appears to have removed part of unit C. Overlying this unconformity are two metres of moderate to well-sorted crinoidal packstones and grainstones. Above them, the basal sandstones increase in thickness southward, reaching a maximum at the Sunnyside Reservoir (see Figs. A-1; 2-6). Sixty metres north of the reservoir itself a small channel infilled with black shale is incised in the basal sandstone (Figs. 2-6; 15-4).

Fig 2-6 The sequence at the north end of Sunnyside Reservoir NS 984 704



2.63 Structure

A major E-W fault, downthrown to the south, displaces the Petershill Fm. approximately 400 m eastward and drags the sequence into a gentle fold at the southern end of Sunnyside Reservoir (Fig. 0-7). The next exposure in the Petershill Fm. occurs at Galabraes Quarry, south of this fault and a large quartz dolerite intrusion.

2.7 Galabraes Quarry Fig. 2-7

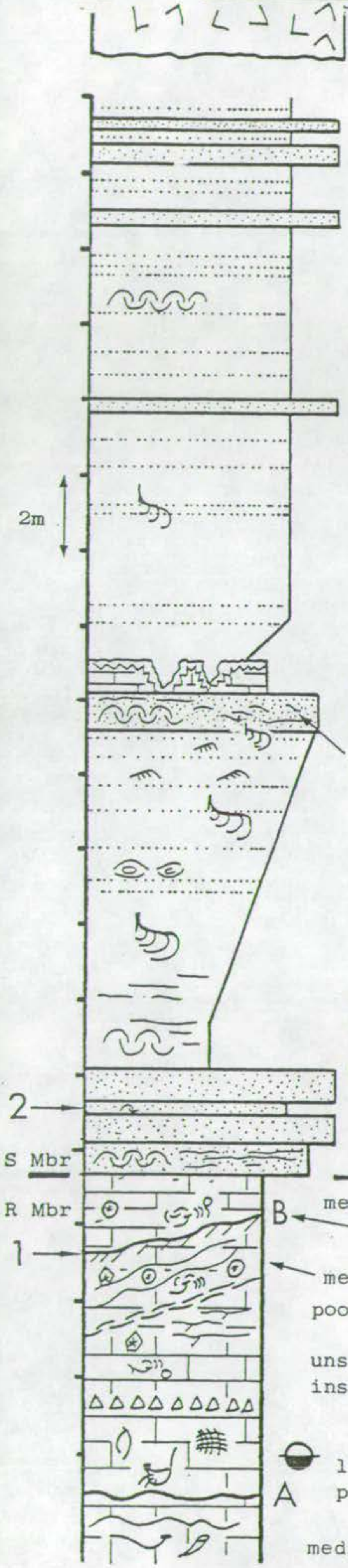
2.71 Field relationships

Galabraes Quarry itself is the northernmost in a line of deep quarries extending south to Petershill Reservoir 2. A complete section through the sequence may be compiled from these exposures as follows: the lowest 7.5 m is exposed at Galabraes Quarry (below 1, Fig. 2-7). The widespread erosion surface (B, Fig. 2-7) roughly coincides with the top of the stratigraphically highest limestone bed in the quarry. This bed can be traced 30 m south to an exposure where it forms the base of the carbonate/clastic sequence above, which is 2-3 m thick (see interval between 1 and 2, Fig. 2-7). Exposures at this horizon continue down to the northern Petershill Reservoir (also called Reservoir 2), where the overlying succession is exposed along its northern bank (Figs. 2-7; 2-8).

2.72 The sequence Figs. 2-7; 2-8

Lensoidally bedded grey biomicrosparites form the base of the sequence. A distinct boundary (surface A, Fig. 2-7) separates these bedded limestones from roughly 7 m of poorly-bedded cream to yellow-brown high-carbonate limestones above (the build-up facies). In this interval, sparsely fossiliferous wackestones and mudstones grade upwards into dolomite laminated crinoidal packstones, before giving way to crinoidal packstones. Erosion surface B separates medium thickness, bedded crinoidal packstones from thicker and better sorted

Fig 2-7 Composite section of the sequence at Galabraes Quarry and Petershill Reservoir 2



basalt lava capping Petershill Fm.

thin planar, laminated sandstones
and sand streaked siltstones
reddened mud flakes and plant debris

black siltstones with micaceous +
sandy laminae
mudcracks in thin sandstone

Zoophycus

smooth-sided vertical dissolution
fissures infilled with red clay
developed along limestone upper surface

60 cm thick argillaceous limestone with
brachiopods, crinoids, Epimastopora

laminated silty sandstone, extensively biot

Chondrites
Zoophycus

laminated black shale passing upward into
siltstone and sandy siltstone

basal sandstone

plane-laminated and sm. scale x-stratified
fine-grained sandstone

pyritic lam. sandy slst.

med. to thick, mod. + well-sorted crin. pksts.

erosion surface

med. bedded crinoidal pksts.

poorly-bedded dolomite laminated crin. pksts.

unsorted layered pksts, common horizons of
insitu productoids and bryozoans

Antiquatonia
Entomoconchus
Conocardium
fenestellids

low-diversity wksts. +
pksts.

med. bedded, grey, slightly argill. bmsps.

packstones above, which contain a sparser in situ fauna (Fig. 2-7).

The top crinoidal packstones of the Reservoir Mbr. are overlain by approximately 2-3 metres of basal sandstones which are interrupted by a thin sand-laminated siltstone. The sandstones pass upward into black shale and sand-streaked siltstones with Zoophycus and indistinctly bioturbated horizons. A discontinuous argillaceous limestone, with fragments of brachiopods, bryozoans and the dasycladacean alga Epimastopora sp. then interrupts the otherwise clastic sequence. This limestone is only exposed along the north bank of the northern Reservoir (shown Fig. 2-8) and cannot be traced laterally with any degree of certainty; while it may be present further south, it is definitely absent further north at the equivalent horizon.

Nearly 15 m of black micaceous and sandy siltstones, and thin sandstones then overly this unique limestone. A basalt lava, exposed west and north of Reservoir 2 (Fig. 0-7), caps the sequence of the Petershill Fm.

2.8 The northern Petershill Reservoir (or Reservoir 2) Fig. 2-8

The sequence along the north bank of this reservoir, already described, provides the southernmost complete section through the Silvermine Mbr. (Fig. 2-8). The uppermost 2-3 m of the Reservoir Mbr. limestones have recently been revealed, as the reservoir itself has recently been drained (see foreground, Fig. 2-8). This new exposure indicates that both the Petershill reservoirs and the quarries leading up to Galabraes were once continuous. Draining has allowed accurate placement of the intermember boundary, at the top limestone bed (as shown in Fig. 0-7, back pocket). This position should be noted carefully as there are plans to refill the reservoir.

Fig. 2-8 The north bank of the northern Petershill Reservoir

This is the southernmost exposure showing a complete sequence through the Silvermine Mbr. The sequence proceeds from the limestones in the foreground towards the left (westwards). Dip and dip directions of different parts of sequence shown.

Petershill Reservoir 2 – north bank

2.9 The Silvermine Mbr.

South of the northern Reservoir, the hillsides in which the old limestone quarries were originally excavated give way to flat fields with small exposures of the Silvermine Mbr. (q.v. Frontispiece). The boundaries and lithological changes in the Silvermine Mbr. in this region can thus only be approximated. Temporary exposures (a power substation and house foundations) have provided several good partial cross-sections through the sequence.

The most important lithological change, which is seen in the quarry sections, takes place at the horizon of the basal sandstone (Fig. A-1). In the region of the main Petershill Reservoir the basal sandstone passes laterally into laminated micaceous siltstones and shales with Zoophycus, serpulids, chonetoid brachiopods, and ostracods (Figs. A-1; 2-11). Marine horizons are also found in the siltstones and shales above. In addition, the sequence as a whole increases dramatically in thickness southwards, as shown in Fig. 1-2.

2.10 The main Petershill Reservoir (abbreviated: the Reservoir)

Figs. 2-9; 2-10

Proceeding south a complete section through the Reservoir Mbr. is exposed in this famous old quarry, slightly complicated by faults.

Field relationships between exposures - A small outcrop of basalt lavas 50 m east of the Reservoir marks the base of the Petershill Fm. The lava is overlain by a variable thickness of mixed sandstones and tuffs. The sequence overlying the sandstones and tuffs is exposed in the northeastern corner of the Reservoir, brought up by a small, normal fault dipping to the south (sequence north of fault, Fig. 2-9). A few metres of calcareous mudstones, which are not exposed, intervene between the base of the section north of the fault (Fig. 2-9) and the mixed sandstones and tuffs east of the Reservoir. This succession was

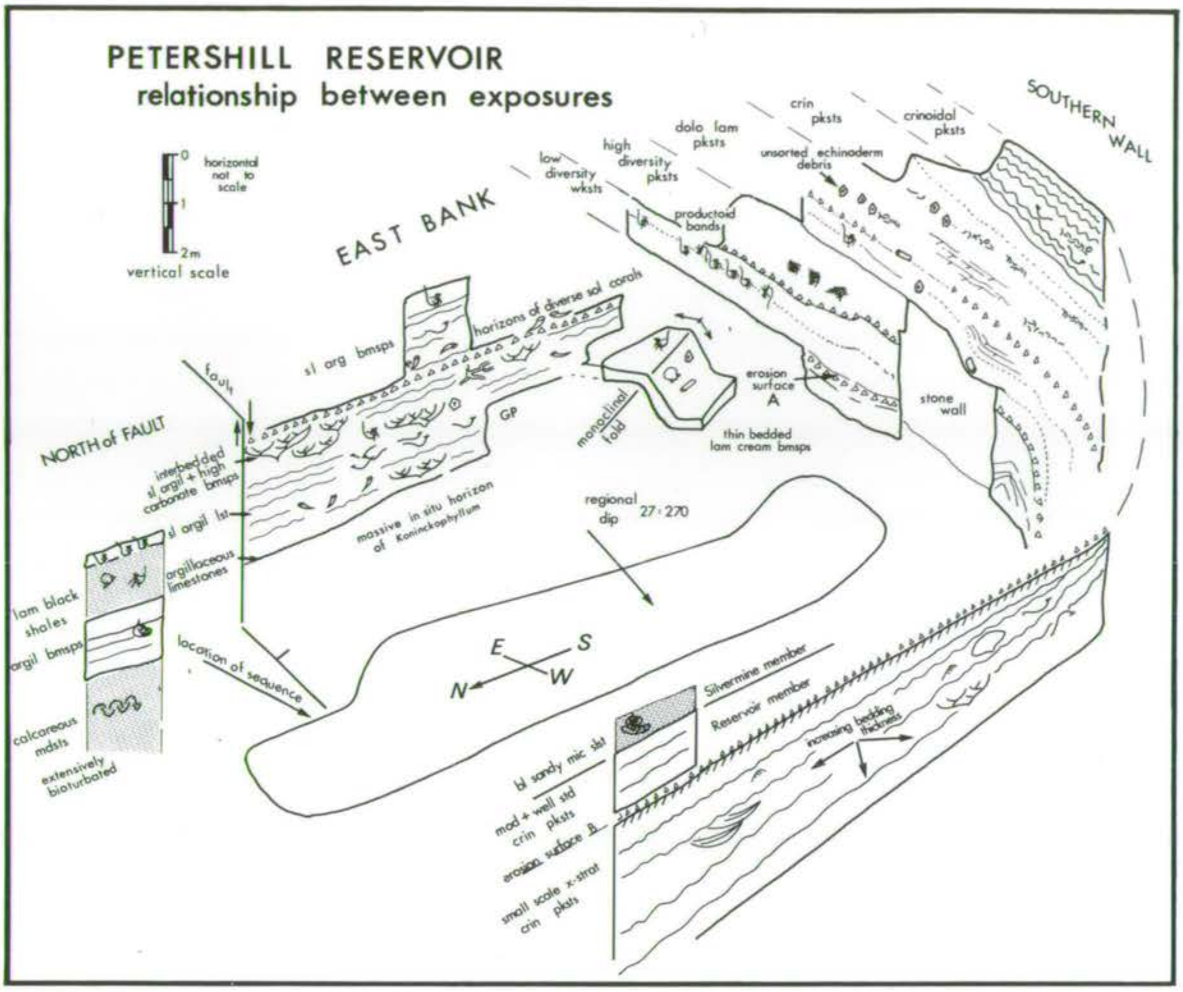

PETERSHILL RESERVOIR
relationship between exposures
0
1
2m
horizontal not to scale
vertical scale
EAST BANK
low diversity wksts
high diversity pksts
dolo lam pksts
crin pksts
crinoidal pksts
SOUTHERN WALL
unsorted echinoderm debris
productoid bands
horizons of diverse sol corals
sl arg bmsps
fault
NORTH of FAULT
interbedded sl argil + high carbonate bmsps
sl argil lst
argillaceous limestones
lam black shales
argil bmsps
calcareous mdsts
extensively bioturbated
GP
massive in situ horizon of Koninckophyllum
monoclinal fold
erosion surface A
thin bedded lam cream bmsps
stone wall
regional dip 27 : 270
location of sequence
E
S
W
N
Silvermine member
Reservoir member
increasing bedding thickness
bl sandy mic slst
mod + well std crin pksts
erosion surface B
small scale x-strat crin pksts

Fig. 2-9

established by sinking borehole No. 3 on the eastern bank of the Reservoir, in beds stratigraphically above those found north of the fault (see Fig. 2-12, and borehole No. 3 description, Appdx B).

South of the fault the sequence along the east bank dips uniformly westward towards the former quarry floor (Fig. 2-9). Towards the southern end of the quarry, these beds are folded slightly over a monoclinal fold which trends obliquely to strike.

The stratigraphically uppermost limestone exposed on the eastern bank lies 1 m below the lowest exposed limestone on the southern quarry face (Figs. 2-9; 2-10). The section obtained from borehole 4 (Fig. 2-12; borehole 4, Appdx B) confirms this relationship.

The southern face of the Reservoir (Fig. 2-10) exposed a vertical sequence approximately 12 metres thick. The top of the succession is formed by a limestone, close to the Silvermine/Reservoir Mbr. boundary. It is difficult to establish if the uppermost bed is in fact the very top limestone bed in the sequence as the surface has been scoured by glacial ice erosion. E-W trending scratches left by ice erosion are well seen along the top of the limestone surface along the western bank.

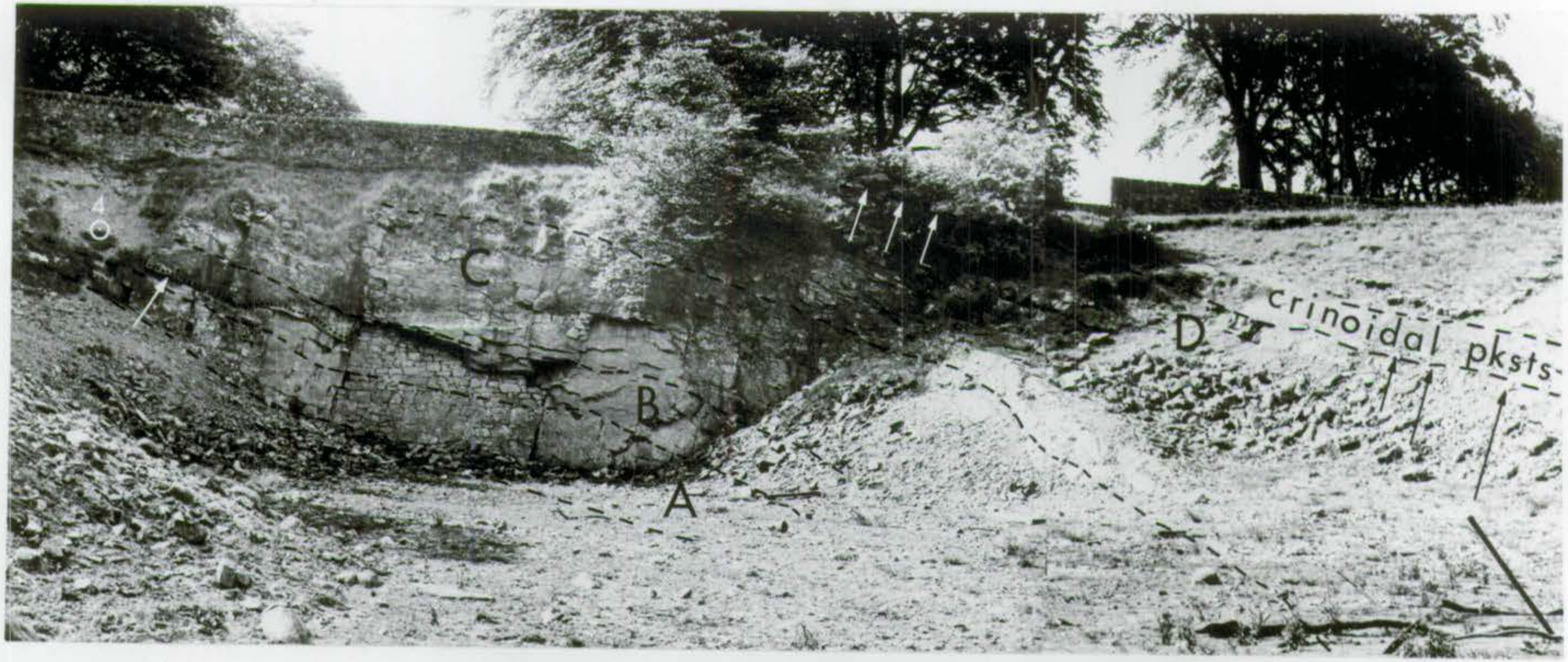
Beds from the uppermost 5 m of the southern face are traceable onto the western bank of the Reservoir, allowing examination of lateral lithological changes (Figs. 2-9; 2-10).

The exposures on the southern and western faces of the Reservoir Quarry and South Quarry, immediately south, are closely continuous. The two quarries were once joined by a short tunnel, now blocked by a stone wall (Fig. 2-10). Two erosional surfaces at the bottom and top of the southern wall succession provide one of several means of correlation. The lowermost surface is exposed roughly 60 cm above the base of the southern face in the Reservoir and an equal distance above the floor in the northernmost exposure in South Quarry, 50 m south (A of

Fig. 2-10 Petershill Reservoir - view of southern and westward faces of former quarry.

The partially bricked-in face is the southern quarry wall; the west bank is at right. The bricked-in area, which is 260 cm high, seals a former tunnel between the Reservoir and South Quarry. Dashed lines delineate subfaces within the build-up (q.v. Fig. 2-9; Ch 11). The location of borehole 4, which confirmed the stratigraphical relationship between this face and the eastern bank (not visible) is shown at left. Prominent breaks with the poorly-bedded build-up (e.g. white arrow at left) are formed by clay wayboards. The vertical arrows at right point out erosion surface B, at the top of the build-up. Note that subfacies D thickens towards observer.

Petershill Reservoir



Figs. 2-9; 2-11). The upper erosion surface B is approximately 12 m above, as measured on the southern quarry face of the Reservoir. It is seen as a prominent break in the limestones, nearly conformable with bedding, approximately 1 m below the intermember boundary (Figs. 2-9; 2-10). In South Quarry surface B is obvious (q.v. Fig. 11-10) as it truncates nearly 3 m of limestones. From South Quarry it extends south at a similar position on quarry faces, 3-4 m from the top of the exposure.

The sequence - Beginning in the northern part of the Reservoir (Fig. 2-9, north of fault) the lowest beds consist of 3-4 m of calcareous mudstones grading upward in argillaceous limestones. Above these are 90 cm of black, laminated shale with an abundant fauna of pectinacean bivalves, serpulids, and small productoids. This sequence is capped by an exceptional cream biomicrosparite containing a layer of Antiquatonia, a spinose productoid. This bed is the stratigraphically highest bed north of the fault in the Reservoir.

Moving stratigraphically upwards, perhaps as much as 1-2 m onto the eastern bank of the Reservoir, the overlying 4 m consist of very fossiliferous, grey and cream, lensoidally-bedded limestones (q.v. Ch 3). Slightly argillaceous and high-carbonate limestones alternate fairly irregularly. One of the distinctive features of this interval is the variety and abundance of the coral fauna. At various horizons, colonies of Lithostrotion junceum and Koninckophyllum dianthoides (M'Coy) have coalesced to form continuous thickets. Horizons of solitary corals, mostly aulophyllids, alternate with bedding planes formed by the thickets.

Moving from the eastern bank to the southern face, bedded limestones pass upward into a poorly-bedded sequence, the build-up (q.v. Fig. 2-10). Cream, blue-grey or yellow-brown, often brecciated, wackestones and mudstones pass upwards through dolomitic laminated packstones to sparry crinoidal packstones and grainstones. The unbedded sequence contains a distinctive fauna consisting of a diverse assemblage of productoids, bryozoans, bivalves, ostracods, echinoids, and crinoids. The fauna in the lower horizons is largely in situ, passing upward into slightly reworked and later extensively transported fossil horizons In the uppermost 4 m of the exposure, bedding once again becomes prominent. This sequence then passes laterally into that seen at South Quarry.

2.11 South Quarry Figs. 2-11; 11-10

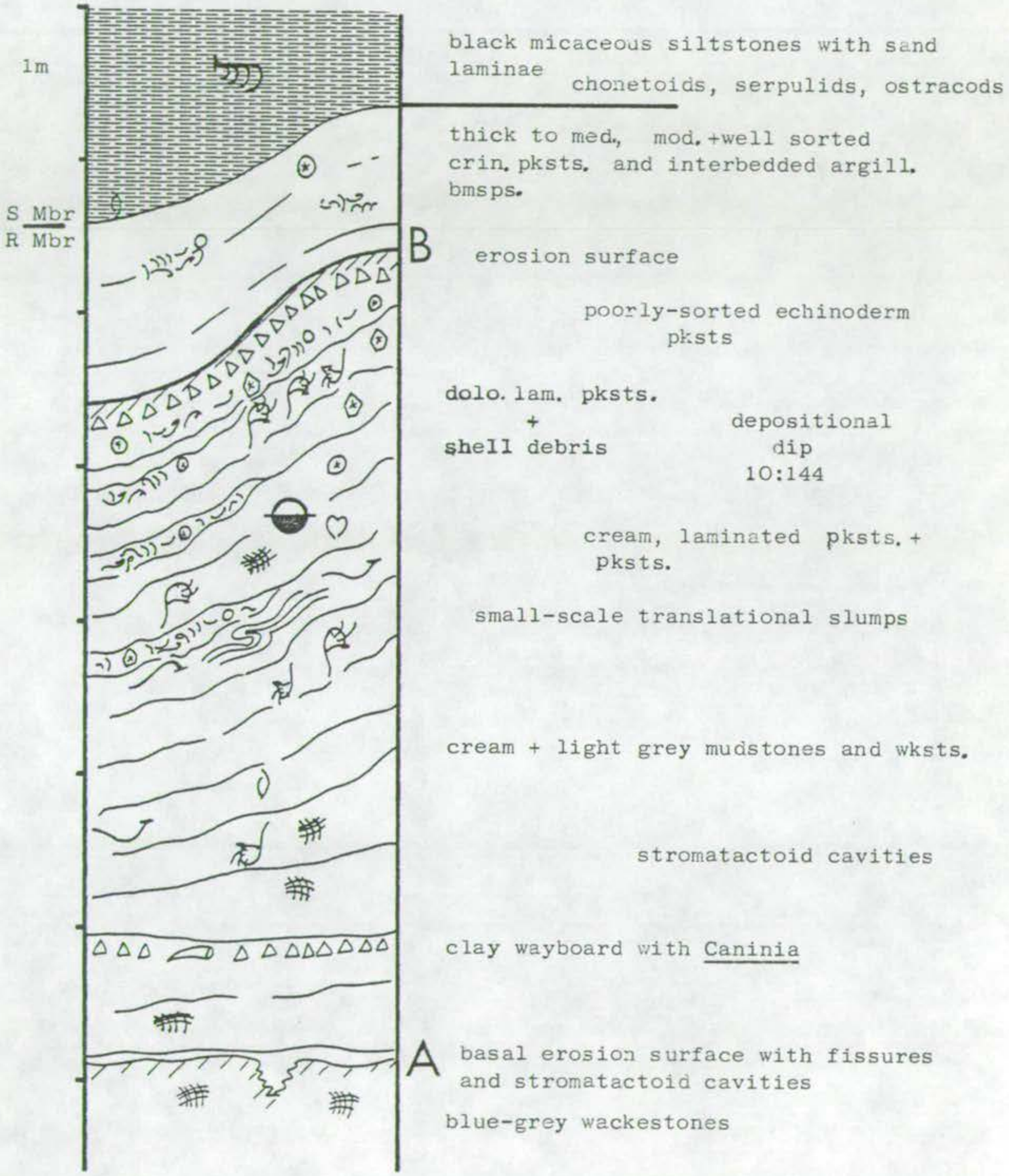
The South Quarry sequence is prominently divided by erosion surface B. Beds beneath surface B increase in thickness and number southward away from the build-up (to the left in Fig. 2-11; q.v. Fig. 11-10). Beds of coarse skeletal debris, apparently derived from the build-up, alternate with beds containing undisturbed fossils. These beds are the flanks of the build-up, one of its subfacies.

The flank beds are erosively truncated by surface B, and overlain by 2-3 m of thick to medium-bedded crinoidal packstones separated by an interval of thinner argillaceous biomicrosparites (Figs. 2-11; A-1). Surface B (described in detail in Ch 13) generally follows bedding but dips more steeply than beds underneath (Fig. 11-10). At South Quarry and further south black micaceous siltstones and shales with marine horizons of brachiopods (particularly chonetoids) ostracods, serpulids, bryozoans, and Zoophycus, directly overlie the top limestone bed (Fig. 2-11).

2.12 South Quarry to Glenbare

Proceeding further south, exposures occur at roughly the same stratigraphic horizon as that of the sequence in South Quarry. Individual beds can be followed between quarries, making exact facies correlations

Fig 2-11 Generalized cross-section of South Quarry NS 985 695



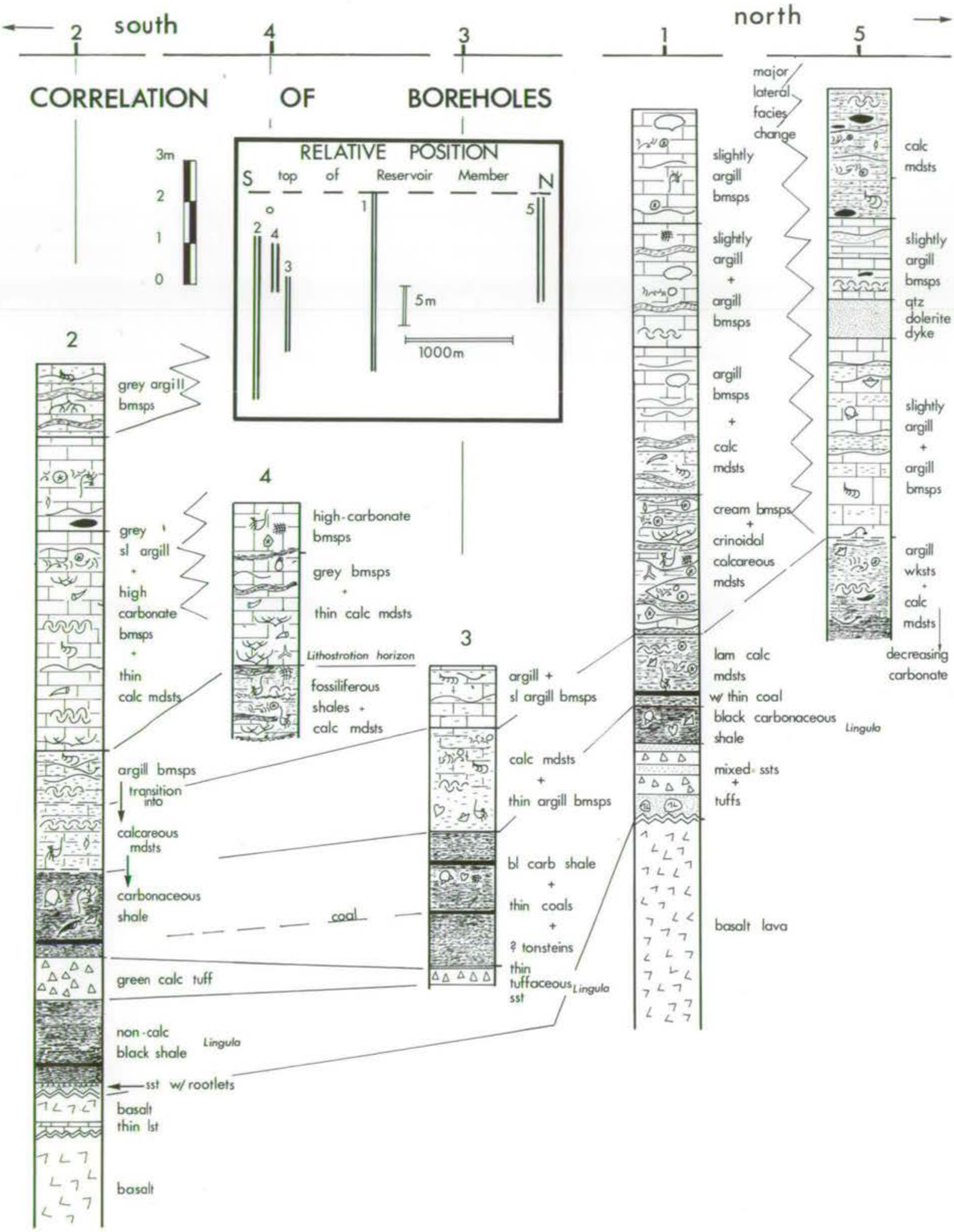
possible. The flanks first pass laterally into a thin tongue of argillaceous limestones, followed laterally by high-carbonate biomicrosparites and further south, slightly argillaceous limestones (Fig. A-1). These relationships are described in detail in Chapters 9, 10, 11.

The former site of Glenbare Quarry, is the southernmost good exposure in the Petershill Fm. Further south, on the hillslope leading to the town of Bathgate (Frontispiece), exposures are discontinuous and lithological relationships can only be approximately mapped out. The base of the Petershill Fm., between the Bathgate lavas and sediments, can, however, be traced fairly accurately, as the lavas have a poor soil covering (Frontispiece). The relative thickness of sediments within the sequence and the upper Petershill Fm. boundary, however, can only be estimated. It appears that the limestones as a whole thin southward.

2.13 Boreholes in the Petershill Fm.

A total of five boreholes were sunk in the Petershill Fm., all located in the Reservoir Mbr. A detailed description of each core is given in Appdx B. Figure 2-12 provides a general log of each, and shows some of the more obvious correlations. Each borehole is located with reference to the top limestone bed in the Reservoir Mbr., as shown on the block insert.

Fig 2-12 Boreholes in the Petershill Fm.



CHAPTER 3

FEATURES DIFFERENTIATING CARBONATE FACIES

3.0 Introduction

Several features which are immediately apparent at an outcrop in the Reservoir Mbr. carbonate sediments, are particularly useful means of distinguishing between facies. Most important among these are the morphology and arrangement of bedding, and colour. All too often, these most immediate data are overlooked. Moreover, it is important to stress the field appearance of the lithologies which constitute the various facies in the Reservoir Mbr. if similar facies are to be recognized elsewhere.

Following Gressly's original definition (translated in Teichert 1958, p 2719) the term facies has been used here to denote the sum total of all features of a particular unit (usually a lithosome) that characterizes an environment. Gressly (ibid) stressed the importance of field appearance in his original definition and, indeed, in choosing the term "facies"*[1]. In the carbonate facies of the Reservoir Mbr. the external appearance, colour, lithological and faunal composition, and textural maturity have been used to distinguish facies. When combined, these criteria provide a means of interpreting and thus also distinguishing some of the environmental differences between these ancient carbonate sediments.

3.1 Bedding

The geometry and thickness of bedding are among the most immediately obvious aspects of a sequence at an outcrop. In the Reservoir Mbr. limestones, both primary (sedimentological) and secondary (deformational) factors have contributed to present bedding morphology. It

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*[1] the term facies actually means "face" or external appearance.

is not always easy to distinguish between these two factions, however, as both bedding and style of deformation have been found to be characteristic of particular lithologies, and therefore of facies.

Bedding thickness figures presented here are based on measurements made while mapping and on the averaged values from metre squares from each facies (selected at random). Thirty measurements were taken per square and a minimum of 3 metre squares per facies were measured.

3.11 Problems of analysis

In sequences of exposed interbedded limestones and calcareous mudstones it is sometimes difficult to obtain meaningful measurements of original bedding thicknesses. During exposure, calcareous mudstones tend to weather preferentially and extrude from between the limestone beds. At Hillhouse Quarry (Fig. 0-7) it is possible to compare directly the bedding thicknesses of a sequence in underground, unweathered workings (Fig. 3-1a) with old quarry faces that have been exposed to weathering for well over fifty years. On the exposed quarry faces the calcareous mudstones are up to 30% thinner than those in equivalent sequences underground. Borehole cores also give a similar impression; that calcareous mudstones are thicker in unweathered sequences. In the present study a greater emphasis has been placed on limestone bedding thicknesses because the mudstones were found to be so susceptible to weathering.

A second problem, which is dealt with in greater detail in subsequent sections, concerns the nature of the bedding surfaces between limestone beds and the calcareous mudstones. In borehole cores and on fresh exposures nearly all bedding surfaces in bedded limestone-calcareous mudstone sequences are gradational over several centimetres. It would be tempting to conclude that such bounding surfaces indicate gradual environmental transitions.

On long exposed quarry faces, however, these interfaces appear to

Fig. 3-1 Lensoidal bedding - general appearance, contrasting unweathered, underground workings (a - upper photo) and long-exposed weathered, quarry faces (b - lower photo).

a. The stall-and-pillar workings at Hillhouse Quarry. The pillars display well the irregular, imbricate, arrangement of sets (inked in) of lensoidally-bedded limestones. Vertical scale = 37 cm.

b. Outcrop of lensoidally-bedded limestones, Petershill Lime Works, probably exposed for several hundred years. Note that bedding boundaries appear to be much sharper than above, 3-1a. Hammer (mid photo, length = 37 cm) has been placed in front of set of beds toeing out to right. The set-like arrangement of beds in this outcrop is drawn out in Fig. 3-2. Note that the limestone bed above the hammer appears to have sheared along a low angle plane. Scurrilous vandal has conveniently written graffitti on set of beds toeing out to left. Height of quarry face = 4.5 m.


WD→

be fairly sharp (Fig. 3-1b). In the Reservoir Mbr. limestones, lithological mixing due to interstratal flow can be shown to have been a factor in creating these gradational boundaries between beds. Sedimentological information which might be obtained from bedding surfaces (of erosive events, rapid sediment changes, sediment consistency, etc.) has therefore been blurred or obscured by interstratal flow. Recent weathering has created an impression that these gradational boundaries are sharp, and that they are primary bedding surfaces.

3.2 Types of bedding

3.21 Thick limestones and thick calcareous mudstones

Bedding is formed by prominent, thick (average 10-50 cm, up to 100 cm) planar limestones interbedded with slightly thinner calcareous mudstones. Separate nodules of limestone within the mudstones are fairly rare. Bedding surfaces vary in undulosity, with surface relief seldom exceeding 5 cm. On a large (decametre) scale, beds are continuous and change only slightly in thickness.

Occurrence - Thick limestones and calcareous mudstones are typical of the argillaceous carbonate facies (q.v. Ch 8).

3.22 Medium thickness, planar limestone sequences

These sequences, simply referred to as "medium thickness" or "medium limestones", (q.v. Figs) consist of 15-30 cm thick limestones and slightly thinner calcareous mudstones. Bedding surfaces are highly undulose, or wavy*[1], the undulosity being more pronounced on the lower surfaces of beds and where beds are thinner. In describing the morphology of similar bedding from a comparable sequence, Wobber (1967) chose four descriptive terms: planar, isolated-nodular, nodular, and semi-nodular beds. These bedding morphologies, as well as intermediate

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*[1] wavy geometry of bedding shown in Figs. 2-5; 3-1; 3-2; 11-10; 13-2; 13-4a.

forms, are common in medium thickness, planar limestone sequences. On a large scale these sequences appear to be continuous and beds do not change thickness markedly.

Occurrence - Medium thickness limestone sequences are common in the slightly argillaceous limestone facies and the high-carbonate biomicrosparite facies.

3.23 Thick limestones and thin calcareous mudstones

These are 30-100 cm thick limestones interbedded with thin calcareous mudstones which seldom exceed 5-10 cm. Bedding surfaces are generally planar with a slightly greater undulosity on lower surfaces. Over hundreds of metres laterally, beds change thickness only slightly.

Occurrence - This type of bedding characterizes the crinoidal packstone facies and unit A of the heterogeneous packstone facies. It occurs in moderate- to well-sorted crinoidal packstone lithologies.

3.24 Poorly-bedded limestones Fig. 2-10

Limestone sequences that are generally massive, several metres thick, with few prominent breaks. Bedding partings undulate gently, formed by thin clay laminae, coarse fossil debris, or dolomite laminae. Thin partings, some of which can be shown to be clay wayboards (sensu Walkden 1972, p 145) were taken as demarcating time lines through these units which otherwise lack reference planes. Changes in thickness of the limestones between these partings suggest that poorly-bedded limestone facies formed lenticular lithosomes (not to be confused with lensoidal beds, q.v. Sect 3.26).

Occurrence - Poorly-bedded limestones form the central mass of the build-up facies.

3.25 Large-scale trough bedding Fig. 13-4a

Medium to thick beds, arranged in gently-curved, often erosively-based troughs, separated by thin calcareous mudstones. Each trough consists of a composite sequence, thickening symmetrically about the trough axis.

Troughs extend 20-30 m laterally, and reach a maximum thickness of 1-2 metres. Beds within troughs often show both large- and small-scale traction current cross-stratification and contain horizons of transported fossils.

The uniform geometry of beds within a trough and the composite nature of bedding suggest that large-scale, trough-shaped beds represent erosional remnants of large, intermittently mobile bedforms, perhaps shallow dunes (sensu Harms et. al. 1975) or bars (sensu Imbrie and Buchanan 1965, p 155; q.v. Ch 13).

Occurrence - Large-scale trough bedding only occurs in the crinoidal packstone facies.

3.26 Lensoidally bedded limestones Figs. 2-4; 3-1; 3-2

Lensoidally bedded limestones or lensoidal limestones are composite units consisting of medium thickness limestone beds (15-30 cm thick, up to 60 cm) and thinner calcareous mudstones (average 10 cm thick). Individual beds are fairly regular in thickness across an exposure but, on a larger scale of 40-100 m, beds often taper gently and pinch out (Figs. 2-4; 3-1; 3-2).

In many respects individual bed morphology is similar to that of medium thickness, planar limestones. Bedding surfaces, particularly lower bed boundaries, are undulose and a continuous range of undulosity is present along a bed and within a sequence of beds. Isolated limestone nodules contained in the interbedded calcareous mudstones are particularly abundant and varied in shape: smooth ellipsoids, brick-shaped blocks (Fig. 3-4), isolated lentils, and laterally linked "boudins" (sensu McCrossan 1958) are common. Some of the smaller

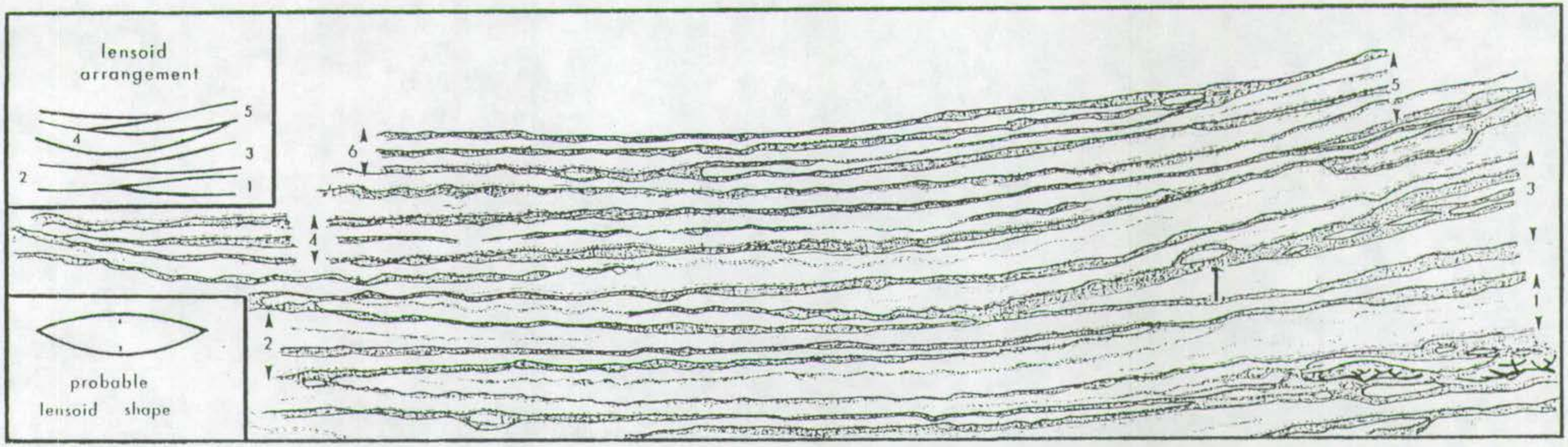


Fig. 3-2. Generalized geometry of lensoidal limestones Petershill Lime Works. Hammer, mid-illustration = 37 cm.

Illustration shows general geometry of lensoidally bedded limestone sets (delineated by arrows). A simplified schematic of the outcrop illustration is shown in the upper block insert (left hand corner). The main illustration has been taken from a photo montage (part of which is shown in Fig. 3-1) in which the vertical scale has been exaggerated in order to emphasize set geometry.

nodules have frequently been drawn out into such thin streaks as to hardly be recognizable as limestone.

The most characteristic feature of lensoidal limestones is their tendency to occur in sets consisting of from 4-8 limestone beds, which thicken and thin uniformly over lateral distances of 50-100 metres (Fig. 3-2). Beds increase in thickness and number symmetrically towards the centre of a set (Fig. 3-2). Adjacent sets typically overlap in an imbricate arrangement or alternate with planar beds (Figs. 3-1; 3-2).

In the Petershill Fm. and the Hillhouse Lst., a complete set spans several outcrops (Fig. 2-4). Thus it is difficult to analyze the shape and orientation of sets in detail. Exposures such as the stall-and-pillar workings at Hillhouse Quarry, however, reveal parts of several sets in three dimensions (Fig. 3-1). From these exposures it appears that lensoidal sets may be bi-, concavo-, or plano-convex, and that they are symmetrical about their midpoints.

Occurrence - Lensoidally-bedded limestones are the most common bedding type in the slightly argillaceous limestone facies and are also found rarely in the argillaceous limestone and heterogeneous packstone facies.

3.3 An analysis of lensoidal limestones

3.31 Origin of the limestones

Differences in the faunal composition between the limestones and interbedded calcareous mudstones as well as the ichnofauna indicate that the limestone beds in lensoidally bedded sequences are of primary (depositional) origin. Several previous authors (see Hallam 1964; Noble and Howells 1974) have reported that nodular microsparites similar to those in the Petershill Fm. may form by either primary or secondary (diagenetic) processes.

Limestones in lensoidally-bedded sequences generally contain an abundant productoid brachiopod and coral dominated fauna, while the calcareous mudstones contain a sparser fauna with higher proportions of chonetoid brachiopods and skeletal debris. Trace fossils, particularly draft-filled forms like Chondrites (Fig. 3-4), provide evidence that the fine-grained matrix in the limestones was primary. These differences in the composition of known primary features between the limestones and mudstones show that the sequence itself is depositional and not formed by diagenetic processes such as rhythmic unmixing or carbonate segregation.

3.32 Deformational structures in lensoidal limestones

Many of the smaller scale structures in wavy-bedded and especially lensoidal limestones clearly show that the present bedding morphology is not, however, entirely primary (Figs. 3-3; 3-4). McCrossan (1958) and Wobber (1967) have described and interpreted similar structures from comparable limestone/shale sequences. It was therefore not felt necessary to re-describe all the deformational structures in the Petershill Fm. Instead a few structures which illustrate different styles of deformation are described, while the general deformational processes are discussed with reference to previous work.

3.321 Lower bedding surfaces Fig. 3-3

The lower surfaces of limestone beds are markedly more hummocky, or wavy than the upper surfaces. The bottoms of many protuberances are often floored by dense and relatively large fossils such as Gigantoproductus, and cerioid coral colonies. Wobber (ibid) attributed such structures to early loading of denser carbonates into less cohesive, calcareous mudstones, comparing their manner of formation to that of load casting.

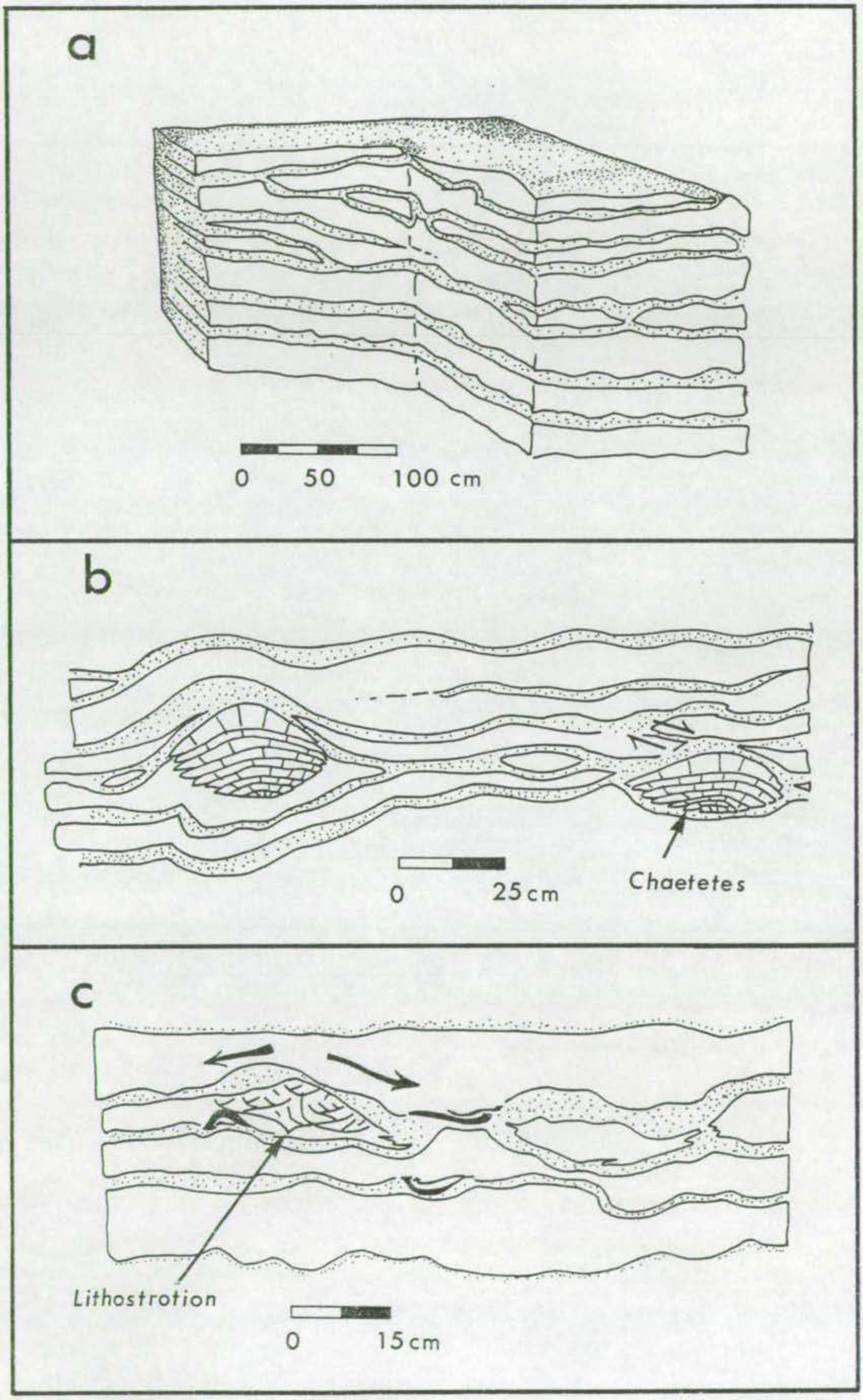
Fig. 3-3 Bedding features of lensoidally bedded sequences; illustrations traced from photographs.

Blank = limestone, stippled = calc. mdst.

a. General features - beds of uniform thickness alternate with more nodular horizons. Some of the limestone beds appear to be refittable. The undersurfaces of beds are more nodular than the tops. Galabraes Quarry, lowest section; slightly argillaceous biomicrosparites.

b. Plastic deformation around rigid skeletal structures. Note how a bed is thinner and has parted above a rigid colony of *Chaetetes*. The same bed has sheared (arrows) above a second colony. Same locality as 3-3a.

c. Signs of interstratal flow - *Gigantoproductus* shells (black) have been flatened and separated by flow at the calcareous mudstone-limestone boundary. Arrows show thinning over a rigid *Lithostrotion* colony. Note also accentuated undulosity of bedding undersurfaces. East bank, Petershill Reservoir.


a
0 50 100 cm
b
0 25cm
Chaetetes
c
Lithostrotion
0 15cm

3.322 Folded and sheared beds Fig. 3-4

Many beds either thin or part over rigid skeletal colonies in a manner similar to that commonly observed along the axes of tectonic folds. In addition, the more nodular portions of beds (see Fig. 3-4b; Fig. 3-2 above hammer) have often separated along low angle shear planes. The style of deformation indicates that some vertical compactive forces have been resolved in a slight horizontal displacement.

3.323 Deformed body fossils and trace fossils Fig. 3-4

The clearest indications of how deformation has taken place are provided by objects of known original form, such as body fossils and trace fossils. In the limestones they are both only slightly compacted, the extent of deformation varying with limestone composition (q.v. Ch 6). In the calcareous mudstones, however, fossils and burrows are extensively flattened and have often been drawn out plastically.

Chondrites burrows are a particularly useful indicator of how and when deformation took place (Fig. 3-4). Interstratal *Chondrites* burrows show progressively greater distortion towards the limestone-calcareous mudstone boundaries. At bedding boundaries they become more deformed and plastically drawn out over nearly 1 cm. This pattern of deformation indicates that lateral movement accompanying compaction was largely taken up by the mudstones and that movement occurred early while the limestones were still plastic.

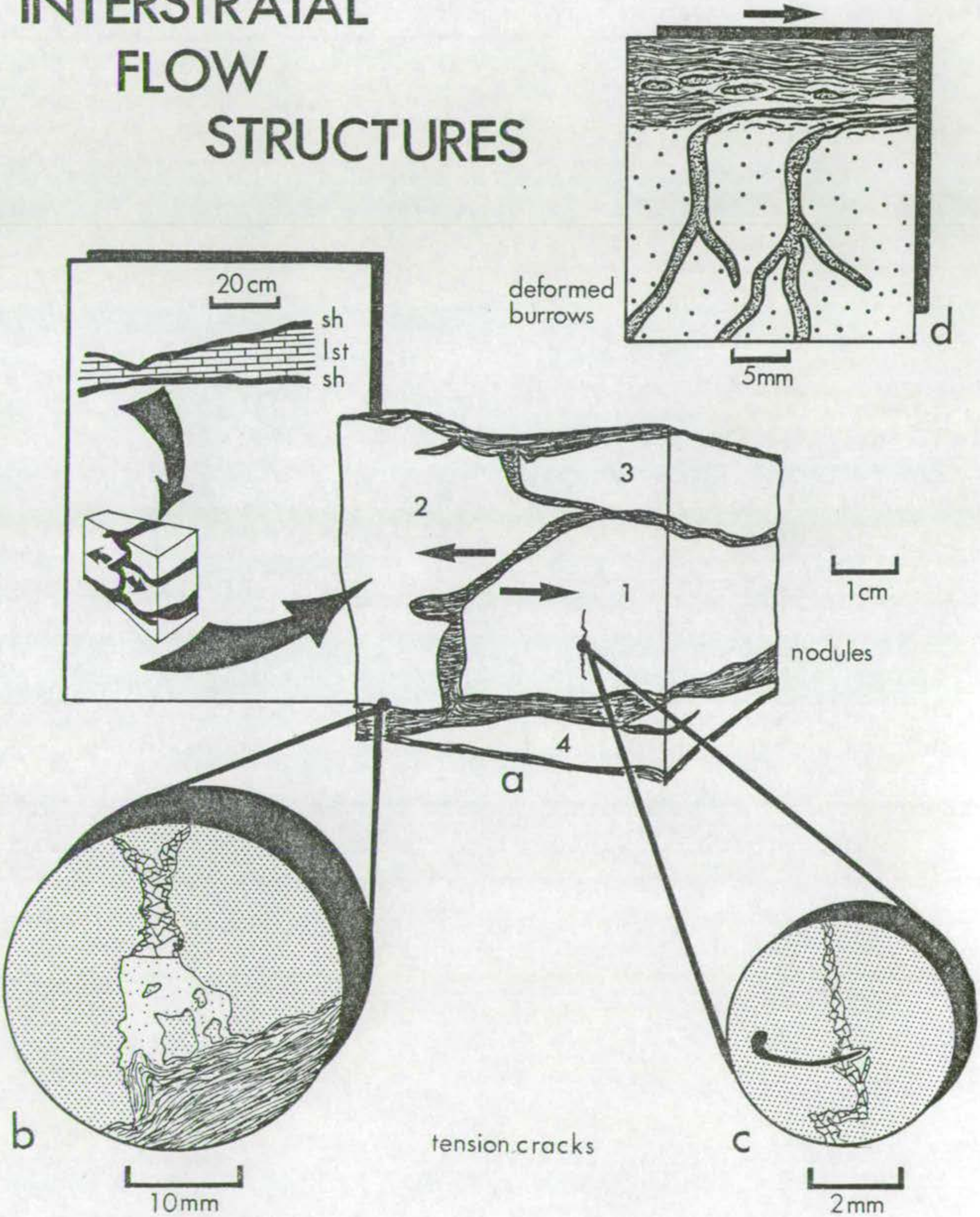
3.324 Small cracks Fig. 3-4

The upper and, more often, the lower bedding surfaces of high-carbonate, fine-grained limestones often display small vertical cracks, or fractures. The earliest cracks contain partial infillings of loosely-packed sediment and angular fragments of matrix,

Fig. 3-4 Deformational structures due to sedimentary boudinage, or interstratal flow; generalized drawings from outcrop, hand-specimen, and peels. G.J. 46,356

A specimen of high-carbonate mudstone, taken from a narrow constricted portion of a bed, which was in the process of separating into discrete nodules (1, 2, 3, 4 of 3-4a). Structures within the nodules, such as tensional cracks, infilled with released sediment (3-4b), crumbly fractures within nodules (3-4c), and drawn out trace fossils (3-4d) establish that tensional stresses have caused once-continuous beds to separate into nodules, soon after burial, while the limestone matrix was still plastic.

INTERSTRATAL FLOW STRUCTURES



presumably detached from the fracture walls (Fig. 3-4b). In other examples, fractures within a bed have separated around, rather than across, very delicate shells, such as the ostracod valve illustrated in Fig. 3-4c. Such fractures, termed here crumbly fractures (discussed and defined more fully in Ch 6) point to early tensional stresses occurring very soon after burial.

3.325 Blocks and nodules Fig. 3-4a

Discrete block- to nodule-shaped pieces of limestone and samples taken from thinned areas of beds provide some evidence of how the present morphology of bedding has been formed. At thinned areas, particularly above rigid skeletons, beds have begun to separate along vertical fractures opening from the tops and bottoms of beds (as illustrated in Fig. 3-4). Further separation has occurred along near horizontal planes within beds, creating interfitting discrete nodules (1, 2, 3, Fig. 3-4a). The vertical sides of these blocks from beds that have begun to separate (e.g. Fig. 3-4a) are sharp and often ragged. The horizontal surfaces, however, are smooth and show signs of relative movement. Pieces of limestone that have moved relatively far are smooth and ellipsoidal; more nodular in form (Fig. 3-4a, nodule 4).

The jig-saw manner in which blocks may be re-fitted, and the differences in crack sharpness between the vertical and horizontal surfaces show that the bed was in the process of separation, ruling out the possibility that the blocks might have been forced together. As for the small cracks, pull-apart nodules show that tensional stresses have acted to draw beds out and create nodules.

Compactional nodules: an alternative hypothesis - While it can be shown that many nodules, particularly the larger ones, have been formed by tensional stress associated with interstratal flow, it is unlikely that all nodules have formed by a similar process. Shinn, Halley, Hudson and Lidz (1977) have recently found that simple compactional stress, exerted on a core of homogeneous mixed calcareous sand from Biscayne Bay, Florida, produced a rock with a nodular fabric and wispy laminae. The general appearance of their core so closely resembles the appearance of many of the smaller nodules in the calcareous mudstones of the Reservoir Mbr. that it seems likely that this process may, in itself, have also formed nodules.

3.33 Role of sedimentary boudinage

From the preceeding descriptions it is clear that many of the bedding structures typical of wavy, lensoidally bedded sequences are the product of loading, early compaction and interstratal flow. McCrossan (1958) and later Wobber (1967) described this process as sedimentary boudinage. In the Reservoir Mbr. limestones, several stages of boudinage may be recognized:

Loading - In the earliest stage the limestones deformed vertically into the less-consolidated calcareous mudstones, forming the rounded protuberances on lower bedding surfaces. Inhomogeneities in the limestones, induced by massive skeletons, partially influenced the pattern of deformation. Density-controlled deformation was particularly important in shaping the lower surfaces of limestone beds, while having a negligible effect on overall bedding geometry.

Compaction and necking - With increasing compactional stress, the differences in the cohesiveness between the limestones and mudstones became important in determining deformation style. The limestones behaved competently under stress, while the calcareous mudstones deformed by viscous flow. As the calcareous mudstones were squeezed from the limestones, the latter were increasingly deformed plastically into boudins, laterally-linked nodules, and eventually into separate blocks and nodules.

Brittle failure - With a further increase in sediment cohesiveness the pattern of deformation changed from plastic flow to shearing and brittle failure. Low angle shears, cracks, and blocky nodules were produced by movement during this stage.

Although brittle behaviour is generally associated with a solid medium, the type of deformation described here almost certainly occurred while the sediment was still plastic, and thus also occurred soon after burial. These differences in sediment consistency, which explain the changes in deformational pattern during burial, are most likely to have been related to an increase in cohesiveness associated with dewatering and lithification. Skempton (1950) and Goldring and Kazmierczak (1974) have shown that consolidation rates in sediments are partially dependent on primary composition, particularly clay content (q.v. Ch 5). Although many variables may affect the way a sediment may deform (rate of sedimentation, depositional slope, bedding thickness) there is a striking correspondence between primary composition and type of deformation in the Reservoir Mbr. limestones (q.v. Ch 6).

Limestones with high clay contents and therefore a lower cohesiveness show signs of more extensive early deformation than high-carbonate (more cohesive) limestones. This suggests that flowage and brittle failure did not necessarily always follow each other. In a sequence of interbedded limestones of differing clay contents, plastic deformation may have taken place in argillaceous strata at the same time as brittle deformation occurred in high-carbonate limestones.

3.34 Possible origin of sets

In the preceding section, the wavy form of bedding and nodules have been explained as originating through deformational processes occurring very soon after burial. These processes do not necessarily provide an explanation for the origin of sets and the large-scale lenticular nature of lensoidally bedded sequences. Either primary or secondary processes (or both) could be responsible for set formation and lens geometry.

Simple sliding of intact beds along low-angle shear planes might produce lensoidal sets. The process seems a plausible one, since low-angle shearing has been observed on a small scale in the Reservoir Mbr. (e.g. Figs. 3-3b; 3-4b) and in other comparable sequences. Large-scale translational slumping similar to that envisaged here has also been described from limestone sequences (Schwarz 1975, p 50). Previous descriptions of slumping on a sufficiently large scale to produce set-like units, also record extensive obvious internal deformation, ruckles and small folds (see Rigby 1950; Kelling and Williams 1966; and Spreng 1967), which are not present in the Reservoir Mbr. Such a secondary origin for lensoidal bedding could, however, easily explain why limestones from various facies, and therefore depositional environments, have a common lensoidal bedding arrangement.

Alternatively, sets could be primary depositional features of an undulose sea floor. The large-scale, gently inclined geometry of bedding, the composition of the limestones, and their lithological alteration might suggest that lensoids represent stable bed forms. Their size and uniformity point to deposition on a level or slightly undulose surface. The high proportion of in situ fossils and extensive bioturbation observed in lensoidally bedded sequences generally indicate slow sedimentation rates in a quiet environment. Gentle current activity seems to be the most likely mechanism to shape individual beds and thus form lensoids, either by differential erosion or uneven deposition. In order to form a lensoid, several similarly-sized sheets of sediment need to be superimposed. Since the evidence within each sheet indicates that sedimentation took place slowly, lensoidally bedded sequences argue for the presence of stable circulation patterns over significant time periods. If the pre-requisites for lensoid formation listed here are correct, then it is likely that they represent bedforms generally typical of quiet areas on even platforms, where waters are sufficiently deep to be unaffected by strong currents, and yet shallow enough to support an abundant biota.

Several observations favour this second hypothesis for the origin of lensoidal bedding. Perhaps most important among these is that if lensoidal bedding is secondary, it is likely to be the product of boudinage, as evidence for other possible deformational processes of the appropriate scale has not been found in the Reservoir Mbr. limestones. In the Petershill Fm. and the adjacent limestone horizons, however, both lensoidal and planar-bedded limestones are found together, both similarly deformed by boudinage. I have examined many limestone sequences elsewhere similar in composition, bedding thickness and extent of bioturbation (as has Wobber 1967) where boudinage has taken place, but in which lensoidal sets did not occur. The most conclusive evidence that lensoidal geometry is a primary depositional feature is suggested by bedding in the North Greens Limestone at Middleton Quarry, East Lothian, where sets are present in a sequence that has not been significantly altered by boudinage.

3.4 Colour Figs. 3-5; 3-6

The colour of the commonly occurring lithologies in the Reservoir Mbr. was found to be a useful general guide to composition. Most of these relationships are well known, having been reviewed by J. L. Wilson (1975, p 89). One colour in particular, a dark blue-grey, was singled out for special attention as its occurrence has not been described previously.

The colour terms used here are taken from the National Research Council Rock Color Chart.

3.41 Common limestone colours

Medium grey (Fig. 3-5) Most limestones in the Reservoir Mbr. fall within the hue range encompassed by medium grey. Fresh samples vary between an olive grey 5Y 4/1 and light brown (5Y 6/1) to olive grey. Weathered surfaces and the outer rind of such limestones are typically lighter, more olive coloured (Fig. 3-5).

Several factors are likely to account for the fairly wide range of grey observed:

A) differences in the degree of weathering;

B) grain size - fine-grained, micritic limestones are darker than coarser, more bioclastic samples;

C) composition - the higher proportions of clay, organic matter and framboidal pyrite in fine-grained limestones lend them a darker colour. A range of hue is even found within the fine-grained limestones, varying with the relative proportions of these constituents. Organic matter and pyrite (and the oxidation state of pyrite) are particularly important pigmenting agents (J. L. Wilson 1975, p 89) as very minor amounts may effect large colour differences;

D) degree of bioturbation - extensively reworked beds or parts of a bed tend to be darker than unbioturbated areas (Fig. 3-5). This is particularly true of burrows left by deposit feeders, such as Zoophycus, which often concentrate clay and pyrite.

Dark blue-grey (Fig. 3-5) Small structures in some limestone beds and, occasionally, entire beds are a striking blue-grey, varying between medium 5B 3/1 and dark 5B 2/1. Within beds, intraclasts, geopetal infillings (which may alternate with sediments of other colours), circumcrusts of sediment presumably bound by algae, Thalassinoides burrow linings, and laminae are often coloured blue-grey. These internal structures, and the beds themselves, have in common an unusually fine grain size (usually micrite or fine microspar) and an exceptionally low clay content.

Unlike other limestone colours, blue-grey is readily lost during diagenesis. Uniformly coloured blue-grey beds may grade laterally (over the space of a metre) into cream or very much lighter limestones although no other lithological change is visible. The edges of fractures, cavities, and brecciated areas in blue-grey limestones are often bleached to a lighter cream or yellow-brown. Less often, irregular bleaching of a bed is observed, which has left a blotchy, mottled blue-grey colouration. Orange-brown staining may also overprint blue-grey colouration.

The occurrence of blue-grey coloured primary structures, surrounded by different coloured sediment, suggests that the colour itself is primary, or associated as a stain with a primary feature of the sediment. These blue-grey structures often show signs of early textural stability associated with early lithification (e.g. fractures, intraclasts). Moreover, blue-grey sediments are likely to have contained high proportions of organic matter (e.g. algally bound surfaces, burrow linings). It seems likely that these two factors (textural stability and high initial organic content) are related and together suggest that blue-grey colouration is due to organic matter trapped in sediments by early lithification. Further documentation of the occurrences of blue-grey colouration from elsewhere may show that this colour is indeed a reliable sign of early fabric stability.

Cream (Fig. 3-5) Light to very light olive grey (5Y 6/1 to 5Y 8/1) limestones, or cream limestones are typically high-carbonate biomicrosparites and biomicrites (this term is additionally suggested by texture). In most cases, several primary structures (such as alternate blue-grey and cream geopetal infillings) indicate that the cream colour is original, and that most cream limestones are not simply bleached blue-grey limestones. Petrographically, however, cream and blue-grey limestones are very similar. In some cases, however, residual blotches of blue-grey within a cream limestone strongly suggest that cream colouration is a residual, left after blue-grey has been bleached or migrated from the fabric. The principal difference between the two colours is in their distribution (Fig. 3-6): cream coloured limestones are much more common and widely distributed, whereas extensive blue-grey colouration is largely restricted to the buildup facies.

The textural and compositional similarities between blue-grey and cream limestones make it very difficult to explain why they contrast so greatly in colour. Differences in the rate of lithification, the amount of, or oxidation state of organic matter, or in iron content, might explain the observed colour differences. The practical significance of both these colours in the present study was that they could be readily used to identify high-carbonate lithologies.

Yellow-brown (Fig. 3-5) A moderate yellow-brown colour (10 YR 5/4), ranging from pink to orange is found in dolomitic samples. Fresh samples are light pink; weathered samples are yellow-brown and often stained. Yellow-brown may stain, discolouring the beds underneath. The dolomite which causes the staining occurs in discrete laminae (Fig. 3-5) and as linings in dissolution cavities. The yellow-brown colouration appears to come from the dolomite crystals themselves, as well as from interstitial opaque ?ferric oxide (limonite) stains which spread from the crystals into the matrix. The extent of staining varies with the amount of dolomite present and depositional texture:

Fig. 3-5 The colour of the commonly occuring limestones in the Reservoir Member.

a. Dark blue-grey intraclasts in a poorly sorted packstone. The intraclasts preserve their blue-grey colour, suggesting that colouration is closely related to a primary feature of the sediment. On the far right, the laminated infilling of a Thalassinoides burrow has a much darker olive green colour due to a high proportion of clay and organic matter. Magnification x 1.2. RSM 1979.1.7

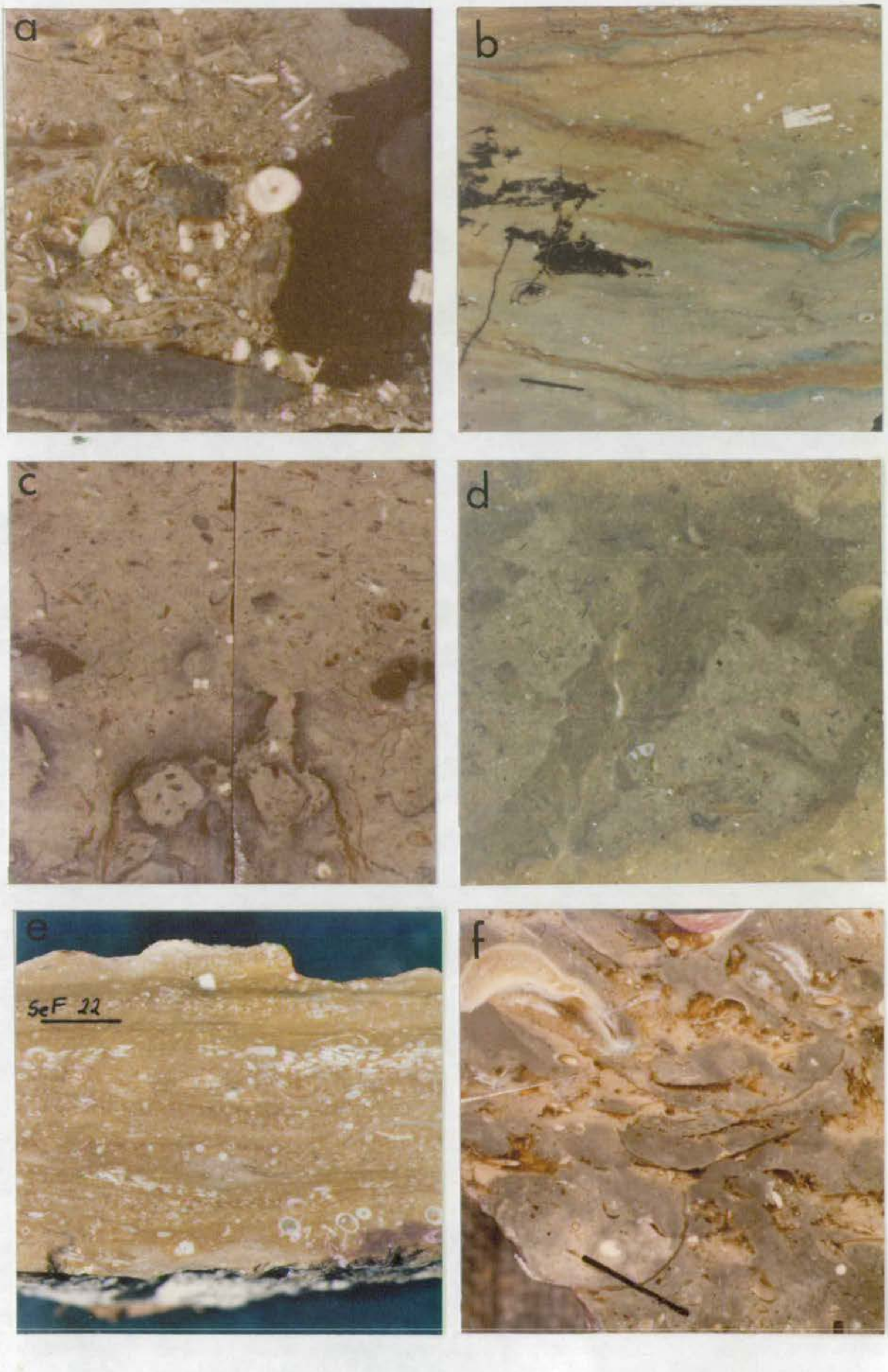
b. A layered high-carbonate biomicrosparite. Medium and light blue tinges in some lower layers indicate the specimen was originally a uniform dark blue-grey. Bleaching and yellow-brown staining obscure the original colour. The dark yellow-brown laminae mark concentrations of dolomite. Black areas at left are cavities infilled with hydrocarbon.
Scale bar = 1 cm. G.T. 46,400

c. A polished section through a core, sliced in half. Upper half shows typical cream colour of high-carbonate biomicrosparites. Multiply excavated Thalassinoides burrows in the lower half are stained blue-grey. The part of the burrow system presumed to have been re-enforced by a mucus lining is stained. The cross-section of the burrow at right reveals interconnection between horizontal tunnel and vertical shaft. Sharpness of walls is a sign of early sediment firmness. Magnification x 1.4 RSM 1979.1.6.

d. A light olive grey, slightly argillaceous wackestone. Colour variation in the sample is due to bioturbation (darker laminated areas in middle) and weathering (at the top and bottom).
Magnification x 1.3. G.T. 46,485

e. Yellow brown laminae in an echinoid packstone. Weathering of the dolomite concentrated in lamination has pigmented the entire rock, except for the losenge-shaped plates and hollow spines of echinoids.
Scale bar = 1 cm. G.T. 46,363

f. A blue-grey biomicrosparite. The matrix is blue-grey, in places fading to cream colour (near 1 cm scale bar). Diagenetic cavities are infilled with coarser, cream coloured sediments predominantly composed of partially dissolved bryozoan skeletons. G.T. 46,434d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open textures are more evenly stained than closely-packed fabrics.

3.42 Conclusion

Colour is, in general, a reliable index of composition and therefore a guide to facies recognition (as shown in Fig. 3-6). Colouration which may be directly related to primary sedimentary features, such as blue-grey and cream colours, provides surprisingly specific sedimentological information. Colour variation due to several variables (e.g. grey) shows a good, although less precise correlation with composition. Colouration due to diagenetic processes may or may not be useful in facies distinction. In the Reservoir Mbr., dolomite lamination is a specific feature of a subfacies, which may therefore be recognized on the basis of its colour alone. Diffuse dolomitization, however, is more widespread, and not facies specific. Thus diagenetic colours are useful, but to a lesser extent.

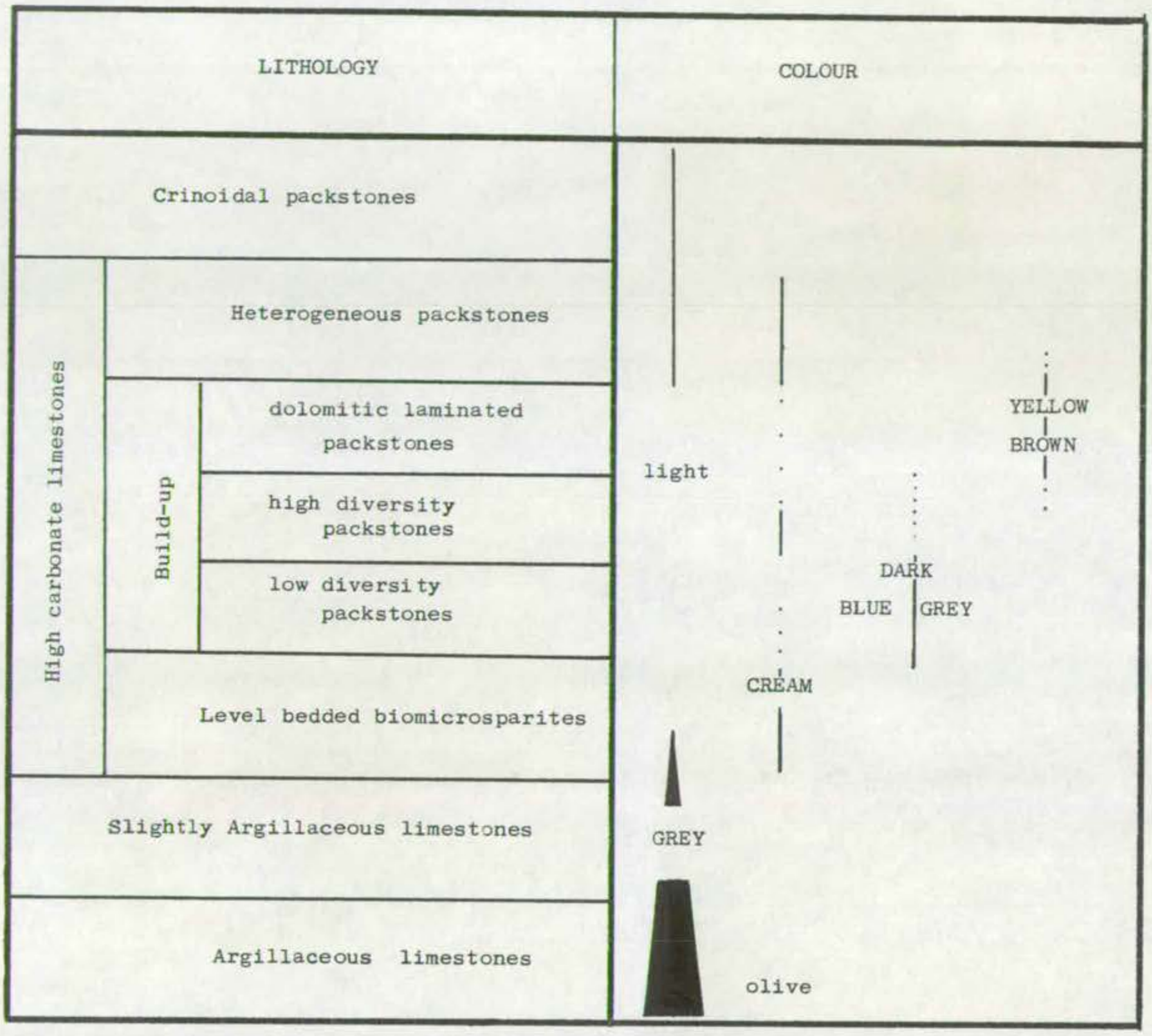


Fig. 3-6 Colour of the commonly occurring limestones in the Reservoir Mbr.

CHAPTER 4

ALGAE, MICROPROBLEMATICA, AND THEIR SIGNIFICANCE

4.0 Introduction

Algae and their degradational products form a widespread and significant constituent in the calcareous rocks of the Petershill Fm., particularly in the Reservoir Mbr. Algae, similar to the forms described here, have been largely overlooked by previous workers in the Carboniferous of Great Britain, especially in Scotland. Several factors may account for this oversight. Algal fabrics are often indistinguishable from textures attributable to biological reworking, diagenesis (recrystallization, cementation), and weathering (selective dissolution). Recognition of non-skeletal algal fabrics, particularly in the absence of stromatolitic growths, relies on the integration of a variety of criteria and a great deal of attential to detail, especially where preservation is poor. Only by combining a variety of techniques was it even possible to discover algae and their pervasiveness.

Several problems stand in the way of interpreting some of the identifiable common algae and possible algae in the Petershill Fm. The phyletic status of some forms is poorly understood. In particular, the hyaline-walled, septate, Aoujgalida have been variously considered as sponges, foraminiferans, or algae. Rather than compound the problems of classification, organisms of doubtful affinity have been considered here as microproblematica. A comparable taxonomic dilemma arises over the description of calcareous, non-skeletal, filamentous algae. In this case, a simple, non-genetic descriptive approach has been adopted. In spite of these hindrances, algae, algal fabrics and products, provide useful sedimentological information as well as being a means of characterizing and distinguishing facies.

4.1 Detrital algal grains

A small percentage of the grains (totaling up to 10-25% grain bulk) in most thin sections have either been formed by, or extensively modified by the activities of algae. More than the skeletal algal thalli themselves, these grains provide evidence that algae were present in all carbonate facies and that algae were significant in the modification and breakdown of other skeletal particles.

Algal lumps or peloids - Round or angular, dense particles of micrite (usually 1-9 mm diameter), which occasionally show a tubular or laminoid texture. Lumps typically lack signs of mechanical deformation, a sign of textural firmness. In some cases they incorporate fine skeletal debris, calcispheres and clusters of algal unicells. Algal lumps may form in any of the following ways:

A. breakdown of entirely biogenic algal forms, such as oncolites or algal crusts (q.v. De Meijer 1971, p 20; Wolf 1965, p 37);

B. direct precipitation of carbonate around unicells or colonies of unicells (Monty 1967, p 73);

C. impregnation of carbonate on the mucilagenous sheaths of filaments or unicells, resulting in aggregates of algae, sediment, and cement (Schroeder 1972);

D. algal corrosion (Monty 1967, p 83; Wolf 1965) may lead to the complete micritization of a skeletal fragment which becomes indistinguishable from grains produced by any of the above processes.

In many cases distinction between a completely bored grain, a faecal pellet, an intraclast, and an algal lump was impossible. The origins of several different types of lumps could, however, readily be interpreted, as listed in Table 4-1 (over).

TABLE 4-1

Transported algal particles

	Shape	Structure + Composition	Origin
1.	round	concentric, laminoid clotted micrite	algal
2.	elliptical, round	uniform micrite, incorporating randomly orientated skeletal debris	algal or faecal
3.	angular	clotted or uniform filamentous micrite	algal or intraclast
4.	angular	uniform micrite with skeletal outline	algal boring

Intraclasts - Intraclasts are distinct, usually angular, crumbly-edged (q.v. Ch 6) fragments of carbonate sediment. Where their matrix is likely to have been originally algally-bound, intraclasts may be considered as a specific type of algal detritus. Intraclasts in the Reservoir Mbr. have originated by mechanical erosion and transportation or collapse of algally bound fabrics. Differences in the degree or sorting and orientation of intraclasts readily allows distinction between these two types of occurrence.

Calcispheres - 60-100μ external diameter, hollow, simple or compound-walled spheres are common, occurring in solitary or clumped groups in those limestones with abundant algae in the matrix. Wray (1977, p 101), Bathurst (1971, p 69), and De Meijer (1971, p 25) have postulated that they are algal reproductive bodies, possibly belonging to dasycladaceans.

Micrite envelopes or micrite moulds - Micrite envelopes (sensu Bathurst 1971, p 384) outline both transported and in situ skeletal particles. In the slightly argillaceous and high-carbonate facies, the majority of skeletal particles have at least a thin rim of micrite. Envelopes are usually the product of multiple algal boring and bore infilling. They may also form by epitaxial micrite cementation not necessarily related to algal boring (Friedman and Sanders 1978, p 149). Where the envelope replaces part of the former skeletal particle, however, it is likely to be of algal origin. The relative abundance of enveloped particles attests to the widespread distribution of algae and provides evidence of their major role as degradational agents in the Reservoir Mbr. limestones.

4.2 Calcareous algae

4.21 Skeletal calcareous algae Fig. 4-8

The preserved skeletal remains of once erect algal thalli are volumetrically the least significant algal constituent in the Reservoir Mbr. limestones. The tendency of erect algal growths to break-up post-mortally, however, is well known. Two of the common genera described here, Epimastopora and Koninckopora, are only known from fragments (Wray 1977, pp 96, 98). Moreover, many Recent Chlorophyta, such as Halimeda and Penicillus, readily disaggregate into fine mud (Neuman and Land 1975; Bathurst 1971). In view of the pervasiveness of other algal structures and products it is probable that skeletal algae were much more abundant than the small percentage preserved would suggest.

Epimastopora sp. Pia Fig. 4-8b - A cylindrical thallus, up to 0.8 mm diameter, variable in size, with pore diameters ranging between 45-200μ; Epimastopora is the only alga to be found in the Silvermine Mbr., in a discontinuous limestone approximately 14 m above the member base.

Koninckopora - Fragments of Koninckopora cf. minuta Weyer have inner polygonal cell diameters between 80-100µ, and a cell wall thickness near 20µ. The cellular structure of Koninckopora was particularly susceptible to dissolution, and like Epimastopora, only fragments were found. The presence of a distinct bipartite (fibrous and non-fibrous) wall structure was considered diagnostic of Konickopora.

Codiacean algae indet. Fig. 7-2 - Fragments unidentifiable beyond family level are common in approximately sixty percent of all fine-grained, high-carbonate limestones in the Reservoir Mbr. In rare instances they may comprise as much as 10-15% grain bulk.

Sphinctoporella sp. Mamet and Rudloff Figs. 0-12; 4-8c - The thallus is sub-polygonal or round in cross-section, with a central medulla measuring between 200-300µ in diameter. Radially disposed endospores (approximately 40µ in diameter) are interconnected by thin tubes (5-10µ in diameter) to the central medulla (Fig. 4-8c). The packing and arrangement of these endospores was used to distinguish Sphinctoporella from a similar taxon Atractylopsis, Mamet and Rudloff (1972, p 84, 100) consider Sphinctoporella to be a dasycladacean alga.

4.22 Filamentous calcareous algae Figs. 4-2; 4-3; 4-4; 4-5; 4-6; 4-7

Three types of filamentous algae are recognizable in the Reservoir Mbr. calcareous sediments: Girvanella, branched filamentous algae (a new undescribed form); and shell-boring algae. The first two types are morphologically very similar and produce comparable fabrics where they have evidently influenced sediment accumulation. In some preparations, it is not possible to distinguish between Girvanella and branched filamentous algae, because of their morphological similarity and mode of preservation. Thus, while the morphology of the filaments of each has been described separately, the fabrics they may produce have been described together.

Girvanella and branched filamentous algae (abbreviated to branched algae) have been collectively referred to as filamentous algae where the distinction between the two could not be made, or was not sedimentologically important.

4.221 Methods

Filamentous algae were studied from insoluble residues (Figs. 4-2a, b; 4-5), on the surfaces of polished and etched blocks (Fig. 4-5) and in ultra-thin, double-polished sections (Fig. 4-3). In order to study filamentous algae, 9 polished plaquettes, 16 thin sections, and 30 shell fragments were etched in a saturated EDTA solution (see De Meijer 1969, for details of method). In order to minimize any possible contamination, the rock samples were taken from bore-hole cores 3-10 m below the surface. Representative samples from every facies were taken. In addition, pyrite infillings of branched filamentous algae were hand picked from the insoluble residues obtained during clay mineral analysis.

Organic walled filaments were extracted from samples immersed in EDTA, etched for 8-40 hours (till the carbonate had been dissolved), and rinsed by gentle irrigation before microscopic examination. By taking great care not to disturb the residue, it was possible to examine the remains of any original filamentous algal fabrics.

Etching normally produced a spongy-textured residue of chalcedonic quartz still retaining the shape of the plaquette or thin section. Immediately above this spongy, coherent residue was a fine, wooly "fluff", probably of organic matter, containing clear filaments of branched filamentous algae (shown in Fig. 4-2a, b), and small doubly-terminated quartz euhedra. Where the fluff had remained attached to the spongy residue underneath, the original fluff fabric appeared to be intact and undisturbed. Filaments above the residue formed a very

Fig. 4-2 Branched filamentous algae from insoluble residues

a, b - transmitted light, c,d,e,f,g - SEM photographs.

a.,b. The organic walled filaments of branched filamentous algae, extracted by EDTA etching. The filament in 4-2a appears to have been compacted slightly. The branched filament in 4-2b twists in three dimensions and is encrusted with chalcedonic quartz. 4-2a scale bar = 19µ; 4-2b scale bar = 12µ.

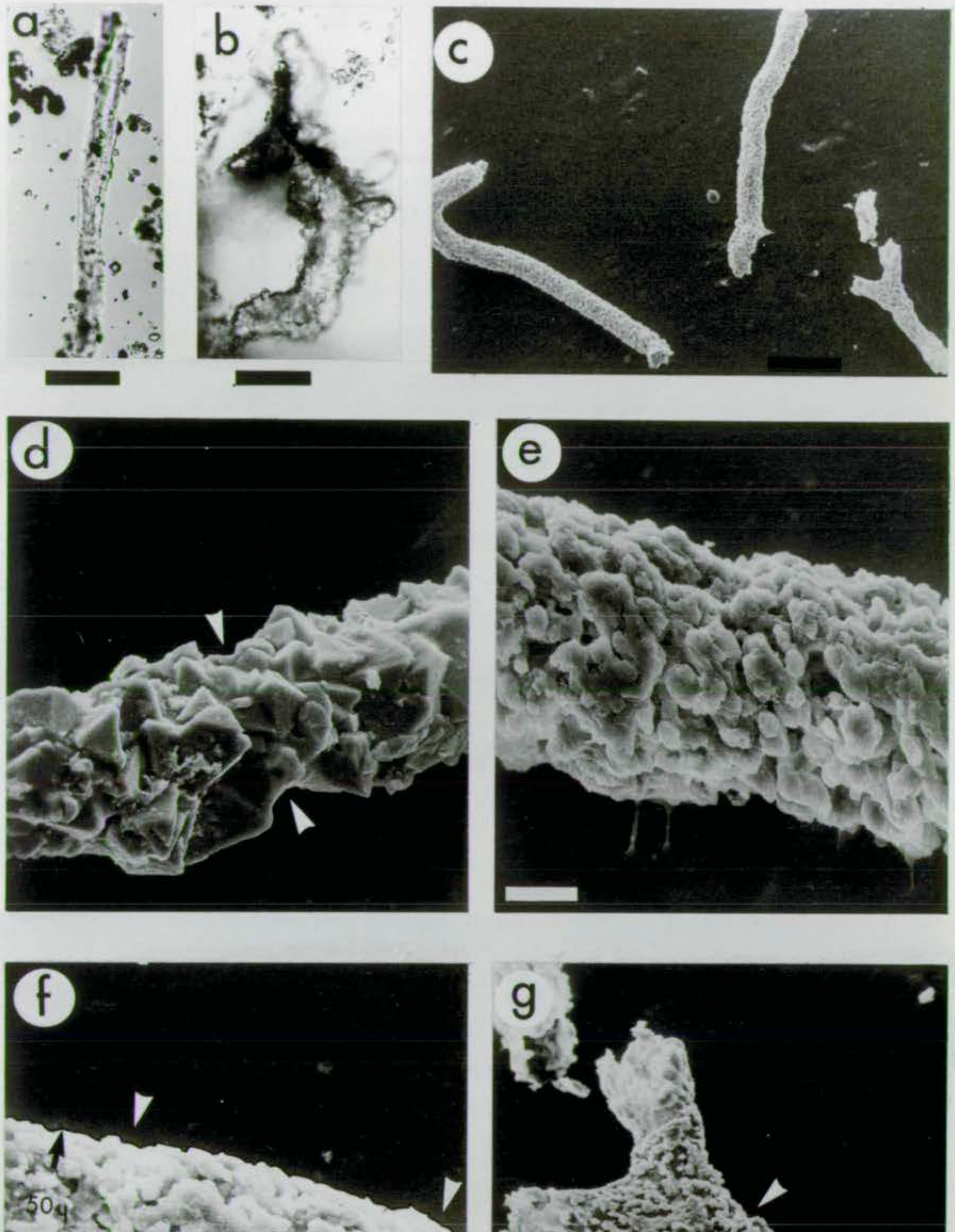
c. Pyrite-infilled branched filamentous algae with sheath replaced by chalcedonic quartz. Scale bar = 235µ. G.T. 46,546 c

d. Branched algal filament. Outer sheath not preserved, revealing the pyrite infilling (q.v. Fig. 4-3). Arrows point to constriction in pyrite at the junction between two cells. G.T. 46,546 c Scale bar = 20µ.

e. Branched algal filament, same magnification as previous photo. The outer sheath has been preserved by a replacement of chalcedonic quartz. Consequently filament appears much larger. Scale bar = 20µ. G.T. 46,546 c

f. Branched algal filament; close-up of cellular structure. Filament sheath has been replaced by chalcedonic quartz. G.T. 46,546 c

g. Algal filament showing branching. Note that filament does not decrease in diameter after bifurcation. Arrows show cellular structure of filament. Filament's outer sheath is unevenly replaced by chalcedonic quartz, which forms an irregular covering over more fine-grained pyrite underneath. The preservation of the cellular structure indicates that pyrite formation took place very early, prior to complete decay of organic matter. G.T. 46,546 c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loose meshwork of crossed, twisting filaments, broadly comparable to, but more open than, the meshworks from Recent mats (q.v. Neuman, Gebelein, and Scoffin 1970).

Attempts to preserve this framework by drawing off the rinse water while simultaneously irrigating with either glycerine or gelatin in solution failed. The fluff and filament fabric were extremely delicate. It was only possible to observe the fabric when this whole treatment was performed on a microscope stage, thus ensuring that the sample was not disturbed.

4.222 Girvanella spp Figs. 4-3; 4-7

Morphology - The Reservoir Mbr. Girvanella specimens consist of a flexuous tube or bundle of tubes usually walled in micrite or fine microspar. The exterior tube diameter ranges between 6-30µ, mean 25 ±5µ (±1 standard deviation); the micrite sheath thickness ranges between 2-8µ, mean 5 ±0.8µ (measurements made on 60 circular filament cross-sections from 28 different thin sections). The sheath thickness/exterior diameter ratio is a fairly constant 0.25 throughout the filament size range present. Branching, which is commonly reported in Girvanella (Wray 1977, p 36) was not observed. The dimensions of the more commonly occurring Reservoir Mbr. Girvanella coincide with those given by Wood (1963) for G. ducii and G. wetheredii. These species distinctions were not found to have any particular significance, however. In several cases more than one "species" was present in a single bundle. The only fairly consistent relationship that may be of significance is that tubes forming lumps and grain coatings are usually smaller than those intergrown throughout the matrix.

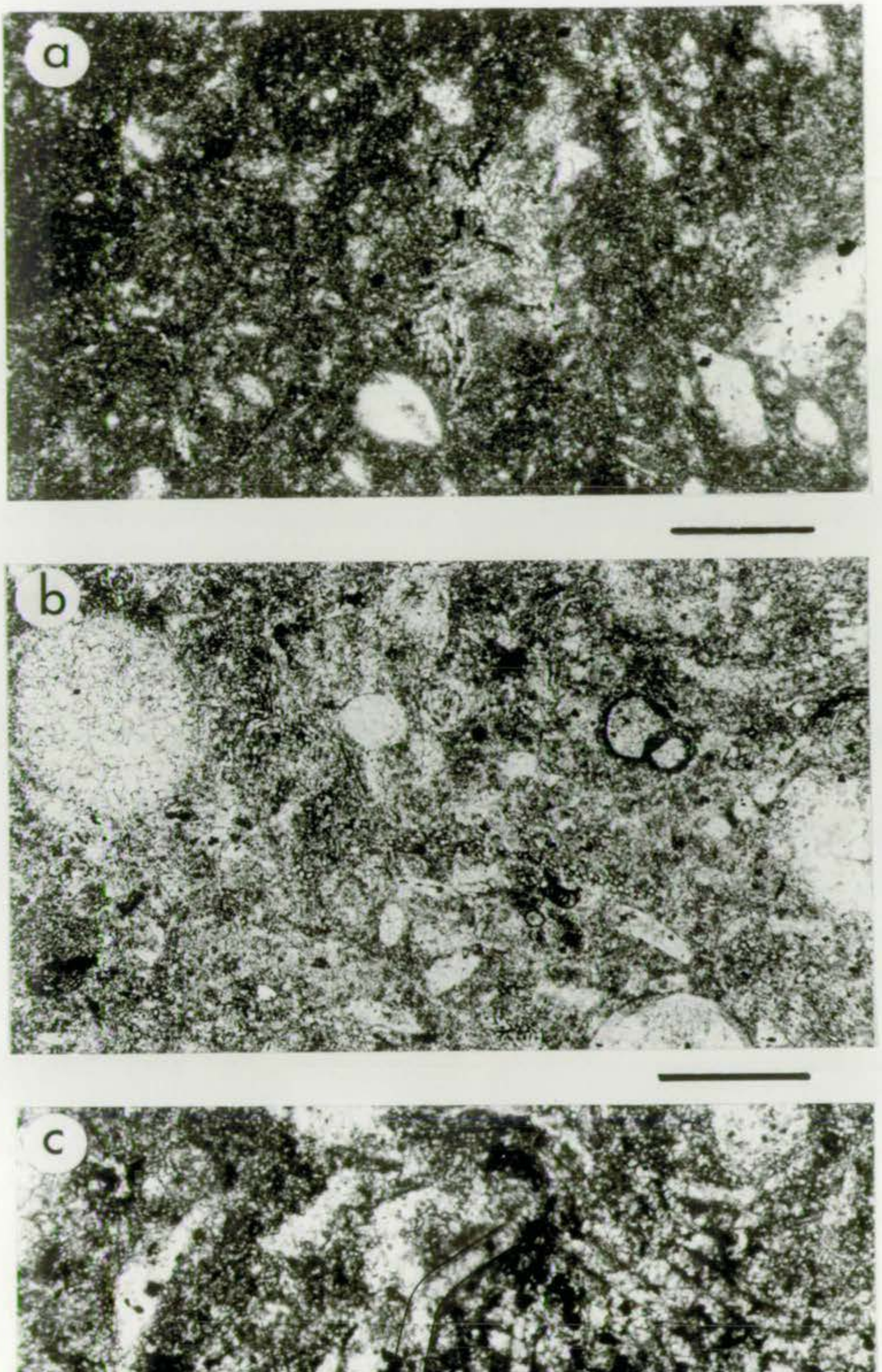
Preservation - The tube of Girvanella is usually composed of dense, unrecrystallized micrite (e.g. Fig. 4-7a). At high magnifications the edges of the tube are dense and difficult to resolve.

