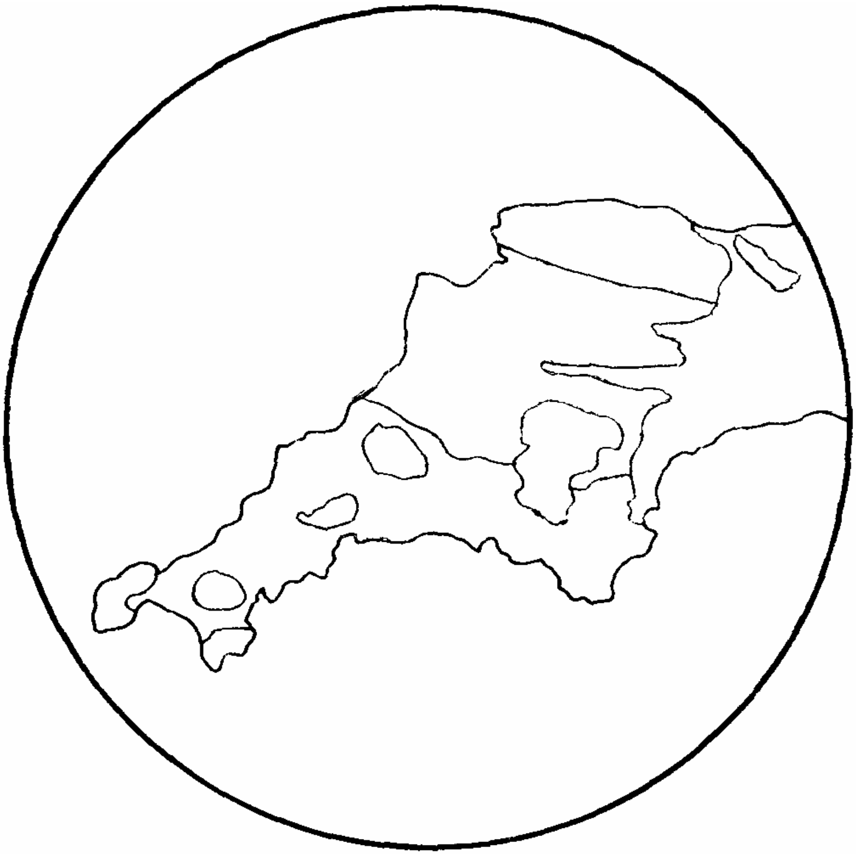
PROCEEDINGS

OF THE

USSHER SOCIETY

VOLUME FOUR

PART THREE



1979

THE USSHER SOCIETY

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Back numbers may be purchased from the Secretary to whom correspondence should be directed at the following address.

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CONTENTS

Conference of the Ussher Society held at Exeter, January 1979

Chairman's Report

The 1979 Conference saw the Society return to Exeter where the Department of Geology acted as host with Mr. P. Grainger of the Department acting as Conference Secretary. Unfortunately, a heavy snowfall on New Year's Day followed by an exceptionally severe frost disrupted travel in the region and as a consequence the numbers attending the Conference were somewhat less than in the last few years. Both the pre-Conference excursion to the Bampton area, which was to have been led by Drs J.M Thomas and C. Nicholas and the post-Conference excursion to the East Devon coast, to have been led by Dr M.B. Hart, had to be cancelled because of the weather; the last time the excursions for the Conference had to be cancelled was in the infamous winter of 1963.

However, the programme for the Conference Sessions on January 4-5 was an excellent one with a wide range of first class contributions. Our Guest Speaker, Dr D.H. Tarling, gave us an excellent review of the current state of knowledge regarding the use of palaeogeographic reconstructions, with special regard to the position of South-West England in Upper Palaeozoic times. Papers on the Lizard, Upper Palaeozoic palaeontology and the Keuper Marls followed, with a series of papers on Cretaceous and Tertiary stratigraphy to round off the day.

The second day started with a stimulating pair of papers by Dr A.S. Batchelor of Camborne School of Mines and Dr C.S. Exley discussing the exploitation of geothermal power and the character of the South-West Batholith in depth. It emphasized how little we know about the granite in depth! A further set of papers later in the day dealt with other aspects of the granites and there was an interesting set of papers on uranium and radon occurrences.

As an experiment, the discussions after papers presented at the 1979 Annual Meeting were recorded on tape, and the edited results are included in this issue of the *Proceedings.*

A further development which is in hand is to organise at the Sheffield meeting of the Geological Societies of the British Isles a joint meeting with the Royal Geological Society of Cornwall. This will take the form of a half day session with 4-5 review papers and topics concerned with the geology of South-West England.

A decision has been taken to re-print those issues of the Proceedings which are close to or completely out of print, so that we can offer complete sets to libraries wishing to purchase them. This investment on printing costs is a good way of making use of the small surplus of funds we have in hand at the moment, which should give us an excellent return in years to come.

In spite of our problems with the weather in January we have had a good year and the Society remains as strong as ever, largely due to the considerable work put in by the Officers, Committee and Auditors. Representing as I do the industrial side of geology it is always a pleasure to attend the Ussher Society Conference where geologists from all sides of geology meet and communicate with one another. Long may it be so!

C.M. Bristow
April 1979

Address of the Guest Speaker

PALAEOMAGNETIC RECONSTRUCTIONS AND THE VARISCAN OROGENY

by D.H. Tarling

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Abstract. Palaeomagnetic studies can only provide a first order constraint on palaeogeographic reconstructions and the Upper Palaeozoic palaeomagnetic data relevant to the Variscan Orogeny are sparse. Nonetheless, the available data indicate consistent motions of both Laurentia (North America and Europe) and 'Western' Gondwanaland (South America and Africa) that place more stringent restrictions on possible palaeogeographic relationships than the data for any one period. Following the Taconic-Caledonian Orogeny. both supercontinents were rotating clockwise, although this was only slight for Laurentia during the Devonian. and both had a northerly motion. Differences in the rate of motion caused an African-E. North American collision (Acadian) orogeny in Middle-Upper Devonian times. This caused Laurentia to begin to rotate slowly anticlockwise, although predominantly northwards in the Mediterranean region. The continued clockwise rotation of Gondwanaland impinged in the Carboniferous on the Iberian massif which then became caught between the two continents. The clockwise rotation of Gondwanaland and anticlockwise rotation of Laurentia resulted in northern South America colliding with southern North America at the end of the Carboniferous. This major impact reversed the sense of rotation of Gondwanaland and closed the Atlantic region again. The Adriatic and other promontories on the African block were also brought into collision with the Iberian massif at the same time, forming Pangaea. The two supercontinents continued to rotate separately during the Permian, giving strong right lateral motions in the Mediterranean area. The northern South America-southern North American collision is interpreted as being extremely significant and responsible for establishing the fractures that were to be opened up as Mesozoic and Cenozoic Oceans. It is emphasised that while these reconstructions are thought to be fairly realistic generalisations. an integrated geophysical-geological approach is essential to improve and refine the nature of the Variscan Orogeny.

1. Introduction

There is now widespread acceptance of the theory of continental drift, now re-named plate tectonics, as a paradigm within which at least the last 200 million years of the Earth's history can be better understood. There is also general acceptance that similar processes operated to cause the Caledonian and Appalachian orogenic events in the Lower Palaeozoic (Dewey and Burke 1973). However it is by no means clear if, or how, this tectonic hypothesis can be applied to the Variscan orogeny in western Europe in the Upper Palaeozoic (Zwart and Donsiepen 1978). As most scientists were converted to the acceptance of continental drift following palaeomagnetic study of continental and oceanic rocks, it is appropriate to review the palaeomagnetic data relevant to the Variscan events in Western Europe. It will be seen that there are still major difficulties in establishing the location of major continental blocks during this period, using palaeomagnetism alone, and that the only solution in the next decade or so must be based on an integrated approach. In this article, the problems and difficulties in assessing the available palaeomagnetic data from North America, Europe, Africa and South America will be outlined and tentative palaeogeographic reconstructions will be provided based upon them. It is emphasised, however that such reconstructions are tentative and indicative of probable relationships that require testing by further integrated studies. Nonetheless, the available data already suggest abroad scenario against which other geological observations can be compared to both understand the evolution of the region and refine the model.

2. Palaeomagnetic Analysis

Most rocks contain impurities of magnetite or haematite and are therefore potentially capable of retaining a remanent magnetisation that was acquired at a specific geological time (Tarling 197Ia). If this magnetisation can be isolated and measured, then the direction of the geomagnetic field at that time can be established and, assuming a specific model for the average geomagnetic field, the palaeolatitude and orientation of that tectonic block can be determined. This block may be small, possibly only the volume of the outcrop, or extend for most of the continent. There are, therefore, four main problems in palaeomagnetic studies -(a) isolating a particular component of the magnetisation of a rock (b) determining the age of this component, (c) determining an optimum model for past geomagnetic fields, and (d) determining the extent to which the results can be extrapolated away from the area of immediate investigation.

(a) Isolating Components of Magnetisation

Many rocks acquire a magnetic component at the time of their formation. In the case of igneous rocks, this is acquired as the rocks cool (thermal remanence). Sediments generally include already magnetised particles in their composition and these particles are likely to have been aligned both during deposition and while the fine particles are free to physically rotate before compaction squeezes out the interstitial waters (detrital remanence). All of these primary magnetic components gradually reduce in intensity as their constituent atomic alignments gradually decay, but the rate at which the component is reduced depends on the composition of the magnetic mineral, to some extent, and the actual size of the particle. In particles around the size of one micron diameter, the rate of decay is extremely slow, even on a geological time scale, and any magnetisation associated with these grains (single magnetic domain particles and similar sized magnetic zones within a larger grain) will persist for an indefinite time unless the magnetic particle is affected by later heating or chemical change. In many sediments, the original detrital remanence may be destroyed by the chemical breakdown of the detrital particles during diagenesis and such rocks then acquire a chemical magnetisation as newly forming magnetic minerals grow in the prevailing geomagnetic field (chemical magnetisation). This new chemical magnetisation may be associated with the chemical breakdown of original detrital minerals, as when olivines and pyroxenes decompose, or with the magnetic minerals that are precipitated from the cementing fluids. Again, the magnetisation acquired during these diagenetic changes will persist indefinitely if the particles grow to single domain sizes, while the magnetisation of both larger and smaller grains tends to decay over geological time.

All rocks lying in the changing geomagnetic field therefore gradually lose some of their original (primary) magnetisation that was acquired during the formation of the rock itself. They also gradually acquire a time-dependent (viscous) magnetisation as the atomically controlled decay processes also allow re-alignments to take place, particularly in those grains that do not lie in the single- domain size range. However , as such time-dependent magnetisations are necessarily carried by grains with a lower magnetic stability, it is possible to preferentially remove these magnetisations, without significant effect on the magnetisation carried by the stable, single-domain particles. Thus the gradually heating of a rock increases the thermal vibrations and causes the less stable magnetisation to become randomised, if cooled in zero external field. Similarly subjecting rock samples to increasing alternating magnetic field strengths, in zero direct field, preferentially randomises the less stable components, thereby isolating the stable, single-domain magnetisations. Other techniques, such as direct magnetic field demagnetisations are used particularly in the U.S.S.R. but all such techniques essentially operate on the same physical basis in which the stably magnetised component is retained while the time-dependent magnetisations are randomised. There is, therefore, no fundament difficulty in isolating any stable magnetisation as long as a few particles are present of the appropriate size.

(b) The Age of Magnetic Components

In most Mesozoic and Cenozoic rocks, the stable magnetisation resides in grains that were magnetised as the rock cooled, in the case of igneous or metamorphic rocks, or during diagenesis, in the case of sedimentary rocks. This can be tested under certain conditions by means of fold (or conglomerate) tests (Graham 1949). If the magnetic component was acquired before a folding event, then the directions will be consistent with the bedding planes, but not with present-day horizontal. Conversely, magnetisations acquired after folding will be more consistent with each other relative to their present-day positions than to the original horizontal. It is not always possible to carry out such fold tests, in which case it is normal to resort to regional consistency tests on the basis that in relatively young rocks it is unlikely that any later processes will uniformly affect a wide area so that lateral homogeneity of magnetisation suggests that the magnetisation is likely to be associated with a common process namely the processes operating when the rocks were formed.

