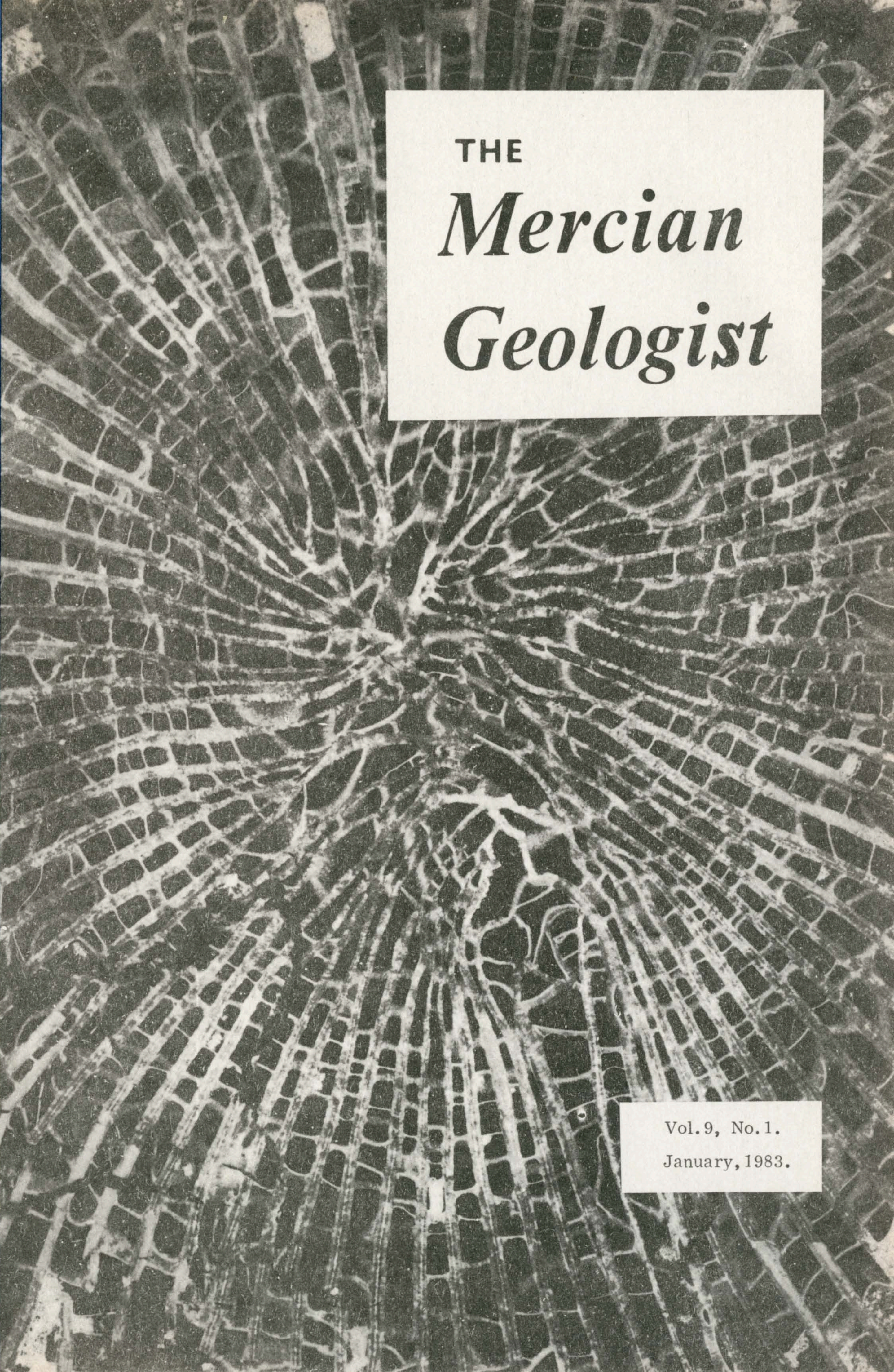
THE

Mercian Geologist



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Address for Correspondence,
General information,
membership details:

The Secretary,
East Midlands Geological Society,
311 Mansfield Road,
Redhill,
Arnold,
Nottingham

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THE PLAIN MAN'S GUIDE TO ENIGMATIC CORAL REEFS

Foundation Lecture, 7th February 1981

by

Julia A.E.B. Hubbard

Summary

Although by no means monomineralic, reefs are often enigmatic structures because the superficial homogeneity of their carbonate components renders their complex internal histories obscure to many forms of detection. This is particularly evident in the case of seismic studies of subsurface phenomena which tend to yield misleadingly uniform lensoid interpretations resulting from refraction at the shale:carbonate and sandstone:carbonate interfaces beyond the margins of the reef *sensu stricto*. But studies of random sections through reefs can be equally baffling in the field. The reasons for the ensuing confusion often results from attempting to compare different diagenetic grades of the same geological age. This account stresses the interdisciplinary nature of reef analysis irrespective of time by means of models and by analogy with present day tropical coral reefs. By drawing on case histories from Zanzibar and the Seychelles and comparing them with data from Bermuda, Bahamas, Florida and the Australian Great Barrier Reef, the oceanic provinciality of sediments is highlighted, and their local variability is related to their oceanographic and geomorphological setting and consequent settlement pattern which is often wind dominated. Then emphasis is placed on integrating ecosystem analysis of the biota and associated sediments with chemical predictions on the preservability of the fabric following burial in the vadose zone and subsequent loading. Intimate details of present day and vadose Pleistocene reef fabrics are illustrated by scanning electron micrographs which draw attention to the fact that quantitative data are only as good as the natural constraints put upon them. Thus one coral clast featuring no less than eleven adhesive dinoflagellates indicates that all the published sediment budgets are preferentially biased against the interstitial biota, the base of the food chain and the role of organic matter so limiting their potential for ecosystem analysis and biasing their palaeoecological utility. Though more readily quantified, this limitation is no worse than the geochemical parameters encountered during burial diagenesis : hence reefs range from the obvious to the obscure.

The enigma

Reefs fascinate geologists, seafarers, oceanographers, biologists, mareculturalists and tourists alike. Herein lies a major problem, that of semantics; this has tended to increase in direct relation to the burgeoning of the literature on what is essentially a multidisciplinary subject. The reason for this break-down in communication is simple : the geologist is faced with ghostly relics in the geological record, yet to interpret these phenomena he needs a good interdisciplinary knowledge which is hard to muster from a distant study of texts. It therefore follows that many misleading comparisons have been drawn which give rise to yet another generation of enigmas, so interpretation becomes increasingly speculative. This paper endeavours to outline some of the common hazards encountered in the geological interpretation of reefs and suggests some methods of coping with them.

The largest conundrum is that of the three dimensional distribution of reefs. In a few lucky instances, such as the well exposed and deeply dissected Devonian of the Canning Basin of Western Australia (Playford & Lowry, 1966), aerial photographic reconnaissance mapping reveals not only the details of discrete locally developed reefs within the reef system but also the regional morphology of the whole complex, but such clarity is unusual. More commonly, as with most seismic interpretations of the subsurface (text-fig. 1), reefs have been picked out because their essentially carbonate cores contrast with siliciclastic flanking sediments. Thus to many economic geologists reefs are effectively pod- or lens-shaped structures of variable lateral extent and thickness. In the seismic traces the most obvious signals come from refraction at the contact between seemingly homogeneous carbonates and heterogeneous bedded shales and sandstones which reflect geochemical and lithological differences. But the fact that much more can be derived from seismic interpretation of carbonate platforms is

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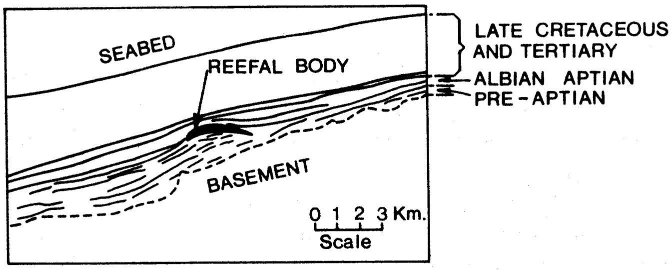
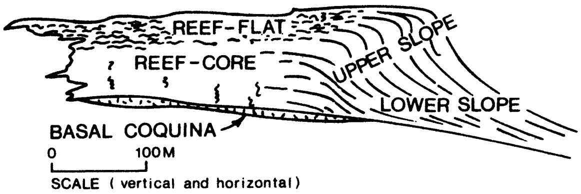
pp. 1-30, 27 text-figs., plates 1-4

eloquently demonstrated in talks on the evolution of the Maldives by Dr E.G. Purdy of Esso Exploration Inc.

The next problem arises from the fact that, as few reefs are well exposed, most geologists are forced to make palaeogeographic syntheses on limited data. Thus it is tempting to attempt to force findings into pre-existing models. The most popular of these is shown in transect form in text-fig. 2. Though, in a generalised way, this model has proved very effective (Wilson, 1975) it seems that many of its users overlook the potential of subtle facies variations within their own case histories, thus limiting the validity of their interpretations.



Text-fig. 1: A typical profile of a subsurface reefal body as detected by multichannel seismic reflections off the pre-Aptian and Albian-Aptian strata of the Porcupine Seabight area on the continental margin S.W. of the British Isles (after Masson & Roberts, 1981).



Text-fig. 2: Profile across a reef depicting the most popularly accepted facies belts of reef core, reef flat, upper and lower slopes on a basal coquina foundation as recorded for the Upper Permian Middle Magnesian Limestone shelf edge reef complex of N.E. England (after Smith, 1981).

The question that arises is how can we effectively improve upon the situation outlined. On the largest scale, to glean more information from seismic sources, strategically placed core, closely related to gamma ray and density - neutron porosity logs is required (Purdy, 1981). But such information needs to be interpreted by someone with experience of the sedimentology and geochemistry of present day analogous reefs and carbonate platforms. So far, only bedded structures have been detected seismically in the Maldives, and these are comparable to those forming around One Tree Island at the Southern end of the Australian Great Barrier Reef to-day (Davies & Marshall, 1981), but frame building reefs have yet to be reported. Not only are these internal textures needed for three dimensional reconstruction, but also, the variation in the geomorphologies of the underlying basement needs to be known. The latter are likely to be of critical importance in determining the resultant geometries, styles and extent of the reefs superposed on them (see Longman, 1981).

Turning to details, which have a considerable bearing on the interpretation of both local and regional geology, the most obvious factor to be considered is the comparability and variability of diagenetic grade. Even in such classic areas as the Canning Basin dispute has arisen over the geological history of the area as a result of earlier studies seemingly evading the diagenetic issue (see Logan & Semeniuk, 1976). Thus, to be effective, like grades must be compared. This, in turn, not only affects but is affected by the palaeontological record which is likely to be artificially skewed towards the silicic and low-Mg calcite members at the expense of the more readily soluble aragonitic and high-Mg calcite components. Hence the lithological end-product needs careful consideration: given a different diagenetic history, the same original sand can result in contrasting rock types with distinctively different biotas (see Reeckman, 1981), while the reef framework can give rise to even more misleading fabrics. Thus preservation has to be analysed carefully before pronouncements can be made on such variables as the influences of both provinciality, reflecting palaeo-oceanographic differences, and evolutionary change, which reflects the time factor.

In summary, the greatest problem facing the reef interpreter lies in the fact that a lack of comparative data on the variability of present day reefs exists with the result that oversimplification has taken place. Thus models based on the Atlantic - Caribbean province have artificially dominated recent thinking. This has resulted in difficulties where (1) data has been forced to fit unnecessarily simple models; (2) variations in microfacies have been ignored at the expense of refining the palaeogeography of the area. Notwithstanding the difficulties of applying uniformitarian principles to the interpretation of ancient environments this lecture attempts to highlight the applicability of some of the variables so encountered.

The consequences of inherited topography

If we accept the principle that inherited topography can have a profound influence on reef configuration (Purdy, 1974; James & Ginsburg, 1979), then it follows that we should consider the variability of facies which ensue. Text-fig 3 depicts the areas of the globe on which there is much intensive literature published in English.It draws attention to the contrasting hydrodynamic and geomorphic settings of the various tropical areas concerned. Though the Florida - Bahamas area has been best known for longest time (see Ginsburg, 1956), representing contrasting settings of drowned Quaternary and Pleistocene limestone terrains, they contrast strongly with the isolated volcanic complex on which Bermuda is founded (Garrett *et at*, 1971) and the even more disparate granitic foundation of the Seychelles Islands (Lewis, 1968). The variability of coastal configurations in relation to prevailing wind systems gives rise to a much greater range of facies patterns and successions than those outlined in synthesis in Hubbard & Swart (1982), herein summarised in text-figs. 4 & 5 respectively. Text-fig. 4 is based on an amalgamation of the salient features seen in transects across the present day Florida and Kenya coasts, where the stepped basement comprises pronounced wave cut platforms intersecting faulted coastal margins. Text-fig. 5 gives an idealised, hypothetical, lithological log of the sequence which could be expected to be formed on a marine regression across text-fig. 4. Within the tidal range, a similar sequence to that proposed could be formed equally well by invoking lateral impounding of the waters by storm induced blockage. But the fact remains that there is considerable variation in coastal configuration as exemplified by comparing the sheltered west coast of Zanzibar from the East African fringing reef system (text-fig. 6) with that of the generally open circulating, mid-ocean situation of Mahé on the Seychelles Bank (text-fig. 7). In turn, these Indian Ocean settings can be contrasted with those Caribbean - Atlantic localities already cited.

Having touched on the theme of the implications of topographic diversity of the basement, it is now proper to turn to the related topic of benthic settlement patterns and the resultant distribution of sediments. Firstly, the settlement of the reef system can be compared with the creation of a rock garden : there are taxa which withstand extremes and others which require shelter. But the majority are fairly hardy and consequently ubiquitous. The tidal regime, current strength, temperature and nutrition impose constraints. In intertidal areas the degree of wetness and desiccation are associated with salinity changes and concomitant chemical fluxes which add further burdens to the ecosystem. In the subtidal areas, fresh water springs and variations in lighting are the chief hazards. Secondly, sedimentation both affects and is affected by benthic distribution patterns : there are regional differences between the gross sediment populations of the Indian Ocean and Caribbean - Atlantic areas described (text-fig. 8). The Indian Ocean populations are more comparable with Pacific distributions, as evidenced by the Australian Great Barrier Reef (Maxwell, 1968), than with the Caribbean – Atlantic province. Thirdly, whereas the present day carbonate sediments of Florida, the Bahamas and Bermuda are all formed on

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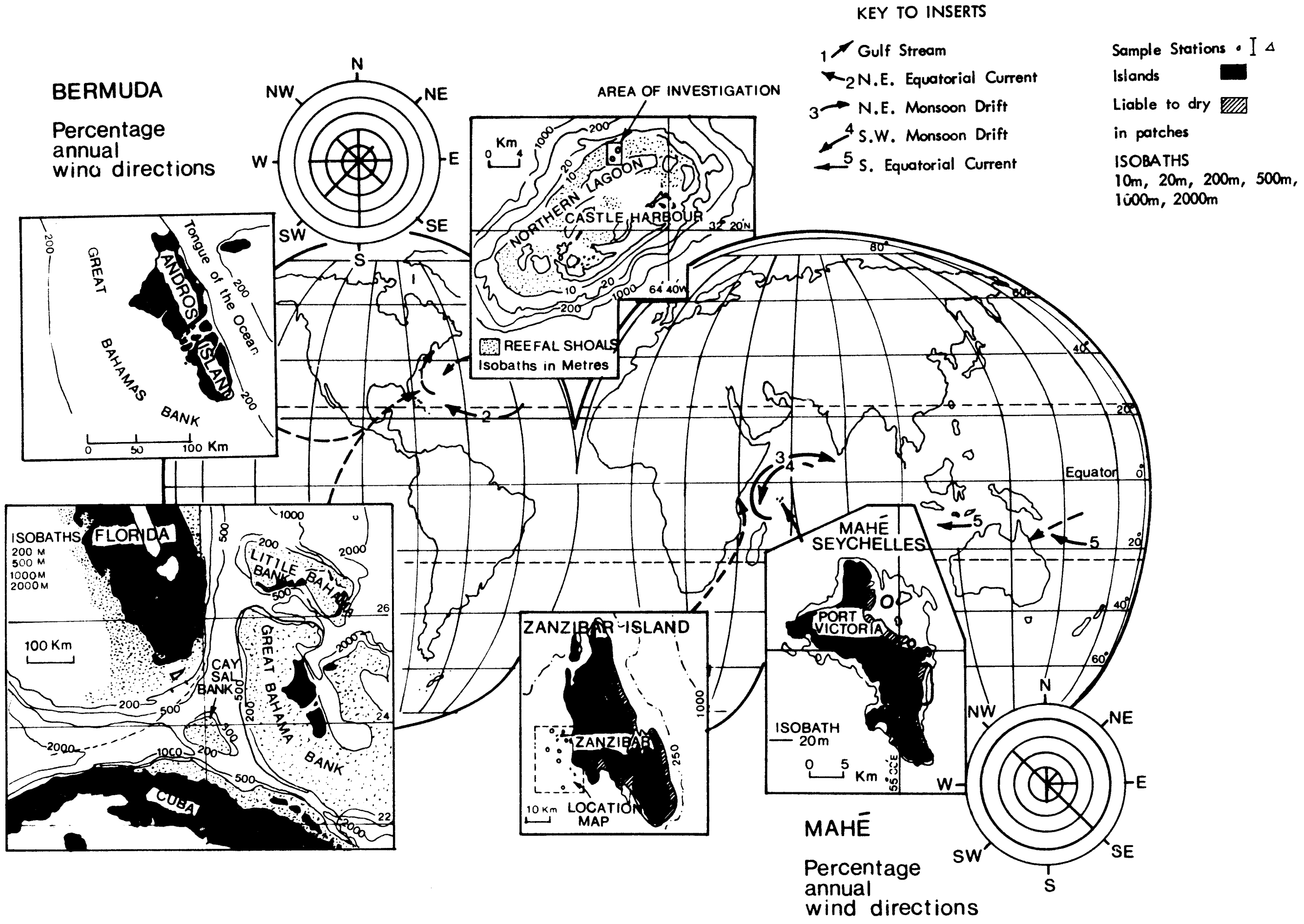
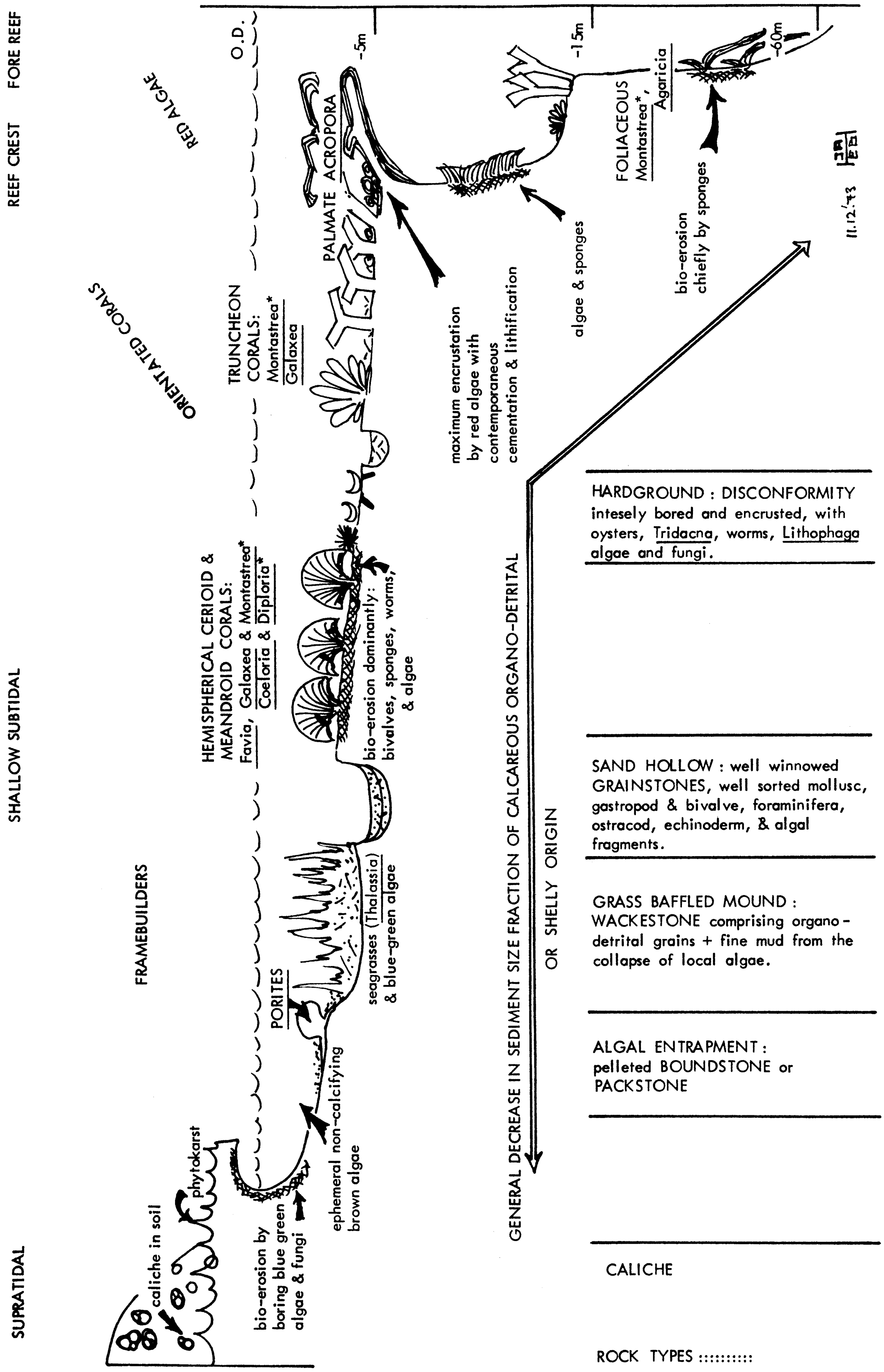
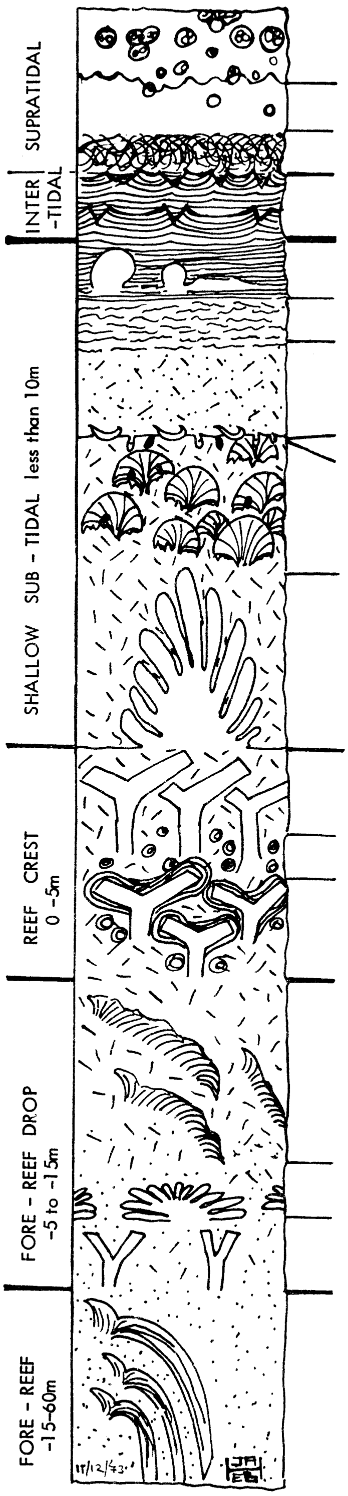


Text-fig. 3: Map of the World to highlight the distribution of the sedimentologically best known carbonate producing tropical reef systems in relation to their oceanographic settings (after Ginsburg, 1956; Lewis, 1969 and Garrett *et al*, 1971).



Text-fig. 4: Schematic section across an idealised reef to show frame-building organism – sediment relationships and their subsequent rock types based on Atlantic – Caribbean and Indian Ocean counterparts. Where these are paired the former are marked with asterisks.



Laterite, caliche or fossil soil.

Unconformity

Calichefield fossil karst - much altered limestone

Limestone ramified with small boring algal and fungal tubes relic from phytokarst

Pelleted fine grained sediments, mud-cracked in the supra-tidal - cracks or polygons increase in size towards the damper areas i.e. towards the sea, pools, or distributaries.

Porites heads and sheets in fine wackestone, the matrix is often pelleted resulting from reworking by herbivorous gastropods (Cerithium & Batillaria).
Algal bound pelleted packstone or boundstone.

Wackestone - bafflestone of algal-mollusc-foraminiferal-echinoderm frame fragments reworked from the contiguous seaward environment with an addition of locally derived fines giving a mud component.

Hardground, disconformity, encrusted with oysters and bored by Lithophaga et al.

HEMISPHERICAL CORAL HEADS characteristically cerioid or "honey comb" (Favia), meandroid or "brain-like" (Diploria*/Coeloria) in a Halimeda rich algal grainstone matrix with intraskeletal borings filled with locally derived mudstone.

TRUNCHEON type framebuilders with Halimeda algal grainstone matrix.

LOW ANGLE Y (PALMATE) GROWTH of Acropora in Halimeda grainstone

"Rhodolithic" or "Rhodolite" encrusting red algal fragments and indigenous Lithothamnion balls.

PALMATE ACROPORA CHARACTERISTICALLY COATED WITH ENCRUSTING RED ALGA (LITHOTHAMNION) distinguishing the area subject to sporadic desiccation when extreme low tides coincide with a lack of cloud protection.

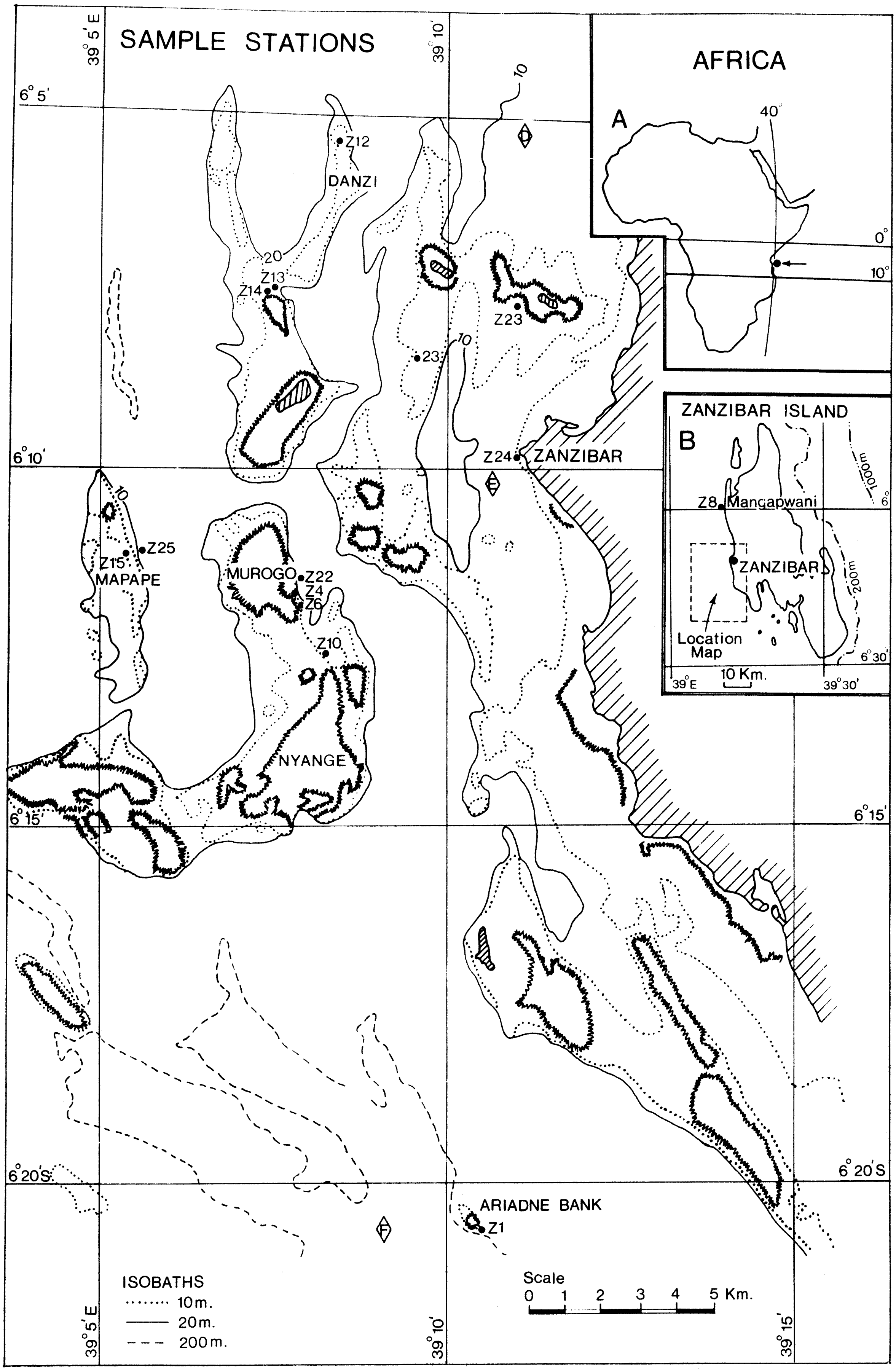
ASYMMETRICAL ENCRUSTING CORALS containing oblique geopetal fabrics filled with locally derived mudstone and set in a matrix of Halimeda grainstone.

SQUAT SCRUBBY TRUNCHEON MOUNDS of Montastrea*/Galaxea set in a grainstone matrix.

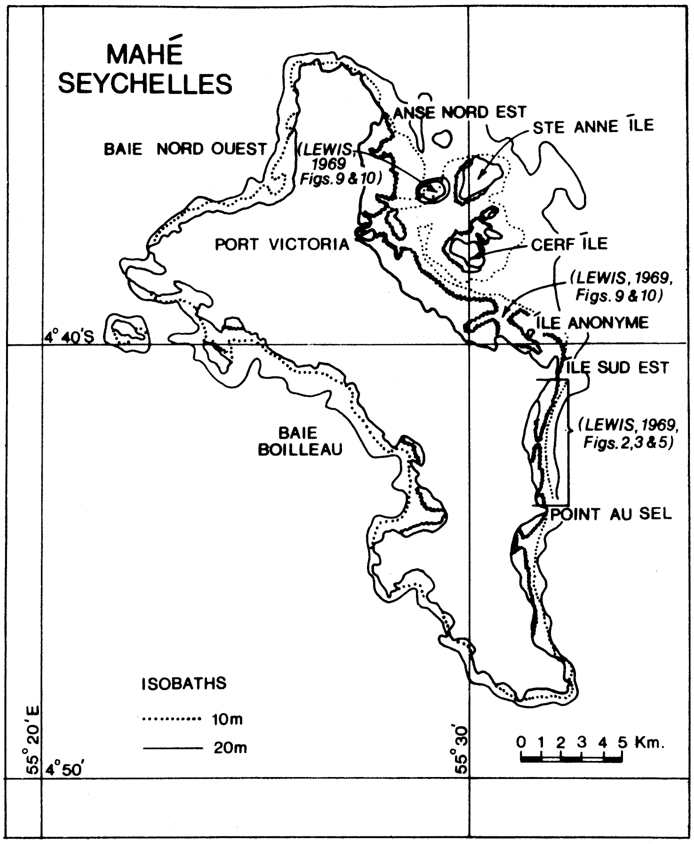
STEEP Y (PALMATE) GROWTH of Acropora set in a Halimeda grainstone matrix.

FOLIACEOUS GROWTH FORMS, heavily infested with sponges, and thereby extremely prone to collapse if subjected to the slightest currents; set in a wackestone or mudstone matrix.

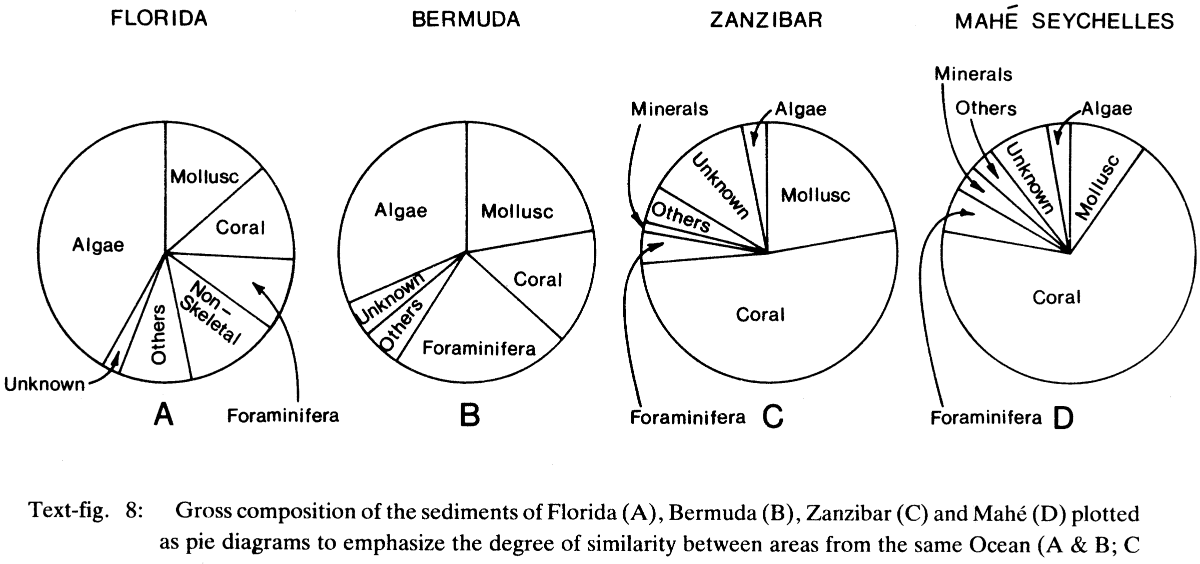
Text-fig. 5: Schematic section through a regressive cycle in a Recent – Pleistocene coral – algal reef based on the hypothetical profile outlined in text-fig 4. As in text-fig 4 where Atlantic – Caribbean and Indian Ocean coral counterparts are paired the former are denoted with asterisks. N.B. since preservation is dependent on the amount and intensity of contemporaneous bio-erosion and subsequent erosion and diagenesis, complete preservation is unlikely.