Fig. 4-3 Filamentous algae: appearance in thin section.

a. Branched filamentous algae intergrown throughout matrix. The uniformly recrystallized matrix shows a poorly-defined swirly pattern, characteristic of microspar almost entirely composed of filaments. In the centre, where the filament infillings have recrystallized to a greater extent, the filamentous fabric becomes visible (see also 4-3c). High-carbonate wackestone, high-carbonate biomicrosparite facies. Scale bar = 315μ. G.T. 46,494

b. *Girvanella* intergrown throughout matrix, showing tendency to form sheet-form growth in middle of photo. Elsewhere, more randomly orientated filaments are preserved as swirly texture. Opaque specks throughout matrix are pyrite, typically associated with filamentous algae. Slightly argillaceous packstone (genetically a boundstone); slightly argillaceous limestone facies, Petershill Reservoir. Scale bar = 520μ. G.T. 46,488

c. Branched algae close-up showing part of intergrowth framework. Filaments are likely to have been originally present throughout, but are only preserved in slightly recrystallized areas. One filament in particular (drawn in) may be traced through various states of preservation. High-carbonate wackestone, high-carbonate biomicrosparites; Petershill Lime Works. Scale bar = 100μ. G.T 46 493


a
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c

In this, the normal preservation state, Girvanella stands out prominently in thin section (Figs. 4-3b; 4-6d; 4-7a).

In the Reservoir Mbr., slight neomorphic recrystallization has often obscured this fabric which is so characteristic of Girvanella (Figs. 4-3b; 4-7a). In slightly recrystallized limestones, the Girvanella micrite sheath has often altered to microspar, lessening the contrast between the tube and surrounding micrite or microspar. The tube and matrix are only distinguishable by a subtle difference in crystal size between similar types of microspar. Equant or elongate (parallel to the tube) neomorphic spar crystals (or rarely dolomite) of a constant transverse diameter form chains in the interior of the tube. It appears that the growth of spar in the tube interior has been inhibited from further lateral growth by the presence of tube wall. These bundles of chains of microspar and, occasionally, pyrite produce a fine swirly texture characteristic of filamentous algal intergrowth and bound fabrics in the Reservoir Mbr. limestones (Figs. 4-3; 4-6; 4-7).

4.223 Branched filamentous algae Figs. 4-2; 4-3; 4-4; 4-5; 4-6; 4-7

Morphology (Fig. 4-4) - The regularly branched filaments are composed of light brown or colourless material, almost certainly organic, averaging 12µ in diameter (±10µ) and ranging between 3-8µ. Filaments branch at acute angles, and appear to maintain a constant diameter throughout each bifurcation (Figs. 4-2g; 4-6). Over several hundred microns in length, the filaments probably taper gradually. The possibility that a variety of large and small filaments of constant diameter are always found together, however, cannot be discounted. The filament infillings have constrictions at regular, 110-120µ intervals, which strongly suggest that the filaments originally had a box-like, cellular, internal structure (Figs. 4-2; 4-4).

Preservation (Fig. 4-4) - Differences in the preservation and preparation/observation conditions create the impression that several types of branched algae are present. These differences must be kept in mind in order to understand how compositionally different filaments have come to be regarded as representing the same taxon. The figures cited throughout this section illustrate the commonly occurring preservation states and their appearance.

Branched filamentous algae may be preserved as: a) an infilling of the organic-walled filament by microspar, dolomite microspar pyrite, or chalcedonic quartz (Figs. 4-2; 4-4; 4-6); b) a micritic or chalcedonic quartz sheath surrounding the filament (q.v. Figs. 4-2; 4-4; 4-5); c) the organic-walled filament itself (Fig. 4-2).

In the most commonly-observed preservation state, the branched algal filaments are surrounded by a micrite sheath (Figs. 4-4; 4-5). In this respect Girvanella and branched algae are very similar. The sheath of branched algae, however, is less optically dense and more susceptible to recrystallization and replacement (Girvanella is shown in Figs. 4-6d; 4-7a; cf. with branched algae in Figs. 4-3a, c; 4-6b, c). The differences in sheath density can sometimes provide a means of distinguishing the two.

Branched filamentous algae are similar to Girvanella in that their outer micritic sheath tends to recrystallize slightly and blend in with the matrix. Where the filament infillings have recrystallized to relatively coarse microspar, swirly patterns (also similar to G. fabrics) may belie the former presence of branched algae. Slightly recrystallized branched algal fabrics and Girvanella fabrics are often indistinguishable. As in Girvanella, the binding nature of branched algal fabrics is most readily apparent where a slight degree of recrystallization

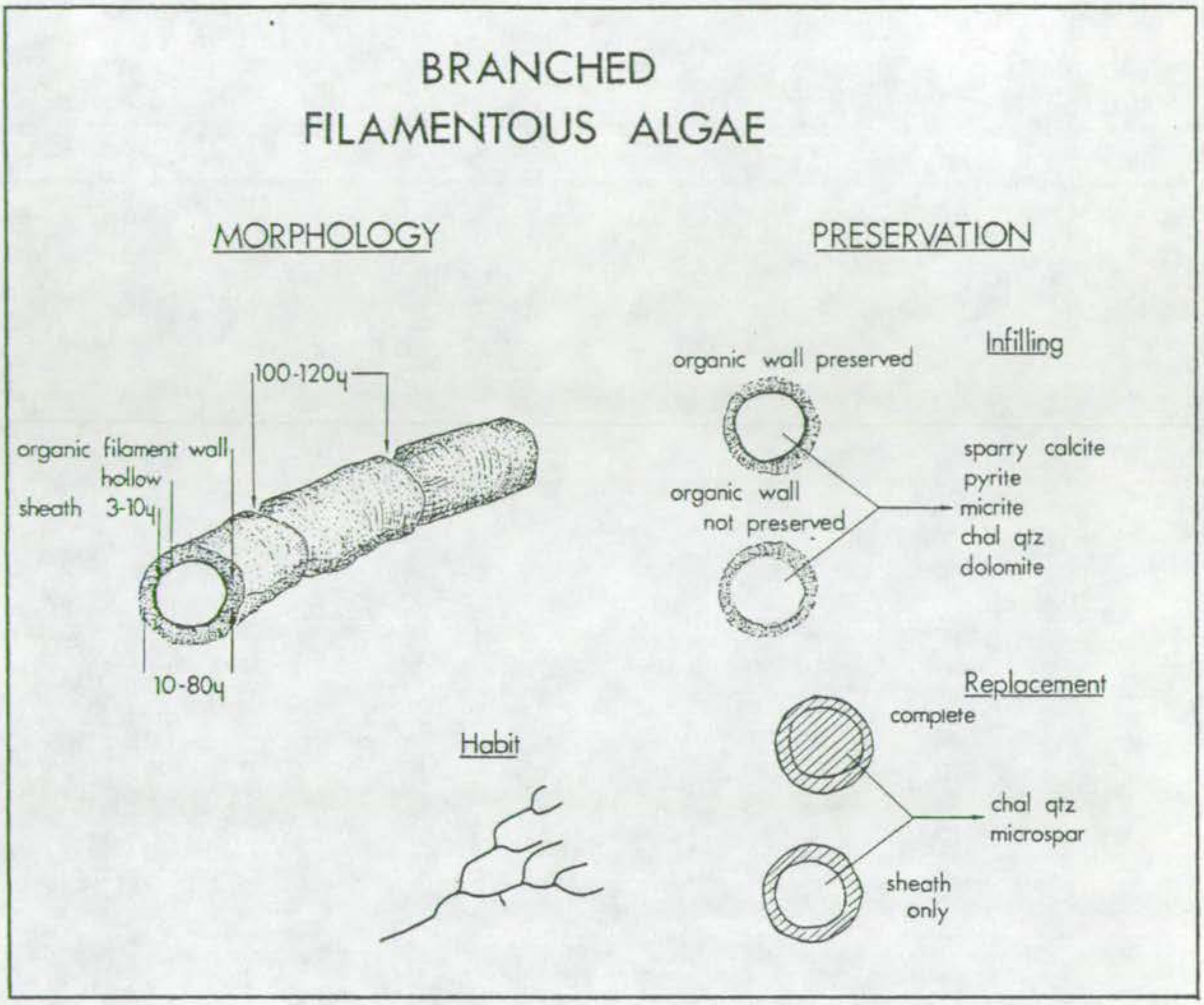


Fig. 4-4 Morphology and preservation of branched filamentous algae.

External habit and commonly observed size range of branched filamentous algae shown, along with the commonest ways in which the filaments may be preserved.

has taken place.

As previously mentioned, pyrite and chalcedonic quartz infillings often partially or completely preserve the cellular filament structure. The presence of such preserved inner cellular structures may be taken as a sign that the infillings are very early, formed while the algal cells were still available as templates for replacement mineral nucleation. In the case of pyrite, these infillings thus provide evidence of early reducing conditions (Kobluk and Risk 1977).

Where the branched algal sheath can be resolved from the matrix (e.g. Figs. 4-3c; 4-5; 4-6b, c), it is uniform in thickness and contrasts sharply with irregular cement impregnations on sheaths described by others on filamentous algae from elsewhere (Schroeder 1972). The regular thickness of the branched algal sheath suggests that the algae exerted some control over sheath calcification (q.v. Riding 1977). Thus it is likely that branched algae were calcareous, and that, where the outer sheath has not been preserved, it has been lost during diagenesis.

<u>4.224</u> <u>Boring algae</u> Figs. 4-6c; 14-5e, f

<u>Morphology</u> - Various types of microborings are common in fossils from all high-carbonate facies. Two boring patterns are especially common and likely to have been formed by algae rather than fungi. One of these is attributable to the branched algae described above; filaments can clearly be traced from the matrix into a shell. A second branched boring pattern is sufficiently different to suggest it may have been formed by another alga. The diameter of the boring algae (average 16μ, range 3-30μ) is similar to that of branched algae, but the growth form differs in having a constant bifurcation of 50°, and in decreasing in diameter by one third following each bifurcation.

Fig. 4-5 Filamentous algae: SEM photos of EDTA etched surfaces of filamentous algal intergrowths. Photos reveal pervasiveness (and probable binding nature) of filamentous algae. All high-carbonate biomicrosparites from the lower build-up facies.

a. Porous fabric typical of fine-grained lithologies abundant in filamentous algae. Scale bar = 56μ.

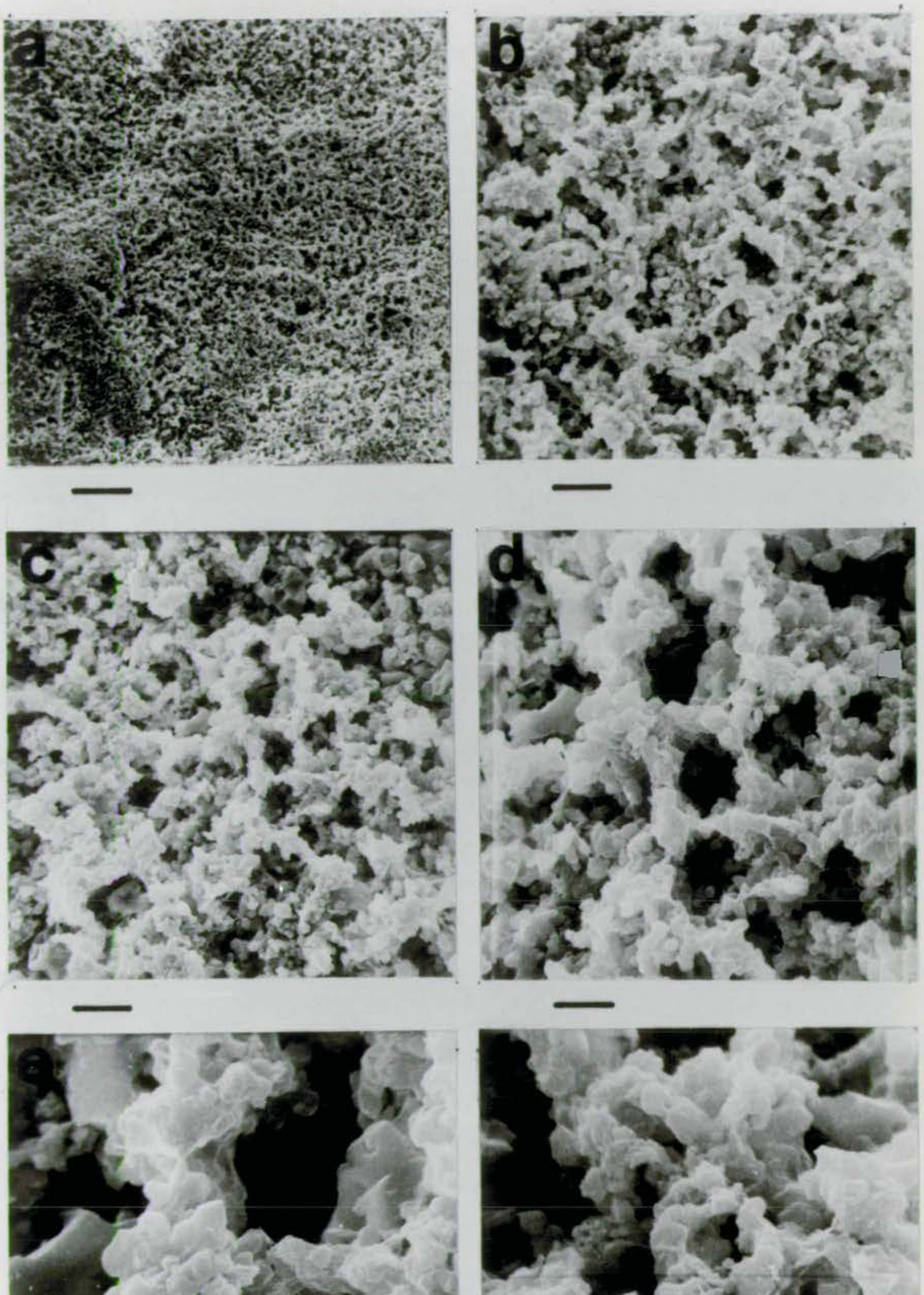
b. Close-up; etching has selectively removed the larger microspar crystals, particularly those infilling the algal filaments (also shown in subsequent photographs), leaving finer microspar and micrite prominent. Scale bar = 24μ.

c. Higher magnification still reveals that "matrix" consists almost entirely of micritic filament sheaths. Note north-south chain of filaments about mid-photo. These are shown at progressively higher magnifications in the succeeding two photos. Scale bar = 18μ.

d. Close-up of filamentous algae. Note that filament walls are fairly uniform in thickness, suggesting the alga exerted an influence over calcification. Scale bar = 11μ.

e. Close-up. Filament sheaths are round in cross section and lack signs of compaction, a sign of early stability and firmness. Organic wall has not been preserved. Scale bar = 14μ.

f. Close-up.of another area where filaments are more randomly directed. Scale bar = 10μ.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e

Preservation - The borings are infilled by pyrite, micrite, microspar, and rarely by chalcedonic quartz.

4.225 Taxonomic status of branched filamentous algae

In the foregoing description it has been assumed that the branched filaments occurring in the matrix and as shell borings correspond to the thallus of an alga. The distinction between algae and fungi must be made with caution, however, particularly between filaments in the 10-30μ range. Algae and fungi overlap in filament size, habitat, and morphology (Bromley 1970). Bromley (ibid) stated that filament sizes larger than 30μ, false-branching, acute branching angles, an association with Fe-minerals, and a random filament growth habit were characteristic of algae. Edwards and Perkins (1976, p 1125) additionally considered that the absence of spherical structures characteristic of fungal hyphae could be used as a further criteria of algal origin. Kobluk and Risk (1977) ascribed an algal origin to borings which are morphologically very similar to those found in the Reservoir Mbr. shells. Together these criteria indicate that Reservoir Mbr. branched filaments are almost certainly of algal origin.

Branched filamentous algae in the Reservoir Mbr. are morphologically very similar to the genera Ortonella and Scytonema (the latter often illustrated as a Recent analogue to Ortonella, q.v. Wray 1977, p 39). The Reservoir Mbr. branched algae cannot be referred to Ortonella, however, as the latter is also an oncolitic form-genus (Garwood 1914). Moreover, Ortonella apparently lacks an organic wall and internal cellular partitioning. Branched algae are tentatively considered to be green or blue-green algae, as they are similar in morphology, habitat and growth form to previously described Recent and ancient forms belonging to these groups.

In previous works, filamentous algae similar to those described here have often been described according to the structures or fabrics they create, rather than by their filament morphology. Pia (1927, pp 36-40) was among the first to make such a distinction in erecting the Porostromata (tubiform calcareous algae) and the Spongiostromata (stromatolitic algae, classified by growth forms and texture). Riding (1975) has pointed out that a great deal of confusion has arisen over this taxonomic distinction, as some algae can be equally correctly placed in either group. Moreover, many stromatolitic growth forms are often environmentally influenced and thus cannot be used for phyletic distinctions.

Numerous alternative descriptive and taxonomic terms have been proposed since 1927 (Wolf 1965; Aitken 1967; Riding 1977). Wolf (ibid, p 137) coined the term pseudostromatic to describe "algal colonies with no particular external form which lack internal lamination". De Meijer (1971) later gave this term a precise definition, describing pseudostromatic fabrics in detail. The terms pseudostromatic and, simply, "clotted", best describe the algal fabrics in the Reservoir Mbr. Branched filamentous algae are widespread throughout the Reservoir Mbr., but do not always show pseudostromatic fabrics. Thus it would be incorrect to regard all branched algae as pseudostromatic, particularly where their characteristic fabrics are absent. Rather than burden the literature with yet another term, branched filamentous algae are described here as such, while it should be noted that they may produce both clotted and pseudostromatic fabrics.

4.3 Algal fabrics : signs of binding

Sediment accumulations which are thought to have been influenced by the trapping action of filamentous algae have several textures and structures in common. In many cases, where the filaments are intergrown

Fig. 4-7 Filamentous algae: fabrics and signs of binding

a. *Girvanella* intergrowth in a poorly-sorted packstone. The microspar matrix is almost entirely composed of *G.* In unrecrystallized areas, *G.* displays the appearance by which it is typically recognized (centre). Differential recrystallization of the matrix throughout most of section has led to partial or complete obliteration of the typical G. habit. Slightly recrystallized areas show a swirly texture (e.g. beneath foraminiferan), while more extensive alteration has left chains of microspar crystals. Such fabrics are typical fabrics showing structures attributable to binding. Double-polished, ultra-thin section; slightly argillaceous limestone facies, Petershill Reservoir. Scale bar = 300µ. g.T. 46,341

b. Blue-grey wackestone circumcrust. Vertically orientated corallites of *Koninckophyllum* cf. *dianthoides* partially circumscribed by a blue-grey algally bound crust. Circumcrust has fractured and begun to detach from the corallite. Crumbly fractures in the crust, a sign of firmness, suggest limited early lithification. Polished plaquette, high-carbonate biomicrosparite; Petershill Reservoir. Width of scale division = 1 cm. g.T. 46,500

c. Partial circumcrust. An overturned, articulated shell of the spinose productoid *Antiquatonia* partially circumscribed by blue-grey, algally bound wackestone. The circumcrust has in turn been encrusted by *Fistulipora* (compound arrow). Other probable algal intraclasts are present above (simple arrows). The absence of sorting and signs of transportation suggest that the intraclasts and brachiopod were freed during post mortem collapse of an algal colony. High-carbonate cream biomicrosparite; quarry 50 m south of South Quarry. Scale bar = 5 mm. RSM 1979.1.5

throughout the matrix, the in situ binding nature of the filaments can be inferred directly (Figs. 4-3; 4-5; 4-6; 4-7). Often, however, sediments lack such an obvious sign of binding, but display structures that can be best explained by the former presence of a sediment-binding surface of algal filaments. Further investigation has revealed abundant algal remains in some of these structures. The structures themselves also provide an insight into the mass properties of algally bound sediments. Moreover, they indicate that these Carboniferous algally stabilized sediments are comparable to Recent subtidal mats.

4.31 Intergrowths Figs 4-3; 4-5; 4-6; 4-7

The most obviously 'bound' fabrics are those in which the fine-grained matrix consists almost entirely of loosely organized filaments spreading evenly throughout, circumscribing transported and in situ fossils alike. Both *Girvanella* and branched algae commonly form such sediment intergrowths. To my knowledge, this habit has not previously been reported in *Girvanella*. Sediments intergrown with filamentous algae simply contain abundant filaments throughout; laminated or ordered stromatolitic growths, however, are absent. These intergrowths may be extensively bioturbated, and may have uniform or clotted fabrics. They show the least degree of algal influence on accumulation.

4.32 Layered and sheet-form growths Figs. 4-3b; 4-6d

Filamentous algae may show signs of slightly greater influence on sediment accumulation where they form layered fabrics (Ch 7) or sheet-form growths (typical of *Girvanella*, Fig. 4-6d). Both are typically undisturbed by biological reworking. The fabrics have formed where filaments grew in fairly dense masses, along a lamination or layer within specimens.

4.33 Circumcrusts Figs 4-7b; 7-4c

Coatings of sediment which circumscribe fossils may be attributed

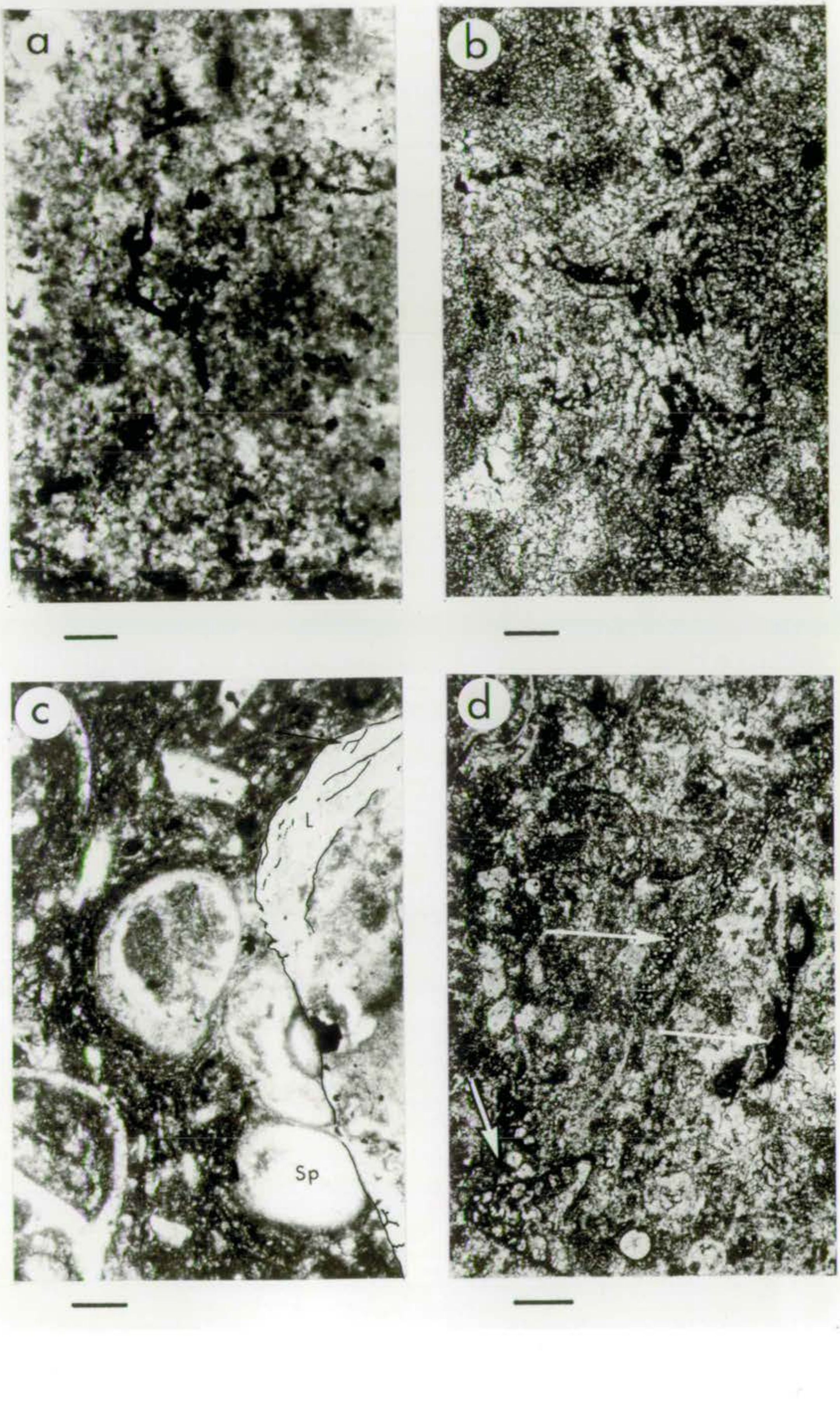
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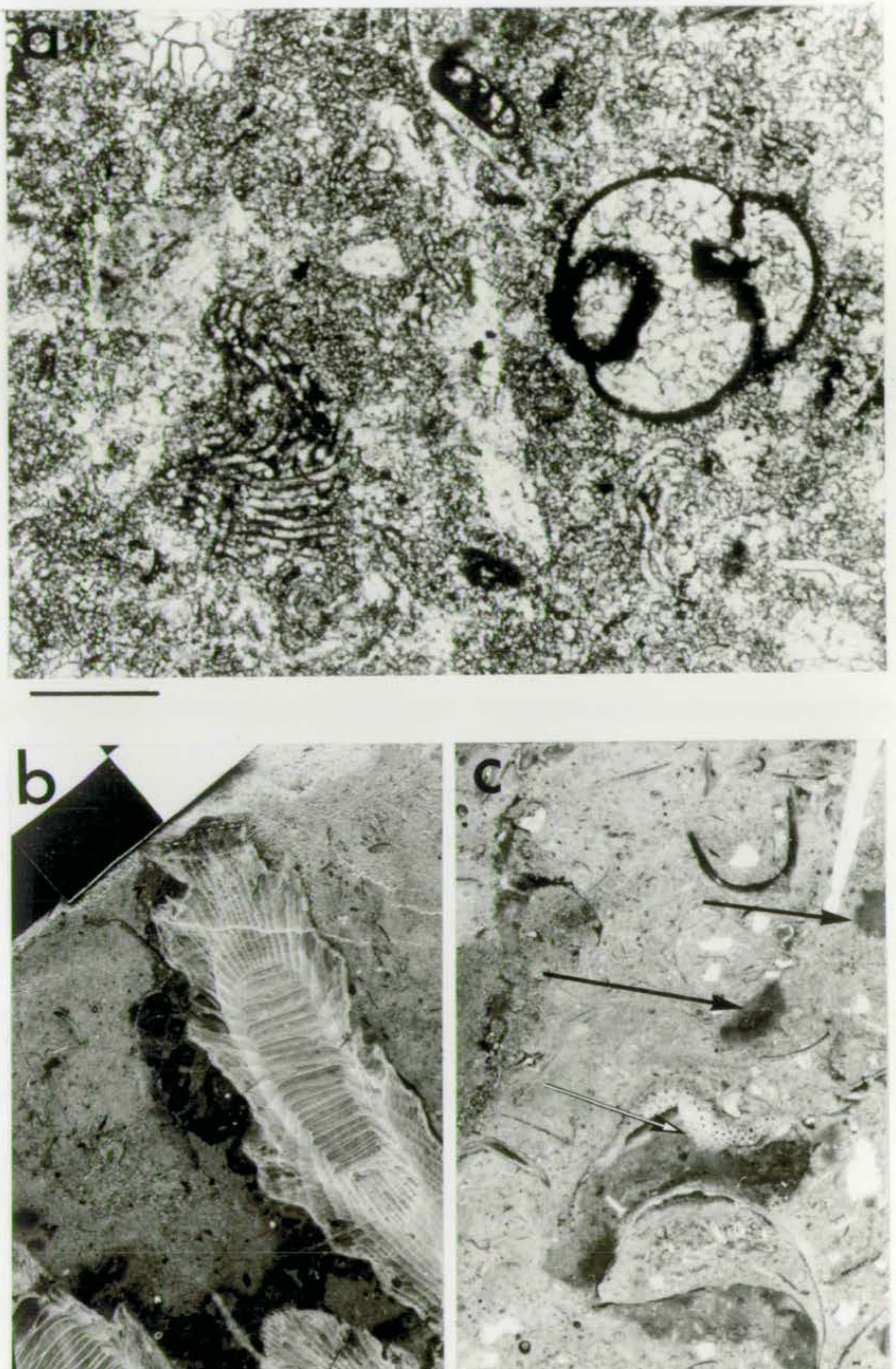
Fig. 4-6 Filamentous algae: fabrics and morphology

a. Branched filamentous algae. Pyrite infillings pick out branched algae throughout the matrix of a slightly recrystallized microspar matrix. Filaments of several sizes are present and intergrown evenly throughout the matrix. Note that, apart from the pyrite infillings, no other evidence is present that would indicate the former presence of algae. High-carbonate biomicrosparite. Scale bar = 76μ. G.T. 46472

b. Branched filamentous algae, close-up. Algal origin of matrix is only apparent in middle where slight differential recrystallization of infilling to microspar provides contrast necessary to resolve actual filaments. Note how difficult it is to resolve filaments from uniformly-recrystallized surrounding matrix. High-carbonate biomicrosparite, Petershill Reservoir; borehole 4, 2 m level. Scale bar = 60μ. G.T 46,303

c. Circumscribing growth of branched algae. Filaments clearly wrap around Spirorbis (Sp.), a worm encrusted onto a bored Lithostrotion colony. Lithostrotion skeleton and borings inked in. The filamentous algae are clearly in situ and part of the sediment as they envelop an in situ benthonic structure. High-carbonate biomicrosparite, Lithostrotion thicket; Petershill Reservoir. Scale bar = 200μ. G.T. 46472

d. Girvanella intergrowth throughout a slightly argillaceous packstone. Filaments of G. spread evenly throughout the matrix except in mid-photo (white arrows) where orientated filaments spread in sheet-form growth. The filaments in the sheet-form growths are crowded, and appear to have formed a stable surface, as shown by the attached foraminiferan, Tetrataxis (compound arrow). The matrix elsewhere appears to have undergone differential recrystallization to a rather poorly clotted fabric. Slightly argillaceous packstone, slightly argillaceous limestone facies, Petershill Reservoir. Scale bar = 75μ. G.T 46,390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to the binding (and perhaps cementing) action of filamentous algae, particularly where such crusts drape vertical surfaces. Two types of crust are common: a) blue-grey wackestone crusts (Fig. 4-7b); b) dense laminated micrite crusts (Fig. 7-4c). The former are relatively thick, reaching up to 1 cm. They often incorporate skeletal grains and may, in turn, be encrusted by Fistulipora, or foraminiferans. Blue-grey wackestone crusts are seldom entirely intact. Most often they are extensively fractured and appear to be pulling away from their encrustation surface, in the process of collapse (Fig. 4-7). The presence of crusts in intermediate stages of decay suggests that some of unsorted piles of small blue-grey intraclasts which are so common in algally-bound sediments represent completely collapsed crusts.

Laminated micrite crusts are much denser and thinner, seldom reaching 1 mm. They also encrust vertical and overhanging skeletal surfaces, such as productoid brachiopods.

4.34 Clotted or pseudostromatic texture

Clotted textures are specific to high-carbonate limestones. Two types are present in the Reservoir Mbr.: a) discrete particles of micrite or fine microspar (5-10μ mean diameter) rimmed by clear prismatic, sparry calcite cements; b) porous frameworks with numerous dissolution voids. Cathodoluminescence petrology clearly indicates that the prismatic spar in these fabrics is cement, and that, in some cases, the cement infills dissolution voids. A more detailed description of these fabrics and their origins is given in Ch 6. Clotted textures are characteristic of algally bound sediments. They are not, however, entirely the product of the stabilizing activities of algae. In the Reservoir Mbr. limestones, clotted fabrics have formed from the interaction of several processes, among which algal binding was (in some cases only) the earliest.

4.35 Non-compaction

Algally bound sediments only show slight signs of compaction or a differential compaction pattern (q.v. Ch 5). Although this feature is not solely the product of binding, it is one of the characteristic features of bound sediments.

4.36 Orientated encrusters

Sediment surfaces stabilized by filamentous algae are often encrusted, particularly by foraminiferans and bryozoans (Figs. 4-6; 7-4). Encrusters reveal that bound surfaces were often somewhat hummocky. Vertical or overhanging surfaces, however, do not occur. The palaeoecology and distribution of encrusters is described in detail in Ch 14.

4.4 Microproblematica

The following forms have been identified from descriptions by authors who considered them to be algae, but a considerable controversy exists over their phyletic status. They form a small, but significant element of the biota associated with algal limestones.

Kamaena cf. delicata Anthropov Fig. 4-8a

An erect, cylindrical thallus, occasionally branching, with regular internal septae normal to the thallus wall. Pore perforations, a characteristic feature, are not clearly visible, but may be present. Kamaena usually occurs as fragments and rarely as in situ growths. Kamaenids never amount to more than a few percent grain bulk. Mamet and Roux (1974) and Wray (1977, p 105) considered that Kamaena is a palaeoberesellid dasycladacean alga. Termier, Termier and Vachard (1975) assigned Palaeoberesellinae to the Order Moravamminida which they considered to belong to the Ischyrospongia. Riding (1975) has suggested a foraminiferal affinity for Kamaena.

Kamaenella cf. denbighi Mamet and Roux

Forms resembling K. denbighi (Mamet and Roux 1974) in thallus size, branching habit, wall thickness, and septal development are common as fragments and growths intertwined among spines projecting beneath productoids. The Reservoir Mbr. specimens tend to twist and double back during growth in manner not illustrated by Mamet and Roux (ibid, p 140), perhaps due to their encrusting growth habit rather than a taxonomic difference. Like Kamaena, Kamaenella has been considered as an alga, sponge, or foraminiferan (refs. given).

Stacheoides spp. Fig. 7-3a

Two probable forms of Stacheoides have been recognized, S. cf. spissa Petryk and Mamet, and S. cf. meandriformis Mamet and Rudloff. The former has laminar cell walls 30-80μ thick (mean 50μ) with well-marked vertical elements tens of microns thick. S. cf. meandriformis has similar dimensions, but is distinguished by a more meandrine habit and more open laminar cells.

Stacheoides is most abundant in the lower part of the build-up facies and the high-carbonate biomicrosparite facies.

Stacheoides has been described both as a foraminiferan and as a red alga (Wray 1977).

Shartymophycus fusus Kulik

An encruster, composed of successive recrystallized, thick laminae of yellowish, hyaline calcite, 80-100μ thick, occasionally interrupted by sediment or encrusting foraminiferans. The laminae are formed of radial, somewhat colloform, masses of calcite crystals, several hundreds of microns in length. This appears to be the normal preservation state (cf. Mamet and Roux 1975). Mamet and Roux (1975, p 166) tentatively place Shartymophycus in the Chlorophyta.

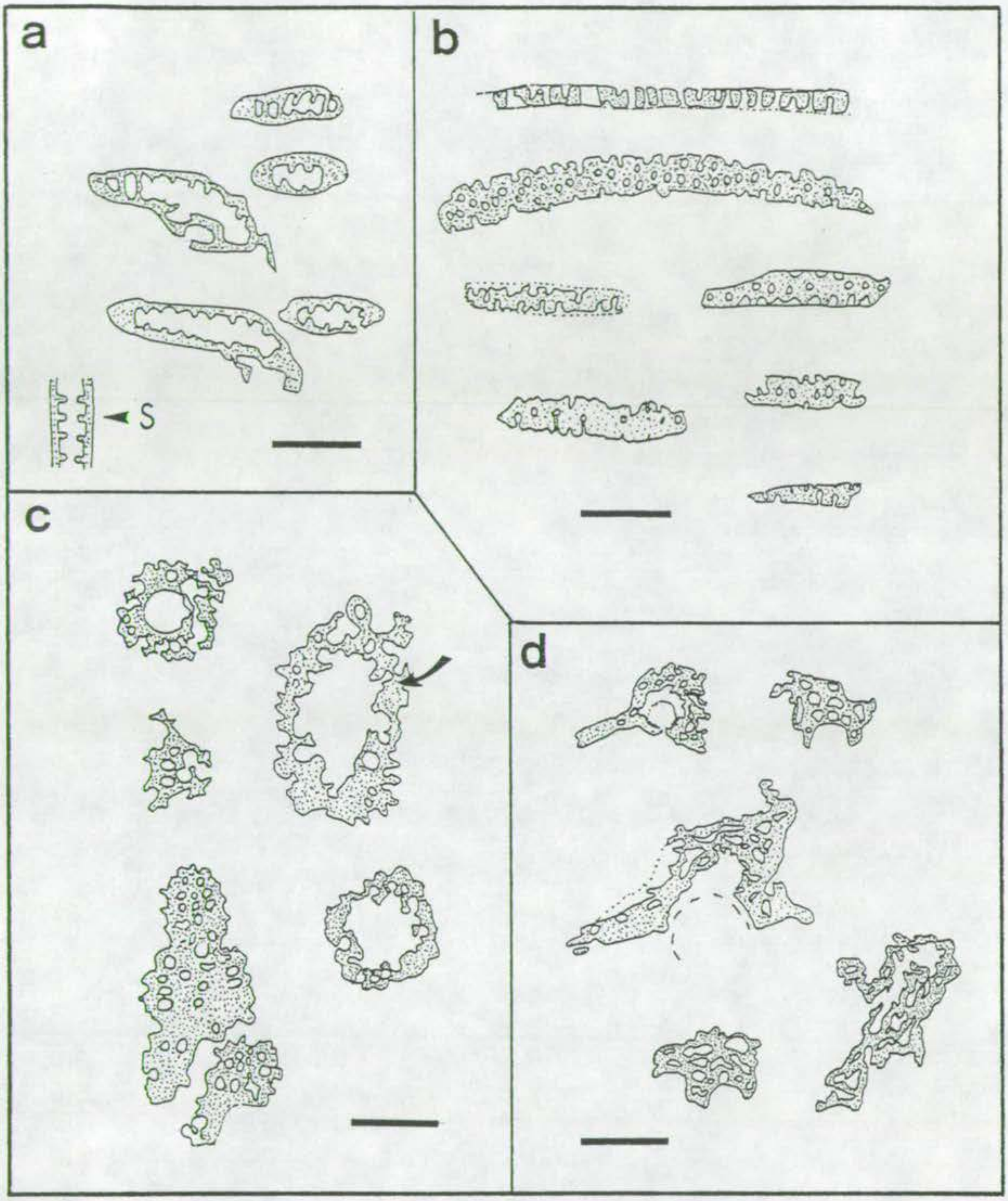
Fig. 4-8 Fragments of microproblematica and algae.
Microprojector tracings, scale bar = 400µ.

a. Kamaena cf. delicata Anthropov. Fragments traced from several thin sections. "S" shows a generalized sketch of septal arrangement, relative wall size and wall thickness.

b. Epimastopora sp. fragments, taken from samples of the discontinuous limestone in the Silvermine Mbr.

c. Sphinctoporella sp. Cross-sections of thallus reveal a round central medulla and radially-connected endospores (arrow). Fragment not showing axial hollow is a longitudinal section.

d. Stacheoides sp. Cross-sections reveal an inner, round canal with fairly regularly-sized cells. The fragment at lowest right, with highly irregular cells, is probably S. meandriformis Mamet and Rudloff.


a
S
b
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4.5 Distribution of algae

Branched algae are present throughout the Reservoir Mbr. and may be present in some of the calcareous sandstones of the basal sandstone facies in the overlying Silvermine Mbr. Girvanella appears to be restricted to slightly argillaceous and high-carbonate limestones. In general, skeletal calcareous algae, microproblematica and algal-bound structures are associated together, and found in fine-grained high-carbonate limestones. Argillaceous and coarse-grained crinoidal limestones very seldomly have structures attributable to binding.

4.6 Significance of algae

The discovery of algae in the Petershill Fm. is particularly ecologically important. The abundant skeletal algal remains (especially those of codiaceans), filamentous algae, and their products provide one of several indications that the Petershill Fm. accumulated in very shallow, well-lit waters (see Wray 1977; Riding 1975). Perkins and Halsey (1971) and others have found that boring algae are also most abundant in very shallow water, and surmised that borers can be an important source of fine-grained carbonate. Algae may thus be used to place a significant depth constraint on the Petershill Fm. deposition, and are likely to have provided an important sediment source.

Studies on Recent subtidal algal mats have shown that filamentous algae may exert a profound influence on the composition, stability and ecology of the sediment surface (Neuman, Gebelein and Scoffin 1970; Scoffin 1970; Bathurst 1971, pp 122-126). Recent mats consist of loose grains of sediment stabilized by intertwining mucilagenous filaments, unicellular algae, and the agglutinated tubes of various infauna (refs given). The density and morphology of the more common Recent mat-building algae is comparable to that of the filamentous algae found in the high-carbonate limestones of the Reservoir Mbr.

Recent algal mats selectively trap fine sediment, such that the grain size of a bound deposit may not directly reflect the strength of the currents in which it formed (Gebelein 1969, p 68). Scoffin (1970) found that algally stabilized sediments were several times more resistant to erosion than the same sediments after the algae had been killed and removed. Moreover, filament-stabilized sediments form an open porous framework, prone to early cementation (Monty 1976, p 219-221). Indeed algae may be instrumental in initiating such cementation (Winland and Matthews 1974). Most importantly, Recent filamentous algae, and the substrate stability they create, provide a habitat for a wide variety of foraminiferans, worms, arthropods, and molluscs (Neuman et al. ibid; Bathurst ibid). In the light of these studies, it seems logical to suppose that the filamentous algae in the Petershill Fm. may have had an analogous role in supporting an abundant microfauna and stabilizing sediment.

Both Neuman et al. (1970) and Bathurst (1971) stressed that, in spite of their profound sedimentological influence, Recent mats are ephemeral structures which soon decay on burial, leaving an essentially unlaminated sediment. Neuman et al. (ibid, p 296) predicted that traces of filaments, agglutinated sand grain tubes and non-uniform grain packing, resulting in a clotted fabric, might be used to identify ancient algal mats. Such structures are indeed present in the Reservoir Mbr. mats, as are the filamentous fabrics themselves.

CHAPTER 5

RESERVOIR MEMBER SEDIMENTS AS SUBSTRATES

5.0 Introduction

The composition and texture of the commonly-occurring lithologies in the Reservoir Mbr. reflect the wide variety of environments in which they were formed. Data based on trace fossils and more general considerations (based on the work of others) indicate that the consistency and stability of the original sediment surface differed between lithologies. These differences in sediment mass properties correlate with faunal changes, confirming that the physical properties of the sediment surface exerted a prime control on the biota. Similar conclusions have been reached by many previous authors working elsewhere, notably Newell et al. (1959), Craig and Jones (1966), Rhoads (1970), Goldring and Kazmierczak (1974), Fürsich (1976), and Johnson (1964). Furthermore, the study of substrate consistency provides additional information on the rates and mechanisms of sedimentation.

In this chapter the physical properties of the Reservoir Mbr. carbonate substrates are described and the information derivable from them is discussed. The detailed relationship between the biota and substrates is only briefly mentioned here, as it has been developed in greater detail throughout this study.

5.1 Factors affecting substrate consistency

The mass properties of a sediment, particularly a carbonate, are controlled by a combination of physical and biological factors. Prior to describing the properties of the Reservoir Mbr. substrates, it is important to consider these factors and how they may interact. The mass properties of unconsolidated sediments are largely related to their water content. Water content is, in turn, controlled by four variables: grain size; composition; the presence of organic matter in various forms;

and extrinsic physical variables (such as sedimentation rate, turbulence etc.). In carbonates these relationships are additionally complicated by their tendency to lithify during accumulation (q.v. Bathurst 1971, p 363) and because biological factors also influence carbonate deposition.

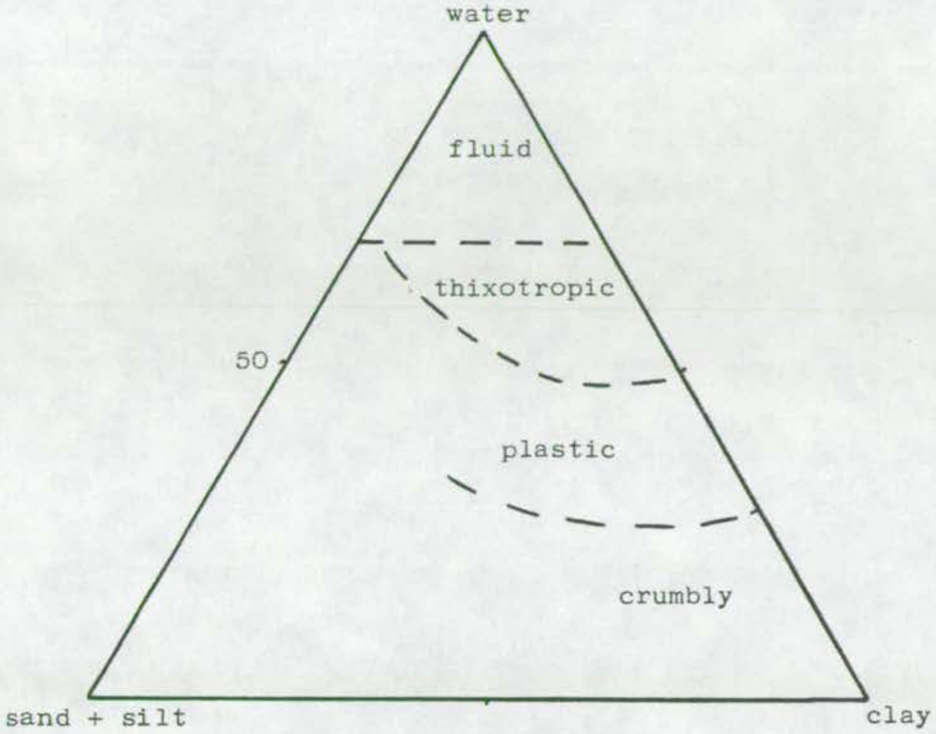
5.11 Grain size

The grain size of a sediment exerts the greatest influence on water content and, therefore, on sediment consistency (Craig and Jones 1966; Goldring and Kazmierczak 1974). In general, the two are inversely related (Trueman and Ansell 1969, p 319). Fine-grained sediments have high water contents and greater fluidity than sandy or gravelly sediments. Boswell (1961) and Rhoads (1970) have shown how grain size, mass properties, and water content are related in clastic sediments (Fig. 5-1). Grain size and packing may also be biologically significant (Purdy 1964). Sandy sediments are more likely to support an interstitial bacterial population which may affect consistency in various ways, (discussed below).

5.12 Organic matter

Organic matter, even in small amounts, may play a very significant role in determining the consistency of a sediment. The influence of filamentous algae as a stabilizing influence has already been referred to (Ch 4). Even where filamentous algae are absent, the possible influence of colloidal or mucous surface films, originating as detritus or secretions from diatoms and bacteria, must still be considered. Organic films on grains within the sediment and at the water interface may act to stabilize the sediment, alter packing, stimulate larval settling, and encourage deposit feeding (Trueman and Ansell 1969, p 320; Webb 1964; Scheltema 1974; Craig and Jones 1966). Heckel (1972b) even suggested that organic material could stabilize a thixotropic

Fig. 5-1 Consistency of sediments in relation to water content and grain size (after Boswell 1961)



medium to the extent of transforming it to a plastic consistency. Organic surface films may thus alter sediment consistency in two ways: a) as physical agents in altering the packing of grains; b) as biological enticements to larval settlement and deposit feeders.

5.13 Composition

The mineralogical composition of a sediment may have a marked effect on its consistency. Goldring and Kazmierczak (1974, p 956) have reviewed how sediment composition and consistency are inter-related, confirming the results of others with their own work. They (ibid) and Zankl (1969) concluded that the proportion of clay minerals exerted a critical influence on the degree, and presumably rate, of consolidation attainable by a sediment prior to burial. Sediments with insoluble residue percentages greater than about 2% weight were inhibited from penecontemporaneous lithification. More importantly, both Goldring and Kazmierczak (ibid, Fig. 2) and Zankl (ibid, p 251) showed that intermediate states of cohesiveness are also influenced by the percentage of detrital clay.

The present study also shows that a fairly good inverse correlation existed between the proportion of detrital clay and firmness in fine-grained substrates. The percentage of insoluble residue was found to be a generally reliable, although not infallible, guide to cohesiveness. The presence of significant proportions of authigenic minerals, principally chalcedonic quartz and pyrite, meant that insoluble weight percentages were not an entirely accurate reflection of the amount of original detritus. Thus, in the present study, insoluble weight percentages were found to be only approximate guides to original sediment consistency (q.v. Appdx F).

These previously described factors may interact in combination to modify the expected properties of a sediment of a given grain size.

The surface stability and consistency of a sediment are, however, ultimately reflected in deformational structures, cross-stratification, and the morphology and composition of the trace fossil fauna. Bioturbation is particularly important because an infauna may modify a sediment in the course of deposit feeding as well as leaving a record of the physical state of the medium (q.v. Rhoads 1970; Rowe 1974).

5.2 Substrate consistencies

The physical structures in a sediment may record evidence of four states: liquid, gel (capable of thixotropic behaviour), plastic, and brittle. The ichnological textural criteria for distinguishing these states are well known, and have been described by several authors (Trueman and Ansell 1969; Goldring and Kazmierczak 1974; Rhoads 1970; and Fürsich 1978). The most characteristic features of each consistency may be summarized as follows:

A Thixotropic sediments - Thixotropy is the property of a gel to liquify on shock, or the application of shear, returning to a gel state afterwards. Burrows in a gel have indistinct boundaries due to high sediment water content and consequent instability. Burrowing is typically accomplished by a swimming or peristaltic action. The looseness of the sediment encourages sediment feeding; consequently temporary traces, preserved in full-relief, typify gel substrates.

B Plastic sediments - Plasticity is the property of a medium to deform uniformly (under ideal conditions) retaining its shape after stress has been removed. The greater cohesiveness of a plastic medium may be seen in the sharpness of burrows, open burrow systems, and broken-up or cloddy textures. Plastic behaviour takes place over a range of cohesiveness, probably reflected in a range of burrowing behaviour. Passage through loose plastic substrates/

> substrates may be characterized by peristaltic movement, while a firmer consistency is indicated by excavation. Burrows tend to be permanent rather than temporary. The most obvious criterion for firmness is an open, unlined burrow gallery.

Evidence of pervasive liquid behaviour was not found in any of the Reservoir Mbr. substrates and hence it is not considered further. The properties of brittle solids are well enough known and they need not be repeated here.

5.3 Indices of substrate consistency

Many of the physical and biogenic structures in the Reservoir Mbr. lithologies provide a means of distinguishing original consistencies. Those features described below, in combination with trace fossils, delineate four substrate types: gel, plastic, firm and granular.

5.31 Compaction Fig. 6-3

A continual spectrum between *uniform* and *differential* compaction is present in the Reservoir Mbr. substrates. *Uniform compaction* is characteristic of lithologies with high detrital clay contents, usually gel substrates. Internal structures such as folded laminae, compacted trace fossils and crushed body fossils indicate that extensive compaction has occurred fairly evenly throughout each bed (Fig. 7-3e). *Differential compaction* (Fig. 6-3), in contrast, occurs in high-carbonate lithologies, and is characteristic of firm, granular, and, rarely, plastic substrates. The fabric as a whole lacks signs of compaction. Even delicate fossil structures and open burrows are typically undeformed. However, within these lithologies, shell bands, clay laminae and inflection points where beds change thickness, may show signs of extensive plastic and later brittle deformation. Deformed and uncompacted horizons may alternate, indicating a very uneven pattern of stress relief.

Both uniform and differential patterns broadly reflect differences in the freedom of depositional fabrics to re-adjust on compaction. Differentially-compacted sediments apparently formed a large self-supporting framework prior to burial, whereas uniformly compacted sediments were loose and free to flow.

5.32 Cross-stratification

Mechanically-produced sedimentary structures, such as current and oscillation cross-stratification, provide the most reliable signs of sediment surface instability or mobility. The most common cross-stratification type in the Reservoir Mbr. limestones consists of small-scale troughs, usually occurring in sets, which may alternate with poorly defined, plane-laminated sets or chaotically textured sets. Current stratification is only found in granular substrates.

5.33 Sediment encrustations Fig. 4-6; 4-7; 7-3d; 7-4; G-2

Organisms which are normally found as shell encrustations may also colonize firm and stable sediment surfaces (q.v. Ch 14). Encrustations by delicate forms such as the bryozoan Fistulipora (Figs. 7-4; G-2) are a clear sign of the firmness and stability of a sediment surface.

5.34 Synsedimentary folds

Small, centimetre-sized gentle folds, probably due to gravity slumping and differential accumulation on irregular, hummocky substrates provide evidence of a plastic sediment consistency. Layers within folded beds do not change thickness markedly, or show signs of extensive fracturing where they have been folded.

5.35 Unfilled skeletal and interskeletal voids Figs 6-3e; 6-4f; 6-10b; 6-11; 7-4

In fine-grained sediments, the visceral cavities of brachiopods, loosely-hinged shells such as ostracods and the voids sheltered between adjoining shells are often unfilled with sediment (spar filled). They provide evidence that the sediment surface was firm and stable, as compaction did not force sediment into these voids.

5.36 Fractures and intraclasts

Both these structures are attributable to brittle behaviour and are therefore signs of firmness. Intraclasts in the Reservoir Mbr. may have several origins and are most common in granular and firm substrates. These structures are discussed in detail in Chs 6 and 7.

5.4 Trace fossil groups of the Reservoir Mbr.

Trace fossils furnish the most specific information on substrate consistency, particularly in fine-grained lithologies. When employed in combination with the other indices, they may provide a means of distinguishing sediment properties in a wide range of lithologies.

In order to obtain the maximum information from the ichnofauna the commonly occurring traces were first described (Appdx G). These trace fossil descriptions are based on both field and hand specimen data. The distribution of trace fossils and their associations was then recorded in a study which compared the ichnofaunas of the common lithologies of the Reservoir Mbr. (Appdx G). A detailed description of the methods employed and the data obtained appears in Appdx G. This comparative study was made on plaquettes and peels in order to ensure a uniform sampling of lithologies. A total of nearly 10 sq metres of sectioned rock was examined.

During the course of this comparative study it became obvious that trace fossils could be combined into groups (A, B, C, Figs. 5-2; G-6). Burrows within a group are equally distinct in outline, often have a common ethological origin, and are found in similar lithologies. The trace fossils groups are:

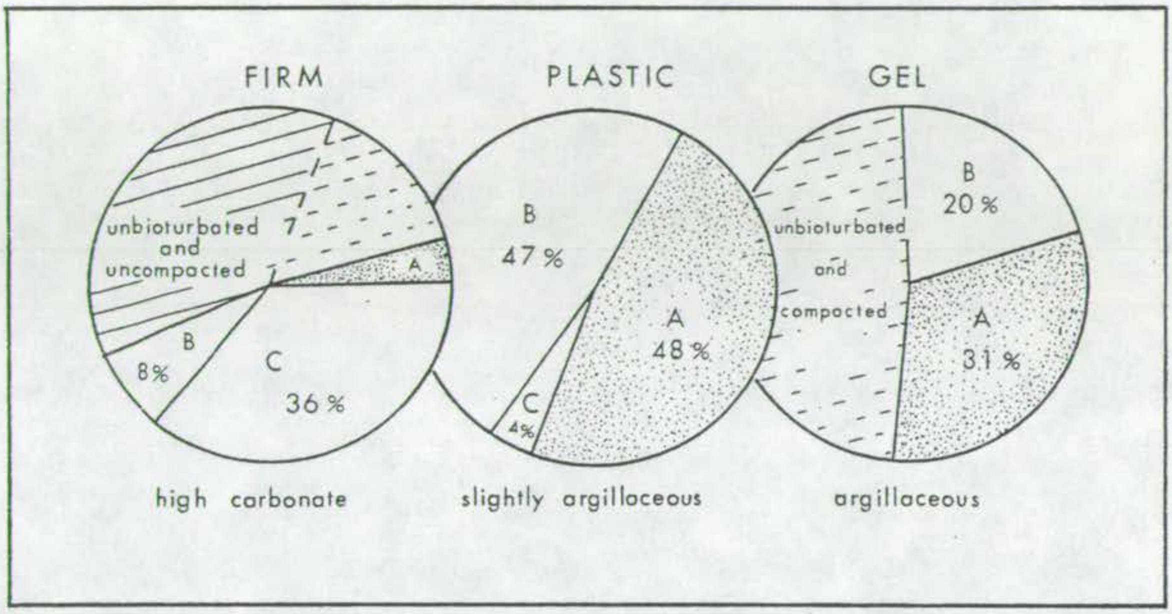


Fig. 5-2 The trace fossil groups (A, B, C) associated in the fine-grained carbonate sediments of the Reservoir Mbr.

The percentage of a lithology reworked by each group was determined in a comparative study (q.v. Appdx G). Solid parallel-lined areas denote fabrics where undisturbed primary structures (e.g. lamination) suggest that the sediment was not bioturbated, but in which former traces may not have been preserved (e.g. compactionally obscured). Trace fossil groups: A - indistinct; B - sharp, often backfilled; C - burrow galleries. "A" has been stippled in for emphasis.

GROUP A indistinct or swirly burrows (type 2 trace fossils Appdx G, part I), lacking a clear outline or shape. The indistinct nature of group A burrows suggests they formed in gel substrates.

GROUP B distinct burrows, usually darker than the matrix, with a clear boundary and outline, usually infilled with sediment derived from the matrix (i.e. not draft-filled from the surface). Burrows in this group include trace fossil types 3, 4, 5, 6 (Appdx G). Group B burrows form intercrossing systems, usually post-dating group A burrows. Most of the B forms are temporary traces, formed during sediment feeding. Burrows in this group are likely to have been formed in both gel and plastic substrates.

GROUP C Lined and unlined, often open, tunnel systems, usually belonging to Thalassinoides (Appdx G). Group C burrows indicate a firm consistency.

Most lithologies contain more than one trace fossil group (Figs. 5-2; 5-6; G-6). Cross-cutting relationships between groups and the manner in which they are associated in a particular lithology provide the most specific sedimentological information. The common trace fossil associations are also fairly lithologically specific, indicating that substrates of differing primary composition had different consistencies and supported a different infauna. Trace fossils alone distinguish consistencies in fine-grained substrates; together with other structures they differentiate the four substrate types described in the following section.

5.5 Reservoir Member substrates Figs. 5-3; 5-4; 5-5

5.51 Gel substrates Fig. 5-3

Sediments which had a thixotropic sediment surface that largely

Fig. 5-3 Burrowing sequence in a gel substrate

5-3a negative peel print; 5-3b illustration of same. 5-3a is at a slightly higher magnification than 5-3b, thus images do not match perfectly. Magnification 5-3b x 2.1. G.I. 46 359

The sample shows burrows at the boundary between a calcareous mudstone (above) and an argillaceous biomicrosparite (below). The earliest period of bioturbation (1) consists of a pattern of indistinct swirls, depicted in the orientation of fine skeletal debris, and the unevenness of the matrix. The boundary between indistinctly burrowed areas (1) and apparently undisturbed matrix, or areas reworked much earlier (blank), is indistinct. Earliest burrowing traces (1) do not reveal shape of burrower, a sign of sediment looseness. A second stage of burrows (2) protrude from and retract into the overlying calcareous mudstone. The manner in which the two sediments have been intermixed by burrowing and the lack of clarity or internal structure in type 2 burrows indicates that the underlying biomicrosparite sediment was loose, even after burial. These post-depositional (2) burrows are particularly valuable as they reveal the final consistency of the sediment surface. These first two burrows are cross-cut by <u>Zoophycus</u> (3).


a


b
retrusive
protrusive
1
1
2
2
3

remained in a gel state until after burial. Gel substrates are argillaceous (with clay contents generally greater than 10% by weight of sample) and are roughly equally burrowed by groups A and B (Fig. 5-2). Gel substrates have undergone extensive uniform compaction; compactional laminae are often arched around densely-packed burrows such as Zoophycus. Although the relative proportion of group A and B burrows is similar to that in slightly argillaceous plastic substrates (Fig. 5-2) the extensive degree of uniform compaction in gel substrates readily distinguishes the two.

Although all gel substrates found were argillaceous, not all argillaceous strata showed evidence of thixotropic (gel) behaviour. In some cases, an entirely independent criterion, such as abundant epifauna, suggested argillaceous lithologies had been firm and stable substrates. In these cases, other extrinsic factors such as the presence of organic matter or abnormally low sedimentation rates are likely to have accounted for stability.

5.52 Plastic substrates Fig. 5-4

These are substrates which show a progressive change from a gel to a plastic consistency, with rare brittle structures. Burrows belong largely to groups A and B and rarely C (Figs. 5-2; G-6). The degree of compaction is slight. The prominent burrows in plastic substrates have well-defined boundaries and internal structure (e.g. backfillings). Plastic substrates are typically slightly argillaceous biomicrosparites (Figs. 5-2; G-6).

The increase in cohesiveness reflected in plastic substrate trace fossils may, in part, be due to burrowing at a greater depth beneath the sediment surface. Sediment water content decreases sharply with depth (Walker 1974). Burrows made well beneath the surface would thus be expected to reflect a greater sediment cohesiveness than burrows

Fig. 5-4 Trace fossils in a plastic substrate. G.I. 46,473

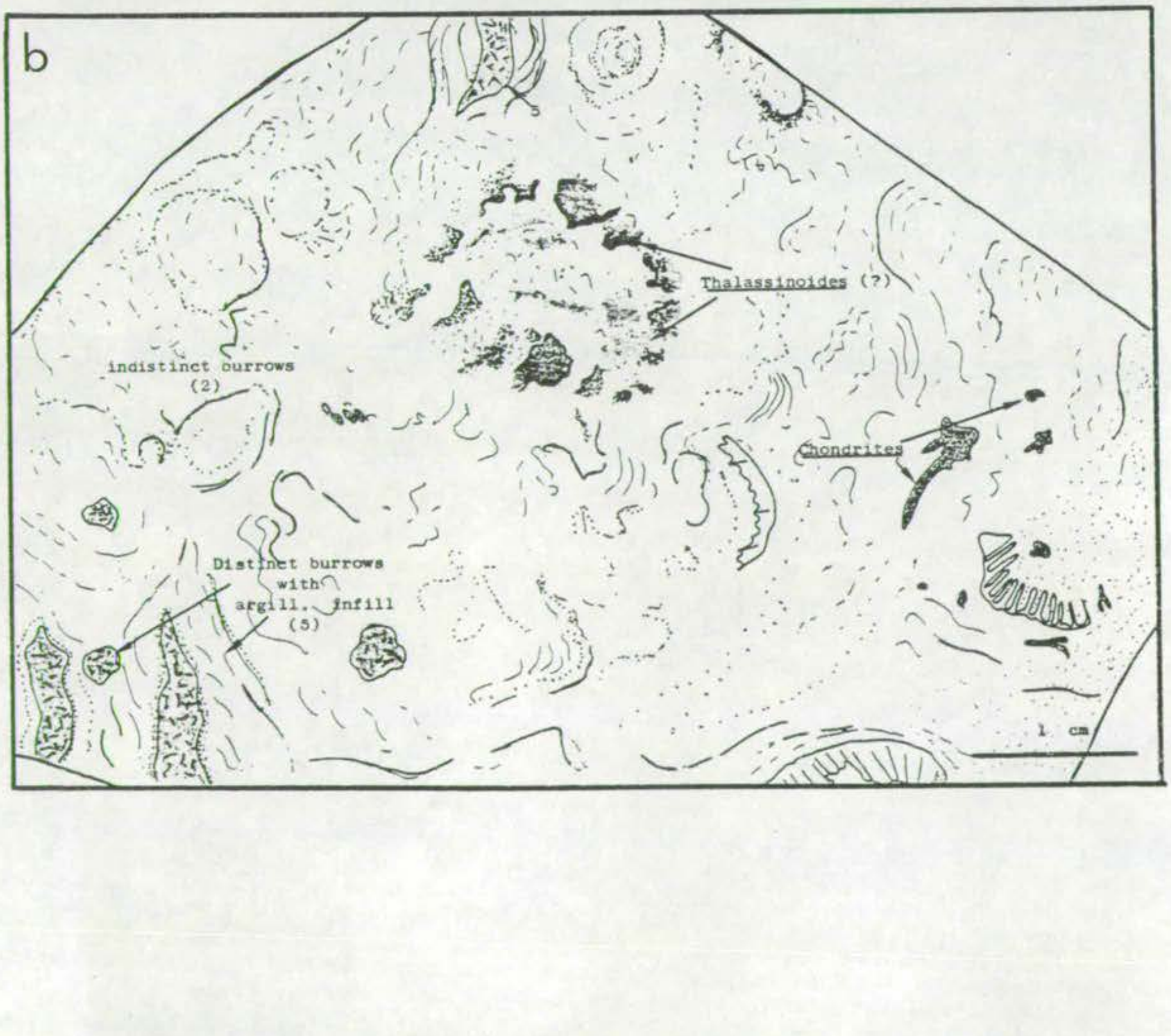
5-4a oil-covered polished plaquette,

5-4b illustration drawn from a peel of a serial section from same sample.

a. Line of dots surround ?*Thalassinoides*; arrow indicates *Chondrites*. Scale bar = 1 cm.

b. Peel reveals that matrix has an indistinct, swirly (Type 2 burrow) texture attributable to reworking while the sediment was in a gel state. A slightly greater degree of cohesiveness is indicated by circular, more distinct, type 5 burrows, with argillaceous infillings. Deformation haloes surrounding type 5 burrows indicate that matrix was still a gel, however. Draft-filled *Chondrites* and the broken circular outline of a ?*Thalassinoides* burrow indicate a more cohesive, plastic consistency. Burrows thus reveal that the sediment has undergone an increase in cohesiveness from a gel to plastic state.


a
18a #3
u


b
5
Thalassinoides (?)
indistinct burrows
(2)
Chondrites
Distinct burrows
with
argill. infill
(5)
1 cm

made near the surface (Rhoads 1970, p 399). Draft-filled burrows, such as Chondrites and Thalassinoides, which required that the sediment form a self-supporting framework from the sediment surface downward, provide clear evidence of a cohesiveness that cannot be explained by burial alone. At horizons where group C burrows are present, trace fossils indicate that the sediment has undergone an increase in cohesiveness which is more likely to be attributable to early lithification. Goldring and Kazmierczak (1974) and Fürsich (1978) have concluded that such consistency changes occur during intervals of non-deposition, or stillstands. Moreover, horizons where the sediment shows a consistency increase also frequently have a concentration of epifaunal organisms, which would independently suggest that these horizons were sedimentation surfaces for atypically long time periods (q.v. Ch 8).

5.53 Firm substrates   Figs. 5-2; 7-2a; G-2; G-3; Appdx G

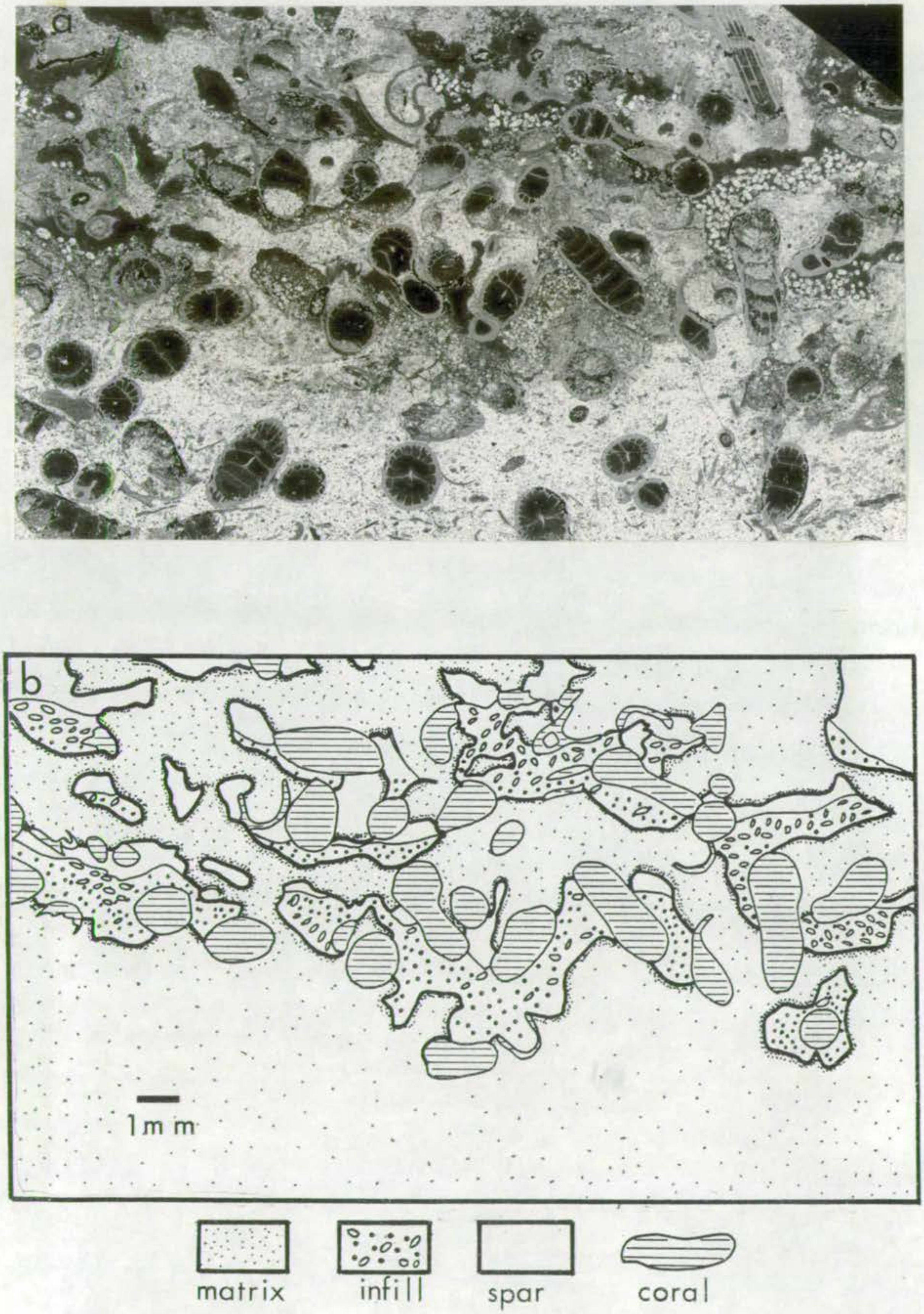
Firm substrates initially formed stable plastic sediment surfaces. They are either extensively bioturbated by Thalassinoides or lack apparent bioturbation (Figs. 5-2; 5-5). Undisturbed laminae and layering (Fig.. 3-5b) suggest that areas of many firm substrates are largely unreworked. Firm substrates are fine-grained, high-carbonate biomicrosparites with <5% estimated clay (q.v. Appdx F). The degree of consolidation indicated by many structures (unfilled inter- and intraskeletal voids, intraclasts, fractures, undeformed open burrows) are also reliable signs of early lithification (cf. Zankl 1969). In spite of this evident firmness, and the presence of areas of brittle deformation, firm substrates were not completely lithified (hardgrounds) as seen in plastic, post-burial folds.

Fig. 5-5 Trace fossils in firm substrates. g.J. 46474

5-5a negative peel print,

5-5b simplified illustration of peel; many of the fossils have been left out.

An open, burrow system of Thalassinoides developed among the corallites of a Lithostrotion junceum colony. Parts of the burrow system are geopetally infilled with loose sediment and faecal pellets. Burrow outlines are very sharp and undeformed, although they lack any lining or sign of reinforcement (type B, Thalassinoides burrows). Such open systems are a sign that the matrix was initially firm and stable.


a
b
1mm
matrix
infill
spar
coral

5.54 Granular substrates Figs. 7-2; 7-3

Granular substrates are composed of coarse skeletal debris forming a supported framework. Burrows are indistinct, and difficult to distinguish from dewatering and other deformational structures. It may be assumed that the coarse grain size and supported framework of granular sediments formed an inherently firm and stable substrate. However, extrinsic environmental factors, such as the strength and persistence of currents, may have altered the stability of the granular sediment surface and hence its suitability for faunal colonization. Thus, the biologically important physical properties of granular sediments were likely to have been environmentally controlled.

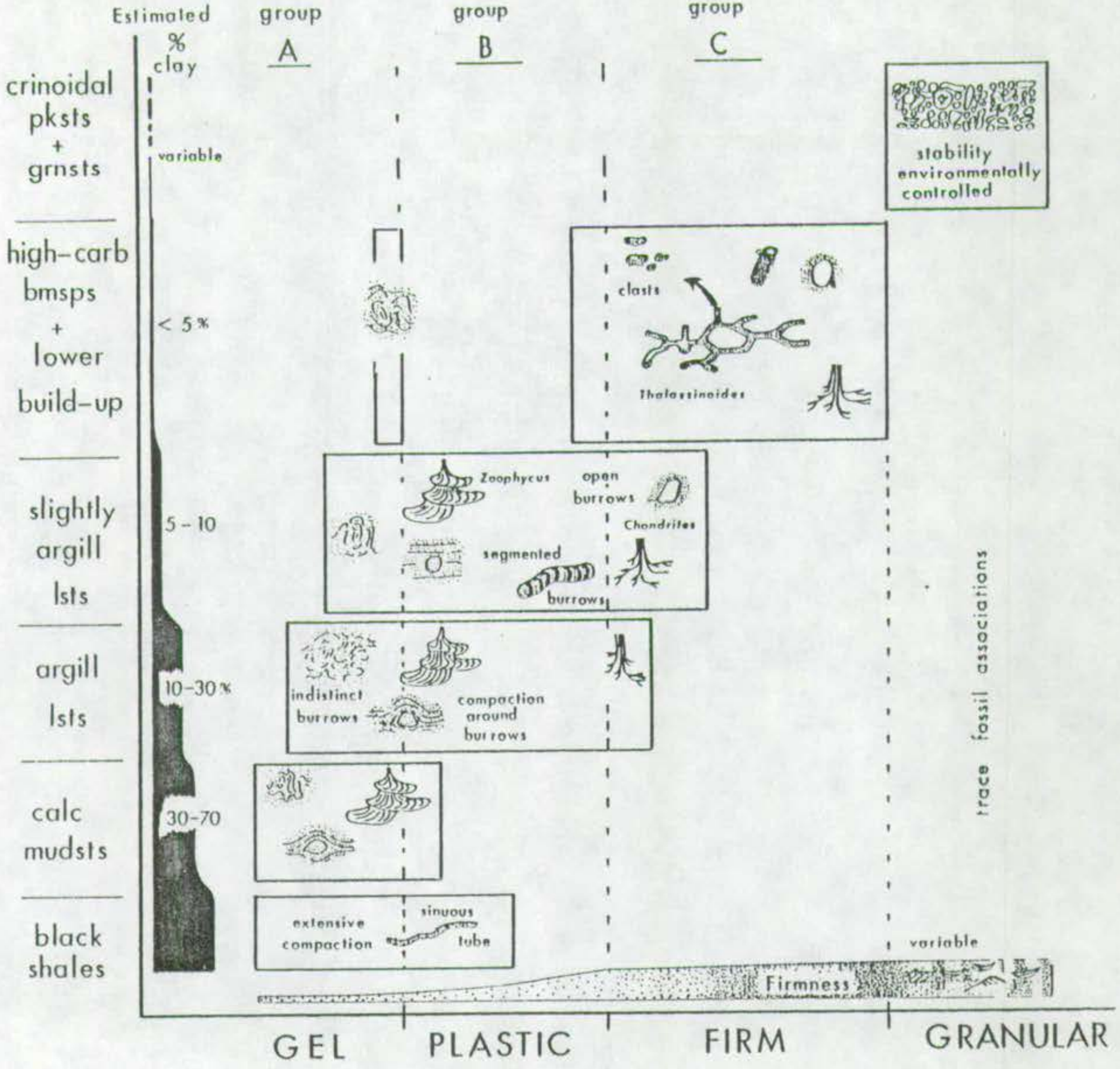
The physical energy of the environment in which granular sediments have formed is reflected in the degree of sorting, textural maturity, and type of cross-stratification (Anderson and Pazdersky 1974). Entirely cross-stratified sequences of moderate to well-sorted packstones mark unstable (continually entrained) substrates, while burrowed, chaotically textured sets are associated with quieter environments and stable sediment surfaces (ibid).

5.6 Summary

The commonly occurring lithologies of the Reservoir Mbr. formed substrates of differing stability and consistency. Each lithology has a fairly characteristic associated ichnofauna. The associated trace fossils and other physical criteria distinguish the mass properties of the commonly occurring lithologies, as summarized in Fig. 5-6. Argillaceous lithologies and coarse crinoidal packstones were largely unstable, the former due to a high water content, the latter because of environmentally controlled instability. Fine-grained carbonates present a spectrum of increasingly cohesive substrates. Cohesiveness generally correlates inversely with detrital clay content. High-carbonate biomicrosparites attained a firmness and stability suggestive of partial early lithification. Sedimentation stillstands are most likely to account for consistency increases observed in slightly argillaceous substrates.

In the Reservoir Mbr. trace fossils provide a useful means of distinguishing substrates, and to a lesser extent lithologies. They are also part of each facies fauna, and in some cases (e.g. Thalassinoides) also a characteristic element.

Fig. 5-6 Substrate characteristics and trace fossil associations of the commonly-occurring lithologies in the Reservoir Mbr., shown in stratigraphical order.


Estimated % clay
group A
group B
group C
crinoidal pksts + grnsts
variable
high-carb bmsps + lower build-up
< 5 %
slightly argill lsts
5 - 10
argill lsts
10-30 %
calc mudsts
30-70
black shales
stability environmentally controlled
clasts
Thalassinoides
Zoophycus
open burrows
Chondrites
segmented burrows
indistinct burrows
compaction around burrows
extensive compaction
sinuous tube
variable
trace fossil associations
Firmness
GEL
PLASTIC
FIRM
GRANULAR

CHAPTER 6

DIAGENESIS OF THE RESERVOIR MEMBER LIMESTONES

6.0 Introduction

Many diagenetic processes have modified the primary (depositional) fabrics of the Reservoir Mbr. limestones. Two of these, compaction and bioturbation, have already been described (Ch 5). In this chapter post-burial diagenetic processes are considered. These processes have modified primary fabrics as well as creating fabrics of their own. Although distinction between primary and secondary fabrics is not always possible, it is important to recognize that several processes may have similar products. Moreover, diagenetic modifications are often specific to a particular lithology, and, therefore, a valuable aid to facies recognition. Information losses resulting from diagenetic changes must be considered in assessing the validity of a particular method of analysis for sedimentological evaluation (e.g. point counting). Thus, recognizing diagenetic products and processes furnishes a more complete picture of the original sediment. In addition, establishing the sequence of diagenetic processes has provided a more complete geological history.

As the emphasis here is on distinguishing primary from secondary fabrics, more attention has been paid to early diagenetic events than to later ones.

PART I

Early diagenetic structures and fabric modifications

6.1 Fractures

Various types of non-tectonic fractures (the "in situ" fractures of Read 1978) are common in high-carbonate biomicrosparites in the Reservoir Mbr. A continual spectrum from crumbly to sharp-edged (q.v. Dunham 1969, p 141) fractures is present in the Reservoir Mbr. limestones. Dunham (ibid) originally introduced the term "crumbly" to describe the texture of a beachrock, friable enough to be broken between the fingers.

The term does not, however, imply a granular texture. It refers, instead, to the weak degree of consolidation indicated by the fracture pattern. Crumbly fractures are characterized by a tendency to break around, rather than across, grains and have a somewhat indistinct edge (Figs. 6-3a,b; 6-13c; 7-4d). Such fractures often contain sediment released by fracturing. The sharpness of the crumbly fracture, and the extent to which its sides may be re-fitted may vary, probably depending on the original sediment consistency. Crumbly fractures are found opening vertically, normal to laminae (Figs. 6-1; 6-3) associated with breccias (Figs. 6-3a,b) and, more rarely, associated with boudinage (Fig. 3-4). Like other early diagenetic features, crumbly fractures may have formed by several processes, including differential compaction, shrinkage and later by dissolution weakening of the depositional framework.

6.11 Sharp-edged fractures   Fig. 6-3c

Sharp-edged fractures have distinct sides and cross-cut grains. They tend to be more irregular and jagged than crumbly fractures and do not conform to depositional textures. They may transect crumbly fractures, the sediments infilling crumbly fractures and early cement stages. In rare cases, however, sharp-edged fractures appear to have formed contemporaneously with crumbly fractures.

6.12 Shrinkage fractures   Figs. 6-1; 6-2; 6-3

Some crumbly fractures have formed by shrinkage. Such fractures tend to develop vertically along the upper and lower surfaces of laminae (Fig. 6-3d). They are not restricted to a particular horizon or series of recurrent horizons. The presence of regular, recurrent shrinkage-fracture horizons might suggest periodic emergence and dessication. Their absence, however, precludes this possibility.

The primary shrinkage fracture (1, Fig. 6-1) is usually directed

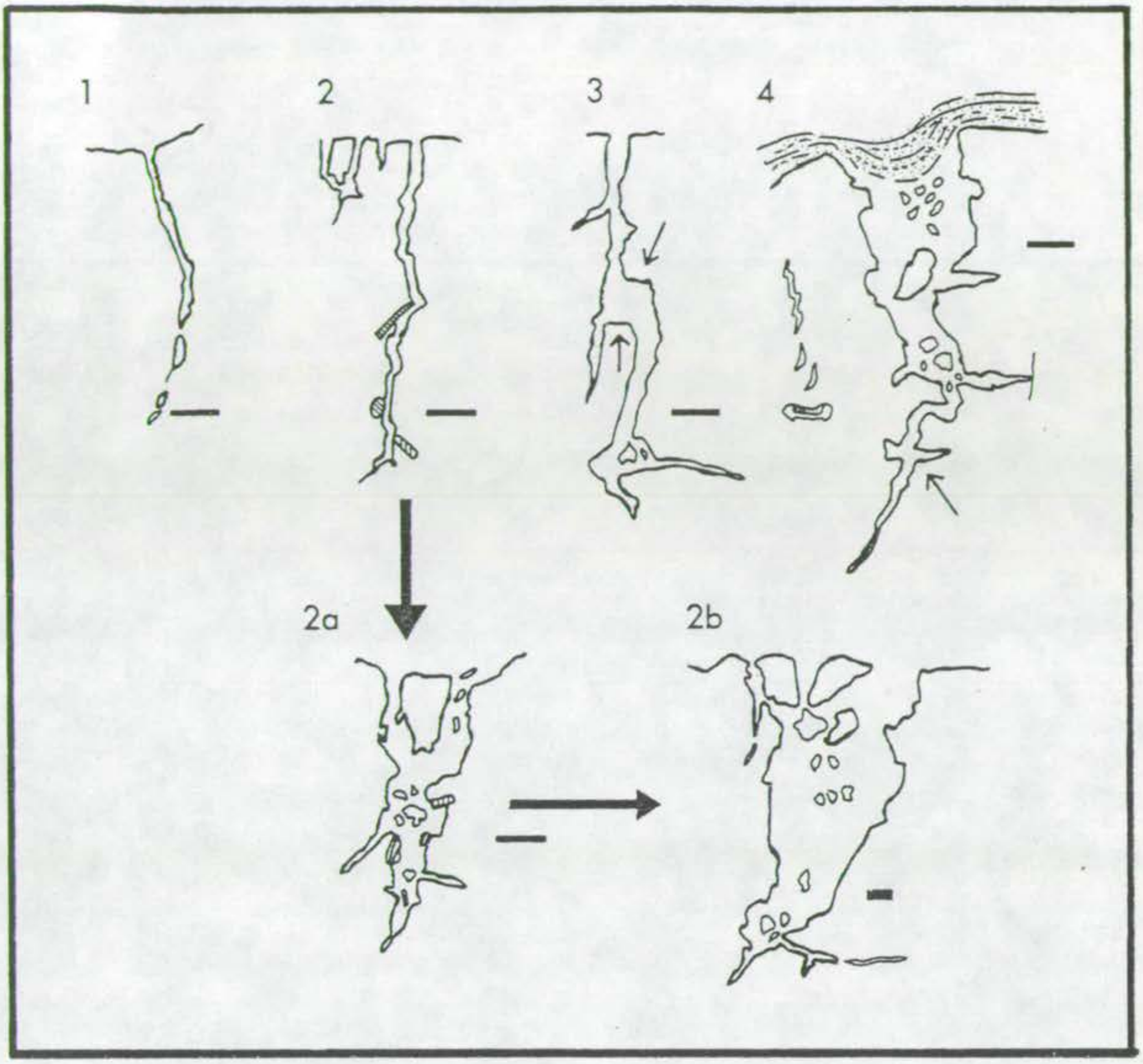


Fig. 6-1 Illustrations of the proposed sequential development of fractures by shrinkage, taken from microprojector tracings of peels and thin sections. These fractures originally opened from both the tops and bottoms of laminae.

1. The primary fracture, usually vertically orientated, forms partly due to gravitational stress.

2. Subsidiary fractures form at the mouth of the primary and may merge (2a, 2b). Clasts fall towards the mouth or apex (up or down) depending on the primary fracture orientation.

3. Secondary fractures develop along the walls of the primary; the apex of the primary may split. Arrows show that the primary also undergoes shrinkage.

4. Clasts are formed by spalling-off from the sides of the primary. Secondary crack edges withdraw from each other equally in three dimensions. Arrow points to skeletal mould, indicating that dissolution accompanies or follows shrinkage.

Scale bar = 1 mm.

normal to lamination, and probably formed largely due to differential compactional stress. Smaller fractures are commonly present near the primary, and often coalesce during development (2, Fig. 6-1). In more advanced stages, secondary fractures open in the sides of the primary. The secondary fractures in particular point to shrinkage as a fracture-creating mechanism, since the sides must withdraw from each other roughly equally in three dimensions (3, 4, Fig. 6-1). The secondary fractures appear to have formed to relieve evenly directed, three-dimensional stress, associated with a net loss of volume, or shrinkage. In this respect shrinkage fractures differ from compactional fractures which form to relieve directed stress. Small tear-like fractures and cavities created by withdrawal of the matrix from a shell may also be signs of shrinkage (Figs. 6-1; 3-4). Transected skeletal moulds (e.g. Fig. 6-1) suggest that dissolution accompanied shrinkage, or followed shortly afterwards.

Shrinkage is particularly significant as a fracture-forming process, because it provides a precise indication of sediment consistency. In order for a sediment to shrink, its constituent particles must still be free to move relative to one another, yet be able to form a supportive framework. Shrinkage fracture thus indicates a weak degree of consolidation. In addition, it is unlikely that a framework could undergo extensive shrinkage and not show signs of compaction, unless the framework were free from the weight of overburden. Thus, uncompacted shrinkage-fractured fabrics also provide evidence of near-surface diagenetic alteration.

6.2 Brecciation Figs. 6-2; 6-3

In parts of the build-up and within level-bedded high-carbonate biomicrosparites, fracturing has been extensive enough to produce breccias.

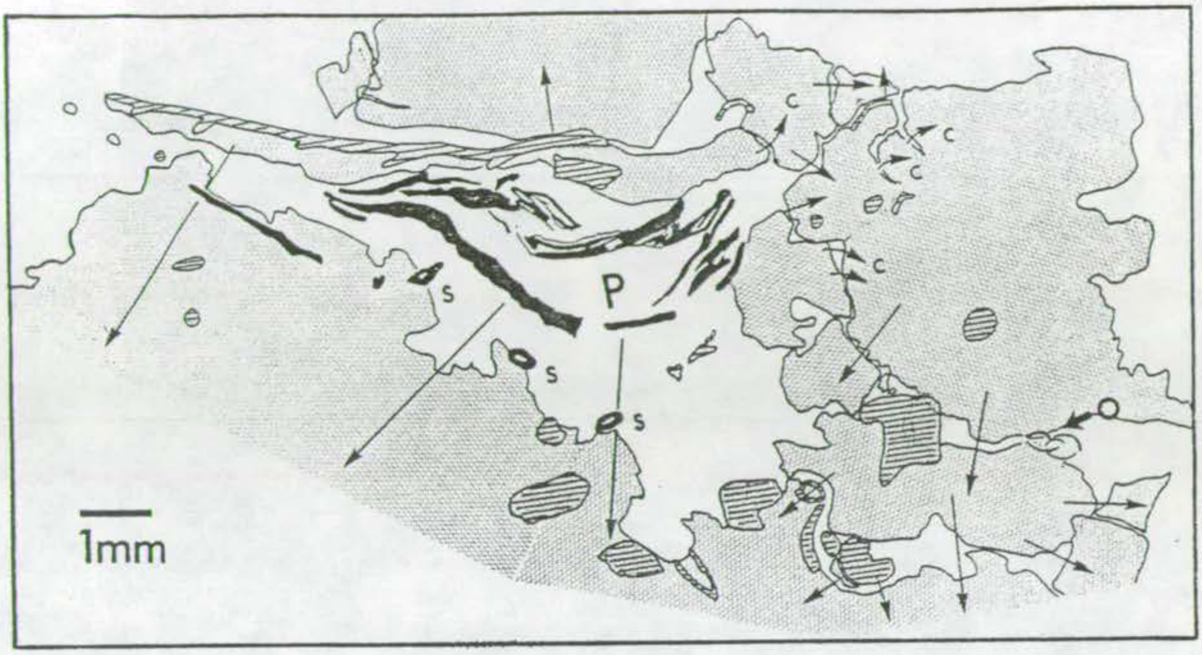


Fig. 6-2 Refittable brecciation. High-carbonate biomicrosparite.

The manner in which a breccia may be refitted illustrates one mechanism of brecciation. This illustration shows clasts that have been refitted using a projection microscope at x 25. Arrows show relative distance and direction each clast has been moved in order to match with adjacent clasts. The spinose productoid (P) has been arbitrarily chosen as the reference origin. Depositional textures in clasts often match when re-fitted. Reconstruction suggests two types of clast movement: a) three-dimensional separation of relatively large clasts (generally shown by long arrows); b) spalling-off of small clasts by separation along possible shrinkage fractures(c).

The disposition of the pedicle spines suggests they are still attached to the shell; presumably matrix originally completely surrounded the shell prior to brecciation. The spines have not been broken off during their separation from the matrix, a sign the matrix was poorly consolidated during brecciation. Delicate structures such as the ostracod carapace are only slightly compacted, a sign that brecciation occurred prior to accumulation of a significant overburden. Fossils other than the productoid are horizontally lined. Ostracod carapace = O.

6.21 General appearance Figs. 6-3; 6-10a

Brecciated areas vary in width from a few square millimetres to elongate, metre wide areas. The textural differences between the large and small brecciated areas are very small. Most brecciated areas are a few centimetres thick and developed along a discrete layer or depositionally unstable horizon. Breccias usually occur within a cavity system (Figs. 6-3d; 6-10a).

Brecciated areas are small-scale features which do not alter the general appearance of bedding or layering at an outcrop. Brecciation does, however, sufficiently alter the depositional fabric of beds in parts of the lower build-up facies so as to create a jumbled texture and intermix once discrete horizons.

Two patterns of brecciation are immediately apparent in the limestones of the Reservoir Mbr.: a) breccias predominantly formed by crumbly fracture, termed here early breccias; b) breccias largely formed by sharp-edged fracture, or late breccias.

6.22 Early brecciation Figs. 6-3a,b,d,e

Early breccias consist of a jumbled array of clasts and fossils enclosed in a clearly visible larger cavity.(Figs. 6-3; 6-10). The actual breccias consist of centimetre sized, sub-quadrate matrix clasts, and broken and whole fossils derived from the break-up and subsequent collapse of the matrix into a cavity. The larger clasts are surrounded by, or, in some cases, supported by fine sediment. Break-up has followed depositional discontinuities within the matrix, with separation occurring along shell surfaces, laminae, and in rare cases, burrow linings (Fig. 6-3b). The latter example, in particular, indicates brecciation occurred at a very early stage of lithification, as there must have still been some contrast in consistency between the matrix and burrow lining. The imbricate arrangement of clasts, the manner in which they may be

Fig. 6-3 Brecciation. Oil-covered, polished slabs, all scale bars = 1 cm.