Mesozoic and Cenozoic rocks may no longer carry their primary component, particularly if subjected to heating or chemical changes during metamorphic events, such as those associated with the Alpine orogeny. Similarly for older rocks, the intrusion of young igneous rocks may be associated with a local thermal remanence that is superimposed upon the original remanence. However, much less geologically obvious are later chemical changes that may give rise to stable magnetisations. In sediments this can clearly arise if diagenetic processes are inhibited or protracted whereby the formation of new magnetic minerals may occur over many millions, or even hundred of millions, of years, as in the case of the Devonian sediments of the Caithness region of Scotland (Tarling and others 1976). Similarly, exsolution and spontaneous decay can occur in minerals in igneous rocks over very protracted time-scales, even though most exsolution appears to take place essentially contemporaneously with intrusion. Even more complex may be chemical changes that arise from moderate to deep burial. In deep burial conditions, the entire area may be subjected to widespread heating that may impart a regional thermal overprint as the rocks later cool. More insidious are the chemical changes that ma y also occur as a result of this circulation of either oxidising or reducing ground waters and fluids with or without significant burial. These are likely to result in regional chemical magnetic overprinting, especially if the fluids are warm and thus more chemically active. It is particularly relevant that, in such situations, the regional temperatures may still be relatively low, say 100-150°C, but their action may be extremely prolonged and the total magnetic effect, both thermally and chemically, may well be equivalent to heating the area to much higher temperatures for a shorter period.

In many of the Palaeozoic or older observations to be considered here fold tests cannot or have not been applied or the rocks have only been involved in Alpine folding and thus such tests only limit the age of the magnetisation to some pre-Alpine event. In general, however, few fold tests have been undertaken and several of these have proved negative, i.e. the magnetisation was post-folding although in some of these cases the folding is thought to have been penecontemporaneous and the magnetisation has been considered to be essentially of the same as the rocks (McElhinny and Opdyke 1973). It has, however, been suggested that many Palaeozoic data, especially from Siberia, have been subjected to extensive overprinting in the Late Palaeozoic (Creer 1968) and Storetvedt (1968), Storetvedt and Markhus (1978), and Roy and Lapointe (1978) have demonstrated the complications that may arise in Mesozoic and Cenozoic rocks alone.

In rocks containing several magnetic components, the timedependent magnetic component is readily removed by partial demagnetisation, and detailed study over short increments of either alternating magnetic field or temperature frequently allows the determination of the other components. If a particular component can be identified over three or more successively higher increments in the demagnetisation treatment then the direction of this component can usually be determined precisely. The age of the different components is, however, much harder to evaluate. Conventionally it is often assumed that the components isolated at the highest demagnetisation levels are the oldest. This is on the basis that (a) the time-dependent decay is proportional to the temperature, and (b) any later thermal heating will necessarily alter the lower temperature ranges first and thus not necessarily affect the higher temperature components. However this assumption is not necessarily valid for rocks that have a later chemical remanence. It is quite possible that the younger chemical changes will result in the formation of single-domain particles and therefore be possibly more or as stable as any pre-existing magnetisations.

Where different stable components can be identified in the same rock, the most effective method of dating the components, in the absence of fold tests, is to compare the directions of the different components with known directions of the geomagnetic field for that region since the formation of the rock. For most components, such directions are now known, or can be interpolated, for most of the Mesozoic and Cenozoic. The situation for the record of directions during the Palaeozoic is less clear, but is becoming better known.

(c) Models of the Past Geomagnetic Field

As the geomagnetic field is continually changing, it is not immediately evident how comparisons between such directions can be made in any meaningful way. However, studies of records of the field since 1600 and archaeomagnetic studies indicate that the long term changes of the field (secular variations) are essentially cyclical and average out over a period of 2 to 8000 years so that the averaged geomagnetic field corresponds closely to that of a bar magnet at the Earth's centre and aligned along the axis of rotation (an axial geocentric dipole). Such averaging is likely to take place naturally in sediments that acquire their remanence over several thousand years, and in deep igneous rocks that cool slowly -in rocks that acquire their magnetisation rapidly, for instance thin lava flows, a large number of observations of different age may be required to average out such changes. The reality of this model appears to be largely substantiated over geological time by the general agreement between palaeomagnetically determined palaeolatitudes and those indicated by palaeo-climatic indicators such as evaporites and glacial tills, although the latter are also strongly influenced by local geographic factors (Tarling 1971a).

Naturally the necessity to average out secular variations introduces a certain 'noise-level' into palaeomagnetic studies. The observations that the geomagnetic field also changes polarity introduces a further noise level as there is a finite time during which such polarity changes occur, approximately 1 per cent of the available time during the Tertiary. Rocks that became magnetised

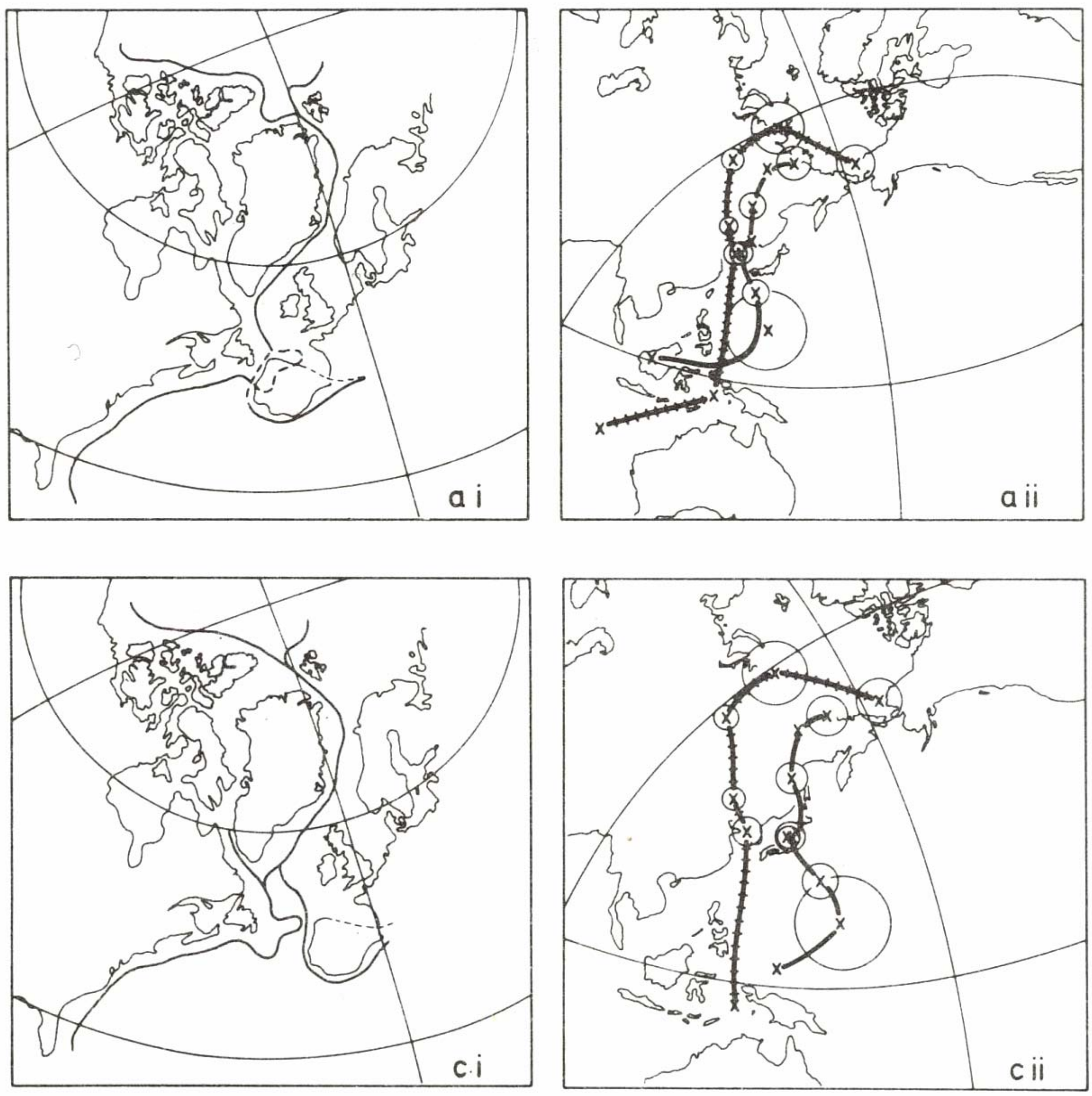
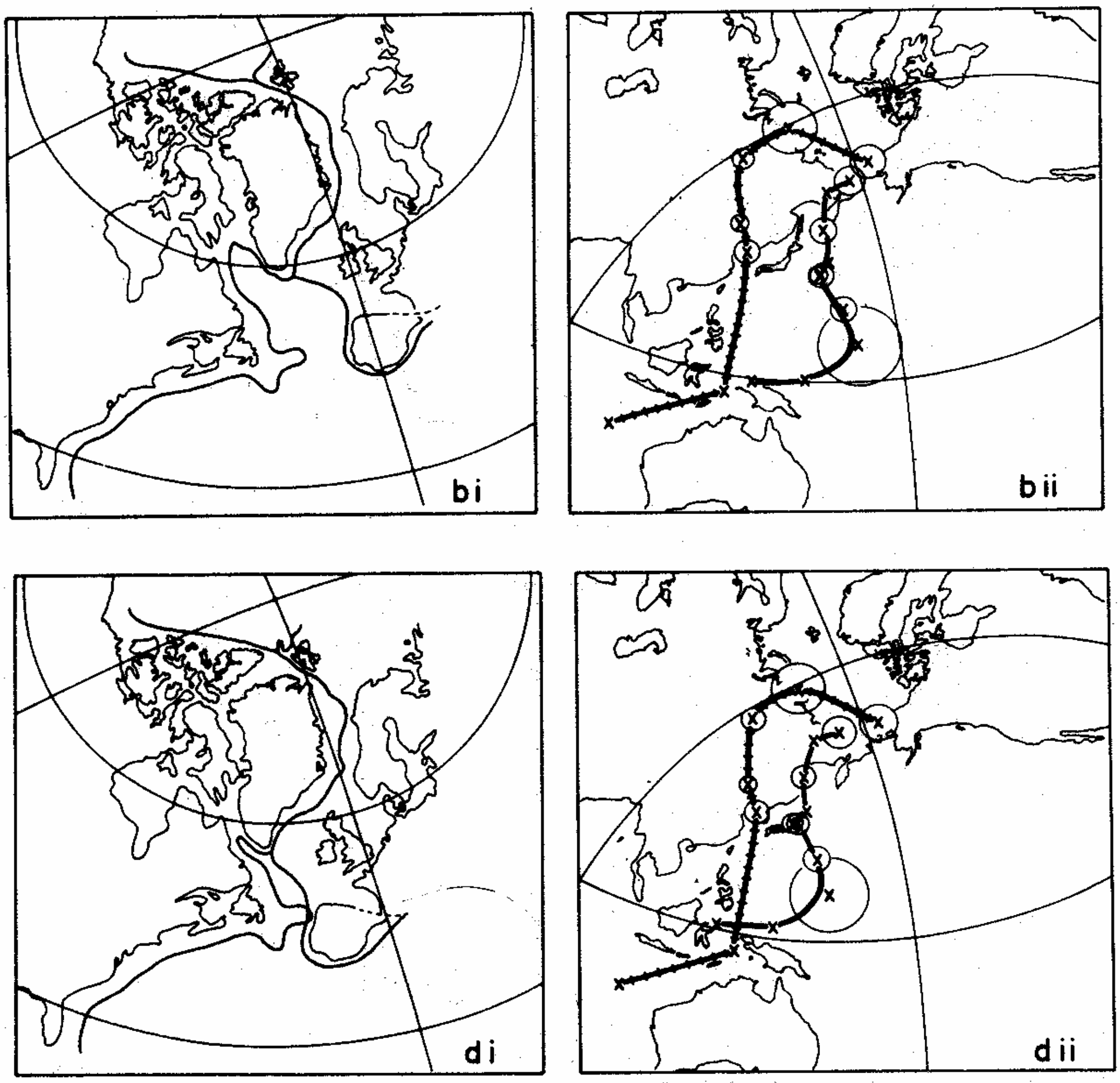


Figure 1. Reconstructions and Polar Wandering Paths for Laurentia

Four postulated reconstructions based on the match of bathymetric contours are shown based on (a) Bullard and others (1965) for Europe-Greenland-Canada, (b) Tarling in Soper (1976) for Europe-Greenland and assuming the Nares Straits to be a simple transcurrent zone, (c) Le Pichon and others (1977) for Europe-Greenland and Greenland-Canada after Bullard and others(1965), and (d) Tarling in Soper(1976)for Europe-Greenland and Srivistava (1977) for Greenland-Canada. In each case, the continental fit is shown on the left (i) and the corresponding polar wandering paths on the right (ii). In each case Europe and Greenland have been rotated to a fixed North America, and the North American polar wandering path is shown as a solid curve. The crosses and circles correspond with the mean pole position and circles of 95% confidence for the Cretaceous, Jurassic, Triassic, Carboniferous and Devonian periods, moving from north to south. Where insufficient observations are available the pole position is shown without a circle of confidence.



during such transitions cannot, of course, be incorporated into any analysis aimed at determining the past latitude and orientation of any particular tectonic block. Such deviatory observations can only be detected by sampling that incorporates both normally and reversed magnetised samples. In general, directions that deviate from an otherwise tight grouping are often attributed to having their magnetisation acquired during a polarity transition. It is, of course, difficult to establish the actual validity of such an interpretation in any single case, but it is common to exclude directions from any analysis that have corresponding palaeomagnetic pole positions that deviate by more than 400 from a clearly defined grouping of other palaeomagnetic poles of the same tectonic unit.