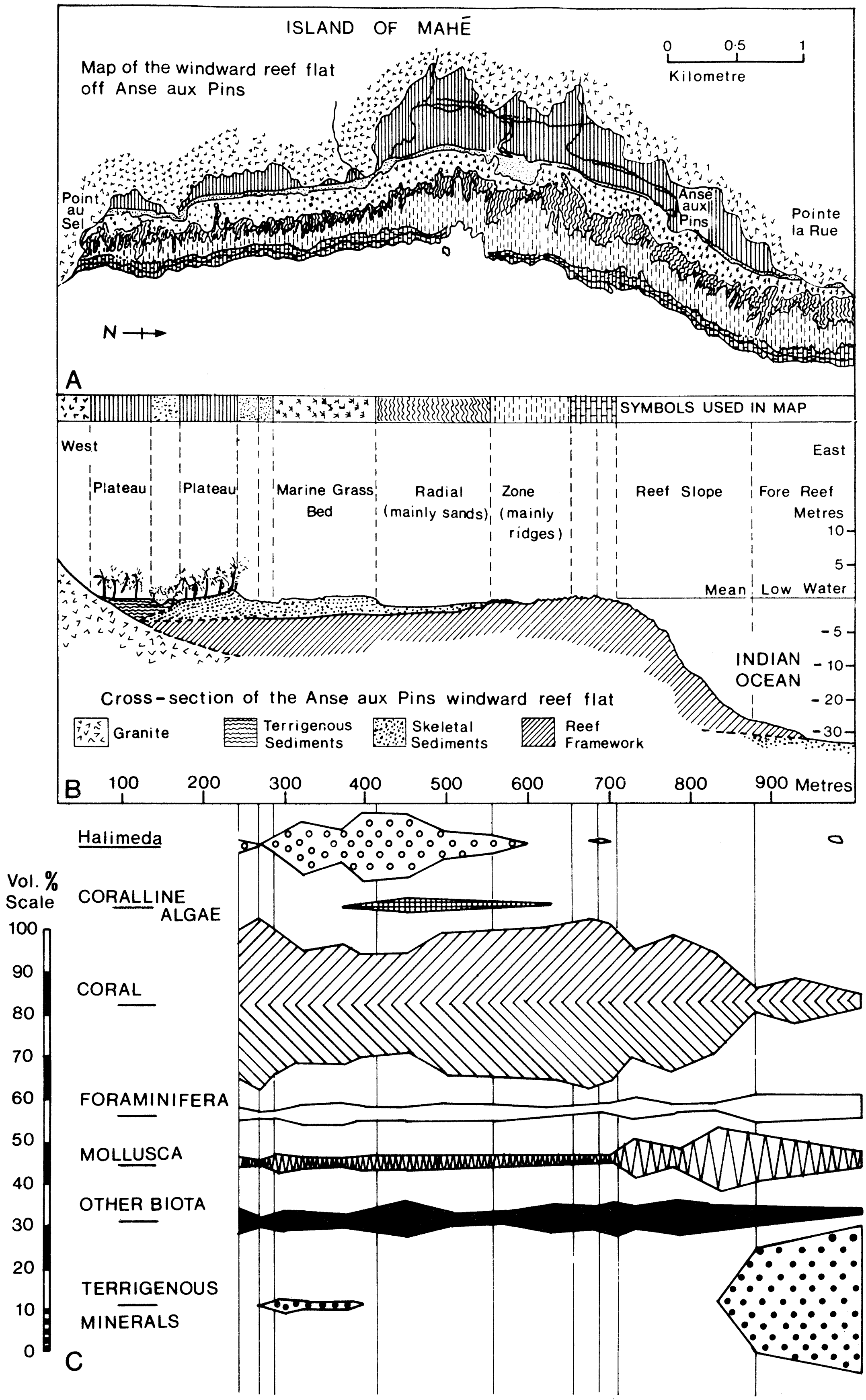
Text-fig. 6: Map of the regional setting of Zanzibar in relation to the African continent (A), and of the local sediment – sampling stations west of Zanzibar in relation to the shelter provided by Zanzibar Island in general (B).



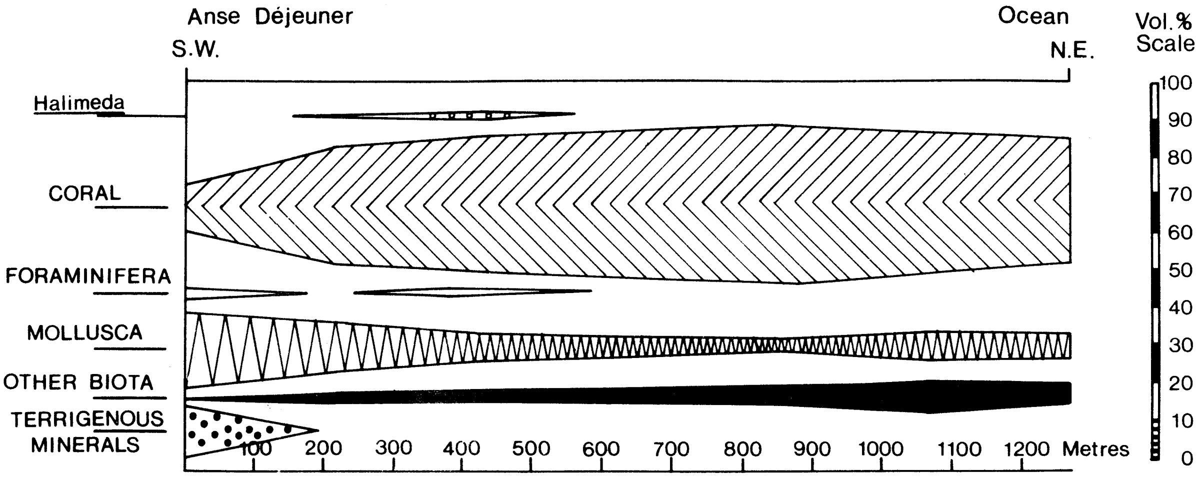
Text-fig. 7: Detailed map of Mahé, Seychelles, to show the variations in coastal configuration and localities from which Lewis (1969) took sediment samples. For half the year the Ísle Sud Est – Pointe au Sel coast is the windward side, while the Port Victoria – Ísle Ste Anne – Cerf – Annonyme area is sheltered throughout the year.



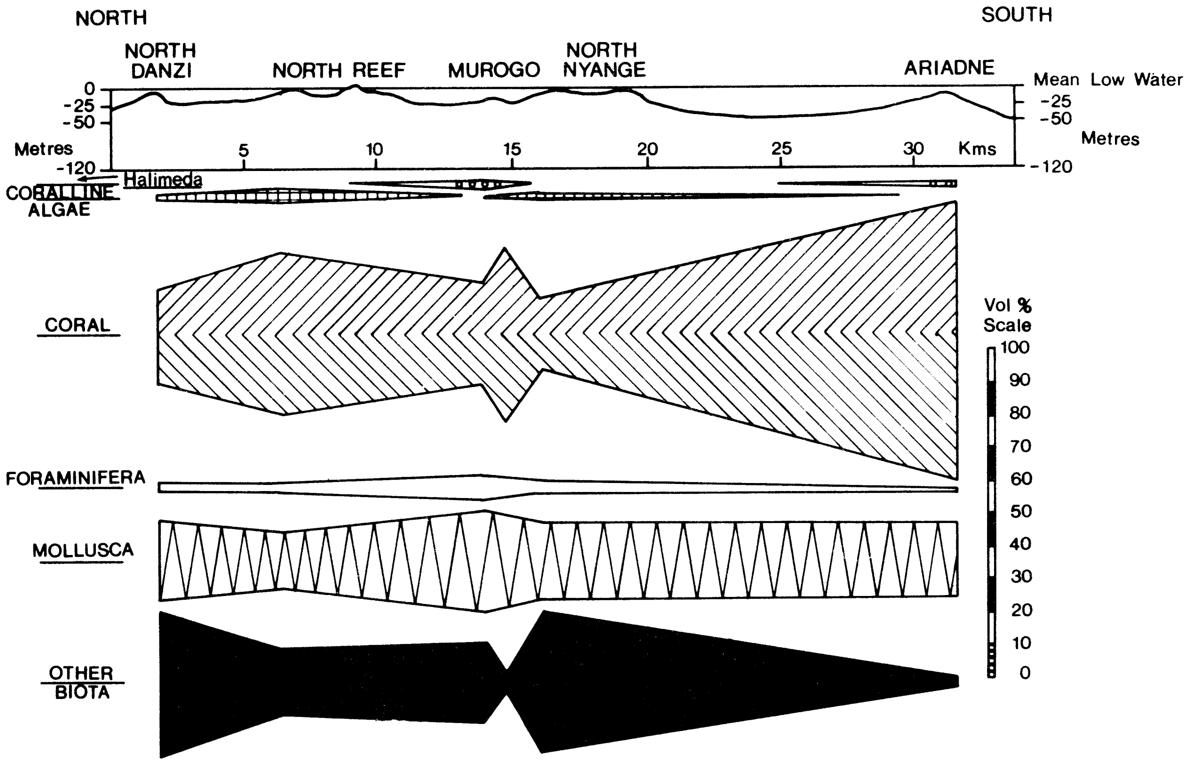
Text-fig. 8: Gross composition of the sediments of Florida (A), Bermuda (B), Zanzibar (C) and Mahé (D) plotted as pie diagrams to emphasize the degree of similarity between areas from the same Ocean (A & B; C & D) and dissimilarity between the Oceans (A & B versus C & D). Notably, whereas the epifaunal coral does not exceed 20% of either A or B it exceeds 50% in both C & D, while the epifloral algae have the reverse representation occupying more than 25% in both A & B and less than 10% in C & D.



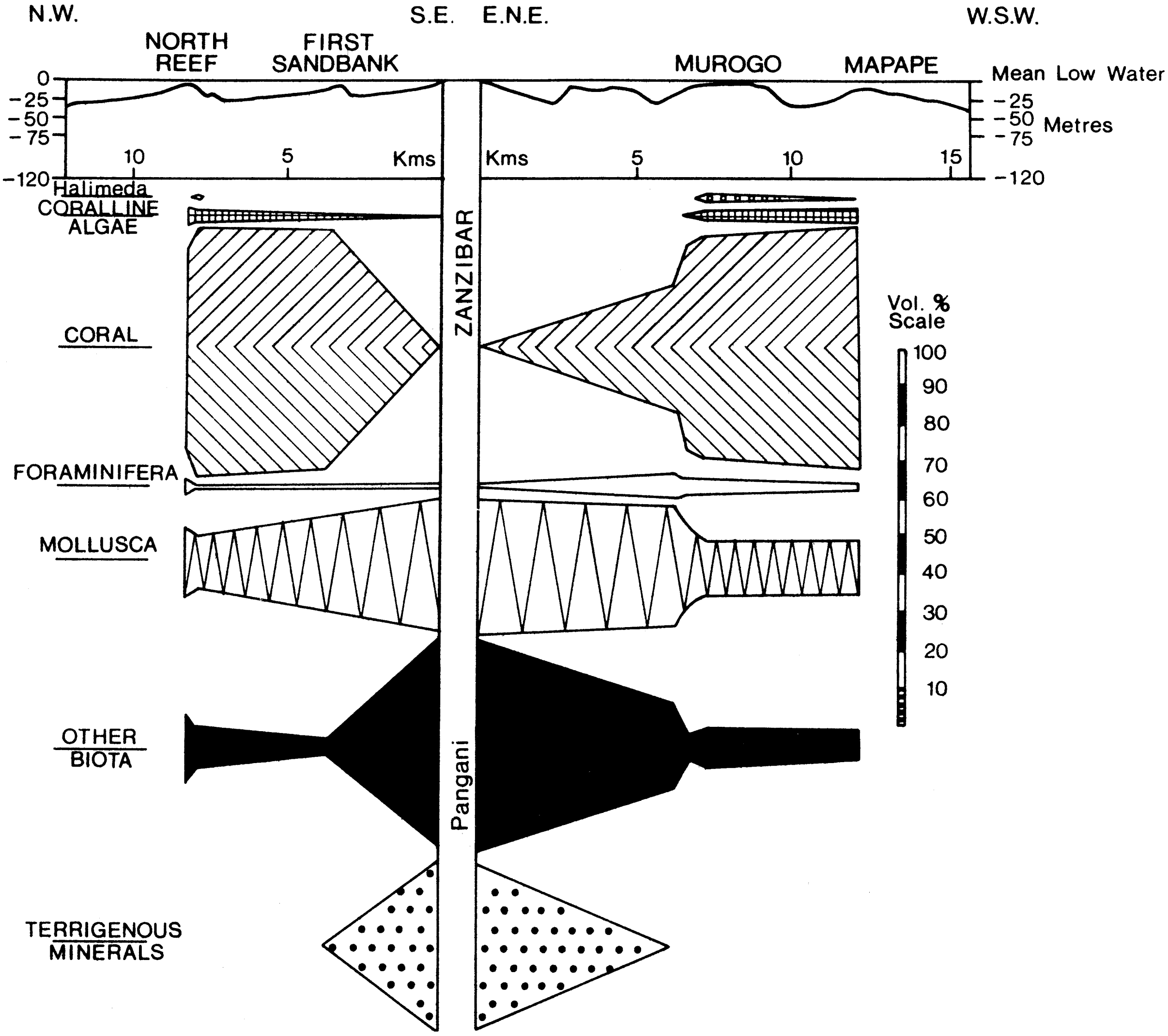
Text-fig. 9: The sediment distribution patterns of the windward reef flat of Anse aux Pins, S.E. Mahé, Seychelles (text-fig 7) are summarised in relation to (A) a map of the local setting, (B) a profile across the area, and (C) a graphical presentation of the variations in constituent composition of the sediment fraction larger thn 0.125mm in diameter across the profile (B). (A & B are after Lewis, 1969)



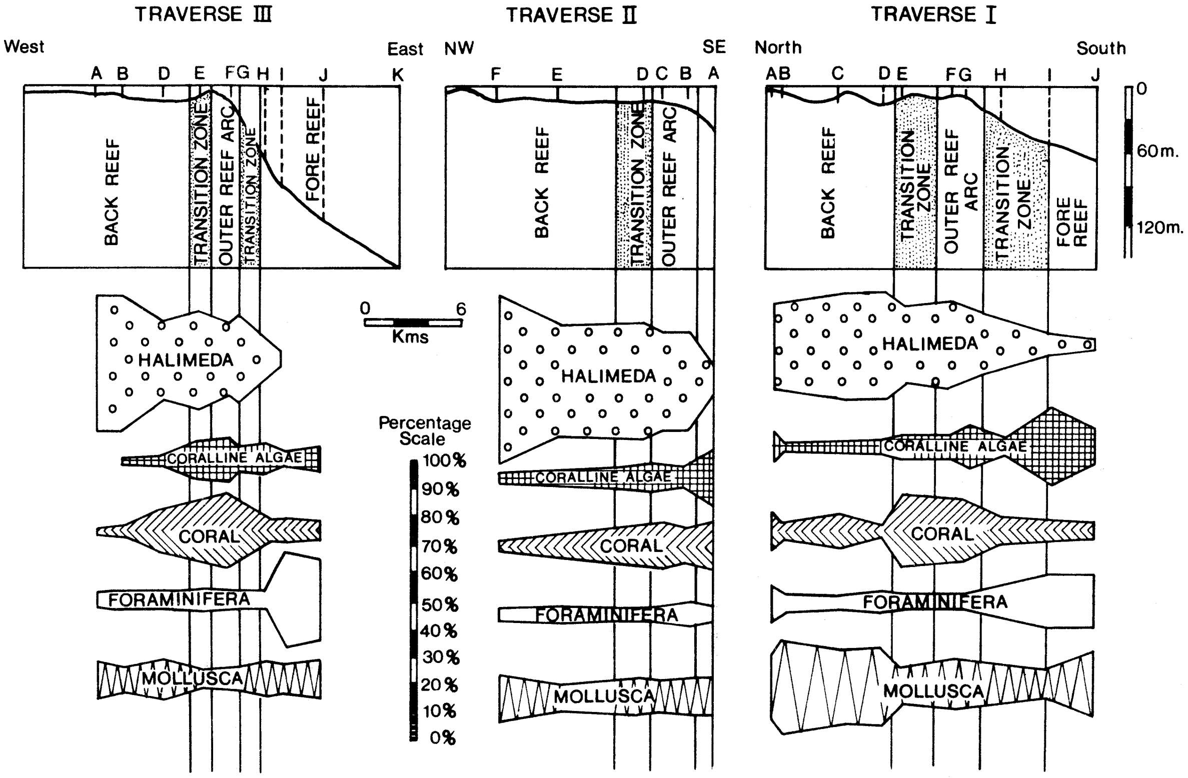
Text-fig. 10: Graphical representation of the sediment distribution patterns of the variations in constituent composition of the sediment fraction larger than 0.125mm across the sheltered reefs seawards of Anse Déjeuner, near Ísle Anonyme, E. Mahé, Seychelles (text-fig. 7).



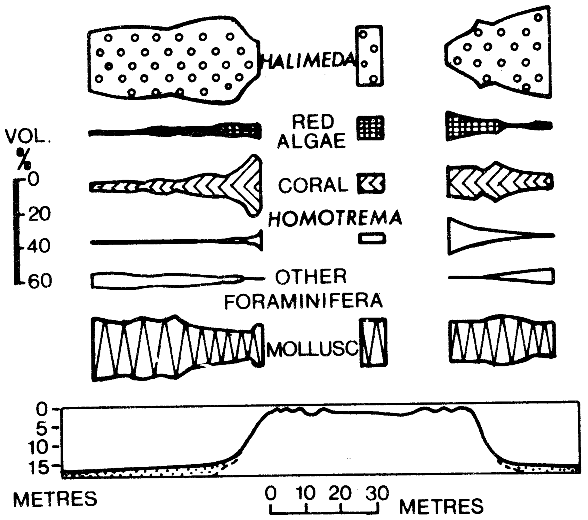
Text-fig. 11: The sediment distribution patterns of the more open circulating sheltered waters seawards of Zanzibar along a profile (A) from N. Danzi in the more restricted North to Ariadne in the more open circulating waters of the South (see text-fig. 6) to show variations in constituent composition of the sediment fraction larger than 0.25mm (B).



Text-fig. 12: The sediment distribution patterns of Zanzibar illustrating the effect of terrigenous in - put at Pangani (B) on the variation in constituent composition of the sediment fraction larger than 0.25mm approximately north west and west of Pangani (A) (text-fig. 6).



Text-fig. 13: A graphical presentation of three profiles across the Florida reef tract (A) to show the variation in constituent composition of the sediment fraction greater than 0.125mm (B) on the open shelf (see text-fig. 3). (After Ginsburg, 1956).



Text-fig. 14: A graphical presentation of the variation in constituent composition of the sediment fraction larger than 0.25mm across the comparatively sheltered Make - Do patch reef, N.W. Bermuda (see text-fig. 3). (After Garrett *et al*, 1971).

pre-existing limestones, the Seychelles, being mounted on a granite, has a considerable siliciclastic in-put. The Zanzibari sediments, by contrast, contain reworked Miocene millet seed dune quartz and heavy minerals from another source.

The range of variability in present day sediment distribution patterns in the Seychelles is well exemplified by Lewis (1969), here synthesised in text-figs. 9 & 10. The former is concerned with the windward profile, while the latter refers to the sheltered reefs. These are matched with comparable plots showing the influence of opening circulation (text-fig. 11), and of terrigenous in-put (text-fig. 12), on the more sheltered coral thickets of Zanzibar.They contrast with the distributions around windward Florida (text-fig. 13) and leeward Bermuda (text-fig. 14).

The influences of provinciality

The most obvious present - day expression of provinciality exhibited by the Indian Ocean as compared with Atlantic - Caribbean biotic distribution is to be found in the ratio of algae to corals. This is marked in the sediment analyses of the Indian Ocean localities, which are consistently higher in their coral component (see text-fig. 9,10,11 & 12), while the Atlantic - Caribbean province are equally consistently dominated by algae (see text-fig. 13 & 14). This Indian Ocean trend is found to extend both into the marginal conditions of Arabian Gulf (Purser, 1973) and into the open circulating system of the Pacific of the Australian Great Barrier Reef (Marshall, 1968). This is perhaps a little surprising when the geographical settings of the sampling areas are considered : the Atlantic - Caribbean and Zanzibari samples are all subtidal in origin, but much of the Seychelles profile lies in the intertidal. In terms of preservation potential there are profound implications in these distributions. The corals and many of the algae are aragonitic, they will be unstable in groundwaters and are liable to be dissolved; at best they are likely to occur as moulds. The coralline algae, by contrast, are calcitic and as such have a chance of detailed preservation.

In quantitative terms the provinciality of the sand-sized sediments discussed is well illustrated in text-fig. 15, while the effect of environment on these distribution patterns is emphasised in text-fig. 16, and their comparability with Australian data is highlighted in text-fig. 17. That there is a certain general consistency superimposed upon local variation can be detected in all these areas (Ginsburg, 1956; Garrett *et al*, 1971; Lewis, 1969; and Maxwell, 1968) including Zanzibar (text-fig. 18). That the Zanzibari sediments bear a very close relation to the thickets of corals which produced them is evident from the fact that they lie loose on a lithified Miocene dune substrate. Thus they are, like petals in a rose garden, closely identifiable in contrast to those of the majority of areas where present day corals grow on inherited Pleistocene reef limestones. On the whole there are more similarities within localities than between similar depth intervals at different localities; the differences here are set by initial settlement patterns.

That scleractinian coral settlement patterns would appear to be hierarchically organised is perhaps more apparent in the more limited populations of the Atlantic - Caribbean province than in the Indo - Pacific (see Hubbard, 1974). Certainly the model given in text-fig. 19, which is based on Atlantic - Caribbean distributions, requires modification in that the Indo - Pacific communities would appear to be dominated generally by foliaceous and branching rather than head forms with the result that the common patch reef outlined is less conspicuous, while complex thickets of shingling, leafy and arborescent growth abound. Thus the resultant geometry, on preservation, will be considerably more complex than the simplified model given in text-fig. 20 which is based upon the modification of a head coral. That such complexities in the variations in scleractinian coral distributions already exist in the pleistocene of East Africa are clearly evidenced by taxonomic and palaeoecological studies (Crame, 1980 & 1981).

The partiality of preservation

Preservation can be described in two forms *viz* real and apparent. The former concerns three dimensional structures in their entirety from general configuration to the intimate details of atomic lattice structure. The latter, by contrast, is a visual anomaly that results from the aberrations that planar sections through three dimensional forms can produce. Text-fig. 20 synthesises the first problem by reference to data obtained from a median section through one coral head in different circumstances. The point of origin in the ecosystem is totally integrated, but what can be inferred from it depends not only on its actual state of preservation, but also on the analysts' capacity for interpreting data perceived. At a glance it is evident that the mouldic form of preservation (text-fig. 20H) is difficult to interpret: in fact this is merely the mirror image of text-fig. 20F which is a montage of repetitions of the initial unit (text-fig. 20A) having undergone the sorts of preservation outlined in text-figs. 20E & 20G. Precisely how much detail will be discernible is dependent on how the specimen has been preserved (see Cullis, 1904). In an area where the unit has been buried in a coarse sand and then been subjected to vadose cementation a mould resembling text-fig. 20B may result. By contrast, if initially cemented at the reef crest and coated in red algae or embedded in clays and fine sediments, then a state more comparable to text-fig 20C might arise.

Text-fig. 21 summarises the second problem, that of having to work with optical illusions caused by random sections through imperfectly preserved materials. Text-fig. 21A represent a hemispherical cerioid or plocoid coral preserved in its entirety, while its bioeroded state is depicted in text-fig. 21B. Text-fig. 21D is a variant on the theme, it represents a fasciculate coral in its entirety as compared with its bioeroded counterpart (text-fig. 21E). As with variations in interpretation of the whole corallum, corallite geometry also appears different in various planes of section : true cross sections (text-figs.-21, A3.2, 21, B3.2, & 21, D3.2) appear to be circular, while oblique sections appear to be oblong (Text-figs 21, A2.2, 21, B2.2, and 21,D2.2). More misleading still is the fact that different planes of section through the corallum can result in misinterpretations of the size of the coralla concerned: marginal sections (text-figs. 21, A4, 21, B4.1, & 21, D2.1) appear to be smaller than their median counterparts (text-figs. 21, A1, 21, B1, & 21, D1). Thus random sections through a collection of coralla and their associated matrices can lead to a variety of interpretations on their palaeoecology and distribution patterns. Similarly the planes of sections through either a deeply bioeroded hemisphere or an initially mushroom-shaped corallum can be equally misleading (see text-figs. 21, B42.1 to 21, B4.6). As if these problems alone were not enough to contend with, there remains a further variable, that is the state of preservation of the component parts, here illustrated by reference a section of the theca and three septa (text-fig. 21,C). Text-fig. 21, C1 shows the skeleton in its entirety, text-fig. 21, C1.1 show the affects of dissolution and precipitation on the same skeletal elements, while text-fig. 21,C1.2 shows its weakening by infestation by endolithic algae and fungi, its preservation by coralline algal encrustation (text-fig. 21, C1.3) and its disintegration by boring sponges (text-fig. 21, C1.4).

So far, in considering 'apparent' variables we have concerned ourselves with phenomena that can readily be checked by using careful measurements of the three dimensional geometrical inter-relationships of the corallites to coralla and of the corallites' details to endoliths, epiliths, cements and sediment-matrices. This means firstly, recording the angles of divergence of internal and external features in order to reconstruct the coralla; then, secondly, relating these data to the sedimentological interpretation of their histories of accumulation and subsequent diagenesis. The models illustrated in text-figs. 20 & 21 are comparatively simple. Supposing the corals are scleractinians they would originally comprise aragonitic skeletons, which in life may record subtle chemical variations (see Swart & Coleman, 1980), but they have little hope of recording the majority of such details on fossilisation: most of the corallum is likely to be dissolved and replaced by low-Mg calcite, only by lit-par-lit cementation can the details be recorded in the associated endoliths and epiliths. The calcitic encrusting algae and bryozoa stand a good chance of detailed preservation and a stable geochemical trace. But, though some secrete calcareous tubes, many of the worms by contrast, are only liable to leave their siliceous cetae and jaw apparatuses in the associated sediments; like the zooxanthellae, on which so much of the corals' metabolism depends, being both loose and tiny they are liable to get washed leewards and landwards of their sites of origin. Whether the boring and encrusting bivalve molluscs are preserved in detail, in part, or as moulds, would depend on whether their skeletons are composed of calcite, mixed calcite and aragonite or solely aragonite respectively. Similarly, precisely how much of the integrity of the voids is recorded would depend on their histories of coelobitic encrustation, internal sedimentation and cementation. In the Pleistocene reef facies of East Africa mouldic preservation of endoliths and coralline algae is common (see Hubbard & Swart, 1982).

Turning to the preservation of corals (text-fig. 21, C1, C1.1, C1.2, C1.3, & C1.4) it is possible to predict the areas in which these styles most commonly occur. Specimens with advanced dissolution and syntaxial precipitation (text-fig. 21, C1.1) are most likely to have experienced an history of burial including a phase in the splash zone of the supratidal area; while specimens which are riddled with bacteria and endolithic algae and fungi (text-fig. 21, C1.2) are best developed in the intertidal zone, though also known from the subtidal. Those corals most heavily encrusted with coralline algae commonly occur on the reef crest and in areas of high energy exposed at low tide (text-fig. 21, C1.3). Those with endolithic sponges beneath the coralline algae (text-fig. 21, C1.3) frequently occur seawards of the reef crest, but are not unknown landwards of it too. The same phenomena affect coral clasts and as such can be used as indicators of coastal proximity (Hubbard, 1976; Hubbard & Swart, 1982). The most heterogeneous facies represented is the storm ridge which accumulates the products of a succession of drastic events. Migrating just seaward of this and slightly more homogeneous are the clasts of the strand line shingle. While the highly infested algal - fungal - bored assemblage represents much of the intertidal storm debris; the coralline algal encrusted debris is largely derived from near the reef crest and analogous high energy which are subject to sporadic

continued on page 20

AVERAGE GRAIN SIZE AND CONSTITUENT COMPOSITION OF REEF-TRACT SEDIMENTS FROM FLORIDA, BAHAMAS, BERMUDA, ZANZIBAR AND SEYCHELLES.

	FLORIDA REEF TRACT (GINSBURG, 1956) (25 SAMPLES)	BAHAMAS		BERMUDA PATCH REEF (GARRETT et al, 1971) (TABLE 3) (3 SAMPLES)	ZANZIBAR REEF THIS PAPER (13 SAMPLES)	SEYCHELLES (LEWIS, 1969) (FIGS. 10 & 12) (60 SAMPLES)
		REEF TRACT (FIG. 11) THORP (1936) (10 SAMPLES)	MARGINAL SHELF EASTERN BAHAMAS ILLING (1954, p.17) (5 SAMPLES)			
GRAIN SIZE WEIGHT PERCENTAGE LESS THAN $\frac{1}{16}$ mm.	9	4	0		8	6
CONSTITUENT COMPOSITION						
ALGAE	42	30	39	35	4	4+
MOLLUSC	14	15	18	25	22	10
CORAL	12	12	12	13	51	68*
FORAMINIFERA	9	26	13	16	4	5
NON-SKELETAL	12	9	14	-	-	3
MISCELLANEOUS	9	8	4	5	7	6
UNKNOWN	8	-	0	6	12	4

Text-fig. 15: Tabular summary of the average grain size composition of the reef tract sediments from Florida, Bahamas, Bermuda, Zanzibar and Seychelles showing distinct oceanic provinciality. * Category includes reef building organisms, corals and algae. + Category includes both the free standing red alga *Amphiroa* and the free standing green alga *Halimeda*.

REGION	FLORIDA (GINSBURG, 1956)		BAHAMAS (THORP, 1936)		BERMUDA (GARRETT et al 1971) (TAB. 3)	ZANZIBAR (THIS PAPER)		SEYCHELLES (LEWIS, 1969) (FIG. 5)						(FIG 10)	(FIG. 2)
SITES	FLORIDA BAY (17 SAMPLES)	REEF TRACT (25 SAMPLES)	WEST SIDE ANDROS IS. (FIG. 10)	REEF TRACT ANDROS IS. (FIG. 10)	PATCH REEF ((3 SAMPLES)	TOWN * (1 SAMPLE)	REEF (13 SAMPLE)	BEACH (5 SAMPLES)	RIPPLED SANDS (1 SAMPLE)	GRASS BED (10 SAMPLES)	RADIAL ZONE (21 SAMPLES)	ALGAL RIDGE (4 SAMPLES)	REEF EDGE (3 SAMPLES)	SHELTER REEF (6 SAMPLES)	WINDWARD FORE-REEF (10 SAMPLES)
GRAIN SIZE WEIGHT PERCENTAGE LESS THAN $\frac{1}{8}$ mm.	49	17	68	4		11	8								
CONSTITUENT COMPOSITION															
ALGAE	$\frac{1}{2}$	42	5	30	35	-	4	1+	$\frac{1}{2}$+	13+	8+	3+	$\frac{1}{2}$+	1+	-
MOLLUSC	76	14	14	15	25	36	22	4	1	6	4	4	3	18	16
CORAL	0	12	0	12	13	-	51	78*	80*	67*	67*	79*	76*	67*	46
FORAMINIFERA	11	9	23	26	16	1	4	3	2	4	4	4	5	1	10
NON-SKELETAL	3^4	12	48^5	9	-	-	-	-	-	-	-	-	-	5	5
MISCELLANEOUS	$\frac{1}{2}$	9	10	8	5	16	7	3	$1\frac{1}{2}$	5	6	10		7	9
UNKNOWN	1	8	-	-	6	1	12	$11\frac{1}{2}$x	15x	3x	3x	3x	1x	1	-
OSTRACODS	2	-	-6	-6	-	-	-	-	-	-	-	-	13	-	-
QUARTZ	6	-	-	-	-	44	1	-	-	-	-	-	-	5	14

Text-fig. 16: Tabular summary of the comparison of grain size and constituents of the sediments from Florida, Bahamas, Zanzibar and Seychelles showing the influence of environmental setting on quantitative in - put. * Category includes reef building organisms, corals and algae. + Category includes both the free standing red alga *Amphiroa* and the free standing green alga *Halimeda*.

AVERAGE GRAIN SIZE AND CONSTITUENT COMPOSITION OF SEDIMENTS FROM FLORIDA BAY AND REEF TRACT, BERMUDA PATCH REEFS, ZANZIBAR THICKETS, SEYCHELLES AND AUSTRALIAN GREAT BARRIER REEF

	FLORIDA BAY (17 SAMPLES¹)		REEF TRACT (25 SAMPLES)		BERMUDA PATCH REEFS (GARRETT 1971) (23 SAMPLES ?)		ZANZIBAR THIS PAPER (13 SAMPLES)		SEYCHELLES (LEWIS 1969) (60 SAMPLES)		GREAT BARRIER REEF AUSTRALIA (MAXWELL 1968)	
	Average %	Range %	Average %	Range %	Average %	Range %	Average %	Range %	Average %	Range %	Range %	
GRAIN SIZE WEIGHT PERCENTAGE LESS THAN mm. <+3φ	49	10-85	17	0-68			8	0-33	6	0-12	Reef	Inter Reef
CONSTITUENT COMPOSITION OF FRACTION GREATER THAN mm. <+3φ												
ALGAE	½	0-1	42	7-61	35	28-47	4	1-8	4+	0-34	27-70	5-80
MOLLUSC	76	58-95	14	4-33	25	23-27	22	15-34	10	0-39	4-15	20-35
CORAL	-	-	12	2-26	13	9-17	51	25-76	67 *	11-86	20-40	5-10
FORAMINIFERA	11	1-32	9	3-32	16	2-23	4	0-8	5	0-17	8-20	15-40
NON-SKELETAL	3	0-3	12	3-24	-	-	-	-	-	-	-	-
MISCELLANEOUS	½	0-4	9	2-23	5	5-6	7	0-38	7	1-20	0-5	5-30
UNKNOWN	1	0-3	8	4-15	6	5-7	12	-	4	-	-	-
OSTRACODS	2	1-6	-	-	-	-	-	-	-	0-2	-	-
QUARTZ	6	0-20	-	-	-	-	1	0-1	3	0-63	-	-

1 Only surface scoop samples and the upper parts of cores are included in this average

* Catergory includes reef building organisms, corals and algae

\+ Amphiroa and Halimeda

Text-fig. 17: Tabular summary of the average grain size and constituent composition of sediments from Florida, Bahamas, Zanzibar and Seychelles compared with those of the Australian Great Barrier Reef. *Category includes reef building organisms, corals and algae. + Category includes both the free standing red alga *Amphiroa* and the free standing green alga *Halimeda*.