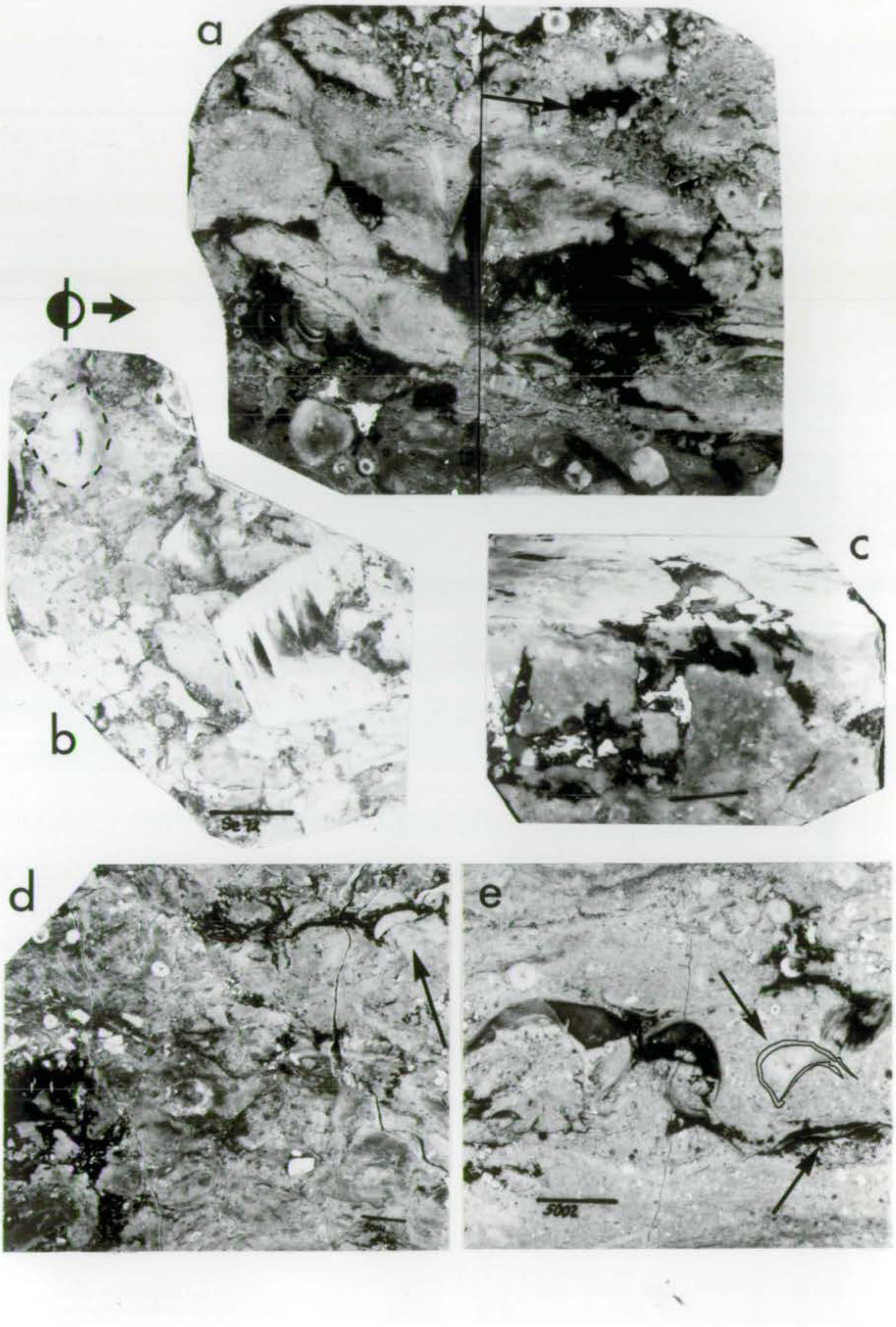
a) Early brecciation. A composite photograph of two vertical sides from a block of a brecciated cream biomicrosparite sliced at right angles. Loosely-packed internal sediments, freed during break-up, overlie and infill spaces between clasts. Finer material is piled on top of flat surfaces, suggesting it may have trickled downward. The clasts and sediment infillings are uncompacted, a sign of lithification soon after break-up. The original inter-clast breccia cavities are dark due to late stage hydrocarbon infillings. A late stage dissolution void (arrow) cross-cuts early breccia fabrics. Build-up, subfacies B. Magnification = x 2.

b) Early brecciation. Jumbled array of early breccia clasts. A partially infilled, lined burrow (dashed line, see sideways geopetal symbol) has separated from matrix to form a clast. G.T. 46,395

c) Late brecciation. Oblique view of vertical and horizontal faces of a limestone block showing a late breccia cavity. Note the high irregular, jagged edges of clasts and lack of internal sediment infillings. White cavity infilling is kaolinite; black is hydrocarbon. G.T. 46,396

d) Layering, shrinkage fractures (arrow), differential compaction and brecciation. A typical example of a brecciated biomicrosparite from the lower build-up facies. Boundaries between layers (arrow) are particularly susceptible to differential compaction and fracturing, in this case by shrinkage. A small breccia-infilled cavity at lower left is partially infilled by large clasts. Build-up, subfacies A. G.T. 46,399

e) Differential compaction. Arrows point to adjacent Antiquatonia shells; the upper (outlined) shell is uncompacted while the lower shell has been completely closed. Open shells (at left of arrows) are only partially sediment infilled and shelter small cavities. These features are typical of initially firm substrates. Build-up, subfacies B. G.T. 46,398


a
b
c
d
e
500μ

refitted (Figs. 6-2; 6-3a) and the occurrence of clasts still partially attached to the enclosing cavity wall indicate that early breccias formed by collapse into a cavity. No evidence was found to suggest that the coarse infillings were transported into pre-existing cavities.

These observations independently point to dissolution as a cause of brecciation. Downward collapse fabrics such as those observed in the breccias require the presence of an underlying cavity. The size and orientation of breccia cavities precludes the possibility that large syndepositional or skeletal cavities were present. Dissolution seems the most likely mechanism for removal of sufficient material to create a cavity into which collapse might occur.

6.23 Late brecciation Fig. 6-3c

Areas of extensive sharp-edged fracturing have led to the development of late breccias. Unlike early breccias, pervasive sediment infillings are absent (Fig. 6-3c). The few clasts present and enclosing cavity walls of late breccias are typically very jagged. Cross-cutting relationships show that, in most cases, late brecciation followed early brecciation.

Although the appearance of early and late brecciation contrast sharply, the origins of the two appear to be similar. Both are associated with dissolution. The most significant difference between the two patterns appears to be the degree of matrix consolidation which they reflect.

6.3 Dissolution (q.v. Appdx D for definition)

Dissolution in the Reservoir Mbr. limestones has selectively removed grains, altered the shape of cavities and created cavities, thus altering the fabric of many limestones.

6.31 Criteria for detecting dissolution in limestones

6.311 Skeletal moulds Figs. 6-4; 6-5; 6-7; 6-10; 6-11; 6-14e; 0-11; 0-12; 4-6b; 4-7

Sparry cement-filled cavities (moulds) formed by the complete or partial dissolution of a fossil whose outline is still preserved, are common in all the Reservoir Mbr. limestones. Nearly all molluscs and siliceous sponges are preserved as moulds. Moulds of brachiopods, corals, bryozoans, ostracods, trilobites, echinoderms and some microproblematica are less common. Bryozoans, particularly Fistulipora and fenestellids are especially prone to dissolution (Figs. 6-5; 6-7; 6-10). Thus dissolution, while preferentially selecting unstable or originally aragonitic skeletons, has been pervasive in dissolving all types of skeletal carbonate.

6.312 Micrite moulds Fig. 6-11

Sparry cement-filled moulds of skeletons surrounded by a micrite envelope (q.v. Friedman and Sanders 1978, p 565) are one particular type of skeletal mould. They usually indicate the former presence of an originally aragonitic skeletal fragment, although in the Reservoir Mbr. limestones, this is not always the case, since calcitic and siliceous skeletal fragments are also dissolved. Bathurst (1971, p 455) and several other authors have proposed that compactional patterns in micrite moulds can be used to infer when dissolution took place. During the stage when the skeleton enveloped by micrite has dissolved, but prior to infilling with sparry cement, the empty space must be held open by the micrite envelope. Bathurst (ibid) and Friedman (1975, p 383) reasoned that a delicate unsupported rim of micrite would easily be crushed by a significant thickness of overburden. Micrite envelopes in grain-supported limestones of the Reservoir Mbr., which may comprise as much as 20% grain bulk, are typically uncompacted.

Fig. 6-4 Dissolution fabrics in Reservoir Member limestones: Thin section photomicrographs. Scale bars = 1 mm unless otherwise stated.

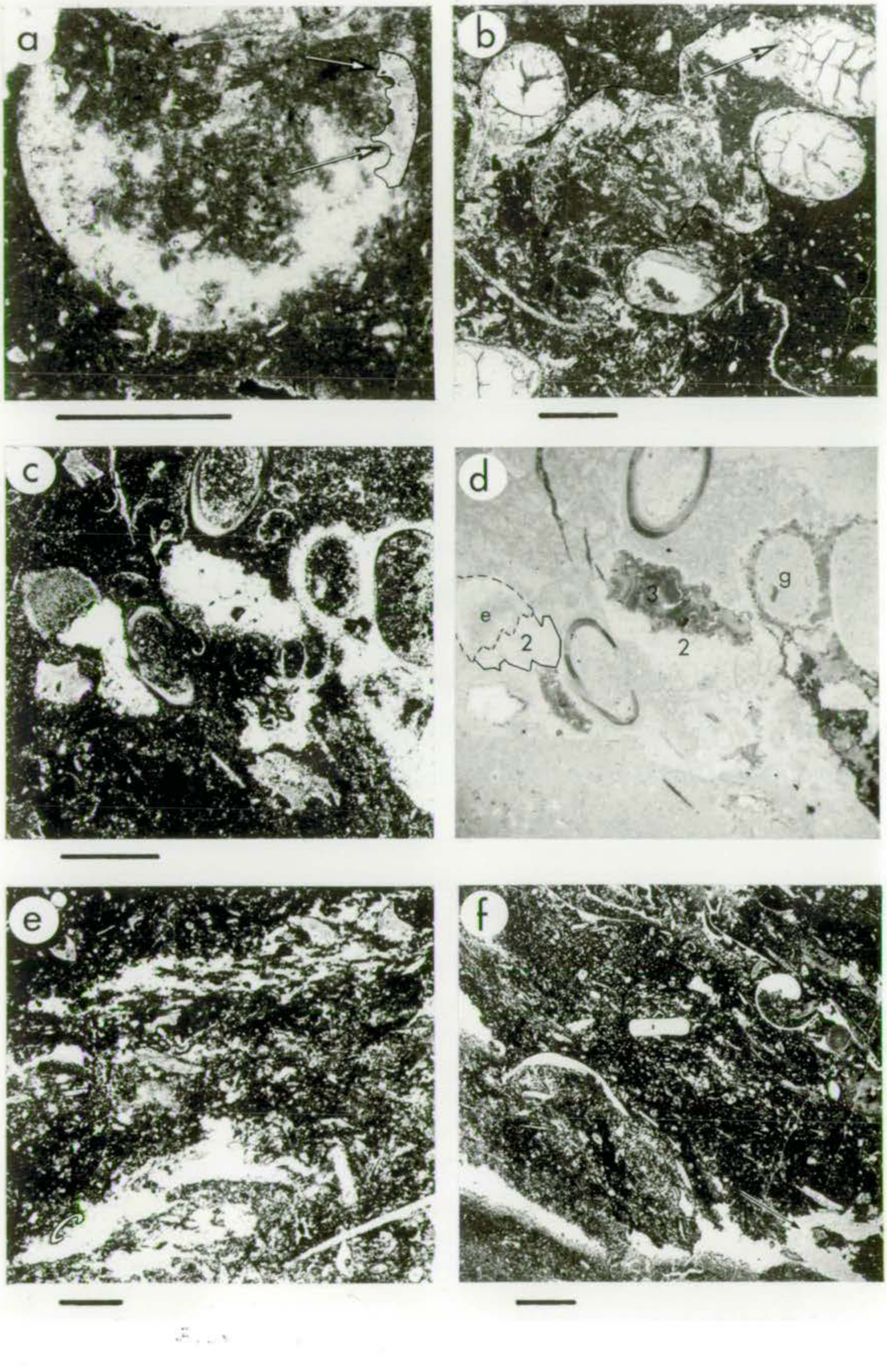
a. Skeletal moulds. A partial mould of Lithostrotion junceum. Arrows point to undissolved skeleton (outlined). The mould contains a few fragments of matrix, the beginnings of an internal sediment. The cavity roof is slightly enlarged, no longer preserving the outline of the corallite. High-carbonate wackestone. G.T. 46 390

b. Microbreccias. A small dissolution-collapse cavity infilled with a jumbled array of fragments of matrix and Lithostrotion. Arrow points to a partially dissolved Lithostrotion epitheca. Note that outside the cavity (area enclosed in dashed lines) the matrix is uniform and undisturbed. G.T. 46, 390

c. + d. Truncated fossils and skeletal moulds. An early dissolution cavity and a gastropod mould (c) in transmitted light, (d) cathodoluminescence. Cavities truncating fossils such as the echinoid spine (e) and the gastropod (preserved as a mould, g) may be used as reliable signs of dissolution. The three cavities shown have a common sequence of cements (luminescent rim stage 2 followed by stage 3) and are therefore contemporaneous. The internal sediments derived from collapse associated with dissolution (2) luminesce brightly due to the intergrown cement, stage 2. Build-up, subfacies A. RSM 1979.1.32

e. Matrix dissolution and stromatactoid cavities. Rather piecemeal dissolution (upper half photo) has created a spongy texture in an otherwise uniform matrix. In the lower half of photo, a larger stromatactoid cavity has formed with typical horizontal floor and ragged roof. Roof truncates skeletal fragments (outlined productoid spine) and interconnects with small skeletal moulds (at left) indicating that dissolution has taken place within cavity. Build-up, subfacies A. RSM 1979.1.33

f. Stromatactoid cavities. Subhorizontal cavities with horizontal infillings, a characteristic dissolution structure. Truncated fossils (arrow) in the cavities provide evidence of dissolution modification. General view of Fig. 6-6. Scale bar = 3 mm. RSM 1979.1.32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c
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2
3
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g
e
f

Along with shrinkage fractures, they are one of several structures which suggest that dissolution took place very early during diagenesis, prior to accumulation of a thick sediment cover.

6.313 Truncated fossils and fabrics Figs. 6-6; 6-7; 6-8; 6-10f

Cavities which truncate depositional fabrics or shells are obviously attributable to dissolution. They are usually also associated with crumbly fractures. Particularly clear examples of cross-cut fabrics include those where shells, laminar bundles of Girvanella and geopetal infillings have been truncated (Fig. 6-10f) and where cavity infillings have been left pendant by subsequent dissolution of the matrix underneath (Fig. 6-8).

6.314 Internal sediments Figs. 6-4e,f; 6-7; 6-8; 6-9; 6-10; 11-12; 11-13

As many as three or four types of sediment may be present in dissolution or breccia cavity systems. These internal sediments are typically lighter than the matrix, stand out clearly, and are thus a reliable means of recognizing dissolution cavities. Three types of internal sediments (A, B, C) are present in the Reservoir Mbr. limestones. The earliest type A, may be primary (depositional) or secondary (diagenetic). Type B is always a diagenetic internal sediment (described below), whereas C, an exceptional type, is an allochthonous marine sediment. Infillings A and C are described in detail as part of the cavity systems in which they occur.

The most common internal sediments are diagenetic, derived from within the parent cavity system by a process of incomplete skeletal dissolution, fracturing or collapse. The composition of diagenetic internal sediments usually closely resembles that of the matrix. Internal sediments in dissolution cavities in Lithostrotion colonies, for instance, contain a high proportion of Lithostrotion fragments, suggesting a local derivation. The earliest diagenetic internal sediments tend to be fairly coarse-grained, whereas later generations are typically finer grained, and may occlude the interstices in earlier infillings.

The distribution of internal sediments is particularly significant. Internal sediments are found in skeletal moulds, between breccia clasts, supporting breccia clasts, and in interconnecting crumbly and sharp-edged fractures (rarely). These common internal sediments establish that cavities of diverse dissolution-related origins formed a well-interconnected system. Where the internal sediments support a breccia, they must also have been contemporaneous with collapse. The manner in which internal sediments partially infill between the clasts and perch on top of flat surfaces suggests that some sediments have been washed downward through the breccias after collapse. These internal sediment piles thus additionally suggest a downward sense of water movement.

6.315 The ragged roof Figs. 6-4; 6-5; 6-6; 6-7; 6-8; 6-9; 6-10; 11-12

The roof of dissolution cavities typically has a ragged appearance. Although not all dissolution cavities have ragged roofs, approximately 90% of cavities with ragged roofs also show other signs of dissolution. The upper surface of these cavities is very irregular and typically denticulate or dome-shaped in outline. In thin section the roof edge itself is particularly unclear or ragged (Figs. 6-4; 6-6; 6-7). It often shows a clotted texture, which passes into more uniform matrix further away from the roof edge. This lack of definition is due in part to minute skeletal moulds that open onto the cavity underneath. Ragged roofs thus appear to have formed by selective dissolution of mineralogically unstable grains and matrix where particles have been loosened and fallen to the cavity floor. It seems likely that cavities acquired a ragged roof soon after skeletal dissolution, during an enlargement phase (q.v. Figs. 6-4a, a cavity which is just beginning to enlarge; also 6-5; 6-6).

6.316 Stylolites

Stylolites and embayed grain contacts are formed by pressure solution (Bathurst 1971, p 462). They originate at points of stress within a framework (ibid) and are not necessarily associated with any particular diagenetic environment in the Reservoir Mbr. limestones. Stylolites are a minor fabric modification, and have thus not been considered in great detail.

6.32 Patterns of cavity dissolution

The evidence already presented indicates that all diagenetic cavities were at least partially formed by dissolution. However, as several processes were involved in cavity formation, it is impossible to describe one diagenetic process without, to some extent, including the others. Cavities in the Reservoir Mbr. may be readily classified by their principal formative processes. Three cavity types can be distinguished: a) those produced primarily by dissolution; b) cavities produced by dissolution and fracture; and c) polygenetic cavities.

6.321 Dissolution modification: enlarged skeletal moulds

Figs. 6-4; 6-5; 6-7

Many dissolution cavities were originally skeletal moulds, which have continued to enlarge after dissolution of the original fossil. In many cases, the shape of the final cavity bears no resemblance to the original fossil. Remnants of the original fossil, or the nature of the internal sediment, may, however, belie the origin of the cavity.

Enlarged skeletal moulds of fistuliporoid bryozoans, usually of Fistulipora encrustans (M'Coy) are particularly common (Figs. 6-5; 6-7; 6-10e). In this case the growth habit of fistuliporoids during life and the pellet-like internal sediment give away the origin of the moulds.

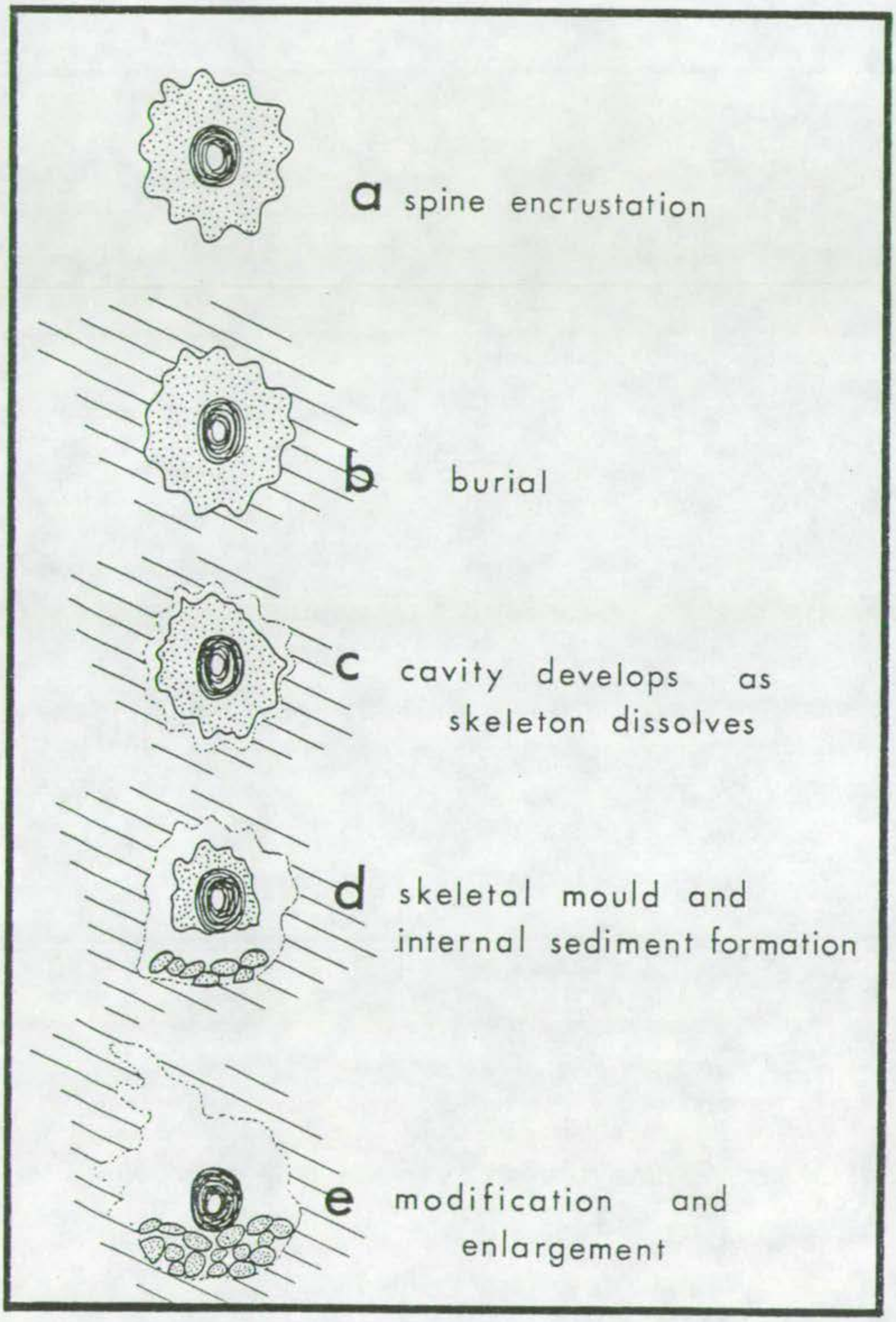


Fig. 6-5 Postulated sequence of events leading to formation of a skeletal dissolution mould beginning with Fistulipora encrustation of a productoid spine, shown in cross-section. This sequence is suggested from various fossils found in intermediate stages of cavity formation.

Fistuliporoids commonly encrust the large pedicle valve spines of productoid brachiopods. The bryozoan colonies grew as an envelope, several millimetres thick, along the length of a spine (Fig. 9-5). During burial, the surrounding matrix infilled the zoecial apertures of the colony (Fig. 6-5b). On exposure to meteoric water, the skeleton began to dissolve from the periphery inward, a dissolution sequence also noted by Scoffin (1972) in Wenlock limestone cavities. As the skeleton dissolved, a cavity formed into which the relatively insoluble zoecial sediment infillings collapsed, along with pieces of skeleton (Fig. 6-5). After complete skeletal dissolution, a cavity was left, with a spine running down its axis (shown in Figs. 6-7; 6-10) and a partial flooring of loosely-packed ("clotted") internal sediment. During subsequent enlargement, the cavity expanded upwards, modifying the form of the original mould. In some cases the internal sediment became sufficiently cemented to support its own dissolution cavities (Fig. 6-8).

6.322 Modification by dissolution and fracture

Figs. 6-7; 6-8

Cavities formed by a combination of these two processes are necessarily more complex. Fig. 6-6 illustrates how skeletal dissolution and crumbly fracture may, together, produce a cavity which is not immediately recognizable as the product of either process.

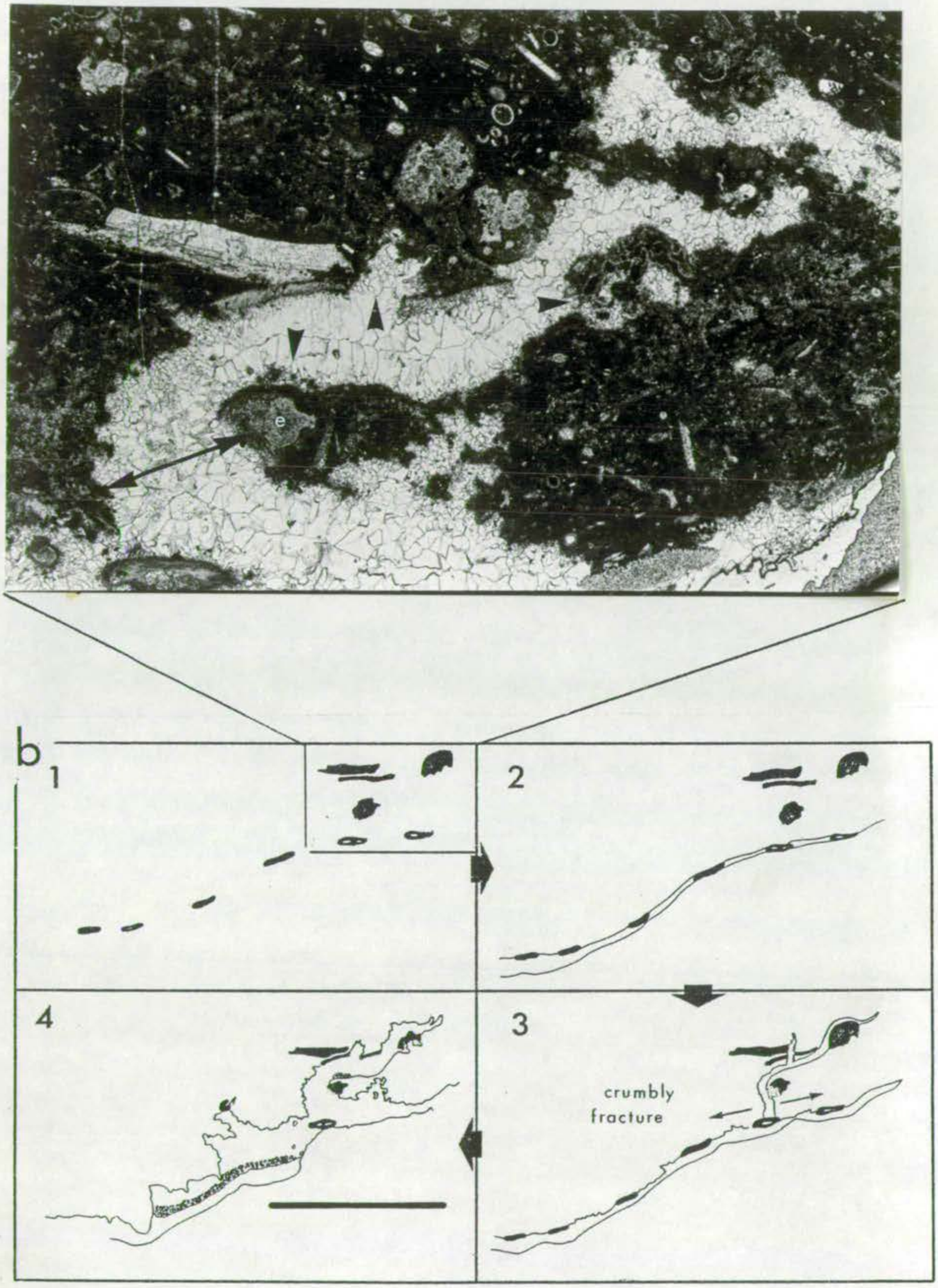
As in the previous example, cavity formation began with the dissolution of a bryozoan, in this case the frond of a fenestellid (b, Fig. 6-6). During early stages, shrinking of the matrix away from the frond may have aided initial cavity opening. Crumbly fractures, such as those shown in Figs. 6-6; 6-7; 6-8, opened soon afterwards in the roof of the cavity. Their disposition suggests they formed by gravitational stress, comparable to cracks in a sagging ceiling. The manner

Fig. 6-6 Cavity development by dissolution and crumbly fracture

a. Transmitted light photomicrograph of fracture in the roof of a dissolution cavity. Double-headed arrow shows apex of fracture. Note that fracture is re-fittable, and that separation has occurred, in part, along a brachiopod shell fragment. The upper and lower surfaces of fracture do not correspond exactly as the roof has been subsequently enlarged by dissolution. Upward- and sideways-facing arrow heads point to signs of dissolution in both roof and fossils. Echinoderm fragments (e) at apex has also been partially dissolved. These structures together with the incipient internal sediment (downward-facing arrow head) all indicate that dissolution has taken place within the fracture. RSM 1979.1.32

b. Probable sequence of dissolution and fracture (1-4) leading to the development of cavity shown above. Box b-4 shows present appearance of cavity, traced from a thin section. Scale bar in b-4 = 7 mm. Sequence is as follows:

1) burial of a fenestellid bryozoan
2) cavity begins to form along frond, possibly due to shrinkage and dissolution
3) tensional stress creates crumbly fractures in cavity roof
4) preferential dissolution enlarges cavity and fracture in roof. Partially-dissolved skeletal debris and fragments of matrix fall to floor forming loosely packed internal sediment.


e
b
1
2
3
crumbly
fracture
4

in which the fracture sides may be refitted, (a, Fig. 6-6) establishes that roof fractures are indeed fractures and not dissolution cavities. In a subsequent stage (4, Fig. 6-6b) both the fractures and the original dissolution cavities expanded upwards.

6.323 Polygenetic dissolution cavities Fig. 6-7

Most dissolution cavities in the Reservoir Mbr. limestones have been formed by several periods of fracturing, dissolution and enlargement. Such cavities are termed here polygenetic dissolution cavities.

Polygenetic dissolution cavities usually originate from skeletal moulds, or rarely, from a fracture (Figs. 6-6; 6-7; 6-8). Cylindrical cavities have formed from fistuliporoid bryozoans encrusting spines; flat cavities developed from fenestellids; and vertical or square cavities were enlarged from fractures. The original shape of a cavity and its proximity to others largely determines its subsequent history. Mechanically weak, flat cavities appear to have been more susceptible to fracture than cylindrical cavities, where dissolution appears to have played a greater role in enlargement. Roof fractures in one cavity have often opened into an overlying cavity (Fig. 6-7). The instability created by this pattern of enlargement has led to further fracturing in both the cavities and, in some cases, their internal sediments. Fractures and dissolution cavities in the internal sediments are signs that cementation began between the earliest and latest periods of internal sedimentation (Figs. 6-7; 6-8). As the process of fracturing, internal sedimentation, and dissolution were repeated, fractures in the internal sediments often became infilled by later stage sediments.

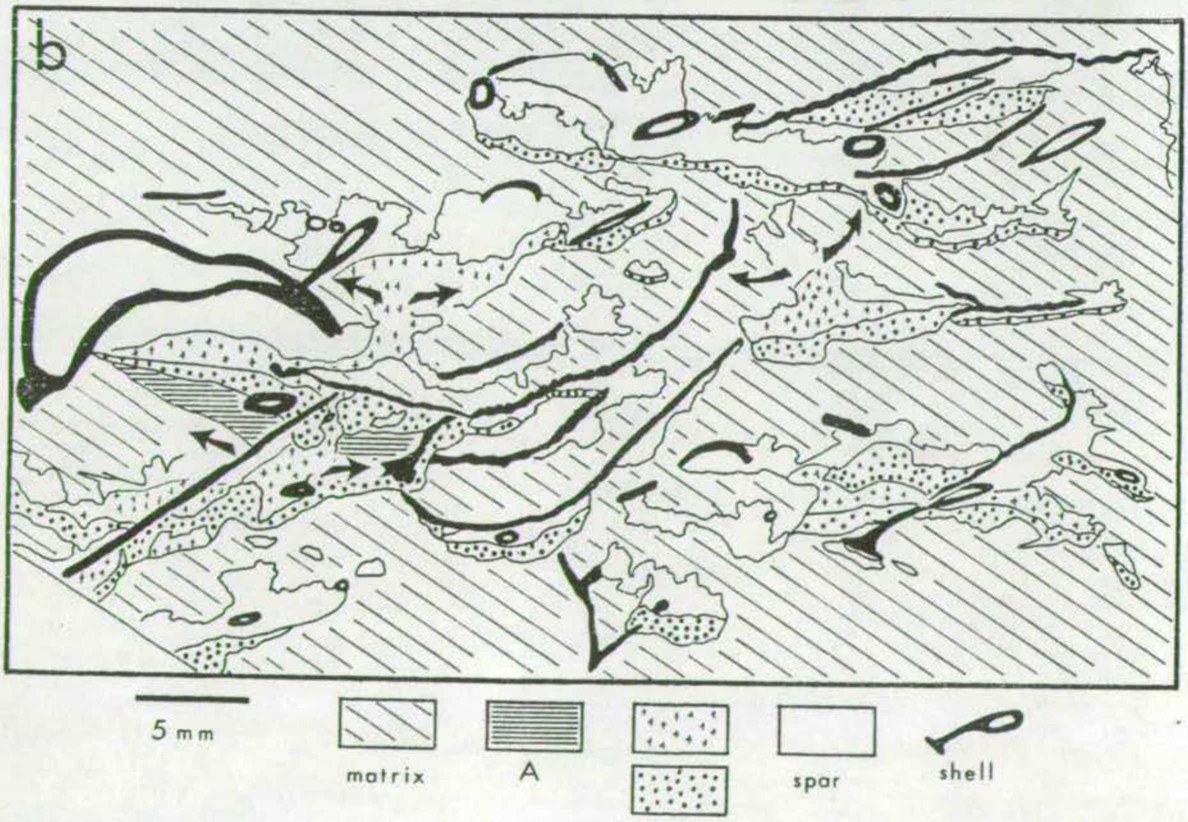
The final product is a fabric of multiple infillings in cavities, and later cavities within the infillings. As two or more generations of cavities became superimposed, the nature of the original cavity

Fig. 6-7 Polygenetic dissolution cavities. G.T. 46,434d

a. polished plaquette; b. simplified microprojector tracing of a.

Blue-grey biomicrosparite; build-up facies, subfacies A.

Earliest cavity (shown by fill A) is apparently developed in the shelter of an overturned spinose productoid. Subsequent cavities (shown by B fills) are diagenetic, in some cases almost exclusively infilled by debris derived from bryozoan skeleton dissolution. Note that such cavities sometimes have a productoid spine running down their axis (suggesting the bryozoan once encrusted spine). Some cavities and early type B infillings are fractured (arrows). Fractured cavities and infillings are covered by later B sediments, indicating that an interval of cementation interrupted dissolution. Note that all dissolution cavities have a ragged roof.


b
5 mm
matrix
A
B
internal sediments
spar
shell

system has often become obscured.

Stromatactoid cavities - Many of the polygenetic dissolution cavities in the lower build-up closely resemble stromatactis as described by Bathurst (1959), Semeniuk (1971) and Heckel (1972). The term stromatactis has been commonly used to describe the sparry infillings of elongate cavities. They are a common structure in many Paleozoic build-ups (see Heckel 1972 for a review of occurrences). The origins of stromatactis are still uncertain. Cavities in the Reservoir Mbr., described as stromatactoid cavities, generally resemble stromatactis from elsewhere in physical appearance and size, but may not have the same origin. The most noticeable difference between most stromatactis sensu stricto and stromatactoid cavities is the absence of an early cloudy radiaxial generation of cement from the latter.

General appearance Fig. 6-9 - Stromatactoid cavities in the Reservoir Mbr. limestones form a system of subhorizontal cavities, usually between 5-10 mm high and several centimetres wide (Figs. 6-4; 6-7; 6-8; 6-10; 11-12; 11-13). General features of the cavities are shown in Fig. 6-9. The stromatactoid cavity roof is ragged and largely lacks shell support. The geometry of the floor is usually masked by one or more infilling internal sediments. In general, the original stromatactoid cavity floor appears to have been fairly smooth, although somewhat uneven (Figs. 6-8; 6-10b). The subhorizontal elements of the system are interconnected by vertically orientated fractures, which may contain internal sediments (Fig. 6-10c,d).

Internal sediments Figs. 6-9; 6-10; 11-13; 11-14

Up to three types of internal sediments infill stromatactoid cavities:

Type A - These, the earliest infillings, are usually light grey or cream fossiliferous wackestones or mudstones,

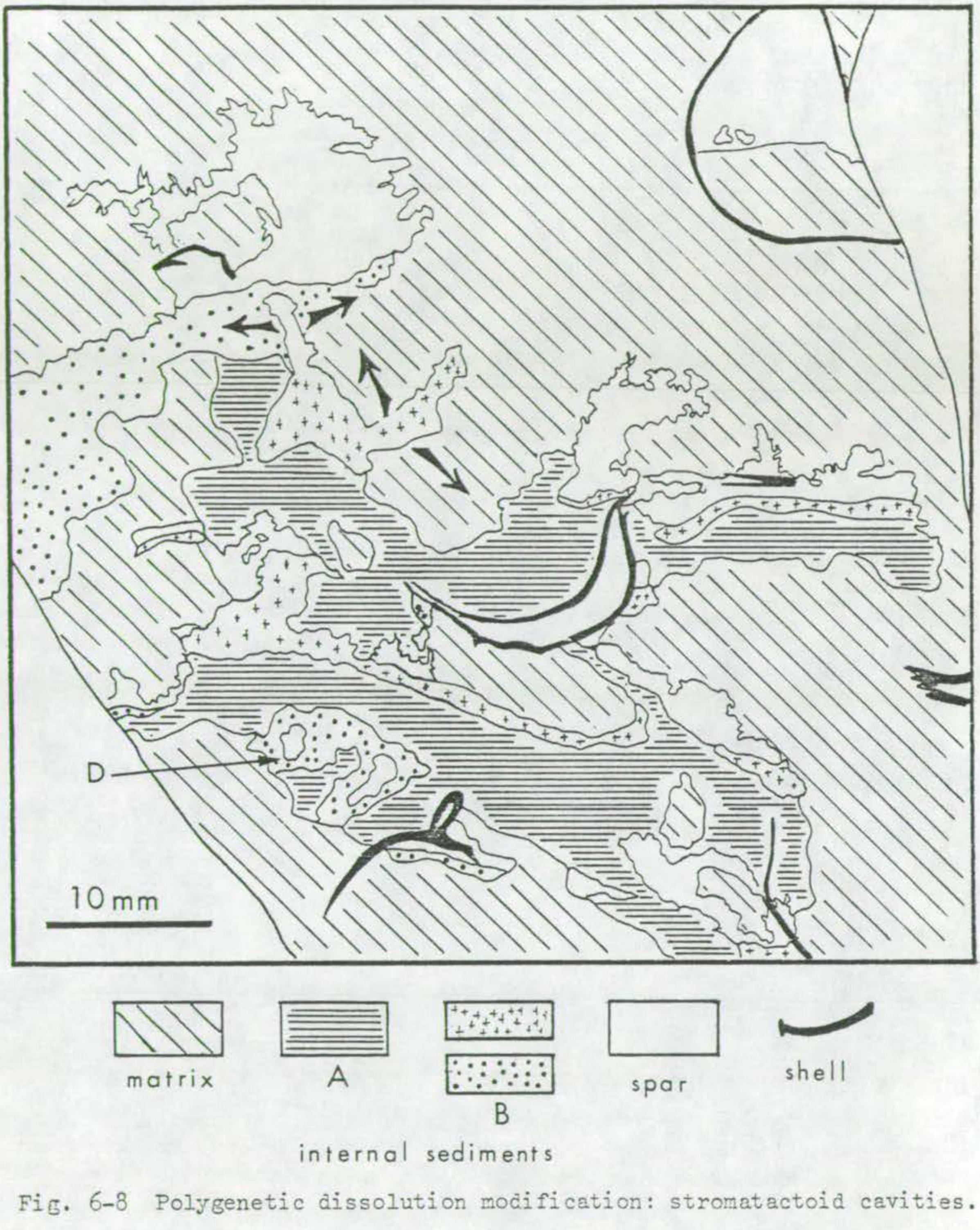


Fig. 6-8 Polygenetic dissolution modification: stromatactoid cavities.

Microprojector tracing of a peel taken from sample shown in Fig. 6-10b. The age relationships between the various internal sediments provides some of the evidence for their origin. The earliest, type A, closely resembles matrix and appears to be associated with fossils, in this case forming around spinose productoids. Type A could, therefore, be marine. Type B sediments are diagenetic, as they infill dissolution cavities in A (e.g. cavity D). Fractures in type B infillings (arrows) which have been subsequently infilled with later B sediments, indicate that type B sedimentation was a multiple event accompanied by lithification. Note that roofs of cavities have a ragged outline. Build-up, subfacies A. 6.T. 46,388.

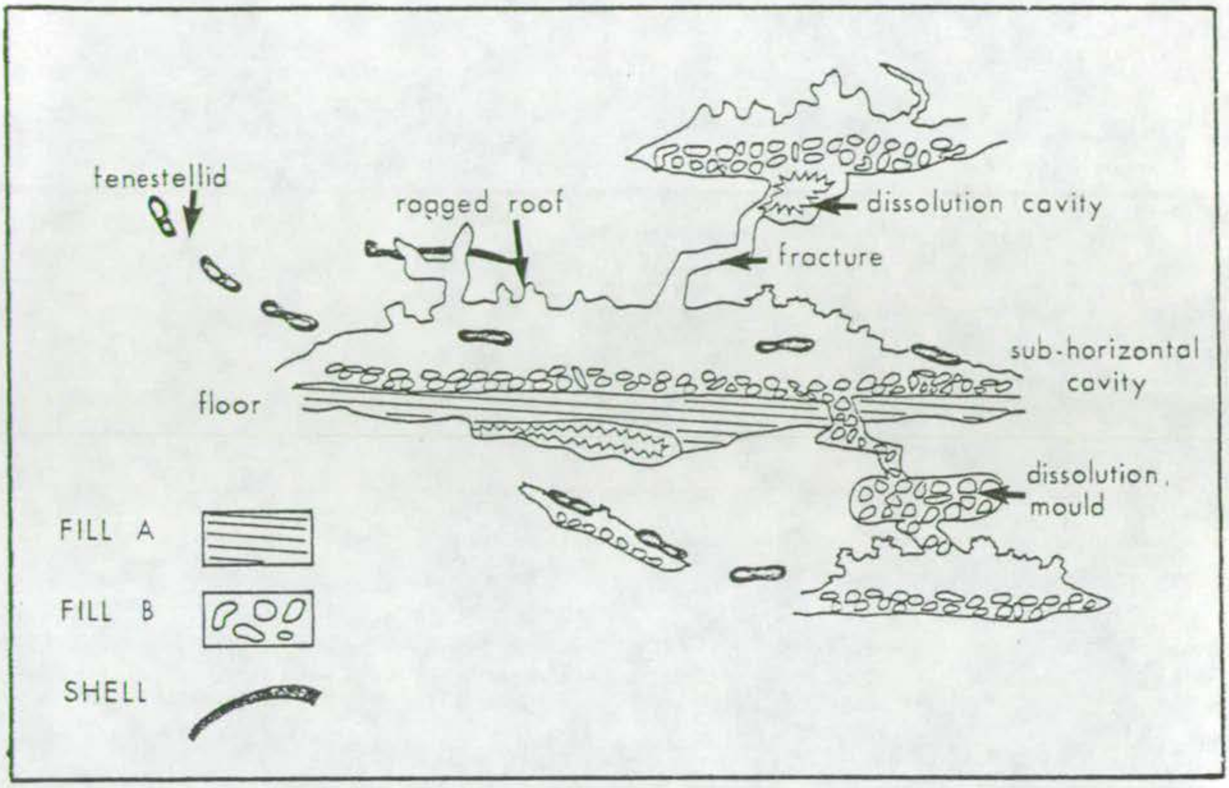


Fig. 6-9 General features of stromatactoid cavities.

similar in composition and texture to the matrix and primary cavity infillings, such as geopetal infillings in brachiopods (Figs. 6-7; 6-8; 11-12). Type A infillings differ from the matrix in that they are usually lighter coloured and finer-grained. The boundary between infill and the matrix is indistinct, and difficult to pick out, particularly in thin section. Type A sediments are rare, only occurring in the subhorizontal elements of the stromatactoid cavity system. In compacted cavities, the infill has deformed plastically: a sign of its early origin. The shape and restricted distribution of type A sediments suggests that, in some cases, it is an infilling of primary shelter cavities and perhaps of very early marine fractures.

Type B - Type B sediments are internally-derived, diagenetic sediments commonly found in all dissolution cavities. They overlie type A sediments (Fig. 6-8) or, more often, form the first stromatactoid cavity infill. Several generations of type B sediments are usually present (Figs. 6-7; 6-8). Later generations may infill dissolution voids in earlier infillings (Fig. 6-8). Type B sediments are petrographically varied, generally composed of loosely-packed (clotted) skeletal debris and matrix fragments. The ubiquitous presence of type B sediments throughout all elements of stromatactoid cavities suggests that isolated cavities did not become integrated into a system until after the onset of dissolution.

Type C Figs. 6-10e; 7-4; 11-12; 11-13 - The stromatactoid cavities beneath an erosional surface interpreted as a subaerial discontinuity in the lower build-up facies (Sect 11.36) contain several allochthonous marine sediments, in addition to sediments A and B. These are grouped as type C infillings. The coarser of these side-fill into the stromatactoid cavity system from a crack developed in the surface. Finer type C infills show evidence of having trickled downward through the vertical elements of the stromatactoid system (Figs. 6-10; 11-12b). Type C infillings indicate that, at least in this one case, stromatactoid cavities formed close to the sediment surface.

Relationship of stromatactoid cavities to fossils - As in other polygenetic dissolution cavities, the geometry of parts of the stromatactoid system often closely resembles, or follows, that of fossils. Many flat cavities (Figs. 6-4e; 6-6b) follow partially dissolved fenestellid fronds or have internal sediments composed exclusively of bryozoan debris (Fig. 3-5). Brachiopods, particularly productoids and schellweinellids also appear to have sheltered the earliest parts of stromatactoid cavities. As has already been mentioned (also cf. Scoffin 1972) fistuliporoid bryozoans may also form a template for dissolution cavities.

Late dissolution Figs. 6-7; 6-8; 11-13 - The stromatactoid cavity system appears to have been particularly susceptible to late dissolution. Late dissolution cavities typically cross-cut early internal sediments (Fig. 11-12). They often lack internal sediment infills, suggesting they formed after initial cementation.

Experimentally produced stromatactoid cavities - In a series of experiments (described in Appdx E), I produced primary cavities which closely resemble the earliest elements of the stromatactoid system. These cavities were created by slowly sedimenting a poorly-sorted Recent, Florida Bay carbonate mixed sand and mud onto a standing framework of coarse plastic mesh. Mesh sizes similar to those of the fenestrules of bryozoans were chosen (Fig. E-1a, Appdx). A thin film of algae was cultured in the sediment surface to add stability. By gently dispersing small amounts of sediment in standing water above the framework, a finely laminated sediment was built up. The algal

Fig. 6-10 Diagenetic modifications of high-carbonate limestones. Oil-covered, polished slices.

a. A dark, breccia-infilled dissolution cavity. Note ragged roof with extremely large pendant (arrow). Sparry cement in the cavity is black due to staining by hydrocarbons, probably albertite. High-diversity packstone; build-up, subfacies B, Galabraes Quarry. Total length scale = 2.5 cm. G.I. 46,394

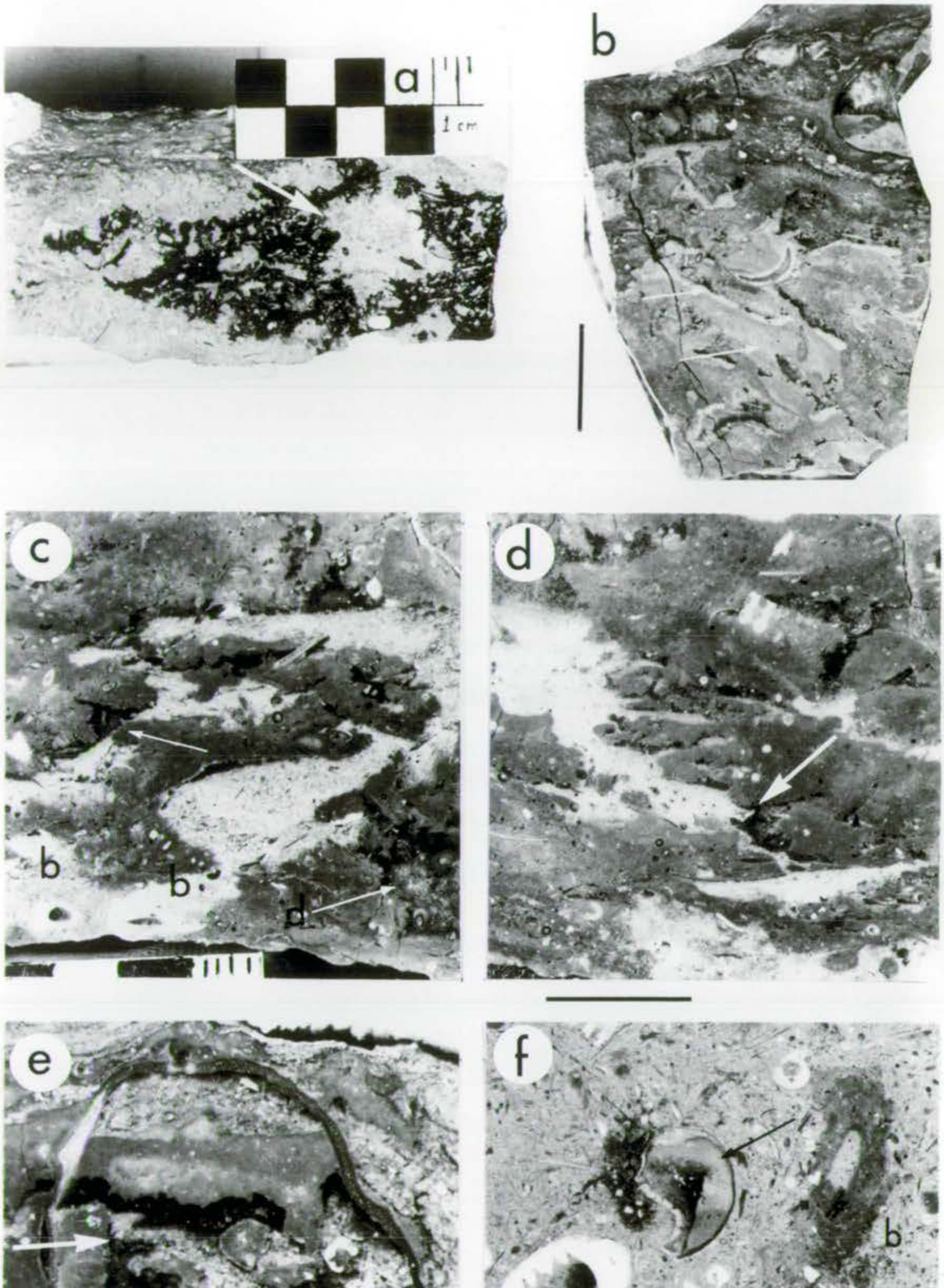
b. Polygenetic, stromatactoid dissolution cavities in a blue-grey wackestone. Successive generations of infilling internal sediments are lighter. Arrows point to type A (lower arrow) and B internal sediments. Fig. 6-8 taken from peel of this plaquette. Build-up, subfacies A, South Quarry. Scale bar = 1 cm. G.I. 46,388

c. Stromatactoid cavity. Ligh-coloured allchthonous (type C) sediments side-fill and trickle-fill downward (arrow) into cavities. Clear, concentrically-lined, open burrows (b) indicate that cavities were near sediment surface at time of infilling, and that type C sediments are probably marine. Note ragged roof of cavities. Late dissolution cavities (d) lack sediments. Build-up; subfacies A, South Quarry. G.I. 46540

d. Stromatactoid cavities. Ligh-coloured sediments infill downward into subhorizontal elements of cavities along fractures. Late dissolution cavities (arrow) truncate both matrix and internal sediment. Build-up; subfacies A. Scale bar = 1 cm. G.I. 46,434

e. Edge of a crack opening onto erosion surface A in the lower build-up. Matrix is dark grey; infilling (type C) consists of light, coarse packstone. The presence of type C sediments in a bryozoan skeletal dissolution cavity (lower arrow pointing to cavity with spine in middle) suggests sedimentation post-dates early dissolution. Late cavities truncating type C sediments (upper arrow) indicate that dissolution also took place after infilling. Scale bar = 1 cm. G.I 46 434 c

f. Truncated fabrics: a criterion for dissolution. Arrow points to geopetal infilling in a brachiopod truncated, contrary to original lamination, by dissolution. Note lined Thalassinoides (type A) burrow (b), partially infilled with sediment. High-carbonate biomicrosparite, Glenbare Quarry. Scale bar = 1 cm. RSM 1979.1.5


a
1 cm
b
c
b
b
d
d
e
f
b

surface film was allowed to re-establish itself after each period of sedimentation. It was felt that the physical properties of the sediment, the plastic mesh, and means of sediment addition (the rate of addition excluded) and the algae were generally comparable with their counterparts in the original depositional environment. Thin sections of the Reservoir Mbr. stromatactoid cavity-bearing limestones show that branched algal filaments were pervasive throughout their matrix.

After several months, a fabric similar to that of many high-carbonate wackestones and packstones had built up. Each pulse of sediment formed a fairly irregular lamination, produced by particles grading and aligning with the depositional surface. Few of the laminae were continuous or horizontal (Fig. E-2, Appdx). Sediments falling on inclined pieces of mesh slid off at fairly steep angles of repose, creating highly inclined laminae and geopetal infillings (Fig. E-2). The influence of the plastic mesh framework was considerable, especially considering that it only comprised 11% grain bulk. The presence of a mesh-supported framework (such as that shown in Fig. E-2) is not likely to be apparent in a standard-sized thin section of a rock, especially after partial dissolution of the mesh itself. In addition to affecting the thickness and disposition of the laminae, the mesh sheltered subhorizontal cavities. Such cavities were formed beneath flat lying mesh at T-interstices and beneath highly curved pieces of mesh (Fig. E-2). The size, spacing, and disposition of these shelter cavities was comparable to that of the cavities interpreted as primary parts of the stromatactoid system in the Reservoir Mbr. limestones (q.v. 11-14). Some larger cavities even contained thin infillings derived from filtering through the mesh, which resembled type A fills.

<u>Origin of stromatactoid cavities</u> - Previous authors have attempted to explain the origins of stromatactoid cavities by

focusing on the shapes of the cement-infilled portions of the cavity, and by assuming that all parts of the cavity system were contemporaneous. The evidence from the Reservoir Mbr. stromatactoid cavities indicates that all elements of the system are not coeval. Only by considering stromatactoid cavities as a cumulative, polygenetic structure does their origin become clear.

Experiments with Recent carbonate sediments indicate that isolated, subhorizontal and irregularly-shaped cavities can form by normal sedimentary processes where a loose framework of bryozoans or shells is present. The principal requisite conditions appear to be that a sufficient number of flattish objects be present to form a loose, but supportive framework and that the sediment stabilize quickly during deposition. It is not necessary to cement a fabric in order to achieve the necessary stability. Moreover, the framework need only comprise such a small percentage of grain bulk as to be very difficult to identify in thin sections and peels. Decimetre square sized sample areas are needed.

The shape of stromatactoid cavities in the Reservoir Mbr. limestones, their relationship to once-supportive skeletons, and their infilling sediments suggest that the system grew from an array of isolated cavities similar to those produced here experimentally. Soon after burial, prior to extensive consolidation, fossils, particularly bryozoans, began to dissolve. The susceptibility of bryozoans to dissolution may be particularly important in creating an interconnected system from isolated cavities. Even partial dissolution of the framework organism would yield a permeable, as well as porous, system.

Soon after skeletal dissolution began, the isolated cavities became interconnected along fractures and skeletal moulds. Once established, the system evolved similarly to all other polygenetic dissolution cavities, resulting in a complex overlay of fabrics.

Although the history and origins of stromatactoid cavities in the Reservoir Mbr. limestones is likely to be fairly unique, the method of approach adopted in cavity analysis is likely to have much wider applications. Previous workers have not considered the possibility that all elements of the stromatactoid system might not be coeval, and have confined their attention to the sparry infilling above the internal sediments, rather than to the cavity system as a whole. In attempting to isolate the different elements of the system and identify them, the origin of the system as a whole becomes clear.

6.33 Matrix dissolution

The most obvious fabric modifications attributable to dissolution are those described above, where megascopic cavities have formed. The undisturbed matrix may also, however, show signs of dissolution modification (Figs. 6-4; 6-11; 11-12). The criteria for recognizing dissolution modifications in the matrix are much the same as those for recognizing cavity-related dissolution, except smaller in scale. Truncated and cross-cut fossils and fabrics provide the most reliable evidence. Extensively modified fabrics have a clotted, pseudostromatic texture which, with cathodoluminescence, can be seen to be comprised of discrete particles rimmed by stage 2 cements*1. The cements rimming the microscopic clots are continuous with those in skeletal moulds, suggesting the whole fabric has been produced by dissolution of a once more homogeneous matrix. The extent of modification and the texture of the original matrix are very difficult to determine. Piecemeal matrix dissolution in the Reservoir Mbr. limestones has given rise to fabrics very similar to those described by others as resulting from early

*1 cements are described in Sect 6.4.

cementation, or differential algal binding (q.v. De Meijer 1971; Monty 1976). Evidence of both these processes has also been found in the Reservoir Mbr. clotted limestone fabrics. Thus, while clotted fabrics show extensive signs of matrix dissolution, it seems most likely they have arisen by interaction of several processes.

6.34 Late dissolution Figs. 6-10e; 11-12; 11-13

A small proportion of dissolution cavities post-date internal sedimentation and brecciation and have therefore been described as late dissolution cavities. They typically lack internal sediments or a ragged roof, and do not follow depositional fabrics in the matrix.

6.35 Distribution of dissolution fabrics

The extent and type of dissolution modification varies according to facies. Argillaceous limestones and calcareous mudstones seldom show signs of dissolution modification, other than moulds of former aragonite skeletons. Slightly argillaceous limestones may have small areas of matrix dissolution, but lack megascopic cavity-dissolution modifications. High-carbonate, level-bedded biomicrosparites show signs of limited cavity-dissolution and fairly extensive matrix dissolution. The lower half of the build-up is extensively brecciated and modified by all types of dissolution, except stylolites. Coarse-grained sediments in the crinoidal packstone facies and the upper build-up contain skeletal moulds and stylolites. An interpretation of this pattern is presented in the summary section of this Chapter, in part III.

PART II

Cementation, neomorphism, and late diagenesis

6.4 Cementation Figs. 6-11; 6-13; Table 6-12

6.40 Introduction

The sequence of cements in different cavities was used as one method of establishing the sequences of diagenetic events (q.v. Table 6-17). Cement sequences were first established from unaltered shell cavities (Fig. 6-11) on the assumption they would preserve the most complete cementation history. Sequences in other cavities were then compared with those in the primary cavities. The cementation histories of each facies were also compared in order to determine if the Reservoir Mbr. limestones had a common diagenetic history. Limestones of the crinoidal packstone facies were not included in this study because they were too extensively silicified and dolomitized for detailed work.

After a preliminary examination, five major cement stages were distinguished. Stages are separated by significant changes in cement composition, crystal habit and size. Often they form separate generations of crystals, based on each other or matrix. Initially, the staining techniques of Dickson (1966) were employed to distinguish stages. Later, cathodoluminescence petrology further refined the accuracy of cement stage recognition. With cathodoluminescence, minor compositional variations within a stage, termed here substages came to be consistently recognizable. Substages were, in turn, described as being "uniform" in composition, or "zoned". Although substages do not separate diagenetic events, they are a useful means of identifying stages, because stages are often incomplete.

Fourteen thin sections, selected from the composite section at the Reservoir Quarry, were examined in transmitted light, using stains and with cathodoluminescence. From these, six were studied in detail, and form the basis of the cement sequence presented here. Approximately 40 sections from throughout the Reservoir Mbr. were then compared to this "typical" sequence.

The term "cement" is used here to describe all passively-precipitated, pore-filling calcite that has grown from a free surface, (sensu Bathurst 1971, p 416). Unless specifically stated, the term refers to sparry calcite. Where the need has arisen, the terms "micrite cement" and "sparry cement" have been used to avoid possible confusion.

6.41 Cement stages in the Reservoir Mbr. limestones

Stage 1 (Fig. 6-11) forms a rim, approximately 20-60μ thick, of acicular low ferroan micrite or spar, orientated normal to internal and exterior shell surfaces. It probably also forms a significant proportion of the micrite matrix (Figs. 6-11; 6-13). Stage 1 is only clearly seen where it forms a rim of crystals based on a shell surface (Fig. 6-11). With cathodoluminescence (Fig. 6-11b) stage 1 cements are medium orange-red, indistinguishable from (and often contiguous with) micrite and microspar in the matrix and biologically precipitated micrite (e.g. *Girvanella*).

Stage 2 is composed of low ferroan calcite. It forms a coarse prismatic rim or fringe of decimicron-size, scalenohedral crystals, seldom exceeding about 250μ in length (Figs. 6-4; 6-11; 6-14). Cathodoluminescence reveals three substages in stage 2:

2A (Figs. 6-11; 6-13g,h) a moderately luminescent orange band consisting of several (usually 3-4) alternating medium- and brightly-luminescent zones, each approximately 15μ thick;

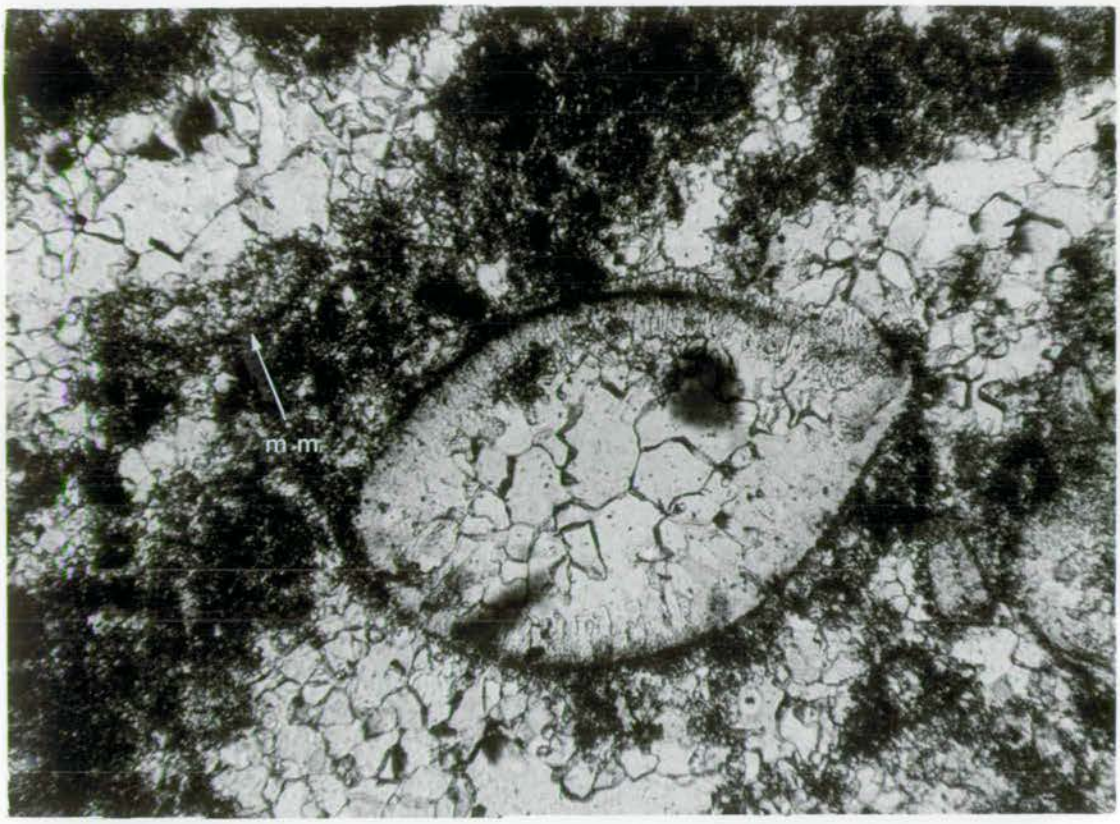
2B a prominent uniform, brightly luminescent, band;

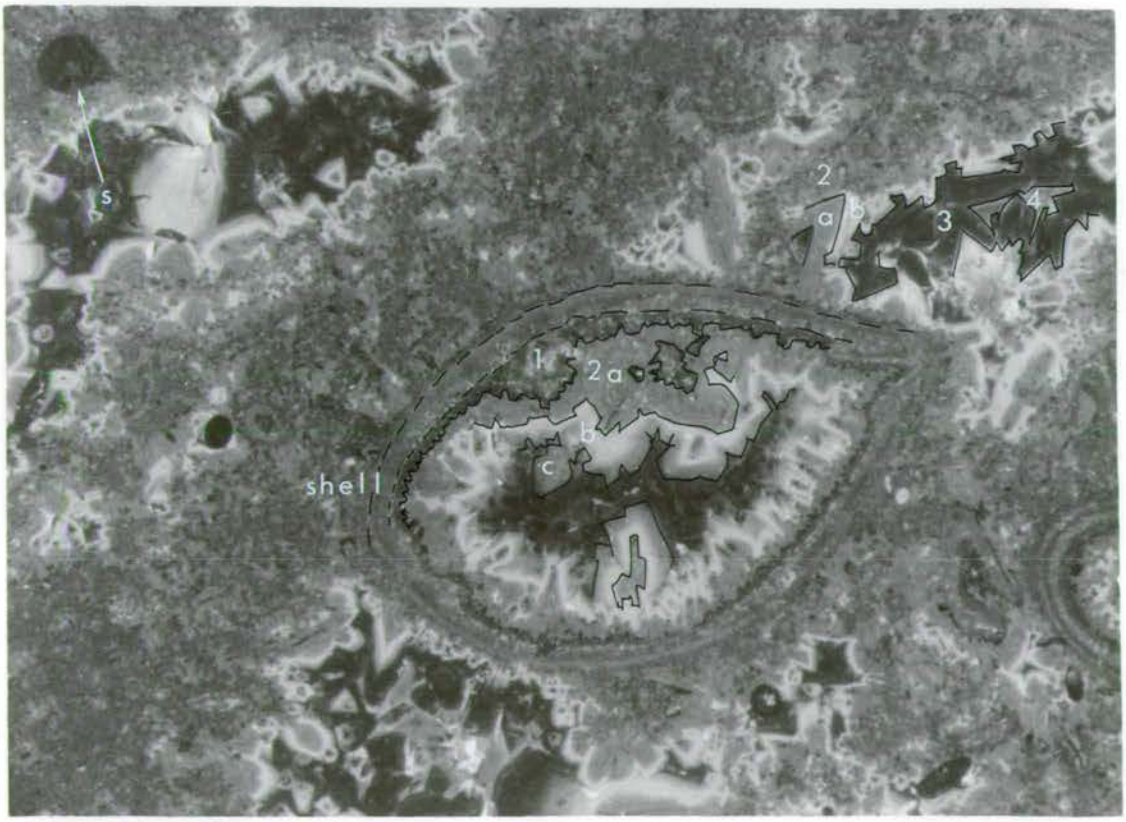
2C a moderately luminescent, unzoned band.

Fig. 6-11 Early cement sequence

Transmitted light (upper) and cathodoluminescent image (lower) photographs of cement sequence in a primary cavity (ostracod shell) and a pseudostromatic, clotted matrix. Cement stages are numbered; substages are lettered. Cathodoluminescent image reveals that matrix once formed an open, porous framework subsequently infilled with stage 2 and 3 cements. The presence of cements intergrown throughout the matrix thus precludes the possibility that clotting is a neomorphic fabric. Micrite mould (mm) with an identical cement sequence as matrix suggests that cementation occurred after dissolution. Note that stage 1 luminesces identically to the micritic matrix. The figure additionally shows that the origin of many sparry blebs can only be interpreted by comparison of the two images (cf. siliceous sponge spicules (sp) and micrite mould).

High-carbonate wackestone; build-up, subfacies A, borehole 4, 30 cm level. Scale bar = 1 mm. RSM 1979.1.33


m.m.


s
2
a
b
3
4
1
2a
b
c
shell

The distribution of stage 2 cements (shown in Table 6-12) is particularly important in establishing the sequence of diagenetic events. They occur as:

a) the first stage of overgrowth on echinoderms (Fig. 6-13g);

b) rims on primary shell surfaces (Fig. 6-11);

c) rims on clasts released by early brecciation (Fig. 6-13b), in shrinkage and crumbly fractures;

d) rims in dissolution cavities including skeletal moulds and stromatactoid cavities (Fig. 6-4);

e) the first visible sparry cement intergrown in clotted fabrics, in internal sediments (Fig. 6-13a,b) and stromatactoid cavities (Fig. 6-13h);

f) rims on sharp-edged fractures (very rare);

g) rims on the allochthonous, marine sediments overlying and infilling cavities in erosional surfaces interpreted as subaerial discontinuities (Fig. 6-13g).

Stage 2 cements are singular in displaying a high degree of fabric specificity, even within a single cavity (Fig. 6-13h). On unfavourable substrates, such as bryozoans and matrix, stage 2 is thinner and individual substages may be abbreviated or absent (Fig. 6-13h). Syntaxial overgrowths are typically thicker and more complete.

Stage 3 (Figs. 6-4; 6-11; 6-13) is initially composed of ferroan calcite, becoming progressively less ferroan. It usually occurs as a separate generation of crystals based on stage 2, but it may also occur as an overgrowth. With cathodoluminescence, two substages within stage 3 become visible:

3A a several hundred µ thick, uniform, non-luminescent dark band (Fig. 6-13g,h);

Table 6-12

The Cement Sequence in the Reservoir Member Limestones

		STAGES							
			rim cement					blocky	
		1	2			3		4	5
Full sequence of cements	**Substages**		A	B	C	A	B		
1	Primary shell cavity	—	—	—	—	—	—	—	—
2	Echinoderm overgrowths		—	—	—	—	—		
3	Stromatactoid cavities		—	—	—	—	—	—	
4	Skeletal dissolution moulds		—	—	—	—	—	—	
5	Early dissolution cavities		—	—	—	—	—	—	—
6	Early brecciation cavities		—	—	—	—	—	—	—
7	Fractures - crumbly + shrinkage		—	—	—	—	—	—	—
8	Fractures - sharp edged			- -	- -	—	—	—	—
9	Dissolution late					—	—	—	—
10	Brecciation late					—	—	—	—
Commonly observed sequences									
1	Primary shell cavity			—	—	—	—	—	
3	Stromatactoid cavities		—	—	—	—	—	—	
3a	Stromatactoid cavities late				—	—	—	—	
4	Skeletal dissolution moulds			—	—	—	—	—	
5	Early dissolution cavities			—	—	—	—	—	
6	Early brecciation cavities			—	—	—	—	—	
7	Fractures - crumbly + shrinkage			—	—	—	—	—	
8	Fractures - sharp edged					—	—	—	

NON-FERROAN

- - - - very rarely observed

——— commonly observed

3B a deci- to centi-micron thick, zoned band, initially moderately luminescent orange-red, becoming more brightly luminescent (Fig. 6-13g,h).

Stage 3 occurs as the first cement in many late dissolution cavities and most sharp-edged fractures (Table 6-12). It is also rarely present in early dissolution and fracture cavities. In general stage 3 was taken as dividing early and late diagenesis, as very little fabric modification could be attributed to post stage 3 diagenesis (Table 6-17).

Stage 4 (Fig. 6-13b,g,h) is composed of moderately luminescent low ferroan calcite, often showing poorly-defined zoning. It consists of large blocky scalenohedral crystals lining cavities and also occurs as an overgrowth.

Stage 5 is composed of blocky crystals morphologically similar to stage 4, commonly showing grey-black, poorly luminescent zoning.

6.42 Discussion

Several observations concerning the distribution of cements are significant and help date the time sequence of diagenetic events.

Stage 1 cements - The origin of stage 1 cements is somewhat problematic, as they show habits of both neomorphic spar and cement. Where stage 1 forms a rim on free surfaces, such as on the inside of empty shells, it is difficult to explain its origin by any means other than direct chemical precipitation. The crystals are based on the shell, and are not a shell replacement, which strongly suggests a cement origin. In several examples, however (Fig. 6-11), stage 1 cements occur on matrix-supported shells, which argues against a cement origin. One explanation of how a cement might form on the outside of a matrix-supported shell is that cementation took place at or close to the sediment surface, largely unrestricted by compactional pressure from

Fig. 6-13 Cement sequences in cavities, Reservoir Mbr. limestones. The common sequence of cements in the various cavities shown here establishes their contemporaneity. a, c, e - transmitted light; b, d, f, g, h - cathodoluminescent image. All samples high-carbonate biomicrosparites.

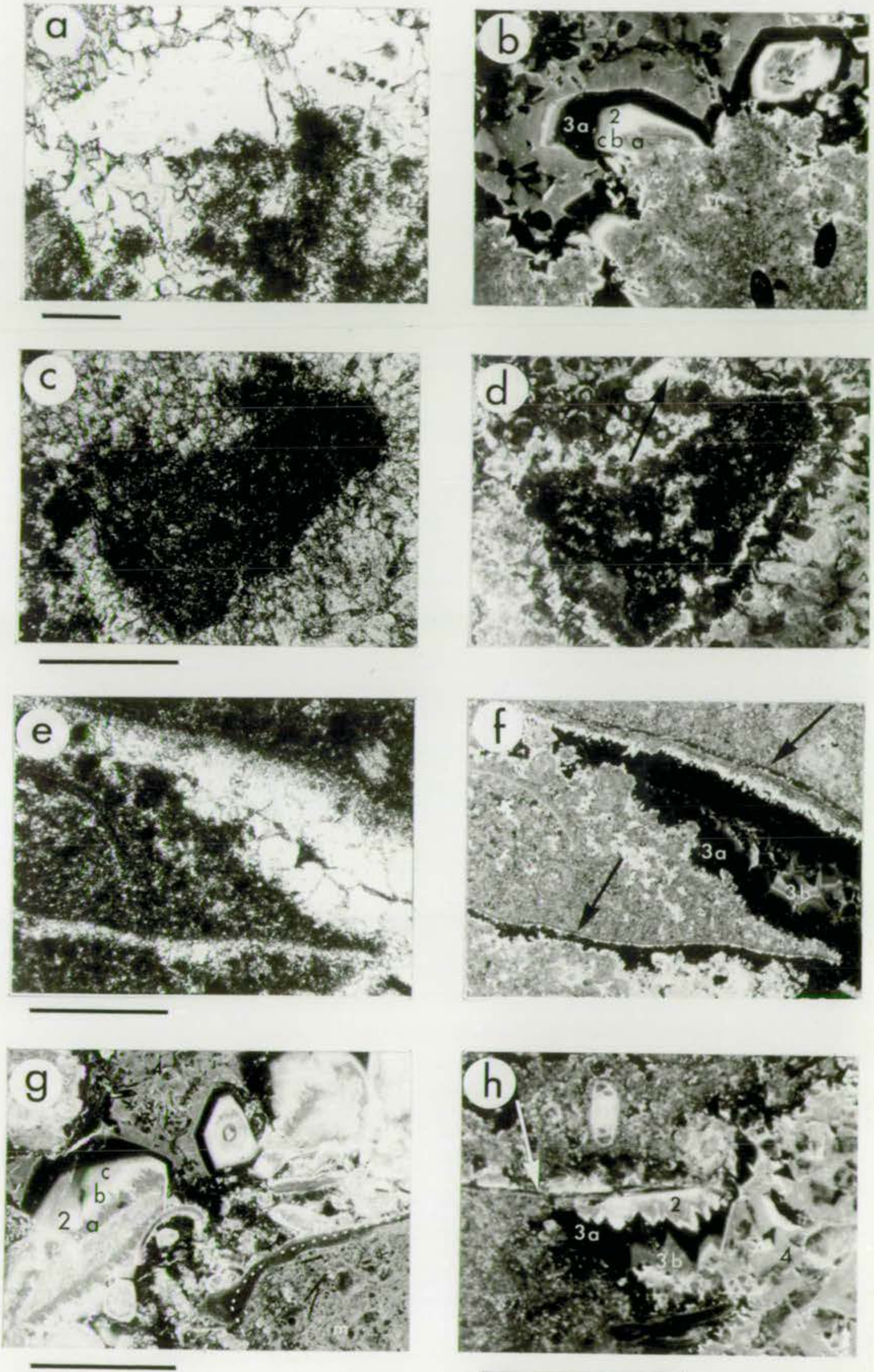
a. + b. Cement sequence in a dissolution cavity. The clotted matrix (lower half) is a type B diagenetic internal sediment. Figure also illustrates the advantage of cathodoluminescence in grain identification; note how sponge spicules become readily apparent. Sample taken 2 m below build-up. Scale bar = 250µ. RSM 1979.1.34

c. + d. Crumbly-edged breccia clast rimmed first by luminescent stage 2 cement (arrow) followed by non-luminescent 3. Scale bar = 500µ. RSM 1979.1.35

e. + f. A shell-supported cavity. Schellweinellid brachiopods (arrows) support cavity with a clotted matrix underneath. Note that some laminae within the shells (upper arrow) are dark with thin fringes of luminescent (2) cements. In transmitted light they are readily confused with neomorphically altered shells. Scale bar = 500µ. RSM 1979.1.36

g. Coarse packstone overlying an erosion surface A (dashed line) in the lower build-up facies. Underlying matrix (m) contains cavities with identical cement sequence (shown in a, b this Fig.). Figures thus show a common cement sequence above and below erosion surface. Scale bar = 1 mm. RSM 1979.1.37

h. Cement sequence in the roof of a stromatactoid cavity. Note that the epitaxial cements on the skeletal fragments (arrow) are larger and have more complete substages than matrix indicating substrate-dependent nature of cement sequence. Bright luminescence of endothyrid foraminiferan (above shell) is similar to that of stage 2, suggesting foraminiferan recrystallized at the time of stage 2 cementation. Lower build-up, subfacies A. Scale bar =37µ. RSM 1979.1.34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surrounding particles. Recent tropical, shallow-water carbonates commonly have morphologically similar thin cement fringes (cf. Bricker 1971).

Bricker (ibid) summarizes the work of various authors indicating that "acicular" fringes of isopachous cements, morphologically similar to stage 1, form in near surface carbonate sediments. These Recent cements differ sufficiently morphologically from ancient neomorphic overgrowths and displacive calcite (q.v. Bathurst 1971, p 491; and Watts 1978) to suggest that stage 1 is a cement and not of neomorphic origin.

Cementation and dissolution - Early textural modifications associated with dissolution (brecciation, Fig. 6-13; internal sediment release, Fig. 6-13; matrix dissolution, Fig. 6-4; and skeletal mould formation, Fig. 6-4) predate stage 2 cementation. The distribution of stage 2 cements establishes the contemporaneous origin of all these features. The absence of stage 2 from later dissolution cavities implies that extensive dissolution, particularly of aragonitic fossils, also occured after stage 2. Some early fractures transect stage 2 cements, further showing that the fracturing process was not complete at the onset of cementation. Cross-cutting relationships (Fig. 6-12) pinpoint the time of stage 2 cementation as taking place during the later stages of early dissolution (Table 6-17).

Differential stage 2 cementation - Stage 2 cements are present on both crumbly and sharp-edged fractures. Although at first this may seem contradictory, it must be remembered that it is unlikely that any carbonate body becomes cemented uniformly. More permeable areas of greater pore water circulation would be expected to lithify more readily than impermeable areas (q.v. Bathurst 1979). One would, therefore, expect to find congruent crumbly and sharp-edged fractures, reflecting differences in the degree of cementation, superimposed on a general trend of crumbly to sharp-edged fracturing.

6.43 The significance of the cement sequence in the Reservoir Mbr.

The sequence of cement stages described above is based on limestones from the build-up and immediately underlying facies at the Reservoir. Primary cavities in other facies of the Reservoir Mbr. limestones elsewhere show the same sequence of stages 2A, 2B, 2C, followed by 3A, 3B. The sequence in any single cavity is seldom complete, but composite sequences from each facies (except the crinoidal packstone facies) can be correlated over the whole of the Reservoir Mbr. As each stage represents a time-equivalent episode of cementation (Meyers 1974, p. 841) one expects that a common sequence of cements throughout a stratigraphic unit might be used to indicate that unconformities resulting from subaerial exposure are absent. It is highly unlikely that two separate episodes of cementation (accompanying exposure) could produce the same sequence of zones observed within a substage, or an identical sequence of substages.

In the Reservoir Mbr. limestones, however, a minor interval of subaerial exposure may have occurred prior to early cementation (q.v. Ch 11). The interval of exposure does not appear to be marked by a distinct cement stage. The implication of this observation is wide ranging; although "cement-stratigraphy" (q.v. Meyers, ibid) may be used to recognize discontinuities, an apparently conformable cement sequence need not imply that discontinuities are absent.

6.5 Neomorphism

6.50 Introduction

All the limestones of the Reservoir Mbr. show varying degrees of neomorphic alteration (sensu Bathurst 1971, p 481). The products of neomorphism are often difficult to distinguish from cements.

Distinguishing between cement and neomorphic spar is, however, of critical importance in any environmental interpretation.

The terminology of Folk (1965) has been employed to describe neomorphic fabrics: micrite refers to <5μ fabrics; microspar to crystal mosaics between 5-30μ; and pseudospar is used for coarser mosaics usually between 30-50μ.

Throughout this section, emphasis has been placed on the Luminoscope as an aid to diagenetic fabric interpretation. As previously mentioned, this is the first known study to apply luminescence petrology to textural studies.

6.51 Advantages of cathodoluminescence to textural studies

The cathodoluminescent image differs from a transmitted light image in several respects which are advantageous in textural studies. The visible light produced by an electron beam striking a thin section is generated essentially at the surface. The resultant image is therefore very sharp, as it does not suffer from the interference associated with passing light through several overlying crystals.

Compositional variation between crystals, particularly variation in Mn++ concentration, may be resolved by a Luminoscope with greater accuracy than by other known methods. Minor compositional differences, even in a recrystallized fabric often depict original skeletal structures, thus aiding in fossil identification. However, when faced with the problem of determining the origin of a particular grain or crystal, lacking distinctive textures, the petrologist must still fall back on established criteria for interpretation. It is important to realize that cathodoluminescence extends levels of resolution far beyond that of conventional petrology, but does not, in itself, provide independent criteria for the origin of a crystal.

6.52 Skeletal neomorphism

The patterns of neomorphic alteration in fossils were examined prior to trying to interpret the matrix. The skeletal mineralogy of Recent counterparts to the Petershill Fm. biota suggests the fossils were variously composed of aragonite, Mg calcite, and calcite (based on Scholle 1978, p xi). During neomorphism they have all been transformed to calcite or ferroan calcite. It was reasoned that the patterns of neomorphic alteration in skeletons of known original mineralogy and texture could provide a basis for interpreting neomorphic fabrics in the fine-grained matrix.

6.521 Luminescent characteristics of fossils

In general, most fossils in the Reservoir Mbr. limestones luminesce moderate to bright orange-red (Table 6-15; Figs. 6-11; 6-14; O-11; O-12). Fossils thought to have originally been composed of aragonite, such as gastropods, bivalves and dasycladacean algae are exceptions. They are usually preserved as skeletal moulds normally infilled with non-luminescent cement (Figs. 6-4d; 6-14; O-11; O-12). Siliceous and calcareous sponges are also preserved as moulds, usually infilled with non-luminescent calcite (Fig. 6-11). Spicule moulds of the siliceous sponge Hyalostelia often luminesce an anomalous bright blue. Nickel (1978, p 87) among others, attributed blue luminesce to lattice defects in the calcite structure.

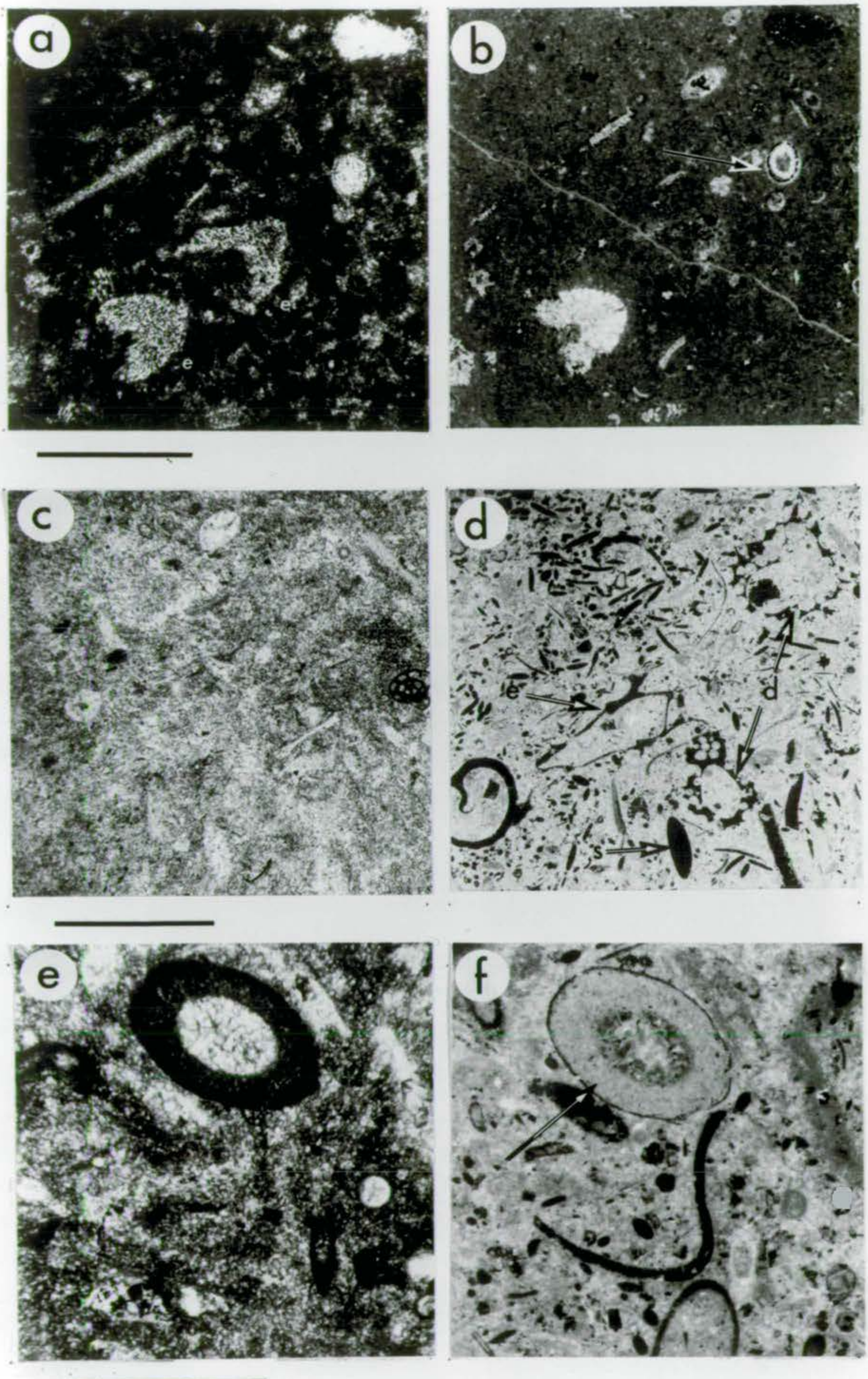
Most skeletons originally composed of Mg-calcite, including ostracods, bryozoans and echinoderms, uniformly luminesce moderate to bright orange-red (Fig. 6-11). Fine-grained, biologically precipitated micrite found in the walls of some foraminiferans such as Earlandia (Figs. 6-14f; O-12) or the filaments of Girvanella luminesces brightly, varying only slightly with degree of recrystallization. Originally calcite skeletons such as those of brachiopods and corals, luminesce dull orange-red.

Fig. 6-14 Neomorphism in the Reservoir Mbr. limestones.
a, c, e - transmitted light; b, d, f - cathodoluminescent photomicrograph.

a. + b. Differential recrystallization of a fine-grained fabric to a porphyroid texture. Porphyroid texture is only apparent in transmitted light, while cathodoluminescence reveals that matrix luminesces uniformly, indicating a neomorphic, rather than cement, origin of the texture. Difference in luminescence between echinoderms (e) is due to preservation. Fragment at left luminesces normally a bright, stage 2 cement colour, while fragment on the right luminesces moderately (like the matrix) due to partial micritization, probably by boring algae. Arrow points to productoid spine in which a few inner laminae have been dissolved and infilled with cement (inked in). High-carbonate wackestone; lower build-up, subfacies A. Scale bar = 500µ. RSM 1979.1.38

c. + d. Uniform recrystallization in a slightly argillaceous packstone. Note matrix luminesces evenly, regardless of degree of recrystallization. Cathodoluminescence reveals that most of the difficult to interpret, sparry, areas are fossils. Fossils that have recrystallized early, presumably at the same time as the matrix, luminesce moderately and therefore contrast poorly. Late stage replacements and skeletal moulds (which are difficult to resolve in transmitted light) stand out clearly (black) with cathodoluminescence. These include the dasycladacean algae (Spinctoporella) (d), siliceous sponges (s) and an echinoid lantern (e). Note tremendous difference in the apparent packing, composition and biotic abundance between c and d. Borehole 3, 3 m level. Scale bar = 1 mm. G.T. 46,302

e. + f. Differential recrystallization within a slightly argillaceous packstone. Both matrix and an originally micritic, benthonic foraminiferan (Earlandia vulgaris, arrow) luminesce uniformly indicating that the differences in crystal size are attributable to neomorphism. Earlandia provides examples of a common type of preservation, Most of skeleton is recrystallized, while outer lamina has undergone mould stage and been infilled with cement (black). Note that many microsparry areas in transmitted light (e) are revealed to be fossils with cathodoluminescence. Reservoir Quarry. Scale bar = 1 cm. G.T. 46,340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The preceeding data, summarized in Table 6-15, suggest that the luminescent characteristics of fossils reflect a combination of factors. Most important among these (q.v. Bathurst 1971, p 490) are skeletal mineralogy and structure. The tendency of all fossils originally composed of Mg-calcite to luminesce brightly certainly points to original mineralogy as a common variable. Sommer (1972, p 282) suggested that the uniform luminescence of a shell indicated that it had recrystallized. He (ibid) found that unrecrystallized shells showed regular (presumably growth related) variation in the concentration of the activator cation, Mn^{++}. His recrystallized shells, however, showed uniform luminescence.

Variation in the degree of crystalographic order of a skeleton may well explain minor differences observed in luminescence between echinoderms and ostracods (both thought to have been composed of Mg-calcite), or the differences between perforate- and imperforate-foraminiferans. Compare, for instance, the echinoderms in Figs. 6-13g, 6-14b with ostracods in Figs. 6-11, 0-11, or the foraminiferans in Fig. 6-14 with those in Fig. 0-12. Similarly, Girvanella, Earlandia, micrite moulds and agglutinated foraminiferans have in common a loose degree of "skeletal" organization, which probably accounts for their similar luminescent characteristics. However, other factors must be involved, because, even within a thin section, all individuals of a fossil group, e.g. bryozoans, do not always luminesce identically (Table 6-15). There are usually a few bright, moderate, and non-luminescent individuals within each group.

It is possible that differences in luminescence between (and to a lesser extent, within) fossil groups may also reflect different times of neomorphic recrystallization. It is suggested that the trend observed in cements from moderate (2A), to bright (2B), to non-luminescent

TABLE 6-15 The Luminescent Characteristics of Common Fossils in the Reservoir Mbr.

Group	Original Mineral[1]	% of Individuals Examined	Luminescent characteristics
1. Foraminiferans:			
a. porcellanous -walled (Endothyrids, *Earlandia*)	A,B	90 10	L = matrix NL
b. perforate porcellanous - walled (*Bradyina*)	C	90 10	NL L = matrix
c. agglutinated (*Lituotubella*)	A,B,C	90 10	L ≥ matrix NL
2. Hyaline - walled microproblematica (*Stacheoides*, *Shartymophycus*)	-	-	L ≥ matrix
3. micrite envelopes	A,B	100	L = matrix
4. *Girvanella*	-	90 10	L = matrix Skeletal mould
5. Dasycladacean algae	A	100	Skeletal moulds 2+3
6. Sponges			
a. siliceous		100	Skeletal moulds 2+3*
b. calcareous	A,B,C	100	Skeletal moulds 2+3*
7. Bivalves	A,C	90 10	Skeletal moulds 2+3 NL 2+3
8. Gastropods	A,C	90 10	Skeletal moulds 2+3 NL 2+3
9. Corals	C	70	L ≤ matrix
10. Brachiopods	C	33 33 33	L ≥ matrix NL Skeletal moulds
11. Bryozoans	A,C	50 20 10 10 10	L > matrix L = matrix L < matrix NL Skeletal mould 2+3
12. Echinoderms	B	90 5 5	L > matrix L = matrix L < matrix
13. Ostracods	A,B	90 10	L > matrix L = matrix
14. Trilobites	?C	100	L > matrix

L = luminesce; = = equal to matrix; > = less than; < = brighter than; NL = non-luminescent; 2+3 = refers to cement stages; A = aragonite; B = Mg calcite; C = calcite; * = cement often luminesces an anomolous blue colour.

[1] data based on Scholle (1978), Wilkinson (1979) and Enos and Perkins (1977)

substages (due to changes in the original pore water Mn^{++}/Fe^{++} ratios) is also followed in neomorphic spar. Early neomorphic stages are bright or moderately luminescent, whereas later stages are non-luminescent. The luminescent characteristics of fossils would thus show that differences in the time of recrystallization largely take place between fossil groups or individuals, and not within the skeleton of a particular fossil. One would expect mineralogic compositional differences between fossil groups to be greater than differences within a group, and differences between individuals to be minimal. Thus fossils of a given group are likely to have recrystallized simultaneously because of their similar mineralogy and skeletal organization. Land and Epstein (1970) noted that, although susceptibility to neomorphism is related to mineralogic stability, early neomorphic transformations are seldom complete, and that a few "residual", unrecrystallized, grains are common after each stage of diagenesis. The few fossils with luminescent characteristics atypical for their group (Table 6-15) may represent such residuals in the Reservoir Mbr. limestones.

The hypothesis that the luminescence trend observed in neomorphic spar parallels that seen in the cement sequence assumes that neomorphism takes place in equilibrium with pore water. Isotopic studies (Land and Epstein 1970; Gavish and Friedman 1976, for review see Alan and Matthews 1977) and trace element analysis (Pingitore 1976) have shown this generally to be the case for Quaternary and Recent carbonates. Although the degree of equilibration achieved between pore water and skeletal fragments may be variable, neomorphically altered carbonates generally show extensive evidence of ionic exchange with meteoric pore water (Bathurst 1979, pp 851-852). Bathurst (unpub. 1977) summarized the work of various authors showing that exchange does take place, although it is variably affected by skeletal mineralogy, depositional fabric, and the rate of water flow. He (ibid) suggested that the openness of a system to equilibration would be seen in the degree of homogeneity of skeletal composition. The similarity of luminescent characteristics in fossils of different primary mineralogies (Figs. 6-14d,e; O-11; O-12) suggests that the Reservoir Mbr. carbonates were generally able to equilibrate with pore water during neomorphism.

Assuming that the compositional trends in neomorphic spar and cements are comparable, the luminescent characteristics of fossils suggest that neomorphism took place at an early stage prior to complete consolidation. The bulk of recrystallized fossils have luminescent characteristics similar to those of stage 2 cements. The textural evidence presented previously indicates that stage 2 cements formed during consolidation. In this respect, the timing of neomorphic alteration in the Reservoir Mbr. limestones was also comparable to that of Recent carbonates, where neomorphism is among the first diagenetic transformations (Bathurst 1971, p 481).