(d) Lateral Extrapolation

Until recently, areas subjected to known tectonic disturbance have been largely avoided unless to study that particular tectonic event

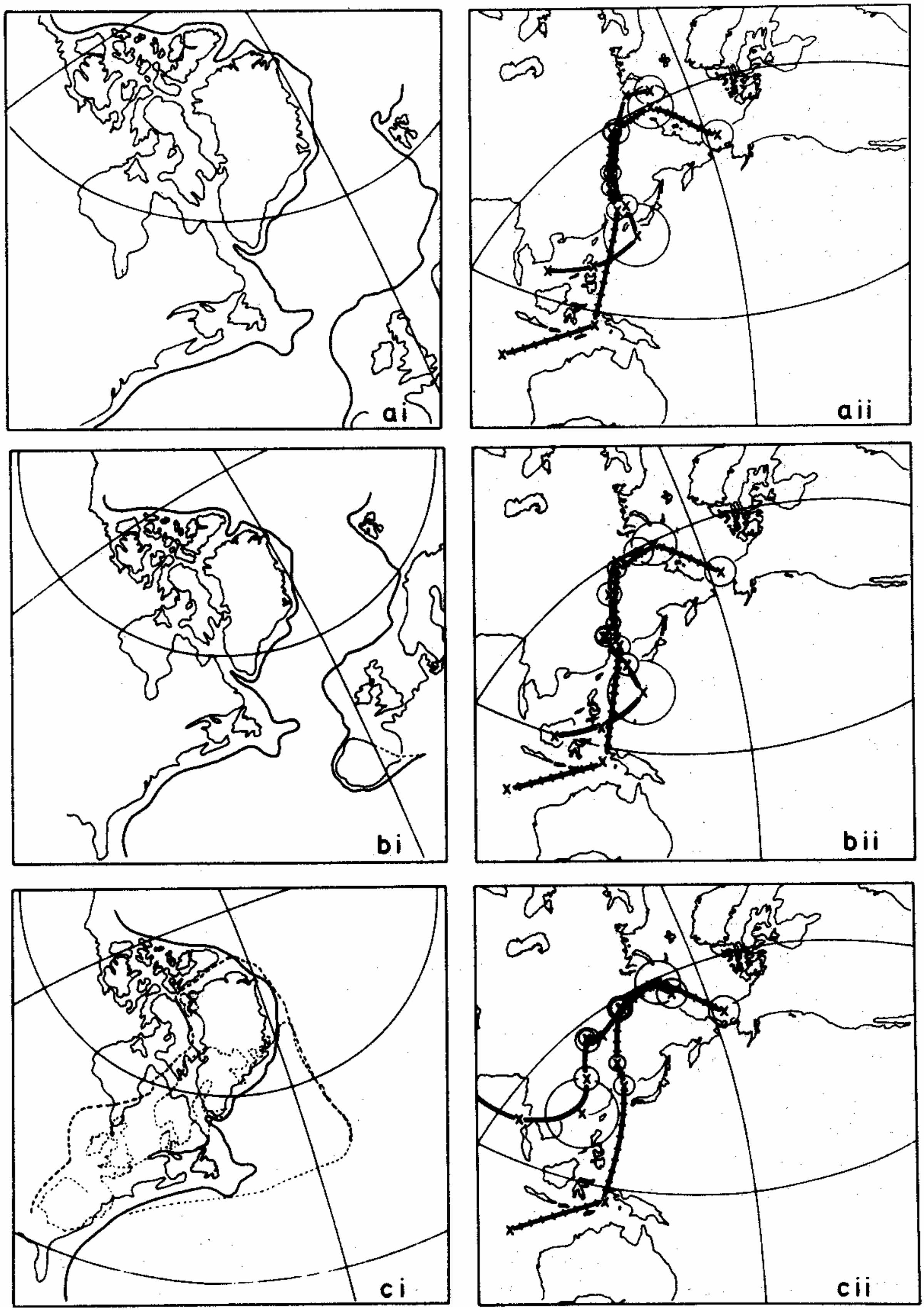


Figure 2. Polar Wandering Paths and Laurentian Reconstructions

This is the reversed situation to the reconstruction in Figure I. The same polar wandering curves and data, as in Figure I, are matched for (a) Permo-Triassic times, (b) Upper Palaeozoic times and (c) Triassic-Jurassic times. The position of the different continents corresponding with these locations of the polar wandering paths (i) are then shown on the right hand side (ii).

such as the way in which a specific nappe formed. It was also generally assumed that the palaeomagnetic data from one area could be easily extrapolated to most of a continental area unless some orogeny had occurred within it. Nowadays, smaller tectonic features are being increasingly studied as it is now possible to distinguish the movements of relatively small tectonic blocks 50 x 200 km (Freund and Tarling 1979). Palaeomagnetic directions are thus now being used to define the previous unity of various tectonic blocks. Nonetheless, it is still often necessary to assume that observations made in one area are, in fact, typical for a much larger area.

3. Palaeomagnetic Reconstructions

The problems still inherit in attempting to obtain precise reconstructions using palaeomagnetic data alone can best be illustrated by the relationships indicated by matching the polar wandering curves for North America and Europe. This is a particularly significant test as there is wide acceptance of the former close relationships between these continental blocks as a single continent, Laurentia, which was formed by the Caledonian orogeny and persisted until the mid Cretaceous and Tertiary. On this basis, the two present-day continents should. have a common polar wandering path when placed in their Laurentian positions.

The most widely followed, and first computer matched, fit of the continents was by Dullard and others (1965). On this reconstruction (Fig. la) the polar wandering paths are similar, but the European curve lies east of the North American, except in the Upper Carboniferous and Devonian. This fit has been criticised in both the northern Atlantic, between Greenland and Norway, and also between Greenland and Canada. The best bathymetric fit between Greenland and Norway (Tarling in Soperand others 1976) differs only slightly from that of Dott and Watts (1971) or Le Pichon and others (1977). All of these however, result in a consistent offset of the European polar wandering path to the east of its American counterpart (Fig. 1 b-d) irrespective of the nature of the Greenland-Canada fit.

An alternative approach is to use the palaeomagnetic data alone as this simulates the approach adopted for Palaeozoic and earlier reconstructions. Differences in the paths for corresponding periods clearly illustrates that there are inconsistencies even for the two continents for which there is the most data (Fig. 2). The best palaeomagnetic fit, assessed visually, for the Upper Palaeozoic (Fig

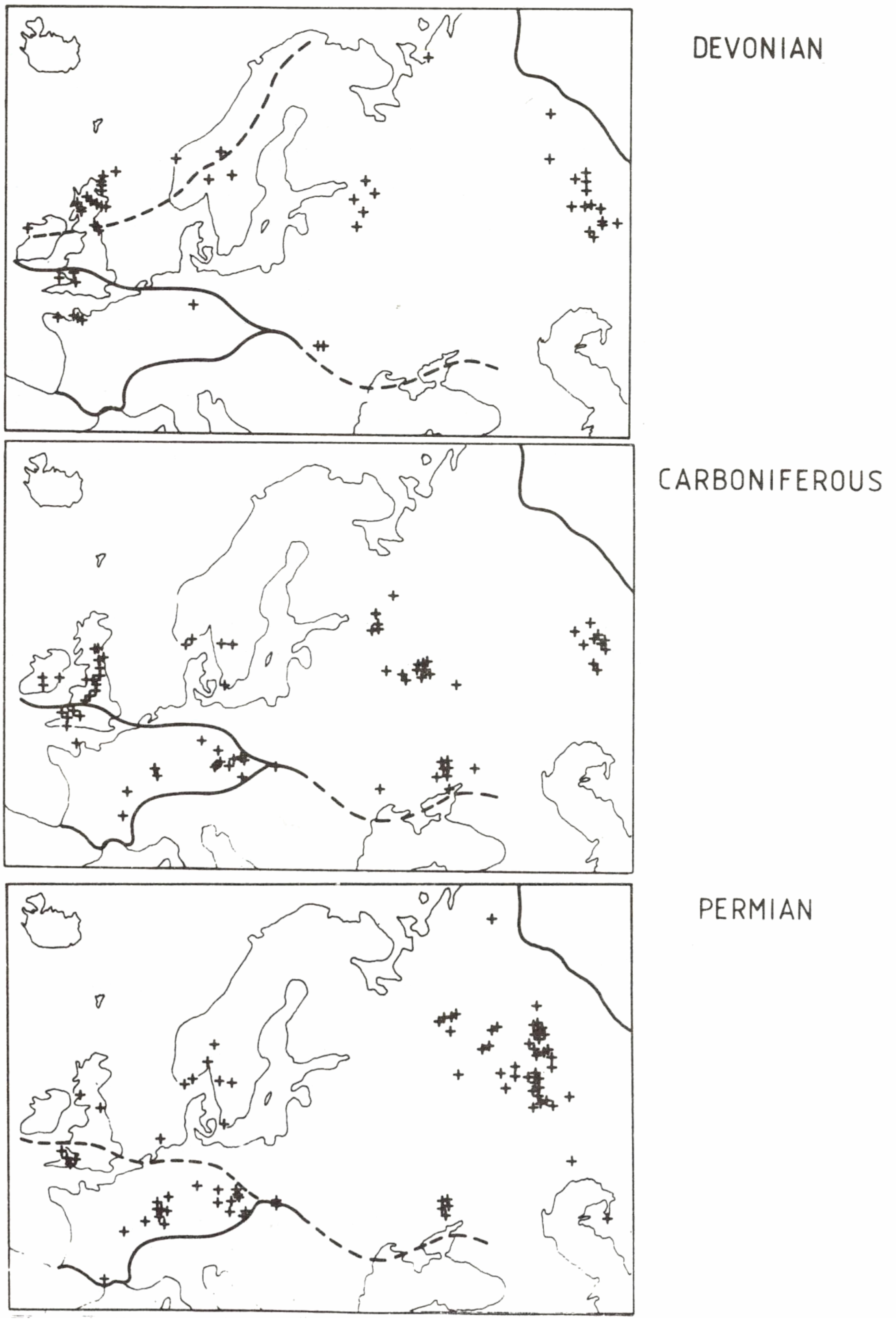


Figure 3. European Upper Palaeozoic Sites

These maps only show sites for areas away from the Alpine orogeny. The solid and dashed lines indicate the probable distinction of different major tectonic units. It is emphasised that these sites are for all rocks that are, or may be, of the age assigned and that the subsequent palaeomagnetic analyses may have demonstrated magnetic instability, overprinting or tectonic disturbance.

2b) yields a reconstruction that is similar to that for the Permo-Triassic fit (Fig. 2a), but differs drastically from the best Triassic-Jurassic tit (Fig. 2c). However, the reconstruction based on the Upper Palaeozoic data appears unrealistic in view of the evidence for the close contiguity of these continents at that time. On the evidence of this test, it is clear that there is still no satisfactory unique reconstruction even for two continents for which a large quantity of data are available. Thus, it is evident that palaeomagnetic reconstructions of the Gondwanan continent and for the Variscan orogenies must be even more suspect. Hailwood (1977) has suggested that the geocentric dipole model for the past geomagnetic may be invalid and that the field is best simulated by a northerly displaced dipole. In this particular example, the two continents, for most of the period, have similar palaeolatitudes and ;were essentially adjacent to each other in terms of sampling site -localities which, on the reconstructed models, would generally span some 5-6000 km. If the inconsistencies arise from the geomagnetic model, then the actual average field must vary on a scale of only some 1000 km or so, yet appears consistent within anyone continental this stage, therefore, it is merely concluded that considerable caution must still be exercised in evaluating past continental reconstructions based on palaeomagnetic data, despite apparent evidence for precision in palaeo-latitude and orientation of better than 5°.