CONSTITUENT PARTICLE COMPOSITIONS % GREATER THAN ¼mm.	SAMPLE NUMBER LOCATION AND DEPTH	GRAVE ISLAND Z23-8'	FIRST SANDBANK Z3-20'	MUROGO LAGOON Z6-5'	MUROGO LAGOON Z4-30'	MUROGO LAGOON Z22-66'	MAPAPE Z15-15'	MAPAPE Z25-75'	N. NYANGE Z10-20'	NORTH DANZI Z12-20'	MANGAPWANI Z8-4'	NORTH REEF Z14-6'	NORTH REEF Z13-40'	ARIADNE Z1-40'	LABORATORY FILTER Z24-12'
ALGAE	*Halimeda*	-	-	4	-	-	-	3	-	-	-	-	-	2	-
	CORALLINE ALGA	8	2	3	1	-	7	1	1	2	1	7	4		-
MOLLUSCA	GASTROPOD	10	4	5	6	5	4	6	10	5	6	3	5	-	11
	BIVALVE	20	19	10	20	26	10	29	16	21	11	15	10	16	25
CORALS SCLERACTINIA	*Scriatopora*	4	1	10	7	3	15	1	4	4	-	5	4	18	-
	Acropora	36	16	6	33	23	39	25	18	15	3	42	55		-
	FAVIID	7	12	10	16	7	10	5	2	5	14	3	9	44	-
	Galaxea	1	-	1	-	1	1	-	-	-	-	-	1		-
	Coeloria	-	-	-	-	-	-	-	-	-	-	1	-		-
	Porites	1	37	32	-	-	1	-	-	4	31	-	-	13	-
OCTOCORALIA	*Tubipora*	-	-	1	-	-	-	-	-	-	-	-	-	4	-
	Heliopora	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	OCTOCORAL	-	-	-	-	-	-	-	-	-	-	-	-	2	-
	GORGONIAN	-	-	1	-	-	-	-	-	1	-	-	-	-	-
	FORAMINIFERA	-	1	5	5	8	1	10	7	3	6	3	1	-	1
	ECHINOID	-	1	3	2	1	2	3	1	2	5	3	2	-	-
	VERTEBRATE	-	-	-	-	-	-	-	-	-	-	1	-	-	-
ARTHROPODA	CRUSTACEAN	8	-	1	1	-	2	2	-	1	6	6	4	-	-
	OSTRACOD	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	CIRRIPEDE	-	-	-	-	-	-	-	-	-	1	-	-	-	15
	SPONGE	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	BRYOZOAN	-	-	-	-	-	-	2	3	-	2	1	-	-	-
	WORM	2	2	-	2	1	1	-	-	1	-	-	-	-	1
	BIOCLAST	-	3	5	6	23	4	10	37	38	11	9	5	-	1
	QUARTZ	-	-	-	-	-	2	3	-	-	-	-	-	-	38
	GREEN MINERAL	-	-	-	-	-	-	-	-	-	-	-	-	-	1
	BLACK MINERAL	-	-	-	-	-	-	-	-	-	-	-	-	-	3
	ORANGE MINERAL	-	-	-	-	-	-	-	-	-	-	-	-	-	2
	Md φ	1.95	0.80	-0.20	1.28	1.58	0.95	1.75	1.15	0.60	1.95	1.25	1.00	0.20	1.10
	Qd φ	0.05	0.75	-0.10	1.07	0.90	0.10	0.30	0.20	0.25	0.57	0.08	0.92	0.30	0.45

Text-fig. 18: Tabular summary of the average composition of the sediments greater than 0.25mm expressed as percentages for individual localities and depths west of Zanzibar (see text-fig. 6).

Key to scleractinian taxa:

Sub-order ASTROCOENINA

Family ACROPORIDAE

1. *Acropora cervicornis*

Family AGARICIDAE

2. *Agaricia agaricites*

Family SIDERASTREIDAE

3. *Siderastrea siderea*

Family PORITIDAE

4. *Porites astraeoides*
5. *Porites divaricata*
6. *Porites furcata*

Family FAVIIDAE

7. *Diploria labyrinthiformis*
8. *Diploria clivosa*
9. *Manicena areolata*
10. *Cladocora arbuscula*
11. *Solenastrea hyades*
12. *Montastrea annularis*
13. *Montastrea cavernosa*

Family OCULINIDAE

14. *Oculina diffusa*

Family TROCHOSMILIIDAE

15. *Dichocoenia stokesi*

Family MUSSIDAE

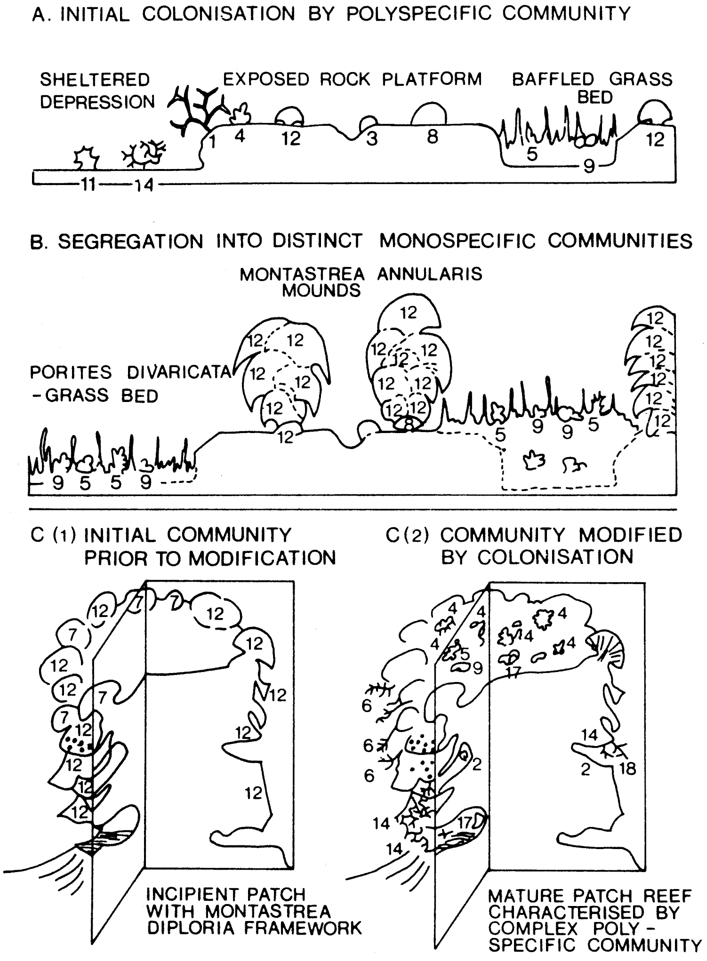
16. *Mycetophyllia lamarkiana*
17. *Isophyllia sinuosa*

Sub-order CARYOPHYLLINA

Family CARYOPHYLLIDAE

18. *Eusmilia fastigiata*

(After Hubbard, 1974, Proc. IV Intnat. Coral Reef Symp.)

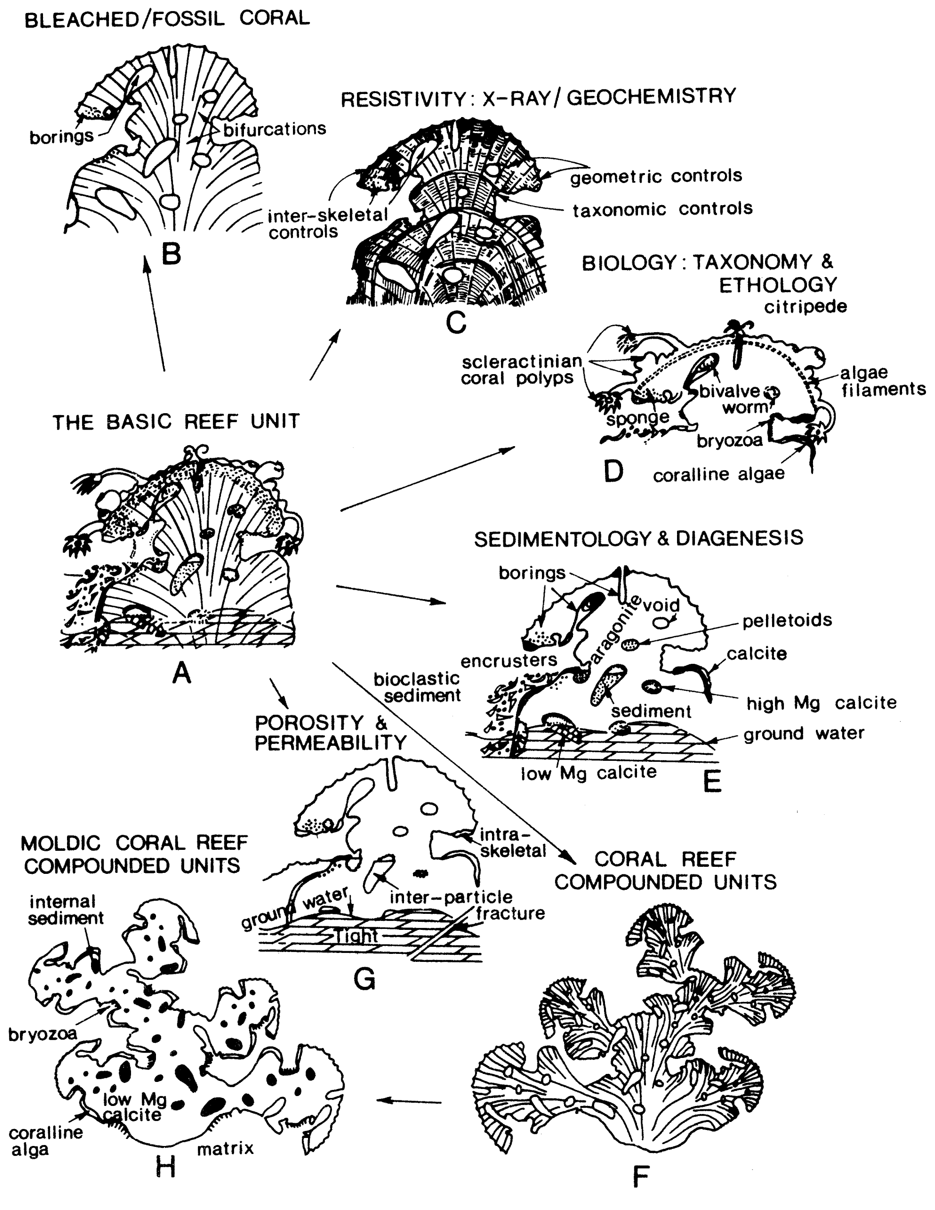


Text-fig. 19: Graphically summarises the relationship between scleractinian coral settlement pattern and community evolution in the Caribbean - Atlantic Province.

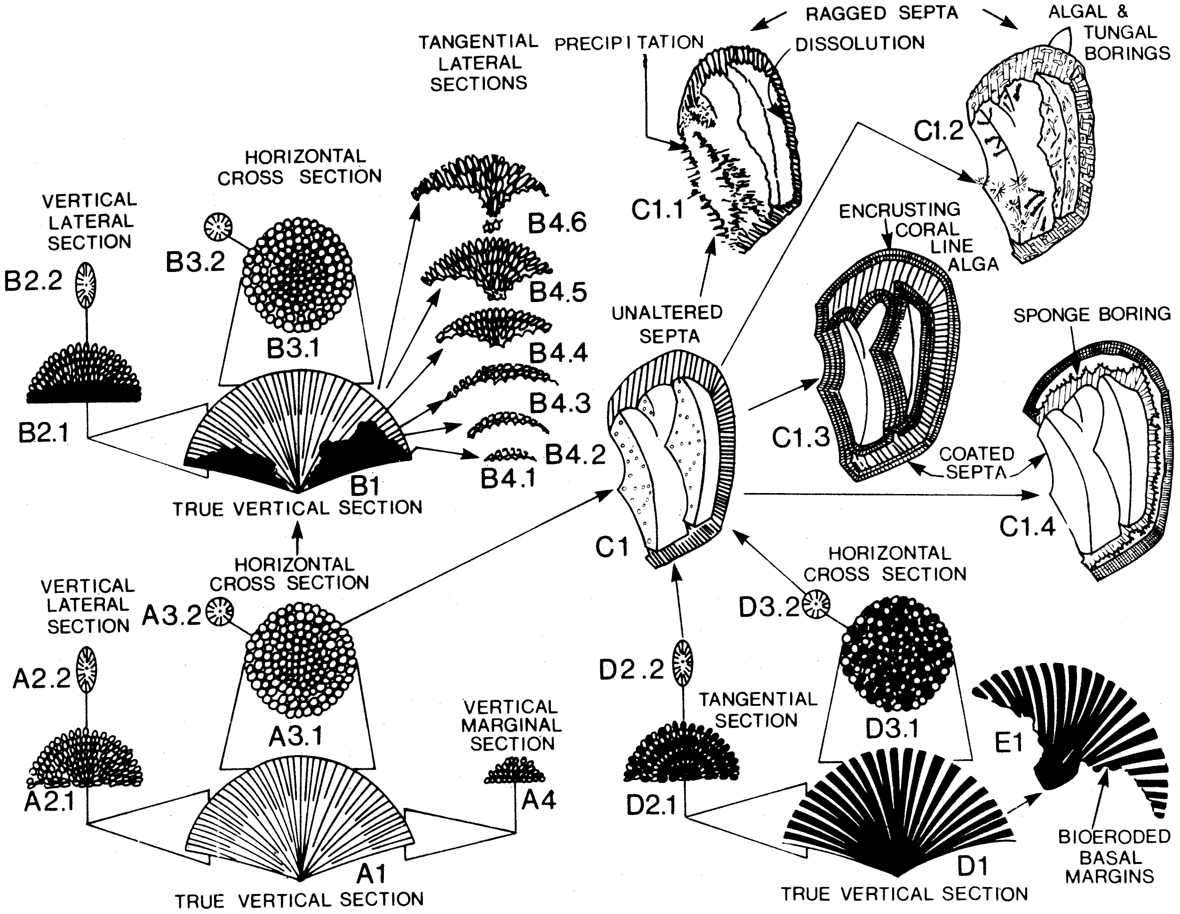
A shows that the original colonisation pattern can be divided into three polyspecific communities representing exposed rock platforms, sheltered depressions and baffled grass beds.

B shows secondary segregation into distinct or monospecific communities dominated by grass bed communities as opposed to open circulating mounds.

C, by contrast, shows the complexity of patch reef development from B by initially segregated settlement in C(1) to complete community modified by subsequent colonisation and niche exploitation in C (2). (After Hubbard, 1974).



Text-fig. 20: This is a graphical summary of the history of preservation of an individual coral head (A) and its associated endoliths and epibionts (D) sediment and cements (E) and their interpretation from bleached or fossil material (B), from X-ray resistivity patterns or geochemical analyses (C) and from the industrialists' porosity-orientated view-point (G). F resembles reef material in that it is made up of a composite of modules of B, while H shows a mirror image replica of F on its preservation in a largely Low-Mg calcite mouldic state after the solution of its originally aragonitic components on its burial in the vadose or phreatic zones.



Text-fig. 21: A flow diagram of the types of optical illusion that random sections through coral heads can cause from the same parent stock. A1 true vertical median section through a hemispherical plocoid or cerioid colony; A2.1 lateral vertical section through the same colony appearing to be smaller than A1; A2.2 cross section of an individual corallite in a quasilongitudinal plane appears to be oblong in contrast to the circular outline seen in true cross section A3.2); A3.1 marginal horizontal section mainly cutting across corallite axes at right angles (A3.2). B1 true vertical median section through a similar corallum to A1 which has been affected by extensive bio-erosion of the undersurface as indicated by the blackened area in B1 and B2.1. B2.1 gives a first impression of being more foliaceous in form than A2.1; while B3.1 shows no sign of difference from A3.1; but tangential sections from the marginal B4.1 to the near median plane (B4.6) show apparently different forms ranging from foliaceous concavo-convex sheets at the margin to pronounced mushroom shape (B4.5) and isolated coral pairs (B4.6) near the middle of the hemisphere, in contrast to the plano-convex sections of A2.1 and A4. D1 represents a true median vertical section through a hemispherical fasciculate form with its analogous lateral (D2.1) and horizontal sections (D3.1) and its bio-eroded counterpart (E1); the blackened areas represent the intercorallite voids. Just as corallite shape appears to vary in geometry according to plane of section as shown by the true cross sections A3.2, B3.2, and D3.2 as opposed to A2.2, B2.2 and D3.2, so too can corallite morphology and septal detail vary according to their state of preservation. C1 represents an unaltered slice of theca with two major and one minor septum and their original surface ornament; the same structures are depicted in shaggy outlines after syntaxial cementation and after preferential dissolution in C1.1; after endolithic algal and fungal boring and bacterial infestation in C1.2; after preservation by red algal encrustation in C1.3; and after partial mouldic formation by the combination of red algal external coating and marginal sponge - mining in C1.4.

desiccation. The sponge-bored red algal encrusted material is slightly more difficult to locate precisely, but it is most likely to have migrated landward from the deeper parts near the reef crest, or seaward down shutes.

So much for the preservation potential of the hermatypic corallum and its associates; they are important on the surface of the living reef, perhaps comprising 25 - 30% of the surface area, whereas void space or cavities occupy another 40 - 60% spatially, and algae appropriate the remaining 30% or, sometimes, much more. But there is a multitude of other actors on the reef scene and they too, can be argued to follow analogous preservational pathways, their degrees of preservation being directly related to their original chemical compositions and habitats within the ecosystem. The sedentary benthos may stay in place if buried, but the vagrant benthos, mobile infauna and nektonic let alone planktonic creatures and plants are liable to be drifted leewards, which is usually landwards, by the prevailing and storm currents.

Let us now consider the implied in-put of sediment particles which fill so much space in the present day reef. Text-fig. 22 outlines the variability of bulk sediment composition amongst Bermuda, Seychelles & Zanzibar reefs. It not only highlights the compositional aspects, but also the fact that the sizing of clasts varies between locations. In the Atlantic – Caribbean it is common to think of the scleractinian corals dominating the finer sand grades (Ginsburg *et al*, 1956 & Garrett *et al*, 1972), but this bias does not appear in the Indian Ocean locations cited here. What is uniformly significant is the fact that there is so much aragonitic material available for dissolution on burial in the vadose zone. Hence the geological record is bound to be compositionally patchy, geometrically holey and geochemically as well as mechanically condensed.

If we consider the sediments in analysing micro-ecosystems it is evident that there is much variation in both bulk terms (text-figs, 9, 10, 11, 12, 13, 14, 15, 16, 17) and in details (text-figs 18, 22, 23 & 25). Text-fig. 24 graphically outlines the succession of contents of a nest of sieves through which one 250 cc sample of sediment has been passed. It clearly demonstrates that the foraminifera, gastropods and micro-bivalves have several distributional peaks; these indicate both in-put of different sized taxa and the fact that non-spherical particles fall through square grids in an irregular manner. But, whereas the former concept is well known to biologists, and is recorded in passing by Garret *et al.* (1971) this aspect is often over looked by sedimentologists who are concerned with the latter fact. That this distribution pattern, taken from –10.2 m at Ariadne (see text-fig 6) is not a standard for all areas and all depths can be seen from comparing a like sample from –1.524 m at Murogo (text-figs 25--). The shallower of the samples contains herbivorous echinoid and algal matter, as well as ostracods in addition. The sands thus represent a mixture of dead bioclastic fragments, and live interstitial and surface biotas.

SIZE		2.0 - 4.0 mm			1.0-2.0 mm.			0.5-1.0 mm.			0.25-0.5 mm.		
CONSTITUENT PARTICLE COMPOSITION / LOCATION		ZANZIBAR This paper (13 Samples)	SEYCHELLES (Lewis, 1969, Fig. 9, 6 Samples)	BERMUDA (Garrett et al, 1971, Tab 3)	ZANZIBAR	SEYCHELLES	BERMUDA	ZANZIBAR	SEYCHELLES	BERMUDA	ZANZIBAR	SEYCHELLES	BERMUDA
ALGAE	Halimeda	1	-	5	-	-	14	1	1	15	1	4	8
	CORALLINE	7	-	12	3	-	19	2	-	14	4	-	16
MOLLUSCA		42	33	23	23	23	22	21	16	26	22	11	15
SCLERACTINIAN CORAL		36	59	5	59	65	11	63	64	14	44	71	44
FORAMINIFERA		-	-	38	-	1	25	4	-	18	7	1	1
UNKNOWN		6	-	10	9	-	5	1	-	4	16	-	10
OTHERS		9	35	7	6	11	4	8	-	9	6	13	6

Text-fig. 22: Grain size percentage constituent particles in reef-top sediment samples from the Zanzibar, Seychelles and Bermuda islands highlighting both compositional and sizing differences amongst localities.

Plots of the bioclastic fragments and mineral matter taken in isolation from the living components of the microecosystem, look quite different (see text-figs. 26 & 27). The scleractinian taxa not only dominate the sand fraction (text-fig. 26) but also vary in their taxonomic in-put. The tougher astrocoeninan skeletons (see Hubbard, 1976 ; & Hubbard & Swart, 1982) have a bimodal distribution dominating granule and fine sand ranges; the faviids dominate the sand sizes showing an artifact, or geometry-dependent, bimodality; and the fungiids, being the most friable, show an unimodal distribution (text-fig. 27).

Just as we have shown that quantitative studies taken in isolation of a mineralogical and geochemical understanding can lead to misconceptions concerning population distributions in fossil reefs, quantitative studies of bulk sediment samples alone can be equally misleading. A single sponge may include as many as a thousand inhabitants, so too a single coral clast is liable to contain a host of algae and sponges (plate 1). How these components are preserved is dependent on their mineralogy and the subsequent chemistries of their microenvironments (plates 2,3, & 4). Plate 1 illustrates the diversity of an individual coral clast's preservation and associated biota from –10.219m at Ariadne (text-fig 6), Zanzibar : A is a general view of a fragment of *Seriatopora* showing four corallites in various stages of preservation; B is a close-up of one of the more poorly preserved corallites showing that a sponge (C) is responsible for its roughening; D shows another calice with unicellular algae adhering to it detailed in E & F; and G shows an algally bioeroded septum of the worst preserved calice and its associated epiflora (H & I). Views J to N show a sequence of close-ups of faecal pellet production by a worm within some hurricane transported acroporid shingle on the intertidal reef flat at Heron Island on the Australian Great Barrier Reef.It is evident that both the foraminiferan (K) and coral bioclasts (M) are incorporated in this organically bonded morsel. O is a similar ostracod containing pelletoids attached to the interstices of a coral fragment from the same sample.

Plate 2 illustrates the inception of algal alteration and its mineralogical consequences. A is a cross section of the thallus of the codiacean alga *Halimeda*; B shows the details of its wall structure essentially comprising complexly interwoven tubes. C, D, E & F show increasing magnification of the external surface at the top of A, clearly depicting the characteristic aragonitic internal fabric. Sequences G to P, by contrast, show increasing magnifications of a fractured surface of the scleractinian coral *Coeloria* from the Pleistocene of Malindi, Kenya. They illustrate the low-Mg calcite forming the mouldic replacement of the septa (G & H), which in turn are cut by an endolithic filamentous alga (I & K) thus introducing secondary void space (L, M & N) through which late stage fluids are passing and cementing remaining voids (O, P & Q).

Plate 3 compares living materials with the earlier phases of cementation in the splash zone of the supratidal. A, B & C show increasing magnifications of an encrusting lithothamnioid red alga from -15m at Heron Island, while D, E & F illustrate similar enlargements of its mouldic formation on fossilisation. G & H give details of syntaxial aragonite cementation on the scleractinian coral *Porites* from the storm ridge at Heron Island, while I shows the relationship and succession of syntaxial aragonitic needle cement followed by rhombic high-Mg calcite micrite cement on an acroporid coral which is also from the storm shingle at Heron Island. J, K & L give the sequence of syntaxial aragonitic cementation and overgrowth filling an intraskeletal void a little deeper in the same acroporid, while M, N & O show substantial rhombic high–Mg calcite micrite cementing the internal interstices of the *Porites* illustrated in G & H.

Plate 4 illustrates the relationship of initial aragonitic cementation to the end - product of mouldic preservation by low-Mg calcite in a Pleistocene acroporid from Malindi, Kenya. A shows coarse vadose cement between spar filled septa. B shows sediment filling the axial corallite and low-Mg calcite spar filling the intrasketetal voids. C is a close-up of the relationship between the sediment filled mouldic axial corallite and the associated vadose spar filling which illustrates at least two generations of vadose cementation. These contrast in scalar details with the acroporid (E), acroporid-aragonite syntaxial needle cement (F), and high-Mg calcite rhombic-cement (G) shown in Plate 3, I.

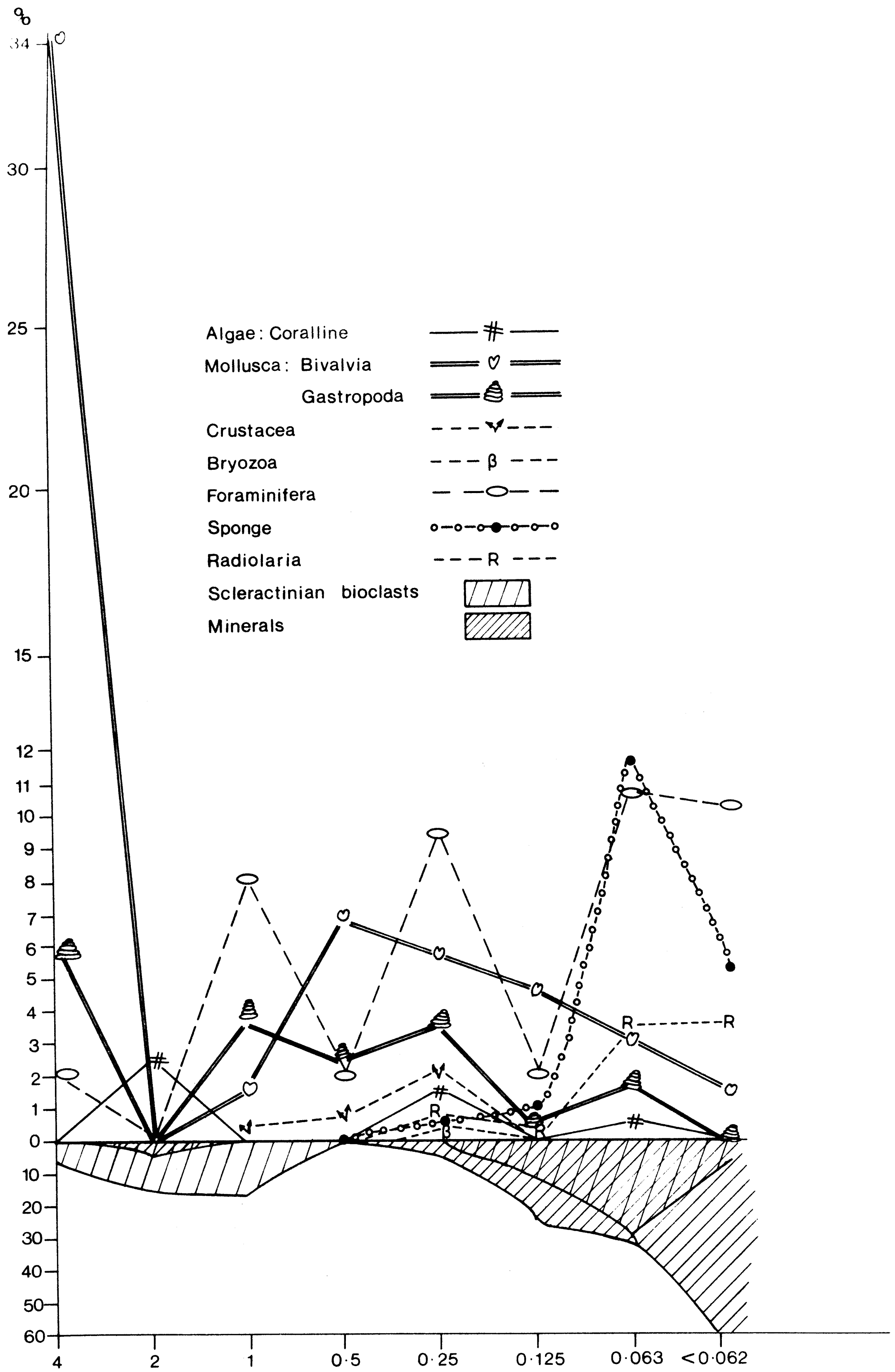
PERCENTAGE OF CONSTITUENT PARTICLE TYPES

CONSTITUENT PARTICLE COMPOSITIONS		PARTICLE SIZE	2-4 mm. FRACTION		1.00-2.00 mm. FRACTION		1.5-1.00 mm. FRACTION		0.25-0.55mm. FRACTION		WHOLE SAMPLE SUMMATION	
	ALGAE	*Halimeda*	1	8		2	1	3	1	5	1	2
		CORALLINE ALGA	7		3		2		4		3	
	MOLLUSCA	GASTROPOD	6	42	5	23	6	21	6	22	5	23
		BIVALVE	36		18		15		16		16	
CORALS	SCLERACTINIA	*Seriatopora*	15	36	13	59	4	63	3	44	7	53
		Acropora	12		26		33		20		24	
		FAVIID	3		13		14		10		12	
		Galaxea	3		1		-		-		1	
		Coeloria	-		-		-		-		-	
		Porites	2		5		12		11		10	
	OCTOCORALLA	*Tubipora*	-		1		1		-		1	
		Heliopora	-		-		-		-		-	
		OCTOCORAL	-		-		-		-		-	
		GORGONIAN	-		-		-		1		-	
		FORAMINIFERA	-		-		4		7		4	
		ECHINOID	-		2		2		2		2	
		VERTEBRATE	-		-		-		-		-	
	ARTHROPODA	CRUSTACEAN	2		2		3		2		3	
		OSTRACOD	-		-		-		-		-	
		CIRRIPEDE	-		-		-		-		-	
		SPONGE	-		-		-		-		-	
		BRYOZOAN	2		-		1		-		1	
		WORM	1		1		-		1		1	
		BIOCLAST	9		10		1		16		9	
		QUARTZ	-		-				-		-	
		GREEN MINERAL	-		-		-		-		-	
		BLACK MINERAL	-		-		-		-		-	
		ORANGE MINERAL	-		-		-		-		-	

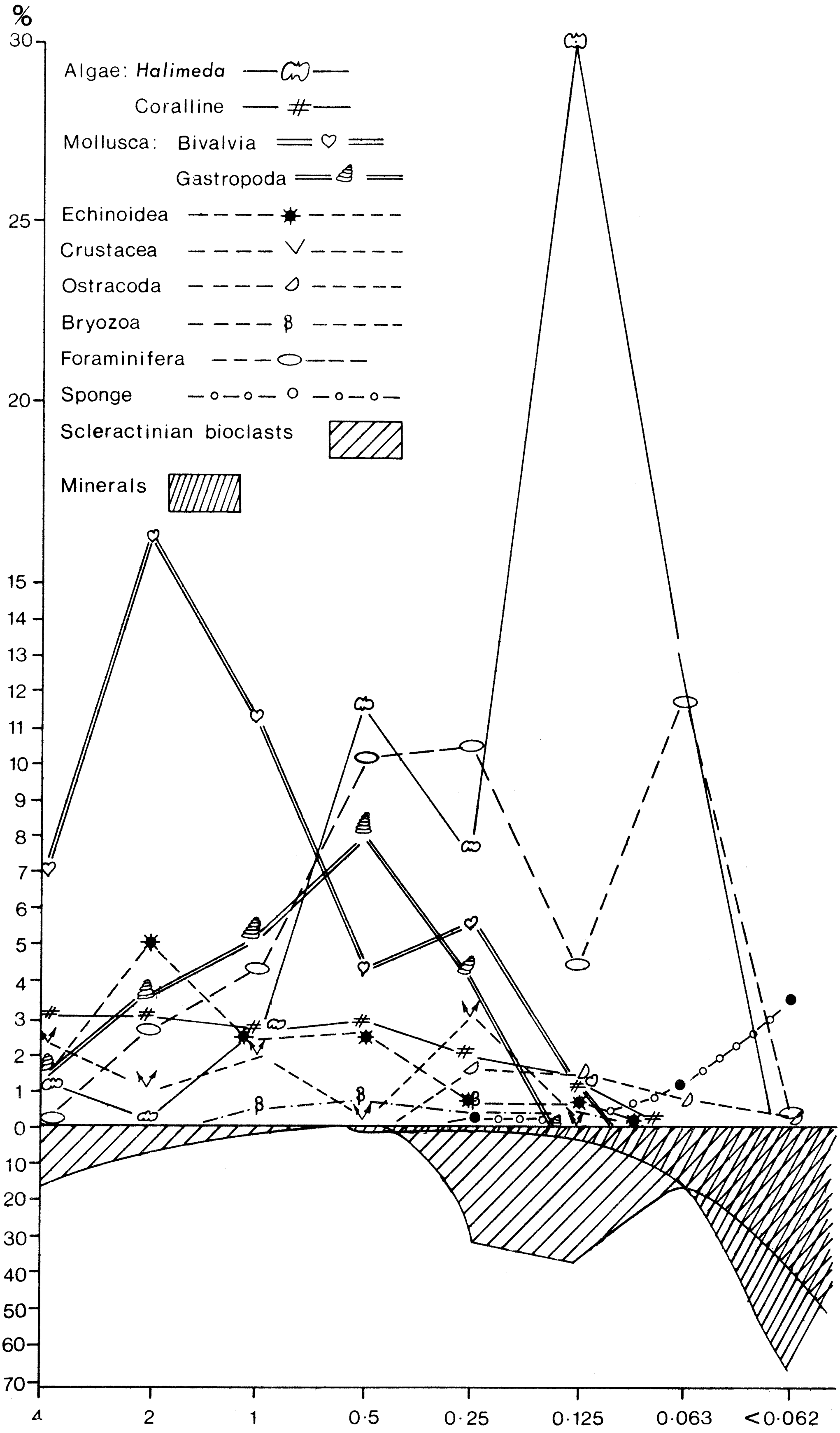
Text-fig. 23: Grain size percentage of constituent particles in reef-top sediment samples from Zanzibar highlighting initial differences in the taxonomic in-put of the grades considered in bulk in text-fig.22.