6.522 Skeletal preservation

In transmitted light, parts of skeletons often lack the microstructural detail found elsewhere in the same skeleton, due to what appears to be a replacement by granular crystals coarser than the original fabric. Ghosts of the original microstructure may sometimes be traced through parts of these unclear areas, giving the impression that they have recrystallized. Often, the unclear areas may only be the thickness of a few laminae within a skeleton (Fig. O-12). A new discovery with cathodoluminescence was that most unclear areas, which were thought to be recrystallized, were infilled with fine fringes of early cement, indicating that these areas have undergone partial skeletal dissolution (Fig. 6-13e,f). This unusual form of skeletal preservation, which appears to have gone previously unreported, was quite common in the Reservoir Mbr. limestones, and may also be common elsewhere.

6.53 Neomorphic spar matrix

In transmitted light, fine-grained limestones appear to have recrystallized to varying degrees. A textural spectrum between uniform (Figs. 6-14c,d,e,f; 0-11; 0-12), porphyroid (Fig. 6-14a,b), and clotted fabrics (described in Ch 4; Figs. 6-11; 6-13e,f) is present. Uniform fabrics consist of a mosaic of fairly equant microspar or pseudospar.

With cathodoluminescence the neomorphic spar matrix of all these fabrics is a moderate orange-red, similar to that of most recrystallized fossils and stage 1 cement (Fig. 6-11). Microspar and pseudospar tend to luminesce somewhat more brightly than micrite, but the difference is very slight, and not always observed. The fine grain size of the matrix inhibits resolution of the true luminescence characteristics of individual matrix crystals. The overall luminescent characteristics of fossils would suggest that the neomorphic matrix recrystallized early, at the same time as the fossils.

The surprising discovery was that little of what appears to be recrystallized matrix in clotted neomorphic fabrics was originally fine-grained sediment. With cathodoluminescence, many indistinct patches of spar are revealed to be fossil fragments (Figs. 6-14; 0-11; 0-12) or cement infilling moulds (Fig. 6-11). In transmitted light, such neomorphosed fossils, particularly micritized fragments, lack a sufficiently distinct outline or internal detail to be distinguished from neomorphic spar.

Cathodoluminescence reveals their shape clearly, and indicates that the proportion of fossils is often much higher than originally estimated. The compositional discrepancy between transmitted and luminescent point counts (see Sect 0.11.) casts doubt on the validity of transmitted light point counting as an analytical tool in distinguishing primary differences between recrystallized fine-grained limestones. Similarly, fine-grained intergrowths of stage 2 cement in a microspar matrix (Figs. 6-11; 6-13a,b) cannot always be resolved as such in transmitted light. The crystals are too small to show diagnostic "cement" habits. With cathodoluminescence the orientation of crystals and their internal zoning stand out clearly, such that they contrast sharply with the neomorphic spar matrix.

The refined accuracy of neomorphic spar distinction reveals two trends in the Reservoir Mbr. limestones:

A) extensive, uniform recrystallization to pseudospar mosaics is characteristic of argillaceous limestones and calcareous mudstones;

B) fabrics which might ordinarily be confused with the products of differential recrystallization, i.e. clotted fabrics, are usually produced by cement intergrowth into an open framework, or between fairly discrete particles. Neomorphically produced clotting, the product of extreme porphyroid neomorphism, was not observed in the Reservoir Mbr. limestones.

6.6 Summary of major early diagenetic modifications

Early fabric modifications of the Reservoir Mbr. limestones began with bioturbation and compaction (Ch 5), followed by fracturing, dissolution and neomorphic recrystallization. Fracturing, dissolution and later internal sedimentation have produced the most extensive fabric modifications, often resulting in the formation of polygenetic cavity systems. The polygene cavities enlarged from both original cavities and skeletal moulds created during dissolution. The earliest stages of spar cementation began during dissolution, and were probably accompanied by neomorphic alteration of an originally polymineralic sediment to calcite.

6.7 Dolomitization

Nearly all insoluble residues from the Reservoir Mbr. limestones contain sufficient dolomite to produce a characteristic peak on X-ray diffraction analysis. Residues containing more than 5% dolomite (point-counted or visually estimated), however, are only found where the dolomite occurs in laminae (see Ch 7). Several petrologic types of dolomite are present:

A) Scattered rhombohedra - A few centimicron-sized euhedral replacement rhombohedra are present in thin sections and residues from all facies. They commonly replace both matrix and fossils. In a few cases, rhombohedra overlap between a fossil and its cement rim, establishing that replacement post-dates cementation. Most dolomite crystals have a calcite core, overgrown by zones of progressively more ferroan dolomite.

B) Dolomite laminae (Fig. 3-5) - Millimetre-thick, wavy laminae of yellow-brown dolomite are common in the upper build-up facies and some laterally equivalent high-carbonate facies. The dolomite in the laminae consist of subhedral and euhedral crystals of replacement origin. Sedimentary structures (e.g. cross-lamination) indicate that lamination is primary. Structures associated with the dolomite lamination, such as geopetal infillings and intraclasts (described in Fig. 6-16 and Ch 7 respectively) show that the dolomite is a replacement of a detrital precursor.

C) Dolomite microspar (Fig. 6-16) - Scattered crystals and geopetal infillings of microspar-sized dolomite are common in the lower build-up. They also appear to replace a detrital precursor.

D) Void-filling dolomite - Breccia cavities, dissolution voids and interparticle voids often contain multiply-twinned dolomite "curved saddles".

Fig. 6-16 Late diagenesis and dolomitization

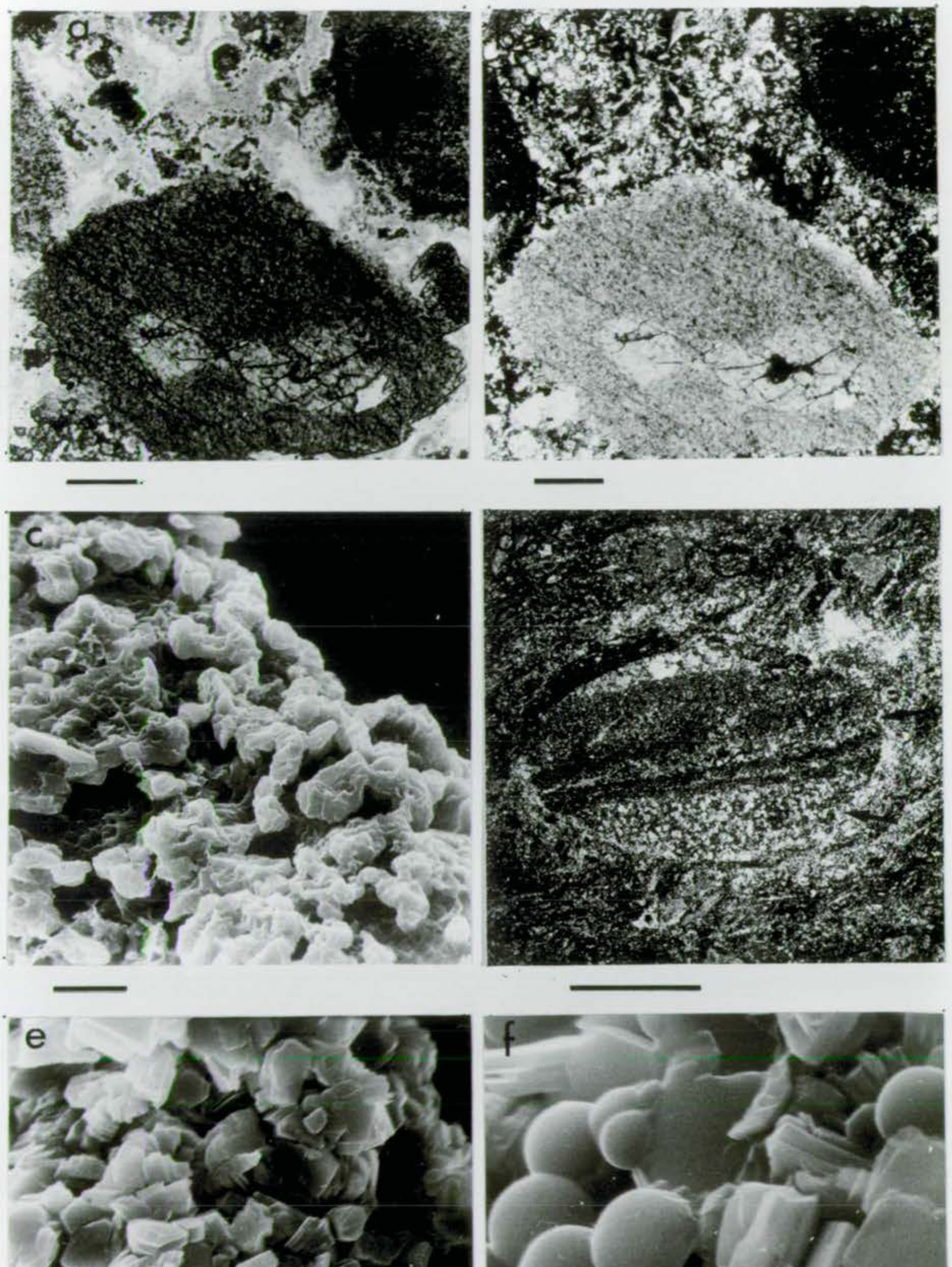
a. + b. Silicification: plane-polarized (a) and cross-polarized (b) photomicrographs of radial-fibrous chalcedonic quartz replacing calcite, particularly the interstitial cement. Numerous residual calcite crystals of both matrix and late stage cements are rimmed by radial fibrous aggregates. Scale bar = 210μ. G.T. 46,370

c. Silicification: SEM micrograph of chalcedonic quartz replacement of the outer sheath of a branched algal filament. Only the outermost sheath has been replaced by chalcedonic quartz, the finer crystals underneath are probably pyrite. Scale bar = 5μ. G.T. 46,546 c

d. Dolomitization: "detrital dolomite". Laminated infillings in a brachiopod shell. Only the first and fourth laminae (arrows) are replaced by dolomited microspar. Other laminae are composed of calcite microspar. The manner in which some mechanically-deposited laminae have been selectively replaced suggests that dolomitization was specific to a particular type of sediment precursor. Scale bar = 1 mm. G.T 46,364

e. Kaolinite: SEM micrograph. Euhedral books of kaolinite showing diagnostic hexagonal-stacked habit and lining a diagenetic cavity. Build-up, subfacies C. Scale bar = 5μ. G.T. 56,547

f. Hydrocarbons: SEM micrograph. Spherical blobs of hydrocarbon, probably albertite, overlying or perhaps intergrown with kaolinite euhedra. Scale bar = 2.2μ. G.T. 56,547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e
f

Dolomitization on the whole is a minor fabric modification of the Reservoir Mbr. limestones.

The timing of dolomitization may be determined by the cross-cutting relationships between dolomite and other diagenetic events. Void-filling dolomite follows stage 3 cements, whereas replacement cross-cuts stage 2 cements, indicating most dolomite to be of late origin (Table 6-17).

6.8 Authigenic feldspars Figs. F-1; F-2; Appdx F

Authigenic feldspars are a minor constituent of nearly all the limestones in the Reservoir Mbr. X-ray diffraction traces of most residues contain the (131) reflection widely used to identify monoclinic K-feldspars (Parsons 1973; Buyce and Friedman 1975). In the residue of one particular sample, it was possible to establish that the monoclinic feldspar peaks were due to authigenic feldspars (Figs. F-2; F-1). Nearly 20% of the residue (5% whole rock) consists of sand-sized euhedral feldspar crystals replaced by chalcedonic quartz, or chalcedonic quartz and kaolinite (q.v. Appdx F). The crystals consist of simple prisms and (010) Carlsbad contact twins, the common habit of monoclinic orthoclase (Deer, Howie and Zussman 1963). One of the crystals (Fig. F-2) has engulfed an ?algal organic filament, positively establishing that the feldspars have grown in situ. Monoclinic feldspar peaks are also present in the X-ray traces from the sample.

Although small amounts of authigenic feldspar are common in carbonate rocks, percentages greater than 1-2 require a special source of K, Al, and Si ions for feldspar growth (Buyce and Friedman 1975). Several authors (q.v. Buyce and Friedman ibid; Carozzi 1960) have suggested that zeolites derived from volcanic glass could provide the necessary source of ions and have therefore used the presence of authigenic feldspars to infer a former volcanic sediment input. Given the proximity of the Petershill Fm. to known volcanic centres, and other volcanogenic horizons within the sequence, it would not be surprising to find volcanic detritus in the residues. The authigenic feldspars and feldspar peaks do, however, indicate that volcanic sediment input was continuous throughout sedimentation, and not as episodic as the infrequent distribution of volcanogenic clay horizons might suggest.

6.9 Authigenic kaolinite Figs. 6-3c; 6-15

Many of the larger cavities in the Reservoir Mbr. high-carbonate limestones contain infillings of kaolinite. The infilled cavities include primary shells, interparticle voids, and early and late breccias. Most infills are soft enough to be picked with a fingernail, except where they have been silicified. Individual kaolinite crystals consist of semi-hexagonal plates 5-20μ in diameter, arranged in books. The books extend outward from cavity walls lined by stage 3 cements and dolomite. Tiny, 5μ diameter spheres of hydrocarbon intergrow or overlie the kaolinite books (Fig. 6-15).

Highly crystalline kaolinite growths, such as those found in the Reservoir Mbr. limestones, are formed by growth on a free surface from an acid solution (Keller 1978; Longman and Mench 1978, p 261). The geochemistry of their formation is poorly understood (Keller ibid). Keller (ibid) does, however, state that kaolinite is readily dissolved and reprecipitated. The distribution of authigenic kaolinite in the Reservoir Mbr. suggests that the parent material may have been the kaolinite in detrital volcanogenic clay horizons, as authigenic kaolinites are only found in facies containing a high relative proportion of volcanogenic clay laminae and partings. It is tentatively suggested that authigenic kaolinite cavity infillings have formed where a suitable combination of pore-space and nearby kaolinite are found. Such kaolinite is thus a diagenetically-redistributed cavity lining.

6.10 Silicification Fig. 6-15

Quartz in various forms is by far the volumetrically most abundant authigenic mineral in the Reservoir Mbr. In the field it weathers out as isolated or interconnected chert nodules similar to those commonly found in bedded limestone sequences. Chert nodules are most abundant in the uppermost 5 m of the Reservoir Mbr. In general, argillaceous and slightly argillaceous limestones are more extensively silicified than high-carbonate limestones, but chert distribution does not appear to be related to an obvious lithological or diagenetic feature.

In thin section, quartz occurs as a cryptocrystalline replacement, and as radial fibrous arrays. Very rarely, geode megaquartz infills primary cavities. The fine-grained replacement quartz is very difficult to resolve from microspar in thin section. Acid-etching of a thin section, however, leaves behind a very fine, sugary-textured mosaic of quasifibrous chalcedonic quartz. Crystal sizes seldom exceed pseudospar size. Skeletons and cements are more often replaced by coarser radial or subspherulitic chalcedonic quartz. The coarser chalcedonic quartz replacements may pass into radial growths showing void-filling habits, in such a way as to make the distinction between replacement and void-filling origins very difficult. It appears that the high pH conditions favourable for calcite dissolution and silica precipitation may have created pores which were sufficiently large, in some cases, to favour void-filling crystal habits, while at other times simply replacing calcite.

Chalcedonic quartz replaces compacted fossils, stage 3 and perhaps stage 4 cements as well as intergrowing with kaolinite. Thus, although silicification is a major fabric modification, it is atypical in that it occurred late in diagenesis.

PART III

Early diagenetic history of the Reservoir Mbr. limestones

6.11 Evidence for meteoric diagenesis

Prior to summarizing the sequence of diagenetic events it is important to draw attention to several of the early diagenetic processes which, in combination, point to a specific diagenetic environment. Figures 6-17 and 6-18 illustrate that dissolution, fracturing, internal sedimentation and early cementation were congruent. By analogy with studies of Recent and other ancient carbonates, these processes are likely to have occurred while the Reservoir Mbr. was in a meteoric, and probably vadose environment (Purdy 1968; Semeniuk 1971; Dunham 1969; Bathurst 1971, pp 357-360; Friedman 1975; Harrison 1977; Toomey, Wilson and Rezak 1977, p.2133).

It is well known that extensive dissolution of shallow marine carbonates only occurs in the meteoric environment, as tropical seawater is usually saturated in calcium carbonate. Percolating meteoric water, however, contains higher amounts of CO_2 and organic acids which readily dissolve carbonates (Friedman 1975, p 383; Read 1978, p 68).

6.11.1 Possible vadose diagenesis

Several early diagenetic features suggest that the extensive meteroic diagenetic alteration of the upper Reservoir Mbr. occurred in the vadose rather than in the phreatic zone. The dissolution of fossils, enlargement of their moulds, cavity-collapse brecciation, and downward redistribution of internal sediments require a substantial flow of water. Semeniuk (1971, p 948) and Dunham (1969, p 160) have argued that the flow of water required to produce these features is most likely to be found in the vadose zone. A similar conclusion was reached by Toomey et al. (1977, p 2133). Phreatic pore waters are generally slow moving and less likely to be undersaturated in calcium carbonate. They tend not to circulate vertically.

Independent evidence from investigations on karst features also supports the vadose meteoric hypothesis. Balweirz and Dzulynski (1976) among others, have found that vadose type circulation patterns readily create dissolution-collapse cavity systems. They (ibid, p 430) concluded that both the flow of water as well as water fluctuations (leading to cavity draining and flooding) are particularly important to dissolution-collapse development, and the production of upwards migrating cavities.

6.12 Compaction Fig. 6-18

The early history of the Reservoir Mbr. limestones is likely to have been as follows. During early burial, compactive stress due to overburden produced extensive textural modifications in some limestone facies. Argillaceous sediments, with high initial water contents (see Ch 5) consolidated by dewatering uniformly. Compaction occurred as water was gradually expelled, and grains re-orientated in order to accommodate to increasing stress. Thin films of water probably facilitated grain re-orientation. Extensive pore-space reduction by compaction occurred soon after burial, probably within metres of the sediment surface. Deformation during this stage, by loading and boudinage (q.v. Ch 3), partially accounts for the present morphology of beds.

Fine-grained high-carbonate biomicrosparites, in contrast, did not undergo extensive compaction. They began to form a stable, resistant framework during sedimentation. Early burial compacted this framework only slightly. Deformation instead took place along depositional inhomogeneities within beds (clay laminae, layering, shell horizons), between beds (at abrupt changes of thickness, and along depositional slopes) and later along lines of weakness introduced by brecciation. This pattern has been described as differential compaction.

The essential differences between uniform and differential compaction point to differences in the consistency of the original sediment: loose sediments consolidated by uniform compaction, whereas already consolidated sediments underwent differential compaction. As one would expect, most limestones in the Reservoir Mbr. show some evidence of both processes. The extent to which either process predominated seems to have been at least partially controlled by clay content.

6.12.1 Exposure and meteoric diagenesis

Following early compaction, the second major sequence of diagenetic events occurred in the meteoric environment as the limestones were uplifted and exposed to fresh water (Fig. 6-18). As previously described, extensive meteoric alteration was restricted to those facies uncompacted by early burial, namely the build-up and level-bedded, high-carbonate facies.

Two lines of evidence indicate that meteoric diagenesis occurred prior to the accumulation of a significant thickness of overburden: the general absence of compaction, particularly of delicate structures, and the poor degree of consolidation shown by fractures. For a poorly-consolidated sediment to fracture without compacting, the amount of overburden must be negligible. These observations provide additional evidence that erosional horizons within and at the top of the build-up facies were formed by subaerial exposure, prior to deposition of the 20-40 m thick overlying Silvermine Mbr. The presence of fractures, even within a poorly-consolidated framework, may be reliably used to infer the existence of an early (stage 1) cement.

6.12.2 Meteoric fabric evolution Fig. 6-18

Among the first modifications to take place on emergence into the subaerial environment were crumbly fractures. As sea water drained from the pore-system it seems likely that the depositional framework responded to greater gravitational stress by fracturing. Further fracturing may be accounted for by shrinkage following the loss of volume associated with drying out. Dissolution and possibly selective loosening, due to the decay of organic matter may have also contributed to fracturing.*1

Extensive dissolution modification soon followed emergence. During what may be termed an early development stage (Fig. 6-18) many separate cavities formed from skeletal dissolution, shrinkage, and fracturing. Some primary cavities, such as those beneath the fronds of bryozoans, and along thin-shelled brachiopod layers (e.g. schellweinellids) may have also been closed by compaction. During the development stage, (Fig. 6-18) dissolution weakened the depositional framework sufficiently to lead to additional fracturing. Early fractures spread through the matrix from separate cavities to coalesce and, in places collapse (Fig. 6-18), forming breccias. Fragments of incompletely dissolved skeletons, mechanically released fragments, and internally-eroded particles began to accumulate in the cavity system. Circulating water then re-distributed the finer grains of these internal sediments, carrying them along horizontal stromatactoid cavities and downward through fractures to underlying cavities.

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*1 The potential significance of crumbly fractures as indices of subaerial and vadose exposure appears to have been overlooked. As previously indicated, crumbly fractures, particularly those formed by shrinkage, point to a specific degree of consolidation most likely to be encountered in the vadose zone. The tendency of carbonates to lithify soon after emergence suggests that the interval available for shrinkage fracturing in a sediment is short. Vadose cementation is likely to lithify a sediment to the point it will no longer shrink before the carbonate body reaches the phreatic zone. As the mechanisms of shrinkage have not been examined in relationship to meteoric diagenesis, it may be premature to accept this hypothesis without reservation. Numerous authors, however, have found that crumbly fractures are common and related to shrinkage, dissolution weakening, or differential compaction (Harbaugh 1960; Dunham 1969; Shinn et al. 1969; Semeniuk 1971; De Meijer 1971; J. L. Wilson 1975, p 200; James 1972; Toomey et al. 1977; Harrison 1977; see also references in Read 1978). Further research may show that crumbly fracturing related to shrinkage is also a characteristic feature of the vadose zone.

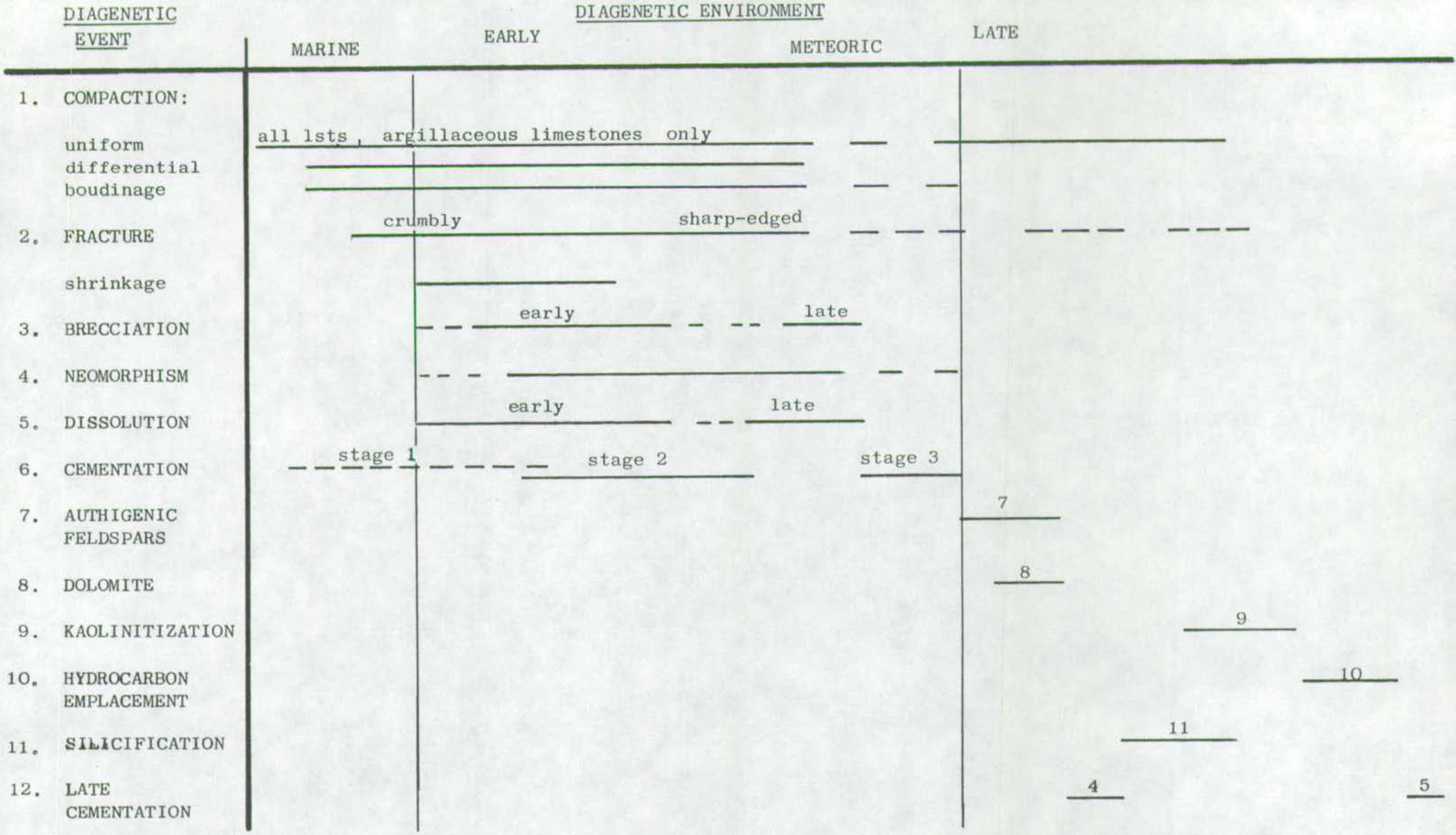


Table 6-17 Sequence of diagenetic events

The development and early <u>collapse</u> stages (Fig. 6-18) were marked by extensive mechanical fabric re-arrangement, as the matrix was still quite loose and crumbly. As meteoric diagenesis progressed, however, the matrix gradually became cemented by a thin rim of sparry calcite, stage 2 (c,d, Fig. 6-18). It is likely that, as the small pores became occluded, dissolution modification shifted to the larger cavities. In open frameworks a small amount of cement may well have promoted the development of a large cavity system by restricting water flow to larger pores. During cavity modification (d, Fig. 6-18) dissolution and cementation enlarged development stage cavities and created further cavities within the internal sediments. At this stage, the mechanical strength added to the framework by cementation gradually began to inhibit fracturing. Extensive framework alteration concluded when the binding strength of cement exceeded that of the sedimentary particles.

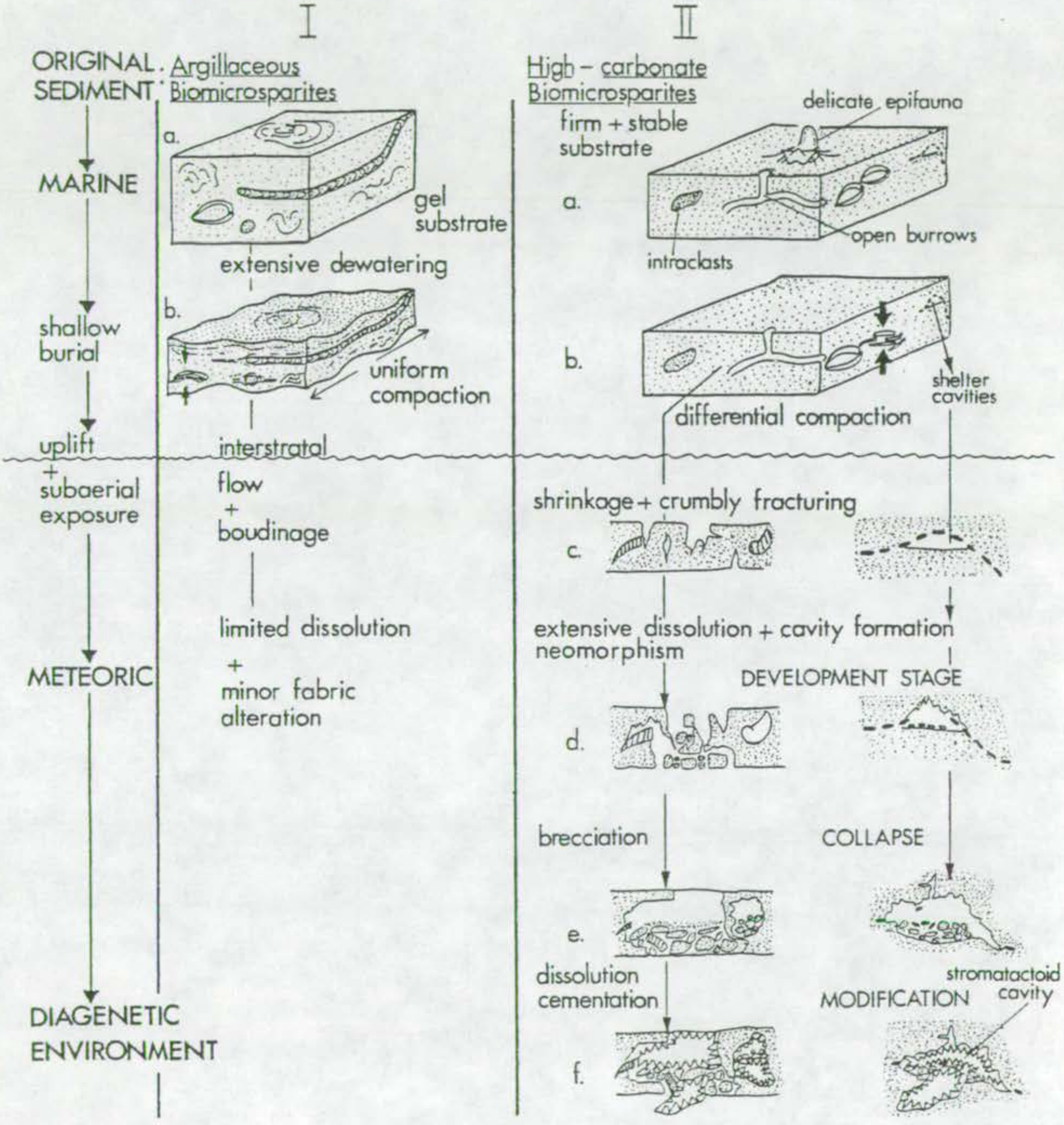
Following stage 2 cementation, a period of dissolution occurred, marked by cavities which cross-cut earlier cavities, their infills, and mechanical inhomogeneities in the matrix. It is unlikely that a significant time interval separates early and late dissolution. The processes of modification were probably continuous, whereas the style of modification changed with the increase in the extent of cementation.

<u>6.13</u> <u>Stage 3 cementation and late diagenesis</u>

Precipitation of stage 3 cements, composed of ferroan calcite, separates early from late diagenesis. Textural evidence indicates that the Reservoir Mbr. limestones were well lithified at this stage. In comparison to previous cement stages, stage 3 cement and subsequent void infillings played a minor part in pore-space reduction. Kaolinite, hydrocarbons, chalcedonic quartz, and dolomite also infilled the remaining porosity. Chalcedonic quartz replacement was the only major fabric

Fig. 6-18

DIAGENETIC FABRIC EVOLUTION OF RESERVOIR MBR LSTS



modification to occur late in diagenesis.

6.14 Economic significance of diagenetic history

Many of the high-carbonate limestones of the Reservoir Mbr., particularly those in the build-up facies, have porosities which could render them economically valuable as potential hydrocarbon reservoir rocks. Indeed, some samples in the lower build-up are saturated with hydrocarbons and will ignite if placed in the flame of a bunsen burner. The volume of hydrocarbon is, however, too small to be worthy of exploitation. In the Carboniferous elsewhere it seems probable that thicker sequences with a similar diagenetic history could contain viable deposits. In the Reservoir Mbr. limestones an extensive secondary porosity was developed in initially firm substrates which were subaerially exposed very early, prior to burial. Initial consistency (related to composition, grain size, and biota) appears to have been very important in controlling subsequent diagenetic modification patterns. The textural criteria and facies-related approach described here may prove a useful means of exploration in Carboniferous cycles elsewhere.

CHAPTER 7

COMMONLY OCCURRING LITHOLOGIES IN THE RESERVOIR MEMBER

7.0 Introduction

The various facies in the Reservoir Mbr. are composed of one or more lithologies; several of the common lithologies are also found in more than one facies. In the following section, the common Reservoir Mbr. lithologies are described, based on their appearance in hand specimen, thin section, and their insoluble residue composition. These lithologies do not always represent distinct environments, although, in some cases, they may also possess a characteristic fauna. The association of several lithologies, together with a distinctive fauna provide the data on which facies distinctions have been made.

7.1 Lithologies

7.11 Basal lavas

The Petershill Fm. is underlain by roughly 10 m thick olivine basalt units, interpreted as separate flows or flow-sequences (Francis 1967). Their general features and petrology have already been described in the introduction and by several previous authors (q.v. MacGregor 1928; Anderson 1963; Francis 1967). A description of one of the lavas examined in this study appears in Appendix B.

7.12 Mixed sandstones and tuffs

Immediately overlying the lavas beneath the Petershill Fm. is a variable thickness of tuff followed by a much greater (but equally variable) thickness of interbedded sandstones and tuffs. Thin lavas may also be interbedded in the lower part of this sequence. The sandstones consist of: a) variable proportions of medium- to fine-grained, subangular to well-rounded quartz; b) rare heavy minerals; c) mm-sized plant debris; and d) black and reddened angular intraclasts of shale. Thin rootlet and indistinctly-burrowed horizons are common. Most samples are weakly cemented by calcium carbonate, chalcedonic quartz and authigenic kaolinite (rare).

The sandstones interbed with medium thickness calcareous tuffs. Most tuffs contain clay (illite/smectite and kaolinite), highly altered brown ?volcanic fragments, and fragments of plants, shale and coal. Mm-sized marine fossil fragments are rare.

7.13 Carbonaceous shales Fig. 7-3a

Black to dark-grey, laminated, largely non-calcareous fissile shales. Hand specimens swell and disaggregate when placed in water. Unfossiliferous specimens consist of clay and finely-divided plant debris with minor amounts of pyrite, mica flakes and quartz silt. Fossiliferous specimens contain a few extensively-compacted complete macrofossils and variable proportions of <1 mm fossil debris, principally brachiopods, bryozoans and foraminiferans. The matrix of fossiliferous shales contains fairly evenly distributed pyrite-filled filamentous algae. In some sections filaments form a fairly loose meshwork. They may well have originally been present throughout most of the sediment and have become largely obscured by compaction.

Dark-brown clay laminae, comparable to tonsteins described by Williamson (1970), and thin sapropelic laminae of plant spores (Figs. 7-3b; F-3) are common, especially in the lower part of the sequence. The tonsteins are dark-brown brittle clay laminae, composed largely of kaolinite and illite/smectite, cemented by quartz. The lower part of the carbonaceous shale sequence contains several thin coals. They probably represent drifted plant accumulations because underlying seatearths or signs of in situ root colonization are absent.

7.14 Calcareous mudstones

Brown to grey, or rarely black, mudstones containing between 30-70% calcium carbonate. Hand specimens may show lamination, but lack fissility. The fossils in calcareous mudstones often show signs of extensive compaction and even of re-orientation during compaction. Point counts from five thin sections provide a rough breakdown of the composition of calcareous mudstones. The matrix (approximately 70% grain bulk) consists of microspar and pseudospar with evenly disseminated clay and wavy clay laminae. The laminae typically arch and become more dense around fossils, due to compaction. Fossils (30%) are predominantly less than 0.4 mm diameter fragments of brachiopods, bryozoans and corals, along with foraminiferans and ostracods. Many fragments are recrystallized. Loose intergrowths of branched algal filaments are common in some thin sections, but it is difficult to estimate how widespread they may have been. Fine plant debris, spores, quartz silt, and heavy minerals are minor constituents of most samples (<5%).

7.15 Argillaceous biomicrosparites Fig. 7-3d,e

Argillaceous biomicrosparites are limestones containing an estimated 10-30% clay. They are grey to olive-green (weathering to brown) microsparites or biomicrosparites. Depositional textures have been so modified by compaction that it is not worthwhile attempting to describe them by their original depositional texture (q.v. Appdx D, definition biomicrosparite). Solution stringers (q.v. De Meijer 1971, p 44; Fig. 7-3e), wispy clay laminae, embayed grain contacts, flattened shells (Fig. 7-3e) and overly close-packed fabrics are common. Typical argillaceous biomicrosparites contain a variable percentage (20-35%) of fossils (mostly occurring as fragments) and matrix (65-75%), with very minor percentages of dolomite, plant fragments and heavy minerals. Fragments of brachiopods, bryozoans, corals, along with whole ostracods, foraminiferans and sponge spicules are predominant among the fossils. Rarer fossil fragments include crinoids, serpulids, gastropods and microproblematica.

The matrix consists of irregularly recrystallized, rather cloudy or dirty-looking microspar or pseudospar (Fig. 7-3d,e). Spar crystal boundaries stand out clearly due to impurities (clays, pyrite, and organic matter) trapped between individual crystals (Fig. 7-3). Both matrix and fossil fragments are often so extensively recrystallized as to make distinction between the two difficult (Fig. 7-3e). Filamentous algae are rarely preserved, but appear to have been fairly pervasive. Structures attributable to binding are rare (Fig. 7-3d).

7.16 Slightly argillaceous biomicrosparites Figs. 0-11; 0-12; 3-5; 4-3b; 4-6b; 4-7a; 5-4; 6-14c

Medium grey to olive-grey limestones containing an estimated 5-10% detrital clay (Fig. 3-5). In plane-polarized light, equal percentages of wackestone and packstone textures appear to be present. Cathodoluminescence reveals that packstones are more abundant, comprising approximately 70% of the sections examined (q.v. Figs. 0-11; 0-12).

The matrix (30-70% grain bulk) consists of fairly uniform microspar with indistinct micritic areas and rare clotted or porphyroid fabrics (Figs. 0-11; 4-6d; 6-14e). Dense intergrowths of filamentous algae are common, particularly where matrix textures have not been disturbed by bioturbation. Most samples show signs of moderate, uniform compaction.

Fossil fragments (mean size <0.7 mm) are the second most abundant constituent of slightly argillaceous biomicrosparites, comprising 30-50% grain bulk. The percentage of fossils, their size, and degree of fragmentation varies greatly. Two fossil-fragment assemblages are consistently recognizable: a fine sand-sized assemblage, and a poorly-sorted assemblage.

Fine sand-sized assemblages often form poorly-defined laminae a few millimetres thick. They are composed of a wide variety of fossils in the 100-250µ range, predominantly sponge dermal spicules (e.g. Fig. F-2b, Appdx), disarticulated ostracods, small foraminiferans, productoid spines*1, fragments of bryozoans, and brachiopod shells. The uniformity of grain size and shape of particles in fine sand-sized assemblages suggests that they represent hydrodynamic accumulations, either winnowed by low-threshold currents, or (less probably) a suspension fallout from pulsatory currents. Where fine sand-sized laminae are preserved, they are likely to have been buried rapidly, before tye could be destroyed by burrowers or currents.

Most slightly argillaceous biomicrosparites contain poorly-sorted fragment assemblages (Figs. 0-11; 0-12; 4-6d; 4-7a). Poorly-sorted assemblages are diverse and show a range of particle maturity. Fragments (usually between 250-1000µ) of corals, bryozoans, brachiopods, and ostracods are common, in addition to foraminiferans, sponge spicules, faecal pellets, and algal lumps. Gastropods, trilobites, bivalves, and calcareous algae are relatively rare. The blocky, dense portions of skeletal fragments (such as the hinges of productoids and rugose coral epitheca) are apparently missing, showing that some hydraulic sorting has taken place.

In addition, mechanically robust particles such as gastropod and Spirorbis shells (q.v. Chave 1964, p 387) often show breakage patterns similar to those interpreted by Schäfer (1972, pp 150-154) as resulting from mechanical impact and abrasion (e.g. Fig. 7-1). Delicate fragments, such as bryozoans, branched forms of Kamaena and articulated ostracods are also common in the assemblage. Thus, poorly-sorted

*1 particularly the very small, hair-like external spines and endospines.

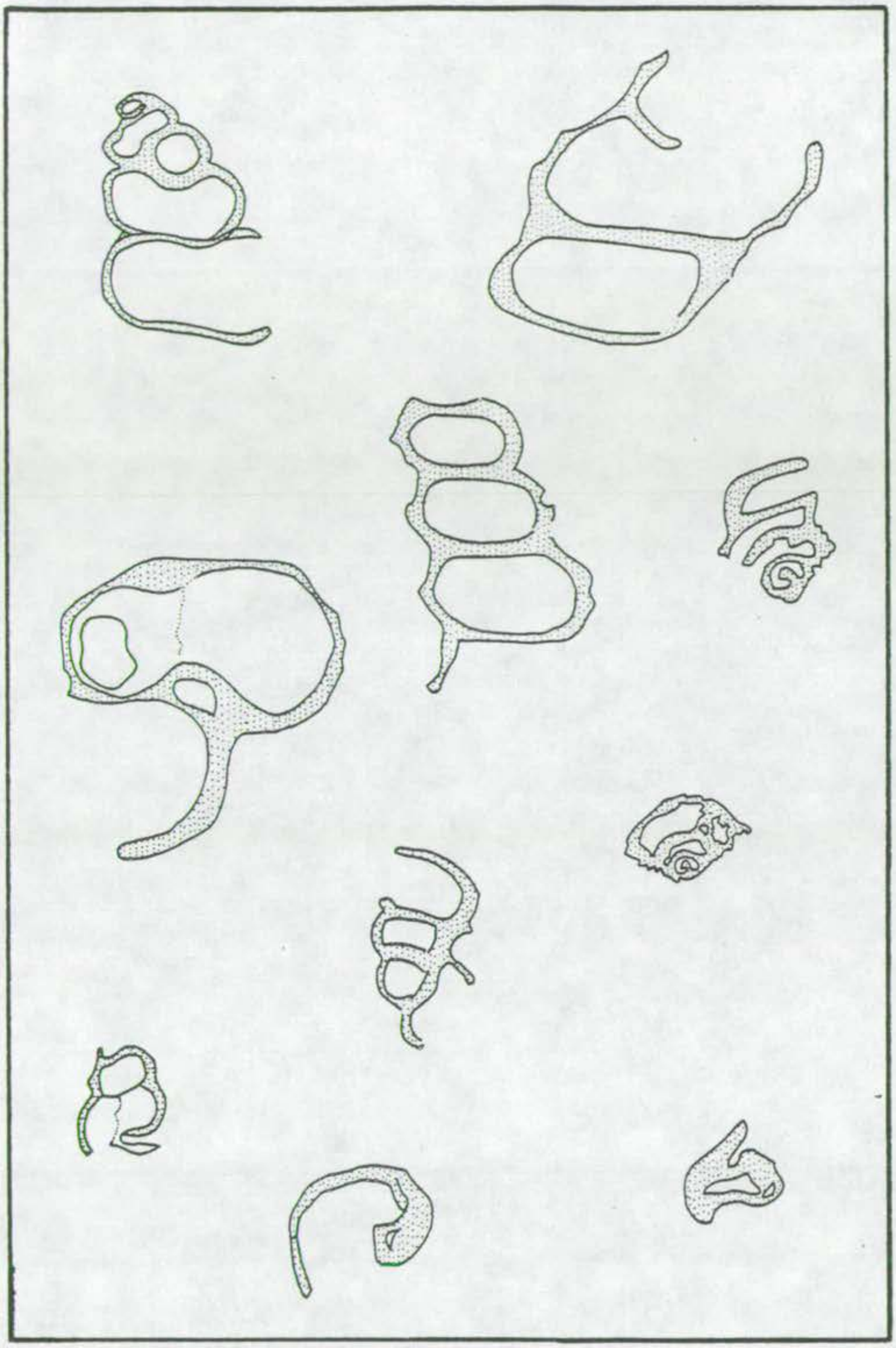


Fig. 7-1 Broken gastropod and serpulid worm shells. Microprojector tracings from thin sections and peels of slightly argillaceous biomicrosparites. Magnification = x 25.

The breakage patterns suggest that these shells have been mechanically abraded. Many features are similar to those described by Schäfer (1972, pp 150-154), notably: broken-off outer whorls of planispiral forms, and the eroded outer whorls exposing the columella.

assemblages incorporate a variety of shell fragments which appear to have been broken at different periods, with shells which originated at or near the site of final deposition.

Unsorted assemblages (q.v. Sect 7.17) occur only rarely in slightly argillaceous biomicrosparites.

7.17 Cream biomicrosparites   Figs. 3-5c; 4-5; 4-6a,b,c; 4-7b,c; 5-4; 6-3; 6-4a,b; 7-2; 7-4b,c; G-2b,c

Cream biomicrosparites are high-carbonate limestones, i.e. they contain an estimated <5% by weight of clay. The total weight of insoluble residue, which is largely authigenic (composed of chalcedonic quartz and pyrite) seldom exceeds 10% weight of the sample (Appdx F). Cream biomicrosparites are typically very light olive-grey and have a creamy texture (Fig. 3-5c).

Depositional fabrics and original fossil orientations are well-preserved as they seldom show signs of compaction (Figs. 7-2a; 5-5). Wackestone and packstone depositional textures are most common; mudstones are rarer. Where the distinction between these three depositional textures was not important, they have been collectively referred to as biomicrosparites, as most samples contain >25% fossil fragments.

The matrix of most samples consists of microspar or rarely micrite, extensively intergrown with filamentous algae. Although algae are abundant, they are not ubiquitous and it could well be that some of the original sediments were not algally bound. Structures attributable to binding (Fig. 4-7b,c) and intergrowths (Figs. 4-3a,c; 4-6c) are best preserved in this lithology.

The cream biomicrosparite matrix (Fig. 7-2a) is typically fairly uniform, micritic and often shows swirly textures brought out by the pyrite infillings within filamentous algae (Figs. 4-6a,b,c; 4-3a). Slightly recrystallized biomicrosparites may have a porphyroid texture

(Fig. 6-14). Areas that have undergone extensive framework dissolution show clotted fabrics. In some cases, however, clotting may also be primary, as clotted shell infillings are found in sediments with a uniform texture elsewhere. In these cases, slight, very early compaction may have homogenized an originally pseudopelleted depositional fabric.

The fossils in cream biomicrosparites are predominantly fragmented, most ranging between 0.5-2.0 mm in diameter. Two types of fossil fragment assemblages are common: poorly-sorted and unsorted. Poorly-sorted assemblages are comparable to those found in slightly argillaceous limestones in that they combine varying proportions of delicate and resistant skeletal particles. Unsorted assemblages are coarser grained, and compositionally and texturally varied. They include a significant proportion of untransportable, fragile structures, such as unfilled ostracod carapaces and codiacean algae (e.g. Fig. 7-2a). The high diversity and mechanical delicacy of many particles in unsorted assemblages suggests they are largely in situ accumulations.

7.18 Layered packstones Figs. 3-5; 7-3c

Layered packstones are high-carbonate, usually cream-coloured, limestones, petrologically similar to other cream biomicrosparites. They display a distinctive layering, visible at outcrop, in hand specimen and in thin section. Individual layers are a few millimetres to a centimetre thick, generally parallel and seldom retain an even thickness for more than a few centimetres laterally. Both upper and lower boundaries of layers are indistinct (Fig. 7-3c). Layers are often folded slightly.

Thin sections reveal that layering is produced by variations in the relative proportions of fossil fragments, in situ fossils, microspar and rarely dolomite microspar (Fig. 7-3c). The fossiliferous layers usually contain 40-75% fossils, primarily: sponge spicules, fragments of brachiopods, bryozoans, and ostracods. A high proportion of the microbiota is in situ, as suggested by extremely high ostracod articulation ratios and delicate attached micro-organisms. As many as 26 of the ostracods in a thin section may be paired, with their carapaces unfilled with sediment (q.v. Fig. 11-4). Ostracods are particularly useful as indices of autochthoneity as they can be readily disarticulated and broken if transported (Dr. E. Robinson, pers. comm.; Pokorny 1978, p 127; see Ch 11). In situ, substrate attached micro-organisms are also abundant, particularly: Lituotubella (Fig. 7-3c), Tetrataxis, Valvulinella, Archaesphaera, spirorbid worms and microproblematica (Shartymophycus, Stacheoides). These fossiliferous layers are, in general, lighter in colour than micritic layers.

The micritic layers are composed of uniform micrite or microspar often almost entirely intergrown wih filamentous algae. It is thus possible that some layers may have formed during intervals of especially prolific algal growth.

Layering is a complex texture created by both primary authochthonous and allothonous factors and accentuated by diagenesis. Variation in the relative proportion of fine skeletal fragments is the most obvious influence on layering. Layering also appears to have been influenced by the in situ biota, which supplied particles and probably selectively trapped and bound the more mobile available grains.

These primary fabric influences have been accentuated by diagenesis: detritus-rich layers have formed pressure solution planes which, in some cases, show signs of lateral movement; fossiliferous layers have sometimes been differentially compacted; and these fabric rearrangements have fractured the micritic layers.

7.19 Stromatactoid cavity wackestones (abbrev. stromatactoid wackestones) Figs. 3-5f; 6-4e,f; 6-7; 6-8; 11-13; 11-14

Stromatactoid wackestones are high-carbonate biomicrosparites, predominantly wackestones, often showing poor layering (Fig. 6-4f). Typical colours are blue-grey or mixed blue-grey and cream (Fig. 3-5). Stromatactoid wackestones are petrographically and texturally similar to other fine-grained high-carbonate limestones in that they are predominantly composed of microspar and contain a diverse (often in situ) biota. The distinctive features of this lithology are stromatactoid cavities, described in Chs 6 and 11.

7.1.10 Dolomite laminated packstones Figs. 3-5e; 6-16

Dolomite laminated packstones are yellow-brown, high-carbonate limestones containing laminae of dolomite microspar, volcanogenic clay, and (rarely) quartz silt and sand. They yield moderate percentages of insoluble residue (predominantly chalcedonic quartz, Appdx F) and contain up to 30% by weight of dolomite.

Dolomite laminated lithologies are predominantly grain-supported. Fossils (40-80% grain bulk) occur in poorly-sorted assemblages dominated by echinoderms, bryozoans, brachiopods (particularly productoids and schellweinellids), sponges and ostracods. Laminae of in situ fossils (especially echinoids) are, however, common.

Dolomite largely occurs in discrete laminae (see Ch 6) and more rarely as euhedra. Dolomitic sediments form intraclasts, sometimes surrounded by non-dolomitic matrix (Fig. 7-4a). These dolomite laminated intraclasts and dolomite geopetal infillings (Figs. 6-16; see also Ch 6) suggest that dolomite formed by replacement of a detrital precursor.

Volcanogenic clays and detrital fine-sand size quartz may also form laminae in dolomite laminated packstones.

7.1.11 Intraclast packstones Figs. 7-4; G-2d, Appdx

These are a group of high-carbonate packstones containing a variety of re-deposited particles, or intraclasts. The packstones are generally coarse-grained, crinoidal, and poorly-sorted. Among the more commonly-occurring intraclasts are fragments of blue-grey wackestone, dolomite laminated sediment, and fossils with adherent matrix. The lithic intraclasts are typically angular, tabular-shaped (having broken up along layering) and have crumbly edges. Some show signs of breakage or compaction after re-deposition (Fig. 7-4a). The intraclasts themselves are always very poorly-sorted and usually float in a matrix of crinoidal debris and more fine-grained material.

Brachiopod shells with blocks of sediment adherent to their outer shell surface are also a type of intraclast (Fig. 7-4). The shells are usually in transported attitudes and the adherent matrix often differs from the enclosing sediment, establishing that they were indeed particles that have been moved after death and burial of the skeleton. In some cases (Fig. 7-4), such shells have double geopetal infillings; the first having formed when the organism was first buried, the second after transportation. The brachiopod shells are usually articulated, unbroken and may even have projecting spine bases, indicating minimal transportation.

In general, intraclast packstones incorporate several types of texturally immature particles. They have accumulated during intervals of intense erosion, but fairly minimal transportation. In addition to providing the actual evidence for erosion, they attest to the firmness of the sediment surface. Their origins are discussed further in Ch 11.

7.1.12 Crinoidal packstones and grainstones Figs. 7-2; 7-3

These are limestones predominantly composed of crinoids, but otherwise varying in fossil diversity, sorting and the proportion of clastic detritus. Slightly argillaceous, argillaceous and sandy (containing more than 5% quartz sand) varieties of crinoidal packstones and grainstones are common.

In general, crinoidal packstones consist of fragmented crinoids (40-95% grain bulk), brachiopods, echinoids, bryozoans, foraminiferans and sponge spicules. Grain interstices are usually infilled with microspar, indicating that most packstones were originally poorly-washed (sensu Folk 1965). Grainstones, which lack interstitial microspar, are very rare. It is difficult to determine the original amount of fine-grained material that may have been present in most samples as they have been moderately compacted and extensively silicified (q.v. Ch 6).

Three textural types of crinoidal packstones are common:

A) poorly-sorted packstones (Fig. 7-2c) Packstones which show signs of slight transportation but limited sorting. Crinoid stems commonly reach 5-10 cm lengths. 5-20% of the brachiopods are articulated, but few are in life attitude. Fossil fragments are usually diverse and include delicate fossils. In some cases, poorly-sorted packstones may consist entirely of echinoid or crinoid debris, and thus appear to be well-sorted (Fig. 11-11). These beds, derived from a single type of fossil, contain particles of widely contrasting hydrodynamic properties and are thus poorly-sorted.

B) moderately-sorted packstones (Fig. 7-3f) These are composed of disarticulated but unbroken crinoid ossicles and fragments of brachiopods, bryozoans, and corals. Mean fragment sizes are typically between 1-2 mm.

C) well-sorted packstones and grainstones These characteristically contain a significant proportion of broken crinoid ossicles and have a smaller mean grain size (0.5-1.0 mm). They are predominantly composed of blocky-shaped particles.

7.2 Concluding remarks

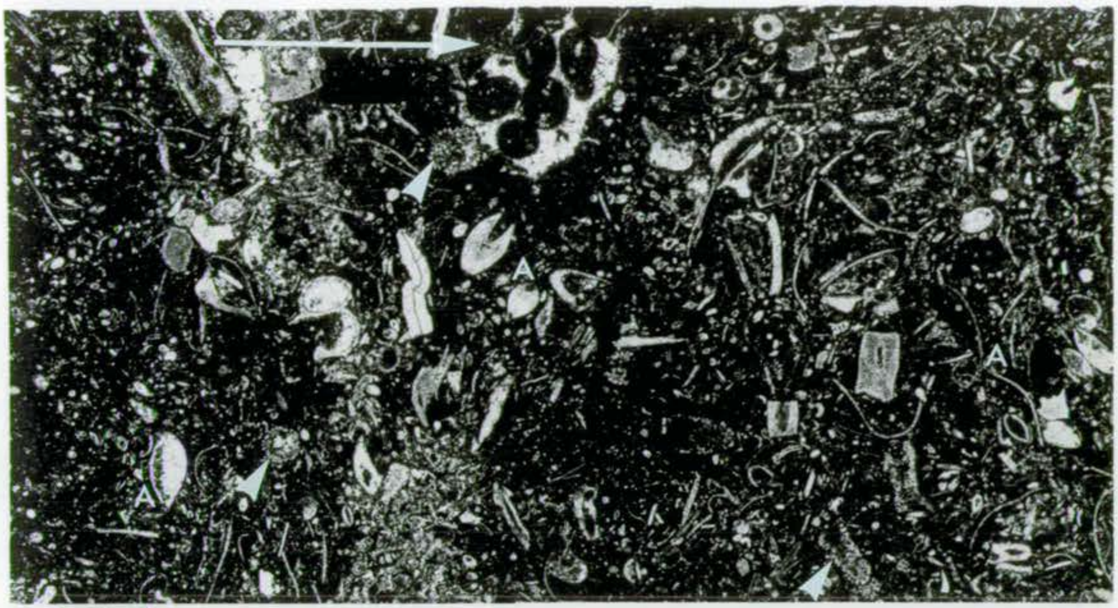
In the following six chapters the lithologic data presented here is integrated with other physical and palaeontological data in a description of the facies in the Reservoir Mbr.

Fig. 7-2 Common limestone lithologies of the Reservoir Mbr.

a. Cream biomicrosparite. Matrix consists of uniform microspar. Fossils form an unsorted assemblage, which includes codiacean algae (white arrowheads) and ostracods (A). Both are delicate structures. An open faecal pellet infilled burrow (white arrow) provides evidence of substrate firmness. Arrow also shows correct way up of sample. Note great variety of skeletal shape and size, and lack of breakage among delicate shells. All are signs of autochthoneity. High-carbonate biomicrosparite facies. Scale bar = 2.2 mm. G.T. 46,300

b. Poorly-sorted sediment of an intraclast packstone. Skeletal fragments include the spines (S) and mouth plates (E) of echinoids and branched fragments of <u>Lithostrotion</u> <u>gracile</u> (L). The coarse skeletal debris shown is fill C-1; the finer grained micritic sediment which overlies flat shells and only partially infills interstices (see arrows) is fill C-2, a possible later infilling (see discussion in Ch 11). Erosion surface A; build-up. Scale bar = 3.6 mm. G.T. 46,541

c. Poorly-sorted crinoidal packstone. Variably-sized crinoid fragments are predominant. The fabric shows signs of moderate, uniform compaction. Skeletal interstices are black due to hydrocarbon. Subfacies D, build-up. Scale bar = 3.6 mm. G.T. 46,372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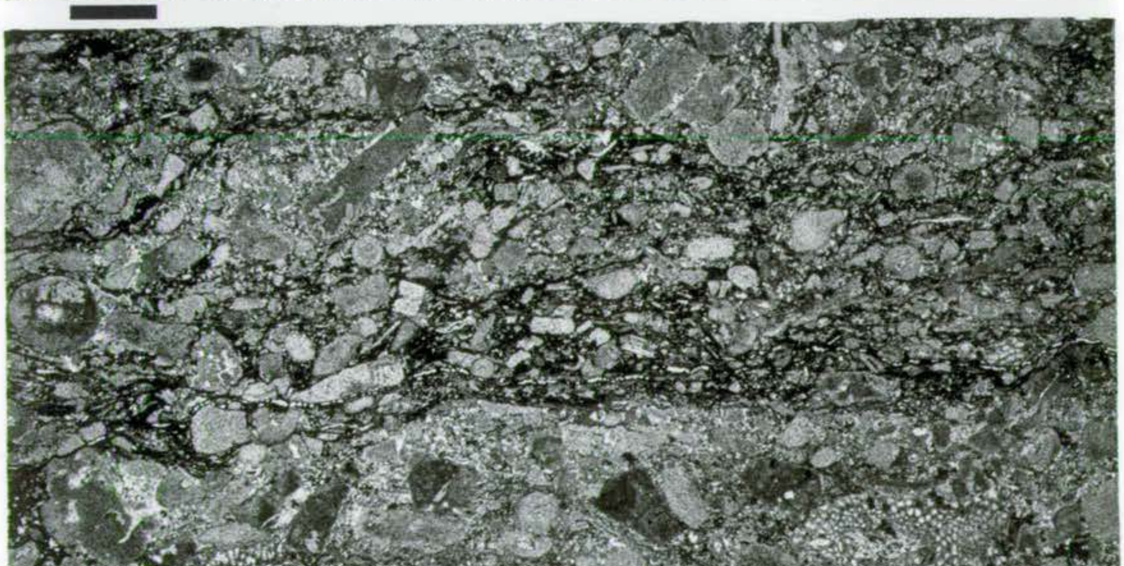


Fig. 7-3 Commonly-occurring lithologies in the Reservoir Mbr.
Photomicrographs, transmitted light.

a. A carbonaceous shale matrix enclosing a productoid spine encrusted by <u>Stacheoides</u> cf. <u>spissa</u>. Other skeletal fragments surrounding encrustation have recrystallized extensively, a typical diagenetic pattern in argillaceous lithologies. Scale bar = 500μ. Carbonaceous shale facies borehole 3, Petershill Reservoir. G.T. 46,326

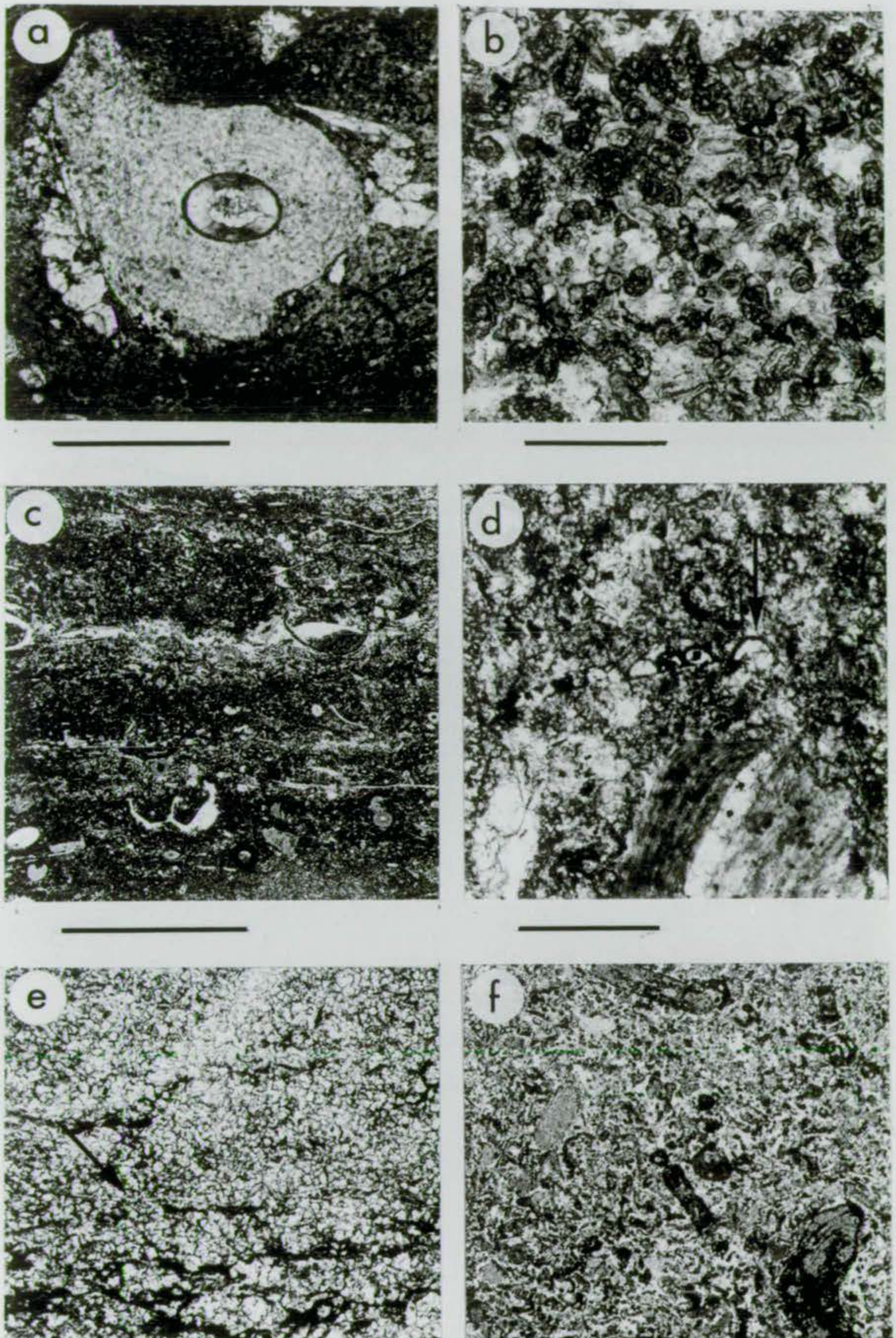
b. Uncompacted plant spores forming a sapropelic lamina. Such laminae are typical of the carbonaceous shale facies. Scale bar = 140μ. temporary preparation

c. A layered packstone. Layering is produced by regular variations in the relative proportions of microspar and fossils. Note the concave up ostracod (upper left) overlain by another thin shell creating a small partially-unfilled void. Such structures are hydrodynamically delicate and thus signs of quiet conditions and sediment surface stability. Round micritic skeleton at bottom (below broken gastropod) is of <u>Lituotubella</u>, an attached foraminiferan. Build-up, subfacies B, scale bar = 1 mm. G.T 46,367

d. Extensively recrystallized argillaceous biomicrosparite matrix. Arrow points to aligned benthonic foraminiferans (Eotuberitina reitlingerae). Such multiple attachments, which reveal a surface within the sediment, are signs of sediment surface stability. In this case filamentous algae are likely stabilizing agents. Evidence of their former presence is seen in black specks of pyrite throughout matrix (filament infillings, q.v. Ch 4). G.T. 46,548

e. Solution stringers concentrating clay, pyrite and organic matter in an argillaceous microsparite. Matrix consists of uniformly recrystallized microspar and pseudospar. Note that extensive recrystallization has also taken place in shells. Arrow points to plastically compacted ostracod valve. Such uniformly-compacted, unfractured shells are likely to have been hydrostatically supported during compaction, a sign of sediment viscosity. Argillaceous carbonate facies. Borehole 2. Scale bar = 1 mm. G.T. 46,360

f. Well-sorted crinoidal packstone. Broken crinoids and other skeletal debris are in three-dimensional contact. Interstitial material consists of replacement chalcedonic quartz. Crinoidal packstone facies, Unit C, Rifle Range Quarry. Scale bar = 2 mm. G.T. 46,389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b
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d
e
f

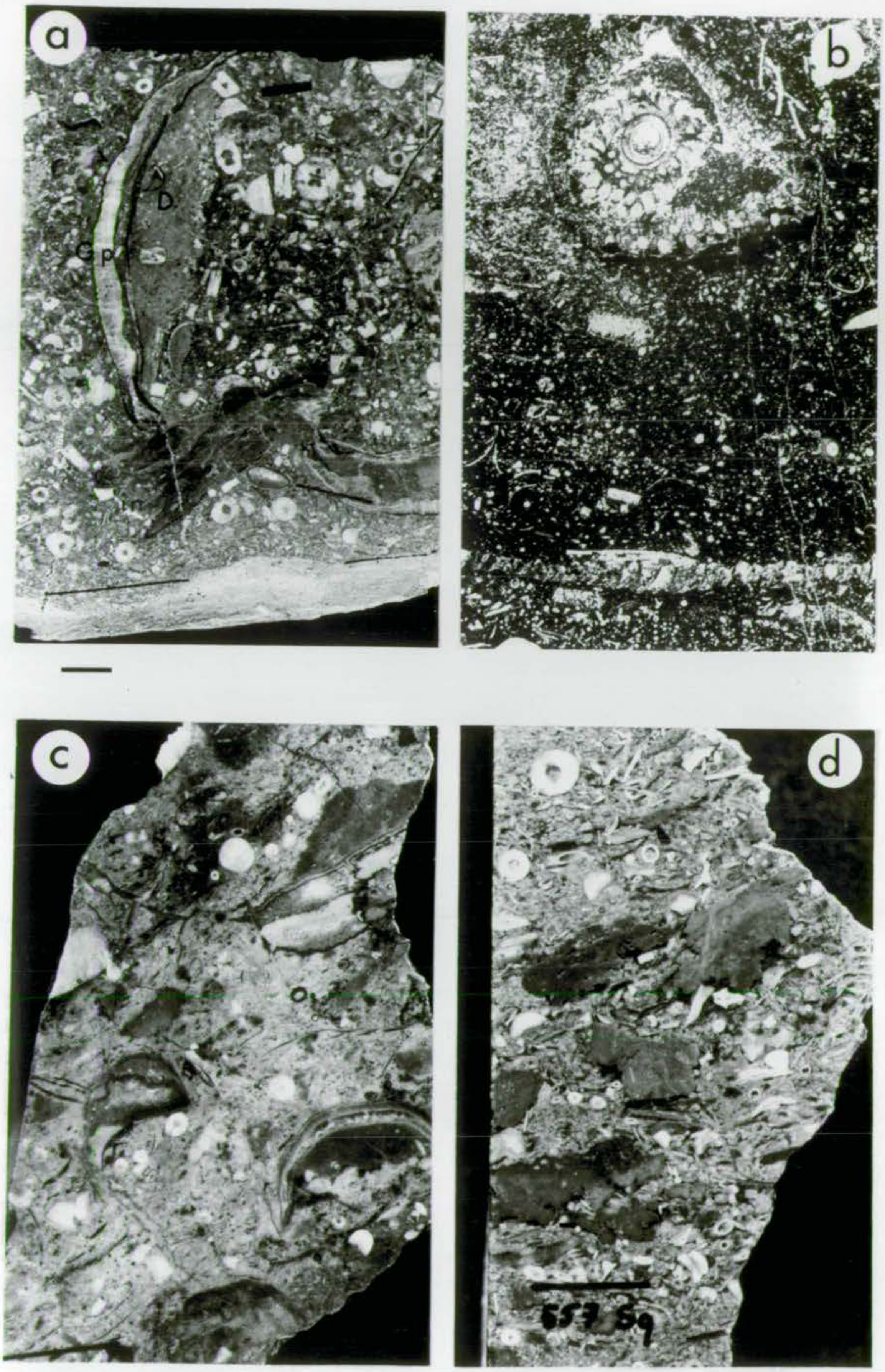
Fig. 7-4 High-carbonate limestones in the Reservoir Mbr.

a. Intraclast packstone; flank beds of the build-up facies; polished plaquette. A large blue-grey intraclast (in) has broken up slightly and some of the surrounding matrix has been forced into its cracks. Such breakage, particularly in the absence of any overall extensive compaction, is a sign of poor intraclast consolidation. A vertically orientated articulated *Gigantoproductus* shell (Gp) has dolomitic sediment (D) adherent to its dorsal surface, indicating the shell has been transported after death and burial. Note smaller productoid intraclast beside *Gigantoproductus* (enclosed in dots). *Gigantoproductus* intraclast is orientated in a hydrodynamically unstable attitude. The angular discrepancy between geopetal infillings (e.g. line below intraclast) and bedding (line at bottom of specimen) provides evidence that this packstone was deposited on a slope of approximately 17°. Block scale bar at top = 1 cm. G.I. 46,451

b. Cream biomicrosparite; thin section photomicrograph. The matrix consists of uniform microspar. Very fine spicules in matrix belong to siliceous and calcareous sponges. Fossil fragments comprise an unsorted assemblage. Upper part of photo shows a productoid spine encrusted by two overgrowths of the bryozoan *Fistulipora*, in turn circumscribed by a dark micritic algal crust. A sheet-form *Fistulipora* colony directly encrusts the sediment surface at the bottom of photo. Such thin, delicate colonies are a characteristic of firm and stable substrates. Width photo = 14 mm. RSM 1979.1.39

c. Intraclast packstone. Chaotically arranged productoids with blue-grey sediment adherent to the outer shell surfaces. One of the productoids in middle has a double geopetal infilling: one lies at the base of the visceral cavity, the other at the top. This sample was taken at a horizon equivalent to erosion surface A in the build-up facies. It shows that two types of sediment; fine-grained cream microspar and coarse crinoidal sediment (Fills C-1 and C-12) are intermixed and likely to have been deposited together. This and other data argues for a primary (depositional) origin for these two fills (see Ch 11). Scale bar = 1 cm. G.I. 46,350

d. Intraclast packstone. Unsorted crinoid and echinoid debris with large, centimetre sized blue-grey wackestone intraclasts. Erosion surface A, build-up facies, sediments infilling a crack. Scale bar = 1 cm. G.I. 46,434


a
D
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CHAPTER 8

LEVEL-BEDDED FACIES IN THE RESERVOIR MEMBER

8.0 Introduction

The basal sediments in the Petershill Fm. (and the Reservoir Mbr.) consist of mixed sandstones and tuffs (Fig. 8-1). These are overlain by three facies which gradually increase in carbonate content upward. They are the carbonaceous shale, argillaceous carbonate and slightly argillaceous limestone facies respectively. These facies only show a slight lateral differentiation along strike (Fig. A-1) and formed level-bottom sediment surfaces. Large-scale cross-stratification and evidence for depositional topographic relief are absent. Together these three facies form a continuous vertical sequence, described here in stratigraphical order.

8.1 Mixed sandstones and tuffs

A variable thickness (approximately 2-20 m) of mixed sandstones and tuffs immediately overlie the lavas beneath the Petershill Fm. (Fig. 8-1). These sediments are described as an informal unit because the amount of data available is limited.

The changes in thickness along strikeseen in the borehole data (Appdx B) and recorded inprevious descriptions of the Petershill lithological sequence (see Ch 2), suggest the mixed sandstones and tuffs infill hollows in the lava surface.

The petrology of the mixed sandstones and tuffs (q.v. Ch 7, and Introduction) shows them to be polygenetic, combining polycyclic quartz sand, and locally-derived plant and volcanic material. Francis (1961, p 138) observed that the quartz sand in the comparable sequence from the Saline district in Fife, was texturally mature and could not have been derived from weathering of the local basalts. He concluded that the quartz sand was, therefore, allochthonous. This is likely to

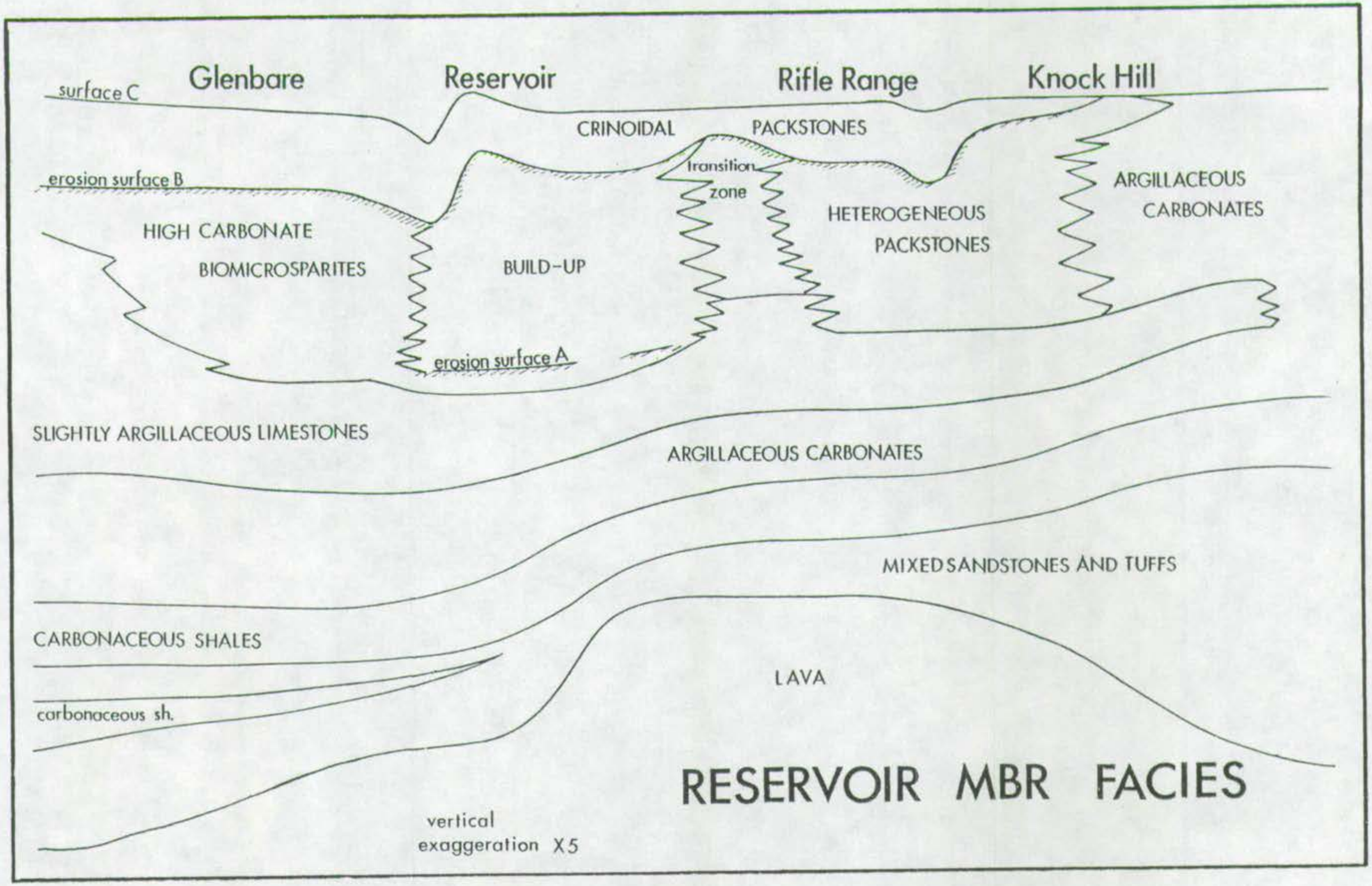


Fig. 8.1 Generalized cross-section of the Reservoir Mbr. facies, based on Fig. A-1, Appendix A, back pocket insert.

be the case in the Reservoir Mbr. mixed sandstones and tuffs where obvious local sand sources are also absent.

The sandstones in the Reservoir Mbr. also include texturally immature particles, such as red shale chips, probably derived from very local, intermittently exposed sources. Rootlet horizons in the sandstones further confirm that the depositional environment was periodically emergent. Fossil fragments and possibly the burrows (q.v. Appdx G, type 1) establish that the environment was regularly subject to marine sediment influxes.

The mixed sandstones and tuffs were the first sediments to overstep the tuff-covered lava surface of the Bathgate volcanic pile. It is likely that the sands formed barriers, shoals, or beaches; coastal deposits protecting shallow embayments where landwardly derived plant debris and re-deposited volcanogenic sediment settled. During intervals of emergence, thin plant covers became established on the sands. On re-submergence, these horizons were reworked and incorporated into the accumulating sediment. The absence of any coarse landwardly-derived sediments supports the hypothesis first put forward by Cadell (1925, p 182) that the relief of Bathgate volcanic pile during emergent periods was minimal.

8.2 Carbonaceous shale facies

8.21 External features and facies relationships

Immediately overlying the mixed sandstones and tuffs are 1.0-1.5 m of carbonaceous shales. This facies maintains an even thickness between North Mine Quarry and the Reservoir. South of this region, the facies thickens slightly and also interdigitates with the sandstones and tuffs underneath (Fig. A-1).

8.22 Component lithologies

In addition to carbonaceous shales (described in Ch 7), thin coals, sapropelic spore laminae (Fig. 7-3b), and possible tonsteins are common. Organic-rich laminae are more prevalent in the lower half of the facies and gradually give way upward to increasingly calcareous and fossiliferous horizons.

8.23 Biota

The biota of the carbonaceous shale facies is generally sparse, restricted to centimetre-thick laminae. The sequences between fossiliferous horizons are well-laminated and unbioturbated. Three types of fossiliferous laminae are common:

A) Lingula squamiformis (Phillips) and an irregular, meandrine burrow (type 1, Appdx G) occur at several horizons in the lower half of the facies. Specimens of Lingula lie parallel to lamination, with valves paired, suggesting they are in situ. In one specimen, the valves are subvertical.

B) Thin laminae containing Eomarginifera longispina (J. Sowerby) in its inferred life attitude become common in the upper half of the sequences observed.

C) Thin laminae containing Limipecten dissimilis (Fleming) (?)Edmondia, gastropods, smooth spirifers, cypridean ostracods and fine fossil fragments occur in the middle and upper part of the carboniferous shales. The larger brachiopods and bivalves appear to be in situ. All specimens observed were articulated (n = 15), flattened, lying parallel with lamination.

Algae - Loose intergrowths of filamentous algae are common throughout most fossiliferous horizons. Although the algal filaments are extensively compacted, in some cases, they can clearly be seen to circumscribe grains, indicating that they are autochthonous.

8.24 Depositional environment

Carbonaceous shales are the first undoubtedly marine facies in the Reservoir Mbr. sequence. They are likely to have accumulated in marginal, normal/restricted marine lagoons or perhaps even in isolated ponds. The accumulation of large amounts of organic detritus requires a quiet and, therefore, probably restricted environment. The manner in which the carbonaceous shale facies and the mixed sandstones and tuffs interdigitate (Fig. 8-1) suggests the two environments were closely associated, perhaps adjacent. The sandstones could have formed barriers, protecting areas of shale accumulation.

The general absence of macrofossils and lack of bioturbation throughout most of the sequence suggests that the black shale lagoons were non-marine or brackish during much of sedimentation. An intermittently greater marine influence is indicated by the occurrence of fossiliferous horizons. Several authors (notably Craig 1952) have concluded that Lingula was both steno- and euryhaline. Laminae with Lingula may thus not be fully marine.

8.3 Argillaceous carbonate facies

8.31 Facies relationships

The argillaceous carbonate facies gradationally overlies the carbonaceous shale facies along the entire strike of the Petershill Fm. (Figs. 8-1; A-1). Between the northern extremity of the Petershill Fm. and South Mine Lime Works this facies occupies nearly the entire thickness of the Reservoir Mbr. At SMLW the facies thins rapidly, but maintains a regular thickness of 2-3 m until the Reservoir, where it begins to thicken gradually southward (Figs. 8-1; A-1).

8.32 Bedding

Argillaceous carbonates typically consist of equally-thick planar or, rarely, lensoidally-bedded limestones and calcareous mudstones.

Individual limestone beds may reach up to 1 m; mean thicknesses are typically between 30-50 cm. Weathered surfaces are dark, olive grey; fresh samples are medium to dark grey.

8.33 Constituent lithologies

The argillaceous carbonate facies predominantly consists of calcareous rocks; argillaceous biomicrosparites and calcareous mudstones, irregularly interbedded with carbonaceous shales. The carbonaceous shales reach a maximum thickness of 80 cm in an exceptional occurrence at the Petershill Reservoir (see Fig. 2-10, north of fault). Individual beds of slightly argillaceous biomicrosparites and rarely of cream biomicrosparites, appear in the upper portion of the facies.

8.34 Fauna

Two faunal associations occur in the argillaceous carbonate facies: the *productoid-coral association* (abbrev. P-C), and a *bivalve-serpulid* association (abbrev. B-S). Complete faunal lists are presented in Table 8-2.

Productoid-coral association - Brachiopods, zaphrentoid corals, and a soft-bodied infauna predominate. Two productoids, *Gigantoproductus* spp. and *Eomarginifera longispina* are the most abundant epifauna or quasi-infauna. Within the association as a whole, most of the productoids are articulated (91%, n = 78) and 85% of the large *Gigantoproductus* specimens are in their inferred life attitude. Chonetoid, davidsonacean and spiriferoid brachiopods are also common (see Table 8-2). Zaphrentoid corals, particularly *Allotropiophyllum* sp. and *Amplexiaphrentis* sp., are less common than brachiopods, but still widespread. Other solitary corals are rare and often smaller than average. Colonial corals are very rare and also appear to be smaller than specimens from other facies.

The epifaunal organisms of the P-C association are sparse and fairly

Table 8-2 Invertebrate macrofauna of the argillaceous carbonate facies

	Faunal Association *1	
	Productoid-coral	Bivalve serpulid
Annelida		
Serpuloides cf. carbonarius (M'Coy)	-	C
serpulid indet.	-	C
Spirorbis sp.	VR	R
S. caperatus Etheridge	VR	R
Anthozoa		
Allotropiophyllum sp.	R	R
Amplexizaphrentis sp.	R	R
Aulophyllum fungites (Fleming)	R	-
? Dibunophyllum sp.	VR	-
Koninckophyllum sp.	VR	
Lithostrotion junceum (Fleming)	VR	VR
Lonsdaleia floriformis (Martin)	VR	-
Syringopora sp.	VR	-
zaphrentoid indet.	R	R
Bivalvia		
Aviculopecten sp.	-	Ab
A. semicostatus (Portlock)	-	Ab
Cardiomorpha sp.*2		
Dunbarella papyracea (J. Sowerby)	-	R
? Edmondia sp.	-	R
Limipecten sp.	VR	Ab
Limipecten dissimilis (Fleming)	VR	Ab
Nucula sp.	VR	R
Pinna sp.	R	R
Stenodiscus sp.	R	R
Sulcatopinna flabelliformis (Martin)	R	R
Brachiopoda		
Antiquatonia hindi (Muir-Wood)	R	-
A. indicus (Muir-Wood)	R	-
A. muricatus (Muir-Wood)	R	R
Composita cf. ambigua (Sowerby)	C	C
Crurithyris urei (Fleming)	C	C
Dictyoclostus sp.	R	R
Eomarginifera longispina (Sowerby)	Ab	Ab
Gigantoproductus sp.	Ab	-
G. cf. giganteus (Sowerby)	Ab	-
Krotovia spinulosa (Sowerby)	R	
Lingula squamiformis Phillips	-	C
Overtonia fimbriata (Sowerby)	VR	-
Phricodothyris sp.	R	R
Productus sp.	VR	R
Pugnax sp.	-	VR
Rhipidomella michelini (Léveillé)	Ab	-
Rugosochonetes celticus (Muir-Wood)	C	R
Schellweinella crenistria (Phillips)	C	-
Schizophoria resupinata (Martin)	R	-
Schuchertella sp.	R	R
spirifers indet.	C	R

*1 Relative overall abundance: VR = very rare, R = rare, C = common, Ab = abundant
- = absent, blank = not examined

*2 recorded by Hind (1896)

Table 8-2 (continued)

	Faunal Association *1	
	Productoid-coral	Bivalve serpulid
Bryozoa		
Fenestella sp.	Ab	Ab
Fistulipora encrustans (Phillips)	VR	VR
Tabulipora sp.	R	C
T. minima Lee	R	C
trepostomatous bryozoa indet.	C	C
Crinoidea		
crinoid stems	R	R
Gastropoda		
Naticopsis sp.	-	VR
Straparollus carbonarius (Sowerby)	-	VR
Ostracoda		
Bairdia brevis Jones and Kirkby*3		
B. hisingeri (Münster)		
B. plebia Reuss		
Cypridella spp. *3		
Nautiloidea		
coiled and orthocone nautiloid fragments	C	C
Porifera		
Chaetetes sp.	VR	-
Hyalostelia parallela (M'Coy)	-	C
H. smithi (Young and Young)	-	VR
siliceous and calcareous sponge spicules	C	C
Tholioasterella sp.	C	-

*1 Relative overall abundance: VR = very rare, R = rare, C = common, Ab = abundant
- = absent, blank = not examined.

*3 recorded by Latham (1933)

evenly distributed. Few fossiliferous horizons occur. Traces of an infauna, however, are quite pervasive and present throughout. The mudstones and limestones show signs of multiple, indistinct burrowing (type 2, Appdx G). The indistinct traces are cross-cut by identifiable burrows, notably Zoophycus, Planolites, and, very rarely, Chondrites. Burrowing has largely obliterated depositional textures.

Encrusting or attached epizoans are relatively rare. The most cosmopolitan encrusters of all facies, Chaetetes and Fistulipora, only occur as small colonies seldom covering or extending beyond the encrusted host skeleton (q.v. Ch 14).

Bivalve-serpulid association - The B-S association occurs in laminated black shales and dark grey calcareous mudstones of the argillaceous carbonate facies. Both the sediment type and the faunal composition of this association are somewhat atypical of the facies as a whole. Most of the information on this association is based on an exposure at the top of the facies in the Reservoir (Fig. 2-9).

The B-S fauna is generally abundant, but concentrated in laminae covered by many individuals. Different types of fossiliferous laminae (described below) alternate, apparently at random, with fairly unfossiliferous unbioturbated black shales (Fig. 8-3). A few fossils, namely Eomarginifera, Productus sp., Penniretopora sp. and Tabulipora sp., occur throughout the sequence as well as concentrating in laminae. Six types of fossiliferous laminae are present:

A. Serpulid mats (Fig. 8-3a) - Dense intergrowths of serpulid worm tubes forming mat-like laminae. Individuals consist of a gently tapering, unornamented, non-septate tube, reaching 6 mm in width. Tubes show a slight tendency to curve, suggesting a helicoidal growth habit.

Although individuals are presently compacted in flat "mats", it is likely they originally grew upright, forming thicket-like colonies (Fig. 8-3). Serpulid horizons conspicuously lack other fossil, except a few productoids.

B. Eomarginifera-fenestellid layers (Fig. 8-3b) - Eomarginifera longispina, fenestellid and trepostome bryozoan colonies and several small brachiopods (Crurithyris, Phricodothyris and rarely Productus) form thin laminae in which individuals are largely in situ. Eomarginifera and Crurithyris show a wide size range. Most individuals are articulated and in their inferred life positions (i.e. upright or with the commissure vertical, Fig. 8-3). Crurithyris typically occurs in small clusters, within which a few shells are orientated with the commissure plane vertical. The productoids still have their spines attached and delicate structures such as the colonies of Tabulipora minima Lee reach up to 30 cm.

The presence of a nearly complete size range within the most common elements of this assemblage, together with a high proportion of individuals in life position suggests that Eomarginifera-fenestellid laminae are essentially life surface assemblages (q.v. Appdx D, definition), undisturbed by currents or bioturbation. The delicacy and fragile nature of many preserved skeletons further suggests that these assemblages formed in very quiet environments, where currents were not a disruptive force.

C. Hyalostelia smithi sheets (Fig. 8-3c) - H. smithi sheets consit of bundles of the large rod-like spicules and smaller (rarer) hexactinellid dermal spicules concentrated in layers, largely to the exclusion of other fossils. The rod-like bundles of large spicules have been interpreted at the anchoring appendage of the sponge (Hinde 1887, p 158). The smaller dermal spicules occasionally preserve a grid-like pattern which is characteristic of an undisturbed specimen. The presence of both anchoring and dermal spicules within the same laminae additionally suggests that these assemblages are largely undisturbed.

Hyalostelia was probably comparable in form and life habit to several Recent siliceous sponges such as *Hyalonema* (Hinde 1887, p 158) and *Euplectella*. The robust anchoring bundle is likely to have served as a stalk for a distally-domed sponge body (see reconstruction, Fig. 8-3c). *Hyalostelia* sheets thus mark intervals of dense sponge colonization, when individuals, by their sheer numerical dominance, may have excluded other suspension feeders.

D. *Limipecten layers* (Fig. 8-2d,e) - *Limipecten* spp. occur in two types of laminae, or layers. In some cases as many as three or four individuals, usually *L. dissimilis* overlie each other to form a layer of horizontally orientated shells (Fig. 8-2e). Nearly all valves in these layers are large (greater than 30 mm maximum length). 40-60% (n = 37) are paired and have hinge axes lacking preferred orientation. Few other fossils occur in these layers.

Less commonly, several forms (probably different species) of *Limipecten* are present. Individuals are typically fairly widely spaced and associated with other fossils: ?*Streblopteria*, *Eomarginifera*, ostracods, fenestellids and rarely *Lingula* (Fig. 8-2d). *Limipecten* valves vary in maximum width between 6-44 mm (n = 16), indicating that a fairly complete size range is present. These layers thus appear to be largely undisturbed.

Many features of *Limipecten*, including its moderate umbonal angle, elongate anterior auricle, plano-convex shell shape, and ornament, point to a byssally attached mode of life (q.v. Stanley 1970, pp 27-33). Similar Recent genera which show these morphological adaptations to byssal attachment may also release their byssus to crawl or swim, (ibid, pp.138-144). Their juveniles may live attached, later becoming mobile when the shell can provide stability.

If, as is likely, Limipecten could live either attached or free, then one of two hypotheses may explain how the commonly occurring, crowded Limipecten layers (Fig. 8-2e) formed. Winnowing might leave a residual assemblage of adults, from which smaller individuals and other fossils have been removed. Conversely, the laminae could represent drifted assemblages of dead, detached individuals. Although the available data does not clearly distinguish between these two and perhaps other possibilities, it does, however, suggest that the layers have been hydrodynamically altered.

E. Dunbarella layers - Dunbarella papyracea (J. Sowerby) and rare Streblopteria and Aviculopecten also form laminae in black shales. These laminae are comparable to the crowded Limipecten laminae in that they are composed of large, articulated shells, and are essentially devoid of other fauna. They also probably represent slightly transported or winnowed, residual assemblages.

F. Pelagic debris laminae (Fig. 8-3f) - Several laminae which are otherwise markedly devoid of benthonic fossils, concentrate fossils and other debris of pelagic origin. These laminae seldom exceed a few millimetres in thickness. They are relatively sparsely covered with fragmented and entire nautiloids, gastropods, wood fragments, phosphatic ?vertebrate plates, and fragments of pectinoid bivalves and bryozoans.

Pelagic debris may have accumulated during intervals of comparatively low sediment influx, when the substrate was unfavourable for colonization, perhaps during brackish water stillstands.

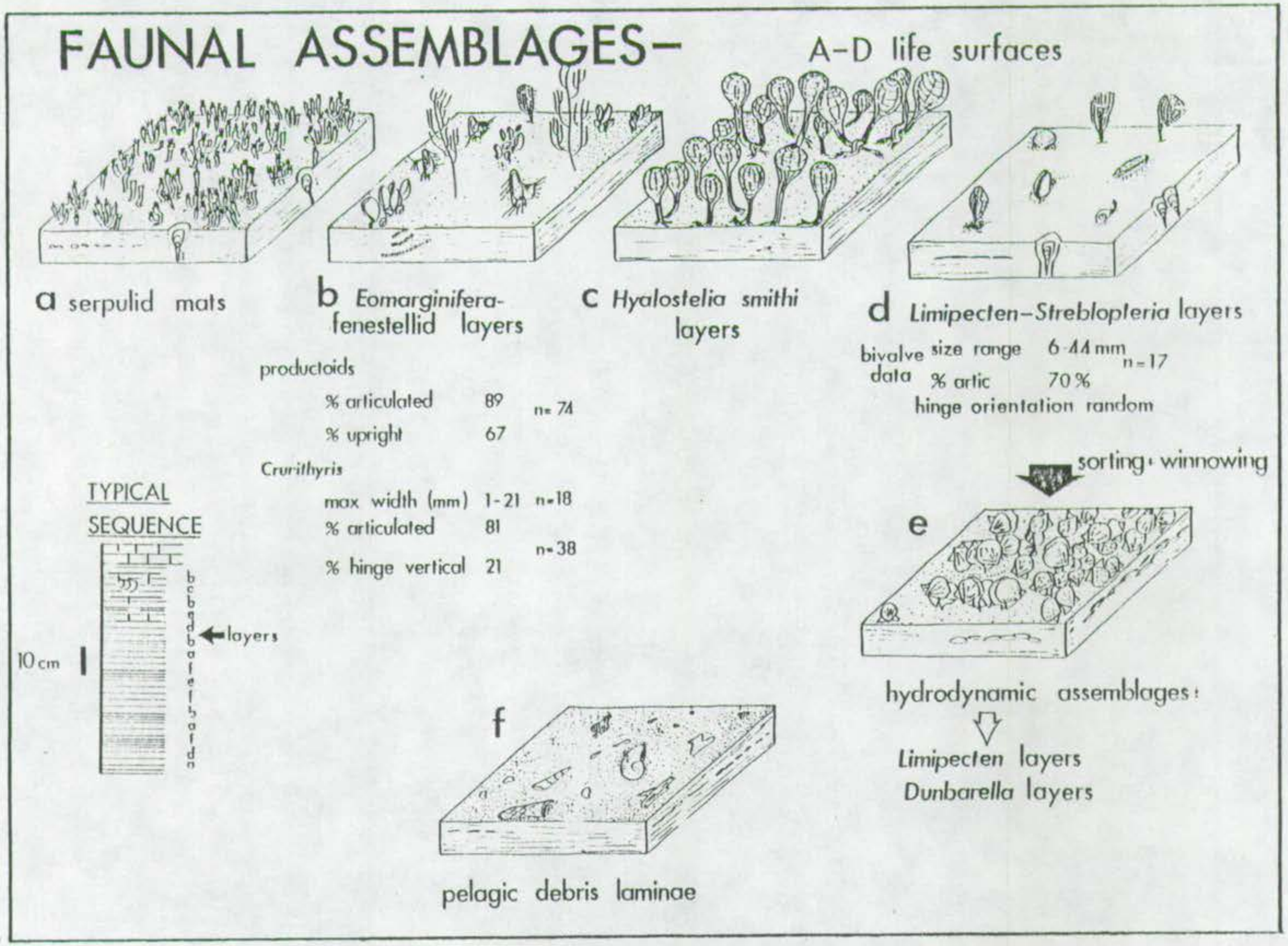


Fig. 8-3 Palaeoecology of the argillaceous carbonate facies.