4. Upper Palaeozoic Palaeomagnetic Data

(a) Europe

Superficially there appears to be considerable Upper Palaeozoic data available for Europe even when sites from within the Alpine zones are excluded (Fig. 3). It is suggested here, however, that while the rocks are of Devonian to Permian age, their magnetisations are frequently of Upper Carboniferous or Permian age. It is not practical to discuss each observation here, but the situation can be illustrated by a general consideration of the Devonian data (Fig. 4). The available pole positions cover a wide area in the Western Pacific but show different patterns for different areas. The determinations for rocks in the South Russia-Moscow region, for example, are quite well grouped close to the European Upper Carboniferous-Permian pole position, while those from the Timan area of the North Russia all lie over 3000 kin south of these, close to the Equator east of New Guinea. The pole positions determined from Devonian rocks in north western Europe are widely scattered over the entire area of the

Western Pacific, but their mean position lies distinctly further east and south of the Moscow data. Some of these Devonian data have previously been considered to represent completely remagnetised Permian observations and it is suggested here that the palaeomagnetic poles lying near to the Equator are, in fact, the best representatives of the 'true' Devonian mean pole position for Europe. The problem then resolves itself primarily into determining the mean longitude of this mean pole position -the observed poles lie between 120 and 180°E. After a variety of different assessments, it is suggested that the Lower Devonian pole for Europe is near to 2°N 150°E. While it is emphasised that this pole is obviously only poorly defined, particularly, in longitude, it is nonetheless thought that it is a better estimate of the Lower Devonian geomagnetic field than the conventional adoption of the mean pole based on either all or physically tested Devonian observations (Irving 1977; Krs 1978a; Van Alstine and de Boer 1978).

Palaeomagnetic observations are only just becoming available from the Armorican Peninsula, but at the moment these are mostly published in abstracts, thus restricting detailed consideration (Bouvier and others 1978; Hagstrum and others 1978; Van der Voo and others 1978). However, it is clear that most of these poles correspond with the general northwestern European grouping as they are mostly strung between Japan and the mean Devonian pole based on all northwestern European data. The occurrence of one pole near the United States testifies to the possibility of local tectonic rotation. Nonetheless, it seems reasonable to interpret these data as indicating a general similarity to northwestern Europe, but while there is uncertainty about the location of the true Devonian pole, the actuality of differences between the two areas must remain unclear.

The Carboniferous data (Fig. 3) will not be discussed as the situation is very similar to the Devonian. Most Carboniferous poles near the Upper Carboniferous-Permian mean position, but some groups of Lower and Middle Carboniferous poles are displaced from it. In general, the pole positions adopted for the subsequent reconstructions have been based on a few poles that are away from Upper Carboniferous-Permian grouping. The Permian data (Fig.3) are clearly well defined (Fig. 4) and the conventional acceptance of the mean is adopted here.

(b) North America

Most Devonian observations are from the Appalachian area (Fig. 5),

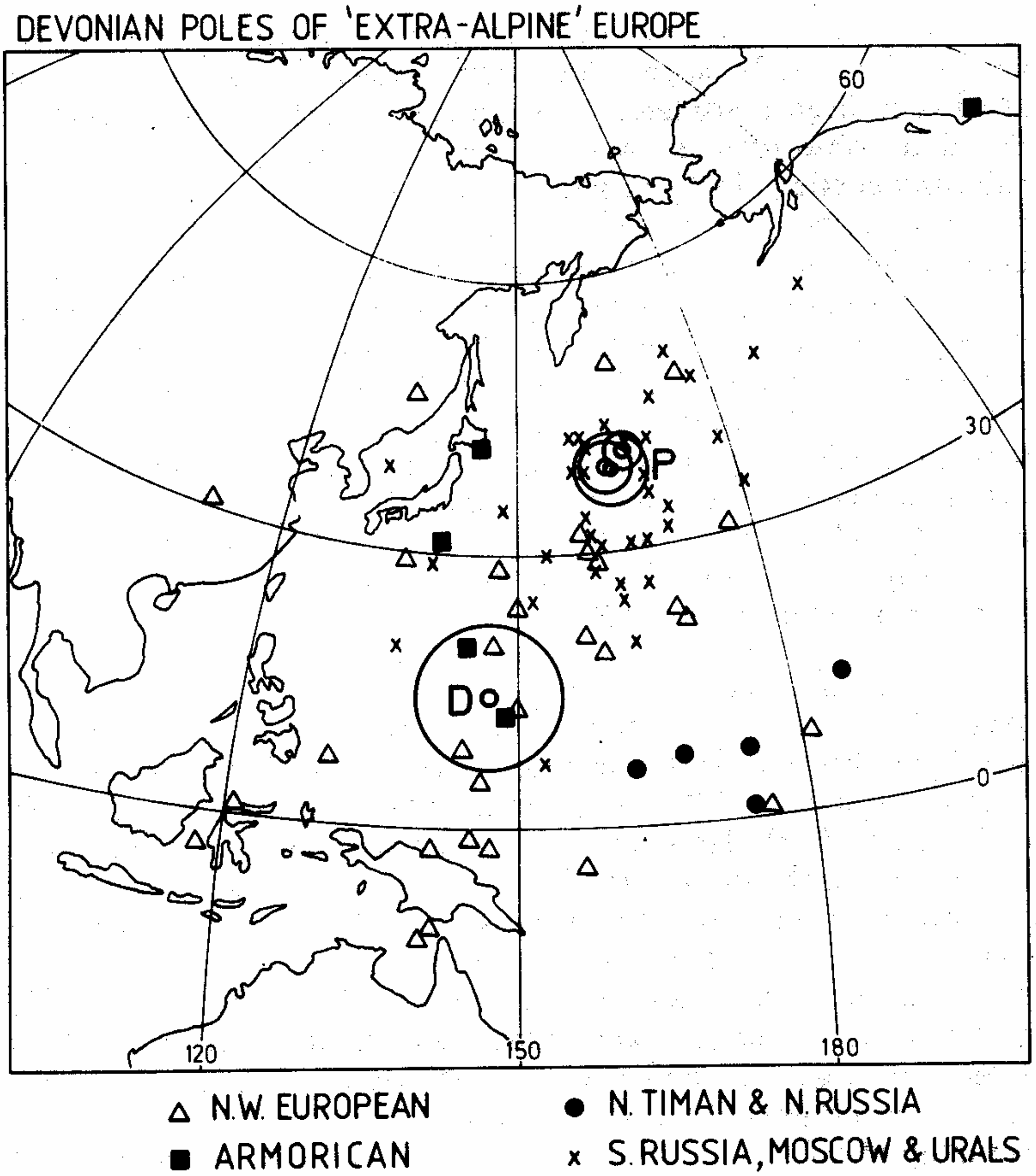


Figure 4. Devonian Pole Positions of Extra-Alpine Europe

The available palaeomagnetic data for Europe are shown on this figure and have been derived from the sites shown in Figure 3. Four groups of data are depicted from different areas. D corresponds to the mean pole and circle of 95% confidence for the data from northwestern Europe. P corresponds to the mean Upper, Middle and Lower Permian and Upper Carboniferous pole positions, with circles of 95% confidence, derived from all European data of those ages outside the Alpine orogenic belt.

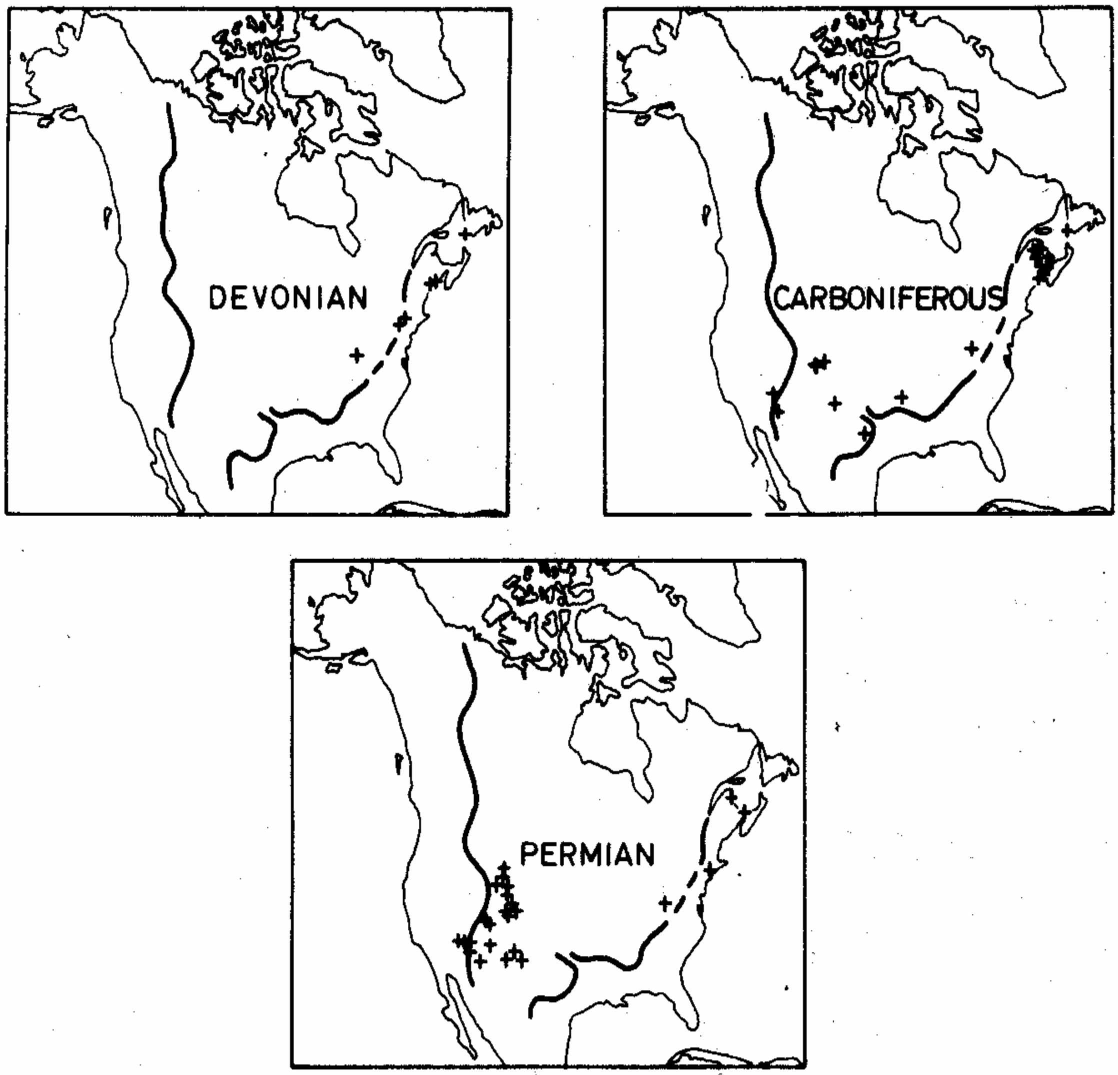


Figure 5. North American Upper Palaeozoic Sites
The approximate boundaries of the Appalachian and Cordilleran provinces are shown.

although mostly outside the orogenic belts. Nonetheless, most poles are located near N. China- Manchuria, close to the North American Upper Carboniferous- Permian mean pole positions. There are only two 'aberrant' poles, one known to be remagnetised, and the only 'acceptable' Devonian (Middle) pole appears to be from the Raisin Dolomite-Columbus Limestone (Martin 1975). The Carboniferous pole positions are mostly based on sampling in the northern Appalachians, but also extend across to the southern Rockies. Most of the rocks sampled are of Upper Carboniferous, or Permo-Carboniferous, age and have pole positions near Korea, with no obvious distinction between Lower and Upper Carboniferous ages. It is suggested that while the Upper Carboniferous pole position is quite well defined, the Lower Carboniferous pole can only be estimated by some form of subjective interpolation between the Mid Devonian and Upper Carboniferous observations. The Permian data are predominantly from the Mid West, with individual pole