The time factor

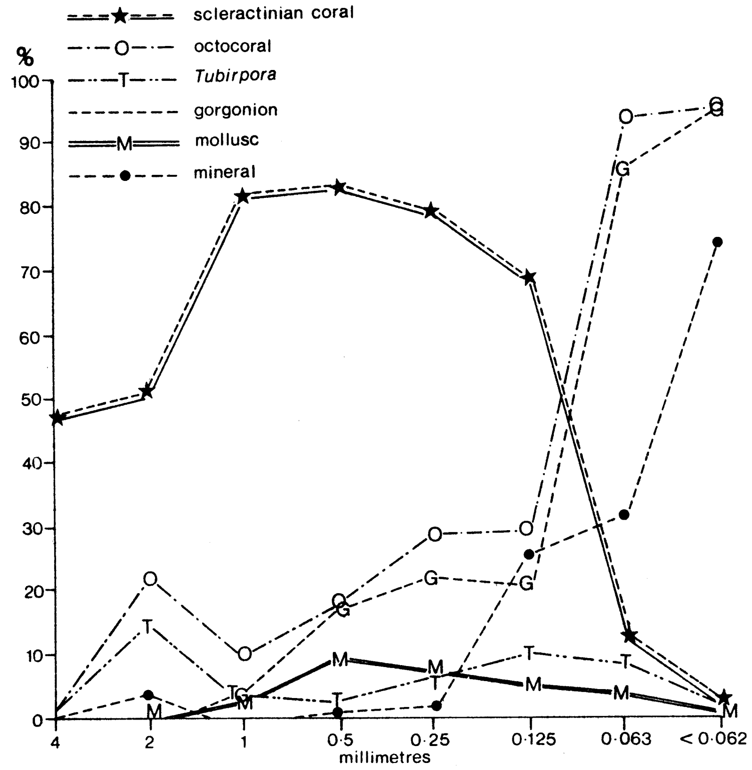
In assessing the variables which affect present - day reefs we are struck by the fact that their chances of preservation, as we see them now, are distinctly limited. Firstly, the external morphology of the reef complex bears little resemblance to its fossilised counterpart. The former is dominated by a conspicuously rugged topography, while the latter contains a seemingly disproportional amount of planar sand bodies and storm accumulates filling the erstwhile hollows. Secondly, the internal textures are subject to considerable alteration by bioerosion, sedimentation and cementation : like a good mature stilton cheese, the reef is often crusted on the outside and shot with diffuse cavity systems on the inside. Thirdly, a high proportion of the frame-building organisms are aragonitic and, as such, unstable out of seawater; consequently the chances are high that either they will be dissolved in the groundwaters, or if lucky, they will be preserved as moulds. Many of the vagrant benthos are equally susceptible to chemical loss. Consequently sound palaeoenvironmental interpretation is difficult. It demands high standards of theoretical knowledge of both ecosystems analysis and skeletal chemistry combined with acute three dimensional field recordings supported by critical petrological details. Whereas modern reefs comprise perhaps as much as 70% voids, and unloaded Pleistocene reefs may contain say 40% voids, many ancient reefs contain less porosity than this; and some, such as those of the Miocene of the Philippines, show considerable evidence of loading in the form of pressure solution affecting constituent particles. All these reefs thus record different states of cementation and diagenesis testifying to the mobility of calcium carbonate during the process of burial. Yet this phenomenon and its related effects are seldom



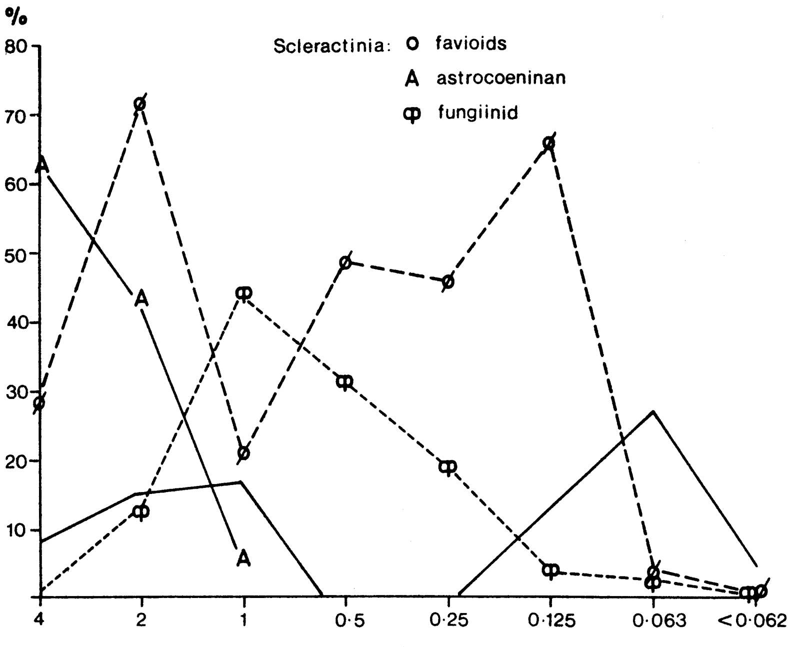
Text-fig. 24: Grain size analysis of constituent particle composition from a 250 cc sample taken from –10.219m at Ariadne, Zanzibar, to show that variations in in-put not only relate to the natural sizing differences of taxa and their component parts, as opposed to the gradational mineral in-put curve, but also to multiple in-put as shown by the bivalves and foraminiferans.



Text-fig. 25: Grain size analysis of constituent particle composition from a 250 cc sample taken from −1.524m at Murogo, Zanzibar, to show that variation in in-put is not only determined by taxonomic grading but by differences in community structure as compared with text-fig. 24.



Text-fig. 26: Grain size analysis of coral, mollusc and mineral constituents of a 250 cc sample of the reef-top sediments from Ariadne, Zanzibar, featured in text-fig. 24, to show increase in mineral and octocoral in-put amongst the fines, in reverse relation to the scleractinian in-put and in contrast to the even distribution of the molluscs.



Text-fig. 27: Grain size analysis of the scleractinian components of a 250 cc sediment sample from Ariadne, Zanzibar, featured in text-figs 24 & 26, to show that the variability of taxonomic in-put related to both the geometry of clast size and the durability of the material. The astrocoenians are the studies with pronounced bimodal distribution, and the fungiids most friable with most uniform geometric properties cluster unimodally in the middle.

recorded in the palaeoecological and palaeogeographical accounts of reefs or the analysis of their constituent particles. Furthermore when diagenetic effects are considered, as in the Canning Basin as interpreted by Logan & Semeniuk (1976), then the initial variabilities of reef facies are not considered fully.

From the foregoing discussion it is evident that, as yet, there is not a single fossil reef which has undergone a sufficiently rigorous, all-round scientific dissection to cite as a classic example of reef analysis and reconstruction, but this does not mean to say that certain specific aspects have not been covered adequately. For example, despite the limitations of models in palaeogeographic reconstruction they have been used extensively (see Wilson, 1975, and Longman, 1981, and Smith, 1981); even the more refined reef models discussed at length in Hubbard & Swart (1982) have had their applications tested in the facies interpretation and reconstruction of the geological history of the well exposed Tertiary, Miocene, Pliocene, Pleistocene and Recent sediments of Bahrain (Hubbard, 1980). So a foundation exists, albeit crude, on which further reef analyses can be based. This can be used, together with the supplementary information on contrasting reef facies given in this account, to unravel other reefs to a higher level of sophistication. This means that more accurate reconstructions should result. These, in turn, should yield improved models for further facies prediction, palaeogeomorphological insight and seismic recognition of marginal areas thus aiding regional basin analysis. But throughout the analytical process the geologist has to think like a detective, linking seemingly random facts and fabrics to a three dimensional whole which often appears to defy the laws of gravity. Cavity systems abound as snares and delusions : some are post-depositional and of late diagenetic origin, having formed from palaeokarstic phenomena at subsequent sea level stands, but others are of contemporaneous origin as evidenced by their wall clinging coelobite communites. Not infrequently the two types of cavities are superposed upon one another and cut by yet another more geometric system, of subsequent origin which can be related to the brittle fracture affects of regional tectonics and their filling by migrating groundwaters. Thus the original framebuilding biota is readily obscured by subsequent events and its community structure is difficult to resolve. The associated sediments, which in themselves represent complex micro-ecosystems, are not much less difficult to analyse as they comprise a relic history of a compound series of both intra - and inter-particle porosities and cementation. When these facies are loaded further complexities arise as a result of a further loss of porosity by pressure solution. Thus the sum total of a reef fabric can range from the simple and readily recognisable to the very complex phenomenon whose origin is, indeed, obscure.

Acknowledgements

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Dr.Julia A.E.B. Hubbard,
Department of Geology,
King's College,
University of London,
Strand,
London, WC2R 2LS.

Explanation of Plates 1 – 4

Plate 1

Plate 1 illustrates the complex inner world of three individual clasts (A - I; J - N; & O) which support diverse populations.

A is a critical point dried grain of *Seriatopora*, from -10.219m at Ariadne, off Zanzibar, showing corallites in various states of preservation.

B detail of sponge - bored apical area; C eleven dinoflagellates adhering to three sponge - pits.

D abraded top left corallite encrusted with a host of algae (E & F).

G detail of upper portion of C to illustrate endolithic boring of algal filaments (G & H) underlying residual dinoflagellate tests (I).

J is a close - up of a worm producing faecal pellets within an acroporid fragment from the intertidal storm shingle at Heron Island, Australia.

K & M show discrete pellets, which internally comprise dinoflagellate fragments (N) and coral clasts (M) organically bonded by fine threads (L).

O illustrates faecal matter containing ostracods from a similar acroporid clast from the reef crest at Heron Island. Bar scales in micrometres.

Plate 2

Plate 2 illustrates the mineralogy of preservation by reference to a dead specimen of the Codiacean green alga *Halimeda* (A - F) from -1.524m off Grave Island, Zanzibar, and a mouldic scleractinian coral, *Coeloria*, (G - P) and its associated endolithic alga (J), algal borings (K - M), and cement fillings after voids (N - Q) from the Pleistocene of Malindi, Kenya. The original aragonitic skeletal structure of *Halimeda* is most readily seen in detail (F) taken from the upper surface of (A) close to one of its utricles (C, D & E) which open to the surface from the twisted tubes seen in B. There is not a sign of the coral's original aragonite skeleton : vadose Low -Mg calcite both coats the septal surfaces as a cement and occupies the cores of septa which have subsequently been bored by algae (H - J), leaving permeable pathways where they are not fully cemented (K - M). Bar scales in micrometres.

Plate 3

Plate 3 is a further illustration of the mineralogy of preservation by reference to the living calcitic coralline alga *Lithothamnion* from -15m off Heron Island (A - C), to its quasi-fossil counterpart from the storm shingle of Heron Island (D - F) and associated quasi-fossil scleractinian corals *Porites* (I - J) and *Acropora* (I - O). A - C illustrate the relationship of the individual coralline cells to their adjacent cells (C), coralsubstrate (B) and whole algal crust (A).

D - C illustrates the cementation of the red algal cells, while G shows a general view of coral skeletal organisation with syntaxial aragonite cements in close detail (H). While J – L show internal filling of *Acropora* by aragonite cement, in depth, and by High-Mg calcite at the surface. Bar scales in micrometres.

Plate 4

Plate 4 illustrates mouldic preservation of *Acropora* from the Pleistocene of Malindi, Kenya.

A shows partial preservation of the septa by vadose cements which are even more distinct in the areas between the septa. The related threads are algal filaments.

B shows the internal mouldic axial corallite, to the right of the field of view, and associated cement external mould forming a chamber to the left, the coral, in between, having been dissolved away.

C is a detail from B illustrating the relationship of the calcitic internal mould to the external mould separated by a space which is being filled by yet another generation of fine rhombic Low-Mg calcite cement. While D – F, which are enlargements from Plate 3, I of a recent acroporid from the storm shingle follows the early development of syntaxial aragonite cement (E) on the acroporid coral (D) which is closely in contact with the later High-Mg calcite rhombic cement (F). Bar scales in micrometres.

Plate 1

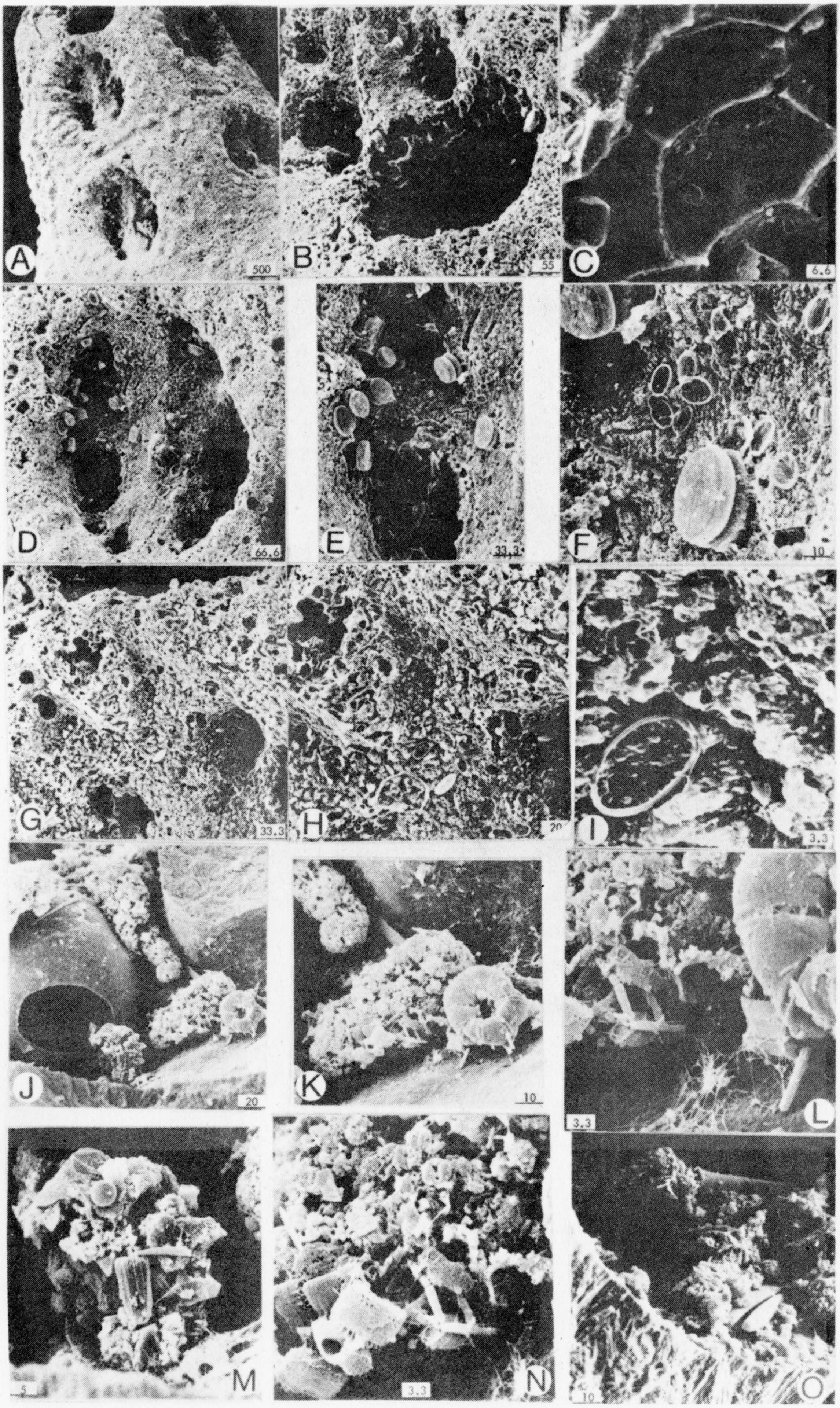
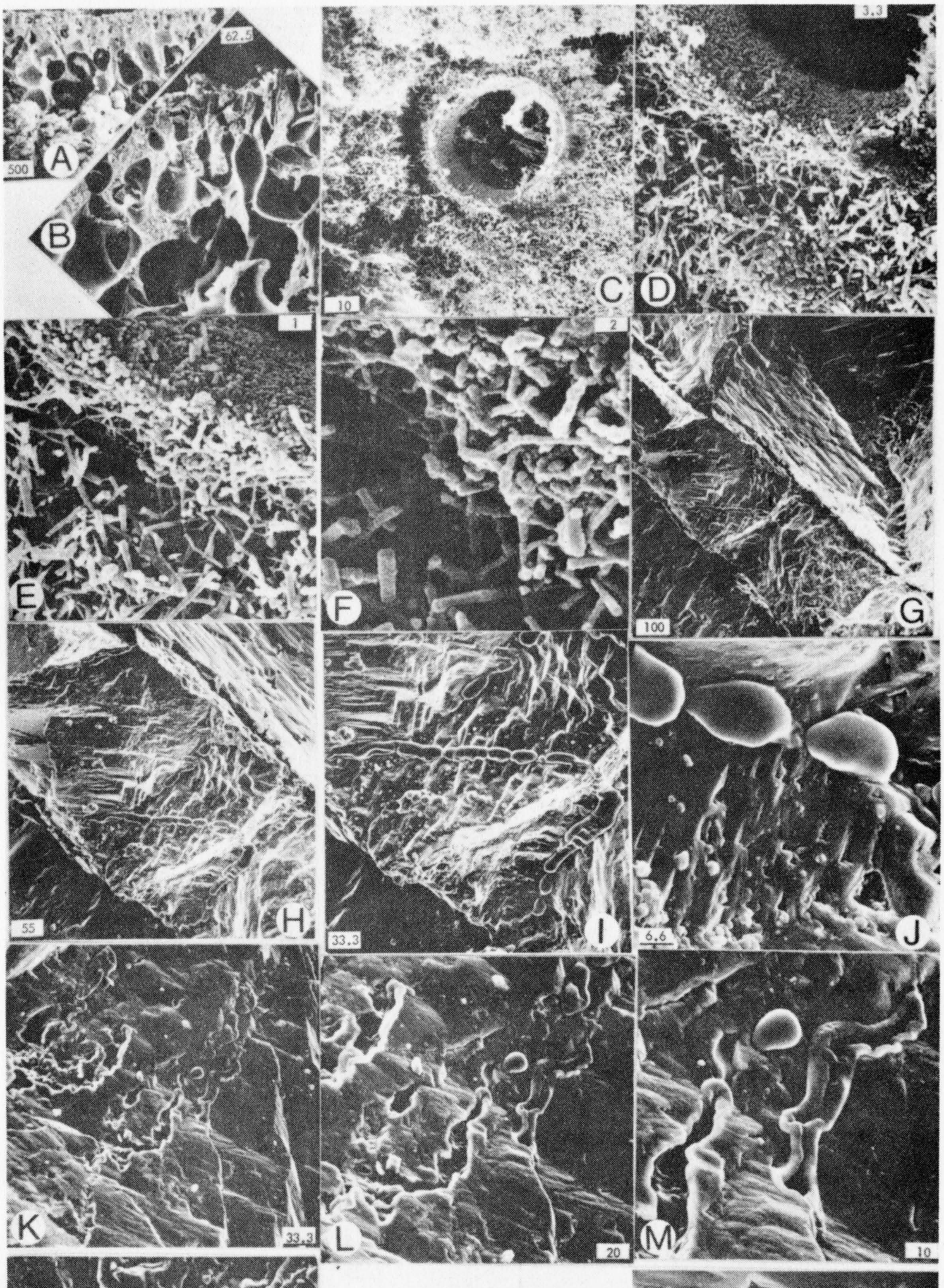


Plate 2


A
500
B
62.5
C
10
D
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E
1
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Plate 3

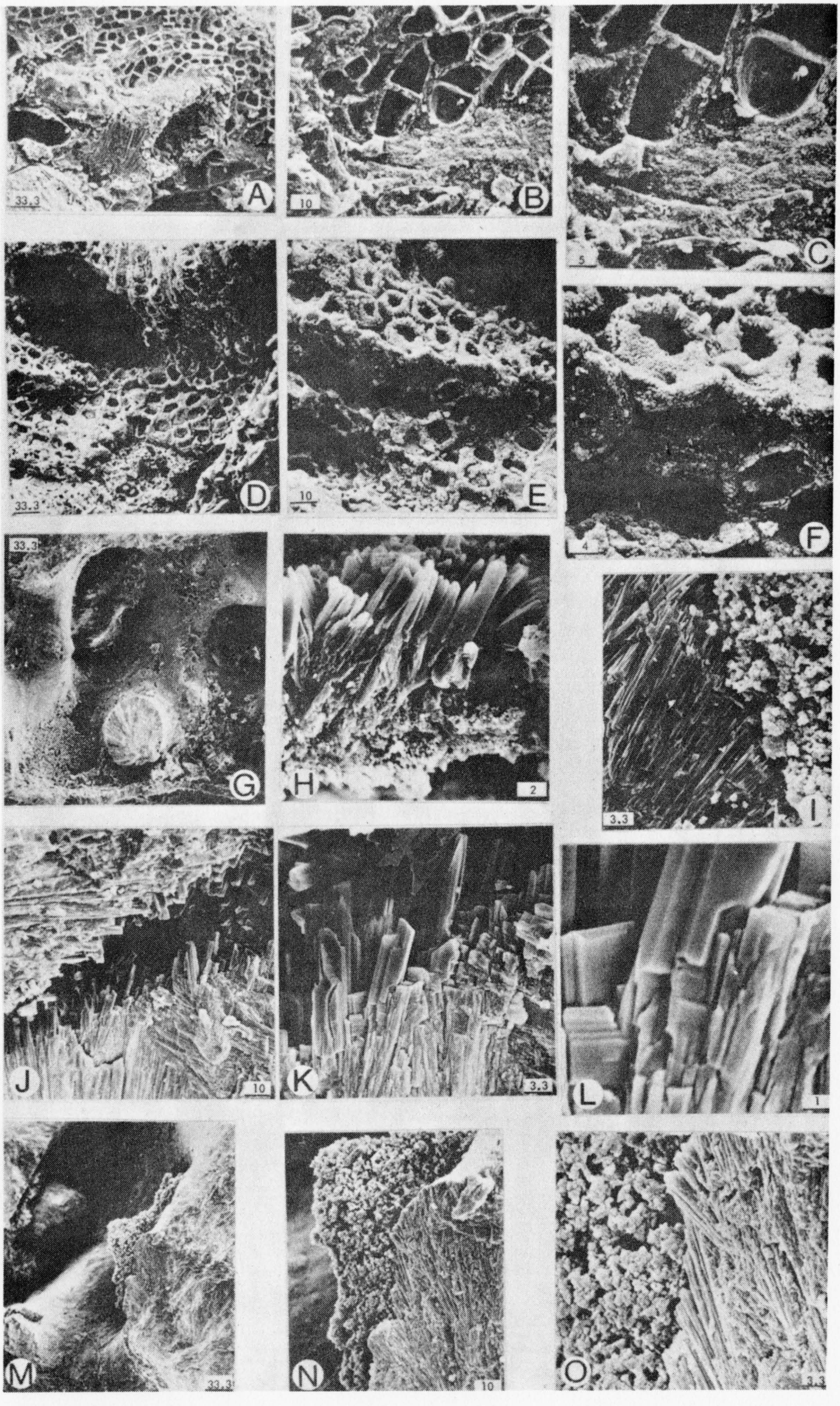
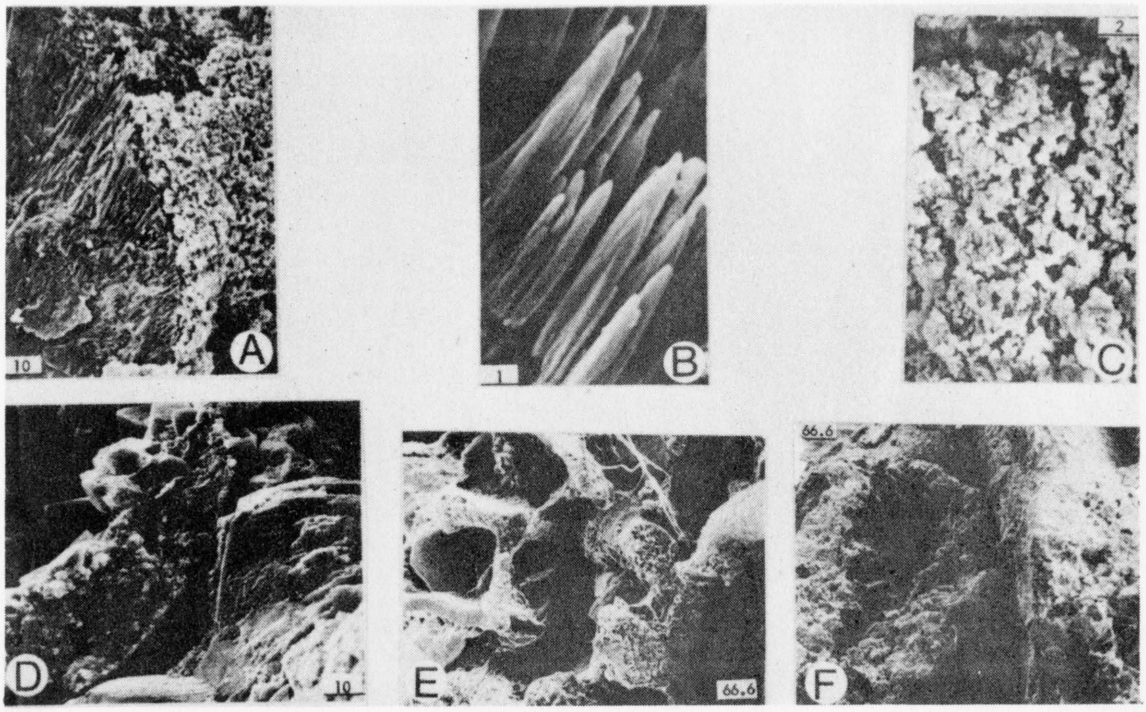


Plate 4



PALYNOLOGY AND STRATIGRAPHY OF THE MUCH WENLOCK LIMESTONE FORMATION OF DUDLEY, CENTRAL ENGLAND.

by

Ken J. Dorning

Summary

Acritarchs, chitinozoa and miospores have been studied from 18 samples collected stratigraphically from the Silurian Coalbrookdale Formation, Much Wenlock Limestone Formation and Elton Formation at Wren's Nest Hill, Dudley, West Midlands, Central England. All the palynomorphs are of low thermal maturation and are in general very well preserved. The acritarchs show a high taxonomic diversity. In addition, the lithostratigraphy of the Much Wenlock Limestone Formation is revised to include a Lower Quarried Limestone Member, a Nodular Member and an Upper Quarried Limestone Member.

Introduction

The Silurian rocks of Central England have long been known for their very well preserved macrofossils, particularly trilobites; the microfossils, including the organic walled acritarchs and chitinozoa, and hard conodonts and ostracods, are also particularly well preserved. Most of the fossil groups contain species rarely recorded elsewhere.

The main exposures of the Much Wenlock Limestone Formation in Central England occur in the Wren's Nest Inlier, just to the northwest of Dudley, where there are several disused quarries that provided the localities sampled. Butler (1938) described in detail the stratigraphy of the area, referring to the Much Wenlock Limestone Formation as the Wenlock Limestone or "Dudley" Limestone.

Several distinct groups of acritarch assemblages can be recognised; as the proportion of sphaeromorph acritarchs increase, so the species diversity of the assemblages tends to decrease.

Sample Details

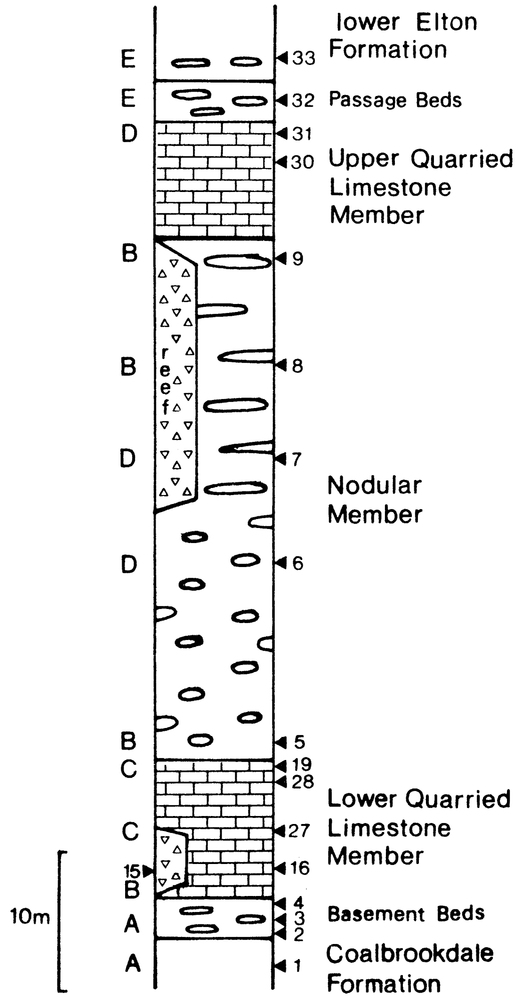
The stratigraphical location of samples is recorded on text-fig. 1. The samples are described in stratigraphical order, WN1 at the base.

1. The codes (5Y 5/2) are rock colors according to the USGS color chart.

WN 1.	Light olive grey calcareous silty mudrock, 5Y 5/2, Coalbrookdale Formation, 1.5m from top of formation, Butler loc. 10.
WN 2.	Light olive grey calcareous mudrock, 5Y 5/1, Basement Beds, base of Butler unit a, Much Wenlock Limestone Formation, loc. 10.
WN 3.	Light olive grey silty limestone, 5Y 6/1, Basement Beds, middle of Butler unit b, Much Wenlock Limestone Formation, loc. 10.
WN 4.	Light olive grey silty limestone, 5Y 6/1, Basement Beds, Butler unit c, Much Wenlock limestone Formation, loc. 10.
WN 15.	Light grey limestone, N7, 'reef', 1.5m from base of Lower Quarried Limestone Member, Much Wenlock Limestone Formation, loc. 30
WN 16.	Medium grey limestone, N5, 'bedded', 2.0m from base of Butler unit d, Much Wenlock Limestone Formation, loc. 30.
WN 27.	Medium grey crinoidal limestone, N5, middle Butler unit d, Much Wenlock Limestone Formation, loc. 29.
WN 28.	Medium grey silty mudrock, N5, interbed between Butler units d and e, Much Wenlock Limestone

Mercian Geologist, vol. 9, no. 1, 1983,
pp. 31-40, 1 text-fig., plate 5-7.

	Formation, loc. 29.
WN 19.	Medium grey limestone, N5, Butler unit h, Much Wenlock Limestone Formation, loc. 30.
WN 5.	Medium light grey silty limestone, N6, 2m from base of Nodular Member, Butler unit i, Much Wenlock Limestone Formation, loc. 8.
WN 6.	Olive grey soft calcareous silty mudrock, SY 4/1, base Butler unit n, Nodular Member, Much Wenlock Limestone Formation, loc. 8.
WN 7.	Medium grey silty limestone, N5, near base of Butler unit q, Nodular Member, Much Wenlock Limestone Formation, loc. 10.
WN 8.	Medium grey silty limestone, N5, middle of Butler unit q, Nodular Member, Much Wenlock Limestone Formation, loc. 10.
WN 9.	Light olive grey silty limestone, 5Y 5/1, middle Butler unit r, Nodular Member, Much Wenlock Limestone Formation, loc. 10.
WN 30.	Medium light grey limestone, N6, 1.0m from base of Butler unit t, upper limestone, Much Wenlock Limestone Formation, loc. 24.
WN 31.	Medium grey silty limestone, middle Butler unit u, upper limestone, Much Wenlock Limestone Formation, loc. 24.
WN 32.	Olive grey calcareous silty mudrock, 5Y 5/3, top of Butler unit v, Passage Beds, Much Wenlock Limestone Formation, loc. 24.
WN 33.	Light olive grey silty mudrock, 5Y 5/1, 0.5m above top of Butler unit w, Elton Formation, loc. 24.



Text-fig. 1. Stratigraphical location of the samples

Palynology

Dorning (1981a, 1981b) has outlined the stratigraphical distribution of acritarchs and chitinozoa in the Wenlock of the Welsh Basin. The environmental distribution of Silurian acritarchs is presented in Dorning (1981c), and the general distribution of microfossils on the Welsh Basin shelf is detailed in Aldridge *et al.* (1981). Eisenack recorded acritarchs and chitinozoa from two spot samples from the Much Wenlock Limestone Formation of Dudley (Eisenack, 1977, 1978).

Table 1, lists the palynomorphs that have been recorded from the Much Wenlock Limestone Formations and see plates 5, 6 and 7:

ACRITARCHS

Ammonidium microcladum (Downie) Lister 1970
Ammonidium waldronense (Tappan and Loeblich) Dorning 1981
Cymatiosphaera octoplana Downie 1959
Cymatiosphaera pavimenta (Deflandre) Deunff 1958
Cymbosphaeridium eurnes (Cramer and Diez) Dorning 1981
Cymbosphaeridium gueltaense (Jardiné *et al.*) Dorning 1981
Dactylofusa neaghae Cramer 1970
Dateriocradus polydactylus Tappan and Loeblich 1971
Dateriocradus tribrachiata (Lister) Dorning 1981
Dictyotidium amydrum (Tappan and Loeblich) Diéz and Cramer 1977
Dictyotidium dictyotum (Eisenack) Eisenack 1955
Dictyotidium stenodictyum Eisenack 1955
Diexallophasis denticulata–granulatisphinosa group
Duvernayspaera aranaides Cramer 1964
Eisenackidium wenlockensis Dorning 1981
Electoriskos aurora Loeblich 1970
Estiastra granulata Downie 1963
Eupoikilofusa filifera (Downie) Dorning 1981
Eupoikilofusa striatifera (Cramer 1970
Florisphaeridium sp
Helosphaeridium pseudodictyum Lister 1970
Hoglintia ancyrea (Cramer and Diéz) Dorning 1981
Gloeocapsamorpha sp
Leiofusa banderillae Cramer 1964
Leiofusa parvitatis Loeblich 1970
Leptobrachion arbusculiferum (Downie) Dorning 1981
Lophosphaeridium citrinum Downie 1963
Lophosphaeridium sp
Melikeriopalla wenlockia Dorning 1981
Micrhystridium inflatum (Downie) Lister 1970
Wrensnestia ornata Dorning 1981
Micrhystridium intonsurans (Lister) Dorning 1981
Micrhystridium spp.
Multiplicisphaeridium arbusculum Dorning 1981
Multiplicisphaeridium cladum Downie 1963
Multiplicisphaeridium eltonensis Dorning 1981
Multiplicisphaeridium triangulatum (Downie) Dorning 1981
Multiplicisphaeridium variabile (Lister) Dorning 1981
Multiplicisphaeridium wrensnestensis Dorning 1981
Nanocyclopis sp.
Navifusa scrutilla Cramer and Diéz 1972
Onondagella sp.
Oppilatala insolita (Cramer and Diéz) 1981
Oppilatala ramusculosa (Deflandre) Dorning 1981
Psenotopus chondrocheus Tappen and Loeblich 1971
Pteropermella foveolata Lister in Dorning 1981
Pulvinosphaeridium pulvinellum Eisenack 1954
Quadratitum fantasticum Cramer 1964
Salopidium granuliferum (Downie) Dorning 1981
Salopidium wenlockensis (Downie) Dorning 1981
Schismatosphaeridium sp
Tunisphaeridium parvum Deunff and Evitt 1968
Tylotopalla robustispinosa (Downie) Eisenack, Cramer and Diéz 1973
Tylotopalla wenlockia 1968
Umbellasphaeridium sp
Veryhachium rhomboidium Downie 1959
Veryhachium trispinosum (Eisenack) Cramer 1964 group
Veryhachium wenlockium Downie 1959 group
Visbysphaera dilatispinosa Downie 1963
Visbysphaera wenlockia (Thusu) Dorning 1963
Visbysphaera sp

CHITINOZOA

Ancyrochitina ancyrea (Eisenack) Eisenack 1955
Ancyrochitina gutnica Laufeld 1974
Ancyrochitina primitiva Eisenack 1964
Conochitina aff. *elegans* Eisenack 1931
Conochitina pachycephala Eisenack 1964
Conochitina tuba Eisenack 1932
Desmochitina acollaris Eisenack 1959
Linochitina cingulata (Eisenack) Eisenack 1968
Sphaerochitina aff. *dubia* 1968.

MIOSPORES

Ambitisporites dilutus (Hoffmeister) Richardson and Lister 1969

Taxonomic references for the acritarchs can be found in Cramer 1979 and Dorning 1981a, and for the chitinozoa, Laufeld 1974.

The stratigraphical distribution of selected acritarchs and chitinozoa is presented in text-fig. 2. Well established records from the Coalbrookdale Formation of the Welsh Borderland are shown as an arrow on the left margin, and records from the lower Elton Formation as an arrow to the right.