8.35 Algae

Branched filamentous algae are present throughout both the argillaceous biomicrosparites and black shales in the argillaceous carbonate facies. Filaments envelop grains, suggesting they have grown in situ. Algal fabrics,however, are absent perhaps obscured by extensive bioturbation (in the argillaceous limestones) or compaction (in the black shales).

8.36 Summary of depositional environment

The argillaceous carbonate facies accumulated in a generally quiet environment, where a significant proportion of the sediment was deposited slowly from suspension. Several factors, including the fine grain size of the sediment, taphonomic data and the hydraulic delicacy of some fossils suggest that prevailing currents were weak. The changes in facies thickness (Fig. 8-1; A-1) indicate that this regime prevailed throughout Reservoir Mbr. sedimentation at the northern and southern extremes of the Bathgate volcanic lava platform. Palaeogeographical reconstruction of the platform sedimentation pattern (presented and described in Ch 12) suggests that argillaceous carbonates accumulated in both proximal (coastal lagoon) environments and in offshore (somewhat deeper) environments.

The composition of the fauna and the sediment in argillaceous carbonate facies point to two depositional regimes, or sub-environments: "normal" marine intervals characterized by the productoid-coral association, and "restricted" intervals in which several types of life surfaces formed in black shales (the bivalve-serpulid association).

The bulk of the argillaceous carbonates accumulated during normal intervals of open marine circulation, when both the water column and substrate were well-oxygenated. The sparseness of the epifauna and general lack of encrusters, however, suggests that shells were buried rapidly owing to high rates of sedimentation. The looseness of the sediment surface (indicated by trace fossils) is likely to have inhibited epifaunal substrate colonization. The pervasiveness of the ichnofauna additionally indicates that the sediment was well oxygenated to a considerable depth.

Bivalve-serpulid sedimentation contrasts sharply with the normal regime. The paucity of deposit-feeding infauna suggest that black shale sediments may have been anaerobic. The only common shelled infauna, Lingula and Nucula were suspension feeders, unlikely to have been adversely affected by reducing conditions in the sediment (Ferguson 1962). Several black shale horizons, e.g. pelagic laminae, accumulated during intervals of exceptionally low clastic sedimentation.

In a detailed study of a Lower Carboniferous shale sequence in Fife, Ferguson (1962) found in situ assemblages which were, in some cases, similar to those of the black shales in the Reservoir Mbr. The sequence Ferguson examined occurs in the same stratigraphic position within a Lower Limestone Group sedimentation cycle as the Reservoir Mbr. black shales. By combining an ecological analysis of the fauna with the data from the sequence as a whole, Ferguson was able to relate the different faunal associations to different environments. He (ibid, Tables 1, 2) found Eomarginifera, Crurithyris and bryozoans associated in a distinct topozone within the sequence, while Lingula and Streblopteria were associated elsewhere. Despite differences in the relative abundance of fossils between Fife and Bathgate, it seems likely that Ferguson's interpretations may be generally applied to the Reservoir Mbr., particularly since the faunal and lithological associations are comparable. Ferguson related the faunal associations he found to environmental changes in depth and circulation occuring during a transgression. He concluded that Eomarginifera, Crurithyris, bryozoan associations formed in an open-marine, subtidal environment, while the Lingula-Streblopteria associations marked intertidal, possibly brackish conditions.

Thus it appears that black shales as a whole represent intervals of restricted circulation, when organic and biological detritus accumulated, undiluted by the "normal" clastic influx. The fauna of some laminae in black shales additionally indicate exceptionally quiet, restricted, nearshore conditions. Although the data on the distribution of black shales within the argillaceous carbonate facies is limited, it appears that the facies shows a general transition from a restricted to normal circulation regime, suggesting a transgressive pattern.

8.4 Slightly argillaceous limestone facies

8.41 External features and facies relationships

The slightly argillaceous limestone facies gradationally overlies the argillaceous carbonate facies along most of the strike section of the Petershill Fm. (Figs. 8-1; A-1). It reaches a maximum thickness of 4-5 m in the transition area, Sunnyside, thinning gradually north and south to 2-3 m (Fig. 8-1). At the northern limit of the Petershill Fm. slightly argillaceous limestones intertongue with the argillaceous carbonate facies. Towards the southern limits the facies almost certainly gives way to argillaceous carbonates.

8.42 Bedding

The slightly argillaceous limestone facies consists of medium-thickness planar and lensoidally bedded limestones alternating with only slightly thinner calcareous mudstones (q.v. Ch 3). Bedding surfaces are highly undulose or wavy. Structures attributable to boudinage (q.v. Ch 3) have extensively modified the shape of bedding and the limestone bedding surfaces.

8.43 Constituent lithologies

Grey, slightly argillaceous biomicrosparites (q.v. Ch 7) are the most common lithology of the slightly argillaceous limestone facies. Thin, cream biomicrosparites interbed at irregular intervals (Fig. A-1). In addition, coarse skeletal debris layers appear in some beds. This skeletal debris is typically unsorted, composed of the common fossils in the facies: small productoids, Gigantoproductus, and fragments of Lithostrotion, crinoids and bryozoans. Roughly equal proportions of articulated and disarticulated brachiopod valves are present. Shells and elongate particles, such as orthocone nautiloids, are often orientated at high angles to bedding. Some debris layers are graded, fining upward. Skeletal debris layers seldom exceed a few centimetres in thickness and do not extend laterally for more than a few decametres. The internal structures of debris layers and fossil attitudes point to rapid, gravitationally controlled deposition. These layers may be storm deposits.

Partings of blue-grey clay "wayboards" (q.v. Walkden 1972) occur throughout slightly argillaceous limestone facies. At least 4 wayboards are present in the 3 m of section at the Petershill Reservoir, and it is likely that many more have become intermixed in the sediment.

8.44 Fauna see Table 8-4: complete faunal list

The fauna of the slightly argillaceous limestone facies is generally abundant and often in situ. Fossils occur evenly distributed throughout a bed, but also concentrate at horizons, usually the tops of limestone bedding surfaces. These faunal concentrations are also largely undisturbed and many of the macrofossils such as brachiopods, are in their presumed life positions. At two sampled horizons, 100% of Gigantoproductus, the largest and most common brachiopod, were articulated, and only 7% were overturned (i.e. pedicle valve uppermost,

Table 8-4 Invertebrate macrofauna of the slightly argillaceous limestone facies

		Relative Abundance *1
Ammonoidea		
Beyrichoceratoides truncatus	(Phillips)	-
Annelida		
Serpuloides sp.		R
Spirorbis sp.		C
S. caperatus	Etheridge	
Anthozoa		
Amplexizaphrentis sp.		C
Aulophyllum fungites	(Fleming)*2	Ab
Caninia benburbensis	Lewis	VR
C. juddi	(Thomson)	C
Clisiophyllum keyserlingi	(Thomson)*2	C
Dibunophyllum bipartitum	(M'Coy)*2	C
Koninckophyllum magnificum	(Thomson & Nicholson)*2	C
Lithostrotion junceum	(Fleming)	Ab
L. variabile	Nudds	R
Lonsdaleia duplicata	(Martin)	R
L. floriformis	(Martin)	C
zaphrentoid indet.		C
Bivalvia		
Limipecten sp.		VR
Lithophaga lingualis	(Phillips)	R
Pinna sp.		R
Smooth bivalves indet.		C
Brachiopoda		
Aliteria panderi	(Muir-Wood)	VR
Antiquatonia hindi	(Muir-Wood)	Ab
A. indicus	(Muir-Wood)	Ab
A. muricatus	(Muir-Wood)	Ab
Avonia sp.		C
Composita ambigua	(Sowerby)	C
Crurithyris sp.		C
Dielasma hastatum	(Sowerby)	C
Girtyella sp.		
Eomarginifera sp.		C
E. longispina	(Sowerby)	C
Echinoconchus elegans	(M'Coy)	R
E. punctatus	(Sowerby)	C
Gigantoproductus sp.		Ab
G. giganteus	(Sowerby)	Ab
Linoproductus sp.		VR
Krotovia spinulosa	(Sowerby)	C
Overtonia fimbriata	(Sowerby)	C
Phricodothyris sp.		C
Productus sp.		C
P. productus	(Martin)	VR
Pugilis scoticus	(Sowerby)	R
Rhipidomella michelini	(Léveillé)	C
Rugosochonetes celticus	(Muir-Wood)	C
Schellweinella crenistria	(Phillips)	C
Schizophoria resupinata	(Martin)	C
Schuchertella sp.		C
Semiplanus cf. lattissimus	(Sowerby)	C
spirifers - smooth, reticulate, costate		C

*1 Relative abundance: Ab = abundant, C = common, R = rare, VR = very rare, - = not recorded, blank = distribution not examined.

*2 organisms typically associated together.

Table 8-4 (continued)

		Relative Abundance *1
Bryozoa		
fenestellid indet.		C
fistuliporoid indet.		Ab
Fistulipora sp.		C
F. encrustans	(Phillips)	R
Penniretopora sp.		C
Tabulipora sp.		C
T. minima	Lee	R
Crinoidea		
crinoid stems		C
Poteriocrinus sp.		R
Woodocrinus sp.		R
Echinoidea		
Archaeocidaris sp.		R
Gastropoda		
gastropods indet.		Ab
Naticopsis sp.		C
Ostracoda		
Bairdia brevis	Jones and Kirkby*3	
B. curta	M'Coy*3	
B. hisingeri	(Münster)*3	
B. plebia	Reuss*3	
B. plebia var alta	Jones and Kirkby*3	
B. subelongata	Jones and Kirkby*3	
Beyrichiopsis sp.		C
Cytherella sp.		C
Paraparchites sp.		C
Porifera		
calcareous and siliceous sponge spicules		C
Hyalostelia parallela	(M'Coy)	C
H. smithi	(Young and Young)	C
Tholioasterella sp.		R
Minor elements		
orthocone and coiled nautiloids		
trilobite fragments		
Particeps scoticus minimus	Osmólska	

*1 Relative abundance: Ab = abundant, C = common, R = rare, VR = very rare, - = not recorded, blank = distribution not examined.
*3 recorded by Latham (1933).

n = 131). These horizons thus contrast sharply with those of graded, fragmented debris described previously. The interbedded calcareous mudstones contain a fairly similar, although less abundant, fauna.

The predominant elements of the fauna are solitary aulophyllid corals, Gigantoproductus, and Lithostrotion junceum. Productoids (Antiquatonia, Eomarginifera, Overtonia and Productus, see also Fig. 8-4) are particularly common, along with several other brachiopods, including Dielasma, Phricodothyris and spirifers. Chonetoids (Schellweinella, Rugosochonetes, Schizophoria, Schuchertella) are more abundant in the calcareous mudstones. Bryozoans, gastropods and trilobites are a common, but relatively minor, element of the fauna.

The colonial coral fauna is almost exclusively dominated by L. junceum. Over 90% (n = 38) of the colonies recorded belong to this species. L. variabile and Lonsdaleia comprise the remaining 10%. Most colonies are small, less than 1 m across, and do not exceed a height of 30 cm. Several colonies usually occur along a particular horizon, but seldom form continuous thickets (q.v. Ch 9). Thus, common but isolated small L. junceum colonies are a characteristic of the slightly argillaceous limestone facies.

Solitary coral aggregates - Aggregates of solitary corals, almost exclusively belonging to the Aulophyllidae, are one of the most characteristic faunal associations in the slightly argillaceous facies. Several aulophylloid genera and species are present in each aggregate, A. fungites being the predominant coral (q.v. Fig. 8-4). These aggregates consist of up to 20-40 corallites several centimetres apart, covering a few square metres of a bedding surface. Corallites exhibit a wide range in size and growth form. A complete size range is present within a cluster, with most individuals measuring between

5-10 cm maximum length (range 0.2-40 cm). Most coralla have simple trochoidal or ceratoid forms (illustrated in Fig. 8-5) which curve in one plane. Examples of turbinate, patellate, sigmoidal and multigeniculate forms are also present. A range of growth forms is found within each genus.

The aggregative tendency of Recent and especially fossil rugosans is well known, and has been described by several authors (see Maerz 1975, p 108 for references). Such aggregates are likely to result from larval selection for areas of favourable circulation or substrate. In a detailed study of Caninia torqua, Maerz (ibid) concluded that aggregates could also form as asexually-produced buds dropped off or broken away from parents. Some Recent corals also produce clusters or patches by this mechanism (Maerz 1975, p 230; J. B. Wilson 1979). Although it is possible, perhaps probable, that many individuals in the Petershill Fm. aggregates were asexually-generated, the aggregates cannot be entirely explained by this mechanism. They typically contain several different genera of corals (Fig. 8-4) and thus must have formed where separate, sexually generated, larvae came to cluster on the sediment surface.

A detailed study was carried out on the composition, attitude, and orientation of the corals in three such aggregates. A statistically significant number of observations could,unfortunately,only be made on one of the aggregates occurring at the top of a limestone bed at the Reservoir. Data from the other two, however, confirm the observations made on the Reservoir aggregate. Forty-two corallites were examined and collected. 30% of these were very small trochoidal forms (less than 3 cm in length); too small for orientation measurements. 20% were complex, sigmoidal forms usually more than 10 cm long, which geniculated in several directions. The orientation of these sigmoidal forms was not analyzed either. This relatively small percentage of the population proved very difficult to describe using the measures employed.

Fifty percent (n = 22) of the corals consisted of simple trochoidal or ceratoid forms that only curved slightly in a single plane (Fig. 8-5). The life position of these corallites could easily be analyzed as their growth form indicated they had remained in a fairly stable attitude during life. In some cases these corals had toppled prior to burial (left and right attitudes, Fig. 8-5).

The simple coral growth forms were analyzed by measuring an azimuth (in degrees from north) drawn between the protocorallite tip and bisecting the calyx, or extending to the distal, convex side of the calyx (Fig. 8-5). The results of a Rayleigh test for uniformity (Fig. 8-5) show that these corallites are significantly orientated, facing the east.

Many studies have shown that Recent corals make numerous morphological and structural modifications towards maintaining a favourable life orientation with respect to food-bearing currents, (Chamberlain and Graus , 1975; Wainright and Koehl 1976; Geister 1972; Hubbard and Pocock 1972; see Wells 1957). Geniculation and torsional growth observed in Paleozoic corals appear to be responses to these same stimuli. The conclusions derivable from the studies of Recent corals (refs. given) would suggest that the Petershill Fm. solitary corals were rheophyllic. Currents in the slightly argillaceous limestone facies are likely to have been very weak and it is thus more likely that the corallites faced into, rather than away from, prevailing currents.

A preferential hydrodynamic orientation on the part of an unstable object, such as an unattached solitary coral, also provides a fairly specific index of the prevailing circulatory regime. Currents must

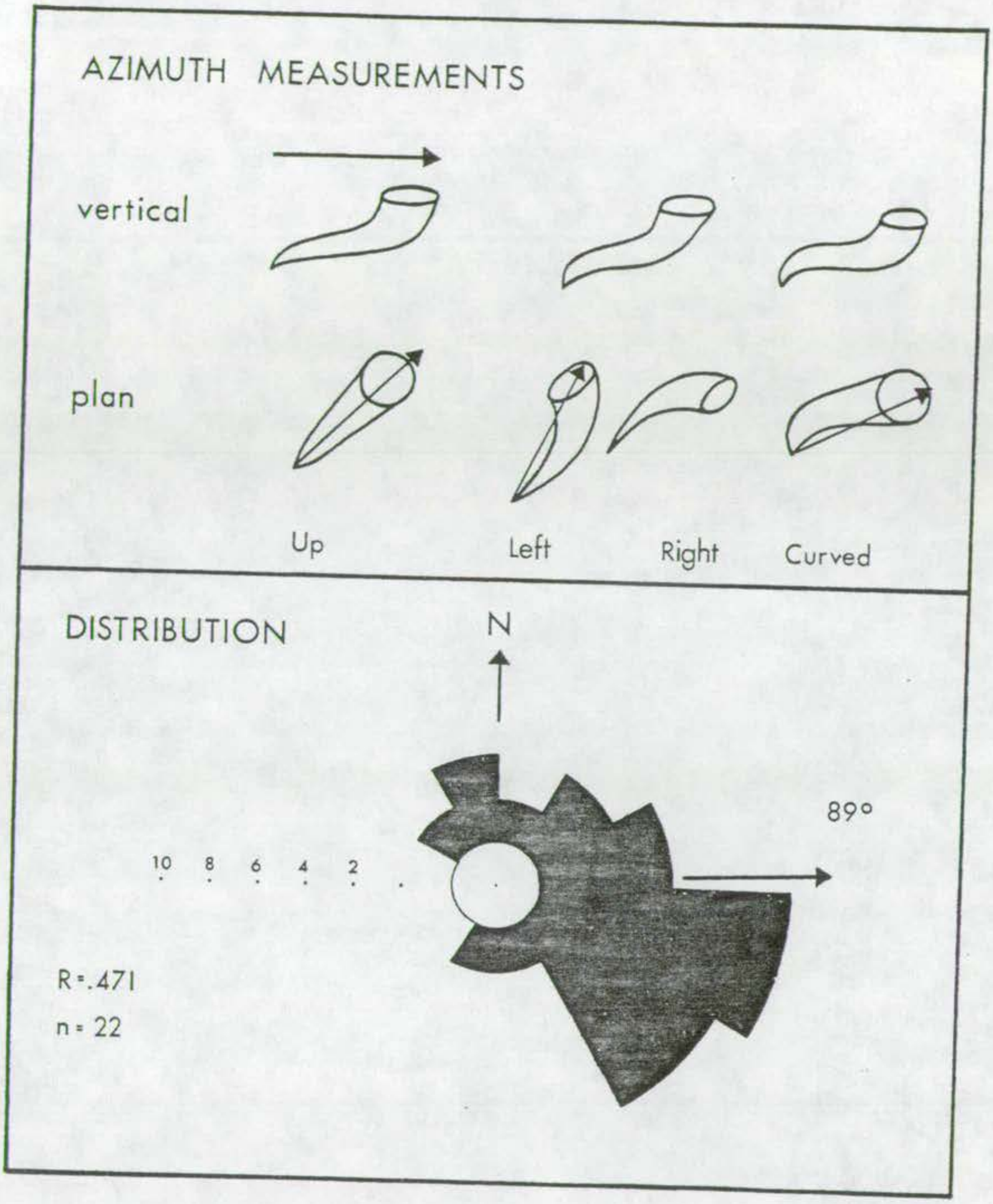


Fig. 8-5 The orientation and attitude of solitary corals occurring in aggregates; slightly argillaceous limestone facies. Arrows show how azimuths were drawn on corallites of differing growth habit and attitude. The distribution of 22 measured azimuth orientations is shown in lower box. The Rayleigh test for uniformity shows that corallites are preferentially orientated towards 89° at 0.1 significance level.

have been sufficiently strong and persistently undirectional to favour individuals orientated eastward, but not so strong as to transport, bury or dislodge them.

8.45 Microfauna

Another characteristic feature of the slightly argillaceous limestone facies is the diversity and abundance of the microfauna. Foraminiferans and ostracods, as well as brachiopod spat, calcareous and siliceous sponge spicules, gastropods and conodonts together may reach up to 40% grain bulk of a thin section. Foraminiferan-rich samples contain on the order of 900 individuals/cm^3 (based on extrapolations from 2 thin sections). Such figures suggest extremely high productivity (cf. Mamet 1977). Endothyrids, archaediscids, and eostafellids are particularly abundant. Attached foraminiferans are also common, but less abundant.

8.46 Algae

Calcareous and non-calcareous algae are also an important biotic constituent of slightly argillaceous limestones. Intergrowths of branched filamentous algae and Girvanella are so widespread as to suggest they were once ubiquitous. Indeed, pyrite infillings from the filaments are present in the insoluble residues of all samples from this facies. Signs of binding and sediment stabilization are relatively rare. Bioturbation, however, is so pervasive that it is likely that many originally bound fabrics have been destroyed. Borings and micrite envelopes are also exceptionally common.

8.47 Trace fossils

Burrows in the slightly argillaceous limestones are pervasive throughout and largely uncompacted. All burrows are endichnial; surface traces are absent. Several types of clearly-defined burrows (types 3, 4, 5, Appdx G) are most common. They cross-cut indistinct swirly (type 2) textures and are themselves rarely truncated by Thalassinoides and Chondrites.

Trace fossils show that infaunal deposit feeders were a significant constituent of the fauna and that, at some horizons, slightly argillaceous limestone substrates underwent a consistency increase from a gel to plastic, to firm state (q.v. Ch 5).

8.48 Depositional environment

Slightly argillaceous limestones accumulated in generally quiet, well lit, shallow waters. The presence of fairly continual and occasionally-directed, gentle currents may be inferred from the composition, preferred growth orientation and diversity of the fauna. Strong traction currents were infrequent and possibly storm-induced. The abundance of algae and calcareous sponge spicules are evidence of generally shallow water (Heckel 1972). Unfortunately, like many platform deposits, neither the fauna nor physical structures provide more specific information on depth, current strengths, or distance from shore. The palaeogeographical distribution of the facies, however, suggests that the slightly argillaceous limestones spanned both the nearshore and offshore zones (a more detailed description of palaeogeography is given in Ch 12).

Slightly argillaceous limestones are likely to have accumulated relatively slowly, as low sedimentation rates generally favour a suspension-feeding epifauna. Horizons along which the dominant elements of the fauna are concentrated are additionally likely to reflect intervals of non-deposition, or stillstands (q.v. Ch 5; Fürsich 1978; Goldring and Kazmierczak 1974). The lessening in sedimentation rate is reflected in the increase in substrate consistency. The fauna at such horizons are condensed assemblages (sensu Fürsich 1978) of successive life surfaces, each characteristic of increasingly coherent substrates.

The earliest colonizers of stillstand horizons were infaunal deposit feeders. Their systematic sediment feeding may have aided in consolidation (as discussed by Rhoads 1970) and thus led to replacement by epifaunally-dominated assemblages of solitary corals, brachiopods, and bryozoans. More detailed research into slightly argillaceous limestone fauna may even reveal successive epifaunal associations.

8.5 Level-bedded facies : synthesis and summary

The level-bedded facies in the Reservoir Mbr. form a continuous sequence of progressively more openly marine environments. The carbonaceous shale facies accumulated in protected, marginal-marine lagoons. The overlying argillaceous carbonate facies mark an interval of transition from restricted to fully marine sedimentation, during a period of relatively high fine-grained clastic influx. Slightly argillaceous limestones accumulated during intervals of a more reduced clastic input.

The environments in the level-bedded sequence show a successively greater faunal diversity and a progressively greater biological contribution to the sediment. During this stage of sedimentation on the Bathgate volcanic platform, environments show few signs of any lateral differentiation.

CHAPTER 9

THE HIGH-CARBONATE BIOMICROSPARITE FACIES

9.0 Introduction

The facies in the upper Reservoir Mbr. form a mosaic pattern of laterally-adjacent, contemporaneous environments consisting primarily of high-carbonate limestones. These are the high-carbonate biomicrosparite facies, the build-up and the heterogeneous packstone facies, shown in Figs. 8-1, A-1 (Appdx). The most notable facies in this mosaic is a biohermal build-up (q.v. Ch 11), which can be shown to have had topographic relief over the surrounding, more level-bedded substrates. In the following three chapters, each high-carbonate facies is described separately, followed by a discussion of the features common to all three.

9.1 External features and facies relationships

The high-carbonate biomicrosparite facies gradationally overlies the slightly argillaceous limestone facies (Figs. 8-1; A-1). A thin, east-west trending tongue of argillaceous limestones (shown in Fig. A-1) separates the high-carbonate biomicrosparite facies from laterally equivalent flank beds of the build-up. Beds of high-carbonate biomicrosparite lithology, very similar to the main body of the facies, intertongue with slightly argillaceous limestone beds in the transition area north of the build-up as well as extending underneath it (Fig. A-1). An erosion surface interpreted as a subaerial discontinuity (B, Fig. A-1, q.v. Ch 13) separates the high-carbonate biomicrosparite facies from the crinoidal packstone facies stratigraphically above.

The high-carbonate biomicrosparite facies consists of medium-thickness planar and rarely lensoidally-bedded limestones and thin calcareous mudstones. Bedding thicknesses are somewhat irregular, partly because beds are thickened by Lithostrotion thickets and possibly because some beds attained slight relief over surrounding substrates. Slight depositional relief within this facies is suggested by small-scale folds, slumps, and changes in bedding thickness similar to those found in the build-up facies (q.v. Ch 11).

9.2 Constituent lithologies

The high-carbonate biomicrosparite facies may be divided into three successive units of equal thickness (Fig. A-1). The lowest consists of cream biomicrosparites (predominantly wackestones), followed by a second middle unit of slightly argillaceous biomicrosparites, passing upward into layered biomicrosparites. The third, uppermost unit, is composed of more crinoidal, dolomitic packstones. The facies thus consists predominantly of fine-grained lithologies which show an overall general tendency to coarsen upwards. All the constituent lithologies are generally poorly sorted and have a diverse fossil assemblage.

Beds of shell debris, often showing small-scale cross-stratification, occur throughout the sequence, becoming more numerous upwards. Fossils in these beds are in transported attitudes, but they are seldom extensively broken-up and a high proportion of shells have remained articulated. Beds of crinoidal debris also become more common in the upper part of the sequence. The shell debris beds and the crinoidal beds both indicate that current activity has been more extensive in the upper third of the sequence, but that currents were fairly gentle (seen in the absence of sorting, extensive breakage, and large scale cross-stratification). The finer-grained lithologies in the lower part of the sequence typically contain a more delicate, relatively undisturbed fauna, where fossils on bedding surfaces are often in their presumed life attitudes (e.g. Figs. 9-2; 9-6).

9.3 Biota see Table 9-1 - complete faunal list

The abundance and diversity of the fauna in this facies exceeds that of all others except the build-up. The dominant elements of the fauna, Antiquatonia spp. and Lithostrotion junceum occur in two widespread and facies-characteristic associations, described below. Burrow systems of the ichnogenus Thalassinoides are also a distinctive feature of this facies. Some of the high-carbonate biomicrosparite fauna also occurs in beds of similar lithology in adjacent facies, namely: Hyalostelia parallela (M'Coy), Entomoconchus spp., Hexaphyllia marginata (Fleming) and, Archaeocidaris urii Fleming (Fig. 9-6), and fenestellids.

9.31 Antiquatonia bands Figs. 9-2; 11-5; Table H-1, Appdx H

Laterally extensive aggregates of shells, concentrated at bedding surfaces or within a bed, are common throughout the lower part of this facies and the lower build-up. These shell bands reach 10-15 cm in thickness and may extend laterally for tens of metres. In the high-carbonate biomicrosparite facies, they often underlie Lithostrotion thickets. The predominant brachiopod is A. hindi (Muir-Wood), along with A. muricatus (Muir-Wood), A. indicus (Muir-Wood), Eomarginifera spp., and Dictyoclostus semireticulatus (Muir-Wood) (see Table 9-1).

The composition and diversity of the associated fauna in A. bands varies between lithologies and facies (compare fauna listed in Tables 9-1 and 11-7). The fauna of a band is generally more diverse in the build-up facies. Fenestellids, encrusting fistuliporoid bryozoans, schellweinellids, costate spirifers, and the bivalve Pinna, are common in the bands of all facies. A few taxa are most common in the bands occurring in the high-carbonate biomicrosparite facies, namely: terebratuliform brachiopods (Composita, Dielasma, Girtyella), solitary corals

Table 9-1 Invertebrate macrofauna of the high-carbonate biomicrosparite facies

	Overall Relative Abundance *1	Faunal Association *2
Annelida		
Cornulites sp.	R	
Serpuloides carbonarius (M'Coy)	VR	L
serpulid indet.	R	
Spirorbis sp.	C	
S. caperatus Etheridge	C	
Anthozoa		
Aulophyllum fungites (Fleming)	Ab	
Caninia benburbensis Lewis	C	
C. juddi (Thomson)	C	
Clisiophyllum keyserlingi (Thomson)	Ab	
Dibunophyllum sp.	C	P
D. bipartitum (M'Coy)	Ab	P
Heterophyllia sp.	VR	
Hexaphyllia marginata (Fleming)	VR	
Koninckophyllum cf. dianthoides (M'Coy)	Ab-C	L
K. magnificum (Thomson & Nicholson)	Ab	L
Lithostrotion junceum (Fleming)	Ab	L
L. variabile Nudds	R	L
Lonsdaleia floriformis (Martin)	R	
Syringopora sp.	R	
Bivalvia		
Aviculopecten sp.	R	
Conocardium cf. aliforme Sowerby	VR	
Limipecten sp.	C	
L. dissimilis (Fleming)	C	
Lithophaga lingualis (Phillips)	C	
Pinna sp.	C	
P. cf. flabelliformis (Martin)	C	P
Streblopteria sp.	R	
Brachiopoda		
Aliteria minutus (Muir-Wood)	C	
A. panderi (Muir-Wood)	C	P
Antiquatonia hindi (Muir-Wood)	Ab	P
A. indicus (Muir-Wood)	Ab	P
A. muricatus (Muir-Wood)	Ab	P
Avonia youngiana (Davidson)	C	
Cleothyridina sp.		
Composita ambigua (Sowerby)	C	L
Dictyoclostus semirecticulatus (Muir-Wood)	R	P
Dielasma hastatum (Sowerby)	C	L
Echinoconchus elegans (M'Coy)	R	
E. punctatus (Sowerby)	R	
Eomarginifera longispina (Sowerby)	C	P
Gigantoproductus sp.	C	
G. giganteus (Sowerby)	C	
Girtyella sp.	C	
Krotovia spinulosa (Sowerby)	C	P
Linoproductus sp.	R	
Overtonia fimbriata (Sowerby)	C	
Phricodothyris sp.		
Productus sp.	C	P
P. productus (Martin)	C	
Pugnax pugnus (Martin)	C	
Pugilis cf. scoticus (J. Sowerby)	R	
Pustula pustulosa (Phillips)	R	
Rhipidomella sp.	R	
Schellweinella crenistria (Phillips)	C	
Schizophoria resupinata (Martin)	C	
Semiplanus sp.	C	P
S. cf. latissimus (Sowerby)	C	
spirifer indet.		
Spirifer striatus (Martin)	C	
Spiriferina cristata cf. octoplicata (Sowerby)	R	

*1 Relative abundances: VR = very rare, R = rare, C = common, Ab = abundant, blank = not examined

*2 Organisms associated in L = Lithostrotion thickets and P = Antiquatonia bands.

Table 9-1 (continued)

	Overall Relative Abundance *1	Faunal Association *2
Bryozoa		
fenestellid indet.	Ab	P
Fenestella sp.	Ab	P
fistuliporid sp.	Ab	P
Fistulipora encrustans (Phillips)	Ab	P
Penniretopora sp.	C	
Stenodiscus sp.	C	
trepostomatous bryozoa indet.	C	
Tabulipora sp.	C	
Crinoidea		
crinoid stems	Ab	
? Poteriocrinus sp.	R	
Woodocrinus sp.	C	
Echinoidea		
Archaeocidaris sp.	C	P
A. urii Fleming	C	
Melonechinus sp.	C	
Gastropoda		
gastropods indet.	Ab	
? Naticopsis	R	
Ostracoda		
Bairdia sp.		
B. brevis Jones & Kirkby*3		
B. curta M'Coy		
B. hisingeri (Münster)		
B. plebia Reuss		
B. subelongata Jones and Kirkby		
Beyrichiopsis sp.		
Cytheredella sp.	R	
Entomoconchus globosus Jones and Kirkby	R	
E. scouleri Jones and Kirkby	R	
Nautiloidea		
coiled and orthocone nautiloids	C	
Pisces		
Petalodus accuminatus (Agassiz)	R	L
Porifera		
Chaetetes sp.	Ab	L
Hyalostelia parallela (M'Coy)	Ab	
H. smithi (Young & Young)	Ab	
siliceous and calcareous sponges indet.	Ab	
Tholioasterella sp.	VR	
Trilobita		
trilobite fragments	C	
Particeps scoticus minimus Osmólska	C	

*1 Relative abundances: VR = very rare, R = rare, C = common, Ab = abundant, blank = not examined.
*2 Organisms associated in L = Lithostrotion thickets, and P = Antiquatonia bands.
*3 recorded by Latham (1933).

and Semiplanus. A complete list of the elements of A. bands appears in Table 9-1.

Several taphonomic criteria indicate that A. bands are largely undisturbed. An average of 60% of productoid brachiopods in all the bands examined are articulated (e.g. Table H-1, Appdx H). The pedicle spines were still attached on 43% (n = 96) of the specimens exposed in such a way that the pedicle valve could be examined. The presence of spines projecting from the shell establishes that it has not been significantly transported. Additional signs of autochthoneity are found in the wide size range of the most abundant shells, as illustrated by the silicified shells found in the insoluble residues of large limestone blocks (Fig. 9-5).

Although the productoids in A. bands appear to be in situ, they are typically in fairly chaotic attitudes as illustrated in Figs. 9-2, 11-5, Table H-1. In order to determine the reason for such shell arrangements, the orientation and attitude of productoids in bands from two facies was measured (see Table H-1, Appdx H). Shell attitudes were described as "upright" with the brachial valve uppermost, or "overturned" where the trail extended horizontally or pointed downward. Several authors have concluded that both the upright and some overturned attitudes could be life positions (Shiells and Penn 1971; Grant 1968; Muir-Wood and Cooper 1960). The overturned attitude, however, could also be current produced.

Separate analyses of the articulated and disarticulated shells in different attitudes in both the build-up and high-carbonate biomicrosparite facies failed to show a significant preferential hinge-normal orientation (e.g. Fig. 11-6, results plotted for build-up). Many of the shells, however, were not in possible life attitudes (e.g. shells with the pedicle trail pointing downward into the substrate). The absence

Fig. 9-2 The undersurface of an *Antiquatonia* band: high-carbonate biomicrosparite facies.

The large articulated shells of *A.* in various attitudes form a layer beneath a *Lithostrotion* colony. *L.* corallites (arrow head) are visible beneath some shells. A sheet form colony of a fistuliporoid bryozoan (arrows) spreads beneath three upright *A.* shells and encrusts along spines. Note that the frontal (living) surface of the bryozoan is directed downward (toward the viewer) suggesting that the shells stood above the substrate. Specimen width = 9.5 cm. G.T. 46,539

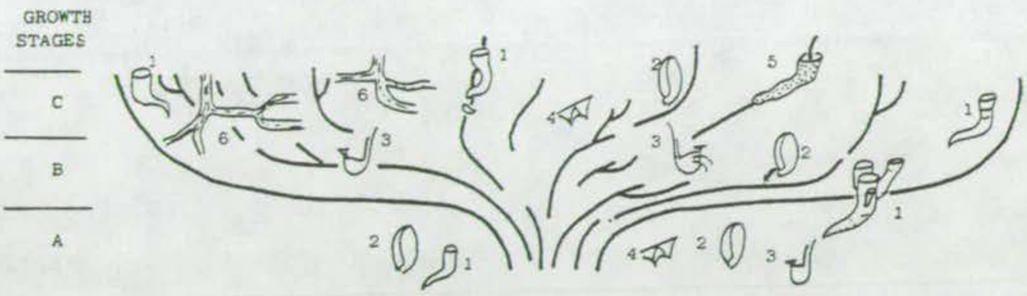
of a marked preferred hinge-normal orientation, particularly among the overturned and separated shells, suggests that strong currents were not a significant factor in separating or moving shells. The activities of scavengers or very gentle currents are more likely disorientating mechanisms.

An insight into the life structure of A. bands is provided by the shell-encrusting fistuliporoid bryozoans (q.v. Ch 14, Fig. 9-2). Sheet-form colonies of fistuliporoids span between shells (Fig. 9-2), or extend upward between two or three overlying shells. They also encrust spines that extend downward beneath shells (Fig. 9-5). By analogy with Recent bryozoans, it is likely that Carboniferous fistuliporoid colonies grew rapidly and were fairly short-lived. The shell surfaces encrusted by a single colony probably stood above the substrate simultaneously (i.e. the bryozoans did not grow upward, keeping pace with sedimentation). Where a colony has spread between several adjacent or overlying shells, it may be assumed that the shells lay piled on the sediment surface. Thus the A. band life-surface probably consisted of a layer of several productoids supported on their spines well above the sediment surface.

A. bands in the build-up and high-carbonate biomicrosparites represent untransported life-surface assemblages specific to firm and stable substrates. Variations in the faunal composition of bands between facies probably reflect the differences in environment that these facies represent. Moreover, the aggregative tendency to form bands appears to have been widespread among productoids in some environments (cf. Muir-Wood and Cooper 1960, plate 33).

9.32 Lithostrostrotion junceum thickets (abbrev L.) Figs. 9-3; 9-4

Crowded colonies of the openly-branched coral Lithostrotion junceum, forming thickets (sensu Squires 1964, p 905) are a characteristic



LITHOSTROTION THICKETS- associated fauna

1 solitary corals-
Koninckophyllum magnificum
Koninckophyllum dianthoides
Dibunophyllum bipartitum
Aulophyllum fungites

		% Articulated	% in life attitude		Sample Size
				vert.	
2 terebratuliform brachiopods-	Composita Dielasma Girtyella	99	24	17	66
3 spinose productoids-	Antiquatonia	100	60	-	16
	Eomarginifera	95	80	-	46
	Dictyoclostus	-	-	-	-
4 other brachiopods-	Schizophoria Schellweinella spirifers Semiplanus	93	-	-	42

5 attached and encrusting organisms-
bryozoans - Fistulipora + fistuliporoids
foraminiferans - Tetrataxis
worms - Spirorbis, Serpuloides
sponges - Chaetetes
algae-- circumcrusts

6 sheltered organisms- crustaceans - ichnogenus Thalassinoides

Fig. 9-3 Biota associated with L. junceum thickets.

Figure shows mode of occurrence of biota (1-6, listed in order of relative abundance) found beneath and within thickets. Data based on field observations, serial sections, insoluble residue material and broken thicket surfaces.

feature of the high-carbonate biomicrosparite facies. They are also present, but less common, in the slightly argillaceous and heterogeneous packstone facies. _L._ thickets reach a maximum size in the high-carbonate biomicrosparite facies, extending over several tens of metres laterally and up to nearly one metre vertically.

Internal structure - _L._ thickets appear to have formed where colonies have grown from approximately the same horizon. Thickets seldom exceed the height of a single large colony in thickness, although parts of one colony may extend over another. Successive vertically-overgrown colonies are absent. In the high-carbonate biomicrosparite facies all _L._ colonies in thickets are upright and appear to be in situ. Layers of _L._ debris, fragmented colonies, and other signs of extensive physical destruction are absent.

Individual colonies within thickets have been traced vertically through 60 cm, although most are 20-40 cm thick. In plan, Fig. 9-4a, most colonies are roughly circular, extending for 40-60 cm, occasionally reaching 1 m diameter. Colonies usually show three growth stages A, B and C (Fig. 9-3). During the initial stage A (Fig. 9-3) the corallites are quite crowded and orientated vertically to form a dense bundle. After reaching a vertical height of 5-15 cm, corallites within a bundle abruptly change attitude to radiate subhorizontally (stage B, Fig. 9-3). The angle of inclination at which corallites radiate varies throughout the circumference of a colony.

During stage B, colonies spread to different distances from their point of inception before again changing growth direction sharply (stage C, Fig. 9-3), avoiding intergrowth with adjacent colonies. At this point (C), the density of corallites thins markedly and the corallites usually turn upward.

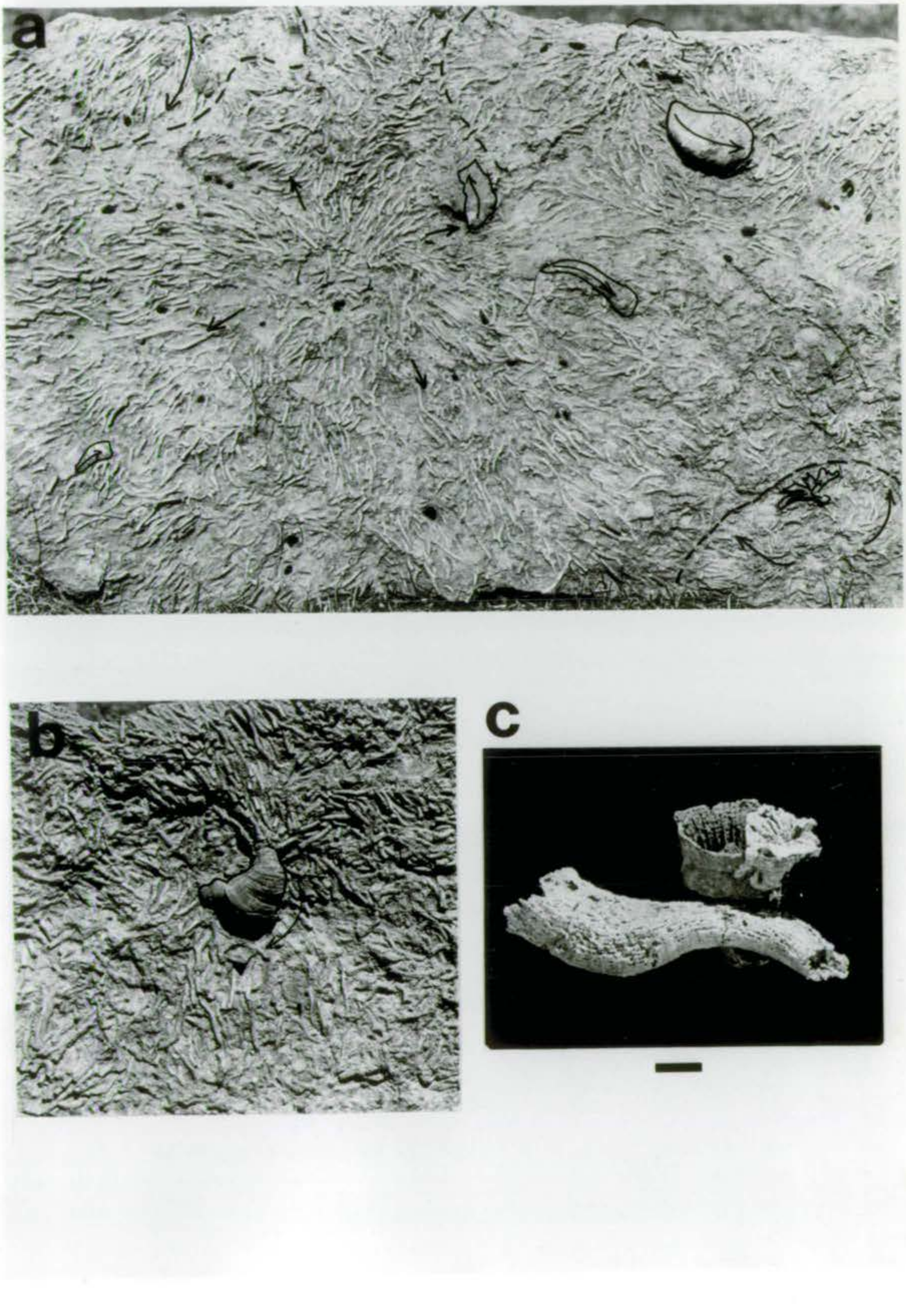
Where two colonies of unequal size have come into contact, the

Fig. 9-4 Features of Lithostrotion thickets.

a. Undersurface of L. junceum thicket; height of specimen = 40 cm. Outlines of colonies (shown at top and lower right) are enclosed by dashed lines. A much larger colony spreads from near the middle of specimen. Large arrows indicate growth directions of colonies during stage B (q.v. text). Smaller dashed lines circle dense bundles of corallites, which are the points of colony origin (stage A). Solitary corals (circled by solid line; arrows show growth directions) are orientated subhorizontally, turning upward into the overlying L. colony during later stages. Openings of Thalassinoides shafts (darkened-in ellipsoids) show extent of bioturbation. Petershill Reservoir, east bank. RSM 1979.1.41

b. An adult solitary coral attached to a L. colony at the point of origin of the colony. Coral later curves upward into colony. This growth habit suggests that after initial attachment, the coral grew upward, keeping pace with the L. colony growth. Length of solitary coral is approximately 5 cm RSM 1979.1.42

c. Two solitary corals attached to a fragment of Lithostrotion. A very small, light-coloured solitary coral is attached to a slightly larger, darker coral which is, in turn, attached to a rare species of Lithostrotion, L. gracile (formerly Diphyphyllum). The smaller solitary corallite has attached to the larger by coiling about its own basal disc. A small talon extends from the side of the coiled protocoralla (q.v. Ch 14). Silicified specimens obtained from dissolution of a L. colony; scale bar = 1 mm. RSM 1979.1.43


a
b
c

larger typically changes growth direction to overgrow the smaller. Where two equally large colonies have met, corallites from the two may turn either upward or sideways. Colony growth usually terminates shortly afterwards. Colonies thus show a strong tendency not to intergrow.

Plan-view growth form - Although most colonies spread radially during the second stage (B), the point of origin is seldom in the centre of a colony. The degree of eccentricity, however, is not very great. The plan-view outlines of 44 colonies were drawn out, revealing that nearly all colonies were roughly circular or slightly elliptical. The only exceptions were small colonies that appeared to have had to accommodate to larger, adjacent colonies early during growth. Thus the shape of L. colonies forming thickets was not found to be markedly asymmetrical. Where asymmetrical colonies were present, their shape could be often ascribed to interference during growth from a neighbour.

Significance of colony shape - In a detailed analysis of the hydromechanical properties of the Recent reef coral Acropora, Graus, Chamberlain and Boker (1978) were able to show a close correlation between colony shape, structure, and current strengths. Their work and that of previous workers (q.v. ibid) shows that corals show various adaptations to strong directional currents. The adaptive strategies shown by corals stem from their need to optimize feeding potential and to reduce hydraulic stress and breakage.

Recent corals inhabiting low-energy environments, where strong directional currents are absent, tend to have delicate, openly-branched growth forms. Such colonies do not show a preferred asymmetry either in the manner of branching, or in the orientation of the branches (Graus et al. 1978). Applying these conclusions to L. would suggest that the currents in environments optimal for thicket development were weak and variably directed.

Associated fauna - Several common and characteristic faunal elements of the high-carbonate biomicrosparite facies are associated with L. thickets (Fig. 9-3). The undersurfaces of many colonies, often a bedding plane, display a higher number of fossils than either the upper surface or the interior of the colony (as revealed by serial-sectioning and broken surfaces). Solitary corals, particularly the dendroid form of Koninckophyllum, K. dianthoides (M'Coy) show the most pronounced tendency to concentrate underneath L. colonies. 37% of the solitary corals examined curved upward into the L. colony (e.g. Fig. 9-4b), indicating that the two had grown contemporaneously. In some cases, L. branches have parted to avoid growth interference with solitary corals. Small productoids, smooth spirifers, and other brachiopods are also concentrated underneath L. colonies. A high proportion are in their presumed life attitudes (Fig. 9-3). Although these faunal concentrations could be fortuitous, it seems more likely that they represent a fauna that lived in the protected habitat beneath L. colonies.

Many of the organisms presumed to have lived beneath the L. thickets are also present amongst the colony branches. The rigid coral structure has preserved an exceptionally high proportion of this fauna in life attitudes. Many of the terebratuliform brachiopods are found with their commissures vertical to bedding, suggesting they were once pedically attached to L. branches (q.v. Ch 14). Small fistuliporoid encrustations also extend along coral branches. Solitary corals are rarely found attached to L. branches (Fig. 9-4c); this growth habit has not been noted previously. Other associated fauna are listed in Fig. 9-3.

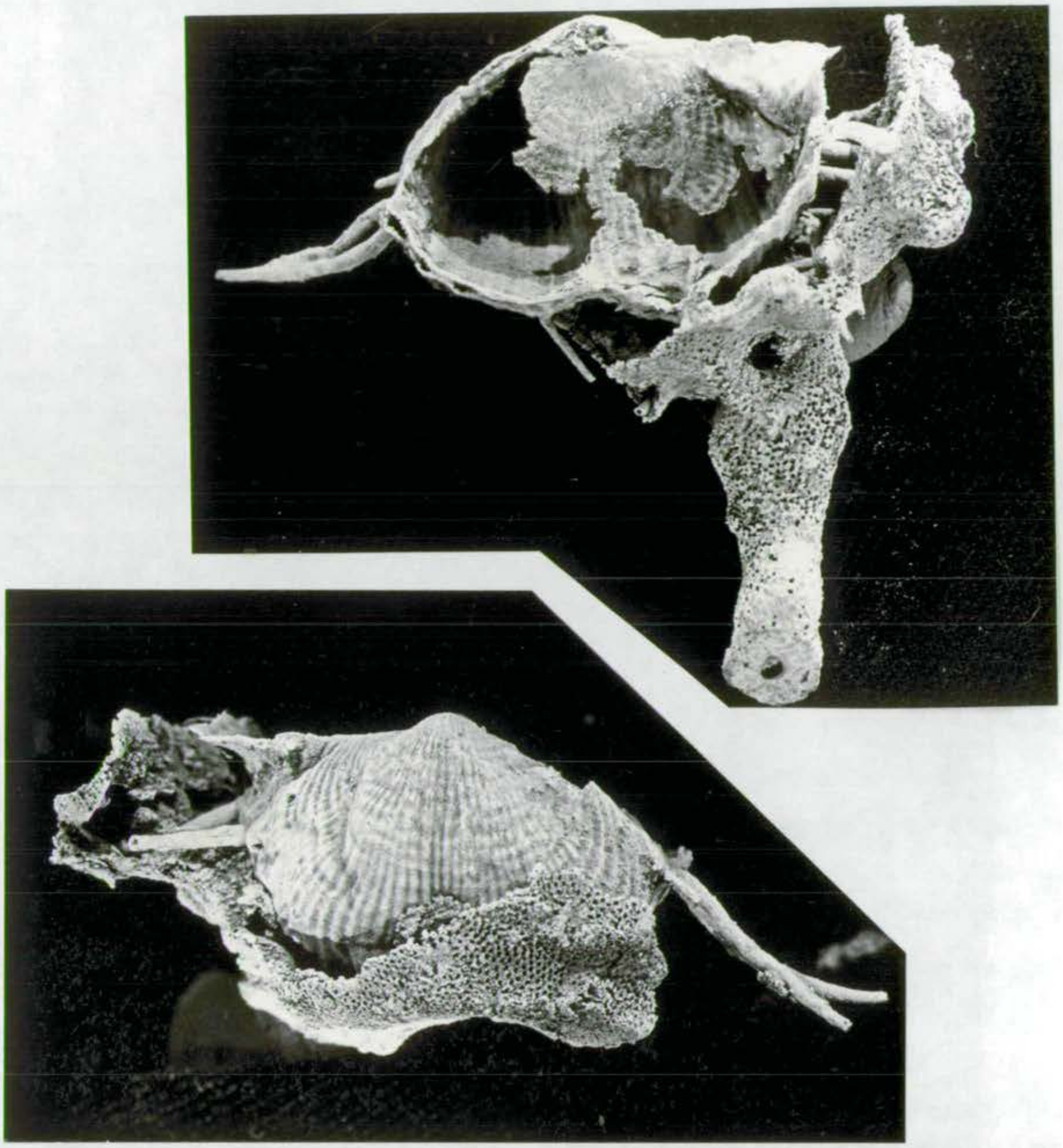
Another previously unrecorded element of the L. thicket association is a presumed crustacean whose burrows are represented by the ichnogenus

Fig. 9-5 Commonly-occurring fossils obtained from acid digestion High-carbonate biomicrosparite facies

a. Dorsal view of Antiquatonia hindi; specimen width = 28 mm.
RSM 1979.1.26

b. Posterior view of same. Note how delicate pedicle valve spines extend outward at hinge (see also 9-5a) growing anteriorly. A fistuliporoid bryozoan extends between spines and encrusts along some of the longer spines. The frontal (living) surface of the bryozoan is directed downward, towards the original sediment surface, indicating that the host brachiopod lived well above the substrate. Note additionally that the bryozoan has grown to within a few mm of the pedicle valve surface, but kept away from actually coming in contact with it. This growth habit suggests that the pedicle spines of productoids may have additionally acted as a protective structure to inhibit encrustation near the commissure, as well as acting as stabilizers for a shell perched above the sediment surface. This specimen was found in its inferred life attitude, with the dorsal valve uppermost; thus it may be assumed to have been in situ and undisturbed.

c. Silicified brachiopod shells, obtained from dissolution of a large (3 kgm) sample of a cream biomicrosparite. Residue contains a wide size range of articulated shells including: terebratuliform brachiopods, Composita, Dielasma, Girtyella (top rows), and spinose productoids Krotovia spinulosa. Note also that spines are present. Large scale bar gradations = cms. The actual size range present in the sample is likely to have been much larger, as less than 5% of shells are typically silicified.
RSM 1979.1.27



Thalassinoides (see Figs. G-2; G-3; Appdx G). Burrow galleries of Thalassinoides were present in the matrix of all thickets examined. The galleries are much more extensively developed in Lithostrotion thickets than in the beds between thickets. The difference in burrow density is so striking as to suggest that a close association existed between L. thickets and Thalassinoides in the high-carbonate biomicrosparite facies. Biffar (1972, p 384) observed that some species of Recent calianassid shrimp, which produce a thalassinoid burrow, commonly dwell among branched coral colonies. The colony presumably provides protection and perhaps food for the crustaceans on those occasions when it emerges from the burrow. The organism which formed Thalassinoides may have derived a similar advantage from Lithostrotion.

Lithostrotion thickets: synthesis - L. thickets formed where environmental factors provided optimal conditions for individual colony growth. Among the physical factors favouring thicket development were firm substrates (for larval attachment) and gentle currents (for stability and to provide food).

The thickets themselves are likely to have formed an open framework through which water could circulate freely. They show very little evidence of having influenced sediment accumulation. In addition, colonies within thickets lack signs of morphological differentiation which might suggest the structure as a whole impeded water flow or contained stagnant areas. Recent experimental work on the flow of water through analogous branched coral colonies (Chamberlain and Graus 1975) indicates that the L. structure would not be expected to impede or deflect flow. This open framework formed a protective habitat for a variety of encrusting, attached, and benthonic organisms.

Fig. 9-6 *Archaeocidaris urii*; bedding surface

A nearly complete, undisturbed test. The slight amount of disarray among spines and plates indicates slight disarticulation before burial. Note also encrusting, sheet-form bryozoan among plates. Large division on scale bar = cms. RSM 1979.1.28

9.33 Koninckophyllum thickets Figs. 2-10; 4-7

Colonies of a dendroid form of Koninckophyllum, resembling K. dianthoides M'Coy, form a unique thicket, occurring at a single horizon between the Lithostrotion thickets along the east bank of the Petershill Reservoir (Fig. 2-10). The thicket is lenticular in shape, extending laterally for 12 m and reaches a thickness of 55 cm. Colonies within the thicket are crowded upright or overturned sideways. The sideways colonies appear to have been re-orientated by compaction.

The associated fauna is similar to that of L. thickets in both composition and mode of occurrence. In addition, many other organisms commonly found in the facies are present, including echinoids, crinoids, fenestellids and Hyalostelia.

Thickets formed by K. have not been apparently reported before, nor have individual coralla reaching the dimensions of the Petershill Fm. specimens. This is clearly an exceptional occurrence of an otherwise common coral and reasons for its development are not obvious. It can only be suggested that the physical factors favouring L. thicket formation (including firm substrates and gentle currents) were at least equally suitable to Koninckophyllum. Further research may show K. thickets to be more widespread and, therefore, not so unusual.

9.34 Microflora and microproblematica of the high-carbonate biomicrosparite facies

An abundant, well-preserved, microflora is also a characteristic feature of the high-carbonate biomicrosparite facies. Algae are most abundant (or best preserved) in fine-grained lithologies.

Fragments of calcareous algae in this facies include Epimastopora, Sphinctoporella, Koninckopora, and indeterminate codiaceans (q.v. Ch 4). Microproblematica forms, particularly Kamaena, Stacheoides and Shartymophycus, are relatively abundant in comparison with other facies.

They occur as part of the encrusting and attached biota (q.v. Ch 14).

Branched filamentous algae, algal lumps and circumcrusts (Fig. 4-7), micritized particles and Girvanella growths are pervasive throughout most of the fine-grained limestones. Structures attributable to binding (q.v. Ch 4) are widespread, suggesting that filamentous algae exerted a stabilizing influence on sediment accumulation patterns.

9.4 Trace fossils Figs. 3-5; G-2; 4-7; 5-5; 5-6

This facies contains roughly equal proportions of bioturbated and apparently unbioturbated beds (Fig. 5-2). Apparently unbioturbated lithologies may preserve layering, dolomite lamination and fossils in life attitudes; alternatively they may be too coarse-grained to preserve unmistakably biogenic structures. Extensive bioturbation is confined to the finer-grained lithologies, where Thalassinoides is common. The ichnology of the high-carbonate biomicrosparite facies is thus characterized by semi-permanent dwelling/feeding burrow systems.

9.5 Environmental discussion

The fine-grained high-carbonate biomicrosparites show various biological structures indicative of substrate stability (q.v. Ch 5; e.g. Fig. 7-4b). Evidence of sediment surface firmness is found in the epifaunal and encrusting mode of life of most of the fauna and, indeed, in the presence of one of the more common elements - cidaroid echinoids. Cidaroid echinoids (Fig. 9-6) have been so widely reported from firm and rocky substrates that their presence is commonly taken as indicative of sediment firmness (cf. Fell 1966, p 313).

Among the physical structures, fractures, open burrow systems, clasts of poorly consolidated sediment and the absence of compaction point to a degree of synsedimentary consolidation which argues for a limited amount of early cement. The physical conditions in which Recent interparticle cements form are fairly well known, and thus provide a useful guide to interpreting high-carbonate biomicrosparite environments.

Widespread early lithification of present day thalassinoid burrows has been reported by Enos and Perkins (1977, p 73). Cementation associated with subtidal algal mats has also been reported by several authors, usually in reef environments (Ginsburg and Schroeder 1973; Schroeder 1972). These authors and many others (q.v. Shinn 1969, p 122; Bathurst 1971, p 367; ibid 1979; Ginsburg, Marszalek and Schneiderman 1971, p 481) have stressed the importance of currents in forming these cements. Current action has been invoked as the mechanism for supplying and renewing the calcium carbonate in pore-spaces. In non-reef sediments, gentle current strengths favour cementation; whereas strong currents inhibit cementation by maintaining particles in motion. Thus signs of early lithification may be taken as suggesting gentle, but continual, current activity.

In the upper third of the facies, cross-stratification and the coarser grain size of the sediment point to stronger and more pervasive currents. Here substrates were more mobile so that algae, burrowers and cementation were less effective stabilizing influences.

The composition and state of preservation of the high-carbonate biomicrosparite fauna provide a more detailed insight into sedimentation patterns in the finer grained limestones. Much of the fauna consists of delicate skeletons of epifaunal organisms that have been preserved in an undisturbed state. The delicacy and mode of life of such accumulations supports the physical data in suggesting generally quiet, but continual circulation patterns, as well as low rates of sedimentation. The manner in which they are preserved, however, is most easily explained by rapid burial soon after death. These delicate life-surfaces could have been readily destroyed by either scavengers or currents if they had remained at the sediment surface for a long interval. Thus the fauna compliments the physical data in indicating gentle, continual currents and provides additional evidence of fluctuating sedimentation. The successive, rapidly-buried surfaces within the sequence argue for a net rapid overall accumulation rate. This pattern of intermittent sedimentation resulting in burial of undisturbed life surfaces may broadly be thought of as being constructive, even though, in this case, biohermal growth did not ensue.

In the upper third of the facies, cross-stratification and the coarser grain size of the sediment mark the onset of stronger and more pervasive current activity. An increase in the proportion of echinoderm debris additionally points to a change in faunal composition. Thus physical structures and mode of preservation point to a greater capacity of physical forces to rework the sediment surface prior to final burial.

These environmental conclusions are integrated in a palaeogeographical synthesis for the high-carbonate facies mosaic as a whole in Ch 12.

CHAPTER 10

THE HETEROGENEOUS PACKSTONE FACIES

10.0 Introduction

This facies predominantly consists of high-carbonate, bedded limestones characterized by variability in grain size, degree of fragmentation and composition. Cross-stratified crinoidal packstones, bands of *Gigantoproductus*, an association of cerioid corals and large colonies of *Chaetetes* are characteristic features of this facies.

10.1 Facies relationships and external features

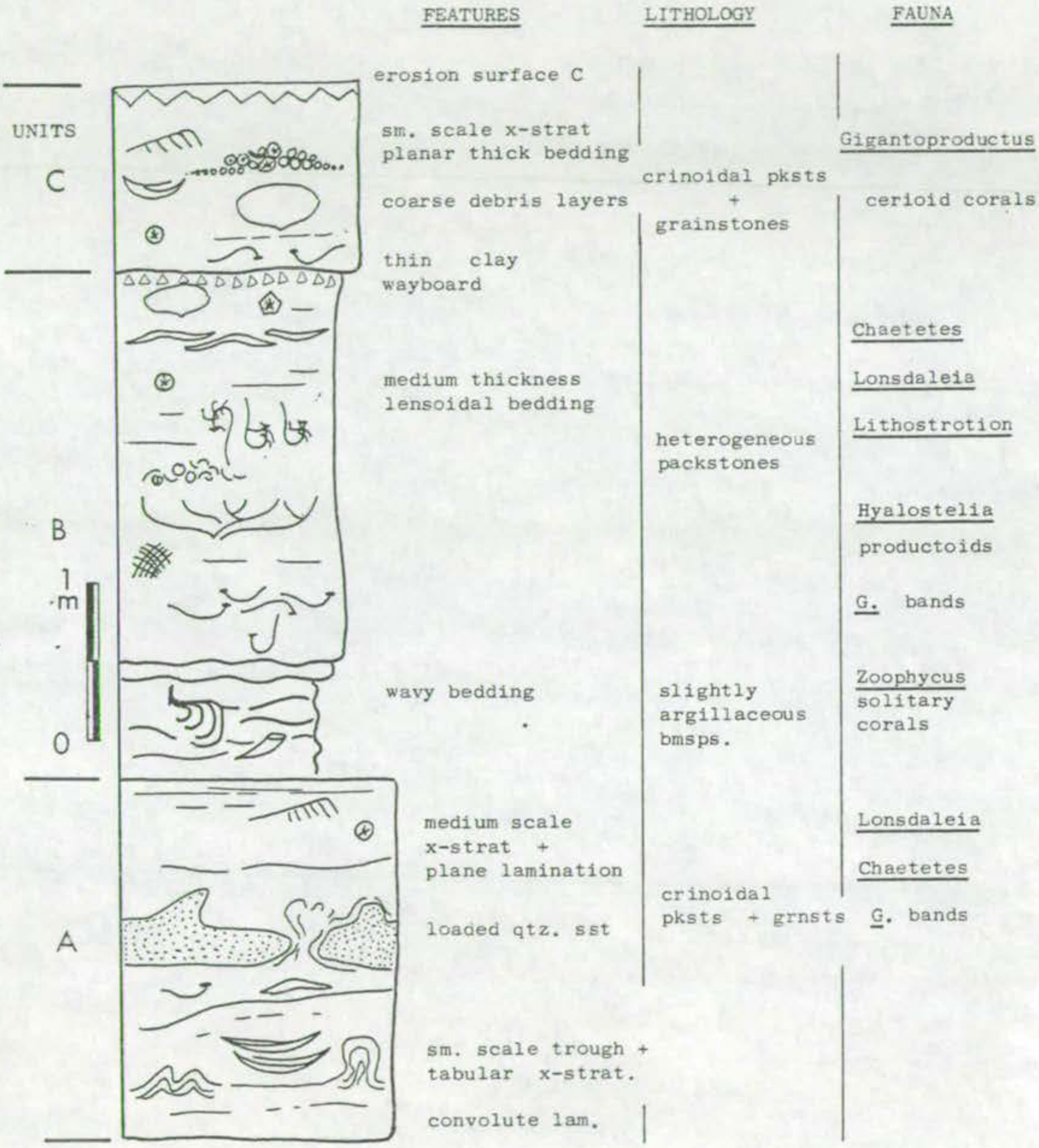
The heterogeneous packstones form a tabular facies, 7-8 m thick, extending from the area of Knock Hill south to Sunnyside (Figs. 8-1; A-1). Lateral facies boundaries are gradational, occurring over relatively wide transitional areas where the adjacent facies interbed (Fig. A-1). The lower boundary is also gradational (occurring over a few beds), while the upper boundary is abrupt, formed by a probable discontinuity, erosion surface C (Fig. 10-1).

10.2 Constituent lithologies

The heterogeneous packstone facies is divided into three units, A, B, and C, shown in Figs. 10-1; A-1; 2-4. These three units show marked lateral compositional and faunal changes in passing from north to south. The most notable trend observed in all three units is a southward decrease in grain size.

10.21 Unit A

This, the lowermost unit, consists of planar-bedded crinoidal packstones and rare grainstones separated by thin calcareous mudstones. In the northern Rifle Range quarries, a discontinuous sandstone occurs in the middle of unit A (Figs. A-1; 2-4; 10-1). With this exception, however, sandstones are absent from the facies. The limestones are predominantly composed of sand-sized echinoderm, brachiopod, bryozoan, Fig 10-1 Generalized cross-section of the heterogeneous packstone facies



coral, and Chaetetes fragments. A significant proportion of the coral fragments can be assigned to Lithostrotion.

Beds within unit A are composite, formed by decimetre-sized sets of different types of internal stratification*1. Sets are generally tabular (planar) in shape, or wedge-shaped (with erosive boundaries.

On the whole, depositional structures within unit A are seldom well-preserved and show a variety of deformational structures, including convolute lamination, over-steepened foresets, and chaotic shell attitudes. These structures, as well as chaotic fabrics within the fine skeletal debris, are probably attributable to several deformative processes, namely dewatering, bioturbation, and re-adjustment following shallow burial.

Where depositional stratification structures are preserved, however, parallel lamination is the prevalent stratification type. Small-scale trough cross-stratification (scour-and-fill) is also very common. Trough-shaped and tabular cross-stratified sets, up to 20 cm thick, also interrupt parallel lamination, or form isolated sets within otherwise parallel-laminated sets.

10.22 Unit B

This unit consists of slightly argillaceous biomicrosparites overlain by a compositionally-varied group of packstones (Fig. 10-1). Within these upper heterogeneous packstones, layers of variably-sorted crinoidal debris alternate with unsorted layers of shell and coral fragments and in situ fossils (corals and brachiopods). Small-scale cross-stratification and overturned shells are common in the coarser debris layers, whereas the finer beds contain a high proportion

*1 stratification terms are illustrated in Fig. 10-2; usage follows Harms, Southard, Spearing and Walker (1975).

of in situ fauna. Large fossils are so abundant as to be in three dimensional contact throughout parts of many beds, forming biostromal accumulations.

10.23 Unit C

The uppermost unit, consists of moderate to well-sorted crinoidal packstones and rare grainstones. The geometry of bedding and of the sets within beds (shown in Fig. 10-2) is generally similar in both units A and C. Medium- and small-scale trough cross-stratification with parallel lamination, occurring in tabular-shaped sets, are the predominant stratification types (Fig. 10-2).

In general, unit C is more poorly-sorted than unit A. It contains a high proportion of echinoderm debris layers and in situ fossil horizons are more common.

10.3 Fauna see faunal list - Table 10-3

The composition of the heterogeneous packstone fauna is strongly dependent on its enclosing lithology (Table 10-3).

10.31 Unit A

The fauna is low in abundance and diversity and typically occurs concentrated along bedding surfaces of the boundaries between sets of cross-strata. The fossils within sets are seldom in life attitudes. Gigantoproductus, Lonsdaleia and Chaetetes are predominant.

10.32 Unit B

The lower interval of unit B contains solitary corals (listed in Table 10-3), Zoophycus and very rarely Chondrites. The fauna is typically concentrated along horizons. In the heterogeneous packstones above (Fig. 10-1) an association of cerioid corals, bands of Gigantoproductus and Chaetetes is common. The fine-grained biomicrosparites contain a few diverse spinose productoid layers, fenestellids, Fig 10-2 Cross stratification in unit C, heterogeneous packstone facies

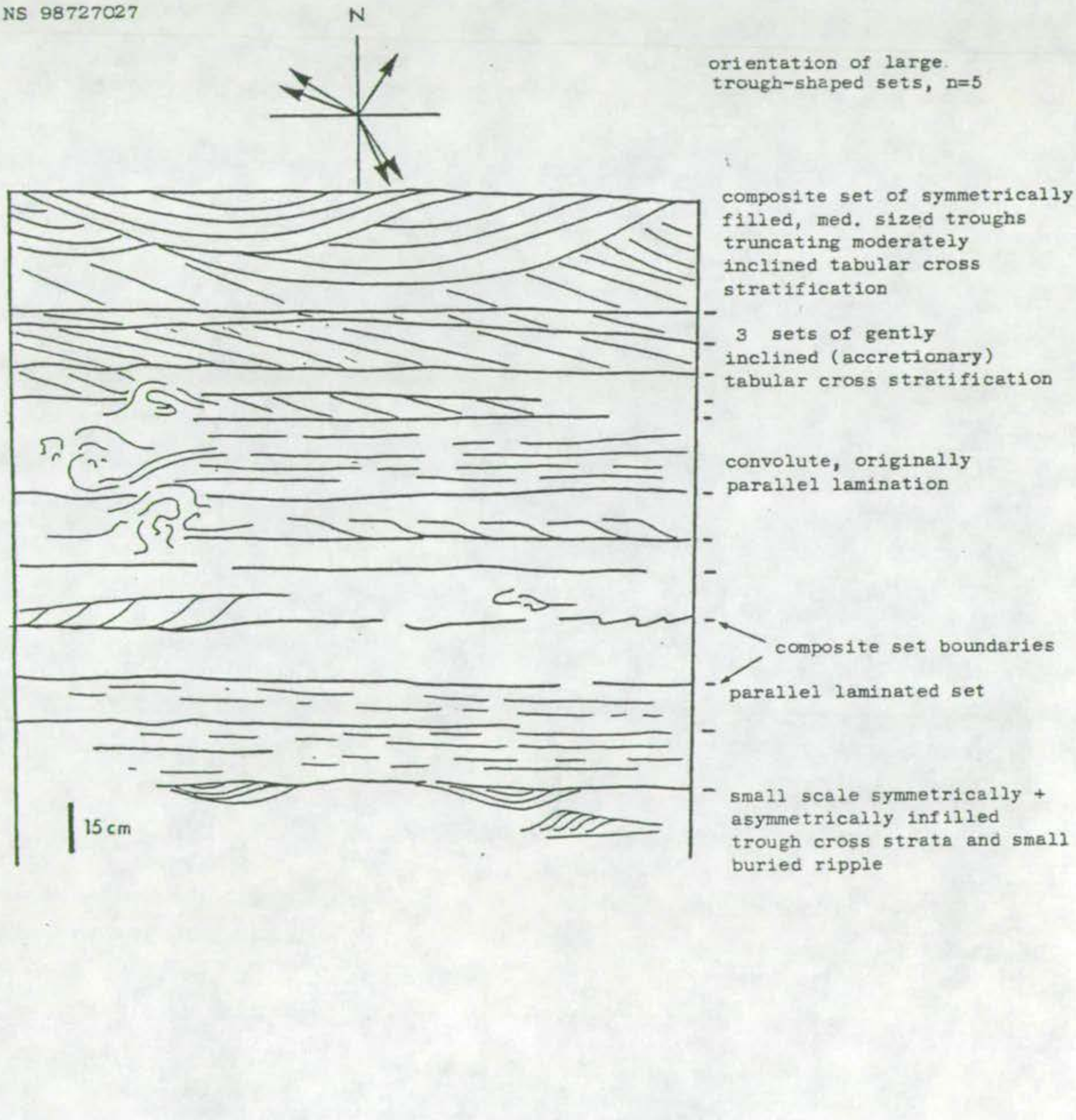


Table 10-3 Invertebrate macrofauna of the heterogeneous packstone facies

	Relative Abundance *1		
	Units		
	A	B	C
Annelida			
Serpuloides sp.	-	VR	VR
Spirorbis sp.	-	VR	-
Anthozoa			
Aulophyllum fungites (Fleming)	-	VR	-
Caninia juddi (Thomson)	-	R	-
Clisiophyllum sp.	-	R	-
Dibunophyllum bipartitum (M'Coy)	-	R	-
Hexaphyllia sp.	-	VR	-
Koninckophyllum cf. dianthoides (M'Coy)	-	C	C
K. magnificum (Thomson and Nicholson)	VR	C	C
Lithostrotion affine (Fleming)	-	R	R
L. gracile *2	-	R	-
L. irregulare *2	-	R	R
L. junceum (Fleming)	C	Ab	R
L. vorticale (Parkinson)	-	C	R
Lonsdaleia floriformis (Martin)	C	Ab	C
Palaeosmilia murchisoni Edwards and Haime	C	C	-
P. regia (Phillips)	-	C	-
? Thysanophyllum sp.			
Syringopora sp.	-	C	-
zaphrentoid indet.	-	VR	-
Bivalvia			
Aviculopecten sp.	-	R	-
? Streblopteria sp.	-	R	-
Brachiopoda			
Aliteria panderi (Muir-Wood)	-	R	-
Antiquatonia sp.	R	C	R
A. hindi (Muir-Wood)	R	C	-
A. indicus (Muir-Wood)	R	C	R
A. muricatus (Muir-Wood)	R	C	R
Avonia youngiana (Davidson)	-	R	R
Brachythyris sp.	C	C	VR
Cleothyridina sp.	-	R	-
Composita sp.	VR	R	-
Dictyoclostus semirecticulatus (Muir-Wood)	R	C	R
Echinoconchus sp.	-	R	-
Eomarginifera longispina (Sowerby)	R	C	R
Dielasma hastatum (Sowerby)	-	R	R
Gigantoproductus sp.	Ab	Ab	Ab
G. giganteus Sowerby	Ab	Ab	Ab
Krotovia spinulosa (Sowerby)	-	C	-
Linoproductus sp.	-	C	R
Productus sp.	-	C	-
? Pugnax sp.	-	C	-
Pugilis sp.	-	R	-
Schellweinella crenistria (Phillips)	C	C	-
Schuchertella sp.	C	C	-
spirifers indet.	R	C	VR
Bryozoa			
fenestellid indet.	VR	C	VR
Fistulipora encrustans (Phillips)	-	C	-
Penniretopora sp.	R	C	C
trepostomatous bryozoan indet.	C	C	C
Crinoidea			
crinoid stems	C	Ab	Ab
Poteriocrinus sp.			
Woodocrinus sp.			

*1 Relative abundance: VR = very rare, R = rare, C = common, Ab = abundant, - = not recorded

*2 identification based on descriptions of Nudds (1975); original author of species not known

Table 10-3 (continued)

	Relative Abundance *1		
	Units		
	A	B	C
Echinoidea			
Archaeocidaris sp.	-	C	C
echinoid plates and spines	-	C	C
Melonechinus sp.	-	R	R
Gastropoda			
gastropods indet.	C	C	C
Ostracoda			
Bairdia sp.	R	C	R
Paraparchites sp.	R	C	R
Nautiloidea			
coiled and orthocone nautiloids	R	C	R
Pisces			
Tomodus sp.	-	R	R
Porifera			
Chaetetes sp.	Ab	Ab	Ab
Hyalostelia parallela (Young and Young)			
H. smithi (M'Coy)	-	C	-
calcareous and siliceous sponge spicules	-	C	C
Trilobita			
trilobite indet.	-	C	-

*1 Relative abundance: VR = very rare, R = rare, C = common, Ab = abundant, - = not recorded

Hyalostelia and rarely echinoids.

10.33 Unit C

Unit C is intermediate in fossil diversity between units A and B. Echinoderms, mostly crinoids, are particularly abundant, preserved in moderate and poorly-sorted debris layers (q.v. Sect 11.33), as are bands of Gigantoproductus, and an association of cerioid corals.

10.34 Gigantoproductus bands (abbrev G.)

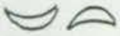
Bands of G. are a characteristic feature of this facies and the overlying crinoidal packstone facies. Although similar aggregates of shells are present in other facies (q.v. Chs 13, 8) G. bands in these facies are unique in the abundance, density, and orientation of their individuals.

G. bands are 5-20 cm thick, formed by laterally and vertically crowded, large shells. Shells are orientated horizontally (i.e. the plane of the commissure is horizontal), either separated by a few centimetres of sediment, or in contact over small distances. Over 60% of the shells in most bands are articulated, while the percentage of overturned shells is more variable (Table 10-4). The overturned, articulated, and disarticulated shells lack an obvious preferred hinge-line orientation*1.

Although each band contains a significant proportion of overturned and disarticulated shells, the overall high percentage of articulation indicates that the gigantoproductids in most bands are basically in situ, or at most, represent minimally transported assemblages (Table 10-4). The extent to which different bands have been concentrated by currents, however, is difficult to estimate.

*1 visual impression - this observation could not be confirmed statistically because of the nature of the exposure.

Table 10-4 Attitude and articulation of *Gigantoproductus* shells in the heterogeneous packstone facies

	SAMPLE SIZE	ATTITUDE (%)				% Articulated	% Overturned
		A 	B 	C 	D 		
Unit A	37	32	16	35	31	67	66
	19	57	5	5	13	62	18
	22	22	14	41	13	63	54
Unit B	10	30	10	10	50	40	60
	8	100	0	0	0	100	0
	9	44	44	0	12	44	12
	67	47	12	30	11	77	41
	47	12	17	21	20	33	41
	37	30	22	40	8	70	48
	22	68	9	14	8	82	22
	14	0	21	57	22	57	79
Unit C	7	100	0	0	0	100	0
	25	25	12	48	15	73	63
	11	18	27	36	22	54	58
	19	31	21	31	17	62	48

Gigantoproductus shells possess a strongly curved concavo-convex shell, heavily weighted in the posterior region of the pedicle valve umbo (cf. Fig. 7-4a). The added weight in this region is likely to have aided in stabilizing the shell in the concavo-convex attitude, orientating the trail obliquely to the sediment surface (Muir-Wood and Cooper 1960, p 44). Ferguson (1978) has shown that the weight distribution of the shell is so uneven that, under certain conditions*[1], the concave-upward attitude is hydrodynamically stable. He found that shells could skid along the sediment surface, as well as be overturned. Thus, a concave-up articulated shell may not necessarily be in situ. However, it is unlikely that a G. shell could be transported for a large distance and remain both concave-up and articulated.

Ferguson (ibid) also found that flow beneath the pedicle valve generated turbulent eddies capable of entrenching a shell in a sand substrate. Under moderate, steady flow velocities, selective sediment removal could leave upright G. shells concentrated as a winnowed assemblage.

A rather unusual shell orientation, found in several bands, consists of 2-3 shells, orientated horizontally, and stacked inside one another. Both articulated and un-paired shells were found stacked together in this fashion. Given the hydrodynamic characteristics of the G. shell, stacked shells may have been formed by either transportation or winnowing. In either case, stacked shells are a sign of extensive current modification of the original accumulation.

In summary, three processes are likely to have contributed to formation of G. bands in the heterogeneous packstone facies:

*1 Ferguson (ibid) carried out flume experiments on hard substrates and sand at moderate flow velocities between 30-40 cms/sec.

a) an initial tendency of G. larvae to aggregate on favourable substrates in an advantageous physical environment (an aggregative tendency); b) selective transportation and removal of some smaller shells; c) residual accumulation by winnowing to produce accumulations with a few stacked shells. The distribution of G. bands would suggest that relatively-short, strong current-dominated intervals were fairly common throughout the facies.

10.35 The cerioid coral association

10.350 Introduction

An association of several genera of cerioid corals, together with numerically fewer fasciculate forms is characteristic of the heterogeneous packstone facies and, to a lesser extent, of the crinoidal packstone facies above.

10.351 Methods

Notes were made on the manner of occurrence of 72 colonies exposed on vertical quarry faces. Where possible, colonies were identified, their size measured and notes made on their encrusting relationships, spacing and manner of colony expansion. The distribution of colonies was mapped out by drawing them on photographs of the exposures. Small colonies were collected, examined, sectioned, and compared with Royal Scottish Museum specimens. These small colonies provided evidence on the manner of growth and colony expansion.

10.352 Faunal composition

The cerioid coral association is dominated by massive, cerioid corals, particularly Lonsdaleia floriformis. Lonsdaleia and other cerioid corals, Lithostrotion vorticale*[1] (Parkinson),

*[1] Nudds (1975) has recently redescribed the Lithostrontiontidae and shown that the species name L. vorticale includes and has precedence over L. basaltiforme and L. clavaticum, to which this form is commonly assigned.

? *Thysanophyllum* and *Palaeosmilia regia* (Phillips), comprise 85% of the association (Table 10-5).

Associated openly-branched fasciculate forms include *Lithostrotion junceum*, *L. affine*, *L. irregulare*, *Koninckophyllum* c.f. *dianthoides* and *Syringopora* sp.

10.353 General description

The association occurs as a concentration of upright colonies which are developed along distinct horizons and often underlain by *G.* bands or coarse shell debris. Colonies that are not based on shells are often not in life attitudes. Most cerioid colonies are 10-15 cm high and 2-3 times wider. Fasciculate colonies are generally 20-40 cm thick and correspondingly 2-3 times wider. The fasciculate colonies are fairly regular in shape, spreading bush-like forms being most common. Cerioid colonies, in contrast, are more variable in shape, ranging from domes, through pancakes, to multi-storey forms (Fig. 10-6).

Most colonies are separated by 20-30 cm of sediment and are not in contact with adjacent colonies. A relatively small percentage occur in thickets (only formed by *L. junceum*) or in structures composed of several colonies belonging to different genera. These multiple-colony structures usually consist of a large colony which has formed the base for several small colonies (Fig. 10-6), or has become overgrown. Less commonly, two colonies show evidence of having grown contemporaneously to form an intergrowth. In many cases it is impossible to distinguish between intergrowths, overgrowths, single large colonies, and complex multiple-colonies. The largest multiple-colonies reach a height of 30-40 cm and spread laterally for 2-4 m. In general, however, most colonies in the cerioid association are small, not in contact with a neighbour, and not part of multiple-colony structures.

Table 10-5 Taphonomic data for the cerioid coral association.

Table lists number of colonies found in different attitudes (illustrated Fig. 10-6). A total of 72 colonies were examined.

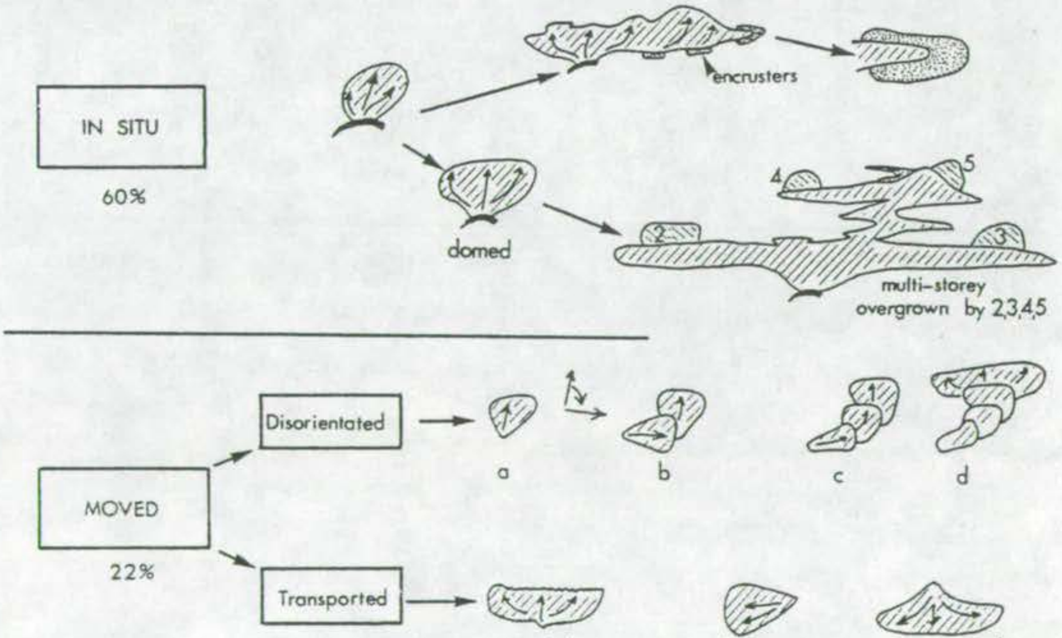
Figure 10-6 Growth form and attitude of cerioid corals.

The common observed growth forms of in situ colonies are shown. Colonies shown growing from Gigantoproductus shell. Encrusters such as Chaetetes, establish that some of the larger colonies lived above the sediment surface. The largest colonies typically have multi-storey forms and are overgrown by smaller colonies (2,3,4,5). Colonies not in situ (those which had been moved from life attitude) were further described as in transported or disorientated attitudes. Changes in growth direction indicate toppling and re-growth during life (arrows).

Table 10-5 Attitude of corals in the cerioid coral association

GROUP	IN SITU	MOVED	UNDECIDED	DISORIENTATED	TOTAL
cerioid indet.	4	12	1	4	17
Lonsdaleia	21	4	3	0	33
Lithostrotion junceum	6	0	0	0	6
Lithostrotion spp. cerioid	9	0	2	0	11
other	3	0	2	0	5
TOTAL	43	16	8	4	72

Fig 10-6



Size - A particularly important aspect of the cerioid coral association as a whole is the large size which colonies commonly reach in contrast to the size of the same species in other facies. Lonsdaleia floriformis colonies, for instance, normally measure 20-40 cm in thickness and extend for 60-80 cm. The thickest recorded Lonsdaleia colony in the heterogeneous packstone facies measured 70 cm vertically and extended 60 cm horizontally. Even the largest colonies from other facies seldom attain the sizes commonly found in Lonsdaleia from the heterogeneous packstones.

10.355 Preservation

60% of the colonies examined were upright and are considered to have been preserved in situ (Table 10-5; Fig. 10-6). 22% had been moved from their life position either by transportation or disorientation. In 11% of the colonies it was not obvious if the colony was in situ or not ('undecided', Table 10-5). Most of the moved colonies were either overturned or sideways; a small number were still in the upright position (but often eroded), a hydrodynamically stable attitude (Fig. 10-6).

Both overturned and upright, in situ colonies were found together at the same horizon. There was no clear relationship between colony size, shape and overturning. Hydrodynamically unstable growth forms and small colonies were not preferentially overturned. Along the horizons where corals were overturned, pebble-to-cobble sized fragments and coarse coral debris were also abundant.

10.356 Disorientated colonies

Corallites in a few of the larger colonies change growth direction very irregularly (Table 10-5; Fig. 10-6). Within a particular colony, corallite growth directions may, at different stages, face upward, downward, sideways, or be nearly opposed to the original direction of growth. Such colonies also have an irregular external shape. The changes in growth direction within a single colony are so varied as to suggest that these colonies have been toppled and that they have subsequently re-grown (similar to the geniculated forms of solitary corals).

These disorientated (sensu Kobluk, Bottjer and Risk 1977b) colonies may reach up to nearly 1 m in width. Associated Chaetetes colonies may also show disorientated growth forms.

Previous reports (cf. Kobluk et al. 1977b) suggest that coral colonies and stromatoporoids which have survived slight movement during life are quite common, particularly amongst colonies lacking a cemented basal attachment. It is likely that the percentage of disorientated corals in the Reservoir Mbr. is much higher than reported here because small changes in colony attitude are not readily reflected in the growth directions of the colonies. Only the most extreme cases of disorientation, where a colony has moved several times, changing direction radically, can be recognized as such in quarry faces.

Several mechanisms may account for disorientated growth forms. In Recent corals, boring organisms may undermine a colony and cause it to topple over (Scoffin 1972b; Kobluk et al. 1977b). The virtual absence of macroborers from the Reservoir Mbr. precludes this mechanism as a possibility. Wave-turbulence, often associated with storms, may disorientate colonies with little regard to their hydrodynamic characteristics, i.e. small and unstable forms are not selectively moved (cf. Kobluk et. al. ibid; Shinn 1968). Alternatively, steady, stable currents could winnow the sediment from beneath a colony, also causing it to topple. Either of the latter two mechanisms may have been significant in moving colonies in the heterogeneous packstone facies.

10.357 Multi-storey growths

The largest cerioid colonies spread outward in multi-storey forms (Fig. 10-6). At each storey the colony forms an open, perforate sheet containing irregular passageways. These colonies often form the base for overgrowths or encrustations.

Encrusting organisms provide an insight into the mode of life of some of these larger cerioid colonies. Numerous encrustions are present beneath colonies, on the holotheca, and rarely at the peripheral edges (Figs. 10-6; 14-6c). In rare cases encrusters have spread from the undersurface onto the upper calical surface.

These encrusters suggest that at least some colonies grew above the sediment surface, rather than keeping pace with sedimentation.

Such encrusted colonies appear to be unique to the heterogeneous packstone facies. The few cerioid colonies which could be examined from other facies lacked an encrusting fauna. This preliminary data suggests that corals could live both well above the sediment surface or surrounded by sediment, depending on substrate type or environment.

10.358 Lithostrotion junceum colonies and thickets

Isolated colonies, or rarely thickets, of L. junceum are interspersed among the cerioid colonies. Thickets in the heterogeneous packstone facies differ in several respects from those in the finer grained, high-carbonate biomicrosparite facies: a) small cerioid colonies commonly inter- or over-grow with Lithostrotion; b) thickets appear to be considerably smaller, seldom exceeding 3-4 m width; c) colonies and thickets show signs of extensive physical destruction - large decimetre-sized fragments of colonies and layers of broken debris are common.

10.359 Chaetetes colonies

Large colonies of the sclerosponge Chaetetes are common amongst the cerioid corals and throughout this facies. Their large size, abundance, and growth forms (q.v. Ch 14) are characteristic features of this facies.

10.35.10 Discussion

The overall abundance and large size of colonies provide evidence of a plentiful food source and sunlight (assuming that cerioid corals were hermatypic). The association is thus likely to have formed in a shallow-water area of moderate current activity. The overturned, fragmented and disorientated colonies additionally show that currents were, at times, a major destructive force. Moreover, the absence of sorting among colonies which have been clearly moved suggests that movement (and also destruction) was associated with turbulence, probably storm-induced.

The evidence of strong current activity raises the possibility that selective destruction may have significantly altered the composition of the cerioid coral association. Scoffin et. al. (in press) found that delicate coral growth forms, which are common in the extant fringing reefs of Barbados, are mostly preserved as rubble in comparable Pleistocene reefs. In view of the evidence for *Lithostrotion* destruction in the heterogeneous packstone facies, there is the possibility that the cerioid association is markedly different from the original life assemblages.

Although the cerioid corals in this facies represent a current-modified assemblage, taken as a whole, enough elements are in situ to consider the occurrence as a valid palaeoecological association. This view is supported by Hill (1938) who described similar coral faunas throughout the British Dinantian (cf. Ch 14).

10.4 The heterogeneous packstone facies : summary and synthesis

The petrology of the heterogeneous packstone facies, its fauna, and mode of preservation provide evidence of two broadly distinguishable sedimentation patterns, shown in Fig. 10-7. Units A and C consist of cross-stratified or chaotically textured crinoidal packstones, with the fauna concentrated at the boundaries between bedding or sets. Trough and tabular (foreset) cross-strata and parallel stratification occur within tabular-shaped sets, or occupy the thickness of a bed. The shape of bedding and its internal set structure suggest that the crinoidal packstones formed extensive sheet-like deposits of ripple- and dune-covered sands and that they were not part of giant bedforms.

Entirely cross-stratified beds may have been storm-produced. Cores through Recent shallow-water carbonates show that storm-produced sequences are selectively preserved, while fair weather processes have a much lower preservation potential (Enos and Perkins 1978, p 58; Ball 1967, p 567). The relative sparseness of the fauna further suggests that the sediment surface during reworked regimes was mobile and thus unsuitable for colonization.

The cerioid coral association, Gigantoproductus bands and large Chaetetes colonies also characterize units A and C. These fossiliferous horizons may represent intervals of relative quiet and constructive growth during an otherwise current-dominated or reworked regime (Fig. 10-7). However, signs of current activity, winnowing, and perhaps turbulence, are even present at these fossiliferous horizons. Fossiliferous horizons may thus have formed in spite of fairly strong current activity where residual shell pavements and coral colonies were available as stable substrates for larval attachment.

The close correspondence between the composition of the fauna and the enclosing lithology, as well as the presence of fossils in intermediate stages of breakdown suggests that reworked units were largely produced locally, on the Bathgate lava platform, and were not transported from elsewhere. In general, reworked units represent palaeogeographical areas and time-periods of high productivity and equally-high rates of skeletal destruction and, therefore, probably low overall rates of sedimentation.

More constructive, quiet intervals are indicated by unsorted and moderately sorted heterogeneous packstone beds. The fauna is dominated by delicate fossils and layers of echinoderm debris (Fig. 10-7). During constructive intervals, the sediment surface was relatively firm and stable. Sedimentation rates are likely to have been high in order to account for the large proportion of fauna buried in situ.