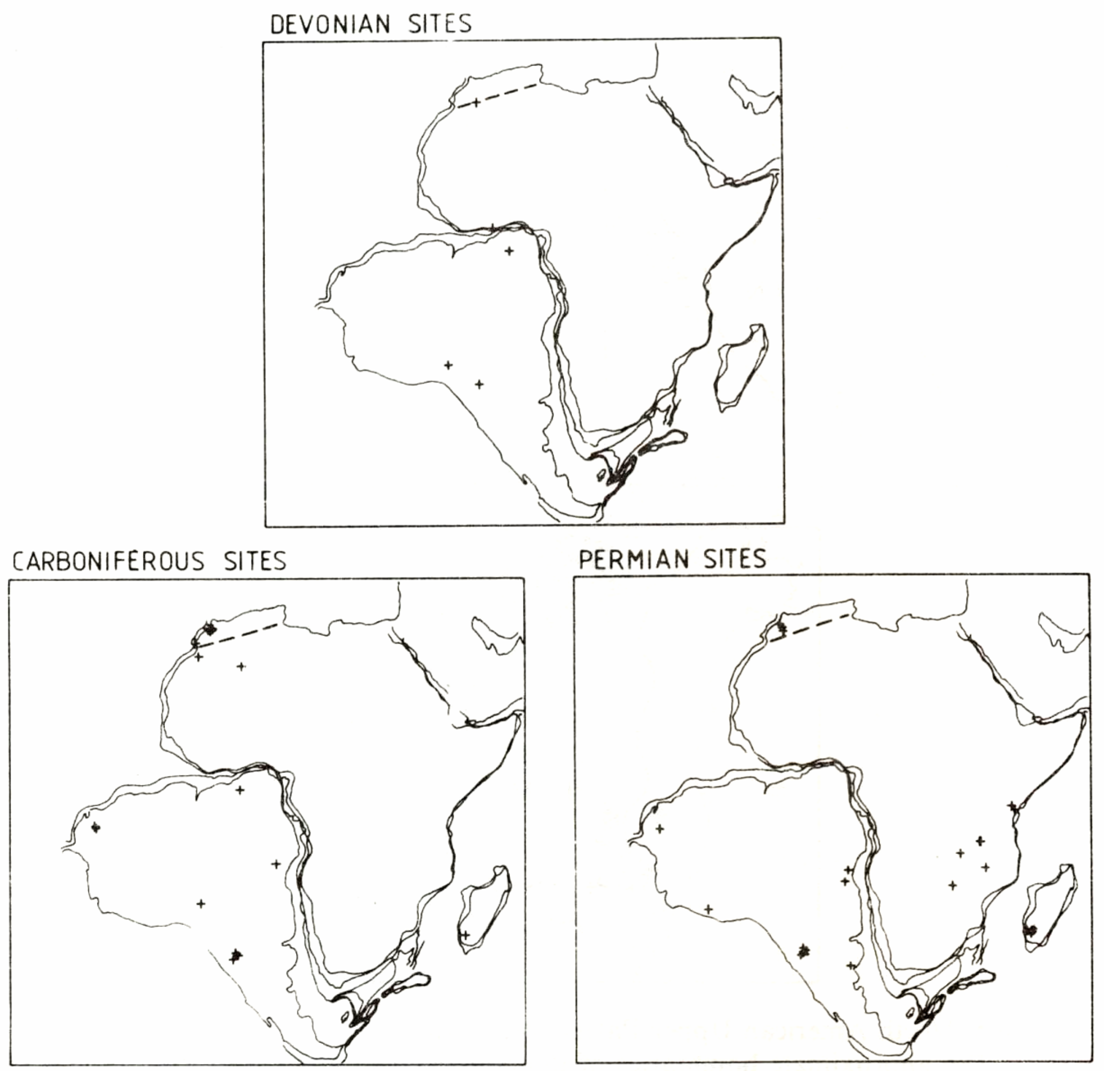


Figure 6. 'Western' Gondwanan Upper Palaeozoic Sites
African and South American sites are shown, with South America united to Africa in its pre-Cretaceous position.

positions extending from northern Korea towards the Verkhoyansk area of the USSR. This polar distribution appears to correspond to a gradual motion of the pole from its Upper Carboniferous position towards the Triassic mean pole, but such a motion is not confirmed by examination of separate Lower and Upper Permian observations. On this basis, the mean of all observations has been adopted as the Permian North American pole.

c) 'Western' Gondwanaland

As there is still no universal agreement on the Palaeozoic configuration of Gondwanaland (du Toit 1937; King 1958; Smith and Hallam 1970; Tarling 1971b; 1972; Embleton and McElhinny 1975) and the commonly accepted fit of Smith and Hallam (1971) is known to be inaccurate on geological grounds (Tarling and Kent 1976), the palaeomagnetic data considered here have been restricted to the 'western' sector of this supercontinent (Fig. 6), South America and Africa, for which there is virtual unanimity on their Palaeozoic configuration. (South America has been rotated to Africa by 56.1 about a Euler pole at 43.9°N 30.1°W as determined by Bullard and others (1965). Even on the reconstructed continent, the total data for anyone period are still few and there are often uncertainties concerning the precise age of the rocks themselves. For example, only recently has a Lower Permian (Sakmarian) age been assigned to most of the Upper Palaeozoic Gondwanan ice sheet deposits (Anderson and Schwyzer 1977) which have been generally regarded as Upper Carboniferous, but sometimes Lower Carboniferous or even Devonian in age. In view of these age uncertainties and the wide scatter of pole positions, the selection of the most likely Upper. Palaeozoic pole positions for this supercontinent is even more subjective than for the other continents considered here. The presence of ice sheet debris of Ordovician age in the Sahara (Beuf and others 1966) is considered to confirm the location of the south rotational pole in this vicinity at that time. The pole position for the Moroccan Mississi Norite (Hailwood 1974) is thus broadly consistent with the estimated palaeoclimatic position for the Devonian rotational pole, and has been only slightly modified by the incorporation of South American observations. The Carboniferous and Permian poles positions are similarly difficult to assess, either objectively or subjectively, and are, in any case, inconsistent with palaeomagnetic observations from 'Eastern' Gondwanaland, irrespective of the Gondwanan configuration adopted (Tarling, in preparation). This wide scatter of poles appears to reflect the strong motion of Gondwanaland relative to the rotational pole during the Upper Palaeozoic. It is considered that the polar wandering path adopted here is consistent with the available palaeomagnetic and palaeoclimatic evidence, but it could easily be drastically modified yet still remain consistent with such observations! However, while the evidence, at anyone time is uncertain, consideration of the total picture itself seems to place quite firm restraints on the probable situation at intermediate times.

5. Palaeomagnetic Reconstructions and the Variscan Orogeny in Western Europe

Despite the paucity of reliable, well dated palaeomagnetic data, and the evidence that considerable caution should be used in any interpretation based on even good data, a high degree of consistency

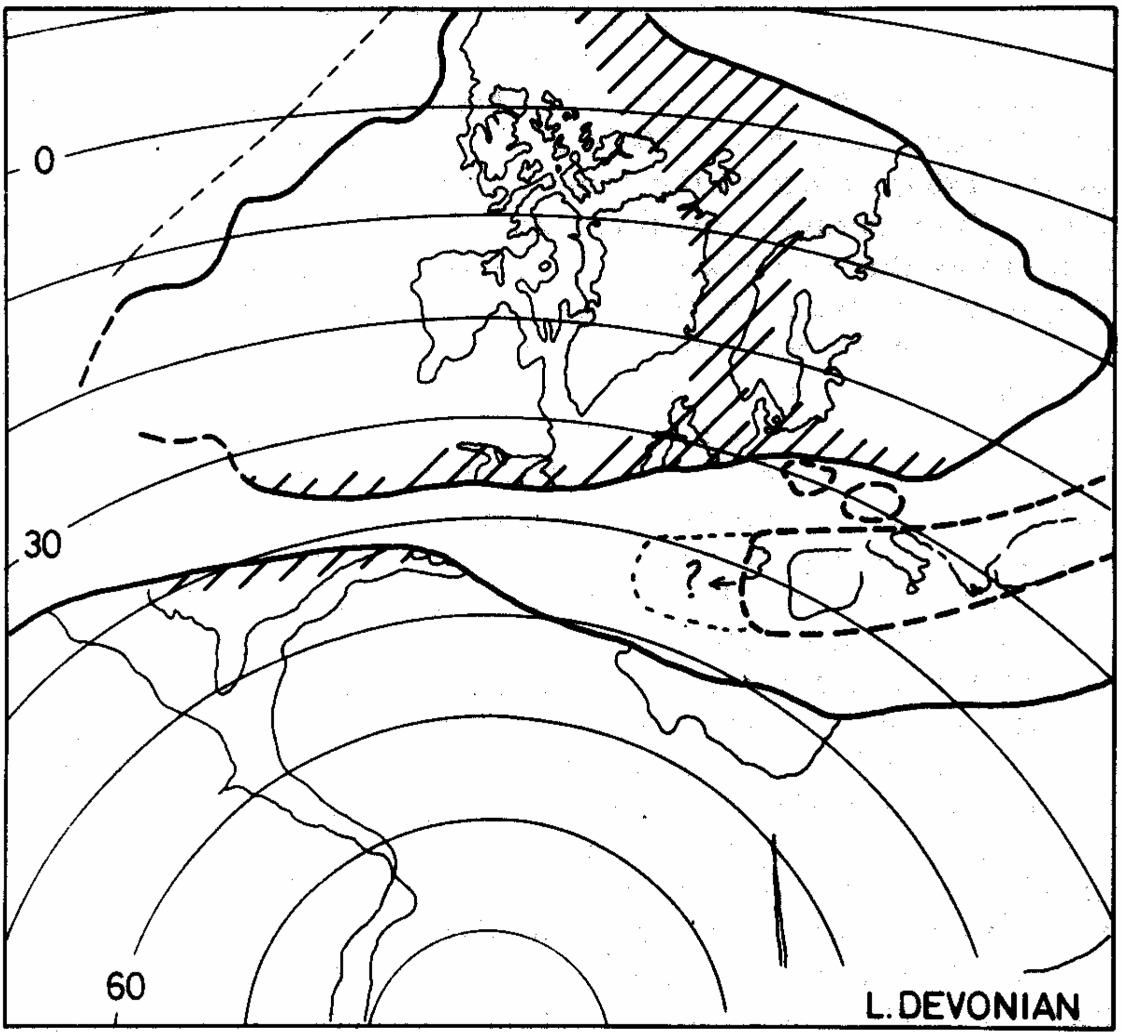


Figure 7. A Lower Devonian Reconstruction

For discussion of this reconstruction, see text. The hatching indicates the approximate limit of areas thought to have been affected by the Caledonian- Taconic Orogeny. The east-west location of the Southern European block is uncertain and it was, in any case, probably formed of several discrete blocks.

was obtained for the polar wandering paths for the two main continents concerned with the Variscan Orogeny –Laurentia (North America and Europe) and 'western' Gondwanaland (South America and Africa). There is also general agreement between the palaeolatitudes evaluated in this way with those indicated by palaeoclimatic evidence such as evaporites, ice sheets, etc., although this is partially a consequence of the subjective evaluation of the Gondwanan data. These polar wandering curves were then used to determine the changing latitudes and orientation of Laurentia and Gondwanaland during the Upper Palaeozoic. Despite the uncertainties for anyone particular time, these reconstructions place strong constraints on the evolution of the intervening periods. The more fundamental problem now appears to be the precise nature of the promontories and isolated continental blocks lying between the two supercontinents. In the reconstructions presented here (Figs. 7-10) most of these blocks are shown as a single Southern European block that comprised the Massif Central, Armorica, the Italian- W . Balkan (Adriatic) block, Bohemia, the Pannonian Basin, the Menderes block, and other blocks, such as Corsica, Sardinia, the Kabiles. However, while this is shown as a single block for most of this period, it is more probable that the land mass comprised a series of separate blocks that were not necessarily completely interlinked. The eastern end, in the Iranian area, almost certainly extended much farther eastwards (relative to Iberia) than today. However, while it is thought that this land mass was, in fact, a series of loosely linked continental blocks, they are generally shown in their Permian relationships to each other.