Some acritarch species range thoughout most samples from the top Coalbrookdale Formation to the base of the Elton Formation; *Diexallophsis* spp., *Leiosphaeridia* spp., *Micrhystridium intonsurans*, *Veryhachium trispinosum* and *Veryhachium wenlockium* are common, long ranging acritarchs; *Cymatiosphaera octoplana, Eupoikilofusa filifera, Leiofusa parvitatis, Onondagella* sp., *Pterospermella foveolata* are long ranging acritarchs that are not always found in large numbers.

Palynomorph assemblages

Some acritarch species are only recorded from the lowest samples, and are considered to have a top of range at about this stratigraphical level: *Cymatiosphaera pavimenta, Salopidium wenlockensis, Tylotopalla robustispinosa, Tylotopalla wenlockia,* and *Visbysphaera wenlockia*. Some species are only recorded in the highest samples, and are considered to have a base of range at about this stratigraphical level: *Multiplicisphaeridium eltonensis,* and *Psenotopus chondrocheus*.

Some acritarch species are recorded in both the lowest and highest samples, but not in the bulk of the Much Wenlock Limestone Formation: *Ammonidium waldronense, Eupoikilofusa striatifera, Helosphaeridium pseudodictyum, Salopidium granuliferum.* These species are considered to be distributed with greater abundance in environments that produced the calcareous mudrock of the Coalbrookdale and Elton Formations. The distribution is not apparently due to the high carbonate content of the rocks, but due to the environment of deposition, as adjacent samples with differing carbonate composition are known to contain similar assemblages, but of different abundances, the numbers per gram of rock reflecting the dilution at a rate depending on the carbonate percentage present.

Some acritarch species are only recorded from the main part of the Much Wenlock Limestone Formation: *Dictyotidium amydrum, Dictyotidium dictyotum, Dictyotidium stenodictyum, Estiastra granulata, Multiplicisphaeridium wrensnestensis, Pulvinosphaeridium pulvinellum* and *Wrensnestia ornata.* These species are considered to favour one or more of the environments that are reflected in the limestone deposition of the Much Wenlock Limestone Formation.

The acritarch assemblages in the samples can be placed into groups of similar composition, apparently reflecting different environments of deposition. Percentages quoted are of the total acritarchs.

Assemblage group 1: Species diversity 25–35 distinctive taxa. Two taxa are dominant, *Leiosphaeridia* 25–35%, *Micryhstridium intonsurans* 10–25%, together forming 40–50%. Other common taxa are *Ammonidium waldronense, Dieallophasis* spp., *Oppilatala ramusculosa, Veryhachium wenlockium* and *Veryhachium trispinosum.* Samples WN1, WN2 and WN3 are in this assemblage group. It is of note that several taxa show a progressive increase or decrease in abundance from WN1 through WN2 to WN3, which are three adjacent samples at about the base of the Much Wenlock Limestone Formation. This may reflect a changing environment, heralding the onset of the limestone deposition.

	WN1	WN2	WN3
Salopidium granuliferum	6%	8%	13%
Ammonidium waldronense	1%	2%	4%
Veryhachium wenlockium	9%	12%	15%
Veryhachium trispinosum	1%	5%	6%
Diexallophasis spp.	16%	12%	6%
Oppilatala ramusculosa	4%	3%	2%
Helosphaeridium pseudodictyum	3%	2%	1%
Muraticavea wenlockia	4%	2%	1%

Care has to be taken in interpretation of this data, as increasing percentage abundance may reflect a greater tolerance threshold for a different environment, rather than a preference for that environment. Sample WN28 is similar in many respects to this group, except that *Micrhystridium* forms 48% of the total. Samples WN32 and WN33 are also similar in many respects to this assemblage group, except that *Diexallophasis* forms 32–37%, and the species diversity is lower at 22–24 distinctive species.

Assemblage group 2 : Species diversity 18–25 distinctive taxa. Two taxa are dominant, *Leiosphaeridia* 28–60%, *Micryhstridium intonsurans* 6–35%, together forming 60-70%. *Salopidium granuliferum* is recorded at 1% or less. Samples WN4, WN16, WN5, WN8, WN9 are in this group.

Assemblage group 3 : *Leiosphaeridia* dominates at 65–90% of the total. Species diversity varies widely, but is typically between 12 and 25 distinctive species. *Pulvinosphaeridium*, *Estiastra* and/or *Hogklintia* forms a significant part of the non sphaeromorph taxa, for example in WN27, WN19 *Pulvinosphaeridium* occurs at 2–3%, and in WN9 *Estiastra granulata* forms 7% and *Hogklintia ancyrea* 2%. Samples WN27, WN19, WN6, WN7, WN9 and WN31 are in this group.

Assemblage group 4: Species diversity very low, *Leiosphaeridia* totally dominates. *Gloeocapsamorpha* is often also present. Preservation is sometimes poor, probably due to a high oxygen potential at the time of deposition. Samples WN15 and WN30 are in this group. Low numerical abundance, high sphaeromorph percentage abundance assemblages have been recorded from reef limestones in the Welsh Borderlands and by D.G. Bell (pers.comm.) from Wenlock Edge.

Most of the chitinozoa recorded occur throughout the late Wenlock; *Ancyrochitina ancyrea* and *Conochitina* spp. were common throughout the section, but their abundances varied widely from sample to sample. *Ancyrochitina primitiva* appears to occur more frequently in the limestones than the calcareous mudrock. Both *Linochitina cingulata* and *Desmochitina accollaris* only occur in the lowest samples; it is probable they are close to the top of their ranges.

Only one miospore species was recorded. *Ambitisporites dilutus* together with other *Ambitisporites* species are by far the most common species recorded from the Wenlock. In the samples studied, the percentage abundance was always lower than 1% of the total palynomorphs. This suggests that the Wren's Nest Inlier was at some distance from land supporting miospore producing vegetation.

Lithostratigraphy

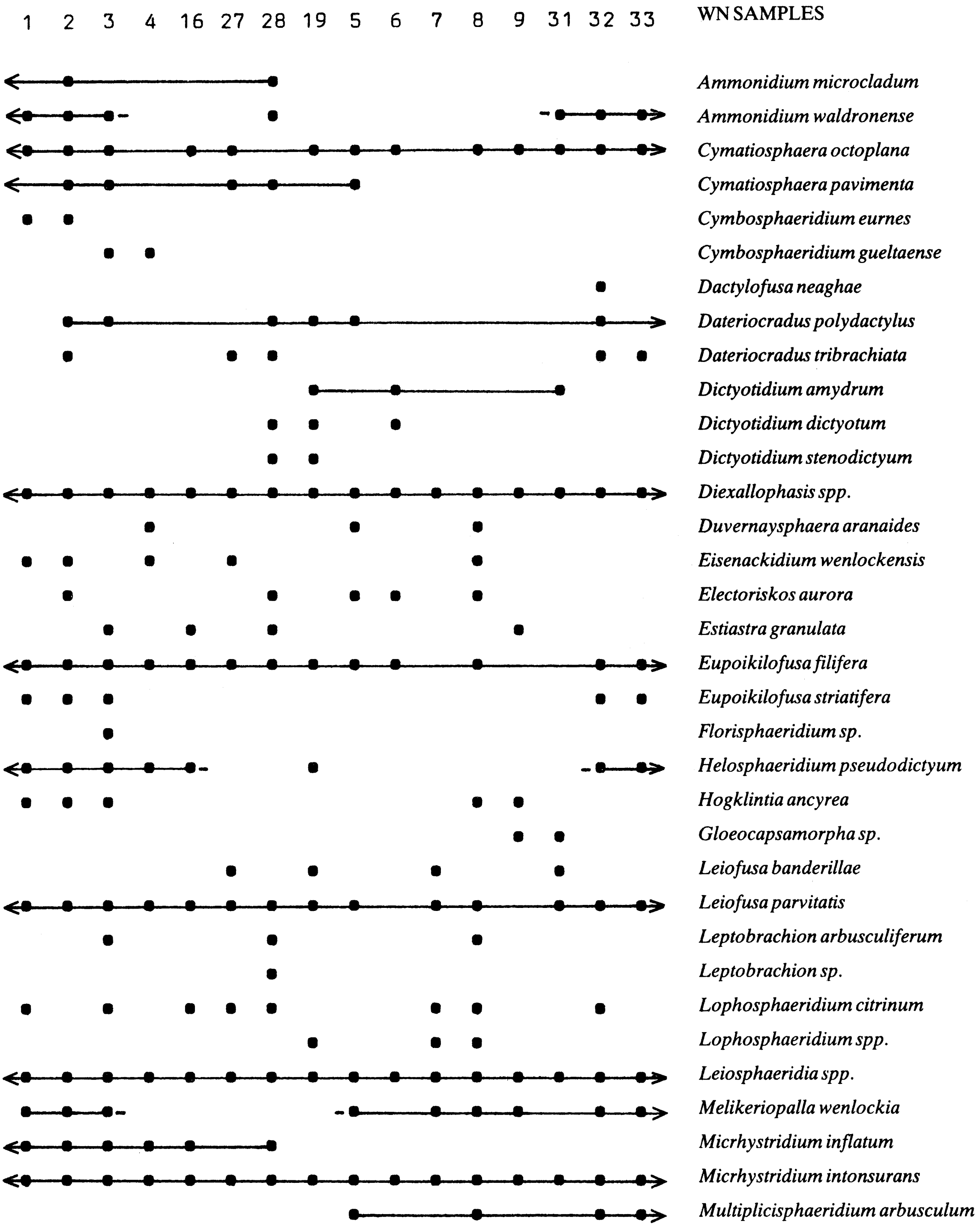
The stratigraphy of the type Wenlock Series in Shropshire has been revised by Bassett *et al.* (1975). The lithostratigraphical units used by Butler (1938) in describing the Wren's Nest Inlier do not conform in format to current nomenclature, and are revised:

Butler, 1938	**Dorning, this paper**
Lower Ludlow Shale	Elton Formation
Wenlock Limestone	Much Wenlock Limestone Formation
Wenlock Shale	Coalbrookdale Formation

Three members can be recognised in the Much Wenlock Limestone Formation in the Wren's Nest Inlier:

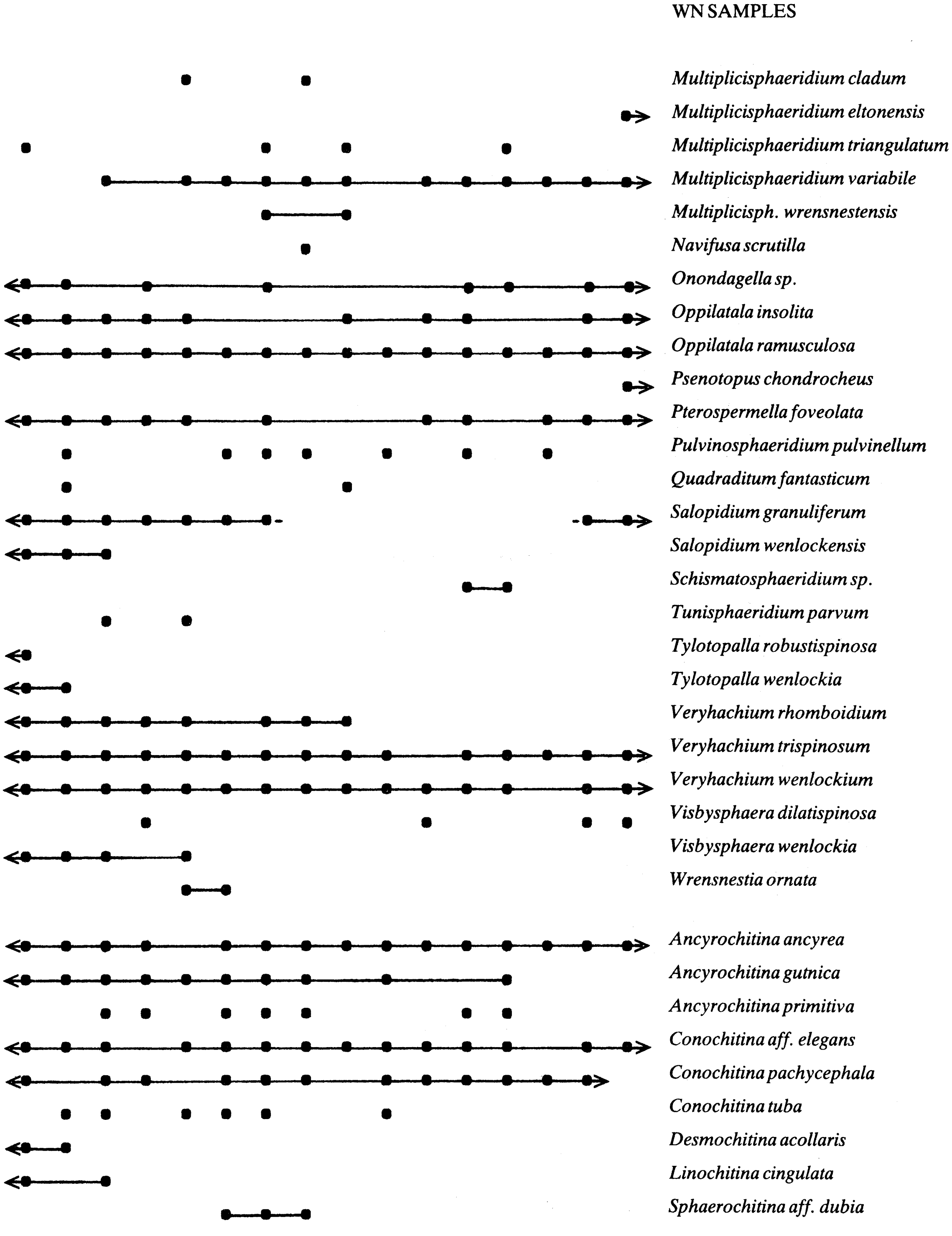
Butler, 1938	**Dorning, this paper**
Upper Quarried Limestone	Upper Quarried Limestone Member
Nodular Beds	Nodular Member
Lower Quarried Limestone	Lower Quarried Limestone Member

The Birmingham Siltstone Formation (Hurst, 1975) was proposed for the apparently Wenlock part of the Lower Elton Beds. As formations are lithostratigraphical units, they cannot be limited by the chronostratigraphy; the Birmingham Siltstone Formation is therefore considered superfluous.



Text-fig 2: Stratigraphical distribution of selected acritarchs and chitinozoa, Wenlock Limestone Formation.

Coalbrookdale Formation, lower Elton Formation



Text-fig. 2: (continued from p.36)

Explanation of Plate 5

1 *Ammonidium waldronense* WN1 K, H41/2
2 *Ammonidium microcladum* WN1 A, N39/2
3 *Oppilatala insolita* WN2 K, D40/0
4 *Veryhachium rhomboidium* WN1 K, Q34/1
5 *Visbysphaera* sp. WN 1 K, G33/4
6 *Cymbosphaeridium gueltaense* WN K, Q46/0
7 *Salopidium granuliferum* WN1 K Q40/3
8 *Micrhystridium inflatum* WN1 K, W37/1
9 *Helosphaeridium pseudodictyum* WN 1 K, M29/2
10 *Leiosphaeridia* sp. WN1 A, 037/4
11 *Lophosphaeridium* sp. WN1 A, 040/4
12 *Multiplicisphaeridium triangulatum* WN1 K, W38/0
13 *Lophosphaeridium* sp. WN1 K, W42/1
14 *Lophosphaeridium* sp. WN2 K, P33/0
15 *Nanocyclopia* sp. WN1 K, N33/0
16 *Muraticavea wenlockia* WN1 K, B39/1
17 *Cymatiosphaera octoplana* WN1 K, V43/3
18 *Visbysphaera wenlockia* WN1 K, H41/2

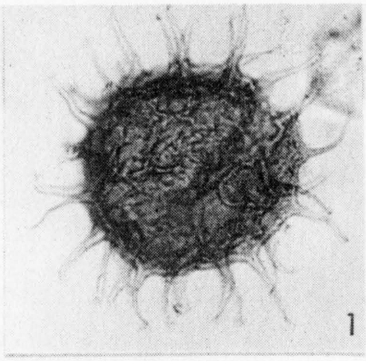
Explanation of Plate 6

1 *Oppilatala* cfr *ramusculosa* WN33 K, S41/0
2 *Diexallophasis* sp. WN33 K, T30/4
3 *Wrensnestia ornata* WN16 K, P38/0
4 *Pterospermella foveolata* WN33 K, E45/4
5 *Dictyotidium dictyotum* WN31 K, T33/3
6 *Dateriocradus polydactylus* Wn33 K, T42/3
7 *Eisenackidium wenlockensis* WN28 K, V29/2
8 *Multiplicisphaeridium eltonensis* WN33 K, M33/4
9 *Dictyotidium amydrum* WN19 K, M37/2
10 *Helosphaeridium* sp. WN33 K, L45/4
11 *Psenotopus chondrocheus* WN33 K, P35/4
12 *Schismatosphaeridium* sp.
13 *Visbysphaera dilatispinosa* WN33 K, Q28/2
14 *Ambitisporites dilutus* WN8 A, N43/3
15 *Gloecapsamorpha* sp. WN30 K, V36/1

Explanation of Plate 7

1 *Wrensnestia ornata* holotype. WN16 K, D41/2, MPK 2912
2 *Muraticavea wenlockia* WN1 K, M36/4
3 *Dictyotidium amydrum* WN19 K, T37/4
4 *Multiplicisphaeridium triangulatam* WN9 K, K32/4
5 *Nanocyclopia* sp. WN2 K, N39/0
6 *Multiplicisphaeridium wrensnestensis* WN28 K, W30/3
7 *Dactylofusa neaghae* WN32 K, G42/4
8 *Multiplicisphaeridium variabile* WN28 K, U30/3
9 *Tylotopalla* sp. WN33 K, 031/0
10 *Umbellasphaeridium* sp. WN3 K, Q35/2
11 *Lophosphaeridium citrinum* WN19 K, F34/4
12 *Dictyotidium* cf *amydrum* WN4 K, K45/0

All the figured material is in the reference collections of Pallab Research, Sheffield, except Plate 6, fig 3, and Plate 7, fig 1 which are housed at the I.G.S. Leeds.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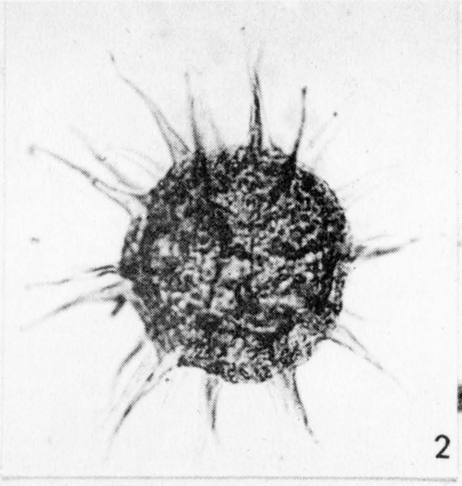
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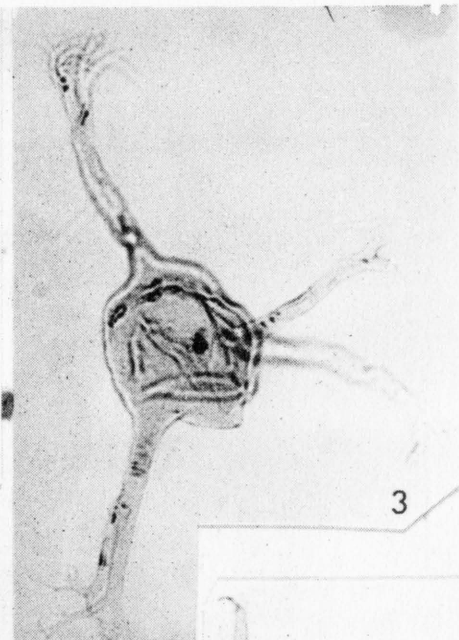
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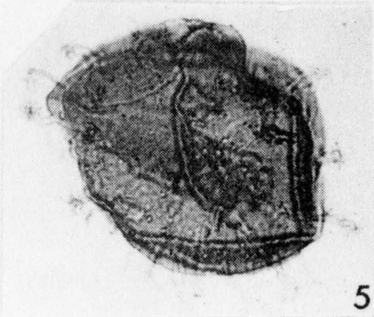
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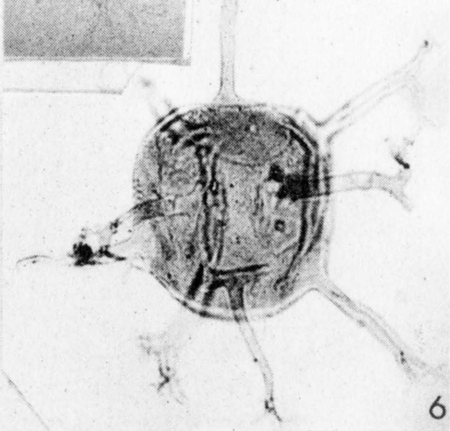
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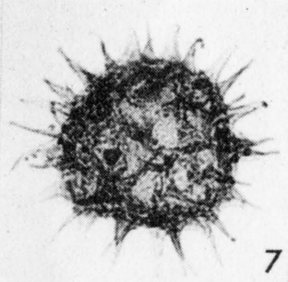
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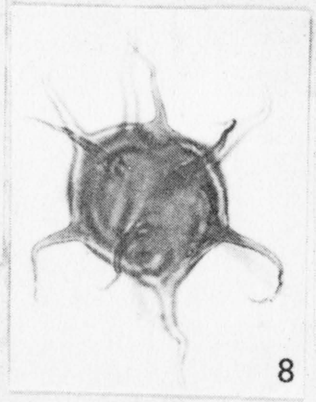
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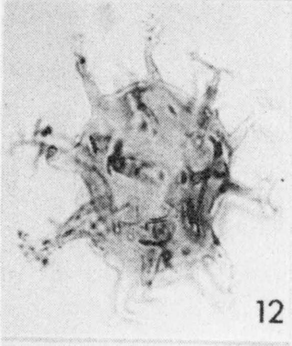
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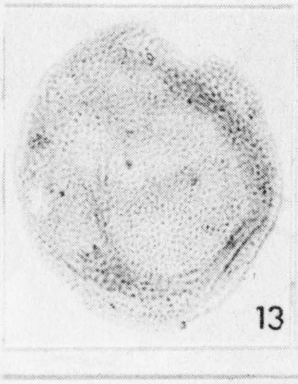
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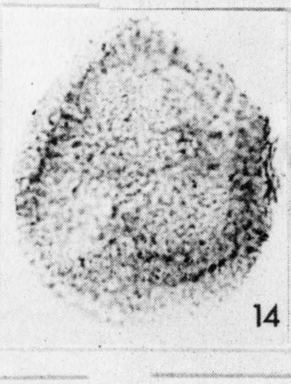
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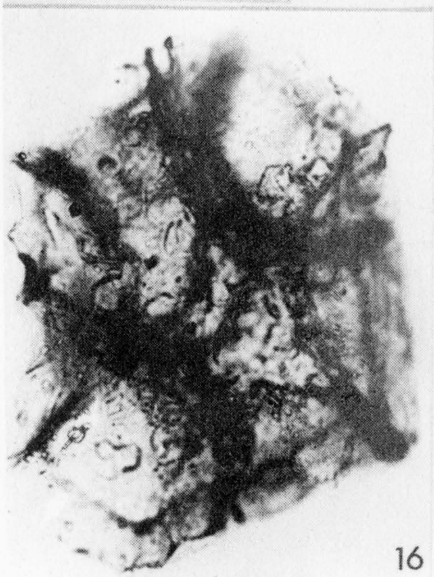
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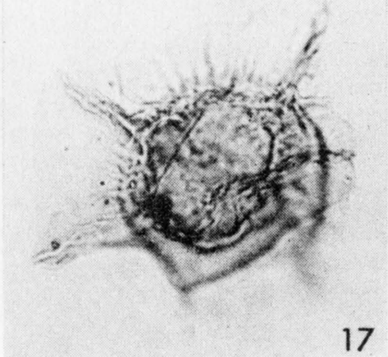
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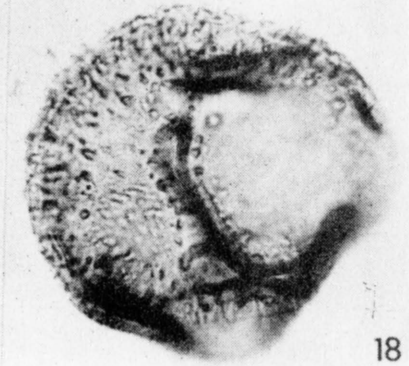
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Plate 6


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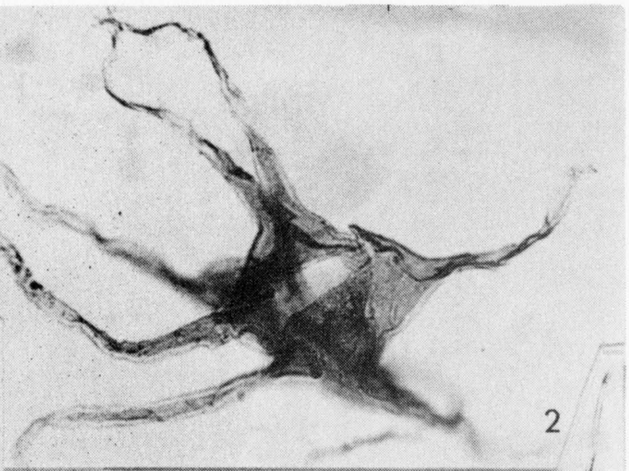
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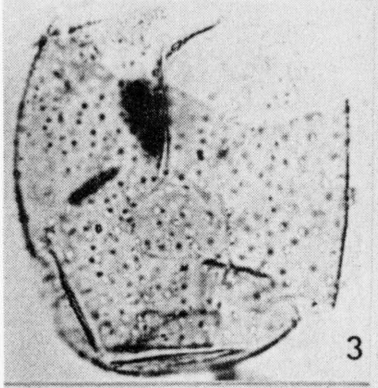
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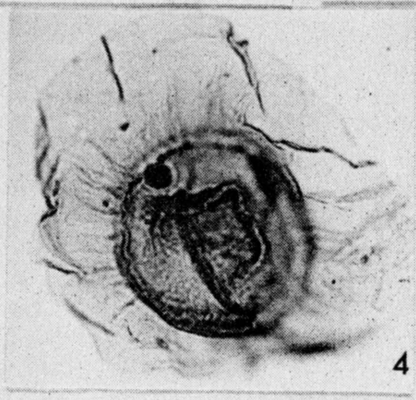
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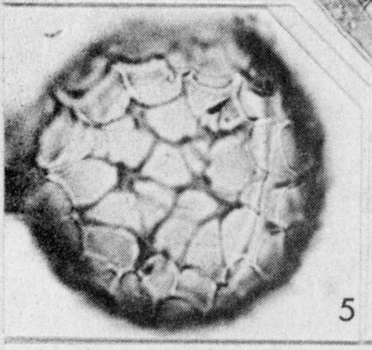
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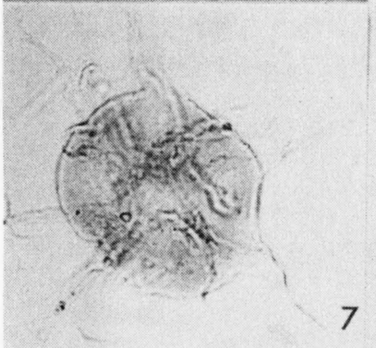
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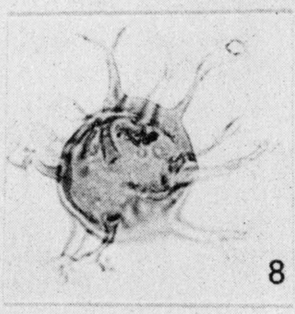
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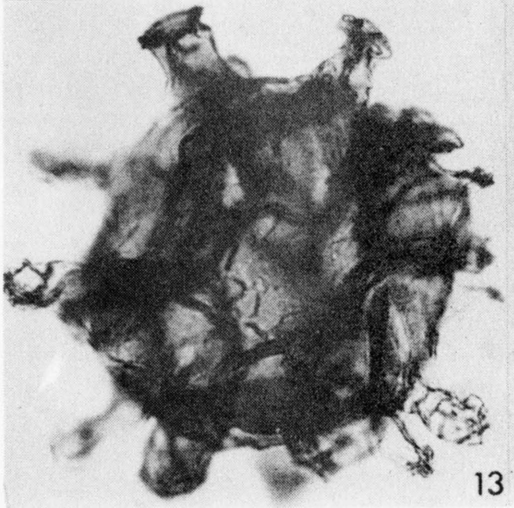
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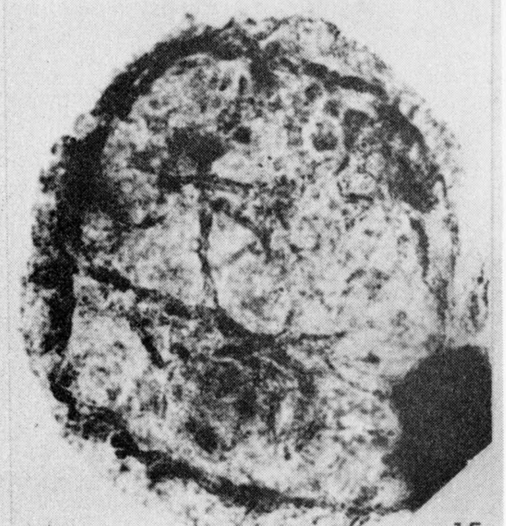
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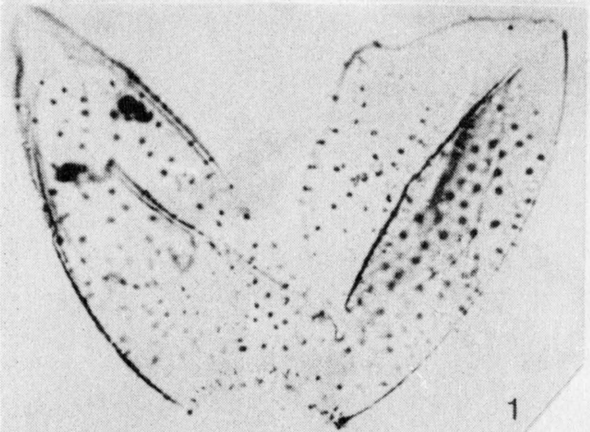
Plate 7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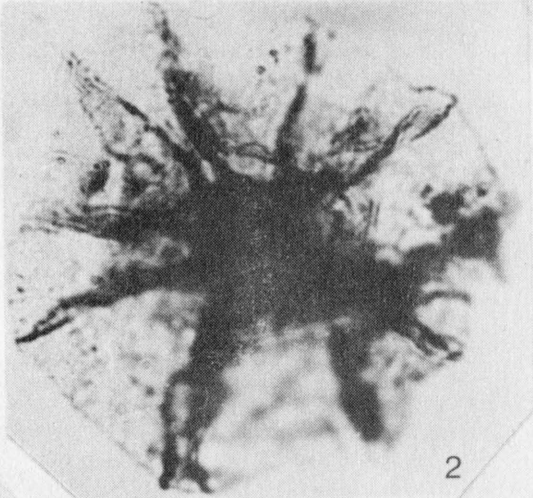
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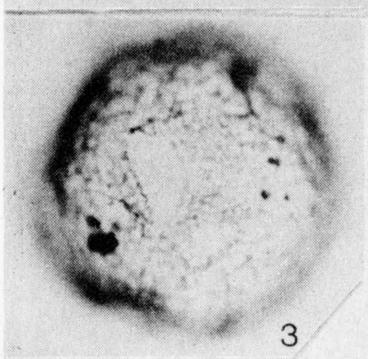
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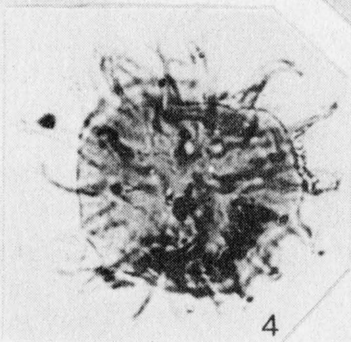
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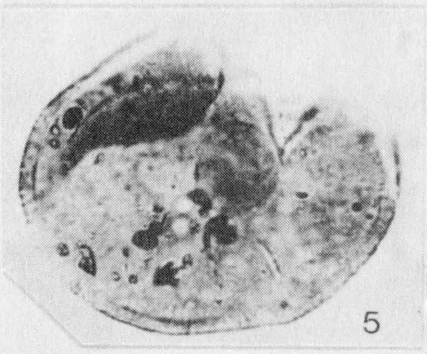
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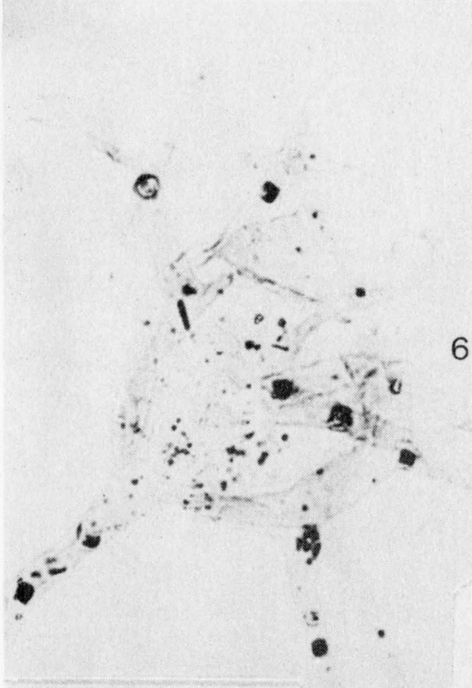
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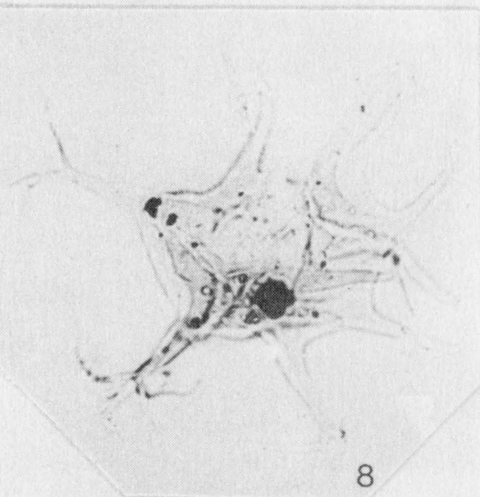
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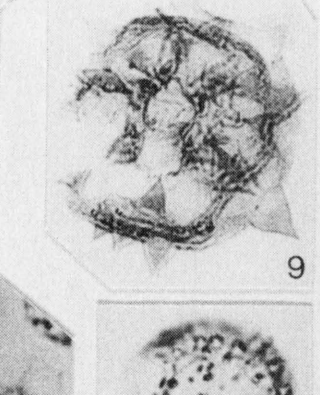
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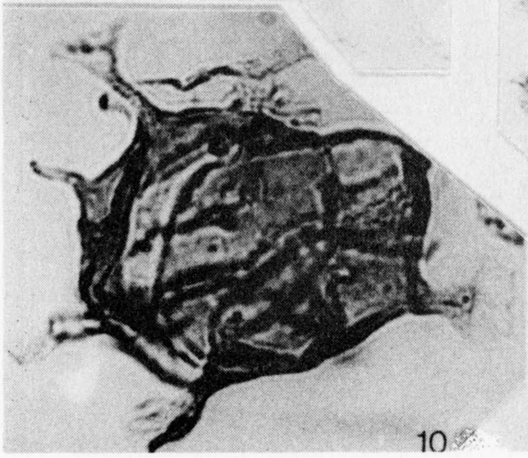
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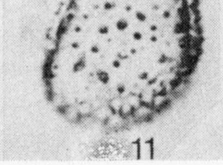
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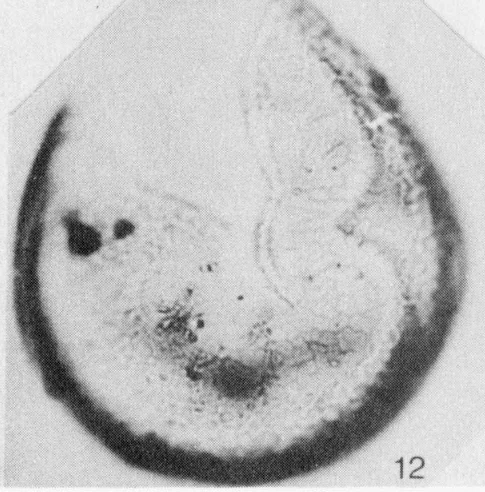
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Biostratigraphy

On lithostratigraphical evidence, the Much Wenlock Limestone Formation of the Wren's Nest Inlier can be readily correlated with the type area on Wenlock Edge. Several of the acritarchs recorded have top of ranges or bases of ranges within the samples studied. In correlation with the known acritarch ranges in the type area (Dorning 1981a), it is probable that limestone deposition began somewhat earlier in Central England, so that the base of the Much Wenlock Limestone Formation at Wren's Nest correlates somewhere near the top of the Coalbrookdale Formation in the type area. Bassett (1974) on the basis of macrofossils suggested that the base of the Much Wenlock Limestone in Central England occurred earlier in the Wenlock than in the type area. On the basis of the acritarch ranges, there is no indication that there is any significant time difference between the end of limestone deposition in Central England and the type area, and it is most unlikely that the Much Wenlock Limestone Formation in Central England extends into the Ludlow.