Fig. 10-7 The heterogeneous packstone facies: relationship between physical structures and sedimentation pattern

FEATURE	INTERPRETATION	DISTRIBUTION	SEDIMENTATION REGIME
1 composite sets of medium + small scale trough and tabular cross-stratification	ripple, small dune + sand wave covered sand sheets	UNITS A + C	current dominated REWORKED high rates of grain destruction low rates of sedimentation
2 composite sets of parallel lamination and small scale trough cross-stratification	planar and rippled sediment surfaces forming intermittently mobile substrates		
3 *Gigantoproductus* bands	transported winnowed assemblages in situ		
4 Cerioid corals and large *Chaetetes*	transported disorientated associations in situ		
5 delicate epifauna: *Hyalostelia* spinose productoids echinoids	firm and stable substrate life-surfaces	UNIT B	quiet gentle currents QUIET low grain destruction high rates of sedimentation productivity > breakdown
6 moderate and poorly sorted crinoid debris layers	slightly altered life surfaces		

CHAPTER 11

THE BUILD-UP FACIES

11.1 Diagnostic features

The build-up is a poorly-bedded facies, approximately 9 m thick, which originally possessed topographic relief over the surrounding more level-bedded substrates (Fig. 2-10). It shows a vertical succession of faunas and subfacies; low-diversity mudstones and wackestones pass upward through high-diversity packstones into dolomite laminated packstones and finally crinoidal packstones. These subfacies pass southward into flanking beds (Fig. 11-1). Evidence of contemporaneous relief and a characteristic fauna are diagnostic features of the build-up.

11.2 Facies relationships and exposures

The build-up is exposed in the northernmost quarry at Galabraes, along the southern face of the Reservoir, and in South Quarry (Figs. 2-7; 2-9; 2-11; 11-10, respectively). The general lithological relationships in the upper Reservoir Mbr. (described in Ch 2) as well as lithological and faunal changes within the build-up allow a close correlation between these exposures, providing a discontinuous section through this facies over a distance of 750 m (Fig. 0-7, back pocket).

The build-up lies between the high-carbonate biomicrosparite and the heterogeneous packstone facies (Fig. 8-1). Its lateral facies boundaries are transitional (Fig. A-1; back pocket Appdx). The lower facies boundary is also transitional, marked by the gradual thinning and disappearance of calcareous mudstones from progressively more high-carbonate limestones.

The build-up reaches a maximum thickness of 10.4 m along the southern face of the Reservoir (Fig. 2-10), thinning to 7.4 m at Galabraes Quarry, nearly 600 m further north. At both these exposures

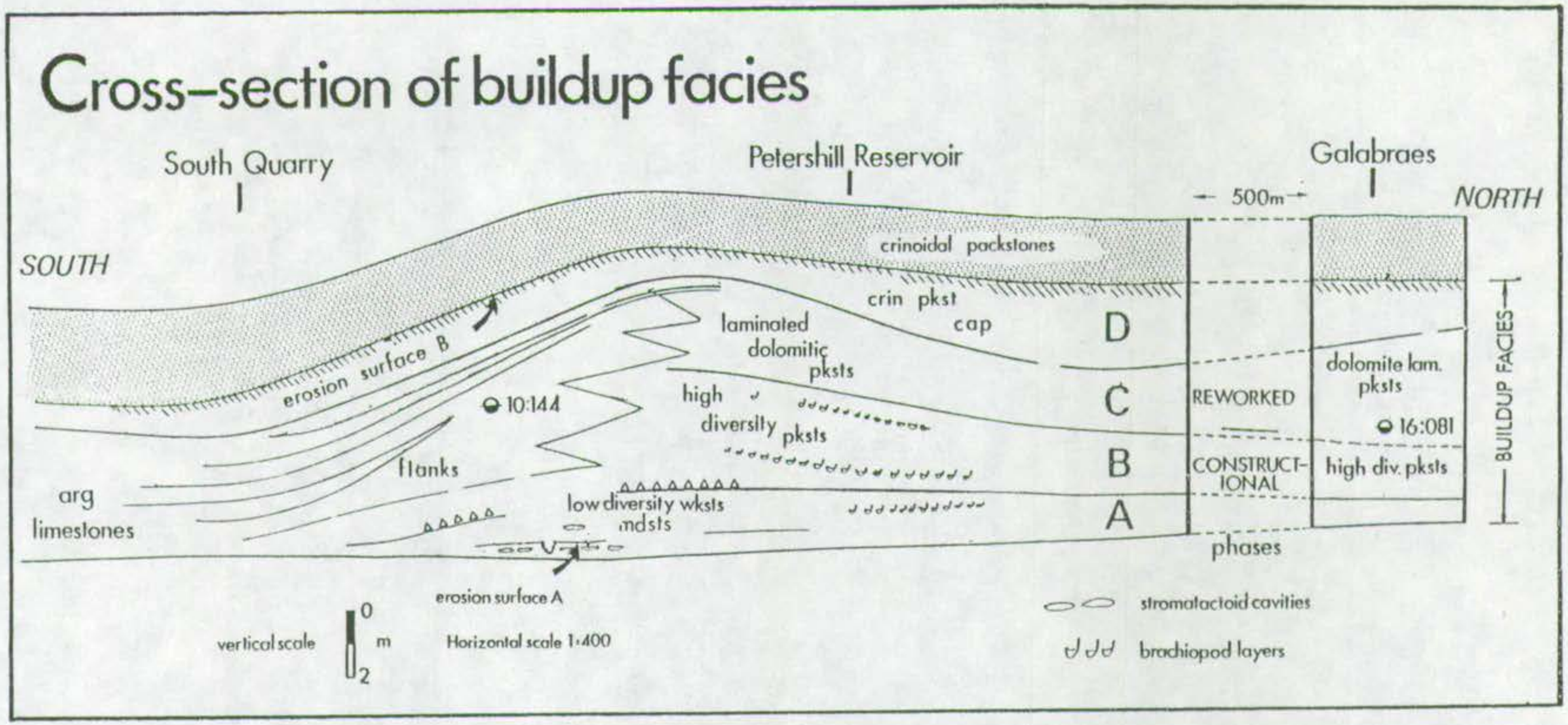


Fig. 11-1 Generalized cross-section of the build-up facies

it appears to thicken westward. Between these exposures, the build-up as a whole and its constituent subfacies change thickness slightly as shown in Fig. 11-1. South of the Reservoir, at South Quarry, the build-up also probably thins before passing laterally into a thin tongue of slightly argillaceous and argillaceous limestones (Figs. 11-1; A-1). The available evidence does not provide a clear enough picture to determine the overall, three-dimensional morphology of the build-up.

11.3 Subfacies

The build-up is divided into five subfacies, all high-carbonate limestones: A) low diversity wackestones and mudstones; B) high-diversity packstones; C) dolomite laminated packstones; D) a crinoidal packstone cap; E) flank beds (Figs. 11-1; 11-15).

11.31 Subfacies A - low diversity wackestones and mudstones

Figs. 2-9; 11-1; 11-15

This is the basal subfacies, consisting of grey and cream bedded limestones passing upward into unbedded limestones. Differences in the vertical distance between fixed horizons (such as brachiopod bands and clay partings) give the impression that this subfacies has a low, mound-like form. Depositional dips could not be measured, however. An erosional surface (A, Fig. 11-1) is present approximately 1 m above the base of this subfacies.

11.311 Petrology

Commonly occurring lithologies include cream, blue-grey, and yellow-brown stained wackestones and mudstones, often containing stromatactoid cavities and brecciated horizons (see Ch 7 and Figs. 3-5; 6-3; 6-4; 6-6; 6-8). The matrix usually consists of microspar or clotted micrite showing layering and containing filamentous algal intergrowths throughout. Depositional textures are largely matrix supported

(Fig. 11-15) and fossil fragments are unsorted.

11.312 Fauna Table 11-2

The number of individuals and species in subfacies A is low in comparison with other build-up subfacies (Table 11-2). Within subfacies A, most macrofossils occur evenly distributed both vertically and probably horizontally, seldom reaching a sufficiently high density to form a discrete layer. Brachiopods and bryozoans are nevertheless, abundant enough to be in three-dimensional contact in a few decimetre-sized areas. Additional exceptions are two bands of Antiquatonia occurring 50 and 130 cm above the build-up base. In these bands and throughout the subfacies a high proportion of the shells are articulated and in life attitudes (Table H-1, Appdx).

The fauna of subfacies A is listed in Table 11-2. It is dominated by spinose productoids (particularly Antiquatonia spp., Eomarginifera longispina) Hyalostelia and fenestellid bryozoans). Schellweinellid, terebratuliform, and spiriferoid brachiopods, along with fistuliporoid bryozoans and trilobites are less common. Caninia juddi (Thomson), a large solitary coral, is an exceptional element of the fauna, occurring in two clay partings considered atypical of the subfacies as a whole.

11.32 Subfacies B - high diversity packstones

The boundary between subfacies A and B is gradational, marked by an increase in the abundance of the fauna and well-defined layering (q.v. Ch 7) within otherwise poorly-bedded limestones. The lower half of subfacies B consists of cream-coloured, layered packstones interrupted by poorly-sorted crinoidal packstones and several thin clay wayboards (q.v. Ch 7). Dolomite laminated packstones become more common in the upper part of the subfacies. The layered packstones are petrographically similar to the finer grained lithologies

Table 11-2 Invertebrate macrofauna of the build-up facies

	Relative Abundance *1				
	Subfacies				
	A	B	C	D	Flanks
Annelida					
Cornulites sp.	-	2	-	-	-
Serpuloides sp.	1	3	3	-	-
Spirorbis sp.	3	4	2	-	3
Anthozoa					
Amplexizaphrentis sp.	1	-	-	-	1
Amplexus coralloides	-	2	1	-	-
Aulophyllum fungites (Fleming)	-	-	-	-	1
? Aulophyllum juv. indet.	1	1	-	-	-
Caninia benburbensis Lewis					
C. juddi (Thomson)	1	1	-	-	-
Dibunophyllum bipartitum (M'Coy)	-	-	-	-	1
Hexaphyllia marginata (Fleming)	-	3	2	-	2
Heterophyllia sp.					
Koninckophyllum dianthoides (M'Coy)					
K. magnificum (Thomson and Nicholson)	-	-	-	-	1
Lithostrotion junceum (Fleming)	-	-	1	2	1
L. variabile Nudds	-	-	1	1	2
L. indet. (cerioid)	-	-	-	1	-
Lonsdaleia floriformis (Martin)	-	-	1	3	1
Syringopora sp.	-	2	2	-	-
Bivalvia					
? Aviculopecten small form	1	3	1	-	-
Conocardium aliforme Sowerby	-	3	2	-	-
C. rostratum Martin					
Lithophaga lingualis (Phillips)	2	5	1	-	1
Pinna sp.	2	3	2	-	2
Schizodus sp.	-	2	-	-	-
smooth bivalve indet.	2	4	1	-	-
? Streblopteria	-	2	-	-	-
Brachiopoda					
Aliteria panderi (Muir-Wood)	-	3	3	-	-
Antiquatonia sp.	3	5	5	1	4
A. hindi (Muir-Wood)					
A. indicus (Muir-Wood)					
A. muricatus (Muir-Wood)					
Avonia youngiana (Davidson)					
Brachythyris sp.	2	5	4	3	2
Cleiothyridina sp.	-	3	3	1	1
Composita sp.	-	1	3	-	2
Dielasma hastatum (Sowerby)	1	5	4	1	2
Dictyoclostus semirecticulatus (Muir-Wood)	1	5	4	-	-
Echinoconchus elegans (M'Coy)	2	5	3	-	-
E. punctatus (Sowerby)					
Eomarginifera longispina (Sowerby)	2	3	3	1	2
Gigantoproductus sp.	1	1	2	3	3
G. giganteus (Sowerby)					
Krotovia spinulosa (Sowerby)	1	5	3	1	2
Phricodothyris sp.	-	3	3	1	2
Productus sp.	2	4	1	1	1
P. productus (Martin					
Pugnax pugnus (Martin)	1	3	3	-	1
Pugilis cf. scoticus (Sowerby)	-	3	2	-	2
Schellweinella sp.	1	2	2	2	2
S. crenistria (Phillips)					
Schuchertella	1	3	3	3	2
Semiplanus sp.	-	2	3	2	4
Rugosochonetes sp.	-	1	-	-	-
Spirifer striatus (Martin)	1	2	1	1	1
Spiriferina cristata cf. octoplicata (Sowerby)					
spirifers indet.	2	2	3	1	1

*1 Relative abundance: 1 = very rare to 5 = very abundant, - = not recorded, blank = not examined.

Table 11-2 (continued)

	Relative Abundance *1				
	Subfacies				
	A	B	C	D	Flanks
Bryozoa					
fenestellid indet.	4	5	3	1	2
Fistulipora encrustans (Phillips)	2	4	2	1	3
Penniretopora sp.	1	4	3	1	2
Stenodiscus sp.	1	2	1	1	1
Tabulipora sp.	1	2	1	1	1
Crinoidea					
crinoid stems	1	2	5	4	3
Phanocrinus sp.					
Poteriocrinus magnus Wright					
Ureocrinus sp.					
Woodocrinus					
Echinoidea					
Archaeocidaris sp.	1	1	5	3	5
A. urii Fleming					
Melonechinus sp.	-	-	5	4	-
echinoid plates and spines indet.	1	2	5	4	3
Gastropoda					
gastropods indet.	2	3	3	1	1
Naticopsis sp.					
Ostracoda					
Bairdia sp					
B. plebia Reuss					
Cypridellina sp.					
Cypridinella sp.					
Entomoconchus globosus Jones, Kirkby, and Brady	1	5	3	2	2
E. orbicularis Jones, Kirkby, and Brady					
E. scouleri M'Coy					
Paraparchites sp.	2	4	3	1	2
Porifera					
Chaetetes	1	2	3	2	3
Hyalostelia parallela (Young and Young)	3	5	3	-	1
H. smithi (M'Coy)					
Tholioasterella sp.	1	2	-	-	-
calcareous and siliceous sponge spicules	1	4	2	1	3
Pisces					
Petalodus acuminatus	-	1	-	1	1
Tomodus sp.					
Trilobita					
Particeps scoticus minimus Osmólska	2	2	-	-	-
trilobite indet.	2	4	-	-	-

*1 Relative abundance: 1 = very rare, to 5 = very abundant, - = not recorded, blank = not examined.

in subfacies A, except that layering is better defined and the proportion of fossils has increased so as to alter depositional texture over small areas.

11.321 Fauna

The diversity and abundance of the fauna within subfacies B is unsurpassed in the build-up or in any other facies in the Reservoir Mbr. Several taxa which are characteristic of the build-up as a whole appear in this subfacies (q.v. Fig. 11-16).

The dominant elements of the fauna include: spinose productoids (listed in Tables 11-2; 11-7); Hyalostelia, fenestellids, and Entomoconchus (a cypridean ostracod). Small pectinoid bivalves, rostroconchs (Conocardium), schellweinellids, chonetoid and terebratuliform brachiopods, and fistuliporoid bryozoans are slightly less common. The fauna as a whole is in situ and undisturbed, as shown by: a) a fairly complete size range of organisms; b) preservation of delicate structures, e.g. spines or attached epifauna; c) a high proportion of shells in life attitudes (q.v. Table H-1, bands d-h); d) absence of sorting. More detailed evidence of allochthoneity follows, given as part of the description of each of the faunal associations which are characteristic of subfacies B.

Four assemblages recur throughout subfacies B. They form discrete layers which may also include the more common faunal elements listed previously.

Hyalostelia mats (Fig. 11-3) - Skeletons of the siliceous sponge Hyalostelia (usually H. parallela M'Coy, less often H. smithi Young and Young) occur in undisturbed or slightly disrupted mats comprised of several individuals (Fig. 11-3). Although H. parallela is present in other facies, the tendency for it to occur in mats is a characteristic feature of subfacies B. Mats consist of two or

Fig. 11-3 Hyalostelia mats, subfacies B, build-up, southern exposure, Petershill Reservoir.

a. Undersurface of an undisturbed mat. The large transverse rays form a rectilinear grid, or meshwork. Several such superimposed meshworks constitute a mat. Note that most of the associated brachiopods, such as Krotovia spinulosa (K) are in life attitude, with the pedicle valve lowermost.
RSM 1979.1.29

b. The upper surface of a cream biomicrosparite etched in dilute acetic acid for several days. Etching reveals a disarray of large H. spicules abundant enough to have had a stabilizing influence on accumulating sediment. Thin section examination of similar specimens suggests that less than 5% of the spicules actually present have survived acid treatment. Most are replaced by calcite and thus not revealed by this method. The attitude of the large transverse rays (H) reveals that the original mat has been disturbed slightly. Etching also reveals other elements of the mat surface: Hexaphyllia (X), a heterophyllid coral which is diagnostic of the build-up as a whole, brachiopod spat (b), and productoid spines (p).
RSM 1979.1.30


K


H
X
b
p
b

more layers of dermal transverse rays (Fig. 11-3). Thin sections reveal that the large apertures within the meshwork of undisturbed mats (Fig. 11-3a) contain microscleres (e.g. Fig. F-2, Appdx), indicating that the original sponge skeleton was a more dense structure than its appearance on a weathered surface would suggest.

Where more than two layers of spicules overlie one another it is likely that more than one sponge was present. Mats, formed by laterally and vertically overlapping skeletons, spread up to 30 cm and reach a thickness of 7 mm. Meshworks from single skeletons may extend up to 9 cm, indicating that the original sponges must have been quite large.

Robust rod-bundles, thought to have formed an anchor (Hinde 1887, p 158) are also present, a sign that at least some of the sponges are in situ. The rod bundles have not, however, been preserved attached to the spicule meshwork. Thus, Hyalostelia mats may represent either life-surface assemblages of individuals compacted together, hydrodynamic assemblages, or both. Aggregates of Entomoconchus (description follows) are often found associated with mats.

Hyalostelia mats and those of other siliceous sponges may have exercised some control on sedimentation in the lower build-up (subfacies A, B). In addition to contributing a significant amount of skeletal material, siliceous sponges may have aided in sediment stabilization. The potential of siliceous sponges in this role has not been considered before.

In the build-up, Hyalostelia and other siliceous sponges are a common skeletal constituent, particularly in sub-facies B. They comprise an average of 10-15% (up to 30%) of 80% of the thin sections examined from these subfacies (n = 29). These point counts are likely to be conservative as microscleres are very difficult to identify.

Moreover, luminescence petrology indicates that the actual percentages may be still higher.

Gentle acid etching of undisturbed and splayed mats reveals a three-dimensional meshwork of spicules that could have easily trapped or retained sediment, particularly when covered with soft tissue (Fig. 11-3; see also Reid 1968; Tasch 1973). Both acid-etching and thin-section examination reveals that mats supported an abundant fauna of encrusting organisms, including: foraminiferans, brachiopod spat, spirorbid worms, and microproblematica (Shartymophycus, Stacheoides). The encrusters occur both attached to the spicules themselves (a post-mortem attachment) and to the micrite in the interstices of the spicule meshwork (an in vivo/post-mortem attachment). The interstitial micrite may represent sediment-impregnated tissue, micrite cement, or mechanically-trapped sediment.

In addition, micrite-impregnated, splayed and undisturbed sponge-spicule meshworks sometimes form intraclasts. These intraclasts are similar to those presumed to have been algally bound in that they represent semi-consolidated particles that have been eroded and minimally transported. Such intraclasts do, however, provide the clearest evidence of the sediment-stabilizing influence of siliceous sponges. It appears that the surface of the sponge body, or its decaying remains, served to entrap fine sediment, while providing a firm surface for attachment. Also, siliceous sponge spicules and mats are so widely spread in the lower build-up as to constitute a significant sediment contribution in themselves. Preliminary observations on their abundance in other Dinantian carbonate mounds suggests they had a similar role elsewhere.

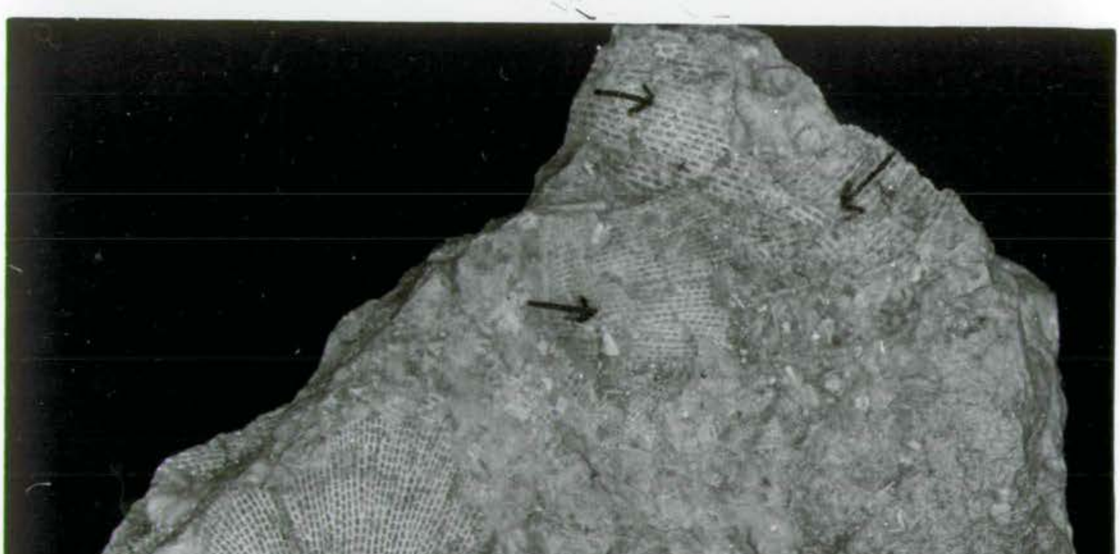
Fenestellid bryozoan mats (Fig. 11-4b) - Fronds of fenestellids, forming loose mats, and fine bryozoan debris are an

Fig. 11-4 Build-up faunal associations: *Entomoconchus* aggregates and fenestellid mats

a. *Entomoconchus* aggregate. A broken rock undersurface, separated along layering, reveals a cluster of variably-sized ostracod carapaces orientated with their sagittal crests parallel to layering. Arrow points to a pair of valves that can be re-paired, an indication that at least some disarticulation has occurred in situ. Other associated fauna include the small spinose productoid *Echinoconchus elegans* (e), *Spiriferina* sp. (s), and the rostroconch *Conocardium* (c). Careful examination reveals a disarrayed *Hyalostelia* meshwork beneath the *E*. aggregate (see in region of h). Magnification approximately x 1. RSM 1979.1.43

b. Fenestellid mat, broken top of rock surface covered in baby oil. Arrows point in growth direction of large, imbricated fenestellid bryozoan fronds. Note also abundant fine bryozoan debris. Different types of fenestrule arrangement suggest fronds represent distinct species. Divisions on scale bar underneath = centimetres. G.T. 46, 411


e
h
c
s



abundant constituent of the lower build-up (subfacies A, B). Individual bryozoan colonies reach 15 cm across and are traceable vertically through as much as 6 cm. A few conical or spirally-shaped colonies are preserved in near vertical attitudes, likely to represent the life-attitude of the original bryozoan (Cowen and Rider 1972, p 156). The delicacy of in situ colonies and their manner of burial are indicative of quiet water and rapid burial.

Fenestellid mats consist of imbricated, slightly compacted fronds forming a loose framework. They may spread laterally up to 30 cm and extend vertically 3-4 cm. The mat fabric is relatively open and small shelter cavities beneath fronds are present. The original mat framework is extremely difficult to study, however, as the mats were particularly susceptible to early diagenetic modification (q.v. Ch 6). The attitude of individual colonies within mats suggests they may have formed in two ways: a) by slight compaction of in situ colonies; b) from transportation of broken fronds.

Mats are particularly abundant in subfacies B, less common in subfacies A; and rare outside the build-up in adjacent facies.

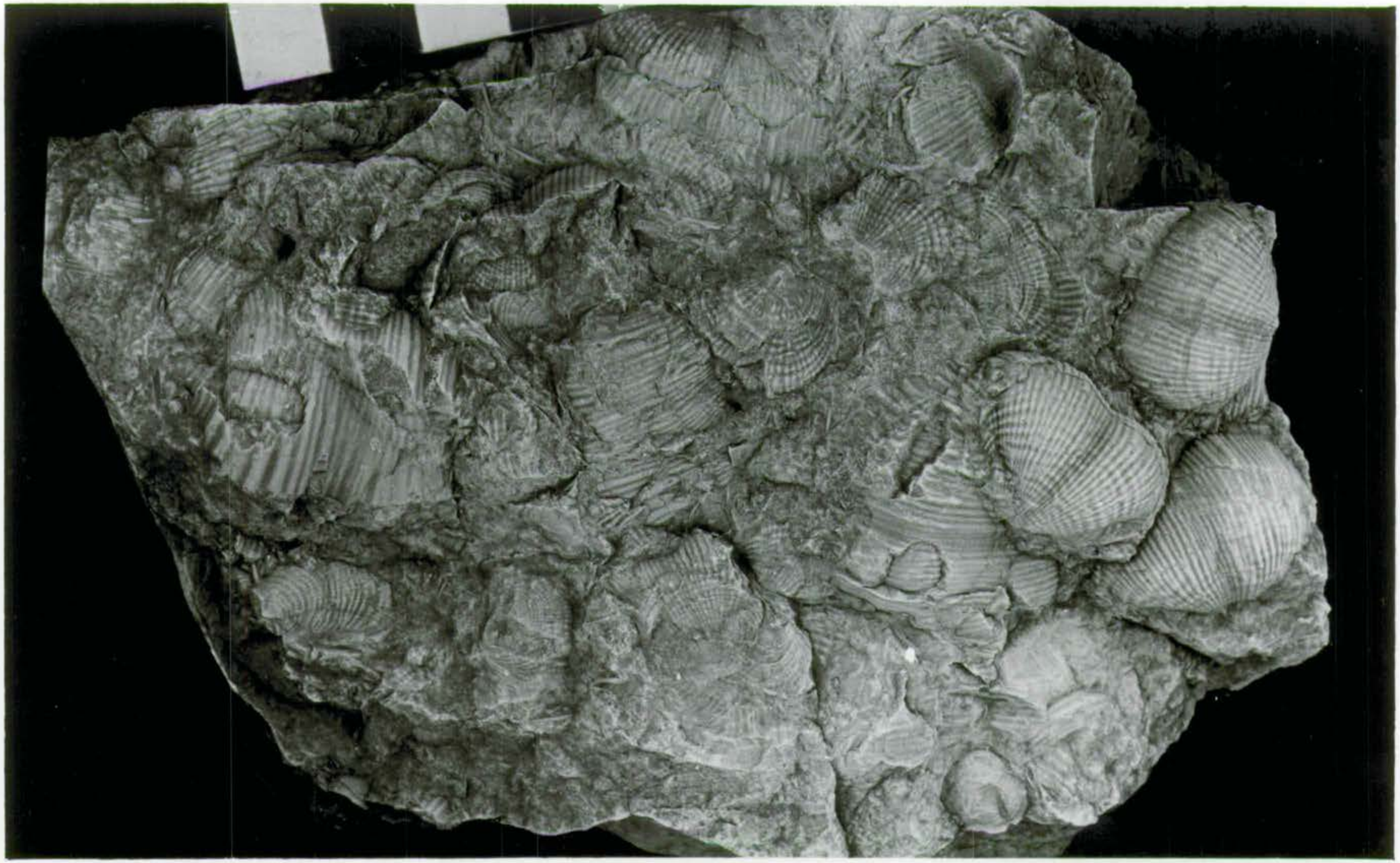
Antiquatonia bands (Figs. 11-5; 11-6; Tables 11-7; H-1, Appdx) - Bands of brachiopods similar to those described in Ch 9 spread at decimetre vertical intervals throughout the lower build-up (general distribution shown in Table H-1). They consist of largely in situ shells, rather chaotically arranged (Fig. 11-5) and in three-dimensional contact over large parts of the band. Most shells are articulated, while a more variable (but still quite large) percentage are upright (Fig. 11-6). Neither upright, nor overturned shells show a preferred hinge-line orientation (Fig. 11-6).

A. bands in the build-up differ from those in adjacent facies in the diversity of their associated fauna (listed in Table 11-7). As

Fig. 11-5 Undersurface of an _Antiquatonia_ band from the build-up facies. 9I 46 394

The band consists of a large number of articulated _Antiquatonia_ shells in chaotic attitudes but in three dimensional contact.

Divisions on scale bar = centimetres.



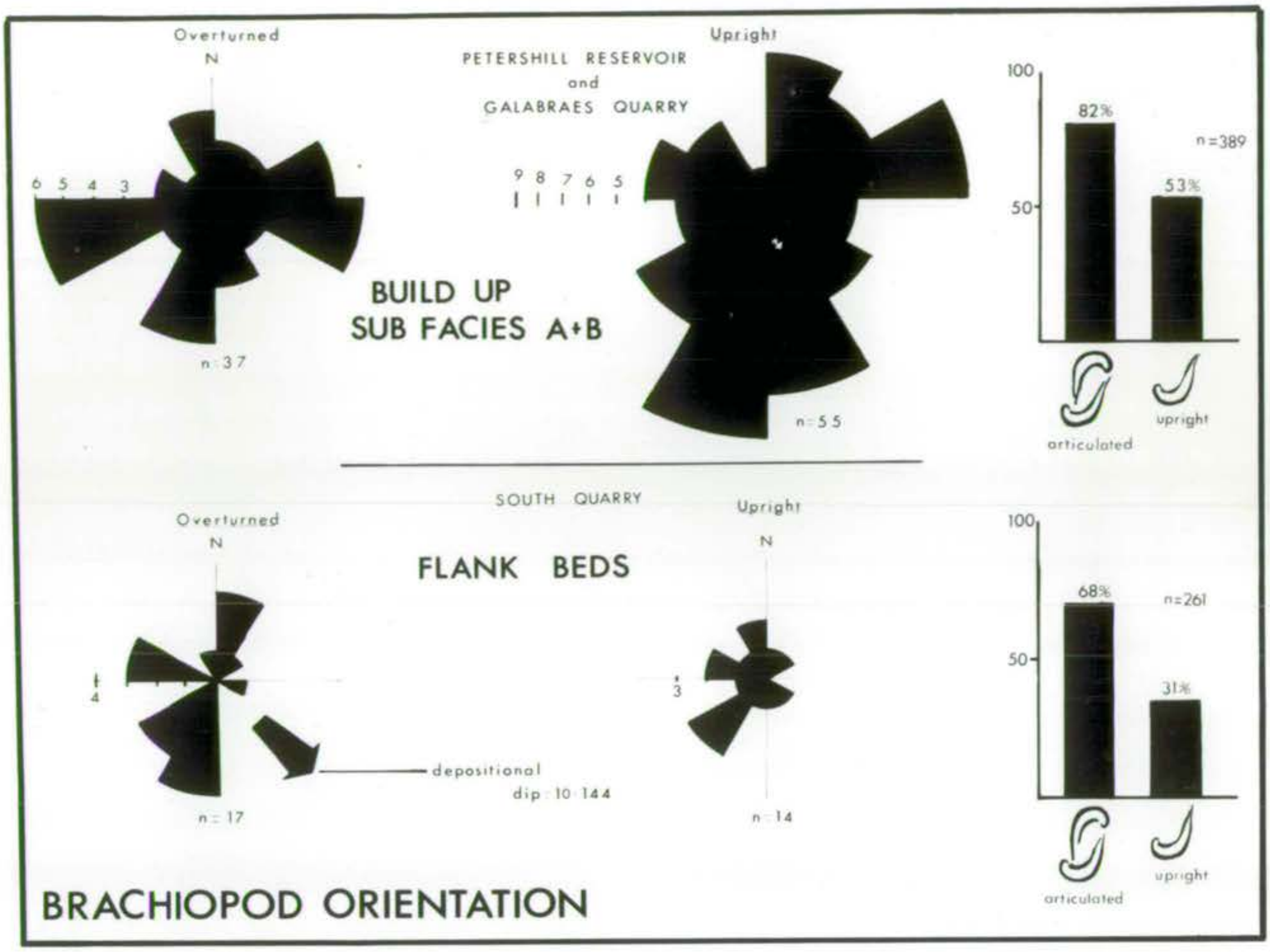


Fig. 11-6 Brachiopod orientation

The orientation of spinose productoids in Antiquatonia bands in the build-up facies. Rose diagrams show distribution of hinge-normal azimuths. These azimuths are measurements of a line drawn normal to the hinge line in the anterior (growth direction) from the umbo. Rose diagrams show that both upright and overturned shells on the flanks and in the lower build-up (subfacies A and B) lack a preferred orientation or a consistent relationship to depositional slope. Histograms indicate that a high percentage of shells are articulated and upright.

Table 11-7 Commonly occurring fauna of *Antiquatonia* bands in the build-up facies.

Antiquatonia band fauna

75%	10%	5%	10%
spinose productoids	other brachiopods	bivalves + bryozoans	other forms
Antiquatonia *	terebratuloids	*Pinna* *	*Hyalostelia*
Eomarginifera	spirifers	fenestellids	*Chaetetes* *
Krotovia	schellweinellids	?*Aviculopecten*	*Entomoconchus*
Dictyoclostus		*Conocardium*	gastropods *
Echinoconchus *			trepostome bryozoans
Aliteria			trilobites
Pugilis			
Overtonia			
*Productus**			

Encrusting and attached organisms:*
bryozoans: *Fistulipora*
sponges: *Chaetetes*
worms: *Spirorbis*
foraminiferans: *Lituotubella*, *Tetrataxis*, *Eotuberitina*

* groups commonly found in all bands

the shells in bands are largely in situ, they may be regarded as an association, which in this case shows a tiered trophic hierarchy. Brachiopods, the dominant elements, and rostroconchs represent the lowest level of suspension feeders. Intermediate level suspension feeders are represented by fenestellids and by byssally attached large bivalves (e.g. Pinna). Highest level feeders are represented by rare crinoids. The sessile benthos in turn have provided a substrate for an attached fauna (bryozoans, foraminiferans and worms). Scavengers are represented by trilobites and gastropods.

Entomoconchus aggregates (Fig. 11-4a; Table 11-8) - Scattered carapaces and valves of the large cypridean ostracod Entomoconchus are a characteristic feature of subfacies B and of the build-up as a whole. Outside the build-up, E. aggregates are rare, only occurring in layered packstones petrologically similar to those of the build-up.

E. aggregates consist of up to several hundred shells, spread along a horizontal layer and covering up to roughly 100 cm^2 (Fig. 11-4a). Three species of Entomoconchus (listed in Table 11-2) along with Cypridella sp., Cypridellina sp., Paraparchites sp., and Bairdia spp. occur together, together with small brachiopods, particularly Echinoconchus elegans (M'Coy) and terebratuliform brachiopod spat (Fig. 11-4a). Undisturbed mats of Hyalostelia were found underlying the 12 of the 16 aggregates examined in detail.

Within an aggregate, ostracod carapaces typically occur in densities of 10-30 shells per 10 cm^2, and may reach up to 60 per 10 cm^2. Separated valves may occur in higher densities. A wide size range of shells (both valves and carapaces) is typically present within each aggregate (Table 11-8).

Articulation and orientation of ostracods in *Entomoconchus* aggregates

	A ◡	B ⌒	C ○	N	Size range
a.	60%	20%	20%	20	0.3-1.5 mm
b.	50	24	26	47	0.7-3.0 mm
c.	43	32	25	32	0.3-5.0 mm
d.	67	18	15	39	0.7-7.0 mm
e.	75	10	15	20	0.4-6.0 mm
f.	43	36	21	40	0.3-9.0 mm
g.	50	19	31	37	0.3-4.0 mm

mean % articulated = 22

mean % ◡ A = 54

Table 11-8 List of articulation and orientation of all the ostracods found in seven (a-g) aggregates in the build-up facies. N= number of shells. Size refers to maximum length.

Within each aggregate, 15-30% of the shells are articulated (i.e. carapaces, C, Table 11-8) and orientated with the sagittal crest parallel to layering in the enclosing matrix. The proportion of concave-up valves appears to be consistently higher than the proportion of those concave-down (Table 11-8). Nests of three or four valves stacked together are common. Stacked valves may be in several positions, including concave-up, concave-down and orientated with the long shell axis normal to layering (usually near vertical). Within each aggregate, 5-10 valves can usually be refitted, i.e. there are carapaces that have separated, but that have been left undisturbed.

Recent experimental work (Kontrowitz 1975) has shown that ostracods are light, readily-transported particles. Moreover, the carapaces and valves of globose forms do not have similar hydraulic characteristics (ibid). Transportation is likely to separate the two into distinct assemblages. Where both valves and carapaces are present within a single aggregate, it is likely that such aggregates are autochthonous.

The brachiopods also found in E. aggregates are small, often articulated, and often still in life attitudes.

Several criteria found in all aggregates examined concur to suggest that they have not been transported: a) a wide size-range of shells; b) the presence of valves and carapaces; c) a consistent association of different ostracod genera; d) high shell articulation ratios. Considering the weak hinging mechanism which entomoconchid ostracods are likely to have had, a very high proportion are still articulated. Since E. aggregates are not of hydrodynamic origin, it follows that they are life aggregates. Moreover, they are a facies-specific association whose hydraulic delicacy provides a valuable indication of gentle prevailing current conditions.

As cypridean ostracods are not especially noted for a tendency to congregate either to moult, reproduce or die (q.v. Pokorny 1978), it seems most likely that Entomoconchus and other ostracods were attracted to a particular substrate type or dwelling in a microhabit for feeding/living purposes. As already noted, many aggregates examined are associated with Hyalostelia mats. Perhaps E. lived attached to, or within Hyalostelia. Recent hyalosponges commonly enclose or support an attached fauna (Grzimek 1974, p 160).

Other characteristic fauna - Several other common fossils in subfacies B are also preserved in life-surface assemblages. Brachiopods, particularly schellweinellids, Krotovia spinulosa (Sowerby) (see Fig. 11-3), and Pugilis spp. often occur in aggregates of 10-50 shells clustered in a small area. Typically more than 70% are articulated and a high proportion are in their presumed life attitudes.

The rostroconch Conocardium, the heterophyllid corals Hexaphyllia and Heterophyllia, and the rugose coral Amplexus coralloides Sowerby are numerically rare and more evenly distributed. Conocardium shells occur orientated parallel to layering suggesting an epifaunal mode of life, rather than in semi-infaunal positions as shown by Ramsbottom (1978, p 160). Heterophyllids (Fig. 11-3) also occur in a subhorizontal attitude, which, in this case, is more likely to be the life position (e.g. Fig. 11-3b).

11.322 Evidence for depositional relief

The discrepancy in orientation between geopetal infillings in primary cavities and bedding furnishes one of several types of evidence that the build-up attained topographic relief over surrounding substrates during deposition of subfacies B (q.v. Appdx I; methods and results described in detail). At Galabraes Quarry, bedding surfaces originally dipped at angles of 16° towards an azimuth of 81°N (q.v. Fig. 11-1), a fairly consistent northeastward slope. Flanking beds, developed at approximately this horizon in South Quarry (q.v. Sect 11.35) dipped at 10° towards 144°N. The accuracy of these measurements was verified statistically and found to vary by ±2-3° of the actual value (q.v. Appdx I).

Numerous cm-sized folds attributable to slumping or gravity-induced deformation also appear in beds occurring on these depositional slopes. They appear to be reliable additional indications of uneven topography. Folds are also present in the central portion of the build-up, suggesting that subfacies B and C substrates formed gentle, undulose surfaces.

11.33 Subfacies C - dolomite laminated packstones

The boundary between subfacies B and C (shown in Figs. 2-9; 2-10) is gradational, marked by the disappearance of the high-diversity fauna, the incoming of thin dolomite laminae and an increase in the number of echinoderm debris layers.

The lower half of this subfacies consists of dolomite laminated packstones and wackestones alternating with poorly-sorted crinoidal packstones. Complete, fragile fossils, such as echinoids (e.g. Fig. 9-6) and small spinose productoids are common. In the upper part of subfacies B, poorly-sorted crinoid debris and layers of overturned fossils become more common. Small-scale cross-stratification and imbricated shell arrangements also begin to appear.

11.331 Biota

The changes in lithology described above are paralleled by equally great changes in the composition of the fauna (q.v. Table 11-2; Fig. 11-16). In subfacies C, crinoids and echinoids, largely preserved as debris layers (description follows), become predominant while the abundance and diversity of other groups decreases markedly. In addition, sheet-form and mm-sized nodular growth forms of Girvanella begin to appear.

Poorly-sorted crinoid debris layers - These are layers largely composed of crinoid stems showing a poor degree of sorting (q.v. Sect 7.1.12) and containing a large number of stems greater than 10 cm in length. Layers are typically a few centimetres thick and may extend laterally for several metres. One layer was examined in detail to determine its origin (q.v. Appdx J for additional details).

The poorly-sorted debris layer was analyzed by distinguishing residual and rolling crinoid stem orientations and multiple-stem arrangements, using methods similar to those employed by Schwarzacher (1963). The maximum length of a single stem was 65 cm, while over half were between 10-20 cm in length. Twelve unusually large (easily distinguished) multiple-stem arrangements have orientations suggesting minimal transportation and little reworking (shown in Figs. 11-9; J-3, Appdx J). Stem arrangements suggesting minimal transportation are: a) single stems or multiple-stem arrangements that curve through 30° of arc, or more, e.g. c, d, Fig. 11-9; j, Fig. J-3); b) radial stem arrays almost certainly formed by collapse of a single crinoid (b, Fig. 11-9); c) imbricated zig-zag trains of stems that consistently decrease in diameter, also suggesting derivation from a single crinoid (a, d Fig. 11-9; f, g, j, Fig. J-3). Broadhurst and Simpson (1973, p 373) interpreted these as arrangements resulting from gentle toppling and slight subsequent stem break-up on impact. In three of the minimally-transported arrangements the tapering direction of stems could be used to indicate the toppling direction (shown in Figs. 11-9 and J-3, plotted in Fig. J-4).

The remaining stem orientations fall into two categories: a) "V" and "T" orientations; b) single elongate stems (Fig. 11-9; Tables J-1;

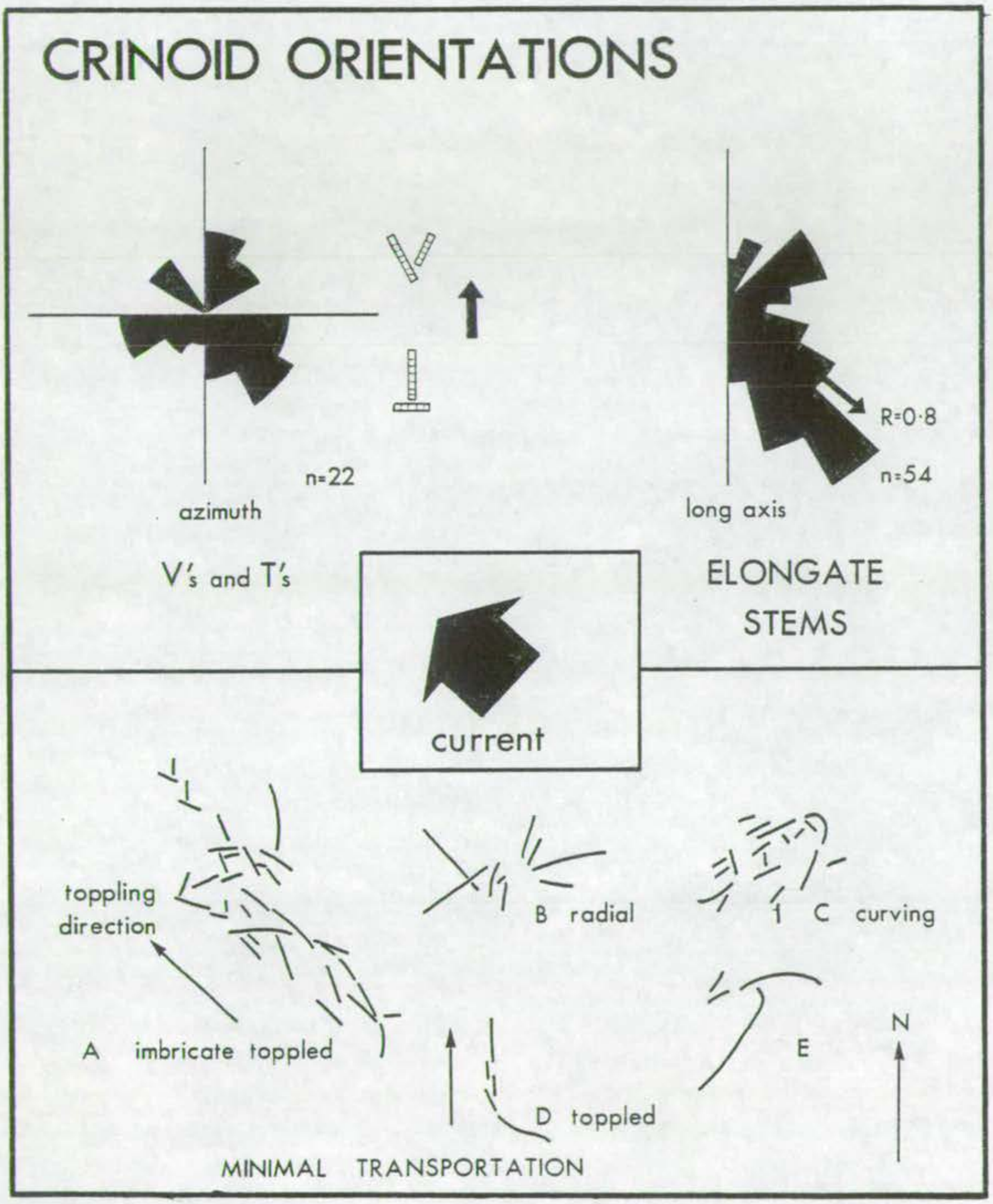


Fig. 11-9 Orientations of crinoid stems, subfacies C, the build-up

J-2). Flume experiments have shown the V's and T's represent residual orientations or stems that have come to rest in hydrodynamically stable positions (Schwarzacher 1963, p 583). They may be used to determine current aximuths, as shown in Fig. 11-9. Only one quarter of the stems examined were in V or T orientations. Their distribution does not show any significant preferential orientation, although 80% of the azimuths fall in the southern half of the distribution (90-270°).

The single elongate stems, plotted as axes (Fig. 11-9) yielded a biaxial distribution showing a significant preferential NW-SE orientation (0.1 probability level, Table J-2). Flume experiments have shown that the maxima and minima of such biaxial distributions coincide with the orientations of transported and residual crinoid stems. Schwarzacher (ibid) stressed, however, that several criteria must be combined in order to determine which axis of the distribution represents the normal-to and parallel-to current orientation. Combining the azimuth current directions obtained from V's and T's, the toppling directions of minimally-transported arrangements and the directions indicated by small-scale cross-stratification, suggests the maxima of the elongate stems parallels the inferrable current direction (as shown in Fig. J-4, Appdx). In other words, most of the elongate stems are in a residual orientation, and have not been transported.

The combined orientation data suggest that stems in poorly-sorted layers are mostly in situ. Crinoid stems are very light sedimentary particles that may even become buoyant after death (Lane 1971). Thus only weak currents would have required to account for the observed stem orientations. Little significance should be attached to the preferential northeastward current directions suggested by the stem orientation. The degree of dispersion between different types of data is more significant in showing that prevailing currents were not very consistently directed (Fig. J-4).

The overall wide size range of stems precludes the possibility that a significant number could have been winnowed from the original assemblage. Thus these layers represent the minimally-disturbed remains of crinoids which lived on the build-up. Owing to their tendency to break-up after death, crinoids are perhaps less immediately recognizable as a predominant faunal element than, for example, a layer of brachiopods. In forming an ecological assessment, however, the two may be at least equally important and the potential sediment contribution of crinoids is, in this case, considerably greater.

11.34 Subfacies D - the crinoidal packstone cap

Subfacies D overlies the central build-up, passing laterally into similar lithologies in the flank beds and adjacent facies. It therefore forms a "cap". The transition into subfacies D is marked by the abrupt return of bedding. The cap thickens north and westward at the Reservoir, while at Galabraes Quarry it thickens westward. This is apparent from measurements of thickness changes between beds along strike. Changes in the overall thickness of the subfacies are not necessarily sedimentologically significant, as the upper surface is erosional (Figs. 11-1; A-1, surface B).

11.341 Petrology

The cap consists of medium to thick crinoidal packstones and grainstones, interbedded with thin calcareous mudstones. Limestone beds are typically composite, formed of decimetre-thick tabular sets of small-scale cross strata and parallel lamination (e.g. Fig. 10-2). Interbedded calcareous mudstones are extensively bioturbated by Zoophycus and contain abundant coarse crinoidal debris.

11.342 Fauna

Apart from crinoids (Table 11-2), the fauna is relatively sparse, not very diverse, and similar to that of reworked units in the heterogeneous packstone facies. Unbroken fossils typically occur along bedding or set boundaries. Cerioid corals and Gigantoproductus are the dominant elements of the fauna. Echinoderms, predominantly crinoids, are preserved in poorly-sorted layers of debris.

11.35 The flank beds

The build-up flanks consist of up to 7 m of bedded limestones which thicken and dip away from subfacies A-D (Figs. 11-1; 11-10; 11-15; A-1). They are a transitional subfacies between the central build-up and laterally equivalent facies. The flank beds display a generally similar succession to that observed in the central build-up.

A complete cross-section of the flanks is exposed in South Quarry (Figs. 11-10; 2-11). Here, beds are continuous between the flanks and a tongue of slightly argillaceous and argillaceous limestones lying to the south of the build-up (Fig. A-1).

11.351 Bedding geometry and significance Fig. 11-10

The lowest metre of the flank sequence consists of 10-30 cm thick limestones thickening southward. Tensional fractures at the upper and lower surfaces of beds and deformed fossils in the calcareous mudstones provide evidence of slight movement between beds. The direction of movement indicated by these structures is southward, consistent with the orientation of depositional dips observed higher up in the flank beds.

The overlying four metres (Unit 1, Fig. 11-10) form a unit which changes thickness uniformly across the quarry. Within Unit 1, successive beds offlap each other, building outward towards the south. Beds are sigmoidal in shape, thickening as they pass southward into

Fig. 11-10 Features of the flank beds

N-S exposure at South Quarry. Flank beds are truncated by erosion surface C, which appears as prominent break in bedding. Note bedding morphology change from north to south across quarry. More prominent surfaces have been inked in on montage.

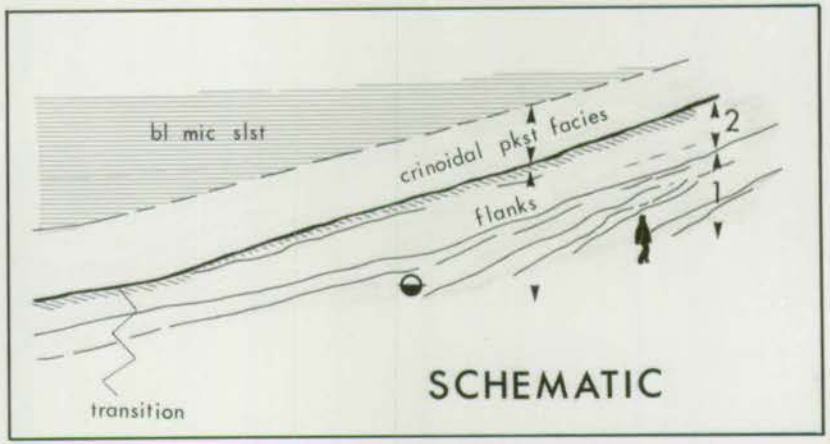
THE FLANK BEDS

South quarry

N →

shells in unstable attitudes

unsorted echinoderm debris



SCHEMATIC

argillaceous biomicrosparites.

Analysis of geopetal infillings in large shell cavities indicates that these sigmoidal beds have been deposited on a slope dipping at 10° towards 144° south (q.v. Appdx I). Although it cannot be confirmed statistically (due to insufficient numbers), geopetal infillings also reveal that the changes in bed geometry across the quarry face reflect the original depositional shape of bedding, i.e. beds were originally sigmoidal in form. By following a single sigmoidal bed from north to south it is possible to trace out an original depositional surface and thus measure the amount of original relief on the build-up. The vertical difference in height along three coarse shell debris beds (which could each be assumed to have been deposited instantaneously) measured 150, 165 and 180 cm. These figures, which do not allow for compaction, provide an indication of the minimum amount of relief present between the build-up and surrounding substrates. Bedding in the flanks thus shows that the build-up formed a low mound with gentle slopes during the period when units 1 and 2 were being deposited.

A marked change in bedding morphology occurs in the uppermost metre of the flanks (Unit 2, Fig. 11-10). Although the general geometry of beds is similar to those underneath, beds here dip at shallower angles. Depositional dips, however, appear to be similar to those of the beds underneath (Unit 1). It is most likely that the dip direction of the depositional surface is different in these upper beds, and that it is no longer parallel to the quarry face. Therefore, these beds appear to be dipping at a shallower angle than the underlying beds, while actually having been deposited on a comparable slope.

At the north end of South Quarry the flank beds are composed of limestones interbedded with centimetre-thick calcareous mudstone partings. Southwards, over the course of 30 m, the mudstones thicken to reach a nearly equal thickness with the limestones. A gradual increase in the proportion of clastic material is also apparent in the limestone insoluble residues (shown in Fig. 11-15). The manner in which the proportion of insoluble residue (reflecting original clay content) changes across the flanks is further evidence of the transitional nature of the flank environment.

11.352 Lithological sequence

The basal metre of the flank beds consists of grey and blue-grey mudstones and wackestones. The fauna, dominated by productoids and fenestellids, is sparse and largely in situ.

In the overlying 4 m of sigmoidally-bedded limestones (Unit 1, Fig. 11-10), the mudstones pass into packstones characterized by a great variation in skeletal composition and degree of fragmentation. Most beds are moderate- to poorly-sorted and show dolomite lamination. The laminae are often crenulated or folded by translational, downslope slippage.

The shelly packstones in this lower unit contain layers of: a) echinoderm debris; b) fragmented shells and intraclasts, and c) whole shells. The echinoderm debris layers show variable degrees of sorting. Stems in some layers are aligned E-W; a downslope, rolling orientation. Some of the more poorly-sorted layers may be largely in situ.

Packstone layers or entire beds containing fragmented shells and intraclasts begin to appear approximately 3-4 m above the base of the flanks sequence (near the Unit 1-Unit 2 boundary, Fig. 11-10). These beds of intraclast packstones are typically wedge-shaped, forming skirt-like deposits spreading outward from the flank front. Individual beds are either composite, formed of several sets, or form a single graded or chaotically-textured sheet. Successive sets within a bed may be conformable or erosively based.

The intraclastic packstones incorporate several types of intraclasts: transported shells with adherent matrix, siliceous sponges with entrapped sediment, dolomite laminated biomicrosparites, blue-grey wackestones, and, rarely, small oncolites. In addition to intraclasts, the packstones contain: a) very large shells, e.g. Gigantoproductus up to 15 cm across (Fig. 7-4a); b) delicate fossils, e.g. bryozoan fronds; c) fragments of corals, up to cobble size; e) typical fossils from both the build-up and laterally equivalent argillaceous limestones. Brachiopod shells in these layers are often in transported attitudes, but a high percentage are still articulated (Table H-1, entries m-s, Appdx). The intraclast packstones thus incorporate a wide compositional and size range of texturally immature particles.

Flat and slightly curved particles in intraclastic packstones provide some of the evidence on how these accumulations formed. Such particles are often orientated vertical to bedding (Fig. 7-4a), a highly unstable attitude for tractive (laterally moving) currents. Highly curved shells are often concave-up and occasionally stacked (Fig. 11-10). Intraclast orientations point to rapid sedimentation from debris flows (Middleton and Hampton 1973; Harms et al. 1975, p 156), probably formed during intervals of strong current erosion. Cross-stratification and shell attitudes in different beds suggest downslope mass movement, westward, and eastward current directions (prevailing sense shown in Fig. 11-15).

Shell bands in the flank beds are generally similar to the bands of Antiquatonia already described (Sects 11.321, 9.31). Most of the spinose productoids are articulated, but seldom in life attitudes, indicating minimal transportation. Gigantoproductus is particularly common in these bands.

In the uppermost metre (Unit 2), the flank beds undergo a marked lithological change to more crinoidal packstones. Moderate and well-sorted beds alternate with thin layers of unsorted echinoid debris (Fig. 11-10). These layers, a few centimetres thick, extend down the length of the flanks. Echinoid plate imbrications point to a down-slope sense of movement.

11.353 Environmental summary and conclusion

The flanks originally built outward from subfacies A as shown in Fig. 11-1. The earliest beds to show signs of slight depositional relief are not lithologically distinct from the central build-up.

One or two metres above the base, lithologically differentiated flank beds become established, presumably because of the size and relief attained by the central build-up. The first of these beds (Unit 1) contain minimally transported fossils, all likely to have inhabited the flanks, as well as fossils perhaps derived from the central build-up.

As the build-up continued to accrete, the flanks became increasingly differentiated as a sub-environment. This tendency is reflected in two features: a) the composition of the fauna; and b) the appearance of debris beds. The fauna of the flank beds is a mixture of the forms characteristic of the build-up, and the equivalent slightly argillaceous limestones (cf. Tables 8-4 and 11-2). The flank beds contain Gigantoproductus, Semiplanus, Dibunophyllum, and Koninckophyllum magnificum, which are rare or unrecorded in subfacies A and B of the build-up. These taxa are common or abundant in the slightly argillaceous limestones. Conversely, Hyalostelia, Conocardium, Entomoconchus and Echinoconchus, which are characteristic of the build-up facies, are either rare or absent in the slightly argillaceous limestones.

Debris beds indicate that, during deposition of the uppermost of flank units 1 and 2, currents eroded the upper build-up surface, incorporating the derived debris with material from the flanks. These beds thus represent intervals of erosion, mass-transportation and rapid deposition not found in the lower build-up (with perhaps one exception, see Sect 11.36). Their appearance is presumably related to the increasing size and steepness of the build-up and to an increase in current strengths. The increased capacity of currents to erode the build-up is unlikely to be related to the few metres in height it might have attained above the sea floor. It is more likely to be due to a general transition into a higher energy environment (which is also seen in laterally adjacent facies).

The uppermost unit (2) of the flanks is marked by changes in sediment composition and degree of sorting which coincide with those observed in the upper part of subfacies C and the crinoidal cap. Further increases in current strengths, shifting of current directions and a change in fauna most likely account for the observed changes in flank composition.

Unlike the flanks of many other biohermal accumulations, the flank beds of the build-up were not solely an apron of derived debris. They constitute a distinct sub-environment which was compositionally and ecologically gradational between the central build-up and adjacent level-bedded limestones.

11.36 Erosion surface A Figs. 11-11; 11-12; 11-13

An erosion surface, interpreted as a subaerial discontinuity, occurs approximately one metre above the base of the build-up (Fig. 11-1).

At outcrop the surface is marked by a thin calcareous mudstone parting, similar to other detrital clay partings throughout the sequence. The erosion surface is exposed approximately 30 cm above the lowest limestone bed at the northern end of South Quarry, and at the equivalent horizon 60 cm above the former floor of the Reservoir (Figs. 2-9; 2-10; 2-11). A similar prominent break is also present at the correlative horizon in Galabraes Quarry, where evidence for erosion might also be present.

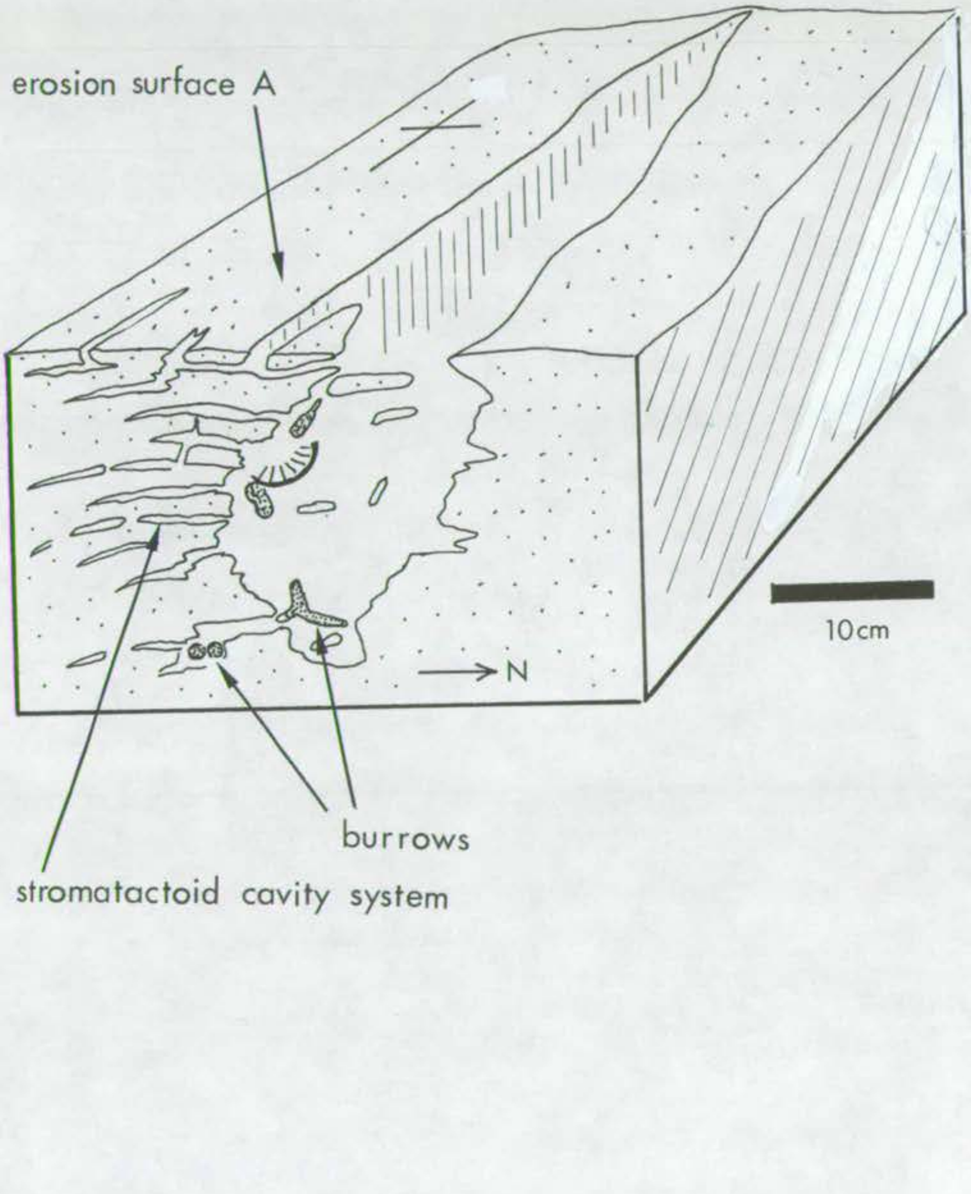
11.361 External appearance

Evidence for erosion and possible subaerial exposure is found in a crack beneath surface A with a complex sequence of infillings (Figs. 11-11; 11-12; 11-13). The crack is roughly V-shaped in cross-section, approximately 20 cm deep, and opens upward to an equal width (Fig. 11-11). In longitudinal section it appears to be trough-shaped, orientated E-W, normal to the palaeoslope measured in the flank beds above. Both shape and orientation suggest that the crack is tensional in origin.

11.362 Matrix

The enclosing bed or matrix of the crack is a blue-grey wackestone, in places a mudstone (shown in Fig. 11-12). Stromatactoid cavity systems are exceptionally well-developed beneath the surface, particularly in the area of the crack. Many of the stromatactoid cavities clearly open into the crack (Figs. 11-12; 11-13; 6-10c, e). Signs of dissolution are also extensive throughout the bed beneath surface A, seen in the development of a rather porous fabric formed by selective matrix dissolution, by small skeletal moulds, and the stromatactoid cavity system itself.

Fig 11-11 Sketch of crack opening onto erosion surface, lower build-up, South Quarry



11.363 Infilling sediments

The crack is infilled by three types of sediment. Their composition and manner of infilling are particularly important in establishing the sequence of events and, thus, possible origins of the surface. These infillings were first referred to in the description of stromatactoid cavities as type C infillings (q.v. Ch 6). In order to illustrate the sequence of events more fully, type C infillings have been further subdivided here into C-1, C-2 and C-3.

Fill C-1 (Figs. 6-10c, e; 7-2b; 7-4d; 11-13) - This earliest sediment, a coarse intraclast packstone, completely infills the crack. Together with the second infill, it is absent from large areas of the erosion surface. No trace or veneer of C-1 or C-2 is present along the 10 m exposure in South Quarry. At the Reservoir, however, a packstone, probably composed of a mixture of C-1 and C-2, forms a bed overlying the erosion surface (q.v. Fig. 7-4c).

Fill C-1 partly side-fills into the horizontal elements of the stromatactoid cavity system (Figs. 11-12; 11-13; 6-10e). It is extremely coarse-grained and, therefore, does not infill the cavity system further than a few centimetres.

Seventy-seven percent (n =140) of the curved shells in fill C-1 are orientated concave-upward, a settling orientation; intraclasts in the fill reach 4 cm (maximum diameter) and their degree of sorting is very poor. These data suggest rapid deposition, probably from a single pulse.

The allochems in fill C-1 are unusually diverse. Most important among them are:-

a) intraclasts - these are centimetre-sized fragments of matrix and shells with adherent matrix. The intraclasts float in the coarse skeletal debris indicating they have formed by erosion along the surface

Fig. 11-12 Crack beneath erosion surface A.

a, b polished slabs. Fig. 11-13 illustrates relationship between various infilling sediments shown in 11.12a. 11-12b is a close-up of 11-12a taken from a different serial section; right and left are reversed. G.I. 46,540 a,b.

General view crack, cut N-S. Matrix (left) contains numerous subhorizontal cavities with numerous types of infillings. Earliest infills (type A) may be present (A, in 11-12b). Infills C-1 and C-2 infill crack from large crack at right, becoming progressively finer away from the crack, see 11-12b. Note highly irregular outline of infilled cavities. Thalassinoides burrow (T, 11-12b, also 11-13) penetrates downward from overlying dark mudstone (C-3, 11-13) incorporating infills C-1 and C-2 in its concentric laminae. Fill C-3 overlies erosion surface (q.v. 11-13) and is present in diagenetic cavities (q.v. 3, 11-12b). Late stage dissolution cavities crosscut both matrix and fills A to C (arrows 11-13).


a
mm


b
A
T
A
1

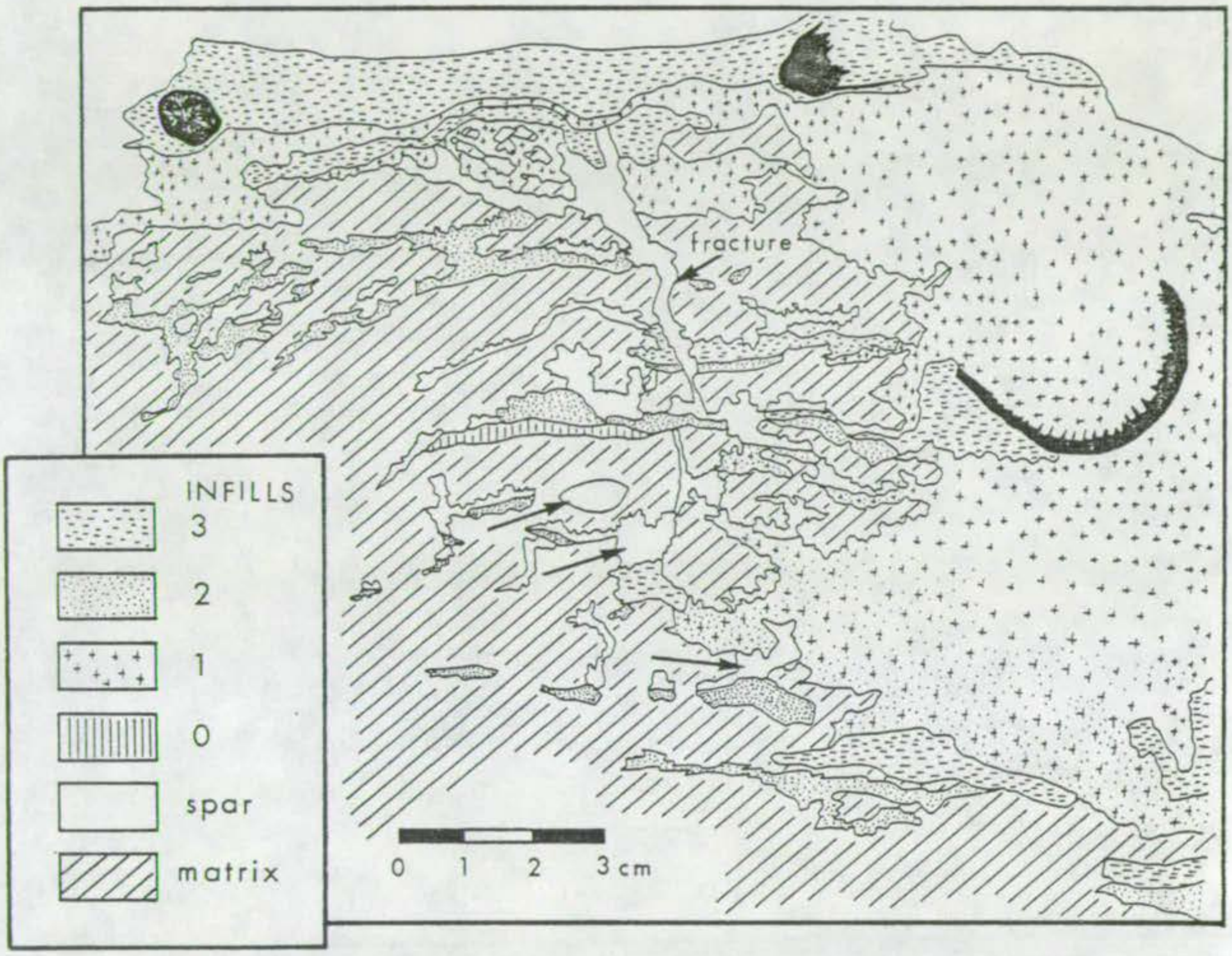


Fig. 11-13 Key showing relationship between various type C infillings, stromatactoid cavities and matrix. Specimen also shown in Fig 11-12a.

and not by collapse of the sides into the crack (q.v. Fig. 7-4d);

b) unusual fossils - Caninia juddi, Lithostrotion junceum, L. gracile, Gigantoproductus fragments, and echinoids are common in fill C-1 (q.v. Figs. 11-12; 7-2b). Although these fossils are common in other high-carbonate facies, they are rare in subfacies A of the build-up (Table 11-2). Lithostrotion has not been recorded from this subfacies. The size and delicacy of some of these particles (e.g. branched Lithostrotion fragments) suggest derivation from very nearby;

c) typical fossils - most of the fossils comprising fill C-1 are also those which are most abundant in subfacies A and B. Most of the brachiopod shells are articulated and unbroken (some occurring as intraclasts) suggesting minimal transportation (q.v. Table H-1, entry j).

Sedimentological significance of C-1 - Fill C-1 represents a polygenetic sediment, combining particles derived from substrate erosion, fossils swept from the immediate vicinity, and fossils derived from adjacent facies. The displaced fauna is particularly interesting as it provides proof that laterally equivalent facies to the build-up were also contemporaneous. In many sedimentological studies it must be assumed that laterally adjacent facies are also contemporaneous; in this case it can be established.

Fill C-2 - The sediment (or sediments) of C-2 are fine-grained, cream-coloured microsparites, in places grading to a micrite (Figs. 11-12; 11-13; 6-10e). Small fragments of bryozoans, foraminiferans, and sponges are identifiable within C-2. Slight differences in primary composition and the degree of recrystallization, give C-2 such a range of appearances that it is difficult to decide if C-2 represents a single sediment or several sediments, and to distinguish it from diagenetic, internally derived sediments.

Fill C-2 infills interstices between the large particles of C-1, in some cases piling on top of flat shells and leaving voids beneath sheltered areas (Fig. 7-2b). In these cases it appears to have trickled through a coarse framework of C-1. C-2 infills vertical fractures opening directly onto the erosion surface as well as side-infilling from the crack. It also becomes finer-grained in cavities further away from the crack. Fill C-2 is present in all elements of the stromatactoid cavity system, including the vertical fractures and dissolution cavities (Fig. 6-10e).

Distinct, concentrically-lined, open burrows penetrate from the crack into C-2 infillings of the stromatactoid cavities (Fig. 6-10c). These burrows establish that: a) at least some of the fine-grained C-2 type sediment is primary, as it has been incorporated in a burrow lining; and that b) the interconnected, horizontal elements of the stromatactoid cavity system were present at the time of crack formation. The manner in which C-2 infills cavities (illustrated in Figs. 11-12; 11-13; 6-10 in particular) certainly suggests that the whole diagenetic stromatactoid cavity system was present at the time of C-2 deposition. Although burrows are present in fill C-1 and C-2, they carefully avoid penetrating the matrix, a sign that it was more consolidated than the fills.

Significance of fill C-2 - Where C-2 can be shown to be a primary sediment (burrow linings) it is likely to represent a fine suspension fall-out emplaced shortly after fill C-1. This may suggest that C-1 was originally deposited as a grainstone, which further confirms its high-energy interpretation.

Fills C-1 and C-2 appear to be distinct, partially owing to their difference in grain size. The finer grained C-2 infill has filtered further through the cavity system. Unfortunately, the fine-grained filtrates of C-2 are very similar to diagenetically-derived internal sediments found elsewhere.

<u>Fill C-3</u> - Fill C-3 is a green, calcareous mudstone, forming a centimetre-thick lamina covering the erosion surface and both previous fills (Figs. 11-13; 11-12). <u>Thalassinoides</u> burrows, formed during or after deposition of C-3 penetrate into the crack, incorporating all three infillings in their concentric laminae. Moreover, the burrows have clearly been excavated in a sediment that was a mixture of very coarse and fine particles (q.v. Figs. 11-12; G-2). Like C-2, fill C-3 also infills the diagenetic parts of the stromatactoid cavity system, both from the crack and downward from the erosion surface (Fig. 11-13).

<u>Sedimentological significance of C-3</u> - C-3 is a marine sediment deposited after removal of C-1 and C-2 from parts of the erosion surface. The burrows which penetrate from C-3 into the underlying fills suggest that all three infillings are closely associated and that they were deposited within a short interval of each other.

<u>11.364</u> <u>The infilling sediments: discussion</u>

The relationships between various generations of infillings and the cavity systems in the matrix provide the key to determining the origin of surface A. In Ch 6 it was shown that stromatactoid cavities are largely diagenetic, formed by fracturing and dissolution. This system is likely to have spread from isolated primary cavities.

Fill C-1 is an undoubtedly marine sediment which only infills the horizontal elements of the cavity system. It cannot be established unequivocably that it lies in diagenetic elements of the cavity system, but this may be due to its coarse grain size.

Diagenetic parts of the system are, however, clearly infilled with fill C-2. Unfortunately, the origin of the C-2 sediment in these cavities cannot be unquestionably established. Fill C-2 appears, at least in part, to be a fine suspension fall-out from C-1. Where it lies in a diagenetic cavity, the obvious conclusion is that subaerial exposure, fracturing and dissolution took place prior to infilling. The most compelling evidence for the primary, sedimentary origin of some C-1 fills comes from burrows which either intermix all three infillings, or have been formed very shortly after C-1 and C-2 deposition.

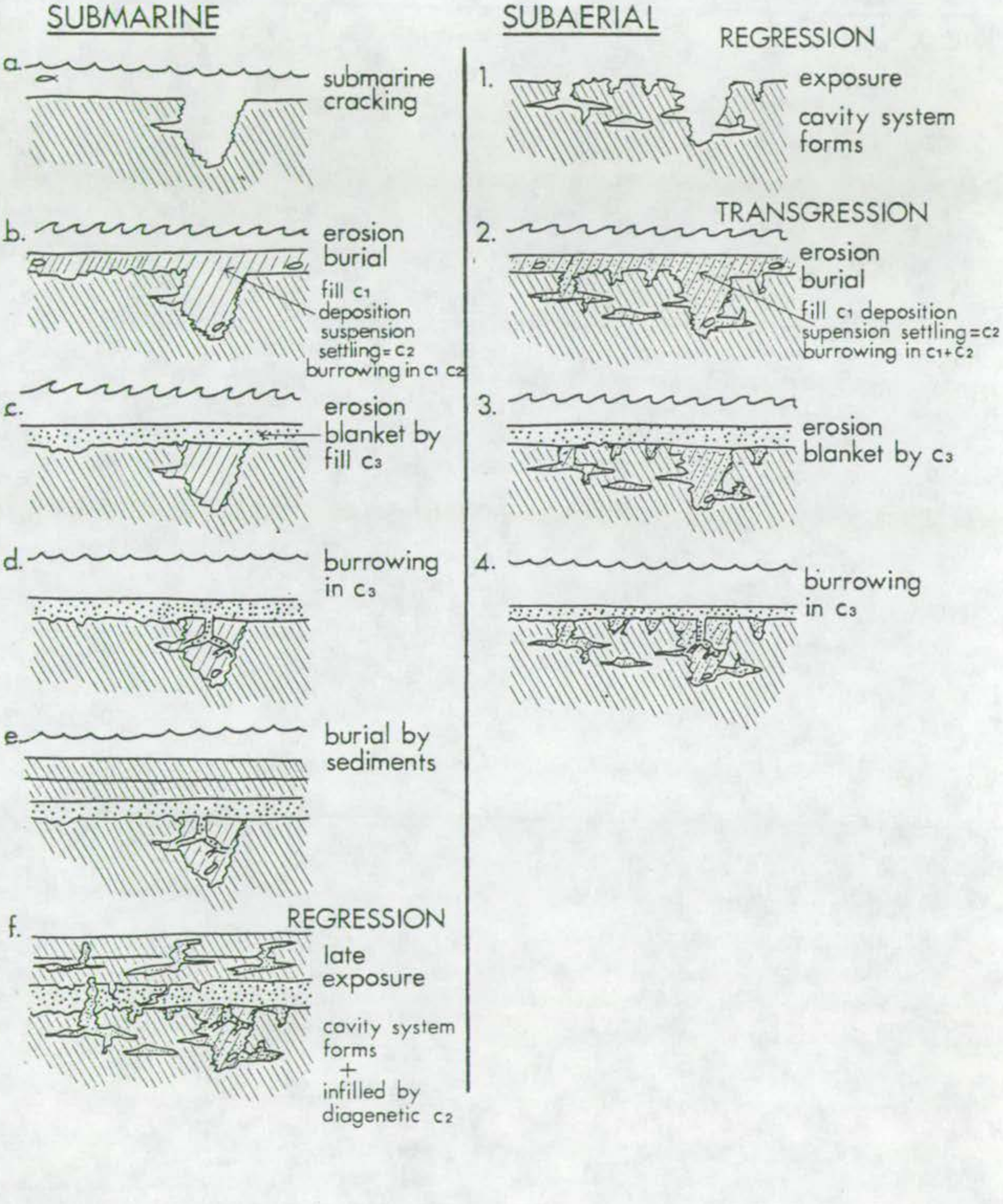
A problem lies in clearly establishing that all C-2 is a single sediment of marine origin. C-2 sediments are texturally similar to internally-derived, diagenetic sediments from elsewhere. The possibility exists that diagenetic elements of the system have spread from primary cavities (infilled with C-1) and been infilled with a diagenetic C-2 resembling a primary C-2. Fine-grained sediments such as C-2 and C-3 might additionally be redistributed downward during development of such a system. This possibility is considered to be unlikely, but not entirely dismissable.

11.365 Possible origins of the erosion surface

The evidence for the origin of surface A is, therefore, somewhat equivocal. Two origins should be considered. The history of the erosion surface may have been as follows, (Fig. 11-14):-

During the early constructive phase of the build-up, a crack opened in the surface of a sediment sufficiently consolidated to support horizontal cavities. The tensional mechanism responsible for crack formation is unknown. The crack itself does not point to a particular environment, since fractures may form in both submarine and subaerial environments. In an area of active volcanism seismic

Fig. 11-14 Possible origins of erosion surface A, lower build-up.



tremors might provide the mechanism for crack formation, particularly if the sediment was being deposited on a slight slope.

Following cracking, an atypical erosive event removed and mixed sediments from several contemporaneous environments, depositing them in the irregularities of the eroded surface. Infilling followed soon afterwards, as the crack edges are not eroded or encrusted. Erosion and infilling may have been related.

If the crack is of submarine origin (Fig. 11-14), then the sequence of infilling was originally restricted to the horizontal elements of the stromatactoid cavity system. The vertical elements could not have been present, as they formed by dissolution and shrinkage associated with meteoric diagenesis (q.v. Ch 6). The present cavity system, with its multiple infillings, must have formed by enlargement of the original cavities. The similarity between internally-derived diagenetic sediments and primary sediments create the impression that the original cavities were originally more extensive.

Accepting this interpretation simplifies the geologic history of the build-up. The erosion surface represents an atypical interval of erosion somewhat more severe than other erosive horizons present higher up in the sequence. The lithological and faunal similarity of the beds above and below the erosion surface additionally argues for this interpretation.

If, alternatively, the erosion surface is also a subaerial discontinuity (Fig. 11-14), then the sequence of infilling is easier to explain, but the geological history of the build-up becomes more complex. Following a period of minor regression and exposure, transgressive marine sediments infilled a cavity system created by dissolution during emergence. The build-up may have become exposed as a small, offshore island similar to the Florida Keys. The signs of exposure thus would not necessarily appear in adjacent environments, nor would significant lateral facies shifts be expected. This hypothesis also implies that the build-up formed in very shallow water.

The sediments infilling the cracks on the erosion surface would be likely to have been composed of material derived from mixing of several nearshore onlapping environments. The infilling sediments might thus be analogous to the marine sediments commonly found in the karst pits in the Pleistocene limestones of Florida (q.v. Enos and Perkins 1977, pp 151-156). On balance, this hypothesis is more plausible as all three infilling sediments seem to have been deposited in close succession and to be of the same origin as those infilling the diagenetic cavities. The other possibility, that primary and diagenetic sediments resemble each other so closely as to be indistinguishable (even in the same cavity), is less plausible. Until more cracks have been discovered, both possibilities should be entertained.

11.4 The build-up: summary and succession

A plot of the range of the more common and characteristic elements of the build-up biota (Fig. 11-16) reveals an ecological succession of faunas (sensu Walker and Alberstadt 1975). Moreover, the major physical changes in the build-up (Fig. 11-15) coincide with the principal faunal breaks. In trying to explain the vertical changes observed in the build-up, the concept commonly adopted of an ecological succession is not nearly so instructive as that of a substrate succession. By considering the build-up as a succession of substrates and focussing on the factors responsible for creating different substrate types, it becomes easier to explain why the biotic succession took place.

In the following section a summary and interpretation of the depositional history of the build-up is given.

Fig. 11-15 Physical features of the build-up

Generalized diagram summarizing major physical features of the build-up. Note that major lithological changes coincide with faunal boundaries in Fig. 11-16. The percentage of insoluble residue found in flank beds is based on six samples taken at the northern, middle and southern parts of South Quarry. Petrographic composition is based on a minimum of 200 points (usually 400) counted on 30 thin-sections and peels.

PHYSICAL FEATURES

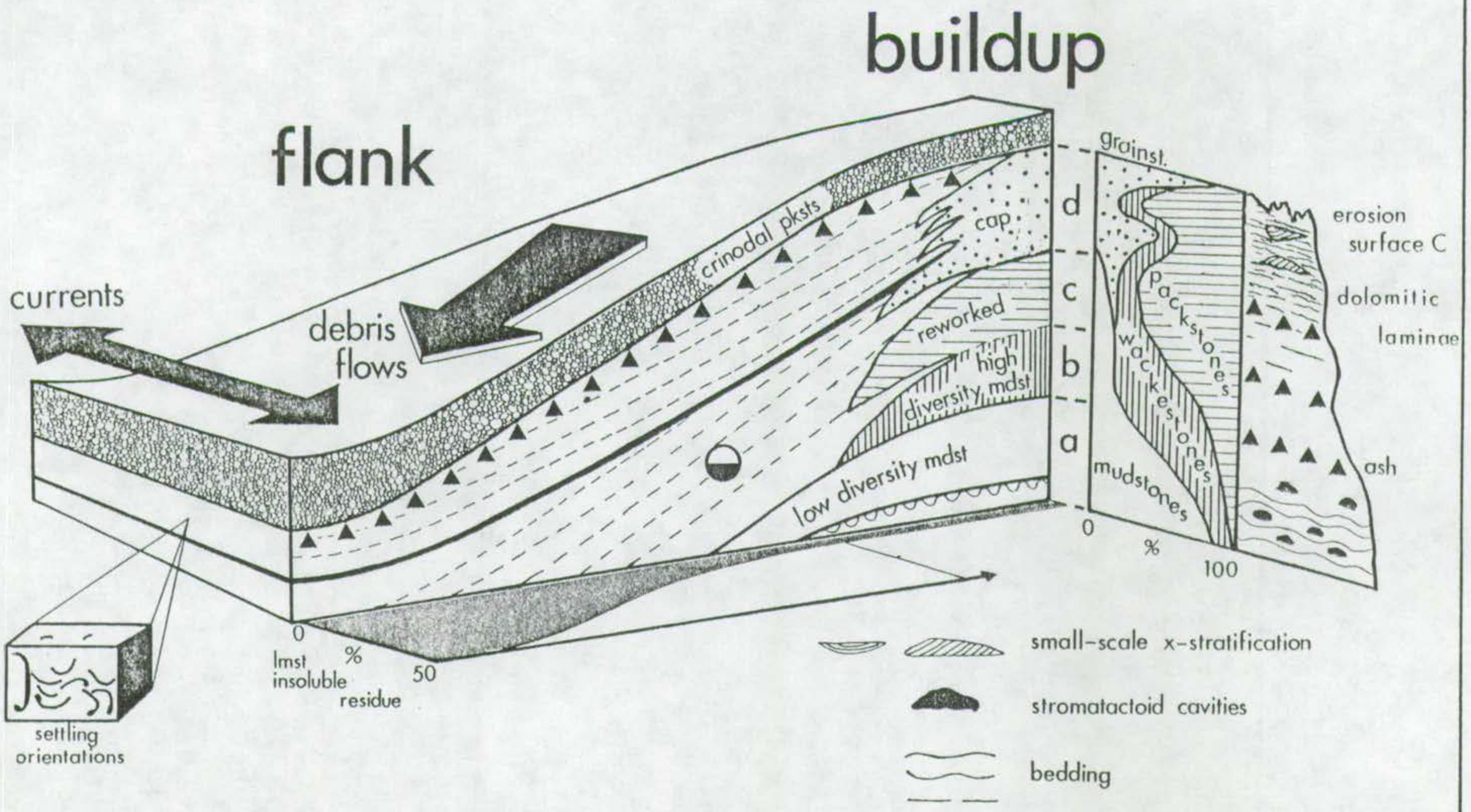
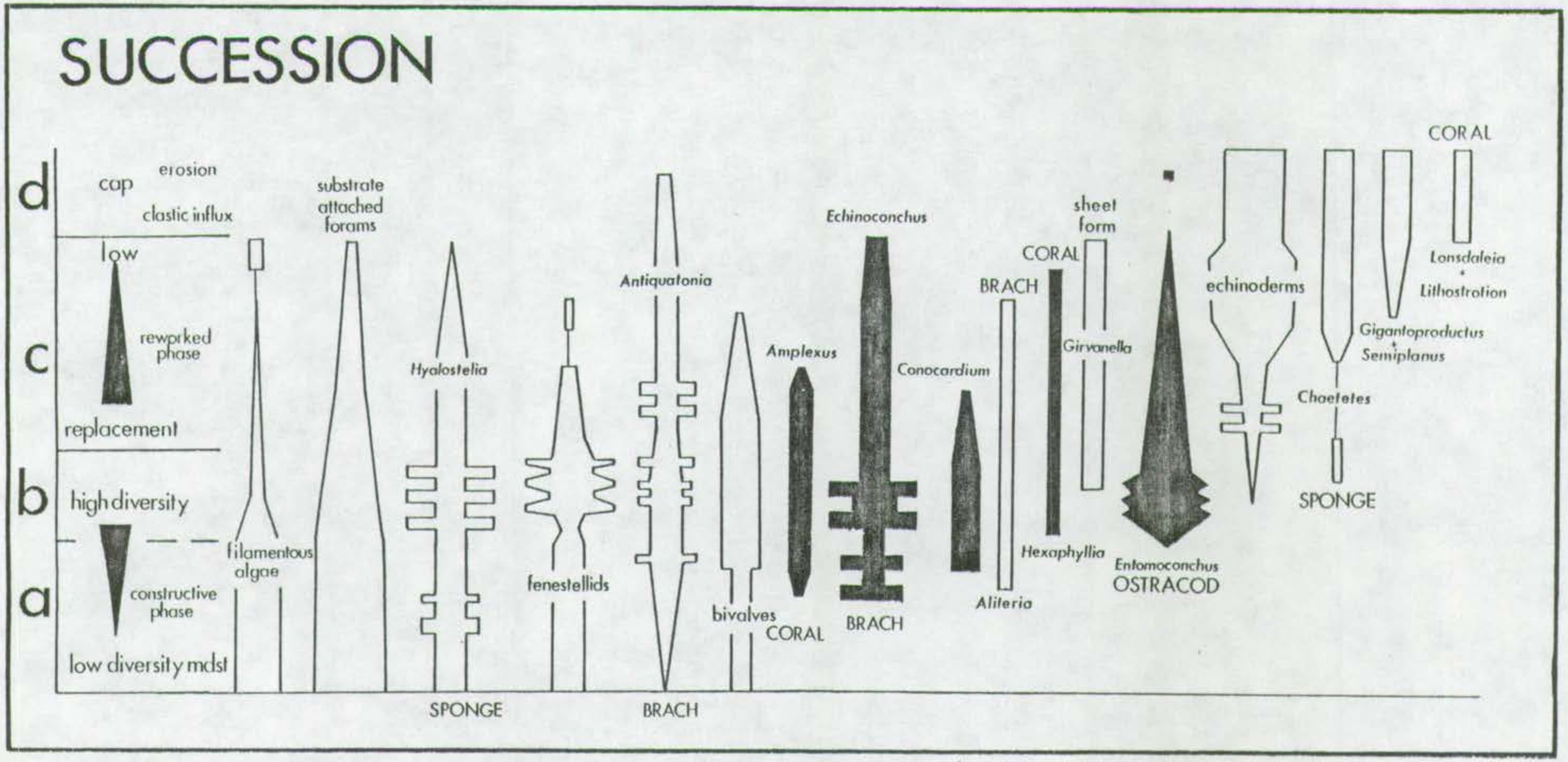


Fig. 11-16 The build-up faunal succession

Kites show range of the commonest elements of the build-up biota. The difference in width of kites provides a rough idea of the relative abundance of taxa. The changes in width along the length of a kite denote differences in the relative abundance of a particular group between subfacies. Toothed sides of kites denote horizons where a particular group forms layers. Black kites represent elements which are characteristic of the build-up, and which might therefore be useful in identifying biohermal facies elsewhere.


SUCCESSION
d
cap
erosion
clastic influx
low
c
reworked phase
replacement
b
high diversity
a
constructive phase
low diversity mdst
filamentous algae
substrate attached forams
Hyalostelia
SPONGE
fenestellids
Antiquatonia
BRACH
bivalves
Amplexus
CORAL
Echinoconchus
BRACH
Conocardium
BRACH
Aliteria
CORAL
Hexaphyllia
sheet form
Girvanella
Entomoconchus
OSTRACOD
echinoderms
Chaetetes
SPONGE
Gigantoproductus
+
Semiplanus
CORAL
Lonsdaleia
+
Lithostrotion

Subfacies A - The build-up originally became differentiated from surrounding, more level-bedded substrates as a low mound, lacking distinct flanks. A short interval of subaerial exposure or erosion interrupted an otherwise fairly uniform accumulation pattern of fine-grained sedimentation and relatively sparse epifaunal colonization. Sponges and filamentous algae are likely to have aided in sediment surface stabilization. Brachiopods and fenestellids occasionally grew in sufficient density to create a skeletal framework, which sheltered small cavities. The delicacy of the epifauna and direct sediment encrustations indicate the substrate was firm and stable.

In comparison with other contemporaneous firm substrates (e.g. Ch 9), the fauna of subfacies A is very low in both faunal abundance and diversity. The sparseness of the fauna argues for some form of localized environmental stress. In the absence of evidence that strong currents, competition, water depth, or turbidity were sources of stress, it is possible that sedimentation rate was a factor in limiting faunal abundance and diversity. Direct evidence for this hypothesis has not been preserved, but it provides a plausible explanation for the observed faunal paucity. Although subfacies A organisms may have actually colonized the sediment surface during intervals of low sedimentation (encrusters and suspension feeders typically have low tolerances to suspended detritus), the undisturbed nature of the fauna argues for rapid subsequent burial. This constructive sedimentation pattern eventually gave rise to a low mound of sediment. The presence of many successive rapidly-buried fossils also suggest a rapid overall sediment accumulation rate (q.v. Sect 9.5). Perhaps net sedimentation rates were such that they discouraged all but the most opportunistic elements of the firm substrate fauna.

Subfacies B - During subfacies B, the build-up underwent a rapid biotic diversification, seen as an increase in the number of organisms and in the number of organisms and in the number of taxa. Six genera of spinose productoids, five genera of other brachiopods, and numerous ostracods, bivalves, and a few corals appear for the first time or become very abundant (Table 11-2). These fauna recur as in situ assemblages. Fossils reached such a high proportion of the accumulating sediment as to alter depositional texture over small areas, creating an autochthonous packstone. In addition, the build-up attained sufficient relief to begin to shed debris and accumulate differentiated flanking beds.

The modes of life and growth habits of the commoner fauna (Fig. 11-16) also indicate that subfacies B substrates were firm and stable. A consequence of the great increase in the number of organisms is that the shelly fauna itself became a second substrate for an encrusting biota (described in detail, Ch 14). During the height of diversification, the fauna formed a tiered association with suspension feeders at various levels above the sediment surface: crinoids (rare) - highest; fenestellids and large bivalves - intermediate; brachiopods and small bivalves - lowest feeding level. The skeletal fragility and undisturbed manner in which the high-diversity fauna has been preserved additionally argues for quiet conditions.

Successive undisturbed life surfaces also indicate rapid burial in this subfacies, although the horizons themselves argue for relatively long periods of quiet and low sedimentation.

Debris deposits in the flank beds attest to intermittent strong erosive events which may not have occurred previously. Several authors (notably Connel 1978; Sanders 1968) have recently shown that recurrent intermediate-scale catastrophes (e.g. storms) can be instrumental in maintaining maximum diversity in some environments (particularly reefs). According to this theory, high-diversity is a natural consequence of non-equilibrium conditions. Under equilibrium conditions, competition will eventually favour a relatively small percentage of the total population able to live in a given environment.

Although the data from the build-up cannot conclusively substantiate this hypothesis, it is tempting to conclude that the abundance and diversity in the subfacies B biota was maintained by storms which periodically cleared the build-up surface of much of its fauna, allowing a diversity of forms to become established. The record of these erosive events is certainly preserved in the flank beds, even though it cannot be shown that these events were the mechanism maintaining diversity. The incoming of the erosive events is likely to have been associated with a long-term regional shallowing (q.v. Ch 12).