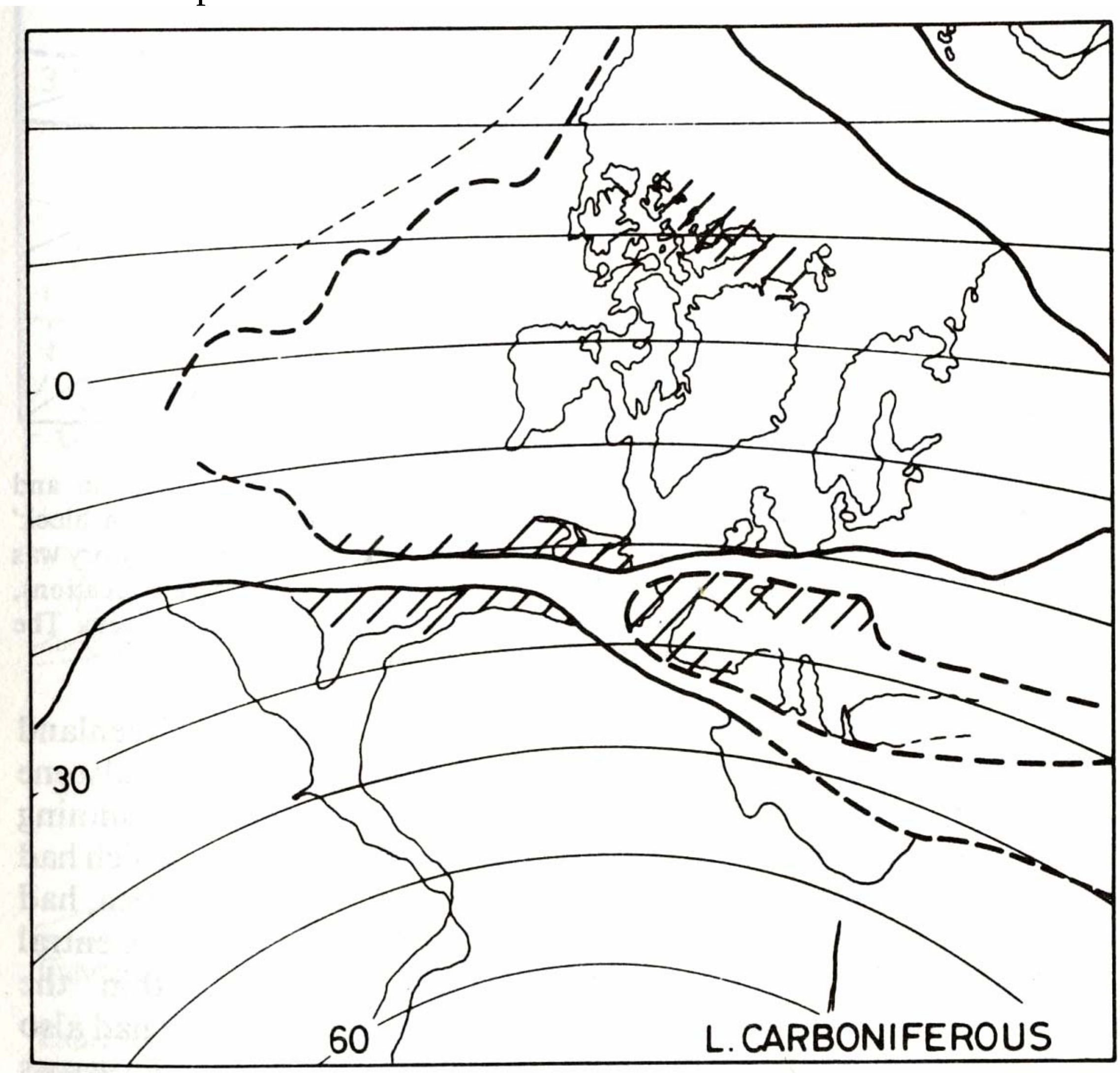


Figure 8. A Lower Carboniferous Reconstruction

Although Southern Europe was probably a series of separate blocks, its position is more closely defined than in Figure 7. The hatching indicates areas affected by the Acadian Orogeny

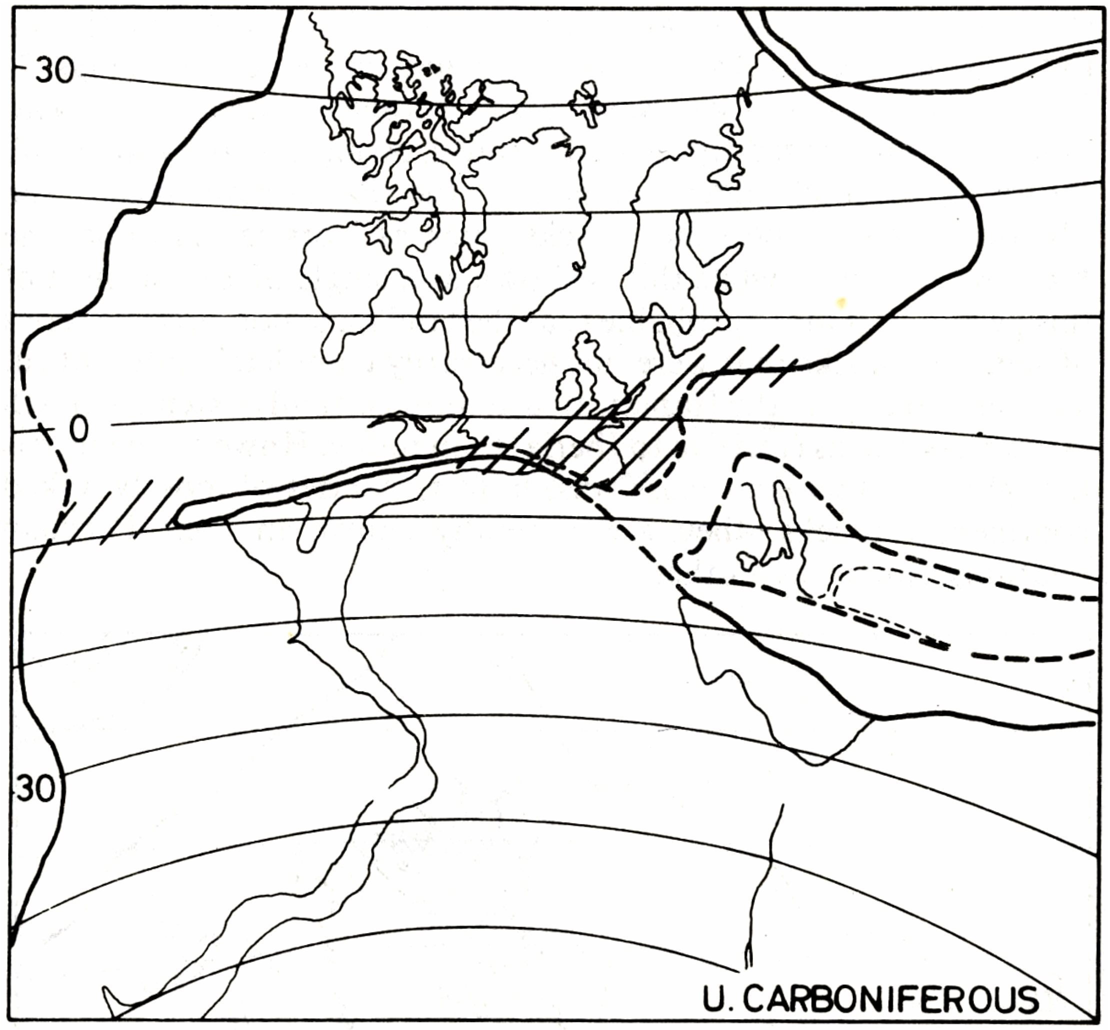


Figure 9. An Upper Carboniferous Reconstruction

While the Iberian block was probably connected to the Laurentian and Gondwanan continents, Italy, and the eastern part of the Southern European 'block' may have been either attached to Africa or, more likely the Adriatic Promontory was attached to Africa and other parts of Southern Europe were in separate locations, some with Europe, some with Africa and others separate from all of them. The hatching indicates areas affected by the Sudetic-Asturian Orogeny.

At the start of the Devonian (Fig. 9), Europe and Greenland had already been united to form the Laurentian Old Red Sandstone Continent (House 1971) with the Caledonian mountains running from the Arctic through to Britain. The Taconic orogeny, which had resulted from the collision between Africa and North America, had since been converted into a tensional area with a new 'Central Atlantic' ocean forming approximately centrally within the mountain belt. In central Europe, the Caledonian orogeny had also formed a mountain chain, paralleling the Tornquist Line, across northern Germany and southwestern USSR. The 'Central Atlantic' was not a wide ocean at this time, mostly only some 300-400 km wide, and may easily have been bridged by continental fragments, or island arcs, to link the Appalachian faunal province (Boucot and others 1969) in the Lower Devonian. This ocean increased in width slightly farther eastwards and eventually formed two separate, but narrow, oceanic arms on both sides of the Southern European landmass. The position of the Southern European land mass is uncertain. (The eastern extremity, comprising parts of Turkey and Iran, is thought to have extended sufficiently eastwards to provide a link for the migration of the ancestral Devonian freshwater fish and other fauna westwards into eastern and northern Europe, and thus into Arctica. China and other southeastern blocks are also thought to have provided migration routes eastwards into Australia at this time

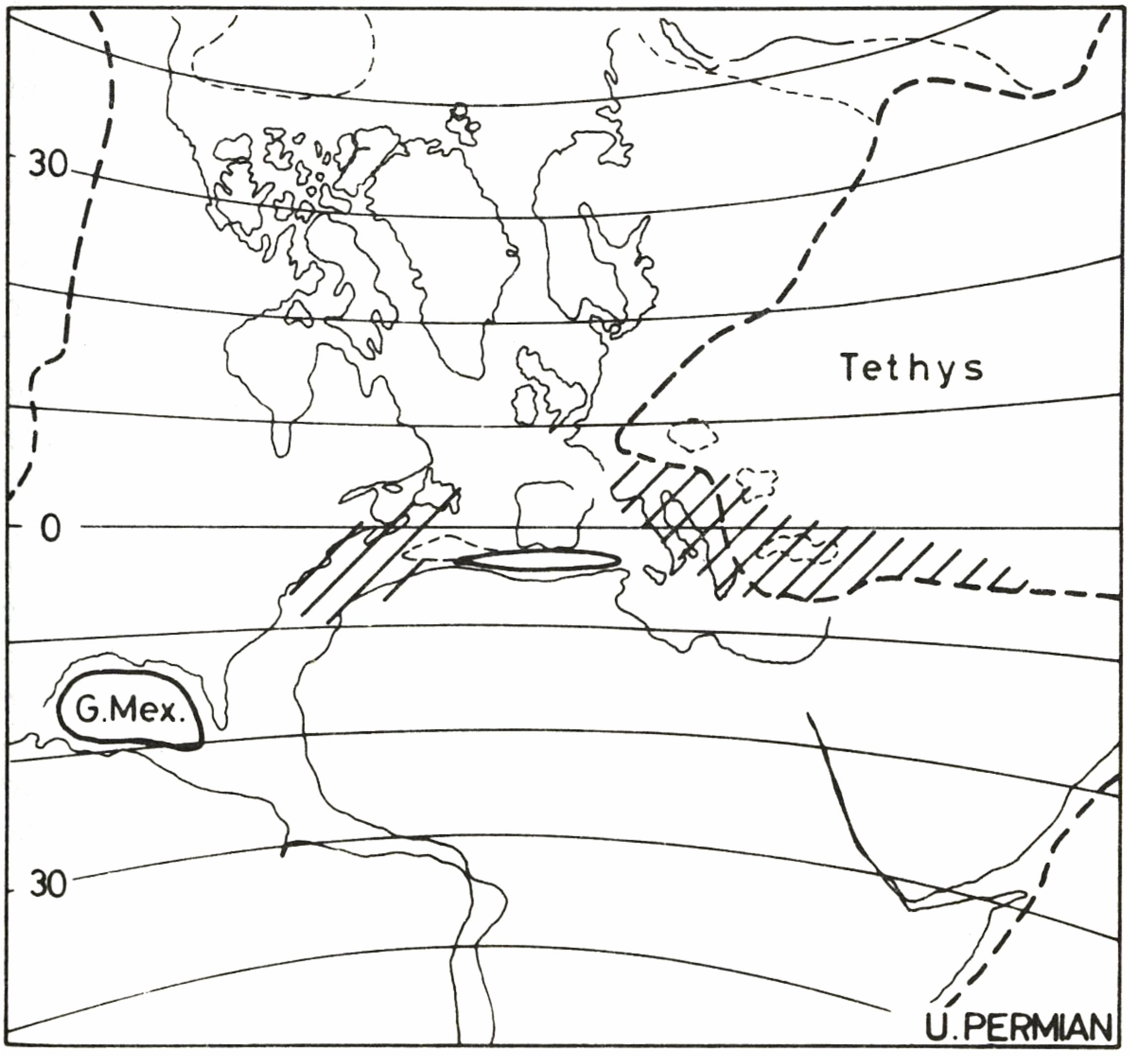


Figure 10. An Upper Permian Reconstruction

Although united as one supercontinent. Pangaea, the two continents of Laurentia and Gondwanaland were still in relative motion, initiating the Gulf of Mexico, a major trough north of the South Atlas fault system and a wide Tethyan Ocean in Eastern Europe. The Iberian and Adriatic Promontory were probably in the positions indicated, but the positions of other units of the Southern European block are extremely problematical. The hatching indicates areas affected by the Alleghenyan Orogeny

(Tarling, in press). It seems probable that the Iberian end of the landmass lay nearer to Britain and northwest Africa than depicted here, with the landmass splintered into three or more units at this period. 'Western' Gondwanaland was largely lying in the high southern latitudes, with northwest Africa at 45°S and northwestern South America at 35°S. Laurentia mostly lay between the Equator and Tropic of Capricorn -Britain being at some 30°S and James Bay (southern Hudson Bay) at 25°S. At this time, Laurentia and 'Western' Gondwanaland were both moving northwards and rotating clockwise.