Acknowledgements

I thank Stewart Molyneux and Ron Woollam for comments on the paper. All photographs on plates 1–3 are copyright of Larix Books, and used with permission.

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Ken J. Dorning,
Pallab Research,
International palynological consultants,
58 Robertson Road,
Sheffield S6 5DX, England.

HYDROTHERMAL ALTERATION Of DOLERITE WALLROCK WITHIN THE IBLE SILL, DERBYSHIRE

by

S.G. Walters and P.R. Ineson

Summary

The mineralogy, petrology, K–Ar geochronology and mode of occurrence of a zone of altered wallrocks in the Ible Sill, Derbyshire, is described. The chlorite-rich nature of alteration constrasts with the smectite and illite-smectite assemblages typically associated with deuteric or hydrothermal altered basalts in Derbyshire. K–Ar isotopic age determinations and alkali-variations indicate a hydrothermal origin and it is proposed that alteration was effected by hydrothermal brines modified by wall-rock interactions.

Introduction

The Ible Sill outcrops over an area of some 0.25 km^2 on the north side of the Via Gellia in Derbyshire (text-fig. 1). First described by Arnold-Bemrose (1894, 1907), the olivine-dolerite sill was intruded into the Bee Low Limestone of Asbian age (George *et al.*, 1976). A 30 m section of the sill is exposed in the disused roadstone quarry at SK 253568 (Walters & Ineson, 1981). The dolerite is traversed by numerous, randomly orientated veinlets (up to 10 cm wide) infilled with fibrous calcite and a green resinous material, originally described as chrysotile-asbestos by Garnett (1923). A more recent analysis (Sarjeant, 1967) however, indicated a chlorite-smectite intergrowth. These veinlets have no attendant visible wall-rock alteration. However, a zone of pale bleached and altered dolerite up to 1.5 m wide occurs along the base of the upper bench in the quarry. The zone is subvertical and trends east-west; it is associated with a thin, impersistent central fissure. The zone margins are indistinct but a rapid graduation into unbleached dolerite occurs.

The alteration of the dolerite was briefly noted by Garnett (1923) and referred to as 'chlorite–rock'. Walkden (1972) and Walters (1981) have subsequently demonstrated that the majority of previously quoted 'chlorite' occurrences in the basalts of the South Pennines were incorrect and that iron-rich smectites (saponites and nontronites) together with interlayered illite-smectites constitute the dominate clay phases.

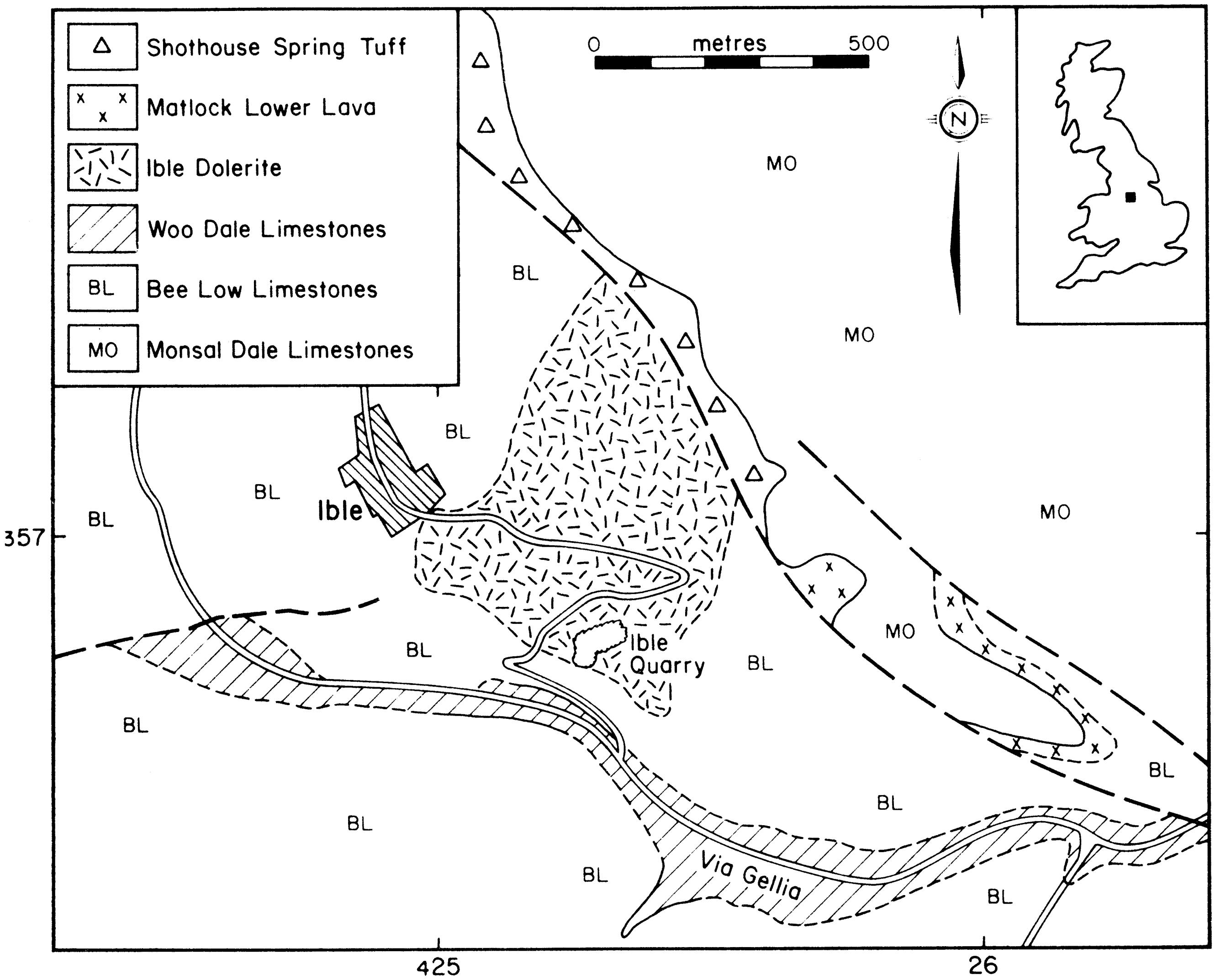
Petrology

The unaltered dolerite (table 1 and plate 8 fig. A) is a typical medium-grained ophitic olivine dolerite. Titaniferous augite encloses labradorite laths which form an interlocking groundmass together with minor ilmenite, magnetite and apatite. Euhedral olivine phenocrysts have been pseudomorphed by red and green pleochroic clay aggregates, as shown in plate 8, fig. B. X-ray diffraction analysis of extracted pseudomorphs indicate that they are iron-rich smectites (nontronites and saponites).

In the altered dolerite, the smectite pseudomorphs after olivine are themselves replaced by an apple-green, homogeneous clay phase which exhibits decreased birefringence and pleochroism relative to the original smectites. Albitised plagioclase representing an earlier replacement phenomena is likewise progressively replaced with increasing alteration. Primary augite is pseudomorphed by an apple green clay phase, with relict grain boundaries marked by concentrations of fine-grained anatase (plate 8, fig. C). Ilmenite and magnetite are altered to aggregates of coarse, euhedral, anatase.

X-ray diffraction analysis of the red and green clay mineral aggregates pseudomorphing the olivine phenocrysts in the altered dolerite indicates the presence of an Fe-rich chlorite. Peaks at 14.5, 7.2 and 3.6Å were unaffected by glycolation but on heating to 55O°C for 1 hour, the 7.2Å peak was destroyed and the 14.5Å peak migrated to 14.0Å. The chlorite constitutes in excess of 60% of the altered dolerite, and in this instance the previous designation of a 'chlorite-rock' by Garnett (1923) is confirmed. The dominance of chlorite and the absence of smectites and calcitisation is in direct contrast with the typical deuteric and/or hydrothermal alteration as reported by Walters (1981) in the South Pennine basalts and this locality is therefore considered to have an unusual alteration assemblage, for Ixer (1972) reported the enrichment of K_2O, Fe_2O_3 and CO_2 as well as a reduction in Mg, Na_2O, FeO, MnO in the Matlock Upper Lava next to mineralisation.

Likewise, Ineson (1968) noted that bleached dolerite in the northern Pennine orefield contained carbonate aggregates, anatase, albite, potassium-rich clays, quartz and apatite which preserved the relict texture of the quartz-dolerite. The clay minerals were identified as illite and kaolinite. Major oxides of CaO, MgO, Na_2O and Fe were reduced while CO_2, K_2O and H_2O were enriched in the hydrothermally altered sill. Similarly the minor, or trace elements were redistributed with an overall depletion of Cu, Ni and Sr and an enrichment in Zn, Rb and Ba adjacent to mineralisation.



Text-fig. 1. Geological sketch map of the Ible Sill, Derbyshire

Geochemistry and K–Ar Isotopic Age Dating

Samples which were representative of the transition from unaltered to altered dolerite were analysed by x-ray fluorescence spectrometry and wet chemical methods. The results are shown in table 1. The C.I.P.W. norm of the fresh dolerite (table 2), calculated on an anhydrous basis and with Fe_2O_3 standardised at 1.5% to compensate for the effects of deuteric alteration, indicates that the sill is of a transitional hypersthene–normative nature. The transitional nature is typical

Table 1. **Chemical analyses of the alteration phases of the Ible Sill**

Constituent Wt.%	Sample Is 1	 Is 2	 Is 3	 Is 4
SiO_2	48.76	45.70	44.14	46.40
TiO_2	1.86	1.84	1.75	1.88
Al_2O_3	14.60	16.71	16.09	16.63
Fe_2O_3	4.60	5.51	4.75	4.52
FeO	6.06	6.92	7.43	8.89
MnO	0.16	0.04	0.12	0.21
MgO	8.35	6.81	6.78	7.87
CaO	9.12	2.92	4.03	1.21
Na_2O	2.61	3.28	3.01	2.24
K_2O	0.79	1.17	1.33	2.18
H_2O+	2.36	6.37	6.09	6.49
H_2O^-	1.26	1.26	1.24	1.00
P_2O_5	0.38	0.28	0.26	0.27
CO_2	Trace	1.75	2.28	0.40
SO_3	0.05	0.09	0.06	0.18
Total	100.96	100.65	99.36	100.37
ppm				
Ba	302	168	168	220
Co	81	103	91	107
Cr	358	509	453	473
Cu	81	82	97	89
Ni	242	297	295	272
Pb	28	trace	trace	9
Rb	17	12	12	24
Sr	345	90	99	90
V	182	245	229	231
Y	27	27	24	20
Zn	104	130	128	111
Zr	128	103	101	101

Sample Is 1 – unaltered dolerite
Is 2-4 – progressively altered dolerite

Analyst: S.G. Walters

Table 2 Modal and normative analyses of unaltered (sample Is 1) dolerite at Ible, Derbyshire.

C.I.P.W. Norm* Mode (%)			Mode (%)	
Or		4.79	Plagioclase	56.4
Ab		22.68	Clinopyroxene	23.6
An		26.54	Pseudomorphed Olivine	15.0
Di	Wo	7.27	Fe–Ti Oxides	2.4
	En	4.37	Interstitial Clay Alteration	2.6
	Fe	2.51		
Hy	En	11.95		
	Fs	6.85		
Ol	Fo	3.56		
	Fa	2.25		
Mt		2.18		
Al		3.63		
Ap		0.91		
Py		0.11		
Total		99.58	Calculated using Fe_20,	
%An		53.90	standardised to 1.50%	

Table 3. K–Ar isotopic age determinations on the Ible Sill

Sample	*K_20%	Radiogenic Argon (mm^3/gm^{-1})	Atmospheric Contamination %	Age (m.y.)
Unaltered dolerite	0.66	$(7.81 \pm 0.07)10^{-3}$	41.3	334 ± 10
Altered dolerite	1.33	$(1.11 \pm 0.01)10^{-2}$	34.0	242 ± 3
Altered dolerite	1.17	$(1.01 \pm 0.01)10^{-2}$	36.0	249 ± 2
Altered dolerite	2.18	$(1.84 \pm 0.01)10^{-2}$	26.8	244 ± 2
Altered dolerite	2.24	$(1.87 \pm 0.01)10^{-2}$	15.7	242 ± 2

*K_2O% are average triplicate analysis

Decay constants: $\lambda_e = 0.581 \times 10^{-10} yr^{-1}$

$\lambda_\beta = 4.962 \times 10^{10} yr^{-1}$

$\frac{40\kappa}{\kappa} = 1.167 \times 10^2$ atom.%

of the South Pennine basalt suite (Walters, 1981).

Geochemical alteration of the dolerite has resulted in a depletion in CaO and an increase in K_2O, FeO, Al_2O_3 and H_2O, while only minor variations in the concentrations of SiO_2, TiO_2, P_2O_5, MgO and Fe_2O_3 are noted. The minor amounts of CO_2 and SO_3 confirm the petrological analysis indicating that calcitisation and sulphides, typical products of hydrothermal alteration, are not important. Initial Na_2O enrichment, reflected in the dominance of albite, is subsequently followed by a depletion of Na_2O associated with the secondary replacement of albite by chlorite. A strong relative increase of K_2O over Na_2O during alteration is noted. A depletion of Ba, Sr and Pb is recorded whilst progressive alteration results in an increase or redistribution of Cu, Ni, Cr, V and Zn. Y and Zr exhibit minimal variations between the altered and unaltered dolerite.

The alteration of the Ible Sill, in which chlorite has been developed in contrast to illite/smectite as well as the absence of calcite is at variance with the previously reported petrological analyses of hydrothermally altered basalts in the Pennines (Ineson, 1968, Walters, 1981). As the factors effecting changes in the activity of components in hydrothermal solutions are extremely complex, a discussion on 'typical-trends' is subject to generalisations verging on incorrect statements. For example, the potential to undertake Na or K metasomatism may be present in both magmatic fluids and seawater brines; both of which may have been detected in the South Pennines. Which process actually occurs, i.e. Na or K metasomatism, may depend on factors such as hornblende stability in a nearby magma (Burnham, 1979) or the effective fluid/rock ratio (Seyfried and Bischoff, 1981). However for readers with little or no knowledge of the above, deuteric alteration is often accompanied by hydration, calcitisation and albitisation while hydrothermal alteration results in a depletion of MgO and FeO and an enrichment in CaO, CO_2 and K_2O while TiO_2, P_2O, Zr, Y and to a lesser extent Cr and V remain immobile.

It is emphasised that the authors are **not** suggesting that alkali (Na_2O) metasomatism has effected the Ible Sill, for the increase from 2.61% to a maximum of 3.28% Na_2O cannot be considered to be of a sufficient magnitude to support such a contention.

The alkali enrichment, however, during alteration of the Ible dolerite is considered to be a hydrothermal feature. K–Ar isotopic age determinations (table 3) indicate initial sill emplacement around 334 m.y. (i.e. Lower Brigantian). Alteration occurred around 244 m.y. and this correlates with a hydrothermal episode recognised in the South Pennine Orefield by Ineson & Mitchell (1973).

Origin of Alteration

If the alteration was hydrothermal in origin, the geochemistry and mineralogy are directly opposed to previously reported variations. The stability of chlorite reflects high concentrations of MgO and FeO, whilst calcite (CaO and CO_3) was in unstable equilibrium. The altered zone is also unusual in that the thin, impersistent central fissure contrasts with the 'veinlet-swarms' accompanying typical hydrothermal alteration in basalts (Walters & Ineson, 1980). Garnett (1923) indicated that the central fissure and its attendant alteration diminished in size and died out with increasing height up the quarry face.

The restricted nature of the channelway may suggest that the hydrothermal flow approached conditions of stagnation and allowed extensive wall-rock interactions to occur and the previously reported depletion and enrichment of major and trace elements associated with hydrothermal alteration in the South Pennines were partially reversed. Thus FeO depleted during wall rock alteration at lower levels in the Sill resulted in a gradual enrichment in the restricted flow of hydrothermal fluids within the fissure and the eventual stability of chlorite as an alteration phase. Similarly, trace elements depleted at lower levels may have been concentrated in the stagnated hydrothermal fluids. The bulk geochemical characterisation of the hydrothermal fluid, i.e. a saline brine capable of H^+, Na^+ and K^+ metasomatism (Rodgers, 1977) were not significantly modified by the extensive wall-rock interactions. As previously indicated, such an hypothesis is very tentative and the variations may have been due to an interplay of numerous conditions.

Conclusions

The geochemistry, mineralogy and mode of occurrence of the zone of alteration in the Ible Sill has not been recorded elsewhere in the South Pennines. K–Ar isotopic age determinations, however, suggest a hydrothermal origin. Extensive wall-rock interactions involving the restricted flow of hydrothermal fluids are envisaged and resulted in the geochemical modifications recorded.

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Dr. J.G. Mitchell of the University of Newcastle provided the K–Ar isotopic age determinations. S.G.W. acknowledges the receipt of a NERC 'Case' research studentship during which this work was undertaken.

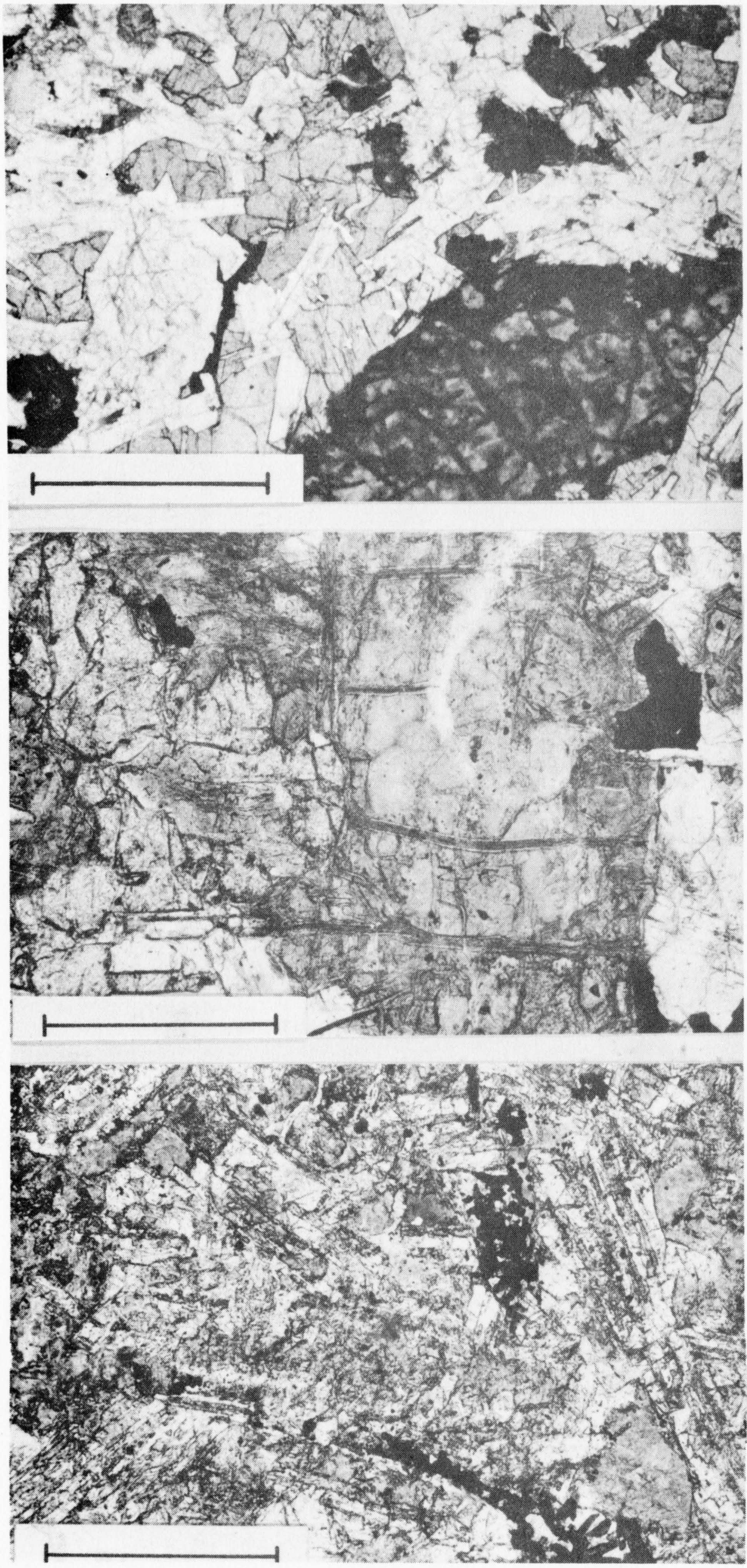
S.G. Walters, PhD., A.M.I.M.M., F.G.S.
B.H.P. Exploration,
Adelaide,
South Australia.

P.R. Ineson, PhD., C. Eng., M.I.M.M., F.G.S.
Department of Geology,
University of Sheffield,
Sheffield, S1 3JD.

Explanation of Plate 8

Plate 8, Fig. A.	Unaltered dolerite, Ible Quarry. Ophitic titaniferous augite (pale grey) encloses labradorite laths and anhedral Fe–Ti oxides. Pseudomorphed olivine phenocrysts exhibit characteristic outlines and preservation of internal cracks (plane polarised light) scale bar = 1 mm.
Plate 8, Fig. B.	Pseudomorphed olivine phenocryst. Primary olivine is replaced by homogeneous (green) pleochroic smectites. Original internal cracks are outlined by (red) pleochroic smectites (plane polarised light) scale bar = O.5 mm.
Plate 8, Fig. C.	Altered dolerite. Primary augite is pseudomorphed by (apple green) chlorite with concentrations of anatase at relict grain boundaries. Albitised plagioclase is partly replaced by chlorite along cleavages. Ilmenite and magnetite are altered to aggregates of coarse, euhedral anatase (plate polarised light) scale bar = O.5 mm.

Plate 8



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FIELD EXCURSION TO SOUTH SHROPSHIRE.

Leader: J. Moseley. Sunday 31st May, 1981

Introduction

The oldest rocks exposed in this area (text-fig.1) are late Precambrian calc-alkaline volcanics (the Eastern Uriconian) that evolved in a marginal continental setting and may be underlain by basement rocks of Rushton schist or of Malvernian type. These volcanics are succeeded by very late Precambrian or early Cambrian (529± 6 ma, Bath, 1974) sedimentary rocks (the Longmyndian) that were tilted and perhaps folded into an isoclinal syncline (text-fig. 2, James, 1956, Greig, *et al.*, 1968) by pre-Lower Cambrian earth movements. The Longmyndian sedimentary pile indicates estuarine and molasse sedimentation probably within a broad, shallow trough. Part of the near vertical Longmyndian succession forms the plateau west of Church Stretton known as the Long Mynd.

In the Comley area (text-fig. 1, G.R. SO 485 965) marine Cambrian rocks rest unconformably on folded and faulted Precambrian, while west of the Long Mynd Cambrian rocks are not exposed. Movement on the Church Stretton Fault Complex during Ordovician times may have influenced sedimentation. Only marine Tremadocian and Caradocian sediments were deposited east of the Long Mynd on the stable Midland block while to the west on the margin of the Welsh Geosyncline there is an almost complete Ordovician succession that has suffered post-Caradocian – pre-Middle Llandovery folding (text-figs. 1 and 2). The Church Stretton Fault Complex is a major N.E.–S.W. trending structural element that has been active intermittently from late Precambrian to early Mesozoic times.

Silurian sedimentation commenced in Middle Llandovery times with a marine transgression that deposited fossiliferous pebbly sands unconformably on earlier rocks. Isolated patches of these ancient beach deposits flank the slopes of the Long Mynd which was an emergent block during the Silurian. Succeeding fossiliferous, marine Wenlock and Ludlow shales and limestones crop out in the Church Stretton Valley and extensively south and east of the Long Mynd, forming scarp and vale topography.

Hope Bowdler

The first locality (G.R. SO 4743 9244), previously recommended as a Site of Special Scientific Interest, shows an unconformable contact between fossiliferous Caradocian shales, known locally as the Harnage Shales, and Eastern Uriconian Volcanics. Although no fossils were found by the party these thin, grey shales have yielded a shelly fauna of trinucleid trilobite fragments and brachiopods. This locality lies east of Church Stretton on the margin of the Midland Block (see introduction).

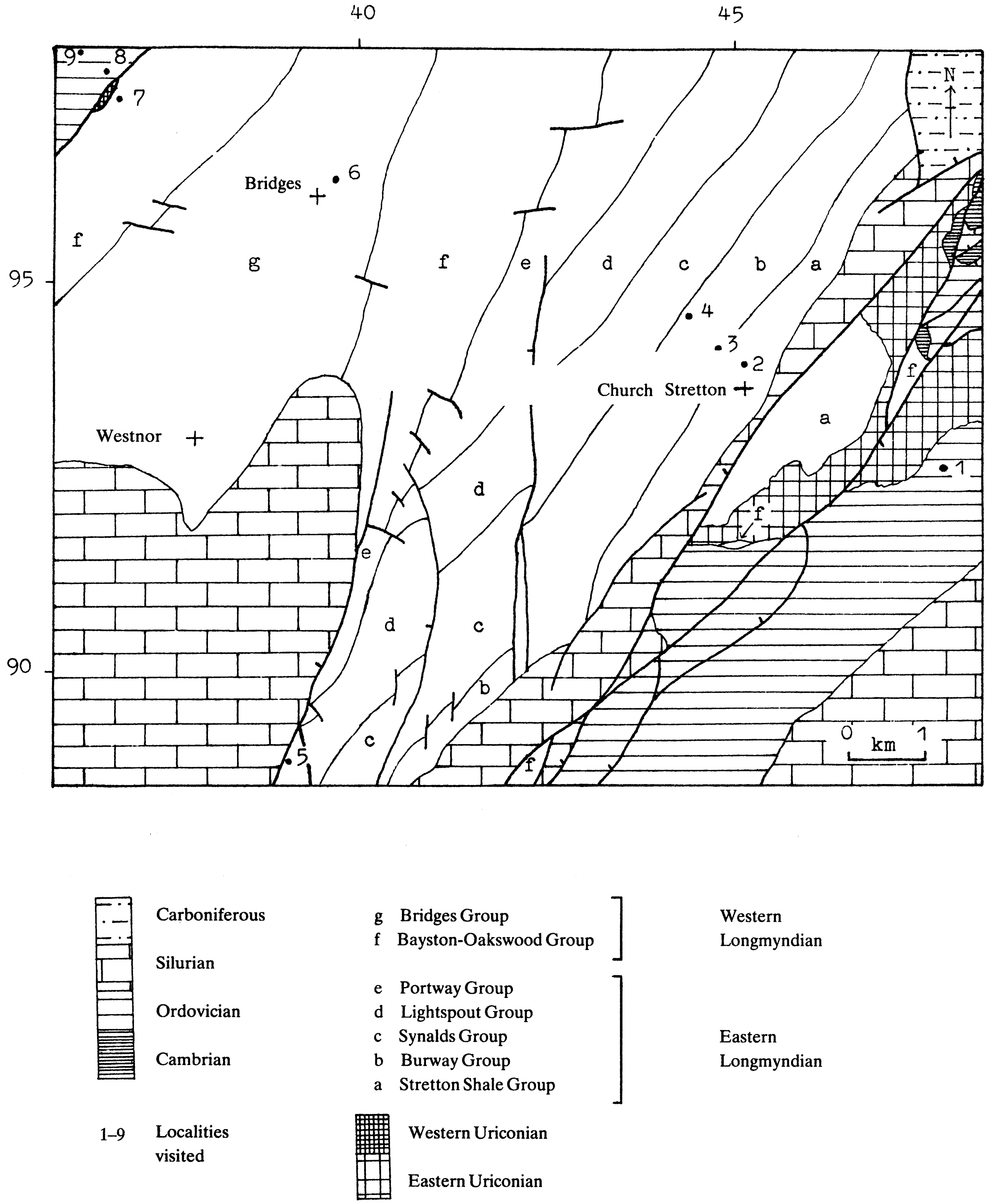
Church Stretton and Cardingmill Valley

The party moved into Church Stretton to examine the lower parts of the Eastern Longmyndian succession that crop out alongside the Burway Road. The Stretton Shale Group (c. 900 m) is the lowest division of the Eastern Longmyndian and at locality 2 (G.R. SO 4523 9388) the more thinly bedded of these grey shales show the development of kink bands and some less angular minor folds. Kink bands are only developed in this Group and are thought to represent an incompetent response to local and/or regional folding or movement on the adjacent Church Stretton Fault Complex.

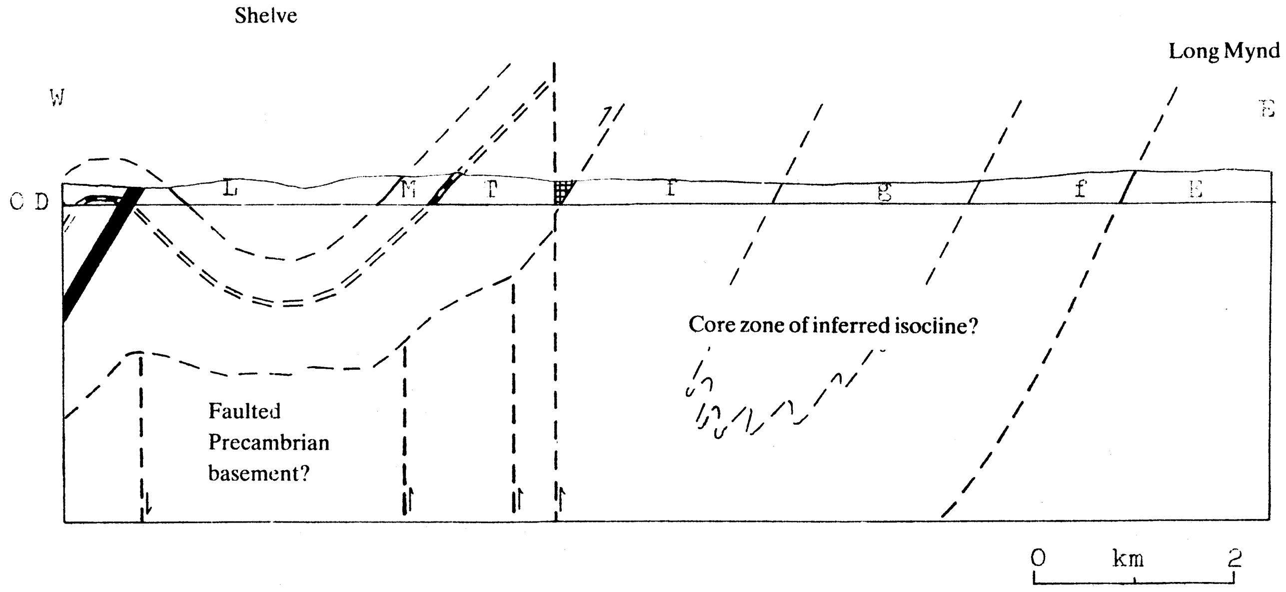
Overlying the Stretton Shale Group at the base of the Burway Group (c. 600 m) is the Buxton Rock (7 m) which is a thickly bedded, silicified, rhyolitic dust tuff that has been used as a stratigraphic marker. At locality 3 (G.R. SO 4485 9412) bedding (45°/285°) and vertical jointing (main trends are 000°, 070° and 290°) in the Buxton Rock are well developed. The predominantly vertical joint pattern is in strong contrast to that observed later in the day near Bridges in the core zone of the inferred, isoclinal fold.

The excursion moved up part of Cardingmill Valley (locality 4, G.R. SO 4446 9449 to 4378 9501) which is one of the narrow, steep-sided valleys that cuts the Long Mynd plateau approximately at right angles to the strike of the highly inclined Eastern Longmyndian strata. Thickly bedded grey siltstones, near the top of the Burway Group, are exposed in the stream bed (G.R. SO 4434 9451) but the Cardingmill Grit, a massive greywacke that marks the top of this Group was not seen. The succeeding Synalds Group (500-850 m) was seen to consist predominantly of well-cleaved purple shales with thin tuffs near the top which are used as stratigraphic markers.

Mercian Geologist, vol. 9, no. 1, 1983
pp. 49-54, 3 text-figs.