Several fossils which appear in the diversification stage (shown in black, Fig. 11-16) are relatively uncommon in the build-up and very rarely found outside it. They are characteristic of the build-up facies. Moreover, two of them (*Amplexus* and *Entomoconchus*) appear to be specific to biohermal or "reef" facies elsewhere (cf. Hill 1938; Jamieson 1971). Where these forms are found in association it seems likely that they may be used to predict the presence of biohermal facies. The distribution of these forms in the build-up additionally suggests that facies-characteristic forms are most likely to be found in the diversification stage of a succession.

Subfacies C - With the transition into subfacies C, the fauna gradually decreased in abundance and diversity. *Antiquatonia*, *Eomarginifera* and fenestellids persisted, while the diverse associations of spinose productoids, *Hyalostelia* mats and aggregates of *Entomoconchus* gave way to new biota, namely crinoids, echinoids, and sheet-form growths of Girvanella. The predominant elements of subfacies C thus constitute a replacement by new elements which were not abundant previously. The appearance of the replacement fauna is also accompanied by an increase in the prominence of dolomite laminae.

The dominant fossils, echinoderms, are largely preserved as poorly-sorted layers in the lower part of this subfacies and as more extensively reworked crinoidal debris higher in the sequence. The differences in the degree of reworking of the fauna, as well as the debris flow deposits on the flanks attest to a general increase in energy throughout subfacies C.

Once established, the replacement fauna may have further altered its environment by changing the nature of the substrate to its advantage. On death and disaggregation, crinoids were likely to have formed light, readily entrainable particles and thus created a mobile sediment surface. Perhaps crinoids and browsing echinoids were better adapted to these mobile substrates than the sessile-benthonic, high-diversity fauna.

Large numbers of echinoderms begin to appear at the same stratigraphic level in upper parts of all laterally-adjacent facies. Along with dolomite lamination, the simultaneous appearance of echinoderms in several environments points to a widespread extrinsic environmental change as the cause of replacement, unrelated to competition between the species inhabiting the build-up.

Subfacies C - In subfacies C the characteristic fossils of the build-up disappear altogether. The petrographic composition and fauna of the cap is generally similar to that of reworked units in the heterogeneous packstone facies. Gigantoproductus and cerioid corals were added to crinoids as predominant faunal elements, occurring in well-bedded, cross-stratified packstones and grainstones. Cross-stratification sequences suggest that cap substrates were ripple- and (rarely) small dune-covered mobile sheet sands. The grain size, degree of sorting, and composition of cap sediments point to extensive reworking prior to final burial. Large coral thickets and disorientated colonies (typical of reworked units) are absent, suggesting more gentle, less turbulent conditions than those found in the adjacent heterogeneous packstones.

The appearance of bedding within the cap sequence provides evidence of regular clastic influxes not seen previously in the build-up. The cap thus marks a return to a sedimentation pattern more like that observed in the adjacent facies.

The build-up succession may be resolved into three major phases. During an initial <u>constructive</u> phase (Figs. 11-15; 11-16) of relatively rapid sediment accumulation, the pioneer firm substrate species diversified to the point of influencing sediment accumulation by the sheer bulk of their sediment contribution. Erosive events and perhaps a net decrease in sedimentation rate may have favoured diversification. In the second phase, the diverse fauna was <u>replaced</u> by an echinoderm-based fauna. Replacement appears to have occurred due to a regional shallowing. Successively higher energy environments (<u>cap phase</u>, Figs. 11-15; 11-16) are marked by progressively more reworked lithologies. Build-up growth was terminated by a widespread erosive event likely to have occurred during subaerial exposure (erosion surface C, q.v. Ch 15).

CHAPTER 12

THE BUILD-UP AND ADJACENT FACIES: AN ENVIRONMENTAL MOSAIC

12.1 Palaeogeography: synthesis and review

The strike section through the Petershill Formation extends from a northerly area of nearly continuous lava flows to the town of Bathgate, where the lavas thin and pinch out. In passing from north to south, the sediments of the Petershill Fm. and the Reservoir Mbr. thicken dramatically as the lavas concomitantly thin (Fig. 1-2). At the northern boundary of the Petershill Fm., the limestones in the upper Reservoir Mbr. become very argillaceous before the entire sequence thins, changes character and perhaps pinches out northward into the area of continuous lavas. The high-carbonate mosaic lies south of this argillaceous limestone facies and passes southward, into slightly argillaceous limestones, where the sequence as a whole begins to thicken.

The subaerial origin of the lavas suggest that an area north of the Petershill Fm. formed a positive mass or barrier throughout most of Lower Limestone Group times. It separated or restricted communication between the area of Hillhouse Limestone deposition on the north side of the Bathgate Hills and that of the Petershill Fm. to the south. The lavas formed a platform onto which the level-bedded facies were first deposited and over which the high-carbonate facies subsequently became laterally differentiated (q.v. Introduction). The line of the Petershill Fm. exposure thus provides a fortuitous environmental cross-section between the landward area to the north and a basinal area to the south (Fig. 12-1). These regional relationships between lavas and sediments provide the general palaeogeographic framework within which the build-up and its adjacent environments may be examined in greater detail.

12.2 Environmental synthesis

The argillaceous carbonate facies represents the most landward environment in the facies profile. It consists of a continuous sequence of organic-rich, extensively bioturbated, mixed calcareous mudstones and argillaceous limestones, probably formed in a proximal lagoon, where land-derived plant debris and muddy sediments accumulated slowly.

The heterogeneous packstone facies represents a zone further offshore from this argillaceous carbonate lagoon (Fig. 12-1). It formed a nearshore shoaling zone of intermitently mobile sheet sands, probably hydrodynamically comparable to Recent Florida inner shelf-margin areas (cf. Enos and Perkins 1977; Multer 1978). Barrier bars may have been present at the northern boundary of this facies, protecting the argillaceous lagoon in its lee. Such an assumption is conjectural, however, as conclusive evidence of barrier bar sequences has not been found. The heterogeneous packstone facies fines southward, reflecting a gradual transition into calmer and, presumably, slightly deeper environments. Analogies with Recent carbonate environments (q.v. Enos and Perkins 1977, pp 39-49, 109) would suggest that the heterogeneous packstones accumulated in shallow water areas where good circulation and low clastic influx provided optimal conditions for biological productivity. The net rate of sedimentation in the heterogeneous packstone facies is likely to have been fairly low owing to equally high rates of mechanical breakdown and reworking prior to burial.

The build-up accumulated in a zone further offshore from the heterogeneous packstones, but still quite close to the presumed coastline. Its delicate and in situ fauna point to quieter and probably slightly deeper water. As a hydrographic zone, the build-up combined optimal conditions for biological growth and preservation. Adjacent landward environments on the open platform are likely to have been too destructive to accumulate sediment, while those offshore were too quiet to promote maximum biological productivity.

The high-carbonate biomicrosparite facies forms the most distal zone in the high-carbonate mosaic (Fig. 12-1). It is likely to have formed in quieter and perhaps slightly deeper offshore waters. High accumulation rates of sediment, perhaps derived from more nearshore environments, may have reduced biogenic carbonate productivity. Taken as a whole, the high-carbonate facies show very slight differences in thickness along strike (Fig. A-1). Nevertheless, the facies differ remarkably in composition, the state of preservation and fragility of their constituent faunas. This suggests that hydrodynamic factors, perhaps resulting from current dissipation across the platform itself, were more important than depth in creating the facies pattern. Very slight differences in water depth, which would not be reflected as differences in facies thickness, may exert quite an important influence on circulation patterns and current strengths on Recent carbonate platforms (Enos and Perkins 1977). Major differences in water depth between facies, however, would be more expected to show up in thickness changes, which are not observed here. Thus the pattern of faunal and textural variation present in the Reservoir Mbr. high-carbonate mosaic is likely to have formed due to changes in hydraulic regime across a gentle depth gradient.

In considering the origins of the build-up, or in exploring for similar deposits elsewhere, it should be noted that in this instance, palaeohydrographic factors (i.e. quiet but continual circulation) were apparently more important than other possible physical factors (antecedent topography or mechanical sediment-piling) as conditions for biohermal growth.

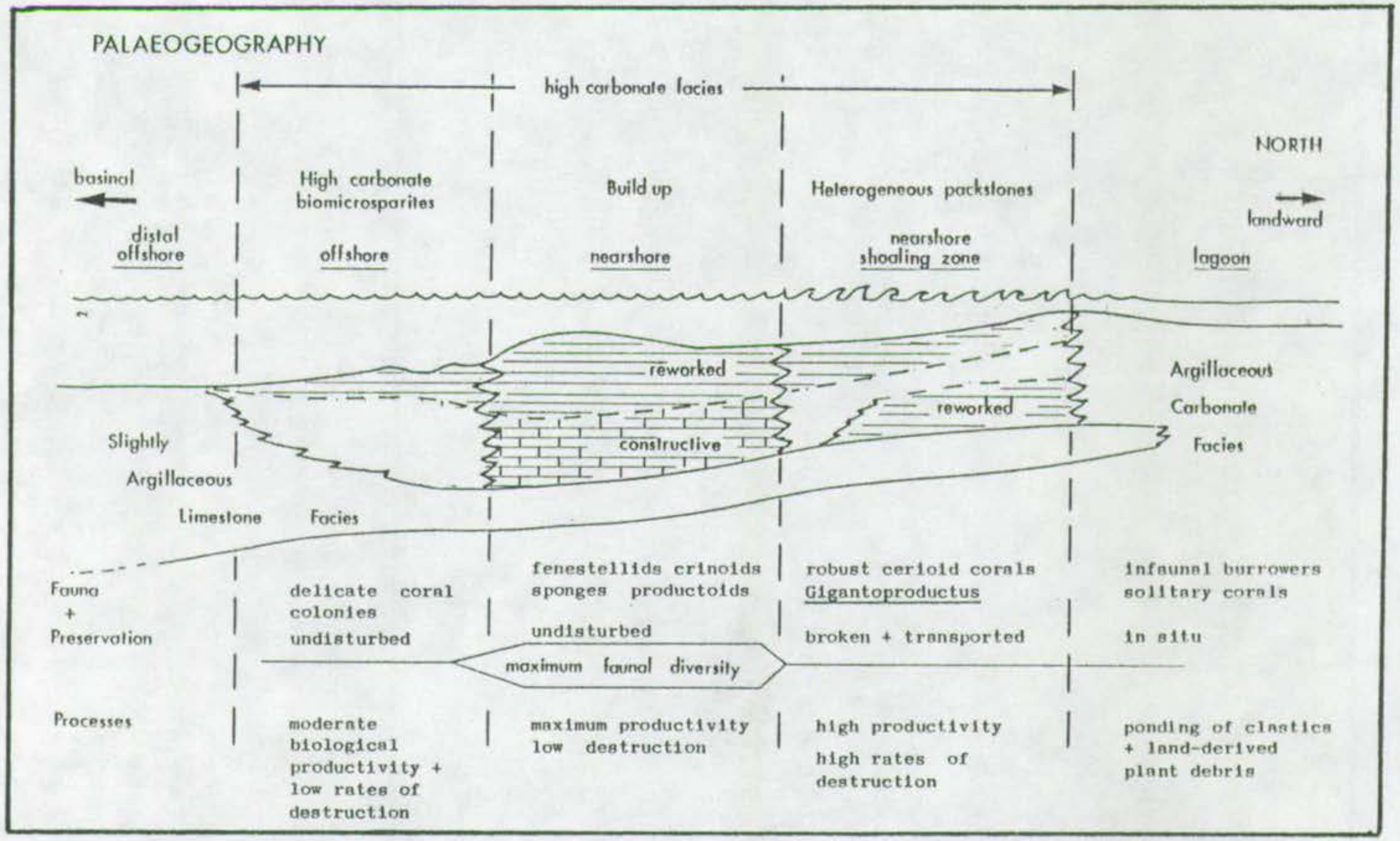


Fig. 12-1 Reconstruction of the high-carbonate environmental mosaic. Vertical scale exaggerated.

12.3 The facies mosaic: significance

The lateral relationships between facies also provide the basis for interpreting a vertical sequence (Walther's Law). In the upper Reservoir Mbr. each high-carbonate facies shows a coarsening-upward trend into progressively more reworked units (Figs. 12-1; 11-15; 10-7). The nearshore facies largely consists of reworked units, which thin southwards, showing a progressively decreasing effect on further offshore facies. This vertical transition parallels that of the lateral nearshore-offshore profile. It thus indicates that the high-carbonate mosaic is a regressive pattern, in which each facies shows a shallowing-upward trend. The regressive nature of the sequence as a whole provides one of several lines of evidence that the subsequent episode of widespread erosion (surface B) took place under conditions of subaerial exposure.

CHAPTER 13

THE CRINOIDAL PACKSTONE FACIES

13.1 External features and facies relationships

The crinoidal packstone facies extends southward from the area of Knock Hill, probably to the limits of the Petershill Fm. (Figs. 8-1; A-1). It forms a thin sheet, bounded by an erosion surface (B) underneath and a discontinuity (surface C) over much of its upper surface.

13.2 The sequence

The vertical sequence is relatively consistent along strike (Fig. 13-1). Over most of its lateral extent, the crinoidal packstone facies consists of 3-4 m thick sequence beginning at erosion surface B, which is covered by 5-10 cm of grey volcanogenic clay and calcareous mudstone, and passing up into medium thickness limestones. These limestones gradually give way upwards into a massive or thick, moderate- to well-sorted crinoidal packstone or grainstone (Fig. 13-1), a continuous bed over much of the Reservoir Mbr. The crinoidal packstone facies as a whole shows an upward coarsening trend, which is seen as an increase in average grain size, the degree of sorting and bedding thickness. This trend is more marked in the northern half of the facies (N. of Sunnyside) where nearly the entire sequence is coarse-grained.

13.21 The north-south strike section

At the northernmost exposure (the Rifle Range north quarry, Figs. 13-1D; 13-2; 2-4) the sequence consists of medium to massively bedded (up to 90 cm thick) crinoidal packstones, sandy packstones, and quartz sandstones. Bedding boundaries are often erosive. The limestones often contain both large and small-scale cross-strata. Cross-stratification types include tabular avalanche sets (sensu

Imbrie and Buchanan 1965) which may show grading, as well as trough-shaped sets (q.v. description which follows). Cross-stratified beds alternate with rather structureless beds where depositional textures have been obscured by bioturbation or diapirism. Within the limestones in the lower part of the sequence, cerioid corals and Gigantoproductus bands are common, preserved in a similar manner to those in the underlying heterogeneous packstone facies underneath. 70% of the cerioid corals examined were in life attitudes, a sign that at least some of the fauna is in situ.

The interbedded sandstones are fine-grained orthoquartzites, containing variable, but generally small, percentages of argillaceous and organic material. They show small-scale trough cross-stratification and plane lamination. Truncated bioturbation horizons and vertical burrows in the sandstones provide evidence of numerous erosional breaks and suggest irregular sediment influxes.

The sandstones and sandy limestones are largely confined to the northernmost quarries. Along the Rifle Range and further south, discrete sandstone beds and sandy limestones give way to more argillaceous beds with only occasional sand laminae. Thus, the clastic fraction shows a marked tendency to fine southward. This trend is also seen in the size of the limestone allochems, but it is much less obvious.

At Sunnyside (C, Fig. 13-1) the sequence is unusually thin, but it is still lithologically typical of the facies, particularly of the area further south. These present day differences in facies thickness may not be significant because the upper facies boundary is erosive.

Further south (A, B Fig. 13-1) the sequence consists of variably-composed biomicrosparites and packstones coarsening upward into the top crinoidal packstone bed. Cerioid corals, Chaetetes and Gigantoproductus are particularly common in the lower half of the sequence.

In the region of the build-up, the lower part of the sequence becomes more crinoidal, passing into fine-grained argillaceous beds further south.

The top crinoidal packstone (Fig. 13-1) forms a thick, in places massive, bed which is readily recognizable and probably continuous from Knock Hill southwards (Fig. A-1). This bed is composite, consisting of planar or trough-shaped sets of cross-strata (Figs. 13-2; 13-4a). North of Sunnyside it displays large-scale trough cross-stratification. Exposures in this region are small and thus a detailed interpretation of this structure is hampered. In some cases, however, the large trough-shaped sets can be seen to be erosively based, with bounding surfaces which are gently curved concave-upwards (Fig. 13-4a). Each set is, in turn, composed of smaller cross-strata, usually low-angle tabular accretionary sets or small trough-shaped sets. The large scale trough-like geometry of bedding points to the presence of large bedforms, perhaps asymmetrically-crested dunes, in turn covered with smaller ripples (q.v. Harms et al. 1975, p 24, 25).

13.3 Fauna

The fauna of the crinoidal packstone facies is generally comparable with that of units A and C of the heterogeneous packstone facies (Table 10-3), although less abundant. Gigantoproductus, cerioid corals (particularly Lonsdaleia) and Chaetetes are characteristic. The lower half of the sequence is generally more fossiliferous, and the fauna is often in situ. In the top crinoidal packstone, whole fossils are rare and seldom in their presumed life attitudes. Considerable lateral changes in the fauna take place in the lower half of the sequence. These changes follow lithological variation. The slightly argillaceous limestones in the sequence, for example, contain a fauna typical of the slightly argillaceous limestone facies elsewhere (q.v. Ch 8).

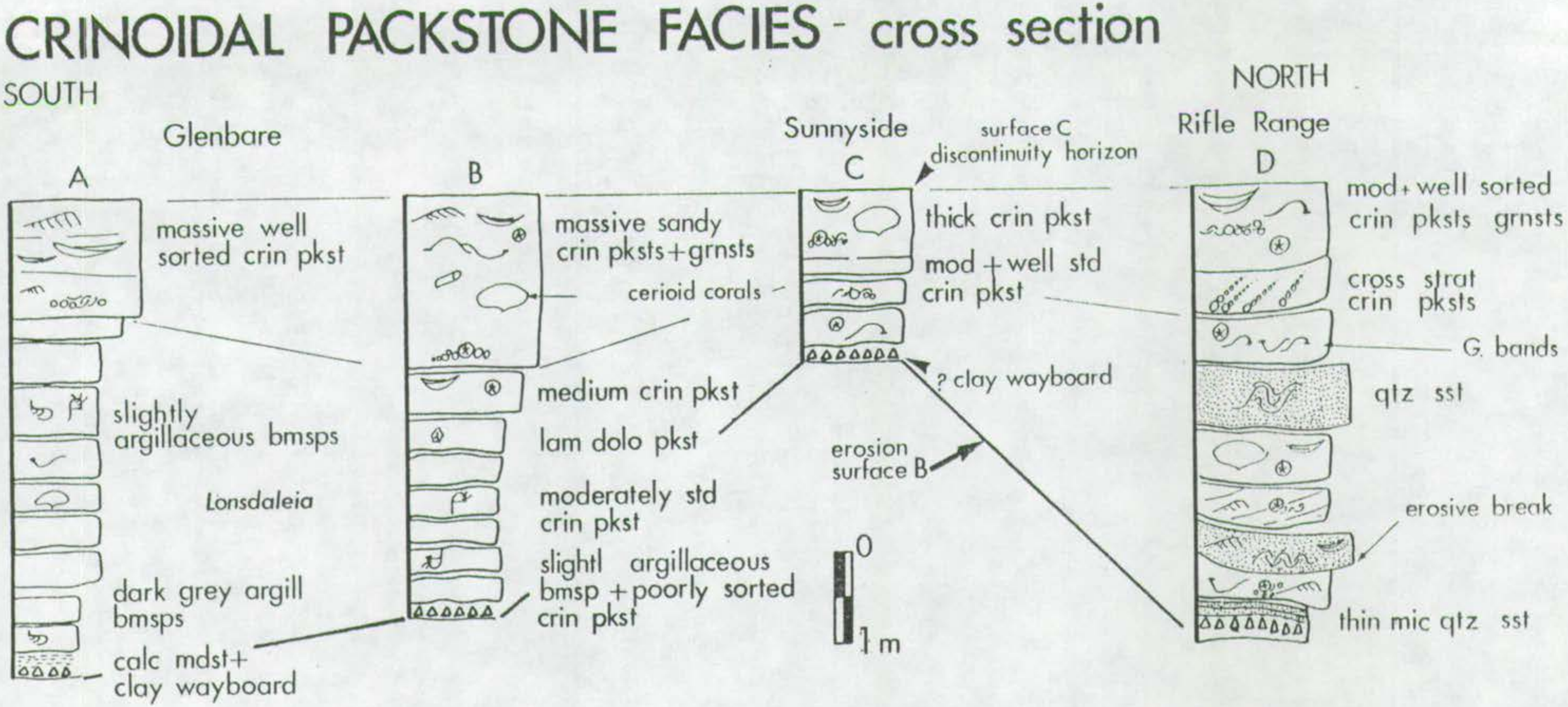


Figure 13-1 Generalized cross-section of the crinoidal packstone facies.

Sections show general features of the facies at south of Glenbare (A), at Petershill Reservoir II (B), Sunnyside (C), and the northernmost Rifle Range quarry (D). Each section compiled from several exposures. At Sunnyside the clay wayboard normally observed at the base of erosion surface B, may have been squeezed from between the limestones. Lines joining columns denote most obvious correlations. Scale approximate.

13.4 Erosion surface B

13.41 Description

The base of the crinoidal packstone facies is marked by a clay wayboard overlying a surface that is erosive over most, and probably all, of its lateral extent (Figs. 8-1; A-1).

Evidence of erosion is present at several exposures along strike (Figs. 13-2; 11-10; 13-4a). In the intervening exposures, surface B is also likely to be erosive, but the nature of the surface cannot be established. At the northernmost Rifle Range Quarry (Figs. 13-2; 2-4) surface B clearly truncates 4 m of the underlying beds. Moreover, it is highly irregular, and possesses several metres of relief over a small horizontal distance of approximately 30 m (see Fig. 13-2). Within this same quarry, surface B may be traced onto faces where it appears to conform with bedding underneath. Along such faces, the erosive nature of the surface can sometimes still be inferred, because the underlying unit, a distinctive crinoidal packstone (unit C of the heterogeneous packstone facies, q.v. Ch 10) is absent or significantly reduced in thickness.

Further south in the Rifle Range quarries (Fig. 13-4a), surface B again truncates bedding, indicating that erosion was not confined to the northernmost region. The northern Rifle Range exposures thus show that the extent of erosion along the surface is variable, but that the erosive nature of the surface itself is not often apparent.

At the Reservoir and South Quarry (Figs. 11-10; 2-9; 2-10; 2-11) surface B forms a prominent break in bedding, which generally follows changes in depositional dip of the beds underneath. The top unit of the flank beds in South Quarry has been truncated (see schematic block insert, Fig. 11-10, Unit 2). Moreover, this unit does not thicken southwards, like the lower flank unit does. These observations strongly

Figure 13-2.

Montage showing various features of the upper Reservoir Mbr. at the northernmost quarry in the Rifle Range (q.v. Fig. 2-4). Units A, B, C of the heterogeneous packstone facies from the base of the exposure. Note distinctive weathering and bedding characteristics of each unit. Changes in thickness of unit C are unrelated to depositional processes due to the erosive nature of surface B. A thin line of grass picks out the clay wayboard that overlies this surface. Nearly 4 m of the underlying facies are truncated. The thick-bedded crinoidal packstone facies overlies surface B. Some of the narrow joints in quarry face (F) are sandstone infilled fissures. The basal sandstone subfacies of the Silvermine Mbr., which overlies the top limestone bed (dashed line) is reduced in thickness to a few centimetres, whereas elsewhere it is usually 3-4 m thick. The overlying black shales weather characteristically to yield a grass-covered slope.

RIFLE RANGE – north quarry

suggest that the beds have been truncated by erosion along surface B. Beds in the flanks, however, show signs of interstratal flow. The truncated calcareous mudstone partings, which define bedding, might be partly secondary, introduced by interstratal movement. Thus, it is possible that the truncated appearance of bedding is a secondary feature and that surface B is not actually erosive. Although this possibility seems unlikely, it cannot be entirely overlooked. Further south, surface B is gently undulose and more prominent than other bedding planes. Exposures are small and, thus, it cannot definitely be established if the surface is erosive.

In summary, surface B is almost certainly erosive between the northernmost Rifle Range Quarry and Sunnyside; between Sunnyside and South Quarry it is probably erosive; while further south it is likely to be erosive.

13.42 Origin of erosion surface B

The stratigraphical context and topology of the surface suggest that it may have formed by either ravinement (sensu Swift 1968) or by subaerial exposure. Although definitive proof is not available, the evidence strongly suggests that the surface is a subaerially-formed discontinuity.

A ravinement is an erosive surface which may resemble a discontinuity, produced by transgressive migration of a barrier environment (Swift 1968; Anderson 1972; Kumar and Sanders 1974; Barvis and Makurath 1978). Ravinements may form by landward migration of the barrier zone, or by tidal inlet migration within the barrier zone (references given). As the barrier environment migrates landward, offshore sediments come to overly more proximal, lagoonal backshore sediments.

Ravinements may also form where shorelines are stable, due to lateral migration of tidal inlets (Kumar and Sanders 1974; Barvis and Makurath 1978). Lateral tidal inlet migration leaves a characteristic upward fining sequence, based on an erosive surface. In both these instances ravinements form by scour of unconsolidated sediments in a moderate to high energy environment. Such erosion is likely to produce a smooth planar, or slightly concave upward surface.

Discontinuities, in contrast, are typically highly irregular (e.g. Walkden 1974; Multer 1978; Enos and Perkins 1977; Purdy 1974). Differences in jointing patterns, conditions of drainage, type of soil cover, bedding thickness and limestone lithology contribute to variable weathering surface morphologies (Kobluk et al. 1977, p 1160; Walkden 1977, p 350). It is not unusual to find that some parts of discontinuity surfaces are apparently conformable, while others are clearly erosive. This is the case with the discontinuity at the top of the Reservoir Mbr, surface C (see Sect 13.5). Therefore, the irregularity of the surface itself strongly suggests that surface B is not a ravinement.

A similar conclusion follows from the stratigraphical context in which the crinoidal packstone facies is found (see Table 13-3). Erosion surface B is unlikely to be a ravinement as the underlying sequence is regressive (q.v. Ch 12), whereas ravinements occur during transgression (Anderson 1972). Moreover, the crinoidal packstone facies itself does not resemble a tidal inlet filling sequence, as it does not fine upwards. Thus, two separate lines of evidence concur in strongly suggesting that erosion along surface B occurred by subaerial exposure and not by ravinement.

13.5 Erosion surface C: a discontinuity at the Silvermine-Reservoir Mbr. boundary

The top limestone bed of the crinoidal packstone facies can unequivocably be shown to have been subaerially exposed (prior to deposition of overlying beds) between the northernmost Rifle Range quarries and Sunnyside (as shown on Fig. A-1). This discontinuity probably extends further south at this same horizon, while further north the sequence appears to be conformable.

13.51 General appearance

Surface C is similar to surface B in that both evidence for subaerial exposure and style of weathering differ between exposures. Beds immediately beneath surface C are often highly jointed, commonly weathering to yield a rubbly slope (Fig. 13-4a). Thin-bedded sequences beneath the surface tend to break up into inter-fitting,round cobble-sized blocks surrounded by red-brown clay or rarely, sandstone (Fig. 13-3a). Thick-bedded sequences beneath the discontinuity surface and near fissures (see below) are often brecciated. At Sunnyside, the overlying sandstones have gently subsided into a 1.5 m deep, somewhat dish-shaped depression where the limestones are highly altered and rubbly. At other exposures, such as the northernmost Rifle Range Quarry, reddened, jointed zones of rubbly weathering are developed beneath the surface.

The uppermost limestone surface itself (which is very poorly exposed), may show a variety of features attributable to solution. In the middle Rifle Range quarry (at the locality shown in Fig. 13-4a) small, rounded pits and runnels similar to those figured by Kobluk et al. (1977, p 1175) as karren forms of karst weathering are developed in surface C. A reticulate system of joints and decimetre-sized grikes (sensu Purdy 1974, p 27) open onto the limestone surface.

These grikes and larger sediment-infilled fissures are often stained brownish-red and have become decalcified. Staining is caused by an intergranular replacement or void-filling by a ferric oxide, probably limonite. In some of the narrower grikes, the staining is vertically laminated. However, not all fissures are stained and a similar alteration pattern is also found in mineralized areas, apparently unrelated to the discontinuity (although occuring at the same horizon). Thus, while staining and decalcification are definitely associated with the discontinuity surface, they may not necessarily be genetically related to it.

13.52 The fissures Figs. 13-3; 13-4; 0-7, back pocket

Nearly vertical fissures, usually infilled with sandstone, are present at eight exposures between the northernmost Rifle Range and Sunnyside (located on Fig. 0-7). Most fissures are funnel or V-shaped. However, the shape and orientation of fissures is fairly variable. Some may open downward, as probably first noted by Howell and Geikie (1861, p 56) in their description of a "remarkable hole" which was almost certainly part of a fissure. Fissures range from a few centimetres to approximately 4 m in width and have been traced vertically up to 8 m. Their sides are smooth and have irregularities corresponding to bedding in the enclosing limestones (Fig. 13-3). In plan view, fissures are rectilinear, extending up to 125 m between outcrops (Fig. 0-7).

13.53 Fissure-infilling sediments Fig. 13-4b,c,d

A variety of lithologies infill the larger fissures. Textures in the infillings are usually fairly chaotic (Fig. 13-4c), produced by a combination of gravity re-adjustment and diapirism. Where the original structures are preserved, however, the infillings are often horizontally bedded or laminated, and occasionally display

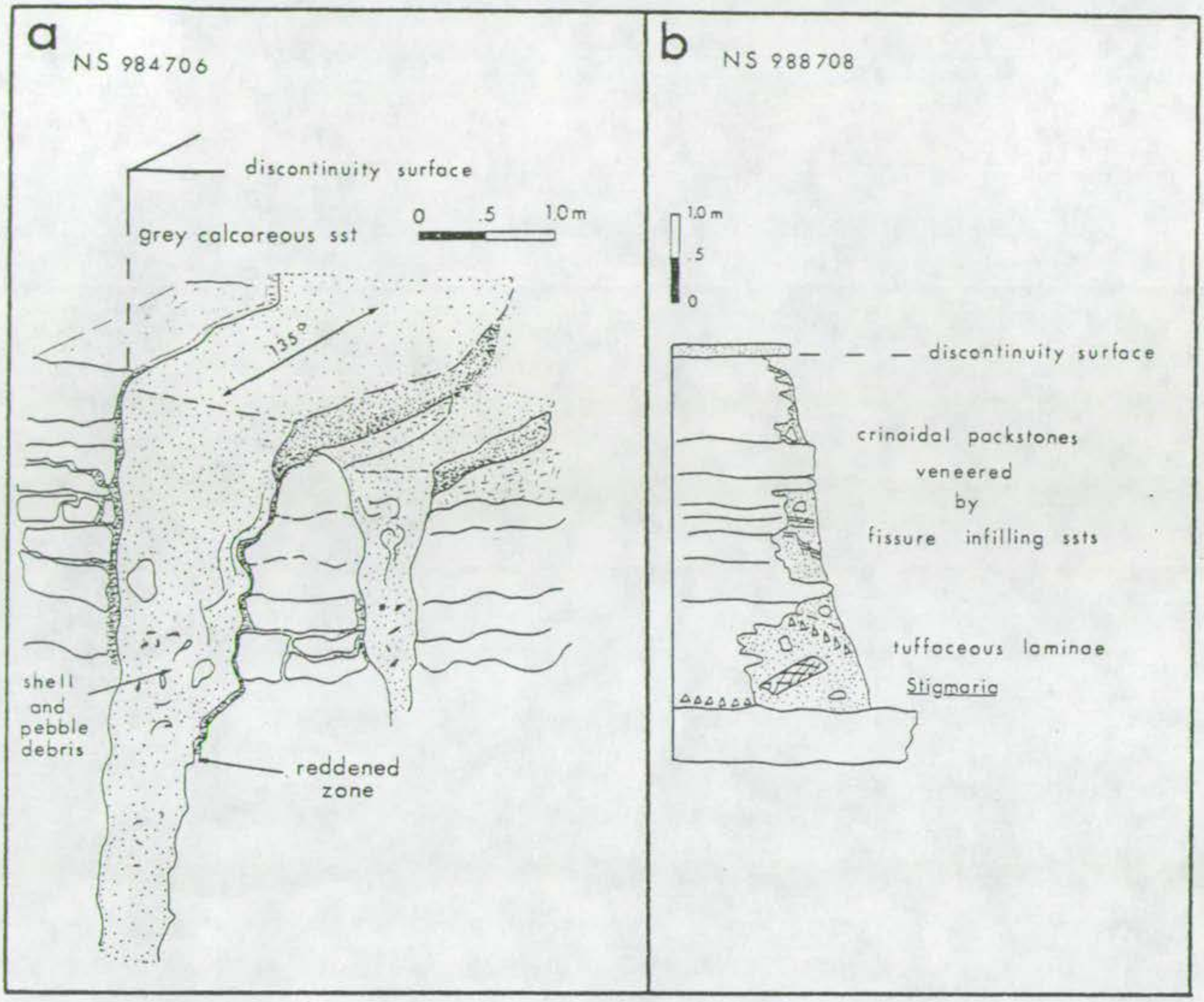


Figure 13-3 Sandstone-infilled fissures beneath discontinuity surface C, Rifle Range quarries (Grid references given).

a. Two, near vertical, smooth-sided fissures taper gently downward. Their position relative to discontinuity surface C has been estimated. Figure traced from a photograph.

b. Cross-section of a fissure which was quarried parallel to its strike. Fissure has thus been preserved as a thin veneer of sandstone on a former quarry wall.

small-scale cross-stratification.

The most common sediment to infill fissures is a fine-grained quartz sandstone with only minor percentages of organic matter, detrital clay, feldspars and heavy minerals. Several fissures are entirely filled with clean, well-washed sandstone additionally containing only a few fossil fragments. More often, the sandstones are interlaminated with a variety of siltstones and tuffs. They also contain several types of coarse debris, including limestone and siltstone intraclasts, large plant fragments, and loose fossils (see Fig. 13-5c).

The limestone intraclasts may reach up to cobble size. Clast surfaces have commonly formed around, rather than across, large or robust fossils. Fossils in these clasts are similar to those found loose in the fissures, as well as in the enclosing limestones. Crinoids, corals, and brachiopods are most common. The manner in which the clasts have been rounded and the faunal similarity between intraclasts, loose fossils, and enclosing limestones, suggest that the carbonate fissure detritus is autochthonous and derived while the enclosing limestones were poorly cemented.

The greatest lithological variation is found among the fine-grained mudstone intraclasts. These include as many as eight different types of red mudstones, black micaceous siltstones and carbonaceous shales. The more extensively reddened intraclasts are rounded, whereas black intraclasts have flat, flake-like shapes indicative of textural immaturity. Infilling plant debris ranges from spores and other microscopic detritus to coalified wood fragments and large <u>Stigmaria</u> reaching 40 cm in length.

Fissure infilling tuffs (Fig. 13-4b) are grey, calcareous and also contain plant and fossil detritus. Nodular calcareous horizons

Figure 13-4 Features of erosion surface C, a subaerial discontinuity

a. Fissures. Arrow and dashed lines show fissures cross-cutting the limestones forming a pinnacle on the eastern side of the middle Rifle Range quarries. Total height of exposure = 8 metres. Note rubbly, broken appearance of the wavy bedded underlying limestones and debris at the foot of pinnacle; these features are typical of extensively altered exposures. Solid line shows boundary between heterogeneous packstone facies below and crinoidal packstone facies above, which show large-scale trough cross-stratification.

b. Tuff from fissure. Broken surface of a calcareous nodule of tuffaceous clay with large cm-sized subround white and green volcanogenic material. Large scale divisions = centimetres. G.T. 46,514

c. A laminated, impure sandstone fissure infilling. Original fine parallel laminae of sandstone, organic material and micaceous siltstones, and crinoidal fossil debris show numerous microfaults formed during gravity-settling of infilling. Total length scale = 10 cm; sliced block. G.T. 46 522

d. Crinoidal packstone pebble-sized intraclast, taken from a fissure infilling. G.T. 46,521


a


b


c


d

within the tuffs preserve centimetre-sized angular-to-round white (kaolinitic) and green-brown (?chloritic) fragments of volcanogenic material (Fig. 13-4b).

13.54 Origin and significance

The fissures are clearly contemporaneous as they are infilled and overlain by Carboniferous rocks. Their geometry and the nature of the infilling sediments suggest that they are solution joints (cf. Kobluk et al. 1977; Purdy 1974). Such joints originate by chemical weathering (karsting) beneath bare or covered limestone surfaces (Kobluk et al. ibid, p 1160; Purdy ibid).

Sediments infilling the larger fissures also provide evidence of events missing from the sequence elsewhere. Although it is likely that much of the infilling debris was initially introduced from above, current-produced, cross-stratification and lamination indicate that the sediments infilling many fissures were subsequently laterally redistributed. Moreover, many of the lithologies and clasts in the fissures (e.g. mudstones and plant fragments) could not have been derived from the beds presently overlying the surface. It is therefore suggested that the discontinuity surface was first overlain by a sequence of clastics no longer preserved immediately above surface C (a possible provenance is proposed in Ch 15). The erosive event which removed the original overlying clastic sequence probably also smoothed the discontinuity surface itself. This may explain why many of the features often found at discontinuity horizons (laminated crusts, caliches, dissolution cavities) are absent.

The original discontinuity surface cover is likely to have been of shoreline or non-marine origin. Extensive plant colonization may have accompanied or followed its deposition. The tuffs may have also been part of the overlying sequence; alternatively they may represent ash accumulations which were deposited while the fissures were exposed. Removal of the original clastic blanket from the discontinuity surface probably accompanied deposition of the present overlying sequence. The overlying post-discontinuity sandstones, belonging to the Silvermine Mbr., are interpreted as nearshore sandstones (Ch 15). If this interpretation is correct, then the original sediment cover is likely to have been eroded during shoreline migration over the exhumed limestone surface. It is therefore suggested that the infilling sandstones are also marine, and that the mechanical erosion and modification to form the fissures occurred while the discontinuity surface formed an inter- or sub-tidal platform. Indeed the Reservoir Mbr. fissures are very similar to both Recent and ancient platform fissures described from elsewhere (q.v. Kobluk 1977).

13.6 Depositional environment and history of the crinoidal packstones

The crinoidal packstone facies shows a lateral environmental profile consistent with that of the underlying facies. The most significant difference is that it accumulated during a period of clastic influx. Trough cross-stratified packstones and sandstones pass southward along strike into progressively finer-grained and more argillaceous limestones. The strike section thus appears to represent a nearshore to offshore transition, developed on a shallow platform. Differences in the thickness of sediments over this platform are very slight. The coarse crinoidal packstones may have formed nearshore shoals or bars, passing offshore into quieter, finer grained level-bottom substrates.

If the erosion surface at the base of the facies is a discontinuity, then this environmental profile became differentiated during transgression over an exposed surface. A subsequent minor regression within the facies resulted in offshore migration of the nearshore coarse crinoidal packstone sands. Shoreline or perhaps even non-marine clastics were then deposited above the uppermost crinoidal packstone. Subaerial exposure may have accompanied, post-dated, or preceeded the accumulation of the original clastic sequence, which is now only preserved in the fissures. Subsequent transgression eroded the overlying cover, planed the limestone surface and enlarged the underlying joints into fissures, while partially reworking and adding to the fissure contents.

CHAPTER 14

PALAEOECOLOGICAL ASPECTS OF THE PETERSHILL FM. BIOTA

14.1 Introduction

Throughout this study the taphonomy, relative abundance and size of fossils and their associations have been shown to be characteristic of particular substrates or facies. In this chapter special attention is given to facies-specific faunal groupings (facies faunas), and to some of the factors responsible for their distribution. Encrusting organisms are used as a specific example of the detailed information which follows from an application of this approach.

14.2 Factors affecting the distribution of faunas

Prior to examining the relationship between facies and their faunas, it is important to consider the principal factors which may have controlled faunal distribution and the ways they may have been inter-related. A summary of these factors is shown in Fig. 14-1, based on evidence from the Petershill Fm. as well as from Recent and other ancient environmental studies (Newell et al. 1959; Purdy 1964; Enos and Perkins 1977; Fürsich 1976). The clearest empirical relationship observed in the Petershill Fm. is between fauna and substrate. Many other factors such as temperature, light, salinity, depth, etc. may have been equally important, but do not directly leave a preserved record. They are more difficult to assess in a geological context.

Those attributes of the sediment which are important in determining the nature and abundance of epifauna and infauna are strongly dependent on the hydraulic regime (Fig. 14-1). The strength and persistence of currents (hydraulic regime) in turn have some direct influence on the composition, distribution, and abundance of epifauna. Purdy (1964) offers an excellent discussion on the relationship between hydraulic regime, sediment composition and substrate properties (see

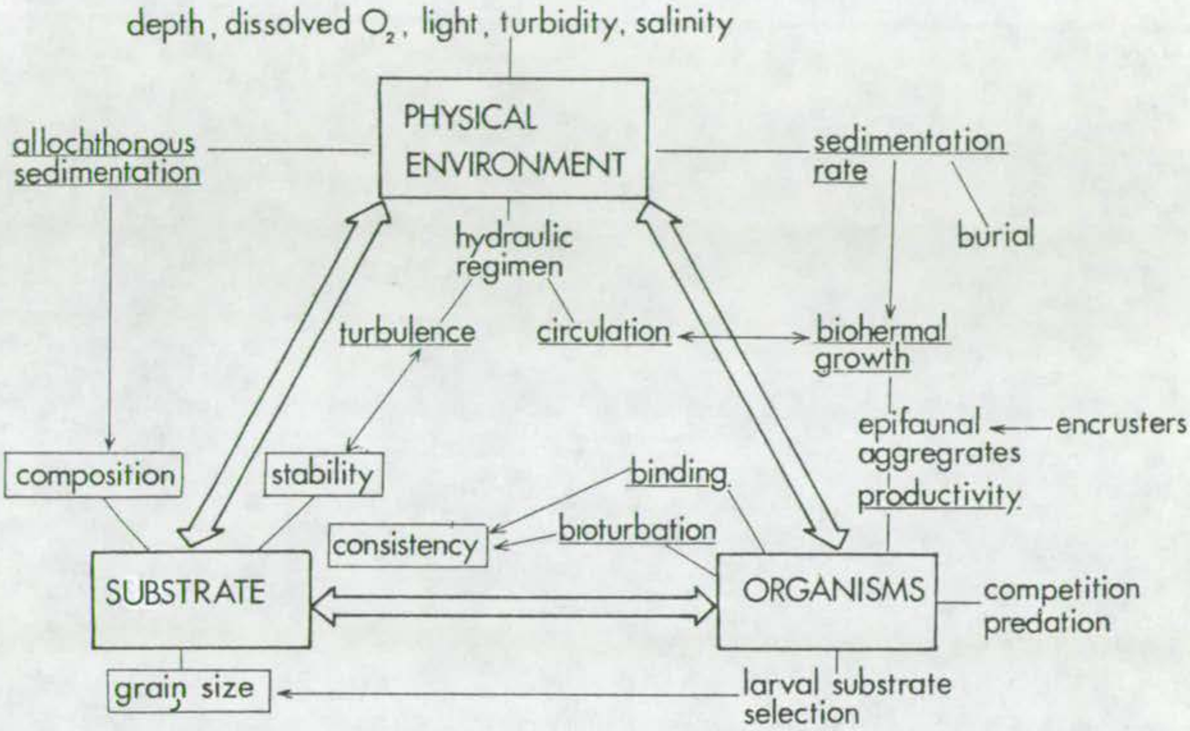


Fig. 14-1 Relationship between major factors affecting substrate properties. Taken from references listed in text.

also Anderson and Pazdersky 1974). Thus, from determining the nature of substrates, some evidence for the type of physical environment also becomes available.

Purdy (1964), Newell et al. (1959) and Enos and Perkins (1977, pp 35, 110) have also stressed feedback between organisms and the sediment as a controlling mechanism in faunal distribution. The most obvious relationship observed between fauna and substrate in the Petershill Fm. is between sediment firmness and epifaunal abundance and diversity. Initially firm substrates possess an abundant and diverse epifauna, which, in turn, largely control the distribution of the encrusting fauna. At many horizons in the build-up the in situ fauna reaches such a high proportion of the sediment as to alter depositional texture. The replacement crinoid fauna is a special example of an in situ fauna which, on death and decay, provided sedimentary particles with different hydrodynamic characteristics to those of the lower build-up fauna. The crinoidal contribution to the sediment is likely to have altered the properties of the substrate, probably creating a more mobile sediment surface.

Among the many ecological factors contributing to a given faunal distribution pattern, the geologist may only deal with those which have been preserved. In the Petershill Fm. and elsewhere, these key factors are reflected in differences in grain size, composition and texture of substrates.

14.3 Attached and encrusting organisms and their palaeoecological significance

14.31 Introduction

Several examples have already been given in this thesis of how encrusting or attached organisms may provide palaeoecological information. As a source of such information, Carboniferous encrusters

TABLE 14-2 Attached and encrusting organisms

ORGANISM	SUBSTRATE TYPE	
	Skeletal	Sediment
Attached forms		
Brachiopods		
productoids	*Chaetetes*(C)	X
terebratuloids	productoids	A,F
Solitary corals	productoids *Chaetetes* *Lithostrotion*	X
Foraminiferans	X	A,F
tetrataxids		
Earlandia		
calcitournellids		
simple spherical forms		
Microproblematica	productoids *Hyalostelia* *Chaetetes*	A,F
Microcrinoids	*Chaetetes*	O
Syringopora	R	0
Encrusting forms		
Algae	X	
Fistuliporoid bryozoans	X(C)	A,F
Cornulites	productoids	O
Spirorbis	X(C)	A,F
Serpuloides	X	-

KEY: X-common on all types; (C)-cryptic; A-algal; F-firm
O-absent; "-" very rare . Note: foraminiferans plotted as a group.

have hitherto largely been ignored, and much of the following material is described for the first time. Encrusters are defined here as forms that are moulded to a surface or which appear to have been cemented to it. Forms which were loosely joined to a surface, or grew away from an initial cemented base are termed attachers. Where the distinction between the two modes of colonization was not easily apparent, or when general statements are made about both modes of life, the term encruster has been used. It should be noted that many organisms may either attach or encrust, depending on available substrate or the prevailing environment. The substrate of an encruster may be either a skeletal or sediment surface.

14.32 Methods

Several thousand fossils from all facies were examined for encrusters in the field. Roughly 80% of these came from the bedded, slightly argillaceous and high-carbonate biomicrosparite facies at the Reservoir, but encrusters were searched for during faunal sampling in all facies. Over 1000 encrusted fossils and several kilos of Lithostrotion fragments were collected and microscopically examined. Of these, the encrusting biota of 200 solitary corals, 250 spinose productoids, 100 gigantoproductoids, and a total of 100 Chaetetes, bivalves, colonial corals and other fossils were tabulated. Encrusters were also tabulated from broken rock surfaces, insoluble residues, and in over 100 thin sections and peels. These data form the basis for the conclusions reached here.

14.33 General considerations

Although encrusters are numerically abundant, it is important to keep in mind the scale on which encrustation occurred. In general, encrusting organisms are small (mm sized) and seldom cover more than 10-30% of a skeletal host's available surface area. Encrustations of colonial organisms are most often small and have a simple form. Massive or multiple encrustations are fairly rare. The majority of skeletal encrusting organisms were probably commensal in that they would have obtained protection, elevation above the sediment surface, and a stable attachment site, without significant detriment to their host.

In the Reservoir Mbr. the number of encrusting organisms occurring in life position and also as detrital particles in the sediment is directly proportional to the area of available favourable substrate, and inversely related to the percentage of clastic detritus. Encrusters were thus notably less abundant in argillaceous facies, even where large numbers of epifaunal shells were present. The fossils in low clastic facies are much more extensively encrusted. In these lithologies many initial skeletal encrustations extend to colonize the sediment surface. Encrusting organisms thus appear to have selected environments where firm substrates were available in the form of both skeletal material and a firm sediment surface, i.e. areas of high biogenic productivity.

A list of the common encrusting taxa and their substrates is shown in Table 14-2.

14.34 Attached and encrusting organisms in the Petershill Fm.

14.341 Brachiopods

Terebratuliform brachiopods (Figs. 14-6a; 9-3; Table 14-2) Shells of terebratuliform brachiopods, mainly Dielasma and Composita are common, often found articulated, with the pedicle foramen pressed closely against a presumed attachment surface. Rudwick (1970, p 77) and others have used this criterion as a basis for supposing that these brachiopods were once attached by their pedicles. The former presence of brachiopods on some surfaces is also indicated by circular

Fig. 14-3 Encrusters beneath *Chaetetes* colonies

a. Holothecal undersurface of a colony with attached aulostegid productoids, spirorbid worms and perhaps a spirifer (sp). Brachiopod spines mould to undersurface. Where they have become detached (S), the outer spine lamellae have remained cemented to the holotheca. Dashed line encloses elliptical patch of borings, a probable brachiopod pedicle attachment scar. *Chaetetes* colony from Rifle Range quarries, heterogeneous packstone facies. Scale bar divisions = cms. RSM 1979.1.25

b. Holothecal undersurface of a *Chaetetes* colony overgrowing an *Antiquatonia* shell (A) at left. Holotheca is encrusted by numerous fistuliporoid bryozoans (F) and *Spirorbis* (S). Petershill Reservoir, high-carbonate biomicrosparite. Scale bar divisions = cms. G.I. 46,478.


S
Sp


f
A
f
f
f
f

or elliptical patches of borings very similar to the pedicle attachment borings figured by Bromley and Surlyk (1973) (Fig. 14-3). Terebratuliform brachiopods are commonly attached to Lithostrotion, Antiquatonia, the pedicle exteriors of Gigantoproductus (Fig. 14-6) and the undersurfaces of Chaetetes. They are absent from the upper surfaces of Chaetetes indicating a preference for protected habitats, at least in some environments.

Aulostegid productoids - Aulostegidae occur very rarely, attached to the undersurfaces of Chaetetes and the pedicle valve exteriors of Gigantoproductus. Where they are found adherent to Chaetetes (Fig. 14-3) both the hinge and spines of the productoid are closely pressed against, and moulded to, the holothecal surface. These attachers thus show that productoids could live in a variety of attitudes. Where shells have become detached, the outermost lamellae of their spines remain adherent to the sponge's holotheca, showing that the initial cementation was quite strong. In some cases, spines and whole brachiopods have been overgrown by the host Chaetetes, additionally showing that initial attachment occurred at the growing periphery of a living sponge.

Costate spirifers - Small costate spirifers occur pressed against vertical skeletal surfaces and horizontal surfaces that were once overhanging (Fig. 14-3). By analogy with terebratuliform brachiopods, it is likely they were also pedicle attached.

14.342 Solitary corals (Figs. 14-4; 14-5; 9-4b)

Solitary Rugosa are among the more unusual attachers. Although previous authors have reported morphological adaptations for presumed attachment (Sando 1977; see Maerz 1975 for review), this is the first occurrence in which the actual attachment substrate has also been described.

The corals with attachment modifications or still attached are all aulophylloids, namely *Aulophyllum fungites*, *Dibunophyllum bipartitum*, and *Koninckophyllum magnificum*. Most of the corallites are small, although roughly half were probably in adult stages of growth. Many of the specimens examined were silicified, having been obtained from acid dissolution of limestone blocks. Of 59 corallites studied, 29 still preserved fragments of their original attachment substrate. In seven of these, both the host skeleton and the corals were still in life attitude: these were corals found in *Lithostrotion* colonies, attached to productoids and *Chaetetes*. In the remaining specimens, the type of host skeleton could often be determined, but the life attitude of the corallite could not always be ascertained. The corals with attachments are fairly typical of the population as a whole, differing only in their exceptionally good preservation. Ninety-five percent of all the corals found that had a well-preserved protocorallite tip showed at least some modifications for initial attachment. This observation leads to the conclusion that all aulophylloids attached in their initial stages of life.

The corals show three morphological modifications for attachment: coiling (Figs. 14-5a,d; 9-4b), moulding to the substrate (Figs. 14-4a-d; 14-5b) and attachment by talons (Figs. 14-4b,c; 14-5b,c). In most cases, these modifications are present in the brephic and juvenile stages of the corallite. Lateral attachment scars (produced by moulding), are also typical in the adult corallites.

Coiling occurs in the very earliest stages of growth. The manner of coiling in the Petershill Fm. specimens is very similar to that described by Sando (1977) in *Cyathaxonia*. The protocorallite tip is spirally coiled through as much as 360°. Coiling is an adaptation for gripping cylindrical objects, e.g. productoid spines and *Lithostrotion*

Fig. 14-4 Attached solitary corals

a. Solitary coral, side view. Corallite shows lateral attachment scar where it has moulded to a bivalve. Part of bivalve shell still remains. Scale divisions = mms. RSM 1979.1.20

b. Solitary coral, side view. Corallite has moulded itself to part of a *L. junceum* colony, as well as enveloping coral with talons. Scale divisions = mms. G.T. 46 477

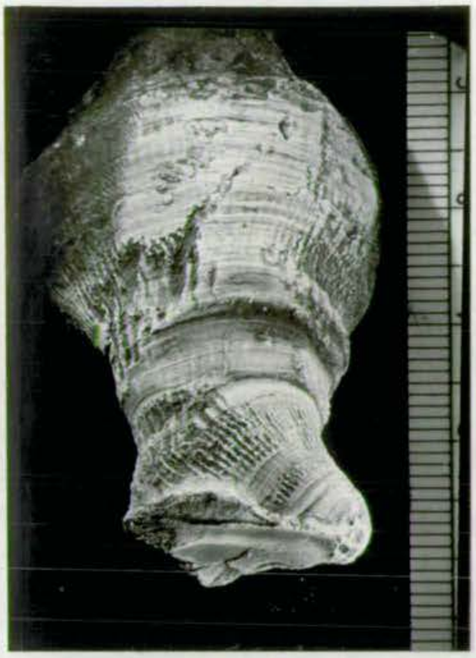
c. Solitary juvenile coral. Protocorallite stage has first moulded to a productoid spine (visible at bottom) and later attached with a talon. Specimen width = 5 mm. RSM 1979.1.21

d. Solitary coral, side view. Corallite shows flattened scar from moulding to unknown hard surface. The bases of numerous broken-off talons are present along sides of scar. The longitudinal groove in side of epitheca is *Corallicolites subcutanea* (q.v. Sect 14.353). Note that epibiont appears to have grown along with coral from protocorallite stage. Scale divisions = mms. RSM 1979.1.22

e. Pedicle valve interior of *Gigantoproductus* with two attached solitary corals, probably *Dibunophyllum*. Magnification x 2. RSM 1979.1.23

f. Pedicle valve exterior surface of *Gigantoproductus*. Attached organisms include solitary coral, a fistuliporoid bryozoan, and *Spirorbis caperatus*. Magnification x 1.4. RSM 1979.1.24

a



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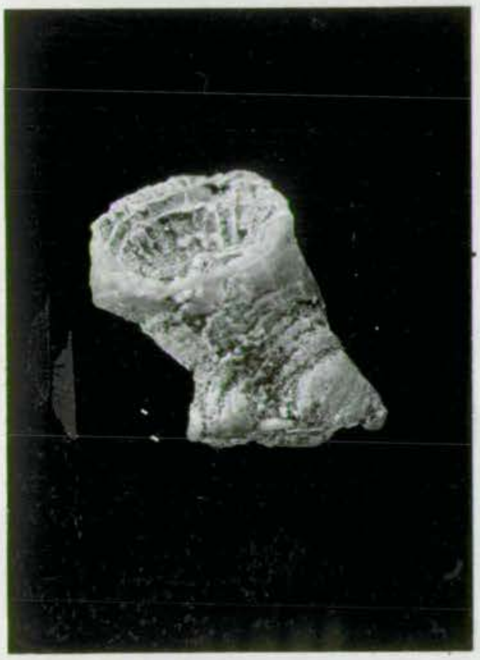

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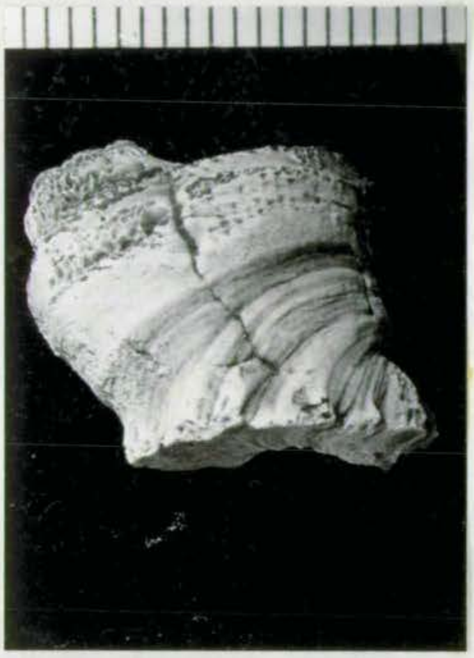
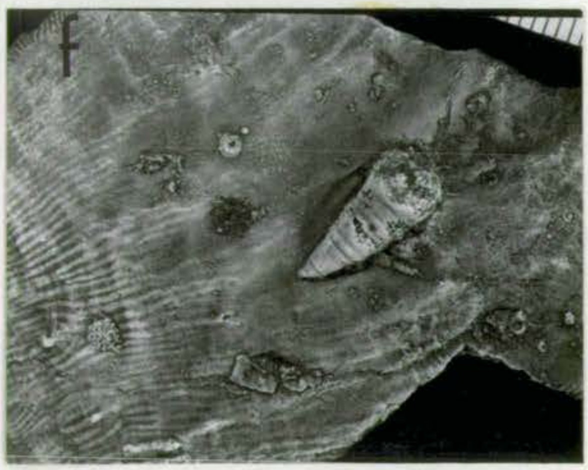




corallites (Figs. 14-4b; 14-5d; 9-4b). In some cases, protocorallites have planispirally coiled about their own point of attachment (Fig. 9-4) rather than another object. This could be a means of rapidly increasing basal attachment surface area so as to obtain a more secure base.

Lateral attachment scars (Fig. 14-4a-d) result from the corallite's epitheca moulding to a contacted surface. The moulded corallite surface often incorporates shell fragments, indicating that the bond was very strong, resulting from cementation.

Nearly 50% of corallite tips examined were pincer-like in form, the pincers being formed by the apposition of the protocorallite and a small talon (Fig. 9-5c). Like coiling, talons are usually an attachment modification to cylindrical objects (e.g. Figs. 14-5b,d; 14-4b). Most corallites have several modifications for attachment. Solitary corals were found attached to the following skeletons (in order of abundance): productoid spines, Lithostrotion, other solitary corals, brachiopod shells and Chaetetes.

In most Petershill Fm. solitary corals, the protocorallite tips are blunt and fairly smooth. Even among the corallites with attachment modifications preserved, the skeleton to which they once attached is often not present. This is especially true for corallites originally attached to productoid spines. Where the tip has not been broken off, it is likely that the brephic stage of the coral or the host skeleton were degraded prior to burial. The epitheca of many Petershill Fm. corals is heavily micritized and bored by algae (e.g. Fig. 14-5 e,f). In some cases, the epitheca was removed before burial, as the underlying dissepiments have been infilled with sediment or encrusted (Fig. 14-6e). Biological degradation is extensive enough to indicate that skeletal attachments and the whole protocorallite could have been

Fig. 14-5 Attached solitary corals: SEM photographs.
All specimens are silicified, obtained from isoluble residues, epitheca partially impregnated with a mounting medium.

a. Solitary coral showing broken, spirally-coiled protocorallite tip. Note numerous microborings. Scale bar = 1 cm. RSM 1979.1.16

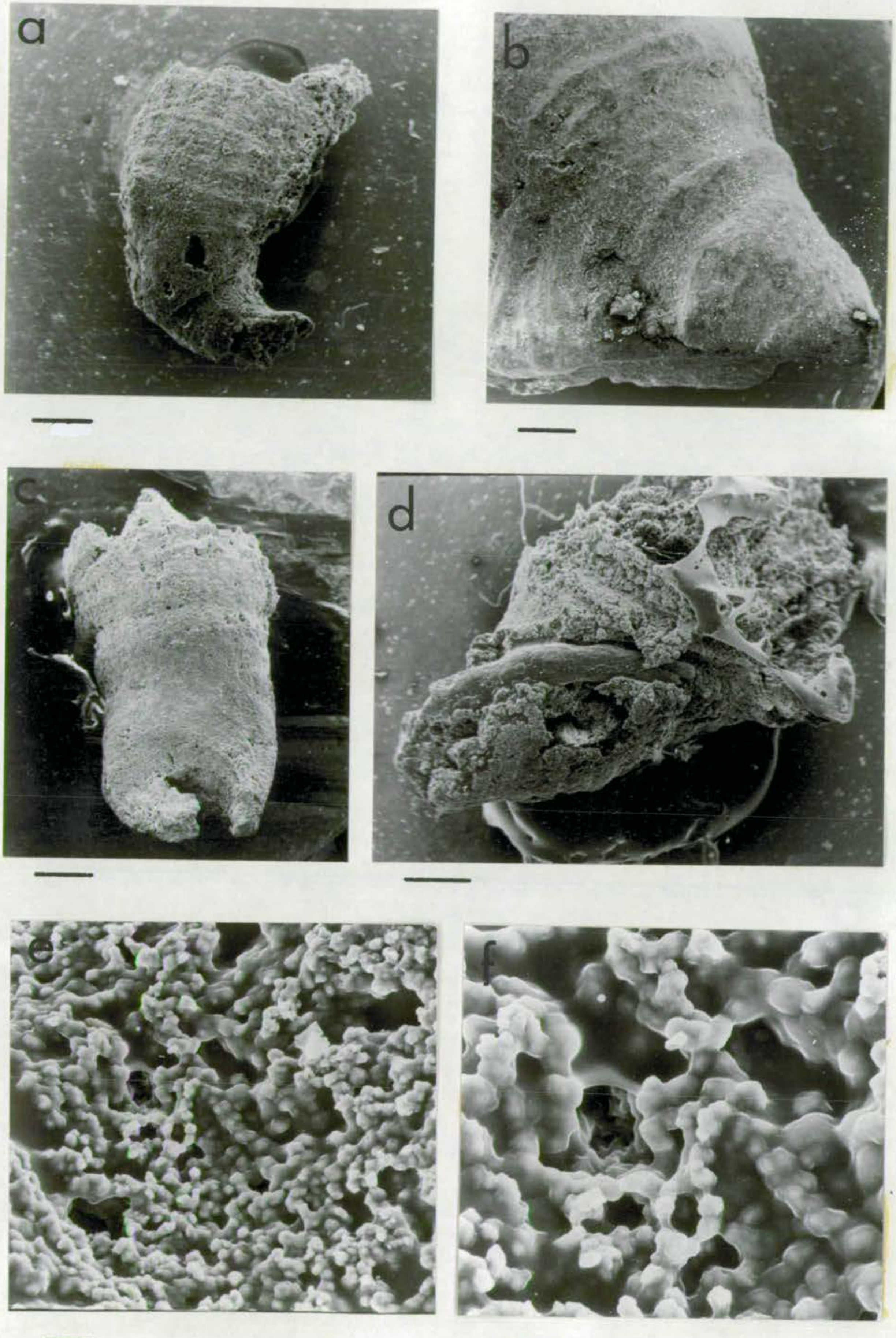
b. Close up of a protocorallite moulded along productoid spine and attached by talon. Scale bar = 1.1 mm. RSM 1979.1.17

c. Pincer-like protocorallite tip formed by the apposition of a talon and the protocorallite itself. Size and shape of this attachment modification strongly suggests corallite initially grew from a productoid spine. Note microborings. Scale bar = 1 mm. RSM 1979.1.18

d. Protocorallite spirally wrapped around a productoid spine. Protocorallite tip (at very left) broken off. Mounting medium covers part of calical end of specimen. Scale bar = 1 mm. RSM 1979.1.19

e. Microborings in coral epitheca. Fine pattern of borings is developed fairly evenly in coral epitheca. Mounting medium occludes smaller borings. Scale bar = 40µ. RSM 1979.1.18

f. Microborings, same specimen, close-up. Scale bar = 20µ. RSM 1979.1.18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removed, in some cases. J. Wilson (1976) found that biodegradation may destroy the basal attachment of Recent scleractininians without detriment to the living coral. This process may thus explain how some Petershill Fm. corals show attachment modifications to surfaces not preserved.

Recently Sando (1977) suggested that coiled protocorallites and lateral scars were modifications for attachment to planktonic algae, and that the coral's inferrable planktonic mode of life could be used to explain the cosmopolitan distribution of some solitary corals. In the Petershill Fm. corals, however, it has been shown that these modifications are adaptations to skeletal attachment and a raised epifaunal mode of life. Sando (ibid) obtained much of his data from acid insoluble residues where the skeletal attachment substrates are seldom preserved. In view of the conclusions drawn from the Petershill Fm. material, it might be profitable to re-examine Sando's material to see whether the simpler interpretation put forward here might be tenable.

14.343 Foraminiferans Fig. 14-6e

Foraminifera (listed in Fig. 14-2) encrust all types of skeletal surfaces. They have been found on vertical, horizontal, overhanging, topmost and the undersurfaces of a variety of skeletons as well as on firm and algal substrates. Lituotubella and Tetrataxis, two of the larger and more obvious forms, exhibit substrate-specific morphological adaptations. Lituotubella forms a flattened or adherent, often coiled, growth on sediment surfaces or very small grains, such as sponge spicules. However, on stable skeletal surfaces, erect, and often branched, growths (extending several mm away from the shell) are most common. Such forms are common among the spines of productoids. In Tetrataxis skeletal attachments are more often flattened, conforming to the shape of the host, while sediment attachments (Fig. 4-6d) are pyramidiform.

14.344 Microproblematica

The general distribution of microproblematica has been described in Ch 4. Encrusting forms are most often preserved on skeletal surfaces. Among these, Kamaena and Stacheoides are most common, occurring as part of the fauna attached to the spines of productoids.

14.345 Holdfasts indet.

Holdfasts probably attributable to various organisms are fairly common on skeletal surfaces. In many cases, the origin of the attacher cannot be determined, although it is likely many belonged to bryozoans. Among the clearly identifiable holdfasts are those of micro-crinoids, which have only been found on Chaetetes.

14.346 Syringopora Fig. 14-6c

In general Syringopora is fairly rare, and colonies are small. Skeletally attached Syringopora colonies are only common in the heterogeneous packstone facies. They typically occur intergrown with Lithostrotion, attached to Gigantoproductus, and encrusting the under and upper surfaces of Lonsdaleia.

14.347 Algae

Algal crusts, envelopes, and borings are present throughout the Petershill Fm. Their structure, appearance, and distribution is described in detail in Ch 4.

14.348 Cornulites sp. Fig. 14-6d

Tubes of this annelid worm are fairly rare. Loose specimens only occur in the high-carbonate biomicrosparite facies, where encrusters are generally abundant. These specimens are likely to have dropped off their original attachment surfaces. Lateral scars on some of the specimens indicate that Cornulites is also one of the productoid spine-encrusting fauna (Fig. 14-6d).

Fig. 14-6 Other common encrusting organisms

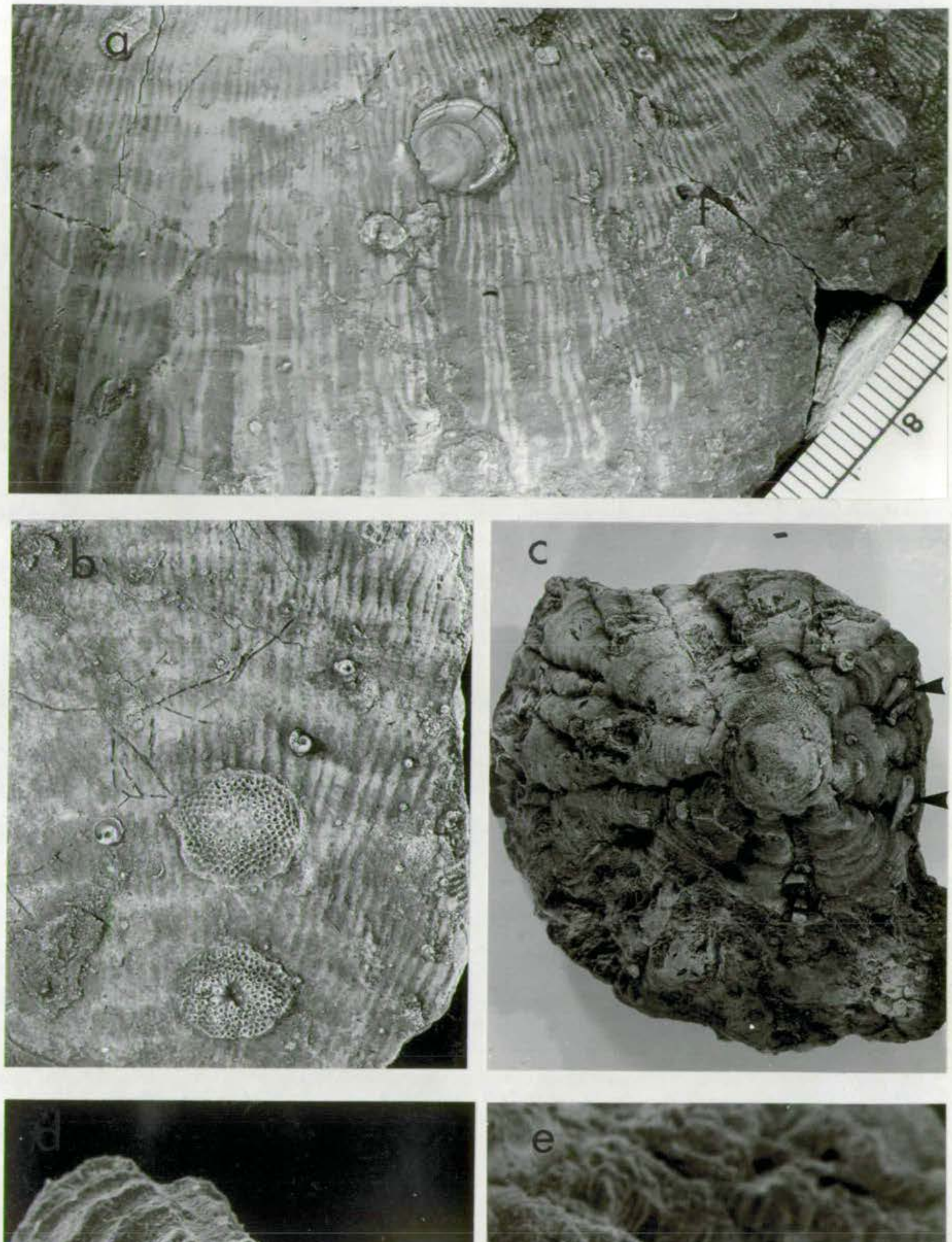
a. Pedicle valve exterior of a *Gigantoproductus* shell with attached terebratuliform brachiopod, probably *Composita*, *Spirorbis* (s) and fistuliporoid bryozoan colony (f). The *G.* shell was collected in a life position, with the pedicle valve lowermost, indicating that encrustations are likely to have occurred during life. Scale bar divisions = mms. G.I. 46,475

b. Pedicle valve exterior of *Gigantoproductus* shell showing numerous attached *Spirorbis*, fistuliporoid bryozoans and the shallow boring pattern of *Vinella*, also likely to have been produced by a bryozoan. Magnification x 3.5. G.I. 46 476

c. Holothecal undersurface of a *Lonsdaleia* colony encrusted by *Syringopora* (parts of which are visible along left side of colony; arrow heads) and fistuliporoid bryozoans. Specimen width = 9.5 cms. RSM 1979.1.15

d. *Cornulites*, SEM photograph. Lateral view of a specimen with a longitudinal furrow formed by moulding along a productoid spine. Magnification x 400.

e. Tetrataxid foraminiferan, SEM photograph. Test is attached to an eroded portion of the epitheca of a solitary coral. Magnification x 70.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14.349 *Spirorbis* spp. Figs. 14-3; 14-4f; 14-6a; 4-3

Four forms of *Spirorbis* are common: *S. caperatus* Etheridge, *S. spinosa* Etheridge, and two indeterminate smooth forms, possibly new. The smaller of the smooth forms reaches a diameter of 1-2 mm after 2 whorls and has a variable pleural angle. *S. caperatus*, *S. spinosa*, and this small smooth form are among the most cosmopolitan of all encrusters. They occur in all facies, being most abundant in the high-carbonate facies, in cryptic habitats. Possible sediment encrustations only occur on algal and firm stable substrates (Table 14-2). Up to 50 individuals were found on shell surfaces.

The large unadorned form has only been found on upper growth surfaces of *Chaetetes*. Its shell diameter (measured at the second whorl) is 4 mm. This is the only spirorbid observed to be host specific. In addition it is the only form that could be shown to have inhabited the sponge's frontal living surface. In seven instances, this form of *Spirorbis* had, after landing on the growing surface, uncoiled and grown upwards to keep pace with its host. In many other cases, this form of *Spirorbis* became detached before being completely engulfed, and thus left a circular print on the *Chaetetes* surface. It seems likely the large unadorned form was commensal with *Chaetetes*.

14.34.10 *Chaetetes* spp. Fig. 14-3

Chaetetes has traditionally been regarded as a tabulate coral. Recent research (Hartman and Goreau 1970; Mathewson 1977) has shown that *Chaetetes* has closer affinities to a new group of sponges, the sclerosponges. *Chaetetes* has been shown to have astrorhizae, spicules, and a microstructure typical of sclerosponges (ref. given; C. T. Scrutton, pers. comm.). In view of this taxonomic re-assignment, species were not distinguished within the Petershill Fm. *Chaetetes*.

In a recent study of Chaetetes, Mathewson (1977) concluded that many traditional species were invalid. Support for his conclusion was found in several colonies of the Petershill Fm. material, where more than one 'species' was present in a single colony.

14.34.11 Fistuliporoid bryozoans Figs. 14-3; 14-4f; 14-6a,b; 7-4b; 9-2; 9-5a,b

The term fistuliporoid is used here as a general designation for several encrusting forms of Fistuliporacea and perhaps Diastoporidacea of similar appearance and growth form. The largest and most common species are Fistulipora incrustans (Phillips) and Tabulipora sp. Other common forms (e.g. Figs. 14-3; 14-6b) were not identified past family level as this whole group is generally poorly described and understood. Most fistuliporoid colonies are small, seldom exceeding 1 cm in breadth and 1 mm thickness. A more detailed description of their occurrence is given in Sect 14.38.

14.35 Other skeletal epifauna

14.351 Browsing molluscs

The ichnogenus Radulichnus Voigt provides evidence that many encrusted shell surfaces also supported a browsing fauna. Radulichnus traces typically cover centimeter-sized patches of shell. Each patch consists of a regular pattern of sub-parallel groups of shallow furrows which are gently U-shaped, approximately 0.16 mm across and up to 3 mm long.

These scratches fit the description of feeding traces of alguivorous molluscs of Voigt (1977). In the Petershill Fm. Radulichnus is confined to (or best preserved on) productoid shells, being particularly common on pedicle valve exteriors. Radulichnus has not hitherto been documented from the Paleozoic. Voigt (ibid) found that Radulichnus could be produced by either gastropods or chitons.

14.352 Boring bryozoans Fig. 14-6b

Boring bryozoans are among the more cosmopolitan shell epizoa. Such bryozoans typically leave a shallow boring or furrow in the skeletons of their hosts, often brachiopods and corals. The trace forms a loose network, branching and spreading from poorly defined centres. The morphology, size and position in the shell of the borings fits that of Vinella (Condra and Elias 1944), which is likely to have been formed by a cheilostome or ctenostome bryozoan.

14.353 Corallicolites subcutanea

gen et sp. nov

Introduction - In the course of this study, a new epibiont was discovered. Some further work is necessary on possible structure before a positive phyletic assignation can be made. A formal description will be published elsewhere, while a provisional description follows.

Occurrence - Corallicolites is specific to solitary corals belonging to the family Aulophyllidae, specifically A. fungites, D. bipartitum, and rarely K. magnificum. On the whole Corallicolites is fairly rare, occurring on 10-20% of the corals present.

Previous reports - Several authors have noted scars on the epitheca of solitary corals which could be attributable to Corallicolites. These scars have been interpreted as gouge marks, formed as the coral settled against a hard object. I have never found evidence of any such gouges. If they exist, they should be easily distinguished from Corallicolites in their lack of branching and failure to follow the coral through torsion and geniculation. Corallicolites is easily distinguished from epithecal cracks or fractures, as shown in Fig. 14-8f.

Morphology and growth habit - Corallicolites appears as a straight or dichotomous, dendritically-branched ridge or groove in the epitheca of a solitary coral (Figs. 14-7; 14-8). Neither the tubes (epithecal growths, Fig. 14-7) nor the folds (endothecal growths) appear to be lined with material which could have been secreted by Corallicolites.

Where Corallicolites has grown endothecally, the coral epitheca is usually folded outward (peripherally relative to the coral) into a rounded ridge or fold, 1-2 mm high, which pinches and swells irregularly along its length (Fig. 14-8). The growth lines of the coral are clearly continuous over these ridges, indicating that Corallicolites was entirely contained within the epitheca in these cases. The prominence of endothecal growths varies somewhat, a sign that the organism could weave in and out slightly relative to its host (see e,g, i, Fig. 14-8). Corallicolites tubes do not, however, penetrate very far into the host corallite. In none of the 143 peels, thin sections, polished cross-sections and acid-dissolved specimens was any evidence found to suggest that the coral's internal structures had been disrupted. Thus Corallicolites appears to have always been confined by its host to the epitheca.

Along most of its length, Corallicolites consists of a tube-like furrow, close to 200μ in diameter. These tubes do not change diameter markedly along the length of a corallite, but there is a slight difference between individual Corallicolites specimens.

Rather fusiform swellings, or expansions, appear at fairly irregular intervals along the Corallicolites tube (e.g. d,e,f, Fig. 14-8). These swellings measure approximately 0.75-1.5 mm in width and are 2-4 times longer than wide. Swellings are only preserved in endothecal growths (q.v. e, Fig. 14-8). In some cases, they appear to have been directed outward (e.g. f, Fig. 14-8) in a manner suggesting that the swellings represent a fusiform organ attached to the Corallicolites

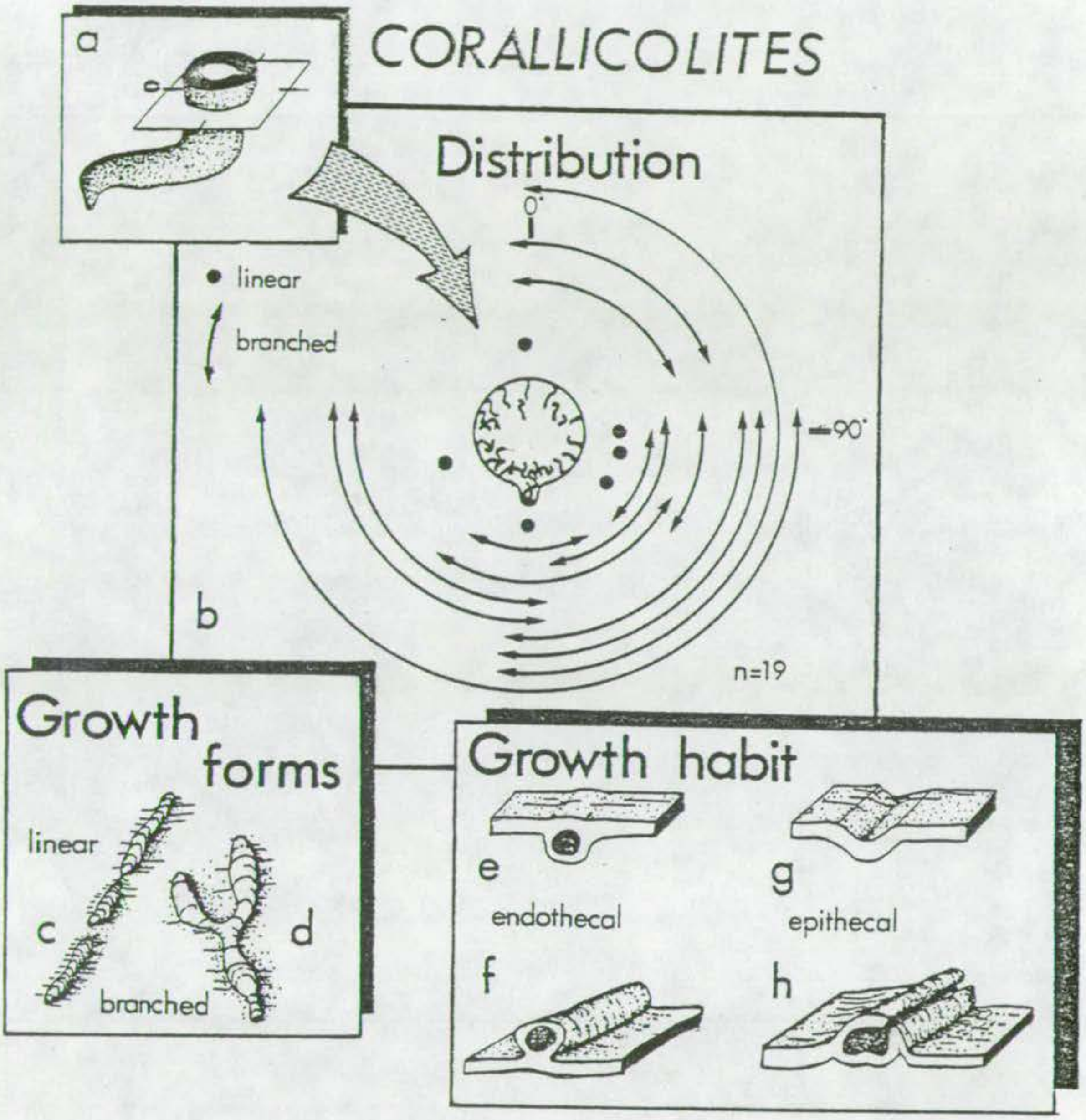


Fig. 14-7 Corallicolites subcutanea: Growth forms and habits and distribution on solitary Aulophyllidae. Both single linear growths and branched growths shown.

tube, rather than an expansion of the tube itself. If the tube had possessed such expansions along its length, then one would also expect to find them preserved in the epithecal growths. Their absence strongly suggests that the swellings instead represent attachments which did not leave an impression, except where they were fortuitously engulfed in an endothecal growth.

Growth position on host - Corallicolites growths are consistently orientated parallel to the growth direction of the host corals. The ridges or furrows run normal to the coral's growth lines, except at branching points. Branching always occurs in the direction of coral growth, i.e. anteriorly. Branches do not, however, always bifurcate in the plane of the coral epitheca. In some cases, branches appear to have ramified peripherally, away from the coral epitheca.

Investigations to date show that Corallicolites is not randomly distributed on its host corallite (Fig. 14-7). The proportion of individual corallites encircled by Corallicolites growths was plotted for 19, well-preserved A. fungites specimens (Fig. 14-7). The position of Corallicolites was plotted relative to the cardinal fossula (at the 180° position, Fig. 14-7) which is maintained on the convex side of the corallite by torsional growth throughout geniculation. The results (Fig. 14-7) reveal that Corallicolites showed a strong tendency to grow in one quadrant, on the cardinal side of the calyx. The tendency to take up a preferred position on the host appears to be strongest among small colonies, which only encircle a few degrees of the total circumference. Larger Corallicolites growths, recorded from exceptionally large corals, appear to have spread from the favoured quadrant to encircle nearly the whole corallite.

Relationship to polyp - The life position of Corallicolites relative to the coral is very unusual. It is widely accepted that

Fig. 14-8 Corallicolites subcutanea. Note that colonies in photographs a, d, e, f, g, h, i are positioned on convex side of corallite.

a. Regularly-branched epithecal growth. Coral epitheca has folded inward to form a furrow. Magnification x 1.25. RSM 1979.1.8

b. Close-up of same, showing manner of branching. Note constant angle and fairly regular frequency of branching. Magnification x 2. RSM 1979.1.8

c. Both endo- and epithecal growth habits. Corallicolites appears to have been weaving in and out of epitheca. Note that coral growth lines are continuous over endothecal portions of growth, clearly indicating that C. was entirely contained in epitheca. Magnification x 2.3 RSM 1979.1.10

d. General view of endothecal growth on A. fungites. Magnification x 1.3 RSM 1979.1.11

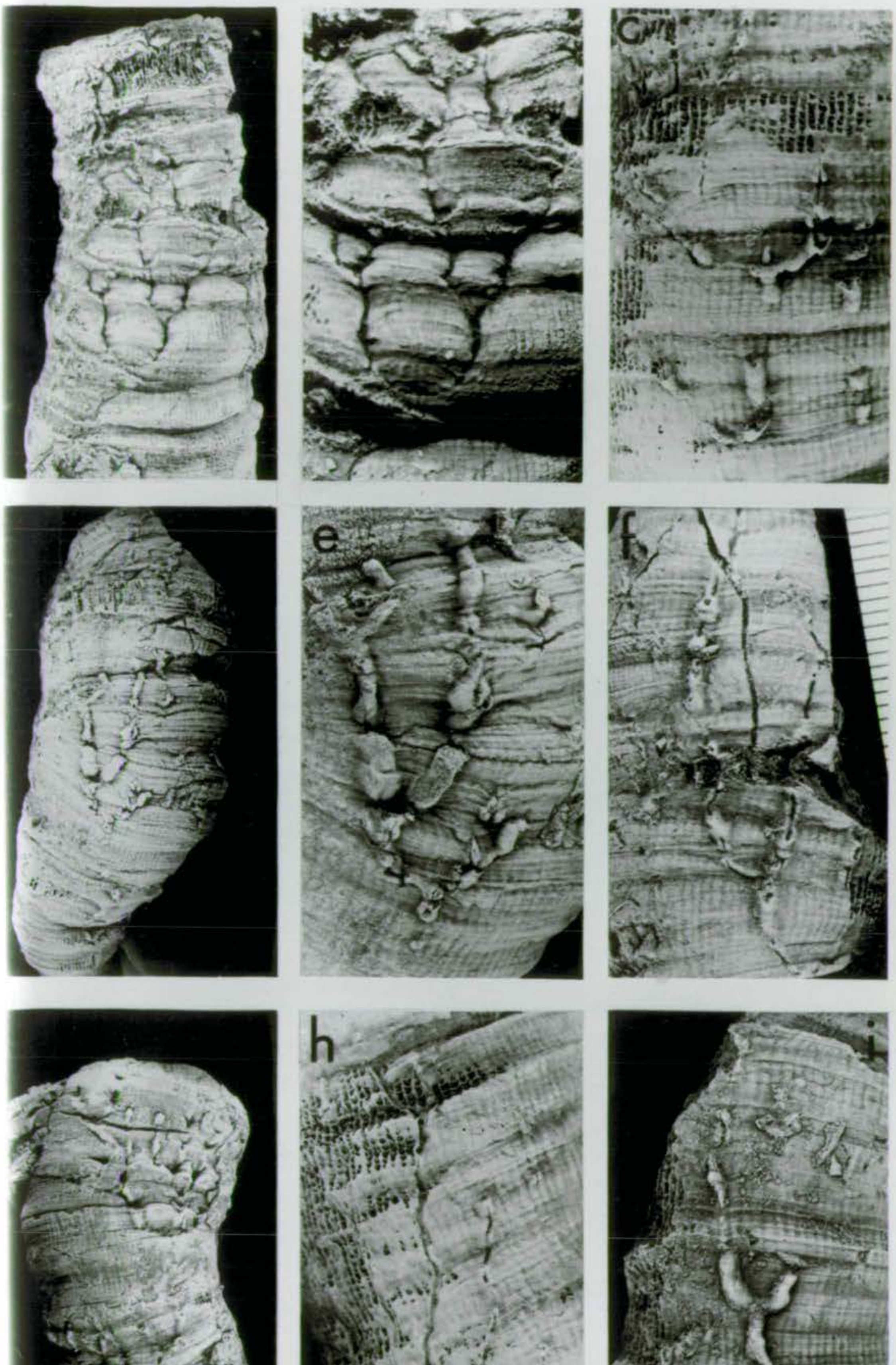
e. Close-up of same. Note irregular swellings along ridge. The broken-open portion of epitheca (middle) reveal that swellings are formed where the tube of C. has expanded into a small chamber, or where a fusiform object was once attached. Magnification x 2.8. RSM 1979.1.11

f. Close-up of branching. Broken portions of endothecal growth clearly reveal the tubular form of C. Note occasional swellings in left-hand branch which appear to offset, branching outwards away from host coral. Coral epitheca is also cracked. Note that such cracks could not be confused with the trace of C. Magnification x 2.3. RSM 1979.1.9

g. General view of large single C. colony showing both endo- and epithecal habits at different stages of growth. Host coral, A. fungites. Magnification x 1.5. RSM 1979.1.12

h. Branching in an epithecal growth, revealing tubular form of C. Note faint trace at right of endothecal growth. Magnification x 2.0. RSM 1979.1.13

i. Prominent, branched endothecal growth. Magnification x 2.4. RSM 1979.1.14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h
i

Rugosa secreted their skeletons extracellularly, i.e. that the coral polyp lived within the skeleton it secreted. In order to be enveloped by the coral epitheca, Corallicolites must have also resided in the calyx, presumably between the outermost calicoblast layer and the skeletal epitheca. It is unlikely that the organism actually resided within the polyp, as signs of disruption are confined to the epitheca. The host coral appears, instead, to have been attempting to wall-off or otherwise exclude its intruder by enveloping it with the epitheca.

Evidence for commensalism - Corallicolites colonies are present on corals in all stages of growth, from juvenile (d, Fig. 14-4) to exceptionally large adults. In all cases the two have grown together from the early stages of corallite development. Corallicolites growths do not show any signs of having been detrimental to the host's growth. Indeed, many of the corals bearing Corallicolites are exceptionally large. These observations form the basis for supposing that Corallicolites and host were commensal. While Corallicolites probably derived protection from the coral's nematocysts and possibly obtained food missed by its tentacles, it probably provided no more than a minor irritation to the polyp, which was induced to form a channel to accommodate the epibiont.

Biological affinities - Corallicolites is the mould or imprint left in the skeleton of a coral by a presumed commensal organism. As skeletal hardparts that might have belonged to Corallicolites have not been found, it should be regarded as an ichnotaxon.

This type of preservation is somewhat unusual. The only similar organisms known to me that have been preserved in the same manner were presumed to have been hydroids (Scrutton 1975). Corallicolites is, however, unlikely to have been a hydroid as it is much smaller and more irregularly branched than presumed hydroid traces (q.v. Scrutton, ibid). The morphology and size of Corallicolites is more like that of stoloniferous ctenostomatous bryozoans (cf. Condra and Elias 1944; Bassler 1953). Moreover, the regular swellings commonly preserved along the Corallicolites tube are similar in size and shape to the zoids of such bryozoans. It seems likely that the tube of Corallicolites is the mould of the original stolon onto which many zoids originally attached. Only a small percentage of the zoids originally present appear to have been engulfed and thus preserved. Most are likely to have dropped off soon after death. Further research is necessary, however, to clearly establish that skeletal material attributable to Corallicolites has not been preserved and thus, that it is an ichnofossil and not a body fossil.

14.36 Palaeoecological significance of encrusters

Encrusters in general provide several types of information about the surfaces they cover. In many cases, aligned encrusters are the only record of a former, once exposed, sediment surface (q.v. Ch 5). The majority of encrusters in the Petershill Fm. were probably suspension feeders, as are their Recent comparable forms. A covering of encrusters thus indicates that a surface was exposed, for at least the life span of the encrusting biota. Scoffin (1972) even expanded this technique using encrusters to map out cavities in the Wenlock limestone. In addition to actually revealing the surface itself, encrusting associations also reveal whether a surface was protected (cryptic), temporarily exposed, or more or less "permanently" exposed. The nature of a surface is shown by two encruster associations commonly found in the Reservoir Mbr. limestones.

A. Cosmopolitan association (Figs. 14-3b, 14-6a,b) - consists of Spirorbis, fistuliporoids, boring bryozoans, small terebratuliform brachiopods, foraminiferans, browsing gastropods, very small Chaetetes colonies and algae. The cosmopolitan association is found on virtually all shell surfaces and on firm sediment substrates. Surfaces which were only available for a short interval before burial, such as the calice and epithecal surfaces of solitary corals, and the calicle surfaces of Chaetetes are typically encrusted by this association. This suggests cosmopolitan encrusters were opportunistic, as are many of their Recent analogues (q.v. Sutherland and Karlson 1977; Martindale 1976) with mobile larvae able to settle and rapidly colonize temporarily available surfaces.

B. Stable association (Fig. 14-3a) - This association includes large terebratuliform brachiopods, aulostegid productoids, large Chaetetes, and adult solitary corals. On the whole these organisms are numerically rare and they seldom occur together on the same surface. Unlike the cosmopolitan association, the stable association taxa are likely to have been long-lived, requiring several years to grow and colonize a surface. Their presence thus provides a means of recognizing surfaces exposed for some time above the substrate/water interface.

Several examples of the detailed insights provided by encrusters into the mode of life of some fossils have already been given (Chs 4, 5). The presence of cosmopolitan association, for instance, has revealed that the pedicle undersurfaces of spinose productoids and coral colonies were cryptic habitats and that the brachiopods lived well above firm substrates. In some cases, the association encountered in a particular habitat may be different in separate facies. This suggests that the mode of life of a particular organism was different, depending on its environment. For example, sheet-form Chaetetes are common in both fine-grained and coarse crinoidal limestones. In the former, however, Chaetetes undersurfaces are only covered by the cosmopolitan association, whereas in the latter the stable association is also present (e.g. Fig. 14-3). Thus, it seems that Chaetetes grew well-elevated above the sediment surface in some environments, but not in others. Environmentally controlled differences in the mode of life of a particular organism are extremely difficult to isolate otherwise. In the following section a more specific example of the interpretative use of encrusters is given.

14.37 Environmental significance of Chaetetes and fistuliporoids

14.371 Introduction

The sponge Chaetetes and fistuliporoid bryozoans are among the most common encrusting organisms in the Petershill Fm. Both occur most often as sheet-form colonies, although Chaetetes growths may be quite variable (Fig. 14-9). The most immediate morphological difference between the two is in colony size and thickness. Fistuliporoids are very thin and delicate, seldom exceeding a few millimetres in thickness, whereas Chaetetes colonies are usually centimetres thick and, therefore, more robust. Differences in size, growth form, habit, and abundance of these two groups of organisms (Fig. 14-9) have been found to be specific indices of substrate type and environment.