The different rates of clockwise motion and the slightly faster northward motion of Gondwanaland resulted in the closure of the 'Central Atlantic' during Middle-Upper Devonian times, resulting in the cessation of the Appalachian faunal province and the creation of the Acadian Orogeny in Eastern North America. The western end of the Southern European landmass was also caught in the eastern extremity closure. The addition of the Kolyma to the Arctic area of Canada also probably took place in Middle-Upper Devonian times, giving rise to an orogenic episode in northern Greenland. The Acadian collision resulted in a change in the relative motions of Laurentia and Gondwanaland whereby 'Western' Gondwanaland had an essentially northern motion during the Middle and Upper Devonian, while Laurentia began to rotate anticlockwise while still moving northwards at a slightly faster rate than Gondwanaland. These motions re-opened the 'Central Atlantic' by Lower Carboniferous times (Fig. 8), as a narrow, 200-300 km wide, elongate ocean, possibly closed in places by individual continental fragments or promontories. The southern European landmass may also have been isolated with narrow ocean arms or marginal basins passing to the north and south of it. (Again it is more probable that the land mass was in disparate pieces, some attached to different parts of the major continental blocks). By the Lower Carboniferous, Britain had reached some 20°S, with James Bay was at 10°S, while northwest Africa and northwestern South America lay at 25°S and 20°S respectively.

During the Carboniferous, Laurentia was now rotating anticlockwise as well as tending to move northwards. This resulted in only a total slight northerly motion of southern North America during this period. Following the Acadian Orogeny, Gondwanaland was still rotating clockwise with a consequential northerly motion of 'Western' Gondwanaland. These motions partially reduced the width of the 'Central' Atlantic during the Carboniferous, but resulted in strong north-south compression and lateral displacements of any separate blocks that became caught between the motions of the two supercontinents. Such deformations particularly affected the Iberian and possibly Armorican massifs which may themselves have buffered any major collisions between the two continents until the opposite sense of rotation resulted in collisions elsewhere. By Upper Carboniferous time (Fig. 9), Britain lay on the Equator, James Bay at 10°N, northwest Africa at some 5°S and northwestern South America at 10°S.

The relative motions between the two continents was drastically changed at the end of the Carboniferous and early Permian times when northern South America and southern North America collided, Gondwanaland, in particular, changing its sense of rotation to anticlockwise. This change in rotation then closed the 'Central Atlantic' and caused the Adriatic Promontory to collide with the Iberian block even though the different rates of northward motion had then slightly separated Iberia from Gondwanaland. It is unclear whether areas east of the Adriatic Promontory were similarly affected by this collision or whether tectonic episodes in these areas were due to the closure of marginal basins, collision with the Menderes block, etc., or to 'Andean' type orogenesis related to southerly subduction of the Tethys Ocean. However, as the Mesozoic history of these areas is not yet sufficiently understood (Channell and Horvath 1976; Boccaletti and others 1976; Hsu and others 1977; Adamia and others 1977; Krs 1978b), its seems premature to attempt a proper analysis of their Palaeozoic history. The right-lateral and northerly motions of the two supercontinents during the Permian meant that, by the Upper Permian (Fig. 10), Britain, James Bay, northwest Africa and northwestern South America lay at 10°N, 7°N, 5°S arid 20°S respectively.

6. Some Plate Tectonic Implications of the Reconstructions

Two major features of the model are the narrowness of the oceanic areas between Africa and Laurentia during all of the Upper Palaeozoic, and the importance of the North and South American collision that is predicted as being of latest. Carboniferous-early Permian age (King 1975). The reaction to this collision is presumably responsible for the extensive Permian faulting that delineated the areas that were destined to form the present-day continental margins

(Kent 1976). It is also probable that the separation of the Central and Southeastern Asian area of the complex blocks from Gondwanaland also occurred in response to these drastic changes. In Western Europe, however, it is the narrowness of the ocean throughout Upper Palaeozoic times that is a major feature of the model.

It is conceivable that the width of the 'Mid European' Ocean was, at some time, up to 1000 km, but it appears to have been generally of the order of 300-400 km wide. Such a narrow extent of ocean has been used to suggest that plate tectonic models would not be applicable as the subduction of such an oceanic plate could not account for the width of the Variscan orogenic events that even today extend for a width in excess of 1000 km, or for the magnitude of the igneous activity associated with them. In general, in excess of 150 km of oceanic lithosphere needs to be subducted at angles of some 45° before the pressure-temperature conditions are attained that result in andestic volcanism and the formation of granitic magma chambers in present-day subduction zones (Karig 1971; Stevenson and Turner 1977; Tarling 1978). Obviously if the total width of oceanic floor that could be subducted during the Upper Palaeozoic were only 600-1000 km, then it would be impossible to explain the magnitude of the Variscan Orogeny by plate tectonic activity using the proposed reconstructions.

The production of oceanic crust does not, in fact, bear any particular relationship with the width of the ocean involved if that ocean basin includes a subduction zone. Thus Andean-type orogenies could have been occurring along much of the ‘Atlantic-Mediterranean' seaboards throughout the Upper Carboniferous. Such a model could allow the production of 1000km of oceanic crust during the Devonian and a similar amount during the Carboniferous if a fairly slow half-spreading rate of 1 cm year -1 is assumed. Furthermore the consumption of such ocean crust would cause the subduction to take place at shallow angles as the density contrast between the continents and oceanic lithosphere that may have only been, on average 20 million years old, would be smaller than for older oceanic lithosphere. This would result in a wider subduction zone than in, for example, Japan, Tonga and the Aleutians today. It is thus likely that transient marginal basins would form more readily and also that the igneous activity would have extended from the subduction zone for great distances during the Variscan Orogeny.

7. Conclusion

While any reconstructions based on palaeomagnetic data alone must be treated with great caution, it is possible to determine a series of model reconstructions for the Upper Palaeozoic that are, at least reasonably consistent with each other and with the possible tectonic evolution of the Variscan orogenic systems. These models are particularly uncertain for the nature and position of constituent parts of the South European continental block(s) yet these are of critical importance in assessing the local implications of the relative motions of the two supercontinents. These blocks formed the pressure points against which the continents interacted and the degree of anticlockwise rotation, that is common to both Laurentia and Gondwanaland during this time, appears to relate to the way in which these blocks became caught between the closing continents. The local expression of the Laurentian-Gondwanan collisions is therefore complicated not merely by the occurrence of relatively minor units within the closing oceans, but also by the way in which the left lateral motion between the two continents as a whole was, at times, converted into aright lateral displacement (in the Mediterranean area in particular) by the relative rates of anticlockwise rotation of the two supercontinents

It is considered that the proposed reconstructions are consistent with a plate tectonic origin for most Variscan tectonic and igneous features. However, it is emphasised that the reconstructions are presented as bases for discussion. It is essential that all geological and geophysical observations are used to modify the extant pattern of events.

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9. Discussion

Dr P .A. Floyd noted that with the girdle base that had been used on many of the diagrams, the author had selected samples farthest away from clusterings in order to avoid the effects of tectonic overprinting. First, was there any systematic change in oxidation ratios in the rocks along the girdle as well, and, second, was there any difference between magmatic rocks and sedimentary rocks along the girdle?

The Author replied that there were very few data available to answer Dr Floyd's first question. The best way to proceed was to note the location that a sample had come from and estimate whether it was likely to have been relatively free from tectonic disturbance.

Comparing results from magmatic and sedimentary rocks, the author said that the vast majority of data were based on measurements from sedimentary rocks. In a relatively few cases, both magmatic and sedimentary rocks were involved, and commonly showed similar results.

The author took two PreCambrian examples to illustrate the difficulties of interpretation of palaeomagnetic data even when detailed work had been carried. The two oldest pole positions determined, at 2700 Ma, were the only two which combined good petrological work with palaeomagnetic work; they were from the Great Dyke of Rhodesia and the Stillwater Complex. In both cases, the magnetisation was not carried by titano-magnetite; in the case of the Great Dyke rocks it was carried out by an iron oxide developed from the breakdown of feldspar; and in the case of the Stillwater Complex rocks the magnetisation was carried in the pyroxenes. It was not possible to say what age the magnetisation was in either case, and he suspected that it had little relationship to the radiometrically determined ages.

The age of oxidation in most cases could only be determined in relative terms, not absolutely.

Dr J.P.N. Badham said that the author had challenged the data that supported the recent conclusion that there had been little relative movement between Armorica and northern Europe; he would like to emphasise that any movement would have been effectively latitudinal and therefore not readily detectable from palaeomagnetic data.

The Author replied that if his reconstruction was right, the latitudinal space for movement was small and the relative motion of the two supercontinents was predominantly longitudinal. Both of these movements are thus detectable with palaeomagnetic techniques, although longitudinal motions require additional control to achieve any degree of certainty.

Dr Badham commented that he was pleased to note that palaeomagnetists were coming to agree with geologists, some of whom had been maintaining for some time that major sinistral movements had occurred.

With regard to the Lizard complex, which was probably an ophiolite, the palaeomagnetic data from the freshest igneous rocks (in which the magnetisation was present in titano-magnetites), indicated that the rocks were either Permian and in place, or out-of-place and of some other age. Did the author consider that Lizard rocks with Upper Silurian ages could have been remagnetised in the Permian with no effect on the isotopic values -i.e. updating?

The Author replied that he would need to study the problem in more detail before he could answer satisfactorily. He thought that a problem was that one was not necessarily dealing with weathering, but with ex solution taking place exponentially with time. If the sample was obviously weathered, then it would be discarded for palaeomagnetic purposes. In many rocks there was long term breakdown of pyroxenes, amphiboles and other minerals, which was not weathering in its normally accepted meaning but still resulted in the acquisition of a stable, younger magnetisation comparable to weathering in its magnetic effect.

PRELIMINARY INVESTIGATIONS OF SOUTH CORNISH MELANGES

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Abstract. A distinct unit of sedimentary (olistostrome) and tectonised melange containing numerous phacoids of diverse provenance can be followed continuously from the northern margins of the Lizard Complex through Roseland to Gorran. The phacoids include Ordovician quartzites and a diverse assemblage of Devonian sedimentary and mafic igneous rocks. The latter have tholeiitic affinities and are distinct from other Cornish greenstones. Nare Head, one of the larger areas of mafic igneous rock, contains volcanic, volcaniclastic (with amphibolite clasts) gabbroic and ultramafic units. The structural trend of the melange unit is ENE with one southerly-inclined penetrative cleavage and a down dip extension lineation. Opposed facing directions characterise the S1 cleavage. The observations are consistent with the development of the unit olistostrome in front of land beneath an advancing ophiolite sheet.

1. Introduction

It has long been recognized that rocks outcropping between the Lizard contact and Gorran (Fig. 1) were characterized by the occurrence of pillow lavas, quartzite phacoids originally dated by Peach (1841) as Ordovician, (confirmed by Sadler (1973)) and units of phacoidal rocks described as "crush breccias". Most of these rocks form the Veryan Series of Hill(1899). Hendriks(1931) redefined part of this Series as the 'Meneage Crush Zone' and included the remainder in her Gramscatho Series. A thorough description of the Meneage and its phacoids (including schists, granophyre, quartzite, pillow lava and conglomerate) was made by Flett (1946) who suggested a single simple stratigraphical sequence based on predominant clast types.

Recent papers on the Meneage and Roseland (e.g. Hendriks and others 1971; Sadler 1973) have suggested severe tectonic disruption of an originally continuous stratigraphical sequence. On the other hand, Lambert (1965) described the section from

Porthallow to Menaver as one of sedimentary slump deposits and conglomerate, and saw no evidence for tectonic brecciation. He suggested a similar origin for rocks elsewhere within the Gramscatho Series (e.g. Poldhu Cove, and in Roseland) within which the quartzite phacoids might be large slumped sedimentary blocks.

An allochthonous origin has been suggested for the Lizard Complex in recent years by various authors (e.g. Strong and others 1975; Badham and Kirby 1976). A detailed study by Kirby (1978) provides substantial evidence in support of such an origin. Emplacement of ophiolites in other parts of the world has commonly been associated with the formation of sedimentary and tectonic melanges (e.g. Newfoundland and Oman). By analogy the melanges in South Cornwall may be related to obduction of the Lizard Complex. This hypothesis is being tested and preliminary results are described below.

We prefer to use the term 'melange' in a purely descriptive and non-genetic sense to encompass all chaotic sequences, whether of sedimentary, tectonic or multiple origin; the term is not used in the strict definition of Hsu (1968).