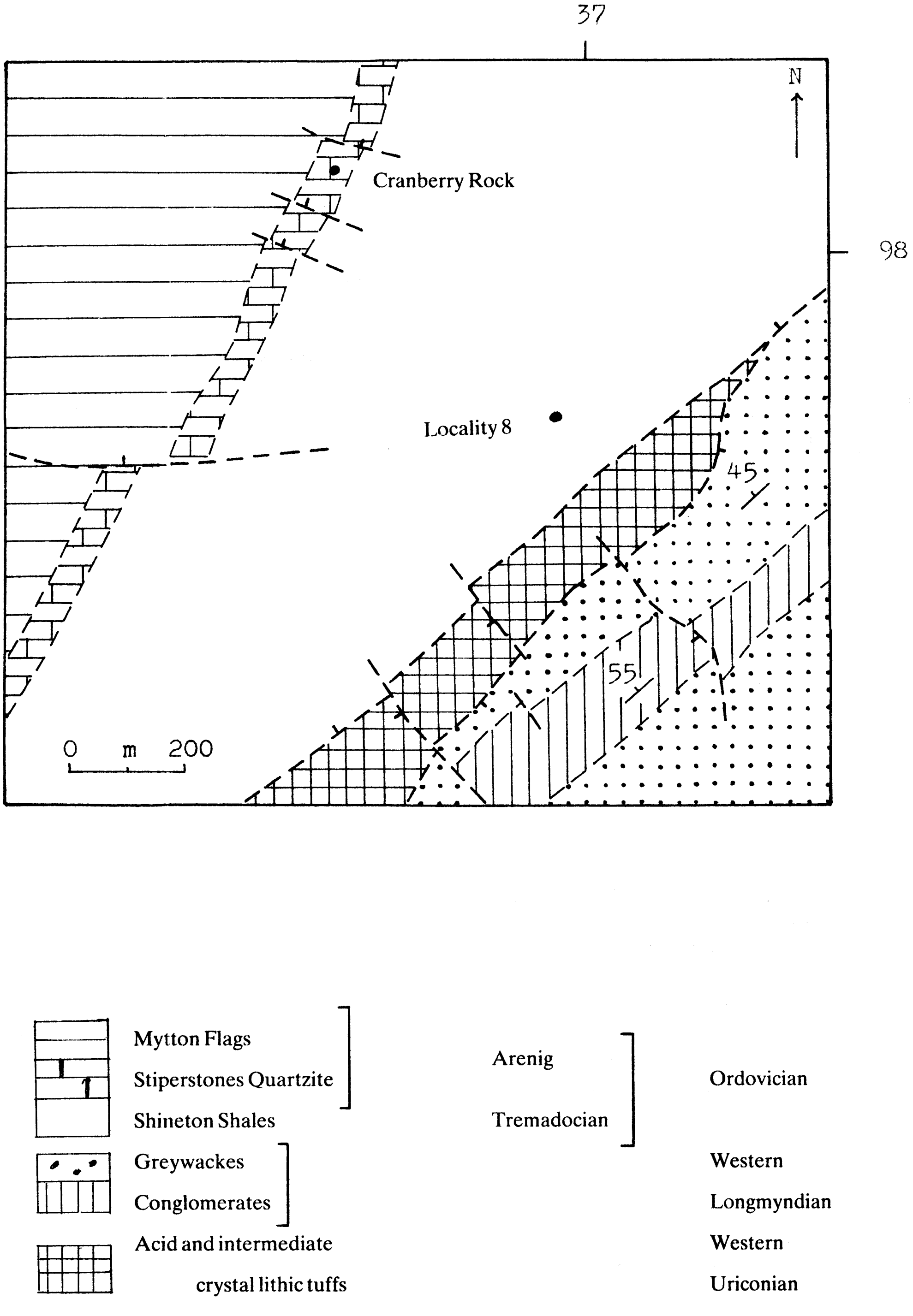
Text-fig. 1: The Geology of the Bridges and Church Stretton area



L	Llanvirn Series		ORDOVICIAN
M	Mytton Flags	Arenig	
▬	Stiperstones Quartzite		
T	Tremadocian		
g	Bridges Group		PRECAMBRIAN
f	Bayston–Oakswood Group		
E	Eastern Longmyndian		
	Western Uriconian		

▬ Dolerite (Post–Caradocian – pre–Middle Llandovery)

Text-fig. 2: Diagrammatic section from Shelve to the Long Mynd



Text-fig. 3: The Knolls and Cranberry Rock

The Western Scarp of the Long Mynd

Departing from the Church Stretton area the party travelled southwestwards and then around the southern tip of the Long Mynd. The steep western slope of the Long Mynd is a fault scarp and at locality 5 (G.R. SO 3891 8879) an angular unconformity between near horizontal, fossiliferous, conglomeratic, Middle Llandovery sandstones and purple shales of the Portway Group (up to 1100 m) that dip at 72°/310° was observed. The Silurian sandstone represents an ancient beach deposit, laid down on an irregular Precambrian surface by the Middle Llandovery marine incursion that was widespread over the Welsh Borderlands. The Middle Llandovery sandstone contains pebbles derived from Longmyndian conglomerates and there is some malachite staining of the Longmyndian shales.

Bridges

The party travelled via Wentnor village to Bridges (G.R. SO 3937 9644) where purple siltstones of the Bridges Group (Western Longmyndian) crop out in the core zone of the inferred isoclinal syncline (text-fig. 2, James, 1956, Greig, *et al.*, 1968). At locality 6 (G.R. SO 3967 9635) these siltstones dip at 75°/282° and are cut by joints dipping at 25°–35° N and 30°–65° S which is in contrast to the mainly vertical jointing developed in the Eastern Longmyndian. The joint patterns are difficult to interpret but it is an interesting coincidence that inclined joints are predominant over vertical ones only in the inferred fold core, this having been established on age-sequence reversals (Greig, *et al.*, 1968). The Western Longmyndian strata is not well exposed and in the light of existing evidence the possibility of a major synclinal structure may be questionable.

The Knolls and Stiperstones

From Bridges the excusion moved west to the Knolls (locality 7, G.R. SO 373 977) where silicified acid and intermediate crystal lithic tuffs (Western Uriconian) are faulted against Western Longmyndian greywackes and conglomerates of the Bayston-Oakswood Group. There is some brecciation (G.R. SO 3732 9769) of these rocks with malachite barytes mineralization (G.R. SO 3702 9736). The faulting is part of the Pontesford-Linley Disturbance that forms the western boundary of the Longmyndian block and brings Precambrian against Ordovician (text-figs. 1, 2 and 3). A small outcrop of the Shineton Shales (Tremadocian, G.R. SO 3691 9769, locality 8) was examined before the party walked to Cranberry Rock (locality 9, G.R. SO 3656 9811) on the Stiperstones.

Very resistant Arenig arenites (90 m) known locally as the Stiperstones Quartzite form the distinctive Stiperstones ridge with its jagged crags. The white-weathering arenites overlie with slight unconformity the Shineton Shales (at least 900 m) and are succeeded by the Mytton Flags (1100 m). They exhibit conglomeratic horizons, cross-bedding and oscillation ripples and have been used locally as a building stone. From the Stiperstones ridge there is an excellent view westwards over the Shelve area which is scarred by derelict lead-zinc mines. In this area, unlike that east of the Long Mynd (text-fig. 1, introduction and locality 1), there is an almost complete Ordovician succession consisting of graptolitic shales, greywackes, tuffs and the Stiperstones Quartzite. This strata is folded into the N.E.–S.W. trending Ritton Castle Syncline and Shelve Anticline and these post-Caradocian folds are cut by pre-Middle Llandovery dolerite intrusions (text-fig. 2).

The party rejoined the coach and began the return journey, passing through Shelve and Shrewsbury.

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J.B. Moseley
27, Dale Avenue
Longton
PRESTON, PR4 5YJ

EXCURSION REPORT

THE PLEISTOCENE DEPOSITS OF SOUTH LEICESTERSHIRE / NORTH WARWICKSHIRE

Leader: R.J. Rice — Sunday, 27th September, 1981

A party of some 25 members was met by the excursion leader at Leicester. It was explained that the primary objective of the day's excursion was to examine the stratigraphy and lithological character of the thick sequence of Pleistocene sediments that underlie the watershed between the Avon and Soar catchments in south Leicestershire and north Warwickshire. As Shotton orginally argued nearly thirty years ago, the present-day drainage system dates only from the withdrawal of the last ice sheet to cover the East Midlands. Prior to that, much of the area now drained by the Avon formed part of the catchment of a northeastward-flowing "proto–Soar river" (Shotton 1953).

The earliest extensive deposit now preserved beneath the modern watershed (text-fig.1.) is the Baginton–Lillington Gravel and the Baginton Sand. This water-laid sequence is interpreted as the product of sedimentation by the proto-Soar river. It is normally succeeded by the Thrussington Till, a reddish diamict of northern or northwestern derivation. The glacial advance responsible for this ice-deposited material apparently reached a line some distance south of Coventry. It was a subsequent withdrawal of the ice front that permitted pro-glacial Lake Harrison to develop very widely across northeastern Warwickshire and adjacent parts of Leicestershire. The Bosworth Clays and Silts that accumulated in this ponded water exhibit local prominent lamination and occasional iceberg-rafted drop-stones. A further alteration in environmental conditions is attested by an upward change into the Wolston Sand and Gravel. This widespread stratum displays an upward coarsening at many individual sites and a regional pattern of increasing fineness towards the southwest. It is interpreted as a sandur (Douglas 1980) laid down by meltwater flowing from an ice front located over central Leicestershire. Thereafter the ice readvanced and laid down the Oadby Till, a very extensive deposit that contains substantial quantities of debris from northwesterly sources, notably chalk, flint, oolitic limestone and Lias limestone.

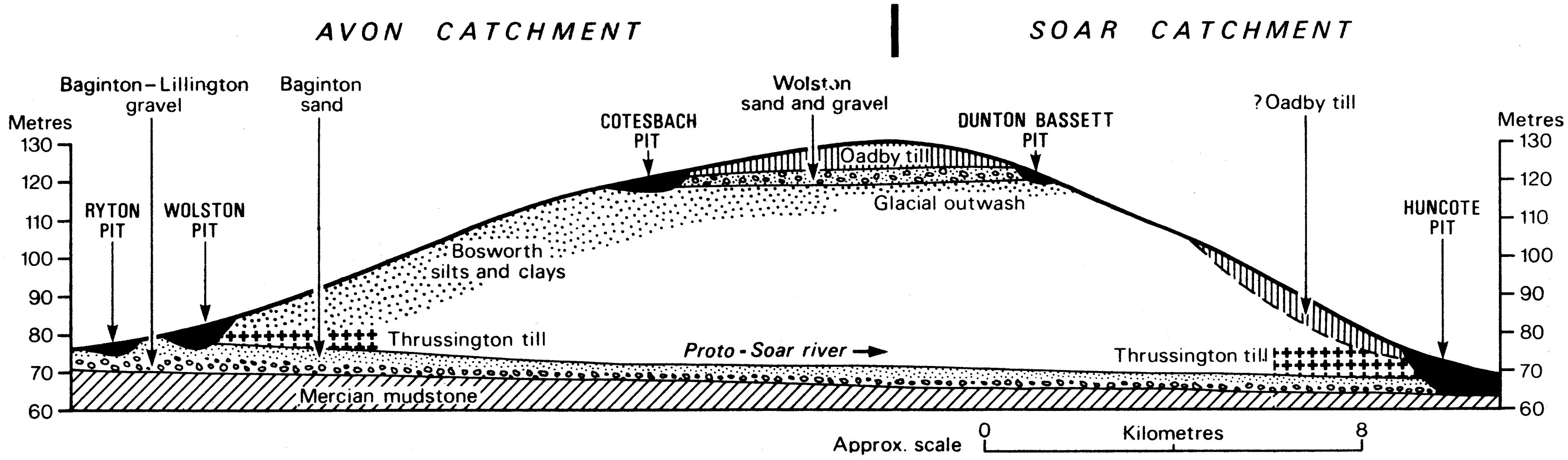
It was decided to start the excursion at the most southerly site to be visited and progressively work northwards across the watershed. To this end the initial journey was along the M69 to Coventry. Today there is very little to be seen in the motorway cuttings, but whilst the engineering work was in progress a number of valuable sections, augmented by borehole evidence, cast additional light on the local stratigraphy (Shotton 1976, Rice 1981a). Five sand and gravel pits were then visited.

1. **The Ryton pit** (SP 387736)

The above grid reference indicates the position of one of the operating faces of a series of pits where, for several decades, Blue Circle Aggregates Ltd., have worked the Baginton-Lillington gravel and the Baginton sand. At the time of the excursion up to 4m of reddish, crossbedded sand was well exposed, but there was no clean face in the underlying gravel. However, it was evident from some of the flooded workings that the gravel rests directly on a bedrock of Mercia Mudstone, and that it is composed almost entirely of pebbles possibly of one the pebble beds of the Sherwood Sandstone Group. The provenance of such material poses a problem since there are no obvious pebble bed outcrops from which the stones could have been derived, and the most likely local source appears to be an earlier till sheet of which only very sporadic traces have ever been found (the Bubbenhall Clay of Shotton 1953). Two aspects of the sand drew comment. The very clear current–bedding should permit an assessment of the water-flow direction at the time of accumulation. It may not satisfy the scientific purist, but there was virtual unanimity among the party that, on the face then visible, the flow appeared to have been towards the northeast i.e. in the opposite direction to the modern Avon and in conformity with the concept of a proto-Soar river. A number of vertical structures transgressing the current –bedding were noted. Some of these appeared to be little more than minor contraction cracks that had filled with sand, but at least one, by virtue of its width and association with deformed bedding, merited recognition as an ice-wedge cast. However, since there was no later sediment across the top of the wedge it was impossible to be sure when it was formed.

2. **The Wolston pit** (SP 410748)

One reason for visiting this abandoned pit, which is the type section for the Wolstonian stage of the British Pleistocene (Mitchell *et al.* 1973), was to demonstrate that mere designation as a Site of Special Scientific Interest is no guarantee of a well preserved exposure! Heavy rain prior to the excursion had caused serious slumping of the small residual face left by extensive tipping of waste. However, it did prove possible to recover samples of both the Thrussington Till and the Bosworth



Text-fig. 1: A sketch section through the main Avon–Soar watershed, indicating the relative positions of the five sand and gravel pits visited in the course of the excursion

Clays and Silts that here overlie the Baginton Sand, and thus to offer an opportunity for comparing these two sediments that can prove difficult to separate where exposures are poor.

Following the visit to the Wolston pit, lunch was taken in the village of Brinklow.

3. **Cotesbach sand and gravel pit** (SP 525820)

This first stop after lunch was still on the southern slopes of the Avon–Soar watershed. The Cotesbach pit of Steetley Construction Materials Ltd. displays the Wolston Sand and Gravel, up to 4.5m thick, resting on Bosworth Clays and Silts and capped by the Oadby Till. At the time of the visit the clays and silts were seen to be clearly laminated, the most obvious difference from those earlier examined at Wolston being their grey rather than reddish brown colour. This appears to reflect an input of fine Liassic detritus that proportionately increases both upwards in the succession and eastwards in the regional distribution. The gravel was similarly noted as having a very different composition from the Baginton–Lillington Gravel seen earlier at Ryton. It was soon discovered that, in addition to flint and oolitic limestone, fossils derived from various lower Jurassic beds are easily collected!

Owing to wet conditions underfoot, access to the main working face was difficult but at least one large ice–wedge cast extending to the top of the gravel was observed. This confirmed the report of cryoturbation at the same stratigraphic horizon during construction of the M1 (Poole *et al.* 1968) and updates the statement by Rice (1981b) that no periglacial fetures have yet been seen at Cotesbach. One further aspect of the face that drew comment was the gentle but obvious cambering of the sand and gravel towards the nearby valley.

4. **Dunton Bassett sand and gravel pit** (SP 541901)

This abandoned pit, formerly worked by Bruntingthorpe Gravels Ltd, was the first site visited within the Soar catchment. The sand and gravel is a northward continuation of that examined at Cotesbach and the major difference between the two locations is the large–scale glaciotectonic folding and faulting that affects the material at Dunton Bassett. The main face is now so degraded that it was chosen with some hesitation for the present excursion. However, the leader was greatly reassured by the way the members of the party still managed to identify for themselves the dominant structures. The face has been described and illustrated in a recent publication (Rice 1981a)and further elaboration here is unnecessary. It will suffice to note that, after accumulation of the sandur represented by the Wolston Sand and Gravel, the southward readvance of the ice caused severe disruption of all the earlier sediments over a broad zone of south Leicestershire; the Dunton Bassett pit is simply the most dramatic demonstration of this fact.

5. **Huncote sand and gravel pit** (SP 514982)

The final pit to be visited, currently worked by Acresford Sand and Gravel Ltd, offered the opportunity to compare the Baginton–Lillington Gravel and Baginton Sand as exposed in the Soar catchment with the corresponding sediments seen earlier in the day at Ryton. Even the brief examination allowed by the time schedule served to confirm significant likenesses in terms of overall succession, composition and sedimentary structures. However, it was the overburden of the sand that attracted most attention from the party. This overburden was seen to consist of a thin reddish till at the base, followed by a much thicker suite of grey chalky tills. Detailed sketches of earlier faces have already been published (Rice 1981a and c), but at the time of the visit a striking new exposure was visible. This showed the chalky material to consist of at least half a dozen layers of greyish till, varying in thickness from less than half a metre to over two metres, and differing in appearance mainly by slight colour variations but possibly also in stoniness. There were no obvious contrasts in the derivation of the erratics, and apart from some thin sandy partings, nothing but till throughout most of the sequence. Discussion centred on whether such a till series could be produced sub–glacially rather than in an ice–marginal position by the superimposition of flow–tills. In a small isolated face a further noteworthy aspect of the overburden was seen since intricate folding of the layered chalky tills had undoubtedly inverted part of the succession. This again suggests that advance of the ice responsible for the Oadby till caused very widespread disruption of earlier sediments.

On the return to the coach, thanks were conveyed to Dr. Rice for his leadership of the excursion. He would now like to take this opportunity of thanking the members of the party for their support, and also of expressing his gratitude to the

various owners for granting access to the pits.

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LETTERS TO THE EDITOR

THE TEMESIDE BONE–BED AND ASSOCIATED SEDIMENTS FROM WALES AND THE WELSH BORDERLAND – Reply, to letters published in the *Mercian Geologist, vol. 8, no. 4,* pp. 311–315, received from D.D.J. Antia.

Dear Sir,

I would like to thank Drs. Lawson, White and Squirrel for their comments on the above paper, published in vol. 8 no. 3 pp. 163–216 of the Mercian Geologist. Typographical and other errors were printed on p. 316 of vol. 8 no. 4, Mercian Geologist. Other points raised were as follows:

Localities. Dr. Lawson suggests that the Downton locality reference p. 166 is incorrect. The location to which I referred is a sandstone quarry about 1 km east of the Downton Castle Bridge along the River Teme on the south side of the river. The Downton Castle Bridge locality described by Elles & Slater (1906) and referred to by Dr. Lawson exposes a section across the Downton Castle Formation to the Overton Formation boundary.

Ozarkodina remscheidensis. (a) The conodont specimen recorded (which is still retained by Dr. Aldridge at Nottingham University) is the earliest known and only published record of this species in the Welsh Borderlands. It is clearly stated on pp. 174 and 182 that I only found a single specimen of this conodont.

(b) My reasons for stating on p. 176 that the specimen indicates a possible lowest Gedinnian age for the section may be amplified as follows:

When I first examined this section, which had been assigned to the Temeside Group by Elles & Slater (1906), I was surprised to find well developed palaeosols and other sedimentary features which would indicate a correlation within the lithologically defined Ledbury Formation of Allen (1974a). I presumed at this stage that the ostracod faunas which were typically found in the Temeside Group (Elles & Slater, (1906); Shaw, 1969)) would also be recorded in this section. However the fossils recorded (p. 174) included a rare but diverse fauna of smooth calcareous ostracod carapaces and valves belonging to species not normally found in the Temeside Formation (Shaw, 1969). They suggested a possible Upper Downtonian age for the section layers 1 – 11 (cf. Copeland, (1964)). This age assignment for the section is consistent with the record of a *Hemicyclaspis murchisoni* fish fauna (Elles & Slater, 1906) in the Temeside Bone–Bed (cf. Dineley & Loefler, 1976, p. 52). The thelodont – cephalaspis fauna recorded contained fairly typical Downtonian thelodont species (cf. Turner, 1973), many of which are also found in the Ludlovian. I wrote (p. 129, 182) that in the Temeside Bone–Bed:

> "The vertebrate remains are black in colour and are highly weathered (see Antia, 1979a) and highly abraded. An X.R.D. analysis of these grains shows that they are made up of a pure carbonate apatite, while the vertebrate remains in the underlying red beds are a translucent yellow colour suggesting that they might be made of a fluorapatite enriched in organic debris (Antia 1979a). Similar colour variations have been recorded elsewhere in the geological column on fish debris, but not interpreted (for example, the Triassic – see Sykes & Simon, 1979). The most likely explanation for the highly corroded, worn and weathered nature of these fish scales, which appear opaque black in all three bone–beds, is that they have been eroded out of underlying red beds and have been redeposited in the vertebrate lags in which they are now found, suggesting that the layer 12/layer 11 boundary may represent a disconformity and that an unknown amount of sediment may have been removed. It is interesting to note that the conodont specimen was unworn and had a translucent fresh appearance suggesting that it might be a contemporary fossil of bone–bed BK1 age, unlike the fish which were almost certainly reworked from an older sediment."

If this conclusion is valid and the layer 12/layer 11 boundary represents a faunal as well as a sedimentological disconformity, then the conodont and plant remains recorded may be the only contemporary fossils of bone–bed BK1 age. When Dr. Aldridge first identified the conodont in 1978 he suggested that it could be of Gedinnian age. If this interpretation is correct then it is probable that the disconformity represents the Siluro – Devonian boundary as I suggest (p. 182). However, the presence of this conodont by itself is certainly not diagnostic of a Devonian age as Dr. Lawson rightly asserts. Its range extends from the highest Silurian into the Devonian. My own examination of the relevant literature during 1978 and 1979 pertaining to this species suggested that it was generally more abundant in Devonian conodont assemblages than in those of the highest Silurian. Consequently, a solitary conodont specimen found in highest Silurian sediments is less likely to be *Ozarkodina remscheidensis* than one found in lowest Devonian sediments. After considering both the sedimentological and

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pp. 59-64.

faunal data collected from this section I concluded that it is probable that the layer 11/12 boundary represents the Silurian - Devonian boundary.

However, as discussed, the evidence for this assignment is in part circumstantial, and the pure faunal evidence only supports the conclusion that the sediments in the section are of late Silurian age or younger. It is obvious from both this discussion and Dr. Lawson's comments that much more palaeontological and sedimentological work needs to be done in the Welsh Borderlands on the Ledbury and overlying Formations before the position of the Silurian – Devonian boundary can be identified with certainty in this region.

Fourth Silurian Series. There is no statement made in my paper (as Dr. Lawson contends) that the name Downtonian is no longer a contender for the fourth Silurian series. Indeed I even published a lengthy paper (Antia, 1980a) on the sedimentology and palaeontology of the type section at Ludlow of the Ludlow – Downton Series boundary as defined by Holland *et al.* (1963) and use the term throughout my paper (e.g. pp. 168, 176, 184, 185, 192, 194, 195, 196, 200, 201, 207). However, as noted (p. 168) an increasing number of authors are using the term 'Pridoli Series' in preference to the term 'Downton Series'. Many of them (e.g. Leggatt, 1980) are using the former term as a synonym of Downton Series when applied to the Welsh Borderlands, despite palaeontological evidence that the position of the bases of the two series, as currently defined, are not identical (Kaljo, 1978).

Lithostratigraphy. Recently Drs. Holland, Lawson, Walmsley and White (1980) renamed a number of essentially faunally defined stratigraphical units (identified in the late 1950's by Holland, Lawson and Walmsley (1963)) by replacing the suffix 'Bed' by 'Formation', thus implying that the units were lithologically defined. These units were originally defined using stratigraphical principles which were in widespread usage in the early part of this century but are outmoded by modern standards. The principal fault (by modern standards of these various stratigraphers was their reluctance to distinguish separate biostratigraphical and lithostratigraphical units. They defined units mainly on fauna but took some account of lithology in their unit definitions. As a result there is a proliferation of stratigraphical terms relating to locally mapable units throughout the Silurian of the Welsh Borderland and with unit names and definitions changing at the boundaries of the various authors' particular area of study. Cocks *et al.* (1971) have attempted for the Welsh Borderland to show how each of these locally defined units fits within the general Silurian chronostratigraphy as outlined by Holland *et al.* (1959, 1963). Cocks *et al.* (1971) correlation was helped to a large extent by the fact that main fossil distributions appeared to be the chief factor in determining the boundaries of locally defined stratigraphical units. However, serious difficulties have arisen in applying Holland *et al's.* terminology in the Welsh Borderland. Phipps (1962, 1963), Phipps & Reeve, (1967) outlined some of the difficulties in attempting a correlation within the Welsh Borderland and using criteria defined by Holland *et al.* (1963). Their basic conclusion was that it is impossible to use the 'new' type stratigraphy (Holland *et al.*, 1959, 1962, 1963) in its present form. The main difficulty was caused by Holland *et al's.* refusal to recognise both biostratigraphic and lithostratigraphic units. A typical example of the serious difficulty so caused is quoted here from Phipps & Reeve, 1967, pp. 352–353:

> "According to Holland *et al.* (1962, 1963) the Aymestry Limestone is a rock stratigraphic unit which cuts obliquely across the boundaries of their new "combined units" (1962, 396). However, they insist that their "combined units" are based upon both biostratigraphic and rock stratigraphic criteria, such that we have the position where a rock stratigraphic unit cuts obliquely across another rock stratigraphic unit! In addition, the Aymestry Limestone is clearly diachronous. In the Bradlow district the upper 40 ft of the Aymestry Limestone yields a typically Mocktree (or Leintwardine) fauna, i.e. these 40 ft are characterized by the lithology of the Upper Bringewood Beds and the fauna of the Lower Leintwardine Beds of Holland *et al.* (1959). Because Holland *et al.* (1962) insist that their "combined units" are rigorously defined on the basis of both biostratigraphic and rock stratigraphic characteristics, it follows that these 40 ft have no equivalent in the Type Area and no correlation is possible. This difficulty would disappear if a dual classification existed for the Type Area. If the Bringewood Beds and Lower Leintwardine Beds were properly distinguished as biostratigraphic zones, and were given biostratigraphic names, it would be possible to demonstrate that the top of the Aymestry Limestone in the Bradlow district crossed a zonal boundary.
>
> The same difficulties apply equally when attempting correlations with other of the "combined units". Because they are all defined on the basis of both biostratigraphic and rock stratigraphic criteria, they cannot exist outside of the Type Area whenever there is a change in facies or where diachronism takes place. This would require complete new sets of local names whenever it occurred. This proliferation of local names could be avoided if the Type Area revision provided both biostratigraphic and rock stratigraphic units."

It should be stressed that *Holland et al.* have not yet replied to these serious objections and do not consider them in their recent paper (1980). My introduction (Antia 1980b) of lithostratigraphic terms (e.g. Overton Formation) was intended to supplement the biostratigraphy of Holland *et al.*(1959, 1962, 1963) to allow a more rigorous approach to be made in the understanding of the region. Holland *et al's* (1980) introduction of biostratigraphically defined 'Formations' in the region does little to aid the understanding of the overall sedimentology, stratigraphy and palaeoenvironments and will hinder geological research in these areas.

Ledbury Formation/Temeside Formation. Dr. Lawson has kindly clarified his understanding of the terms, Ledbury Formation, Downton Castle Formation and Temeside Formation. His usage of the terms strictly conforms to the old stratigraphical system of Elles & Slater (1906) and Holland *et al.* (1963). Their definitions have been largely superceded by a modern sedimentologically defined lithostratigraphy outlined by Allen (1974a), who has adapted existing names like Temeside Group or Downton Castle Sandstone and defined proper lithostratigraphic formations. This usage can create unnecessary confusion. In addition to this lithostratigraphic revision Shaw (1969) defined biostratigraphical ostracod zones in the Downtonian which can be correlated with similar well defined ostracod zones in Nova Scotia (e.g. Copeland, 1964). Between them these two papers have completely transformed the pre-existing concepts of the British Downtonian and provided a modern framework for research. The two sections described in my paper, which Elles & Slater (1906) recorded, were both originally assigned to the Temeside Shales. The Onibury section contains undisputed intertidal sediments representing the Temeside Formation (Allen, 1974). However, the Temeside Bone-Bed section contains 'supertidal' sediments and palaeosoil horizons which are characteristic of the Ledbury Formation (Allen 1974). Murchinson's (1852) drawing of the river section is far more complete than any currently exposed and is more complete than that documented by Elles & Slater (1906). This section reproduced on p. 164 (Antia, 1981) clearly shows the red bed sequence described (p. 172–182) and indicates that they occur just below the base of the main red bed sequence in the area. The stratigraphical position of this unit with respect to both the Downton Castle Formation and the Ludlow Series is confused by the presence of a fault (Antia, 1981b, p. 164) across which **accurate** field mapping correlation is not currently possible. The sediments within this section show some similarity with leveé deposits and hydromorphic soils deposited in Devonian alluvial plains and could be interpreted as such. However, the presence of marine microfossils in the sequence suggests that the marginal marine environment outlined (Antia, 1981b) is perhaps a more probable explanation.

I do not dispute the occurrences of the Temeside Formation in the vicinity of Downton Castle (as documented by Allen, 1974). However, I was pointing out that in the Quarry at Downton this Formation is absent and that the Ledbury Formation rests directly on the Downton Castle Formation. This observation shows that locally in the Downton – Ludlow region the Temeside Formation is absent, and that some diachronism of the Downton Castle and Ledbury Formations may occur, a point not demonstrated before in the area and important because it shows that the Temeside Formation may always be expected to occur as a mappable unit.

The Brewins Bridge canal section, which I first visited in 1977 with Dr. Lawson, consists of two exposures split by a canal. The inaccessible exposure (from the point of view of sediment sampling and section examination) containing the Temeside Bone-Bed is a cliff going down to water level which can be adequately sampled while suspended from ropes. The easily accessible part of the section on the opposite bank of the canal, exposes an igneous body and a few feet of red shales. The bone-bed is not exposed in this part of the section. The Ludlow railway cutting section was not exposed during 1976–78 inclusive.

Fossil identifications and location of collections. Fossil identifications were made with reference to identified material and collections at Ludlow Museum; Geological Survey Museum, London; the Natural History Museum, London; I.G.S. North Acton Rock Store; and Leicester University. Original species descriptions were examined and reference made to appropriate experts: macrofossils – chiefly Dr. Lawson; ostracods – Dr. Siveter; conodonts – Dr. Aldridge; thelodonts – Dr. Turner. In mid 1979 the collection was edited to 20 – 30 Admat boxes of fossiliferous material at Dr. Lawson's request. Subsequently, Dr. Lawson kindly arranged despatch of this remaining material from Glasgow University to the National Museum of Wales, Geological Survey Museum and Ludlow Museum in mid 1980. Prior to their despatch some boxes of specimens (including the Cennen Beds samples) were lost. I have deposited in Ludlow Museum petrographic slides, microprobe slides, microfossil collections, photographic record of sections, S.E.M. photographic negatives and macrofossil photographic negatives, including photographs of key fossils in the Cennen Beds collection.

Sedimentology. Dr. Lawson questions the reliability of my sedimentological conclusions. They are broadly in agreement with those of Professor J.R.L. Allen who has spent many years studying the sedimentology of the highest Silurian/lowest Devonian sediments of Wales and the Welsh Borderland (e.g. Allen 1974(a)), but differ in interpretation from many earlier (pre 1970's) studies in detail. For example Hobson (Ph.D thesis, 1963, Birmingham University) suggested that the Downton Castle Sandstone was a deltaic deposit; whilst this may be true in South Wales and the Malvern area, which I have not studied, it is certainly not true of the Ludlow area where the deposit is a marginal marine facies. However, ideas and concepts do change and it is probable that a detailed sedimentological study will be made for the region which may produce yet another answer.

The Cennen Beds. Drs. Squirrel and White (1978) recorded a fauna of 'Leintwardinian' type macrofossils (mainly brachiopods) and an enigmatic occurrence of the Downtonian ostracod *Frostiella groenvalliana* from the Cennen Beds. Their conclusion that the sediments were of Leintwardinian age hinged on two important observations. Firstly that a fragmentary trilobite belonged to a typical Upper Leintwardinian species and secondly, that the macrofaunal assemblage which included the brachiopod *Hyattidina canalis* indicated by comparison with the Ludlow area an Upper Leintwardinian age for the sediment. The material collected by Dr. Atkins and recorded in Appendix 2 contained the fauna listed. The brachiopod ? *Brachzyga* sp. closely resembles *H. canalis* in external appearance, but has its brachial skeleton on the opposite valve to *H. canalis* (photograph in Ludlow Museum). This observation was checked by Drs. Atkins, Lawson, Lockley and Burton. Dr. Burton, after much thought, suggested a possible assignment to *?Brachzyga* sp.with which I concur. The fossils assigned to *Protochonetes* cf. *missendensis* or *P.* cf. *novascoticus* differed principally from the typical Ludlovian brachiopod *P. ludloviensis* in having a very rounded junction where the hingeline and commissure meet. (Photograph in Ludlow Museum). I have only seen one *Protochonetes* specimen like it in the Ludlow area. This specimen was in the Downton Castle Formation of Deepwood, Nr. Ludlow (locality described by Holland *et al*, 1963). The remaining macrofossils recorded could also be found in Leintwardinian sediments. The ostracod fauna recorded contains two positively identified species, *Frostiella groenvalliana* (also recorded by Squirrel and While, 1978) and *Londinia kiesowi* (photograph in Ludlow Museum). The *Londinia* species is not diagnostic of age and has been recorded in the Ludlow – Corvedale region in Ludfordian and Downtonian sediments (Antia 1979b, 1980b). The *Frostiella* species has been recorded in a wide variety of environments throughout the Baltic, Scandinavia and Britain and was generally considered (until Squirrel and White's 1978 paper) to have been a diagnostic biostratigraphic indicator of the Downton Series (e.g. Shaw, 1969). As a result, Squirrel and White were presumably placed in a paradoxical situation, either they believed the trilobite identification and assigned a Leintwardinian age to the fauna or they believed the undisputed *Frostiella groenvalliana* identification and assigned a Downtonian age to the section. Drs' Squirrel and White took the former option. However the Leintwardinian type macrofossils recorded by Squirrel and White and in Appendix C could during the Downtonian have been restricted to the very sandy 'high energy' environment presented by the Cennen Beds facies. Alternatively, since the base of the Cennen Beds is an undisputed unconformity it is possible (but probably less likely) that the fossils (which all occur in a shell laminae) were reworked out of Leintwardinian sediments. (Whitaker (1962) has recorded reworked Ludlovian macrofossils in Ludfordian sediments in the Leintwardine area). Such an interpretation would have allowed the ubiquitous species *F. groenvalliana* to have remained a diagnostic biostratigraphical indicator of the Downton Series. It is currently the only faunal species recorded (Antia, 1980a) in the type section of the Ludlow – Downton Series boundary (Holland *et al*, 1963) which appears to be restricted to the Downtonian. If Squirrel and White are correct in their assertion that the Cennen Beds are of Leintwardinian age, then the last remaining supposedly diagnostic Downtonian fossil in the type section is no longer diagnostic and it will be impossible to correlate, using macrofossils and ostracods, the Ludlovian-Downtonian Series boundary as defined at Ludlow, elsewhere in Britain or Worldwide. Drs. Squirrel and White report that Drs Turner and Dorning have recorded well preserved Ludlovian age acritarchs of equivalent age to that of the Upper Leintwardine Beds or Lower Whitcliffe Beds. They do not, however, say which acritarch species were recorded. It is well established that acritarch species (including British Ludlovian Acritarchs) can be highly facies or environment dependent, (e.g. Dorning 1981a). The Cennen Beds bears no relationship to the Lower Whitcliffian/Upper Leintwardinian facies in the type Ludlow area. As a result two conclusions are possible. Firstly, that the Cennen Beds are of Upper Leintwardinian/Lower Whitecliffian age, or, secondly the supposedly diagnostic acritarch species lived in the Downtonian environments present by the Cennen Beds. The acritarch fauna of the British Downtonian is currently unknown, due largely to the marginal marine and fluvial facies presented by it in the type area.