14.372 Fistuliporoids

Fistuliporoid encrustations most often occur (or have been preserved most often) in protected and cryptic habitats: enveloping fasciculate coral colonies, on the undersurfaces of large Chaetetes and cerioid corals, and on the pedicle surfaces of Gigantoproductus and spinose productoids (Figs. 14-6b; 9-5a,b). In argillaceous and slightly argillaceous limestones, small encrustations on shells are virtually the only type of growths present (Fig. 14-9). Fistuliporoids are most abundant in the high-carbonate biomicrosparite and lower build-up facies, where both shells and the adjacent sediment surface are colonized (Fig. 7-4b). In high-carbonate facies encrustations are larger, spanning between shells and spreading widely onto the sediment surface. Small colonies also directly encrust the sediment surface or are based on miniscule shell fragments that could not have provided much support. In the heterogeneous and crinoidal packstone facies, fistuliporoids are relatively rare, and largely restricted to cryptic habitats.

Thus, fistuliporoids occur as skeletal encrustations in all carbonate facies, but reach their maximum size and abundance in high-carbonate biomicrosparites, where they additionally encrust the sediment surface.

14.373 Chaetetes

Chaetetes colonies are most abundant in the heterogeneous and crinoidal packstone facies. Here, sheet-form, pancake-shaped colonies are so prolific that they occasionally form bands extending laterally for several metres. These colonies have spread directly over the sediment surface, or are based on very small bioclasts. Individual sheets may reach up to 8 cm in thickness. Several growth forms are specific to these facies. These include (Fig. 14-9) gigantic multi-storey colonies, spherical, and disorientated, massive growths. Irregular changes in growth direction, (seen as changes in the disposition of laminae) suggest that the massive growths have been moved during life (Fig. 14-9). Environmental studies by other workers (Mathewson 1977) confirm the pattern observed in the Petershill Fm., that massive colonies are relatively high-energy growth forms and thus potential indicators of these environments. Bioclasts (particularly crinoid stems) circumcrusted by small growths indicate that *Chaetetes* was also able to lead a mobile life, comparable to an oncolite.

In the high-carbonate biomicrosparite facies, *Chaetetes* colonies are smaller, less common and less morphologically varied (Fig. 14-9). Sediment encrusting, sheet-form colonies are considerably smaller,

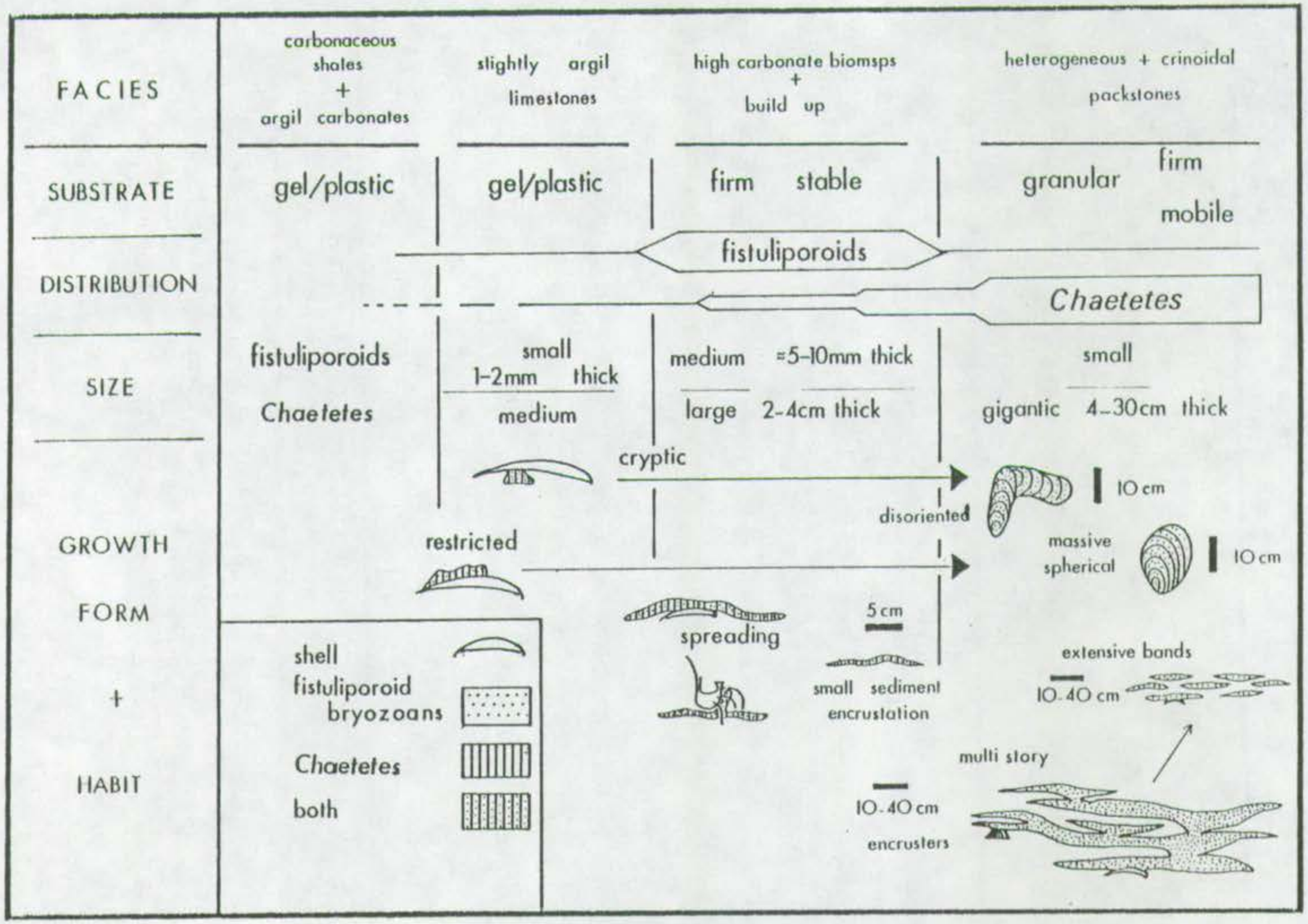


Fig. 14-9 Growth habit and distribution of fistuliporoids and Chaetetes in the Reservoir Mbr.

seldom exceeding 4 cm in thickness. Colony growth forms and habits are comparable to those of fistuliporoids, except in size (Fig. 14-9). In limestones with a high proportion of detrital clay, *Chaetetes* colonies are less common still. Colonies seldom reach the size of their skeletal host, and sediment encrustations are virtually absent.

14.374 Factors affecting the distribution of Chaetetes and fistuliporoids

The shell-restricted habits of both *Chaetetes* and fistuliporoids in argillaceous and slightly argillaceous limestone facies suggest that the sediment surface in these facies was unsuitable for direct colonization. Trace fossils additionally establish that argillaceous substrates were unstable (q.v. Ch 5). Both *Chaetetes* and fistuliporoids apparently had a low tolerance to loose, fine-grained, gel substrates. Firm and stable fine-grained substrates, however, provided an optimal surface for fistuliporoid colonization, well reflected in the relative abundance of colonies found on these surfaces.

The abundance and colony forms of *Chaetetes* by themselves point to strong currents and turbulence as affording optimal growth conditions. The variety of *Chaetetes* growth forms, adapted to mobile granular substrates, indicate that the sponge was able to grow well on these surfaces, where it is likely to have had relatively few competitors.

14.375 Summary

Encrusting organisms form only a small portion of the Petershill Fm biota. Nevertheless, their distribution is broadly related to facies and more specifically influenced by certain combinations of: available skeletal surfaces, suitable sediment substrates, and water turbulence. In this respect, the study of encrusters is a valuable aid in facies discrimination and environmental interpretation.

Furthermore, the characteristic associations of some encrusters provides a hitherto overlooked means of discovering the mode of life of some of their host organisms. It is therefore concluded that encrusters are an informative source of palaeoecological information, worthy of more attention in future studies.

14.4 Faunal associations and environments

There is a definite tendency for certain fossils or fossil groups to occur in associations which are characteristic of a particular lithology (Fig. 14-10). An environmental interpretation of each association can be attempted by integrating the inferences derivable from taphonomic data, substrate consistency, and hydraulic regime (Chs 8-13).

Each association discussed here consists of one or more different types of assemblages. Each assemblage varies in the extent to which the original life-surface has been altered by the physical or biological environment. In some cases, the associations characteristic of a particular environment (facies) also integrate changes in that environment with time (e.g. the build-up). Thus the associations described here cannot be regarded as communities, since the facies-characteristic organisms seldom actually lived together. They are more correctly regarded as facies-specific faunas, i.e. groups of organisms adapted to a particular set of physical parameters, and preserved in a similar manner. Within the continual spectrum of facies and faunas, five discrete groupings (facies faunas, Fig. 14-10) can be distinguished.

A. Lingula-large pectenoid bivalve-zaphrentoid fauna

Along with serpulids and *Hyalostelia smithi*, these fossils occur in separate horizons of in situ or slightly altered hydrodynamic assemblages, associated with carbonaceous and calcareous shales. They probably represent shallow, nearshore, protected lagoons or bays, with well-established, but variable, marine communication.

B. Solitary aulophyllid coral aggregates

Groupings of solitary aulophylloids, predominantly *A. fungites* and *D. bipartitum*, occurring with isolated fasciculate coral colonies of *Lithostrotion*, small spinose productoids, and *Gigantoproductus*. This fauna is associated with medium-bedded, slightly argillaceous, grey biomicrosparites, which show boudinage and are extensively bioturbated by indistinct burrows. Shallow platform areas of quiet circulation and fairly low clastic input are indicated by this facies fauna. Periodic sedimentation stillstands resulted in a gradual increase in substrate cohesiveness, from gel to plastic, with a consequent rise in epifaunal diversity.

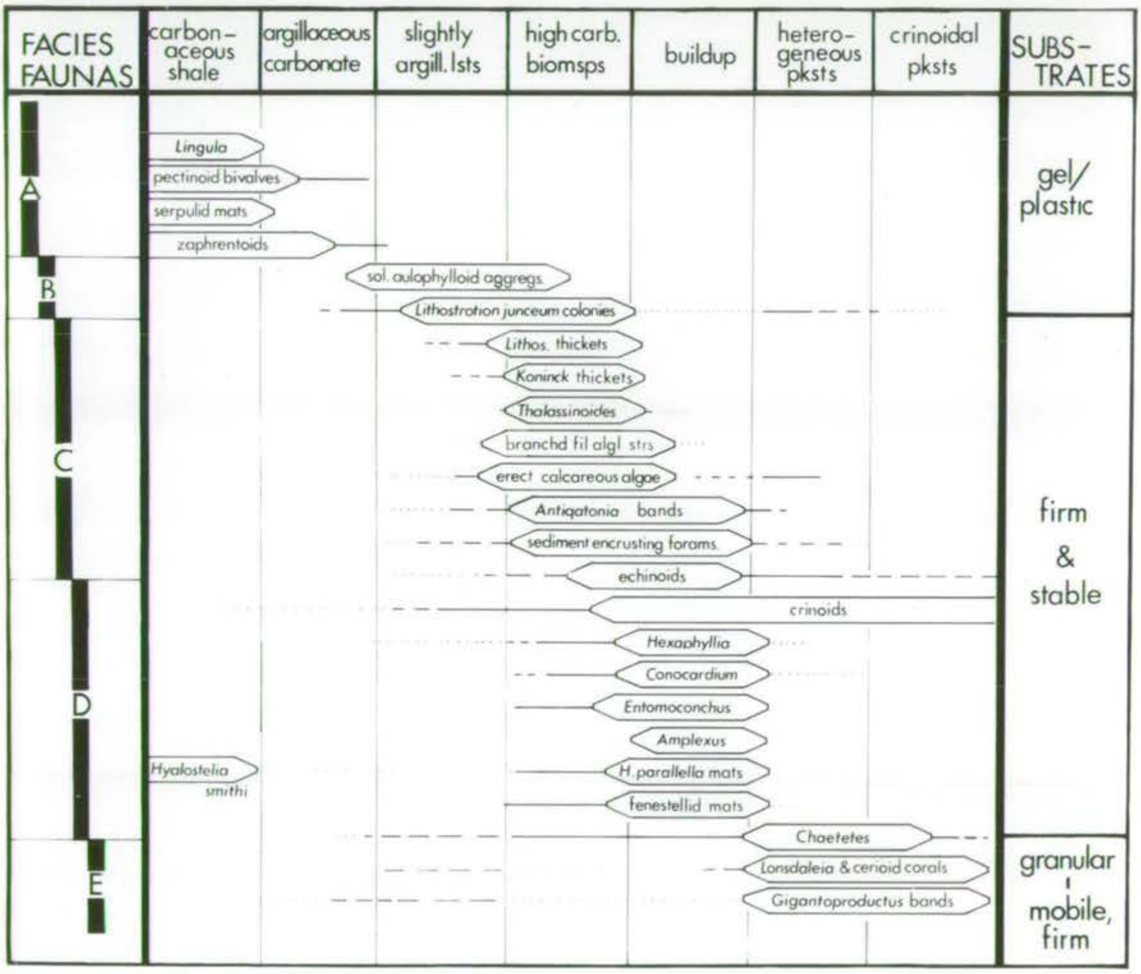
C. Antiquatonia-Lithostrotion-Thalassinoides fauna

A diverse epifaunal group, consisting of several life-surface assemblages of associated organisms, centered around large fasciculate coral thickets and spinose productoid bands. Skeletal calcareous algae, echinoids, sponges, fenestellid bryozoans and infaunal crustaceans were most common. The firmness of the sediment and the existence of an abundant epifauna provided ideal substrates for an encrusting biota. This fauna is associated with cream coloured, high-carbonate biomicrosparites. It is suggested that this facies fauna typified shallow platform areas with quiet, continual circulation, only forming during periods of virtually no clastic input, thus encouraging high biological carbonate productivity.

D. Conocardium-Entomoconchus-crinoid fauna

Essentially in situ assemblages of diverse, spinose productoids bryozoans, sponges, and crinoids, providing an optimal habitat for encrusters and sufficient sediment to initiate biohermal growth. The associated sediments are poorly-bedded, blue-grey or cream coloured,

Fig. 14-10 Facies faunas in the Reservoir Mbr.



high-carbonate packstones. This facies fauna is characteristic of a distal nearshore zone of continual current activity during intervals of little or no clastic input.

E. Cerioid coral-Chaetetes-Gigantoproductus fauna

Moderately to extensively altered assemblages of cerioid corals along with massive sponges and bands of Gigantoproductus are associated with cross-stratified, variably-sorted, crinoidal packstones. These represent a shallow nearshore, sub-tidal bar/shoal zone, where periodic turbulence created unstable, mobile skeletal sands.

14.41 Summary and discussion

Several of these associations are new, others are closely comparable to associations described elsewhere, particularly in Carboniferous sediments. For example, fauna A is commonly reported associated with black shales (Watkins 1975; Ferguson 1962). Jamieson (1971) and others have widely reported Conocardium from reef facies in the Devonian of Canada. Indeed it appears that Conocardium is characteristic of bioherms.

In the case of coral dominated associations, Hill (1938) and Tsien (1968) have used coral faunas as a basis for distinguishing facies. The work of Hill (ibid) is particularly significant, as she worked on the Carboniferous of Scotland and on the Petershill Fm. fauna. The general pattern she recognized has been borne out in the present study (Fig. 14-10). The only noteworthy difference concerns her terminology and her conclusions regarding the distribution of heterophyllid corals.

In this study, heterophyllid corals and Amplexus were found to be characteristic of the build-up facies, whereas Hill (ibid, p 31) considered heterophyllids to be associated with solitary aulophyllids. The findings of this study suggest that heterophyllids could more usefully be regarded as part of a biohermal fauna. Hill also found that cerioid corals were a valid facies fauna. Hill, however, named the association the "reef-coral" fauna. At least in the present context, and probably elsewhere, this association might more usefully be described as a "coarse-bioclastic" or "turbulent-nearshore" fauna, since evidence of depositional relief and biohermal growth are absent.

Within the spectral environmental distribution of the Petershill Fm. fauna (Fig. 14-10), there are a number of facies faunas which, when critically assessed by taphonomic procedures, yield important information on palaeoenvironments. Some of these facies faunas are so specific that it seems certain they may be used to distinguish similar environments elsewhere. In many cases, facies faunas provide a remarkably accurate means of distinguishing environments. This is well illustrated in the case of the build-up. The build-up fauna is a discrete "sub-set" of the firm substrate fauna as a whole, excluding several elements and containing new, characteristic forms. It appears therefore, that environmental factors which are more specific than those reflected in the substrate alone, are reflected in the fauna. When incorporated with physical criteria, the fauna provide a necessary complement for environmental modeling.

CHAPTER 15

THE SILVERMINE MBR.

15.0 Introduction

The upper half of the Petershill Fm. has been named the Silvermine Mbr., based on the typical sequence exposed near the old Hilderstone Silvermine workings (Ch 1). As the Silvermine Mbr. is almost entirely clastic, a lithofacies classification scheme has been employed in its description. It is divided into an upper coarsening-upward facies (CU), underlain by a basal sandstone (BS) facies, which is subdivided into four subfacies. The major facies represent distinct environments which also show marked lateral variation along strike.

15.1 Facies shape

At its northernmost exposure, North Mine Quarry (Fig. 2-1), the Silvermine Mbr. is at least 12 m thick. Most of the sequence is taken up by a basalt, interpreted as a contemporaneous flow (Ch 2). Clastic sediments belonging to the Silvermine Mbr. are likely to be present above this flow and to pass laterally northward into the transitional area between the Petershill Fm. and the Hillhouse Limestone. South of N. Mine Quarry, the Silvermine Mbr. increases gradually in thickness for over 2 km (till Sunnyside, Fig. 1-2). Further south the sequence expands rapidly to reach 36 m, nearly three times its thickness at N. Mine Quarry. The Silvermine Mbr. is thus roughly wedge-shaped, increasing in thickness southward.

15.2 The basal sandstone facies

Figs. 15-1; 15-2; 15-3; 15-4
15-5; 15-6

A composite facies, predominantly composed of sandstones, directly overlies the Reservoir Mbr. between N. Mine Quarry and the Petershill Reservoirs (Fig. A-1, Appdx). This basal sandstone facies (BS) is readily divisible into four subfacies: a) a coal-bearing subfacies; b) a fining-upward subfacies (FU); and c) large-scale cross-bedded sandstones which contain d) the plane-laminated subfacies (Fig. A-1).

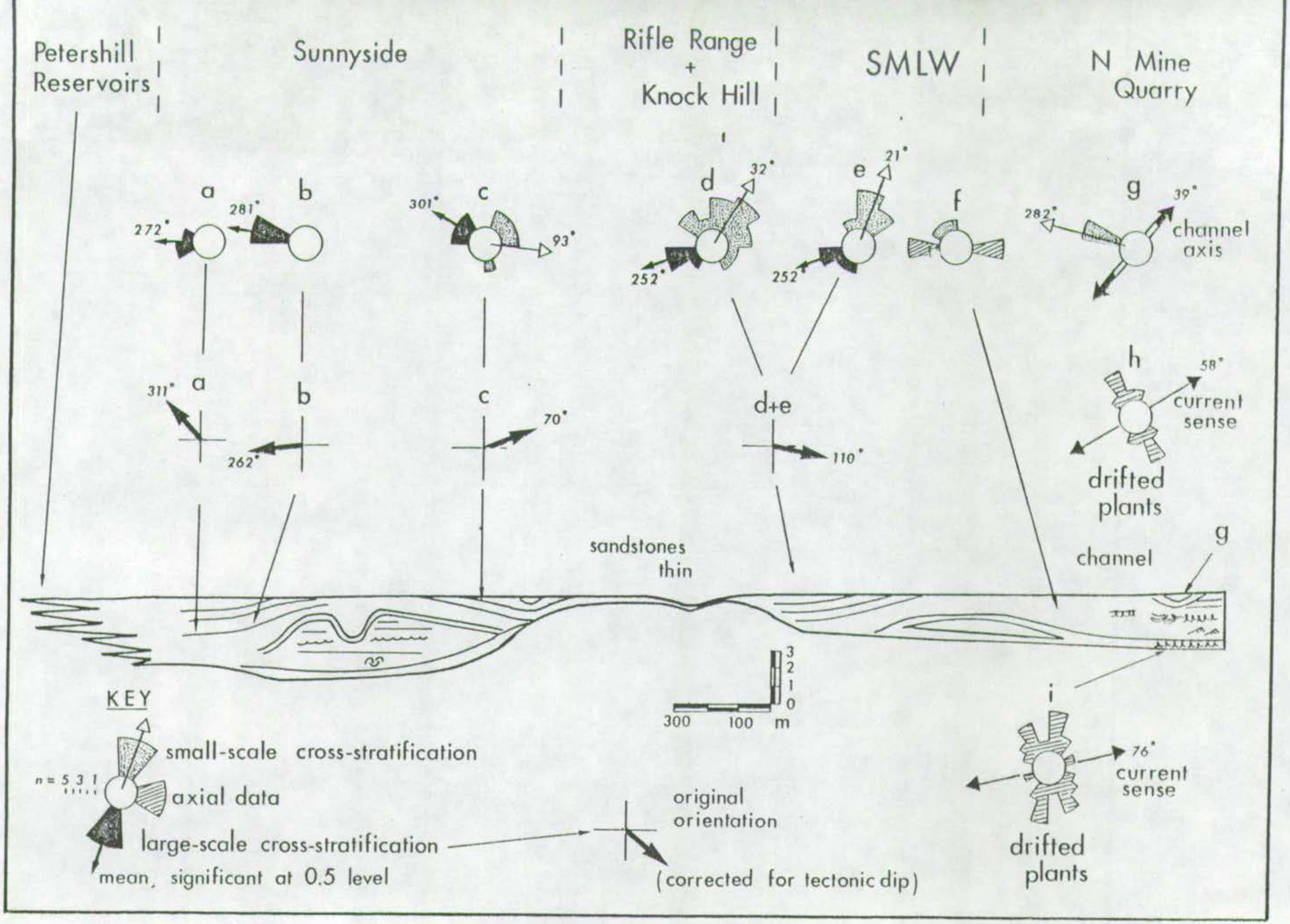
15.21 Shape and subfacies relationships

The shape of the basal sandstone lithosome is one of its most remarkable and important features. It forms a thin continuous sheet, extending southward for approximately 3 km from N. Mine Quarry (Figs. A-1; 15-1). It almost certainly also continues northward from this point, into the area of continuous lavas (Frontispiece). The basal sandstone facies thins gradually from approximately 4 metres at N. Mine Quarry to a few centimetres in the area at approximately its strike midpoint. In this area, along the northern Rifle Range and Knock Hill, it is reduced to a veneer, as little as 5 cm thick, covering discontinuity surface C for a strike distance of 580 m. South of this area, the BS again thickens to 4-5 m before passing laterally into black shales similar to those which overlie it over much of its lateral extent.

At its northernmost exposure, the BS consists of the coal-bearing subfacies overlain by the fining-upward subfacies, which is covered by a thick tuff (Figs. 15-2; A-1). The coal-bearing subfacies and tuff pinch out at S. Mine Lime Works towards the central area where the entire basal sandstone begins to thin (Fig. A-1). At the most northern point away from Knock Hill, the tuff reaches a thickness of 2.5 m, which is a considerable thickness for a lithology in the Silvermine Mbr. South of Knock Hill the BS thickens again gradually into the cross-bedded sandstone subfacies. Here the tuff and coal-bearing subfacies are absent.

Fig. 15-1 Orientation of directional structures in the basal sandstone facies

Generalized cross-section shows shape of BS, drawn from a datum placed at its top surface; scales are approximate. Top row (a-g) of orientation data shows relationship between large-scale cross-stratified sandstone dip surfaces and their small-scale internal structures. Arrows show statistically significant mean orientations, tested for by using the Rayleight test for uniformity. Second row (a-d+e) shows restored orientation of large-scale cross-stratification obtained by correction for tectonic dip. Bedding orientations restored using stereographic projections. Data from N. Mine Quarry show orientations of a small channel, small-scale cross-stratification beneath channel and orientation of drifted plants with their inferred current sense.


Petershill Reservoirs
Sunnyside
Rifle Range + Knock Hill
SMLW
N Mine Quarry
a
272°
b
281°
c
301°
93°
d
32°
252°
e
21°
252°
f
g
39°
282°
channel axis
a
311°
b
262°
c
70°
d+e
110°
h
58°
current sense
drifted plants
sandstones thin
channel
g
3
2
1
0
300
100
m
i
76°
current sense
drifted plants
KEY
small-scale cross-stratification
n = 5 3 1
axial data
large-scale cross-stratification
mean, significant at 0.5 level
original orientation
(corrected for tectonic dip)

15.22 Composition

The sandstones in all subfacies of the BS are calcareous orthoquartzites, predominantly composed of fine-sand sized quartz (90-97% grain bulk) with minor percentages of feldspars, weathered ?volcanogenic grains, plant debris, heavy minerals and mica flakes. Authigenic kaolinite, pyrite, and chalcedonic quartz cements are common, while calcite is the most pervasive cementing agent. The sandstones of the BS facies are polycyclic, incorporating a small, variable amount of locally derived plant and volcanogenic material. They are petrographically uniform along strike.

15.23 Subfacies

15.231 The coal-bearing subfacies

At most exposures this sequence consists of roughly 1 m of micaceous sandstones with numerous carbonaceous silty laminae, passing upward into 10-30 cm of coal. At N. Mine Quarry (Fig. 15-2), the top coal is itself interlaminated with thin sandy laminae, while further south, at Silvermine, the coal forms a discrete layer becoming more bright upwards as proportions of vitrain increase.

The sandstones beneath the coal contain numerous rootlet horizons, reddened clay partings and rare mud flakes. A relatively thick rootlet horizon is developed beneath the coal at the top of the sequence. Rootlet horizons are interspersed with extensively bioturbated laminae containing indistinct burrowing traces and a J or U-shaped burrow, probably Arenicolites. Arenicolites is usually considered to be a marine or marginal-marine ichnogenus (Chamberlain 1978, pp 182-183). Small-scale oscillation and current ripples are common throughout the thin coal-bearing sandstones, as are large fragments of drifted plant debris (i, Fig. 15-1).

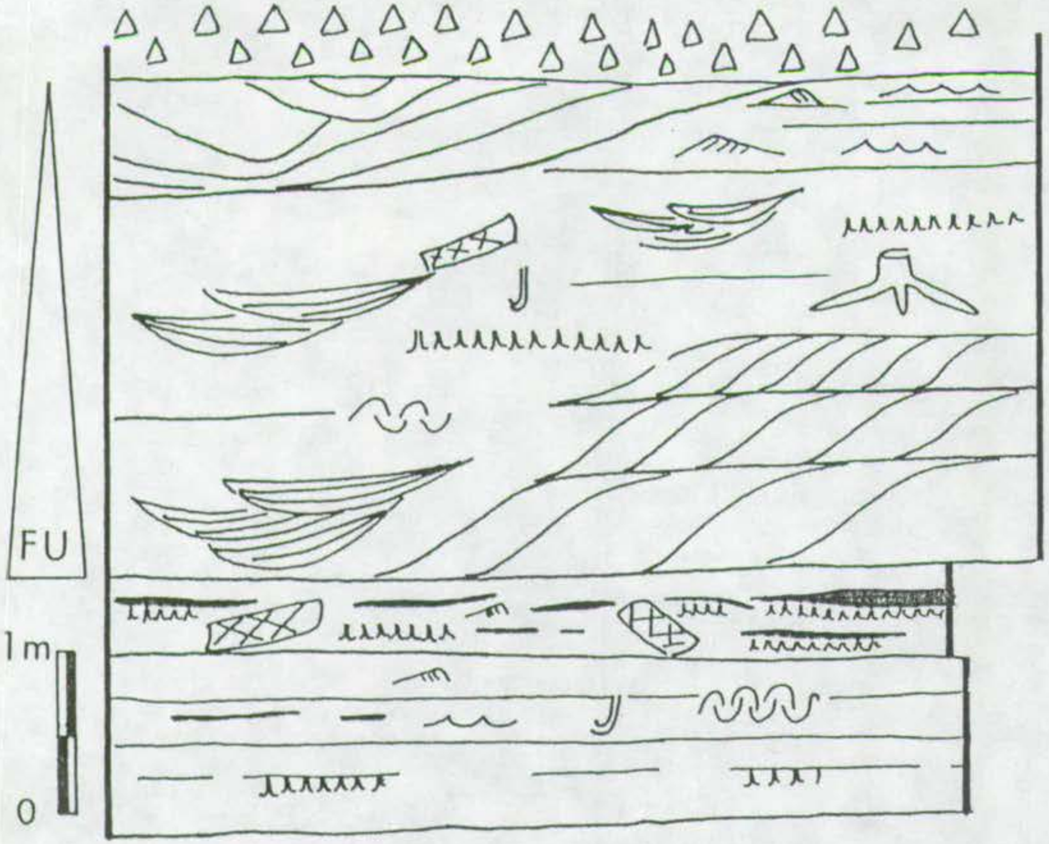
At S. Mine Lime Works a lenticular body of sandstone showing large scale cross-bedding is developed within the coal-bearing sequence (Fig. A-1). With this exception, however, the sandstones in the sequence are thinly-bedded.

Interpretation - The thin-bedded sandstones in the sequence show structures attributable to repeated exposure and deposition in very shallow water. The overlying coal is likely to have accumulated in a more-continually submerged body of standing water shallow enough at times to support plant growth. The presence of preferentially orientated plant debris at some horizons within the sequence additionally suggests that plant debris was also transported into the area. (?)Arenicolites burrows may provide evidence of at least an intermittent marine connection. A marginal coastal embayment or back-barrier lagoon are the most likely depositional environments.

15.232 The fining-upward subfacies (FU)

At N. Mine Quarry, the sandstones overlying the coal-bearing subfacies show a fining-upward trend (Fig. 15-2). Here, medium-scale, planar sets of tabular cross-stratification pass upward into smaller sets of trough cross-stratification. Boundaries between successive sets are marked by thin clay partings, rootlets, or bioturbation horizons. A shallow channel, approximately 8 m wide, truncates the uppermost 50 cm of the sequence. In cross-section, the channel curves gently lacking inflection points at its margin or base, suggesting that it was formed subaqueously (McKee 1957, p 133). It is asymmetrically infilled by thin sandstones containing numerous erosional breaks, rootlets, and bioturbated horizons. Palaeocurrents, measured from drifted Stigmaria and cross-strata in the sandstones from beneath the channel, show a unidirectional, westward trend (282°) directed

Fig 15-2 Basal sandstone facies, North Mine Quarry



grey calcareous tuff with fossiliferous laminae

small channel incised into thin-bedded, sm-scale x-strat ssts

medium thickness parallel sets of trough x-strat. set boundaries show bioturbation and rootlets

?Arenicolites

parallel sets of tabular x-strat passing into trough x-strat

Coal-bearing subfacies

thin coal laminae, drifted plants, rootlets

thin-bedded ssts with carbonaceous and silt laminae

?Arenicolites

nearly normal to the channel's axis (g, Fig. 15-1).

Interpretation - The sequence of sedimentary structures in the FU subfacies was formed by currents of decreasing strength and, probably, also in decreasing water depths. An upward reduction in the size of cross-stratified sets additionally indicates a diminishing sediment input during current-dominated pulses. The current-dominated sedimentation pulses are separated by intervals of stillstand or subaerial exposure, represented by bioturbated horizons and rootlets. The unidirectional sense of current-formed sedimentary structures points to deposition within a channel. Together, these data suggest that the FU sequence was formed by an ephemeral stream migrating laterally (and outwardly) across the underlying back-barrier lagoon or bay sediments of the coal-bearing subfacies. Storms or seasonal flooding may have periodically charged the channel with sediment.

15.233 Large-scale cross-bedded sandstone subfacies

Most of the BS shows large-scale cross-bedding, or cross-stratification (Figs. 15-4; 15-5). The FU sequence passes laterally southward via trough-bedded sandstones into sequences showing this cross-bedding (Figs. 15-1; A-1). The cross-bedded sandstones in turn pass laterally into thin, plane-laminated sandstones where the entire BS thins, reappearing further south, in the southern Rifle Range (Figs. 15-1; 15-3). This subfacies thins and changes character once again at Sunnyside (Fig. 15-3), thinning over the plane-laminated sandstone subfacies (Fig. 15-1).

Geometry - Large-scale cross-stratification is formed by 15-40 cm thick sets or cosets inclined at 2-8° to the bounding surfaces of the entire sandstone unit. At most exposures, the inclined surfaces dip uniformly in one direction (Figs. 15-4; 15-5). Individual sets usually thin slightly down dip (Fig. 15-4b). At large exposures, where an inclined set can be traced for a greater horizontal distance, the surfaces can be seen to flatten out near the base of the unit, in some cases even suggesting a trough-like or lenticular bedding form (Figs. 15-3; 15-4). The inclined set surfaces are usually concave downward and only rarely slightly convex.

The prominent boundaries between sets are formed by thin clay partings, which may reach a few centimetres in thickness. These boundaries are occasionally erosive, as shown by discontinuous partings and mudflakes in the overlying sets. Numerous erosional breaks are also present within the sandstone sets, indicated by truncated sedimentary structures and bioturbation horizons. Each set is itself complex, composed of one or more sequences of plane lamination followed by small-scale trough cross-stratification, and/or a bioturbated horizon. The internal sequences within sets are seldom complete, due to the erosive nature of the plane laminae. They are comparable in appearance and scale to the "plane-to-ripple" sequences described by Davidson-Arnott and Greenwood (1976).

At outcrop, the inclined surfaces of sets are variably-directed, dipping generally westward (Fig. 15-1). When the original orientations are restored, however, by rotation of the bounding surface of the sandstone unit to the horizontal, it emerges that the inclined surfaces were originally orientated both east and westward (Fig. 15-1 a,b,c,d+e). Small-scale cross-strata within the inclined sets are fairly consistently orientated eastwards, at an oblique angle to the dip of the larger inclined surfaces (Fig. 15-1).

<u>Sunnyside</u> - At Sunnyside cross-bedded sandstones thin where they erosively overlie and infill a small channel (Figs. 15-1; 15-3; 15-4b). The manner of erosion and infilling provide accessory

Fig. 15-3

Generalized reconstruction of basal sandstone facies in the region south of Knock Hill; scales approximate, note vertical exaggeration. The BS as a whole thickens away from the northern Rifle Range. The large-scale cross-bedded sandstone subfacies erosively overlies the plane-laminated sandstone subfacies. At Sunnyside, a small E-W orientated channel has been incised into the underlying subfacies. Further south (still in Sunnyside Reservoir) the sequence returns to large-scale cross-bedded sandstone.

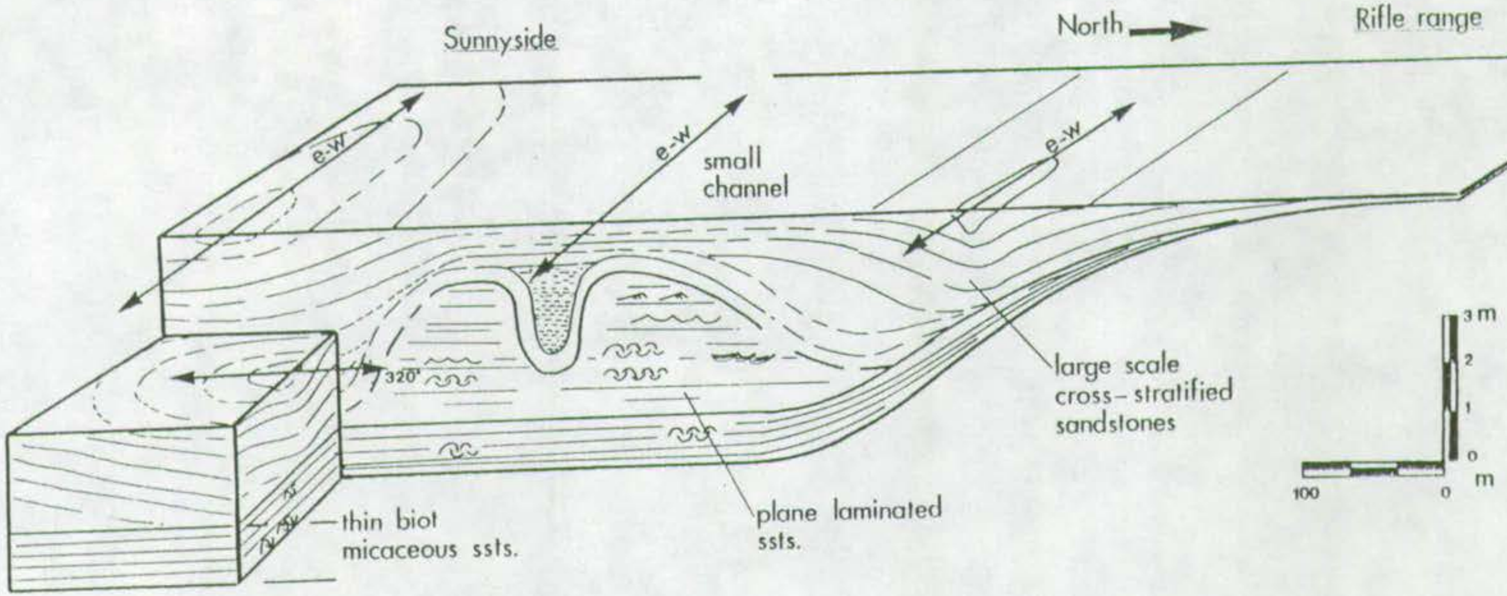
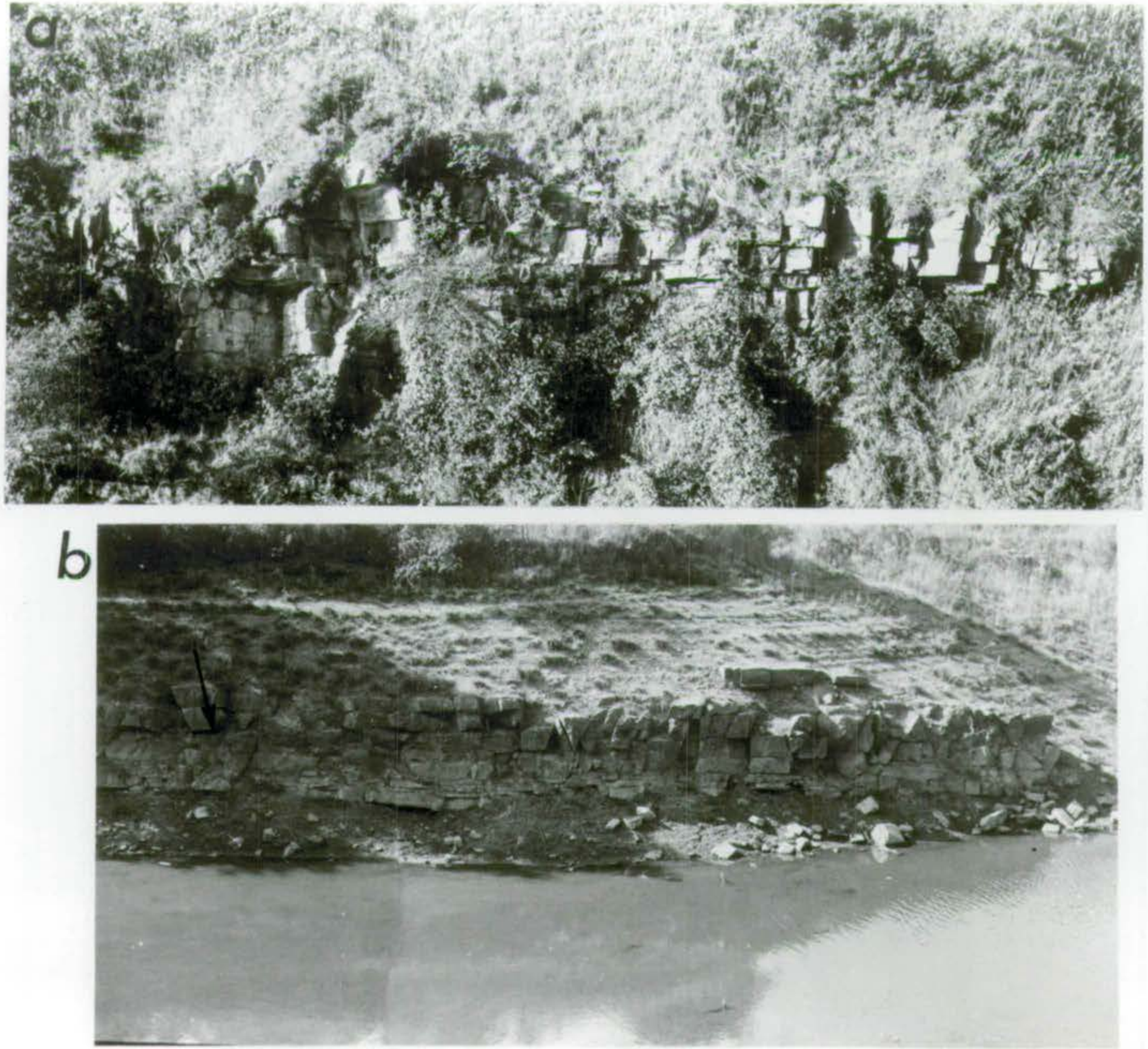

Sunnyside
North
Rifle range
e-w
e-w
small channel
e-w
320°
large scale cross-stratified sandstones
thin biot micaceous ssts.
plane laminated ssts.
3 m
2
1
0
100
0
m

Fig. 15-4 Large-scale cross-bedding in the basal sandstone facies

a. Upper half of quarry face (approx. 3 m thick) reveals large-scale cross-bedding in the basal sandstone facies. Upper and lower bounding surfaces are parallel. Thin clay drapes pick out gently-inclined bedding dipping northward within the unit. Northern Sunnyside Quarry.

b. Basal sandstone facies at Sunnyside Quarry. Note change in geometry of cross-bedding across face (arrow): gently-inclined beds thin and become nearly parallel to bounding surfaces down dip. Sequence approximately 4 m thick.


a
b

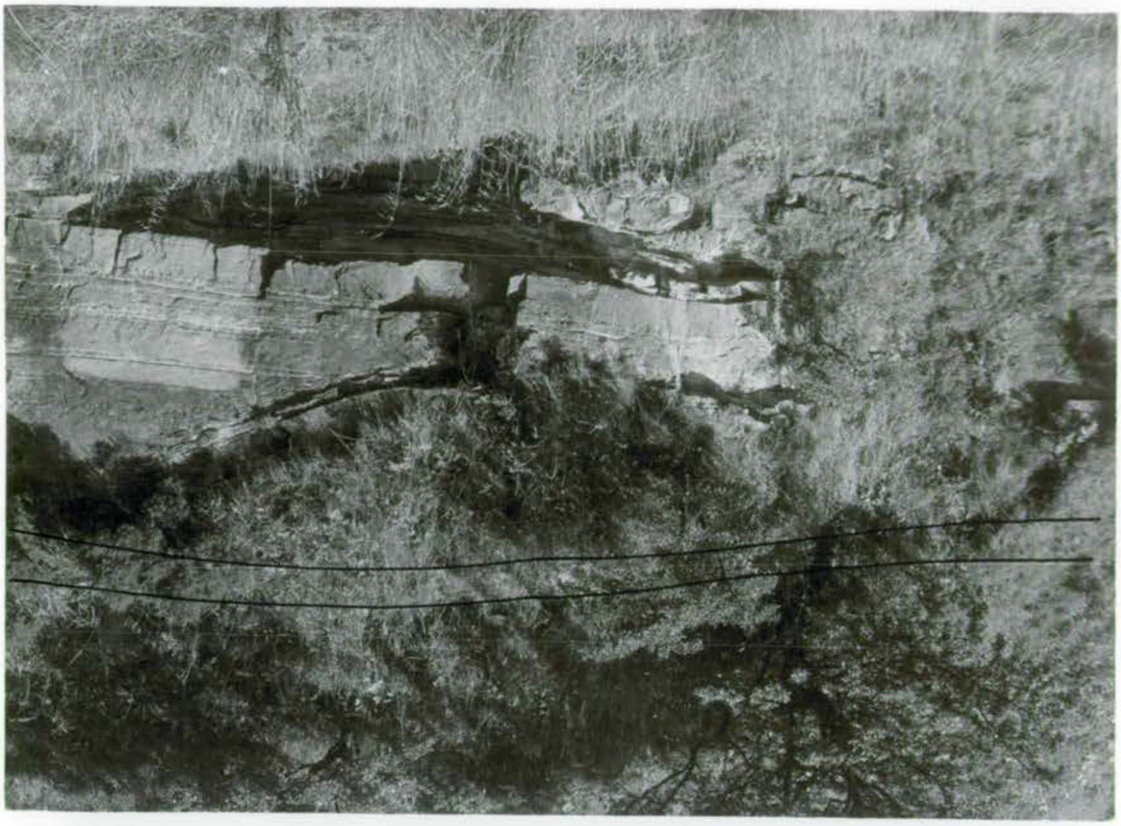
data on the environment in which large-scale cross-bedding formed, as the channel-infilling sandstones pass into inclined cross-strata (Fig. 15-3). The channel is cut into the plane-laminated sandstone subfacies, which consists of thin sets of parallel laminae followed by small-scale oscillation ripples and bioturbated horizons. Plane-laminated sandstones have thus been formed by repeated sediment influxes followed by quiescent periods of bioturbation and wave redistribution. Incised into this subfacies is shallow, flat-bottomed channel with sharp inflection points at its margin and base (Fig. 15-4b). A planar bed of sandstone, which is continuous with cross-bedded sandstones north and south (Fig. 15-3), then blankets the erosional surface of the channel base. Black shales form a thin plug within these overlying sandstones blanketing the channel. A second planar sandstone sheet, also continuous with the cross-bedded sandstones north and south, then covers the shale infilling (Fig. 15-3).

The cross-sectional shape of the channel suggests that it has been eroded subaerially (McKee 1957, p 133) and, therefore, that the erosional surface as a whole was exposed. It appears that the cross-bedded subfacies has been modified into planar sheets where it overlies a subaerial high. The channel was probably also incised during the interval exposure. Both the channel and surrounding areas of plane-laminated sandstones were then blanketed by a thin sandstone bed. Black shale then infilled the channel, followed by a re-blanketing of sandstones which are continuous with cross-bedded sandstones north and south (q.v. Fig. 15-3). The manner in which the channel has been infilled by a shale suspension fallout not present elsewhere may suggest subaerial exposure after shale deposition, within the cross-bedded subfacies, at least in the area overlying the channel. This general pattern of sedimentation provides evidence of the very

Fig. 15-5 The basal sandstone facies : bedding structures.

a. Large-scale cross-beds dip at 6° southwestward to the bounding surfaces of the sandstone unit as a whole. Sets flatten out near base of exposure to become near parallel with lower bounding surface. The sandstone sequence is 240 cm thick. The complete lithological sequence consists of slightly argillaceous limestones at the base, followed by the prominent basal sandstone facies, overlain by black shales at the base of the CU facies. Small dyke (inked in) covers part of the limestone exposure. South end, South Mine Lime Works.

b. An E-W trending channel truncates the plane-laminated sandstone subfacies. Plane-laminated sandstones show sequences of plane lamination and alternate burrowed or cross-stratified laminae (which weather preferentially). Sandstones belonging to the large scale cross-bedded sandstone facies overlie the eroded channel surface. Note sharp inflection points at base and margin of channel, and that sandstone does not change thickness in passing from the axis out over the banks. A second sandstone bed (drawn in) then overlies the channel and its shale infilling. Sunnyside Quarry. Height of exposure in sandstones is 3 m.



shallow water origin of the BS as a whole.

Interpretation - Environmental interpretation of the large scale cross-bedded subfacies relies, in part, on the interpretation of the BS facies as a whole. Several criteria indicate that the BS is marine or marginally-marine along the whole of its strike extent:

A. it passes laterally southward into carbonaceous shales with a marine fauna (q.v. Figs. 2-11; A-1);

B. south of the Rifle Range, the BS is overlain by a similar sequence of shales which additionally contain a marine ichnofauna (Zoophycus and Chondrites) and a discontinuous limestone bed;

C. north of the dividing area of Knock Hill, where the BS thins, it is conformably stratabound by a siltstone with a marine fauna and a tuff containing transported marine fossils;

D. at its northernmost exposure, the BS probably contains the marine/marginal-marine trace fossil Arenicolites.

A second aspect of the BS derives from consideration of its lithosome shape. As previously described, the BS thins to a few centimetres along the mid-point of its strike, where it overlies a fissured limestone discontinuity surface. Here, the sandstones are condensed to a few thin laminae which pass into the cross-bedded units that thicken away north and south (Figs. 15-1; 15-3). These sandstone thickness changes suggest that the midpoint formed a topographic high, which was intermittently breached by currents. Evidence for the topographic high may also be present in the underlying limestones, as the effects of karst weathering are most pronounced in this region (q.v. Ch 13). Relief on the topographic high is likely to have been very small, as spillover lobes or other evidence of sediment-piling on either side are absent.

Large-scale cross-bedding is a complex structure, formed by the interaction of currents on several scales. Variations in lithology and internal structure reflect the broad range of energy regimes within which the structure has formed. The large-scale, inclined surfaces themselves are considered to be essentially wave-formed. Their geometry appears to be closely analogous to the gently-inclined surfaces formed by waves shoaling on beaches, barrier bars, or longitudinal bars (Exum and Harms 1968; Harms et al. 1975, Ch 5; McKee 1964, pp 275-296; Sheldon 1967). Comparable surfaces have been described from both ancient and Recent wave-formed sand bar sequences (Johnson 1977, pp 251-253; Davidson-Arnott and Greenwood 1976, p 154).

In addition, many of the internal structures are typical of those formed by shoaling waves. Plane-to-ripple and plane-to-burrowed sequences result from the interplay of two hydraulic regimes (Davidson-Arnott and Greenwood ibid; Kumar and Sanders 1976; Goldring and Bridges 1973). Plane lamination is produced either at high current velocities or at low velocities by sediment-starved ripple migration (Clifton 1976, p 143). The general lack of bioturbation and the erosive nature of plane lamination in the BS favours the former origin. Quieter intervals of relative sediment stability are marked by weaker, obliquely-directed current cross-stratification (Fig. 15-1) and extensive biological reworking. Many studies in modern and ancient nearshore sands (reviewed in Johnson 1977) have shown that such sequences result from alternate storm and fairweather intervals. In many modern nearshore areas, short-lived storms exert a dominant influence over sedimentation, transportation, and deposition (Kumar and Sanders 1976, p 146). Recognition that such storm-control is also characteristic of ancient deposits appears to be one of the most promising means of recognizing shallow marine clastic environments.

The thin, regularly recurrent clay drapes separating inclined sets suggest that tides were also a significant influence on sedimentation (see Reading 1978, pp 235-236). In addition, the continuity of the drapes over the inclined surfaces indicates that inclined surfaces were, at least periodically, completely submerged. Definite evidence for exposure among the inclined cross-strata has not been found, but the lateral relationships between large scale cross-strata and topographic highs (e.g. Sunnyside) make it likely that inclined set surfaces were emergent in some cases.

The geometry and internal structure of inclined cross-strata further suggest they may have formed mega-scale bar-like bedforms. However, the limitations of exposure make it difficult to establish the relationship between the inclined surfaces and the three-dimensional bedform they may represent. It is impossible to determine the original orientations of these bar-like forms. In some cases, inclined cross-strata could also represent infillings of very shallow channels between bars. The variable orientation of inclined cross-strata points to a mosaic of sinuous crested bars. This bar and perhaps barrier zone formed most of the BS, thinning over and surrounding topographic highs as well as eroded remanants of previous environments (Fig. 15-6).

15.234 The BS facies: environmental synthesis

A broad topographic high divides the basal sandstone facies into an area of quieter, more restricted accumulation to the north, and a more current-dominated zone to the south (Fig. 15-6). Substantial accumulations of coal and tuff provide evidence for a more restricted back-barrier bay or estuary in the northern area. This bay is likely to have closed against the positive area formed by the Bathgate volcanics to the north-northeast. Embayment was initially fluvially influenced, seen in the accumulation of the coal-bearing and

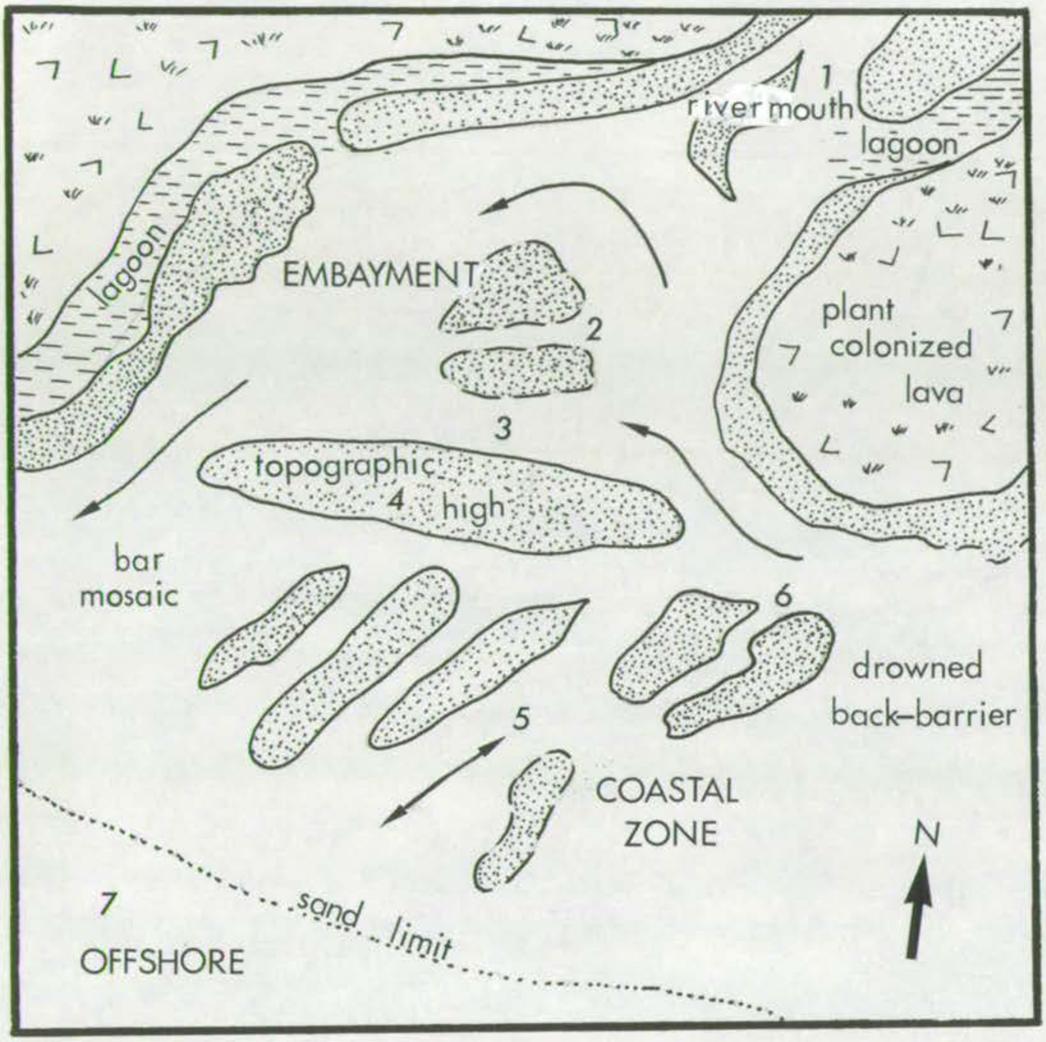


Fig. 15-6 Palaeogeographic map showing time averaged reconstruction of basal sandstone environment. Not drawn to scale.

1) N. Mine Quarry; 2) Silvermine; 3) S. Mine Lime Works; 4) Rifle Range and Knock Hill; 5) Sunnyside Reservoir; 6) Sunnyside Quarry; 7) south of Petershill Reservoir.

fining-upward sequences. Fluvial channels, incoming from the northeast (suggested by g, Fig. 15-1) are likely to have deposited fining-upwards sequences, which may pass into cross-bedded sands representing marine bars later swept into the bay (Fig. 15-6). The topographic high, where the bar system thins, may have been located near the bay mouth, suggested by the greater degree of current influence seen in the BS subfacies further south. South of Knock Hill, the BS formed a nearshore zone, probably including both the foreshore and shoreface. It is tempting to place the lower limit of the shoreface in the region of the Reservoirs, where the sandstones pass into shales (Fig. 15-6).

Thus, the strike section through the BS reveals an environmental profile extending between a bay to the north, across a topographic high, seaward onto a nearshore platform. The bay was initially infilled under quiet, marginal-marine conditions when abundant plant debris accumulated to form corals. Rootlets and reddened horizons throughout this sequence attest to numerous periods of exposure. Subsequent deposition by streams and marine bars is likely to have followed. The paucity of exposure limits a more precise description of the relationships between these two sedimentation patterns. Marine bars developed south of a slight topographic high, on a nearshore shallow platform. A generalized reconstruction of this sedimentation model is shown in Fig. 15-6.

Evidence for diachroneity - The nearshore sand bars of the BS facies extended over a limestone platform created during subaerial exposure. It has been tentatively proposed (Ch 13) that this limestone surface (C, Fig. A-1) formed a beach rampart or exposed platform onto which the basal sandstones transgressed. The plane-laminated sandstone subfacies, exposed at Sunnyside, is likely to represent an erosional remnant of a former back-barrier environment, left during one of several environmental shifts of the basal sandstones over this platform (6, Fig. 15-6). This subfacies provides evidence that the BS as a whole is complex and should not be regarded as representing a straightforward environmental profile. Additional evidence for this theory is found in the nature of the sediments infilling the fissures in the underlying limestones. They contain clasts of limestone, sandstone, plant fragments and tuffs not found in the sandstones above (Ch 13). Thus at least two major periods of subaerial exposure took place within the basal sandstones in the area south of Knock Hill.

The infilled fissures, below the BS south of the topographic high (Fig. A-1) contain tuffs which are remarkably similar to horizons within the tuff overlying the BS north of the topographic high. The petrographic similarities between these tuffs could suggest that they are genetically related. Perhaps all or part of the BS north of Knock Hill was deposited before the sandstones blanketing the fissure system south of this topographic high. This, in turn, would suggest that laterally equivalent sandstones north and south are not time-equivalent. It is, therefore, possible that the discontinuity surface south of Knock Hill (C, Fig. A-1) was exposed while the sandstones further north were being deposited.

<u>Implications of diachroneity</u> - If the time-lines proposed here for the upper Reservoir Mbr. sequence are correct, then the diachronous nature of sediments could also explain several anomolous aspects of the depositional history of the crinoidal packstone facies. These suggestions are put forward tentatively as more information is required for their confirmation.

One general pattern, which is apparent throughout carbonate sedimentation, is that area north of Knock Hill was a site of quiet sedimentation throughout Petershill Fm deposition. These argillaceous lagoonal sediments pass via an inflection point onto a more open platform, which shows a southward transition from high to low energy environments. This pattern is seen in the high-carbonate facies mosaic, the crinoidal packstone facies and the overlying BS facies. Throughout these sequences it appears that the most-proximal, landward zone was located to the north or northeast, while the shallow nearshore zones were developed southwards. Moreover, this pattern is also suggested by the distribution of the lavas.

If both major erosion surfaces in the Petershill Fm. (surfaces B and C, Fig. A-1) were formed subaerially, then it is anamolous that the effects of subaerial exposure are best developed in the nearshore zone, while seemingly absent from the argillaceous carbonate sequence further north (nearest land). This point is clearly seen in Fig. A-1, which shows how the two erosion surfaces are traceable into an apparently conformable carbonate sequence north of Knock Hill. Theoretically, those facies nearest land should have become exposed first, and hence show most extensive signs of subaerial weathering. Evidence for weathering is apparently absent from the carbonate part of this sequence. Numerous exposure horizons are present, however, in this area in the clastic sequence above, represented by coals and rootlet horizons.

It is, therefore, tentatively proposed that both the intervals of exposure represented by discontinuity surfaces in the limestones south of Knock Hill could correlate with the exposure horizons in the clastics north of Knock Hill. This assumption would then explain the distribution of the tuffs. It is also supported by the evidence from within the basal sandstone facies south of Knock Hill, which reveals that it is complex, and probably diachronous. It would additionally explain why large amounts of quartz sand are found in the crinoidal packstone facies. As previously stated, the crinoidal packstones are unusual in containing a large amount of quartz sand in the northern Rifle Range quarries. The presence of this sand could be explained by supposing that the crinoidal packstones were deposited on the subaerially-exposed platform (represented by surface B) while clastics had already begun to accumulate further north of the inflection point, Knock Hill.

15.3 The coarsening-upward facies (CU)

The basal sandstone facies is overlain by a sequence that coarsens upward along most of its lateral extent (Figs. 1-2; 2-2; 2-5). This CU trend is seen in an upward transition from carbonaceous shales, through parallel-laminated siltstones, to thin sandstones, ending in medium-thickness sheet sandstones. The sequence also shows a marked lateral differentiation. Most marked is a lateral change in the average proportion of sand within the sequence. North of Sunnyside, sandstones comprise roughly one-third of the total sequence thickness (e.g. Fig. 2-5). South of this area, sandstones comprise less than 5 per cent of the sequence. The loss of sand from the sequence coincides with a marked increase in total thickness, and the appearance of a limestone (Fig. 2-7). This major lateral lithological change takes place at roughly the southern limit of the underlying BS.

Two lenticular basalts, almost certainly lava flows (Ch 2) interrupt the CU facies a few metres above its base at N. Mine Quarry and south of Knock Hill (Fig. A-1). Both flows appear to be enclosed by the CU sequence and do not seem to have affected sedimentation patterns markedly. Indeed, the sequences north and south of the flow at Knock Hill are remarkably similar (cf. Figs. 2-2 and 2-5). Less information is available on the lava at the northern limit of the Petershill Fm. outcrop. It may have formed part of the barrier between the Petershill

Fm. and the Hillhouse Limestone to the north.

15.31 Biota

On the whole, the CU facies is very sparsely fossiliferous. The fossils which are present, however, are particularly valuable as environmental indices. In the region south of Sunnyside, the shales above and equivalent to the BS contain a shelly marine fauna. Brachiopods (mainly chonetoids), bryozoans, zephrentoid corals, ostracods, and smooth-shelled bivalves occur in untransported assemblages at several horizons up to 20 m above the base of the sequence. Zoophycus and Chondrites are also present (Fig. 15-7b). Both these trace fossils are marine and typical of quiet, sublittoral and deeper environments (Frey 1975, pp 13-39). Fourteen metres above the base of the sequence a thin limestone occurs which contains a marine shelly fauna and the dasycladacean alga Epimastopora.

The presence of a marine biota and ichnofauna at discrete horizons throughout the sequence south of Sunnyside establishes the marine origin of the CU facies. The intermittent manner of occurrence does not, however, rule out the possibility of non-marine incursions.

North of Sunnyside the fauna does not provide such conclusive evidence for marine conditions. Transported fossils are present in the basal tuff, and Latham (1933) reported marine ostracods in the shales above the limestones at Silvermine. These shales are no longer exposed and body fossils could not be found in equivalent beds in the present study. If fossiliferous horizons are present, they are certainly very rare. Sandstones in the upper CU sequence contain marine/marginal marine Planolites and Gyrochorte (Fig. 15-7a), a widely accepted marine trace fossil (Seilacher 1978, p 186).

15.32 Lithological sequence

The CU facies begins with an uncemented brown or black carbonaceous shale, usually very finely laminated. Cm-sized moulds of plant fragments, e.g. Sphenophyllum, Calamites, Cordaites and Alethopteris are common, as are thin horizons of ironstone nodules. Two metres above the base, thin sand and silt streaks begin to appear. In the overlying 5 metres the streaks increase in abundance to form a sand laminated siltstone. Individual laminae are 1-2 mm thick, parallel and laterally continuous for tens of metres. These parallel laminae are interspersed with very gently inclined laminae, starved ripple trains, indistinctly bioturbated horizons and rootlet horizons (described below). Numerous small-scale deformation structures such as sand dykes, loaded ripples, and flow-rolls are present in the thicker sandy units. Discrete thin sandstones begin to appear in groups, approximately 7 m above the base. Sand laminae, occuring in groups separated by a variable shale thickness, are also present in the upper CU sequence. Sandstones become more prominent upward and eventually coalesce into 2-3 metres of medium to thick sheet sandstones, separated by thin shales (q.v. Figs. 2-2; 2-5).

Most of the thin sand laminae are small fining-upward sequences in themselves. In these laminae, fining-upward is seen in the gradational manner that the sandstones pass upwards into siltstones, or by the presence of a clay/organic drape. The overlying thin sandstone beds also show a fining-upward trend seen in their sequence of internal structures. Plane lamination is followed by small-scale cross-stratification, nearly always attributable to oscillation currents (described below). The tops of sandstone beds are often burrowed, covered in wave-ripple marks, or form rootlet horizons.

15.33 Wave-formed sedimentary structures

Many of the sedimentary structures throughout the CU facies are attributable to wave-generated currents. De Raaf, Boersma, and

Fig. 15-7 Features of the coarsening-upward sequence

a. Gyrochorte Interfacial trails, preserved in epirelief, in a thin mud drape covering oscillation ripples. Trails show a tendency to meander in ripple troughs where organic matter is likely to have concentrated. Note that parts of ripple crests have been planed off. Such planing occurs while the ripple crests are exposed, while their troughs are still infilled with water. Planed-off ripples are thus a sign of very shallow water. Scale bar = 1 cm. South Mine Lime Works, approximately 15 m above base of Silvermine Mbr. In situ specimen

b. Interference ripple patterns and rootlet casts. Undersurface of a sandstone bed showing two perpendicular sets of ripples, preserved as casts. The most pronounced ripple train is orientated vertically in photograph (E-W), while the subordinate train trends horizontally (N-S). Interfering ripple patterns, such as these are usually wave-formed. Many ripple crests are rounded due to planing. Small, dark round holes in sandstone are weathered rootlet casts. Middle Rifle Range, top sandstones, 12 m above base of facies. In situ specimen

c. Zoophycus Undersurface of a laminated siltstone. Petershill Reservoir II; specimen not in situ. Scale bar = 15 cm.

van Gelder (1977) have recently pointed out that parallel siltstone laminations, comparable to those described here, can be formed by waves. They interpreted the lamination as forming by reworking of sandy laminae by waves, followed by rapid suspension fall-out of the finer grained sediment. The small-scale cross-stratification at the top of the FU sandstones typically shows many structures diagnostic of wave formation figures by these and other authors (q.v. De Raaf et al. ibid). The most important of these include variably-inclined foresets, thin clay drapes, scoop-shaped lower set boundaries, chevron-like laminae, and hummocky laminae. In addition, symmetrically-shaped ripple sets are present within and at the tops of nearly all the sandstones (e.g. Fig. 15-7). Bedding surfaces are typically covered with symmetrical ripples. The ripples show many characteristics of having formed in very shallow water and of emergence; bifurcating straight crests, planed crests (Fig. 15-7a) and interference patterns (Fig. 15-7b). These ripple structures indicate that the sandstones were deposited near to mean sealevel.

Current directions of these wave-formed structures (Fig. 15-9A) show a significant eastward orientation. Many of the measurements plotted were taken from small-scale ripples also likely to have been wind-formed. The predominant current (and wind) direction indicated by cross-stratification is similar to that indicated by large plant stems (Fig. 15-9B). Small-scale cross-strata throughout the Silvermine Mbr. show a fairly consistent northeasterly orientation (cf. Figs. 15-1 a-e and Fig. 15-9A,B). This confirms the earlier suggestion that small-scale structures were wave-formed, and further points to a northeastward land direction. One would expect that the wave ripple-crest trends would be orientated parallel to palaeoshoreline.

Most importantly, however, wave-generated structures are so widely spread throughout the CU sequence as to indicate that virtually all the sandstones have been either reworked or deposited by waves.

15.34 Evidence of subaerial exposure

Numerous structures provide evidence of different intervals of subaerial exposure within the coarsening-upward subfacies. Among these are mud cracks (preserved as sand infilled casts, Fig. 15-8), reddened mudstone flakes, rounded red mud pebbles, and rootlet horizons, (Fig. 15-8). These structures are particularly prevalent in the upper sandstones in the sequence, although rootlets are also present in the sand-laminated siltstones underneath. There are two further indications of exposure in the sequence:

"Rootlet casts" - Apart from undoubted rootlets there are structures which have been interpreted here as rootlet casts, but which lack some of the features of unequivocable rootlets.

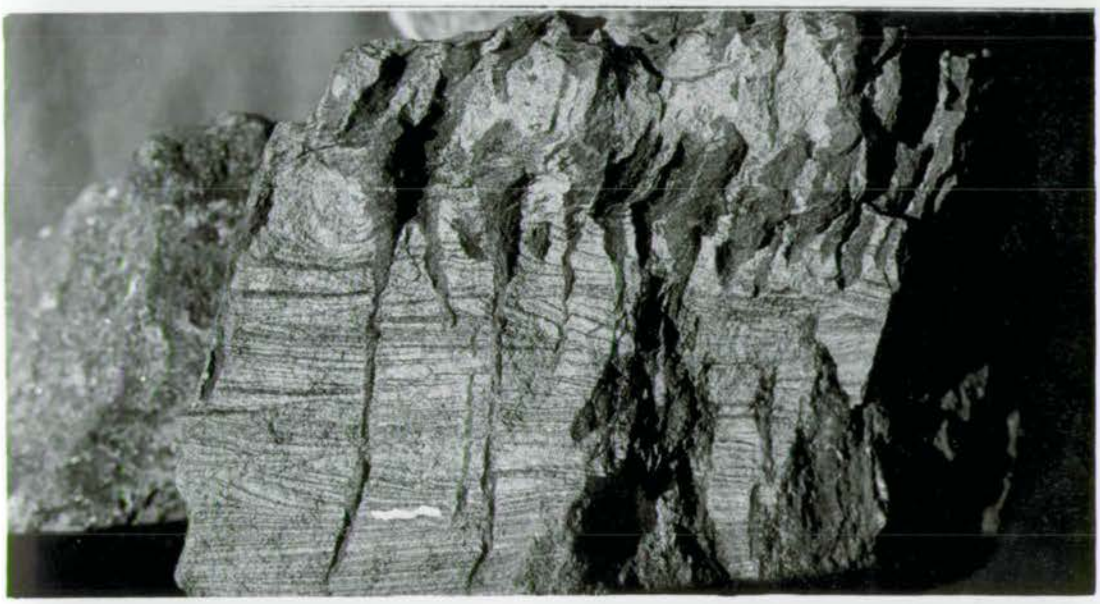
Structures (usually preserved as casts) which taper and branch-out downward are common and can unquestionably be given a plant origin. In addition to these undoubted rootlet casts there are at least 50 horizons in the CU facies containing somewhat more problematic structures of probable plant origin. These supposed rootlets (Fig. 15-8) are preserved as sand or silt-infilled casts. In horizontal cross-section they are usually elliptical, approximately 7 mm in diameter. Longitudinal cross-sections usually reveal that the cast has an outer carbonaceous film, a series of concentric laminae and an innermost draft infilling of coarser sediment. The internal structures and types of infilling sediments are variable, however. In vertical (longitudinal) section, the structures are typically trumpet-shaped, tapering gradually from an expanded aperture, measuring 1-2 cm in diameter (Fig. 15-8). The tops are often obviously eroded. From the expanded area, the problematic cast tapers gradually to a microscopic terminus. The terminal few

Fig. 15-8 Features of the coarsening-upward facies

a. A thin limestone with a fissured discontinuity surface. Both the smooth-sided fissures and the limestone upper surface have become decalcified and have altered to a darker crust, particularly visible on right side of fissure, beneath pencil. The top surface is overlain by a dark, compacted mudstone, chips of which are also found in the fissure infillings. Fissure shape and manner of alteration are comparable to the alteration observed on discontinuity surface C in the Reservoir Mbr. Petershill Reservoir II, north bank, 14 m above base of sequence (q.v. Fig. 2-8).

b. Problematic rootlet casts in a silt-laminated sandstone. Sandstone shows plane-to-ripple sequences consisting of parallel or slightly-inclined laminae followed by small-scale trough and wave cross-stratification. Scale bar at bottom of specimen = 1 cm. Middle Rifle Range quarries.

c. Mud-crack casts. Undersurface of a sandstone bed which originally covered a black shale. Sandstone casts infilled the cracks in the black shale. Petershill Reservoir II, specimen shown not in situ, likely to have come from top sandstone in the sequence.



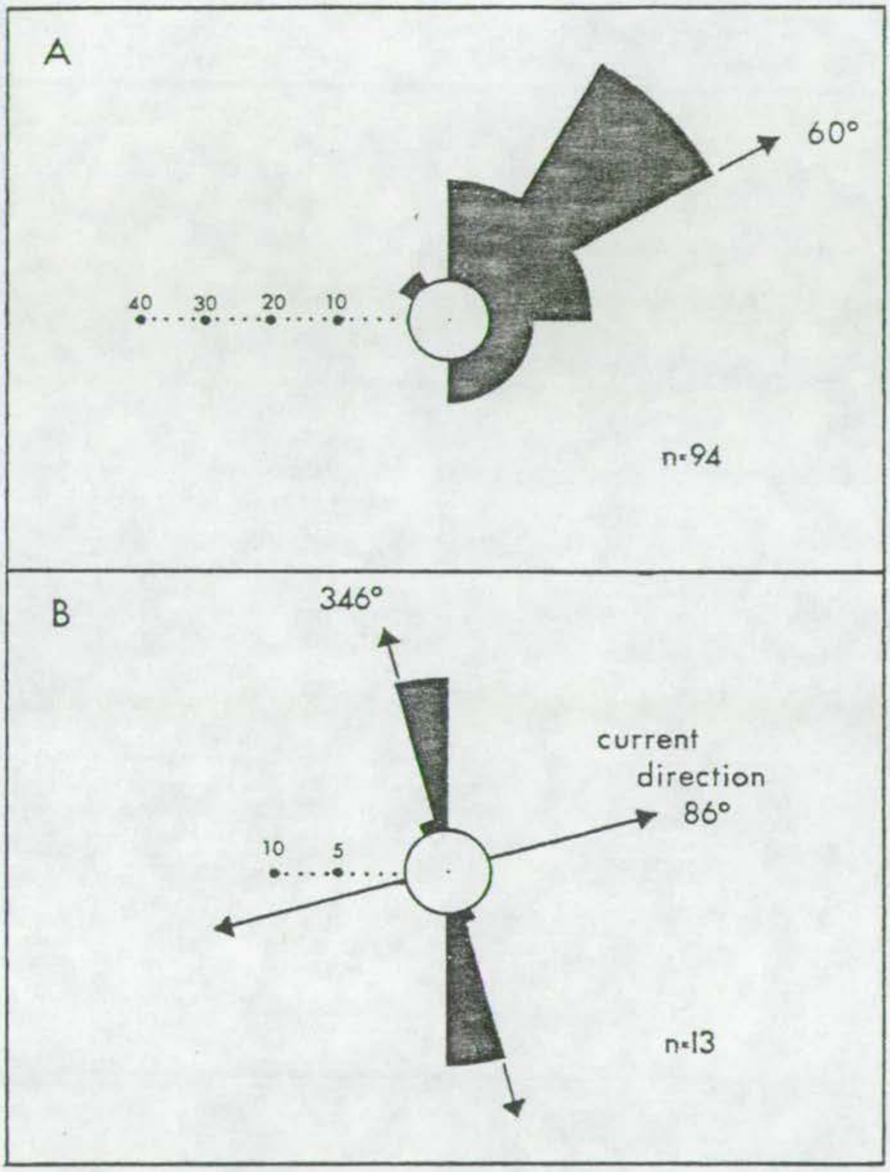


Fig. 15-9 Wave and wind orientated structures, Silvermine Mbr., S. Mine Lime Works.

A. Downcurrent azimuths of small-scale asymmetrical wave and current ripples in the upper sandstones of the CU facies. Arrow shows mean orientation, significant at 0.5 level.

B. Axial orientation of large plant fragments likely to be in drifted or rolling orientations, same locality. Inferrable current direction is thus shown normal to trend of plants.

centimetres are so fine as to only be preserved as a thin carbonaceous film.

These structures are interpreted as the root casts of fossil plants, probably lycopods. They are generally similar to the lateral rootlets which branch from Stigmaria. On decay, the root pith-core and cortex became infilled with sediment. Rootlet horizons have formed where the overlying plant-colonized surface has been removed, as the rootlets have not been found beneath in situ plant accumulations. Thus it may be that every one of the problematic rootlet horizons has an erosive top, or that the plant itself readily decayed to become disaggregated.

Chisholm (1968, pp 111-113), however, considered that a structure from the Carboniferous of E. Fife, very similar to these "rootlets" was a burrow, describing it as Monocraterion. In my opinion, the size and manner of termination are sufficient grounds for better interpreting this structure as a plant root cast, probably a new form. If this interpretation is correct, the problematic rootlet horizons indicate that the area north of Sunnyside supported a lush vegetation. Plant colonization may have taken place either in shallow standing water or on emergent surfaces, as in present day Equisetum stands.

A minor-discontinuity surface (Fig. 15-8) - The top surface of the limestone 14 m above the base of the CU facies shows many features characteristic of subaerial exposure, comparable to those previously described from the limestones in the Reservoir Mbr. (q.v. Ch 13, surface C). Its top surface is reddened to a depth of several centimetres and overlain by a compacted red-brown mudstone. The limestone surface is gently fluted and dissected by a system of small fissures (Fig. 15-8). These fissures are smooth-sided and, in some cases, open downward, suggesting a dissolution origin. They are infilled with loose fossils, chips of the overlying mudstone, and a red clay. The fissures, therefore, appear to be penecontemporaneous. This surface provides evidence of an extended period of exposure in the CU facies south of Sunnyside. It is likely to correlate with the many rootlet horizons in the sequence further north.

15.35 The CU sequence - environmental synthesis

The CU sequence was deposited episodically, each pulse marked by a rapid sediment influx followed by wave reworking and then standstill. The current-deposited sequences may have been entirely wave-generated (cf. sequences of De Raaf et al. 1977). The general sedimentation pattern is comparable to the "plane-to-ripple" sequences described in the BS facies, although intervals between sedimentation pulses, the types of available sediment, and water depth, differ markedly. This pattern is typical of storm sedimentation (De Raaf et al.,ibid). Storm sedimentation may have been seasonal, as suggested by the manner in which sand influxes are grouped. The intervening "fairweather" intervals are marked by suspension accumulation of fine clastics and organic matter, very shallow standing water, emergence, and plant colonization.

Lateral lithological differences between areas north and south of Sunnyside may be attributed to hydrodynamic variation along the postulated onshore-offshore environmental profile. The area to the north formed a shallower and slightly higher energy environment. To the south was a quieter area, less disturbed by storms and seasonal sealevel fluctuations. This profile points to a depositional model similar to that suggested for the basal sandstone unit, i.e. of a bay to the north opening southeastward into an open marine shallow platform.

The vertical sequence within the CU subfacies may be attributed to gradual infilling of the bay and coastal progradation (see Elliot 1975). Initially, basal shales would have accumulated in relatively deep and quiet areas of the bay. The gradual upward coarsening and progressive influx of sand reflect a gradual increase in current velocities and sediment input, typically associated with bay infilling (Elliot ibid). The widespread influence of waves and storms throughout the sequence may point to a coastal rather than interdistributary bay.

15.4 The Silvermine Mbr. - environmental synthesis

The widespread clastic influx that forms the Silvermine Mbr. is a major allocyclic change in the Petershill Fm. sedimentation pattern. Such regional sediment influxes have been attributed to the advance of Carboniferous deltas into the Midland Valley (Moore 1959; Greensmith 1966). Coastal processes, acting over the platform underlain by the Bathgate volcanics and the Reservoir Mbr. limestones modified the allogene sediments into the onshore-offshore profile described above.

CHAPTER 16

THE PETERSHILL FORMATION : GEOLOGICAL HISTORY AND SUMMARY

16.1 Geological history

The depositional history of the Petershill Fm. can be most easily interpreted in terms of major sea-level fluctuations and changes in the influx of sediment into the Midland Valley basin. These fluctuations are likely to have occurred on several scales due to local tectonic effects associated with Bathgate volcanism and regional eustatic sea-level changes. The geological history of the Petershill Fm. may be summarized as follows:

1. Initial transgression (1, Fig. 16-1) - Subaerial eruption of lavas and tuffs from a system of vents on the south side of the Bathgate volcanic pile gave rise to a broad platform extending 8-10 km away from a large volcanic centre (a subaerial or intermittently exposed area), located north of the present-day exposure of the Petershill Fm. Subaerial lava weathering followed eruption.

Inundation of this lava surface led to clastic sedimentation in a series of coastal or perhaps freshwater lagoons, where organic material, derived volcanogenic debris, and sand accumulated slowly. Many of the irregularities in the lava surface were infilled during this initial sedimentation phase. However, antecedent topography may have continued to influence subsequent sedimentation patterns. The presence of an inflection point in the depositional surface near Knock Hill could explain why facies changes occur throughout the sequence in this region. After this initial infilling of the major irregularities in the lava surface, continued coastal lagoon sedimentation gave rise to a fairly uniform blanket of black shales. These shale lagoons were areas of restricted circulation and quiet accumulation of plant detritus and clays, with periodic marine incursions.

2. Marine transition (2, Fig. 16-1) - Continued relative subsidence and water deepening led to a gradual transition into fully marine conditions. This is likely to have occurred slowly, allowing sufficient time for several distinct faunal associations to become established: a) the bivalve-serpulid association which characterized restricted intervals of sedimentation when black shales accumulated; b) the productoid-coral association, formed during intervals of more open circulation. This transition from marginal to fully marine conditions occurred during a period when the platform as a whole was receiving large amounts of clastic detritus.

3. Level-bedded carbonate sedimentation - Further transgression and a relative decrease in the extrinsic sediment supply to the platform led to high biological productivity and predominantly carbonate sedimentation. The clastic influx continued to decrease throughout level-bedded carbonate sedimentation, reflected in the decreasing clay content of successive limestone environments.

With the initiation of carbonate deposition, the biota began to play a progressively greater role in modifying the patterns of sedimentation. The lower, argillaceous level-bedded limestones formed loose, gel and plastic substrates which only supported a sparse Gigantoproductus-zaphrentoid coral fauna. Slightly argillaceous limestones, however, at times underwent progressive consistency increases which favoured extensive epifaunal colonization. The increase in consistency may be attributed to the combined effects of bioturbation and cementation in a sediment with a low initial clay content. Such consistency changes took place during intervals of non-deposition, or relative stillstands. Level-bedded carbonates accumulated in generally quiet, non-turbulent waters. Limited evidence of gentle, regular circulation patterns is seen in the preferred orientation of solitary corals and perhaps in the lensoidal form of bedding. The origin of this particular bedding type, however, still remains uncertain.

The position of these level-bedded carbonates in the sequence (Fig. 16-1) and the evidence for gentle circulation patterns suggest that they accumulated during maximum transgression. The sequence below shows a progressively greater marine influence which may be attributed to deepening, while the high-carbonate facies mosaic above shows greater influence of currents characteristic of shallower water deposition. The presence of algae (particularly dasycladaceans) and an erosional surface in the immediately overlying sequence (probably formed by subaerial exposure; 4, Fig. 16-1) would suggest that water depth, even during maximum transgression, was not very great.

Level-bedded carbonates are not markedly differentiated across the lava platform. At the northernmost (landward) extreme, they become more argillaceous and organic-rich, in an area interpreted as being lagoonal throughout Petershill Fm. sedimentation (perhpas due to a topographic barrier further south, at Knock Hill). At the southern limits of the lavas, level-bedded facies pass into more basinal facies, representing areas of deeper water and greater clastic deposition.

4. Environmental and faunal diversification - Following maximum transgression and development of a rather uniform carbonate sedimentation, a period of shallowing led to increased current influence with a concomitant lateral facies differentation. A nearshore-offshore facies profile became established, consisting of (from N-S): a) a coastal lagoon; b) a nearshore turbulent shoaling zone (the heterogeneous packstone facies); c) a distal nearshore zone of biohermal accumulation (the build-up); d) a quiet offshore zone of high-carbonate accumulation (the high-carbonate biomicrosparite facies), passing into distal platform zones of reduced carbonate deposition.

The composition and mode of preservation of the fauna in each high-carbonate facies shows a close correlation to its prevailing local hydraulic regime. The distribution of colonial coral faunas provides one of several examples of such hydrodynamic influence. Robust colonial coral growth forms are characteristic of the high energy facies, whereas delicately-branched colonies typify quieter environments. In these aspects the Petershill colonial corals are closely comparable in growth-form distribution to Recent tropical reef corals. Colonial corals are, however, conspicuously absent from the build-up, the area of greatest in situ biological accumulation. The reason for this may be that rugose corals, like Recent scleractinians, grew relatively slowly, and were thus not able to compete with the abundant and more rapidly growing productoid-bryozoan-sponge fauna.

The shallowing-upward trend continued throughout high-carbonate sedimentation, terminating in widespread erosion almost certainly in the subaerial environment (surface B, Fig. 16-1). The build-up itself may have been exposed for a brief interval early in its history, forming a low nearshore island (4, Fig. 16-1).

5. Exposure and sea-level fluctuations (5, Fig. 16-1) - The sequence of events associated with sea-level fluctuations at the Reservoir-Silvermine boundary is complex. The observed relationships between facies at this horizon are best explained by assuming that laterally-adjacent lithologies are, in some cases, diachronous (q.v. Ch 15). The postulated sequence is as follows:

A. Regional regression during high-carbonate mosaic sedimentation culminated in widespread subaerial exposure of the limestone platform, creating surface B. Exposure at this horizon may be attributable to a major eustatic sea-level change, as a clastic influx into the whole of the Midland Valley accompanied or soon followed this regression. These clastics were first deposited in the nearest shore areas of the Bathgate volcanic platform (north of Knock Hill).

B. A minor carbonate transgression and regression (the crinoidal packstone facies) occurred south of Knock Hill during terrestrial accumulation further north. North of Knock Hill coal swamp/marsh sedimentation was taking place, while further south, the crinoidal packstones were deposited in a marine nearshore zone. The atypical amounts of quartz sand found in the crinoidal packstone facies point to an allochthonous input not seen previously in the Petershill Fm. limestones.

C. A period of intense weathering followed the regression in the crinoidal packstone facies (C, Fig. 16-1), leading to the formation of fissures in the carbonate platform. The fissure surface was probably first covered by terrestrial deposits extending from the north. A brief interval of volcanism may have then simultaneously deposited tuff above the terrestrial deposits north of Knock Hill and also infilled the fissures.

D. Subsequent transgression onto the limestone platform resulted in deposition of the present basal sandstone facies, which is likely to have reworked the original sedimentary cover. Environmental shifts within the basal sandstone left small erosional remnants, such as the plane-laminated backshore sandstones at Sunnyside.

6. Bay infilling (6, Fig. 16-1) - Clastic sediment deposition continued after the initial sand blanketing of the subaerially-exposed parts of the carbonate platform. A coarsening-upward sequence formed during infilling of a coastal lagoon. Bay migration over the basal sandstone may have occurred during continued transgression (as shown in Fig. 16-1), or it may be due to relatively minor adjustments

in a stable coastline. A brief interval of extrusive volcanism (the lavas, 7, Fig. 16-1) does not appear to have affected the general sedimentation pattern. Short intervals of exposure in this coarsening-upward sequence may represent seasonal drying-up and gradual bay-infilling. One exceptionally long period of exposure subaerially exposed the top surface of the discontinuous limestone at Petershill 2 (8, Fig. 16-1). Subsequent shoreline progradation finally filled the bay. Petershill Fm. sedimentation was terminated by a widespread interval of volcanism, which led to re-blanketing of the platform by fresh lava flows.

16.2 Discussion

As originally stated, the purpose of this thesis has been to describe the various environments in which the Petershill Fm. was deposited. In the course of integrating the different types of data discovered, it became clear that this method of analysis, bringing together observations on as many scales and from as many sources as possible, was a particularly informative approach. These methods (q.v. Fig. 0-10) are especially applicable to variably-exposed sequences or borehole studies, where observations must be made on polished surfaces and in thin sections, i.e. in sequences where natural exposures are not very accessible. This integrated approach has yielded a more detailed geological history of a Lower Limestone Group sedimentation cycle than any previous studies. In addition, several findings of this study are likely to have wider applications, namely:

A. Role of algae - Various calcareous algae, particularly filamentous types, are likely to be common in fine-grained biomicrosparites of Carboniferous shallow-water environments. Their preservation relies, in part, on the diagenetic history of the sequence, as a slight degree of neomorphic recrystallization must take place for them to become readily visible. Their growth habits in the Reservoir Mbr. would suggest that these algae were significant degradative agents capable of weakening skeletons and providing fine-grained sediment. Although filamentous algal frameworks show signs of synsedimentary stability, and even limited early lithification, algae in themselves cannot be invoked as the mechanism for accumulation of masses of sediment that stood above surrounding level-bedded substrates. Filamentous algae are present throughout the carbonate sequence, but only show structures attributable to binding and early firmness in relatively quiet environments during intervals of exceptionally low clastic influx. Thus a combination of physical and biotic factors ultimately determined sediment accumulation patterns.

B. Significance of substrate consistency - The mass properties of a sediment surface were important in controlling faunal distribution and the subsequent diagenetic history of a lithology. The study of sediment consistency may also form the basis for environmental interpretations. Trace fossils are most useful in determining the original consistency of a substrate. When other sedimentary structures, analyses of faunal growth forms and trace fossil data are combined, it is possible to distinguish both the mass properties of a sediment and its changes in consistency with time.

For example, initially firm and stable substrates provided optimal surfaces for epifaunal colonization and diversification. In distal nearshore environments the fauna occasionally reached such a high proportion of the sediment as to create a framework and promote biohermal growth. Firm substrates preserved much of their original porosity and were therefore particularly susceptible to early diagenetic modification by dissolution, shrinkage and fracturing. The ease with which meteoric water could flush through a framework appears to have been closely related to depositional fabric. Thus, the study of consistency becomes a key to both palaeoecological interpretation and unraveling diagenetic history.

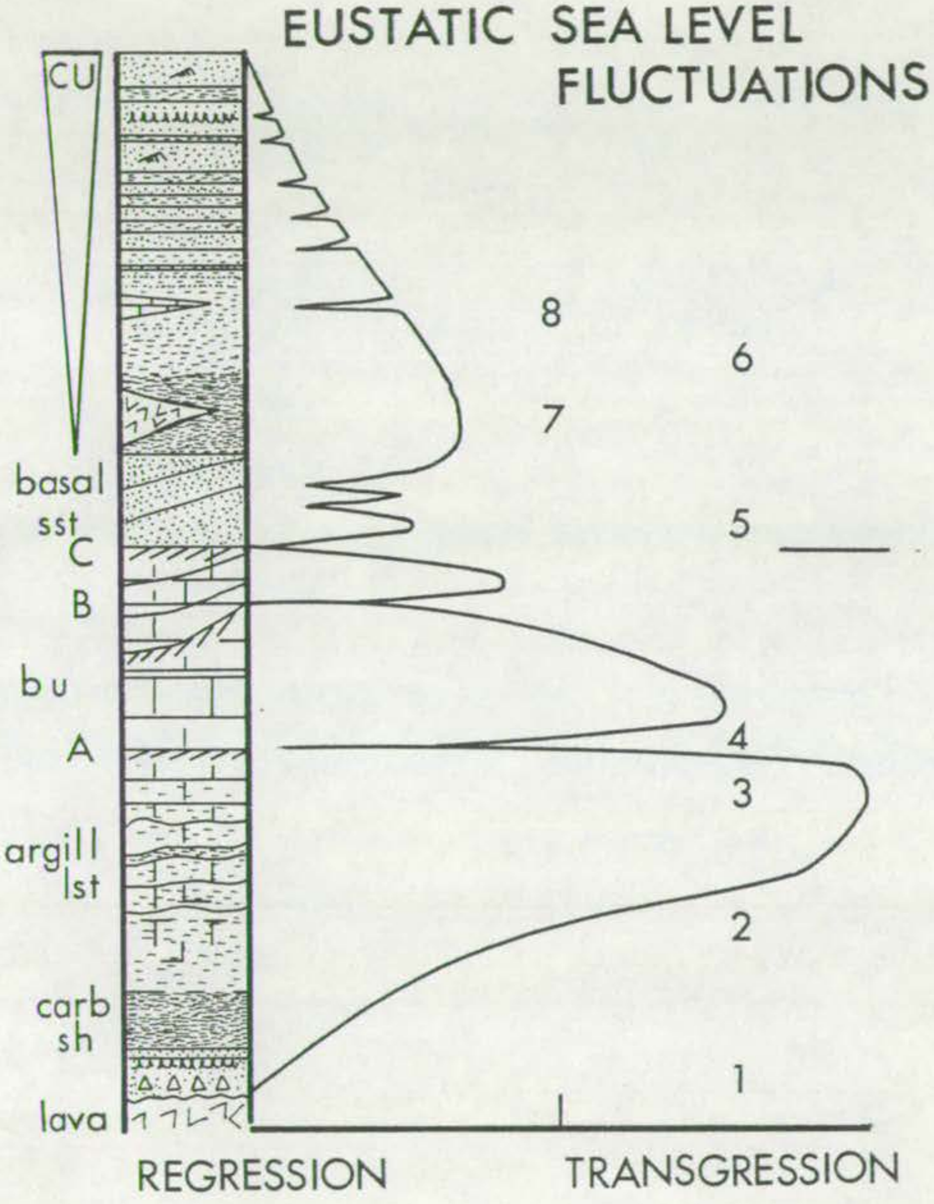
C. The environmental and ecological significance of encrusting organisms - Attached and encrusting organisms furnish a wide variety of information about the nature of their host surface. Direct encrustations by delicate organisms, such as Fistulipora, attest to the firmness and stability of a sediment surface. A number of encrusters found among the branches of L. junceum colonies, on the pedicle valve undersurfaces of spinose productoids, beneath Chaetetes and cerioid coral colonies show that their host skeletons lived above the sediment surface. Encrusters may thus reveal the life position of a host, relative to the sediment surface. Moreover, encruster associations may reveal whether a surface was more or less permanently exposed or only temporarily available for colonization. Some solitary aulophyllids in the Petershill Fm. were commensal with Corallicolites subcutanea a new, previously undescribed commensal organism, probably a bryozoan.

16.3 Overview

The Petershill Fm. is an anomalous unit in the Scottish Carboniferous in many respects. It has an unusually thick carbonate sequence which displays greater faunal abundance and diversity than virtually any other limestone in the Midland Valley. The diversity of its fauna is matched by the variety of environments (facies) in which they are found.

Several factors are likely to account for the atypical nature of Petershill Fm. sedimentation. Most important of these is the position of the Petershill Fm. in the Carboniferous tectonic basin. It was deposited on a mid-basin high, formed by successive outpourings of the Bathgate volcanics along the Burntisland Anticline. The accumulated thickness created by the volcanics provided the necessary relief to elevate a platform-shaped area and thus isolate it from surrounding basinal sedimentation regimes.

Fig. 16-1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REGRESSION
TRANSGRESSION