With regards to the usefulness of palynological versus macrofossil correlations a number of points have to be considered. Firstly, it is not uncommon for palynological and macrofossil information to contradict each other. Secondly, it is not uncommon for palynologists from different commercial concerns to come up with major series boundary identifications whose vertical position differ by several zones. Consequently, until it is unequivocably established that the acritarch species in the Cennen Beds are not present in undisputed British marine Downtonian sediments or alternatively that *F. groenvalliana* does occur elsewhere in Ludfordian sediments where the age is established by graptolites, then the age of the Cennen Beds will be open for dispute. The available but contradictory faunal evidence for these Beds as documented by Squirrel and White (1978) supports either a Ludfordian or a Downtonian age.

I hope in this reply that I managed to clarify most, if not all, the points, raised by Drs Lawson, Squirrel and White, to my paper.

Dr. D.D.J. Antia,
Exploration Dept.,
Oil & Gas Division,
Broken Hill Proprietary Co. Ltd.
Collins Tower
35, Collins Street,
Melbourne,
Australia.

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A PRINCE AMONGST AMATEURS

H. H. (ARNOLD–) Bemrose, 1857–1939

by

G. Miller

Every student of the Derbyshire igneous rocks is familiar with- and indebted to the classic papers which H.H. Arnold-Bemrose read to the Geological Society of London, 1894 and 1907. Not many, however, know that the author of them was a Derby businessman who became an amateur geologist in his mid-twenties, gained the respect of some of the greatest professionals of his day, and with their help turned himself into a first-rate petrologist and a leading authority on his own field of study.

Henry Howe Bemrose was born in Derby on March 13th, 1857 - the first child (and only son) of Henry Howe and Charlotte Bemrose. His father and his uncle, William were partners in the flourishing printing and publishing business founded by William Bemrose senior in 1826. From preparatory school at Spondon Henry Howe junior went to Denbigh Grammar School to acquire amongst other things, an affection for North Wales that was to last all his life. In 1874, at the age of 17, he went on a three-week walking tour in Switzerland with a remarkable man, the Reverend John Magens Mello, M.A., F.G.S., the Rector of St Thomas's church at New Brampton, near Chesterfield.

Mello had once been curate at All Saints, Derby, and must there have made the acquaintance of the Bemrose family. Hearty, vigorous (he continued even in old age, to go to camp as Chaplain to the Volunteers), full of good humour (he once wrote a comic history of England for his daughters). Mello was already interested in both geology and archaeology in 1874. His little 'Handbook to the Geology of Derbyshire' appeared around 1866, and a revised version ("respectfully dedicated to His Grace The Duke of Devonshire") was published by Bemrose & Sons in 1873. Two years later he was to make the archaeological discoveries at Creswell Crags in Nottinghamshire with which his name will always be associated.

From the crossing of the Rhone Glacier with Mello the young Bemrose gained an interest in glaciology that endured until his death 65 years later. In 1875 he went up to Clare College, Cambridge, as Foundation Scholar in Mathematics and took his degree in that subject four years later. University reading parties at Criccieth and family holidays at Fairbourne strengthened his love of the North Wales mountains (& Cader Idris in particular), and on his doctor's advice he became a dedicated walker. After leaving Cambridge he joined the family firm (where his first work was to introduce a proper system of double-entry book-keeping and accounting), he was initiated into the Tyrian Lodge of the Freemasons, and settled at Lonsdale Place in Derby with his parents.

Apprenticeship.

In 1880 Henry Howe Bemrose junior became Honorary Secretary to the Derby branch of the Cambridge Society for the Extension of University Teaching - a step that was to change his life in several ways. The Derby branch had been launched seven years earlier and in 1874 its syllabus had included a series of lectures on 'Physical Geography and Geology' given by Jethro Justinian Harris Teall. Teall was the posthumous son of a modest landowner in Oxfordshire. Some eight years older than Bemrose, he went up to St John's College, Cambridge in 1869, and was then persuaded to forsake Mathematics for Natural Science by his tutor, Professor T.G. Bonney. Teall took his degree (and became a Fellow of the Geological Society for London) in 1873, was made a Fellow of St John's two years later, but then devoted himself to University Extension teaching at several centres and to the petrological research which was to make him famous.

The Derby branch suspended its activities between 1875 and 1880, but when it resumed Teall returned to lecture on 'The Origin of the Rocks and Scenery of the British Isles'. The young Bemrose certainly attended these lectures - and probably Teall's further series in 1881 and 1882. Moreover, his connection with the Derby branch was to bring him a great deal more than an interest in geology, for amongst his fellow students was a Miss Ellen Hyde, daughter of the late Reverend John Hyde of Derby and Manchester, whom he was to marry nearly ten years later.

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pp. 65-74, plate 9.

In 1882 he took his M.A. at Cambridge - and with a sturdy independence of mind assumed the name of Henry Howe Arnold-Bemrose to distinguish himself from his father and so avoid the confusion of invoices and letters between father and son living in the same house. His admiration for Arnold of Rugby explains the choice of name (and perhaps his life-long preference for a cold bath before breakfast!). A year later he attended (and spoke at) a conference in Cambridge on the problems of the Extension scheme. Photography was being used at Bemrose's works in Derby from 1884 onwards, and Arnold-Bemrose was interested and involved in the process (photographs of the Tideswell Dale marble quarry were taken by him as early as the winter of 1885).

It was in that year that persuaded by Teall, he began (in his own words) "to take an interest in the igneous rocks of Derbyshire and to work out their structure by the modern method of examination of thin slices under the microscope". Teall encouraged and advised him, must have taught him the basic techniques, and lent him specimens for study (of iddingsite, for example, and Eycott Hill lavas). Arnold-Bemrose may indeed have been involved with Teall in another enterprise. The latter's 'British Petrography' started appearing in monthly parts in February 1886, but it came to a halt with the failure of the publishers. Teall was compelled, as he wrote. "to take the work into his own hands" to secure completion, and it ultimately appeared in one volume in 1888 - published by Dulau and Sons of London, but printed by Bemrose and Sons of London and Derby. It seems probable that Arnold-Bemrose was personally involved in the salvaging of this classic book, and he is also believed to have done much of the colour photography of its thin section drawings himself.

In December 1886 Arnold-Bemrose was elected a Fellow of the Geological Society of London, being proposed by Teall, Archibald Geikie, J.E. Marr and others. He attended meetings of the Society, read widely, began to collect specimens in the field (an erratic from Kedleston in addition to igneous rocks). In 1889 he bought his own Dick microscope from James Swift & Son in London (at a total cost with quartz wedge and micrometer, of £26–8 shillings). Thin sections were cut for him by a Gottingen firm in the main, with some by a Derby concern.

1890 proved to be a doubly important year for Arnold-Bemrose. First Ellen (Nellie) Hyde became his wife - indeed a true 'consort battleship' in his life and work - and they went to live at 56 Friargate, Derby. Secondly he joined the Derbyshire Archaeological and Natural History Society which already included his father and uncle amongst its members. It was to the Natural History Section of this body that on April 15th he read his first paper "Notes on the Geology of Derbyshire". In it he reviewed work-in-progress within the county - by, for instance, the archaeologists-cum-geologists (including Mello, and John Ward of Derby at Rains Cave, Longcliffe); by Sorby on the Millstone Grit; by R.M. Deeley (a Derby locomotive engineer and distant relation of Arnold-Bemrose) on the glacial drifts. He touched on the Carboniferous Limestone and the problematical Newhaven clay deposits; briefly referred to his own thin-section studies of the 'toadstones' ("I hope next year to have a paper ready on the lava and beds of fragmental rocks"); and ended with a plea for more photography of temporary rock sections (especially those on the two new railways, Buxton to Ashbourne and Dore to Chinley).

In 1891 the family firm was incorporated as Bemrose and Sons Ltd - Directors Henry Howe Bemrose, William Bemrose, H.H. Arnold-Bemrose, and William Wright Bemrose (William's eldest son). Two years later Arnold-Bemrose's first son, Karl, was born at Derby, and in the same year he contributed a long article on the Derby Company of Mercers to the Journal of the Derbyshire Archaeological and Natural History Society. Despite all the calls of business and family life, he worked away steadily at his field and petrological study of the 'toadstones'. Here he was breaking largely virgin ground. The Geological Survey's one-inch maps (revised in 1867 by Green and Dakyns) covered most of the relevant exposures with a fair degree of accuracy. But apart from some errors of detail, they simply showed 'toadstone' without distinguishing between different lava flows, pyroclastic and intrusive rocks.

The second edition of the accompanying Survey Memoir ('North Derbyshire' by Green, Foster, le Neve and Dakyns, published in 1887) improved on the maps but was still little more than a sketch. From the study of a few important sections and the observations of earlier geologists (John Alsop and J.B. Jukes, for example), the Memoir concluded that there were two main flows of 'dolerite' (with a third in places; that they were contemporaneous with the limestones; and that the 'toadstones' ranged from a vesicular lava to a bedded ash, even a coarse agglomerate. As to detailed petrological studies, these were limited to thin-sections of much altered lavas from the Matlock area in Samuel Allport's 1874 paper to the Geological Society of London, together with Teall's description of the Tideswell Dale dolerite and the Cave Dale basalt in 'British Petrography'.

To fill in this skeleton outline of the Derbyshire igneous rocks Arnold-Bemrose set off most Saturday mornings - calling at the works first and then catching a train to one of the stations on the invaluable Derby to Manchester line. From railhead he clearly had to walk considerable distances at times before returning to Derby in the evening. Confirmed pipe smoker, moderate drinker (a pint of ale at the Anglers Rest Inn in Millers Dale was a regular routine), he tramped the hills and dales in all weathers and almost always in shorts (he even wore them when dining in hall at Clare in Scout uniform!).

In addition he clearly read a good deal of geological literature and made full notes on his studies. One of his 'Daybooks (or notebooks) for 1894 still survives, with its many references to British, French, Belgian, German, American and Australian sources. His ability to read French and German was a considerable help, and as one entry shows, he would even tackle a German paper when travelling back in the train from London. Most of his reading, however, seems to have been directed towards current problems in his own studies - for instance, sedimentary dykes, siliceous limestones, quartzites, olivine nodules in basalts.

By the end of 1893 - two years later than he had hoped - Arnold-Bemrose must have finished his paper "on the microscopical structure of the Carboniferous dolerites and tuffs of Derbyshire", and heard of its acceptance by the Geological Society of London. Before he could read it, however, he learned that Sir Archibald Geikie himself proposed to visit Derbyshire to gather material for his book on 'The Ancient Volcanoes of Great Britain' (which was to be published in 1897). Director-General of the Geological Survey since 1882, knighted in 1891, Geikie was an ebullient and controversial geological giant of his day. Arnold-Bemrose at once invited him to stay at his Derby home and offered to conduct him over the ground. In due course (probably in April 1894) Geikie arrived and together they undertook what Sir Archibald himself described as a week's "scamper" - or more decorously, "rapid traverse" - through Derbyshire. By train, horse and trap, and on foot (with one night spent at Grangemill), they visited Castleton and Peak Forest, Millers Dale, Litton, Tideswell Dale, Bonsall, Grange Mill, Hopton, and Kniveton. Geikie's main interest lay in identifying possible volcanic vents, but he also looked at the lavas, tuffs and likely sills. To Arnold-Bemrose the tour was of critical importance. Not only did he have Geikie's help in distinguishing the various vents and in locating probable sills at Peak Forest and Tideswell Dale, Geikie actively encouraged him to work out the field relations of the igneous rocks, and at Grange Mill gave him a brief course in geological mapping on the six-inch scale. 'Even Homer nodded', however, and it was always a source of some private amusement to Arnold-Bemrose that in 'The Ancient Volcanoes of Great Britain', Geikie's plan of Grange Mill showed the dolerite dykes incorrectly aligned north-south instead of east-west.

On June 6th, 1894, two papers were read to the Geological Society of London - one by Geikie and Teall "on the banded structure of some Tertiary gabbros in the Isle of Skye", and Arnold-Bemrose's own contribution. In addition to its detailed petrological analyses his paper suggested several amendments to the Geological Survey maps - dropping six localities, adding the Potluck dolerite, and identifying the separate lavas and tuffs at Litton and Tideswell. It was illustrated by Arnold-Bemrose's micro-photographs of thin-sections - the results of his own experiments and the first ever to be published. Geikie was present, and in the discussion referred to his Derbyshire visit and paid warm tribute to the author.

Subsequently Arnold-Bemrose sent a copy of his paper to Bonney who added his own congratulations (but raised doubts about Geikie's identification of the Tideswell Dale sill). Arnold-Bemrose also wrote to Geikie, expressing some fears that his mapping of the area would have to be so lengthy a process that other workers might anticipate him in publication. Geikie's reply was typically breezy and reassuring -"you can practically take your own time in the research" - though he did add a warning that palaeontology must be involved in working out the limestone succession, in order to determine the sequence of lavas. So in November 1894 Arnold-Bemrose began his task of mapping the igneous rocks on the six (and sometimes twenty-five) inch scales - "in my spare time", as he later wrote.

In the same year he published "Notes on Crich Hill" in the Journal of the Derbyshire Archaeological and Natural History Society. Much of his description of the area's limestone, clays and 'toadstone' related to the Wakebridge Mine which he had descended one weekend two years earlier - 420 feet by means of narrow ladders! In 1895 his father, Henry Howe Bemrose, became Conservative Member of Parliament for Derby (he was to be knighted two years later), and in 1896 Arnold-Bemrose's second son, Roderick, was born. In that year the breadth of his interests was illustrated by a paper on "the discovery of mammalian remains in old river gravels of the river Derwent at Allenton, Derbyshire" which he and Deeley read to the Geological Society of London. The latter had already contributed a paper to the Society's proceedings in 1886 on "the Pleistocene succession in the Trent basin", and he was also in touch with (and helped by) Teall. Further evidence of Arnold-Bemrose's widening researches appeared in 1898 with his paper to the Geological Society of London "on a quartz-rock in the Carboniferous Limestone of Derbyshire" - an account of the silicified and quartzose limestones near Bonsall and round Pindale, Castleton. Bonney took part in the discussion, together with Watts and Strahan.

Maturity

1899 was a busy - and splendid - year for the 42 year-old Henry Howe Arnold-Bemrose. It began with his paper to the Geological Society of London on "the geology of the Ashbourne & Buxton branch of the London and Northwestern railway; Ashbourne to Crake Low" - a full description of the pyroclastics and limestones exposed during the construction of the new railway. Teall spoke in the discussion, with Lamplugh, Hull, Sollas, Watts and Strahan. Two months later Arnold-Bemrose read a second paper to the Society - "on a sill and faulted inlier in Tideswell Dale, Derbyshire" - in which he unravelled the complexities of the igneous sequence in the dale, and acknowledged his own "conversion" in 1894 to Geikie's view that an intrusive sill was present. In June Arnold-Bemrose made yet another contribution to the Society's deliberations in the shape of a petrographical study of agglomerates and tuffs which appeared as an appendix to the paper by Gibson and Wheelton Hind on the volcanics of Congleton Edge, Cheshire.

In the same year Arnold-Bemrose and his wife joined the Geologists' Association (of which Teall was then President), and in July he read "a sketch of the Carboniferous Limestone in Derbyshire" to the Association. The survey - from the Lower Carboniferous to the Pleistocene - was illustrated by his own photographs,and it disclosed that in addition to igneous rocks, he had collected (but not yet examined in detail) a number of thin-sections of Carboniferous limestones. The paper was a 'curtain raiser' to the Association's excursion to Derbyshire from August 2nd to 10th, with its headquarters at Matlock Bath. Arnold-Bemrose and Wheelton Hind were amongst the directors, and the party visited by train and coach a variety of localities round Matlock, then over to Tissington, up to Millers Dale and Tideswell, and onward to Hayfield, Edale, Peak Forest and Castleton.

In addition to mapping the 'toadstones', Arnold-Bemrose began in 1900 a study of the glacial deposits in the northern part of Derbyshire in collaboration with Deeley. In the next five years he collected and photographed specimens from a considerable area - as far as Glossop in the north, the Goyt valley in the West, and southwards to Ashbourne, Derby and Crich. One of his many sources was Bakewell cemetery - the gravedigger was supplied with stamped and addressed postcards on which to communicate news of likely finds during his excavations; and on receipt of these, Arnold-Bemrose would hurry up by train from Derby to collect his specimens at the cemetery!

Caving was one of many interests, and it was on Boxing day 1900 that he was waylaid at Millers Dale station by friends in the Derby-based Kyndwr Club. Although on his way to spend a few days mapping round Tideswell, he gladly went with them to the Eldon Hole Cavern near Castleton to enjoy a two-&-a half minute descent in a bosun's chair. A few months later he undertook with the Club a similar descent of the Bottomless pit at the Speedwell Mine, Castleton. In 1902 his third son Clive, was born and the family moved to Ash Tree House, Osmaston Road, in Derby. The house was spacious; one room near the front door was fitted up as his study and library; one became his dark room, another housed the long enlarging camera; while a long loft over the stables and coach-house was turned into a museum for his specimens. For many years he not infrequently slept out in the large garden, under a shelter open on two sides.

In September 1902 he spent a fortnight at Little Longstone to continue his mapping, and during the year he was much engaged in a salvage operation at Hoe Grange quarry, Longcliffe, where John Ward of Derby had discovered mammalian remains in the workings. He duly reported his find to Arnold-Bemrose who took immediate and energetic steps to safequard the deposits, have them dug out scientifically, and transferred to his loft (and ultimately to Derby Museum).

It was through pointing out mistakes in the labelling of specimens at the Museum that he was co-opted on to the Museum and Libraries Committee of Derby Town Council. A Conservative by tradition rather than ideology, he was elected to the Council in 1903 and served it faithfully and with distinction for some 35 years - twice Mayor, Alderman from 1910 onwards, member of the Education Committee for the entire period and its chairman for 15 years. Despite all these new responsibilities he still found time to read the second part of his paper to the Geological Society of London on the Ashbourne to Buxton railway line cuttings - covering the limestones and clay wayboards of the northern section. Amongst the many places he visited during the year was Cop Round, near Peak Forest, in the company of Samuel Moore of Castleton who had written to the 'Geological Magazine' earlier about his discovery of a lava exposure there.

In 1904 his fourth son, John Maxwell, was born; Arnold-Bemrose became a J.P.; wrote a short article - "Geological Notes on Arbor Low" - for the Journal of the Derbyshire Archaeological and Natural History Society (a special issue on the Arbor Low Stone circle); and also contributed two more substantial papers to the Geological Society of London's proceedings. The first -"on some quartzite dykes in the Mountain Limestone near Snelston" - dealt with sedimentary dyke structures; while in the second -"on an ossiferous cavern of Pleistocene age at Hoe Grange, Longcliffe" - he and E.T. Newton described the finds made there in 1902 and 1903. Earlier in the year he and Lapworth had been amongst the directors for the Geologists' Association Whitsuntide excursion to Derbyshire. With its headquarters in Buxton the party visited localities around the town, the dams under construction in the Derwent valley, Wormhill and the Wye valley, Monsal Dale, Ashford and Crich (to study erratics and boulder clay).

The following year - 1905 - brought Arnold-Bemrose the first of several honours for his services to geology - an award from the Wollaston Donation Fund of the Geological Society of London which he received on the day that Teall (now Director of the Geological Survey) was presented with the Wollaston Medal. The first volume of the Victoria County History of Derbyshire was published, containing Arnold-Bemrose's substantial chapter on the geology of the county. In 1906 he became a member of the Council of the Geological Society (serving till 1908, again between 1911 and 1916, and being appointed a Vice-President in 1914). During the winter of 1906-1907 he gladly found time to pilot T.F. Sibly through the Carboniferous Limestone country during the latter's study of its faunal succession in his attempt to apply Vaughan's scheme for South-West England to Derbyshire.

1907 carried him to the apogee of his geological researches - the delivery in August to the Geological Society of London of his definitive paper on "the toadstones of Derbyshire". The audience was a distinguished one with Sir Archibald Geikie (the President) in the chair, and Greenly, Lamplugh, Wedd, Hull and Sibly amongst others present. Twenty-one years of 'sparetime' study in the field and laboratory had gone into the presentation of a paper which at last established a firm and comprehensive framework for the igneous rocks of his native county.

In 1908 a further honour came to him when he was made Doctor of Science by Cambridge University for his scientific contribution (plate 9). Sir Archibald Geikie, too, included his name amongst "those associated with the great petrological revival of the 19th century in Britain", during his Anniversary Address to the Geological Society. Early in September he travelled to Dublin for the 78th meeting of the British Association for the Advancement of Science (of which he had been a member since 1893), and there he read his 'Notes on the microscopical structure of the Derbyshire limestones'. Based upon an examination of some 400 thin slices of both Carboniferous and Permian rocks in the county, the paper described his identification *inter alia* of oolites, foraminifera, sponge spicules and "fossils which have not been previously described and which may be new forms of calcareous algae".

In 1910 there was a further burst of literary activity. In January he published in the 'Geological Magazine' a paper "on olivine-nodules in the basalt of Calton Hill, Derbyshire" - a description of the agglomerate & tuffs exposed by new quarrying, and of the olivine-nodules within the basalt (which he believed to be "segregations from the magma and not inclusions of older rock"). Dr Arnold-Bemrose also contributed a paper on "the Lower Carboniferous rocks of Derbyshire" to 'Geology in the Field', the Jubilee volume of the Geologists' Association. Largely a revision of his 1899 "Sketch", the paper included references to Sibly's recent work, and took account of the new scheme for the classification of the 'Yoredale' rocks in the county. In quite a different vein was the little volume on 'Derbyshire' in the Cambridge County Geography series, compiled with the help of his wife on aspects of Derbyshire history and architecture. He also wrote a chapter in the Reverend J.M. Fletcher's 'Guide to Tideswell' - an action typical of the generosity with which he would always put his specialist knowledge at the disposal of others (whether they were professional or amateur geologists, librarians or museum curators).

In 1911 his father, Sir Henry Bemrose, died (and his mother soon afterwards). In the resulting reorganisation of the board of Bemrose and Sons Ltd, he was appointed Deputy Chairman, with his cousin, William Wright Bemrose, as Chairman. In June he dropped the 'Arnold-' from his name and became Henry Howe Bemrose again. His public work and responsibilities were increased by membership of the Derwent Valley Water Board (he was to be Chairman for 22 years) in an appointment which met both his geological and civic interests. Since becoming Mayor, too, he had given his enthusiastic support to the Scout Movement in Derby, and he became District Commissioner in 1913. Geology, however, was not neglected, and in Easter that year he joined the Geologists' Association excursion to the Lizard (his photograph of the directors, Flett and Hill, still survives). 82 members were present, one of them being bitten by an adder and "considerably inconvenienced for a day or two"!

Before Christmas Dr. Bemrose sprained an ankle and this hampered him somewhat in his preparations for the Geologists' Association summer excursion to Derbyshire in 1914. His co-director, Henry Crunden Sargent of Fritchley, bombarded him with suggestions for the itinerary (together, with petrological queries) during the first months of the year, suggestions to which Dr. Bemrose responded with characteristic tact and firmness! The Association party assembled at the Matlock Bath headquarters on July 21st, and spent nine days exploring the county by train and - an innovation - "covered motor car". Amongst the localities visited were the New Haven and Brassington clay pits, Calton Hill, and the Derwent Valley dams (reconnoitred earlier by Dr. Bemrose in the company of Professor W.G. Fearnsides of Sheffield University). On the final Tuesday the party "took tea" at Millers Dale, caught the 4.25 train, had their luggage put on at Matlock Bath, and dispersed south to Derby and London. The date was August 4th - at midnight the British ultimatum to Germany expired and the country was at war.

Interregnum

The first World War imposed great strains upon Dr. Bemrose and it is little wonder that his geological activities were suspended 'for the duration'. For some time he was one of only two Directors remaining in Derby. He acted as Company Secretary for 14 months; supervised the collotype and photographic branches; carried out the photography himself, made the collotype plates with the leading artist, and was responsible for a number of improvements and inventions at the firm's works. In addition to office burdens, his family was grievously affected by the loss of his two sons. Karl Bemrose, the eldest, joined the Sherwood Foresters and was killed on the Somme in 1916. Roderick, the second son, died in hospital in November 1918, after serving with the RFA, being wounded and awarded the Military Cross.

During the early 1920's Dr. Bemrose's time was fully taken up by his business commitments, his public and political activities, and by Scouting (he became County Commissioner in 1922). In 1926 Bemrose and Sons Ltd celebrated its centenary, and to mark the occasion Dr. Bemrose compiled a substantial volume, 'The House of Bemrose, 1826-1926', which must have taken him some time to research and write. His geological expertise and knowledge, however, were always available to be put at the disposal of other workers. Amongst the many he helped was a young Japanese student, R. Ohashi, who came in 1921 to look at Derbyshire's ancient igneous rocks after studying the Recent volcanoes of his native country.

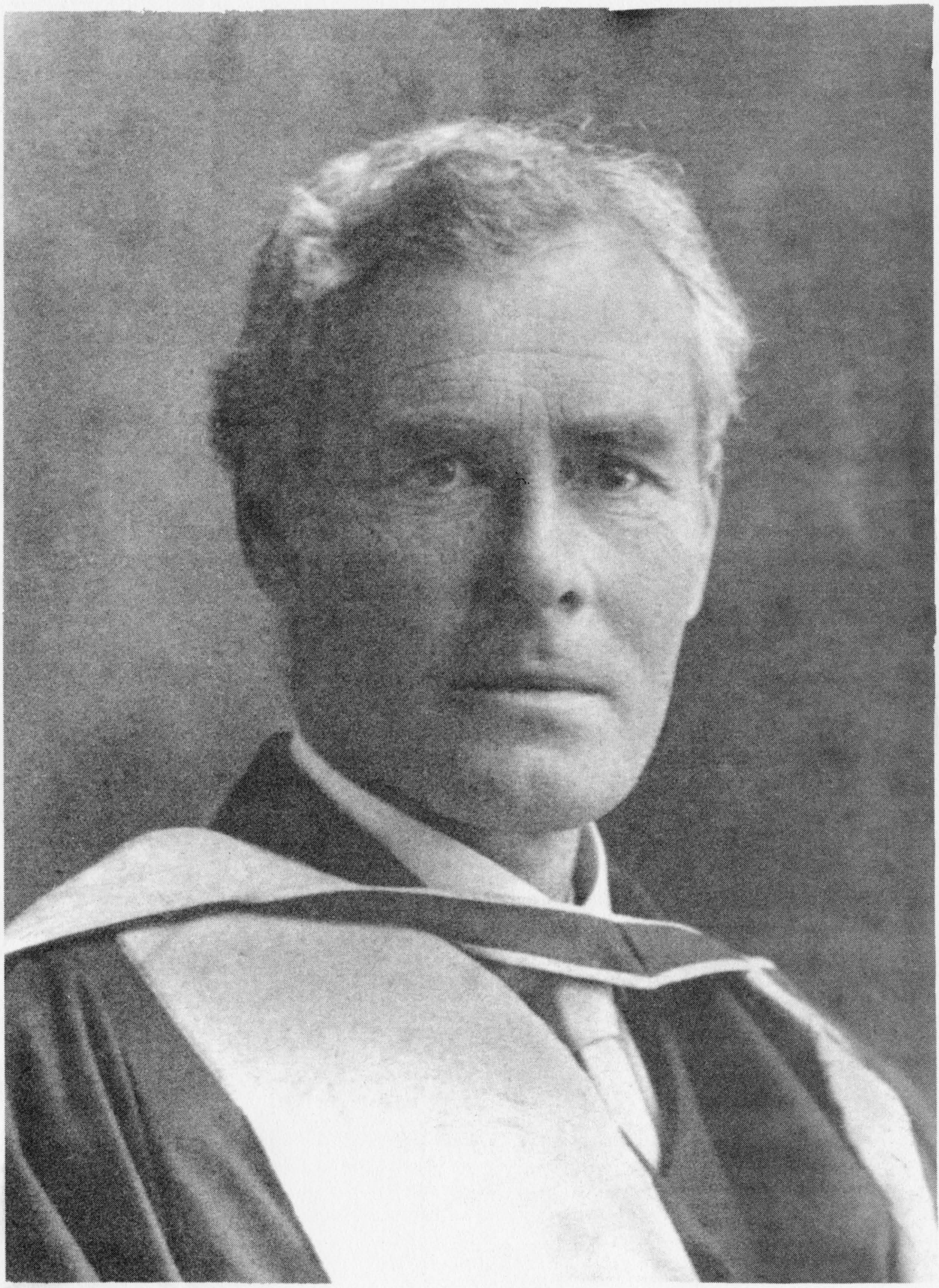
Back in The Field

It was around 1928 that Dr. Bemrose resumed regular weekly field trips - often travelling on the 0945 train from Derby in the company of Philip Speed, a Nottingham University College student whom he had first met through the Scout movement. "Walk with a purpose" was his advice, and together they revisited many of his original localities in the Millers Dale area. He began to take notes on his reading again, sometimes filling empty spaces in his old 'Daybooks' (generous as he was, he always had a rooted aversion to the waste of money and resources). Further specimens were added to his collection of erratics; he contributed by letter to the discussion of S.I. Tomkeieff's paper to the Geological Society of London on "the volcanic complex of Calton Hill" in 1928; and in the following year he took a party from the Yorkshire Geological Society round the Grangemill vents. At Easter in 1930 he joined the Geologists' Association excursion to North Wales. On April 18th he was with the group that ascended Snowdon by the Pyg Track in snow and decended by the Watkin path (in shorts and at the age of 73!); and he was chosen to give the vote of thanks to the Excursion Secretary on behalf of the members.

In 1931 he retired from Bemrose and Sons after 51 years of service, and with more time to spare at last, stepped up his geological pace. Though illness prevented him from attending the Geologists' Association Easter excursion to the county in 1932, he enjoyed a holiday in Skye with his wife that August, looking at the Tertiary igneous rocks. He was about in Derbyshire a good deal - now transported in a chauffeur-driven car - to photograph exposures, look for erratics (he paid several visits to the Goyt valley whilst the new reservoir was under construction) and collect specimens for the South Kensington Geological Museum which opened in 1935. Amongst his finds was an erratic boulder of Eskdale granite which with typical thoughtfulness he had transported from a Derby garden to the school in the city that still bears his name. With Philip Speed, too, he went to the Lake District to see for himself the source rocks of many Derbyshire erratics.

In 1933 the University College, Nottingham (with which he had been associated for many years) invited him to give the 8th Abbott Memorial Lecture, and Dr. Bemrose chose as his subject something certain to appeal to a general (and young) audience - "The Caves in Derbyshire". He and his wife travelled abroad in 1935 for an extended holiday in Egypt and Malta. In response to a request from L. du Garde Peach, Dr. Bemrose wrote six popular articles on the county's igneous rocks for "The Derbyshire Countryside", and these appeared in the magazine between January 1935 and April 1936. Illustrated by photographs old and new, these articles on the lavas, tuffs, necks and sills include his observations on some exposures that were well beneath the ground during the mapping labours of 1894 to 1907.

In 1935 he was disconcerted - perhaps even outraged - to read a letter in the 'Geological Magazine' from a Mr. Jessop of Sheffield, questioning his interpretation of the Potluck dolerite as a sill. He reacted with typical vigour and thoroughness - visiting the area and new trial holes several times, and demolishing his critic with an authoritative reply which appeared in the same publication in 1937. In July of that year the Chief Scout, Lord Baden Powell, stayed with him at Ash Tree House, visiting the Drum Hill Scout Camp and receiving from Dr. Bemrose the lease of the land upon which the Camp was situated. At the end of the month he and his wife went to stay in Dalbeattie, and from there he joined in the Geologist's Association excursion to the Southern Uplands.



In 1938 there were new honours to crown his life. He was made a Freeman of his native Derby; be became Vice-President of the Council of University College, Nottingham; and in February the President of the Geological Society of London, Professor O.T. Jones, presented him with one of the Society's highest awards - the Murchison Medal. In his Ash Tree House study (to which he would retire, thankfully, without his tie!) he continued to work with Philip Speed on the first drafts (with corrections in green ink) of his paper on "Boulders of the Derbyshire drift". Begun as he wrote, in 1897, it contained a mass of information about over 700 glacial erratics collected throughout the county, with notes on their petrology. The final version was submitted after his death to the Editor of the 'Proceedings of the Geologists' Association'; but wartime publication problems prevented its appearance, and unfortunately the paper cannot now be traced.

It was perhaps fitting that at the end of his life, Dr. Bemrose should return to glaciology - that aspect of geology which had first caught his interest when he crossed the Rhone Glacier at 17. The last reference in the revised draft was dated June 20th, 1939, and it read -

"I met Mr. S.T. Nash of Cubley who asked me to call at his house, and see some boulders he got from blue clay in digging a well." At the time, too, he was busy with Philip Speed on detailed plans for a field trip by a party from Abbotsholme School, and as always, he was most anxious that the excursion - to Bonsall and Wirksworth - should go well. But in the event he could neither visit Mr. Nash nor lead the excursion. A stroke intervened, and on July 17th in his 83rd year, Dr. Bemrose died at his home in Derby.

How does his major opus - on the Derbyshire igneous rock - stand today after more than 70 years of further research? The Institute of Geological Sciences staff have suggested alternative interpretations of some features - the dolerite at Low Farm, Bonsall; his New Bridge sill (Miller, 1980); and his vent at Cracknowl, Bakewell, which is now mapped as part of a lava flow, although fragments of agglomerate and tuff are certainly present together with lava debris (Miller, 'Amateur Geologist', forthcoming). He was mistaken - as he unhesitatingly admitted in 1928 - over the origin of the Calton Hill olivine - nodules, and he perhaps missed the spilitic affinities which his co-worker, Sargent, found in some of the Derbyshire basalts and described to the Geological Society of London in 1917. Quarrying operations since 1907 have exposed the Great Rocks Dale dykes, the complexities of Calton Hill and Waterswallows; later exploitation of the Mill Close Mine has shown the presence of additional lava flows in the Matlock area.

These however, are comparatively minor details in Arnold-Bemrose's great scheme, and for an amateur geologist working in his spare time, its construction was a remarkable feat. It is true that he did his major work in an age when professional geologists were thin on the ground, and when the relationships between professionals and amateurs were easier and closer than they often are today. But within the context of so rich a public and private life, his achievement is surely quite outstanding. It endures, and so everyone today who explores the igneous rocks of Derbyshire's hills and dales walks with Henry Howe Arnold-Bemrose, at least in spirit, by his side.

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