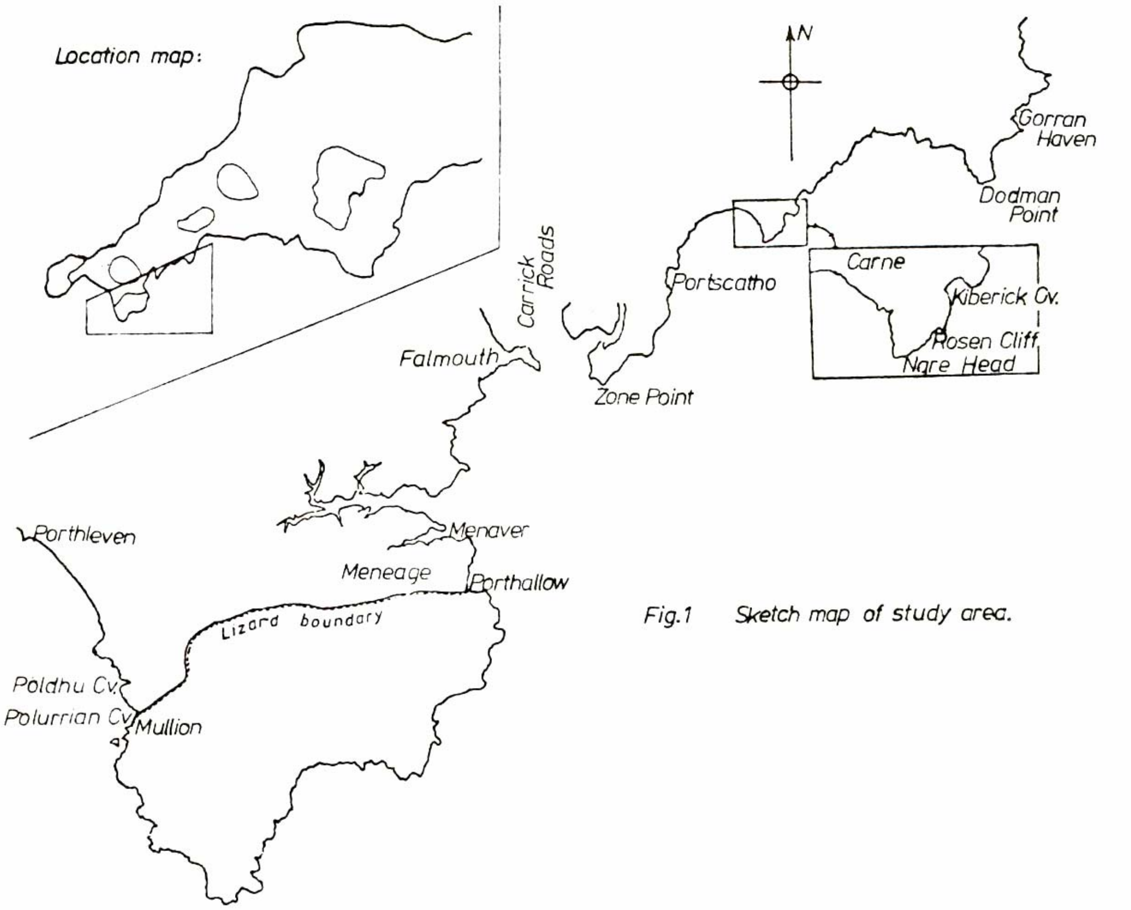

Fig.1 Sketch map of study area.

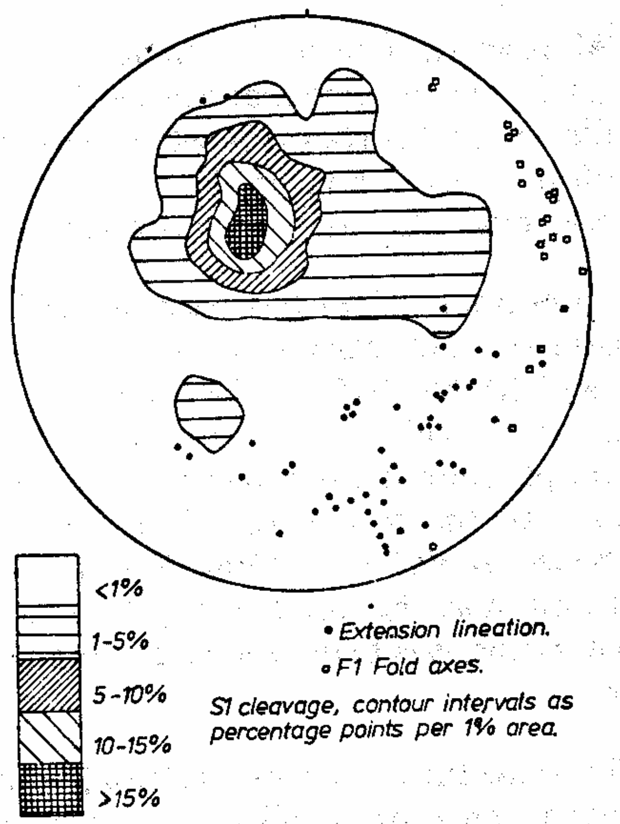

Fig.2 Poles to S1 cleavage, plots of F1 fold axes and extension lineations; Porthleven to Gorran.

2. Brief description of lithologies

Rocks in the study area (Fig. 1) may be divided into those which retain a reasonable stratigraphy, i.e. are bedded; and those which do not i.e. are 'chaotic', (melange). The former are predominantly slates with interbedded siltstones (1cm thick) or arenites (1m thick) which commonly show grading and more rarely cross-lamination and are probably turbidite deposits. Locally the arenites are calcareous: for example a thick calcarenite-slate sequence outcrops on Came Beach in Roseland. Internally ordered, large igneous rock bodies occur which retain many original features and will be considered later.

Melange outcrops on all scales from large independent units to units within the bedded rock sequence. Thin units of the latter kind are of sedimentary rock clasts in a fine matrix and are clearly sedimentary slump deposits. On a larger scale, units consisting entirely of greywacke phacoids in slate are common. Rocks of this type are among those described from the Meneage by Lambert (1965) where phacoids range in size up to I m thick and 3 m long. These are also slump deposits (Lambert 1965) of sedimentary origin. Similar rocks outcrop in Polurrian and Poldhu Coves (an inverted greywacke raft of dimensions 100 m x 10 m with bedding preserved internally occurs completely surrounded by melange at the latter locality) and in Roseland. Sedimentary rudities are common, a particularly good example being the Menaver Conglomerate, outcropping just north of the Meneage. This contains abroad assemblage of sedimentary , igneous and metamorphic clasts (listed by Flett 1946) in a sparse arenitic matrix.

On a very large scale, the Ordovician quartzites occurring from Meneage to Gorran are phacoids within a slaty melange matrix and range in size from a few centimetres up to a hundred metres in length. These quartzite units are internally deformed and adjacent phacoids bear no relationship to one another. No other Ordovician rocks have been found in South Cornwall. There are also large phacoids of mafic igneous rocks, the boundaries of which are always faulted against the surrounding melange. These phacoids reach considerable sizes, e.g. the Nare Head greenstone, in Roseland, spans 0.75 km^2 and forms cliffs 90 m high. This unit is predominantly composed of pillow lavas and pillow breccias, with tuffs, agglomerates and, near Kiberick Cove, two gabbro lenses and small amounts of ultramafic rock. Lithic and crystal fragments in the volcaniclastic rocks vary in metamorphic grade from unaltered to greenschist facies. A particularly interesting agglomerate occurs at Rosen Cliff on the east side of Nare Head. Here clasts of amphibolite and flaser gabbro can be recognised among more abundant clasts of basalt, dolerite and gabbro in a tuffaceous matrix. The amphibolites and gabbros are very similar to rocks described from the Lizard by Kirby (1978). The rocks appear to have been derived from a lava pile metamorphosed at greenschist facies grading to amphibolite facies at depth. They are now incorporated in an allochthon surrounded by sedimentary melange.

3. Geochemistry

Analyses are available for Ti, Sr, Rb, Y, Zr and Nb on specimens collected from Nare Head in Roseland and some basic sills near Porthleven. These are compared (Table I) with analyses of the same elements in Lizard dolerites, and Meneage greenstones (both from Kirby 1978). It is clear that the Nare Head and Meneage greenstones are very similar to tholeiitic (Kirby 1978) Lizard rocks. They are all significantly different from the alkaline Porthleven sills which compare favourably with Cornish greenstones elsewhere (Floyd 1972 a and b). The Kiberick Cove gabbro is remarkable for its very low Ti, Y and Zr concentrations which support textural evidence that it is a cumulate.

	Ti(%)	Rb (ppm)	Sr (ppm)	Y (ppm)	Zr (ppm)	Nb (ppm)
Greenstones - Nare Head	1.14	21	81	59	149	4
Greenstones - Meneage	1.38	5	188	48	140	12
Dolerites - Lizard	1.47	15	237	43	140	7
Gabbro - Kiberick Cove	0.25	22	117	11	10	n.d.
Dolerite Sill - Porthleven	2.22	1	76	63	207	18

Table 1: Selected trace elements in some South Cornish greenstones.

4. Structure

Only a brief survey has so far been made of some of the more accessible sections around the coast. Major structures with axes trending ENE and plunging gently in this direction are recognised from Loe Bar to Gorran. They are recumbent or inclined isoclinal folds with an axial planar penetrative slaty cleavage dipping consistently to the SSE (Fig. 2). No evidence was seen in the sections studied of earlier structures hence these folds are here designated FI and cleavage SI. Northeast trending second fold structures are developed locally, usually as small scale upright or inclined folds with an axial planar crenulation cleavage dipping steeply to the SE. In the Polurrian to Porthleven section there is a further crenulation cleavage, which together with sporadic occurrences of kink bands throughout the area, represent late structures of minor importance.

The Dl phase of deformation described above represents the only important phase of tectonic shortening over most of the area of study, and is of very variable intensity. However in the Porthleven area, deformation is more intense, the rocks are severely flattened and three cleavages are present (Stone 1962; 1966). The relatively simple structural pattern displayed by the rocks to the south and east of Jange-ryn is in sharp contrast to the complex picture described from around Porthleven by Stone (op. cit.) and from North West Cornwall by Smith (1965 a,b).

Oblate strain seen near Porthleven is in contrast to more prolate strain in the rocks to the south where a stretching lineation trends consistently SE (Fig. 2). The strain markers are clasts in the numerous coarse clastic rocks (e.g. conglomerates, arenites and igneous breccias), early pyrite in slates and tuffs and fibrous infills of extension fractures.

In some sections S1 cleavage is downward facing, principally at Nare Point in west Meneage, and also in short sections at Porthleven sands and Pendower beach (Roseland). Downward facing on S1 in the Porthleven section may be explained by a Do fold phase associated with the So cleavage recognised by Stone (1966) but in the rest of our study area earlier tectonic structures are absent. Bearing in mind the likelihood of a very unstable sedimentary environment characteristic of recent melanges, we suggest that large scale pre-cleavage slump folds could have inverted large sections of the stratigraphy. Later superposition of the cleavage would explain the opposed facing seen in the field.

The orientations of the F1 structures, and of the stretching lineation are compatible with deformation produced in a shear zone beneath an ophiolite being thrust northwards.

5. Summary and Conclusions

The following points arise from work so far carried out on South Cornish melanges:

1. Sedimentary slump deposits, coarse conglomerates, and possibly the opposed facing of FI structures in South Cornwall, indicate tectonic instability during sedimentation.
2. There are large scale FI structures with an axial planar slaty S1 cleavage and down dip extension lineation, and there is asystematic change in deformation from oblate (pure flattening) strain towards prolate increasing towards the Lizard contact.
3. The presence of greenstone phacoids of comparable geochemistry to Lizard rocks and the presence of 'Lizard type' rocks in igneous breccias confirms a close genetic association with the Lizard.

We suggest that the melanges from the Meneage through Roseland to Gorran arise from olistostromic deposits in a trough adjacent to the advancing Lizard ophiolite, which were subsequently tectonised in a shear zone beneath the overriding ophiolite.

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RODINGITES IN THE LIZARD COMPLEX

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Abstract. Rodingites are metasomatised rocks and veinstones that occur near the contacts of serpentinized periodites. The occurrences described in this note are of two types: rodingitic alteration of gabbro, observed at Coverack; and discrete rodingite veins in serpentinite, observed at Enys Head.

1. Rodingitic alteration of gabbro

There occur on the shore at Coverack many boulders of a gabbro showing a structure described by Flett (1946) as "brecciform". It appears to consist of blocks of a dark coloured gabbro set in a matrix of lighter coloured gabbro. The darker coloured blocks are somewhat angular in appearance but not sharply bounded, leading Flett to the view that the gabbro had been fractured while still hot and then bound together by further injection of a similar but more leucocratic magma. This conclusion, if true, is of importance in that it would preclude the mapping of any cryptic variation in the gabbro.

In fact, the lighter matrix of the brecciform gabbro does not represent a second injection of magma, but is due to post magmatic metasomatism concentrated about a number of interlacing planes. This feature was not immediately recognised as a type of alteration because the zones of alteration do not correspond to the present directions of jointing and only rarely does the alteration product appear in discrete veins. The lighter coloured gabbro has been partially replaced by prehnite, and the darker gabbro is simply its unaltered equivalent. The white material in the most altered examples is composed almost entirely of fine-grained colourless prehnite.

The best examples of the brecciform gabbro are seen in the well-polished beach boulders on the shore at Coverack, but gabbro of a similar type occurs in situ in the gabbro north of the village, and boulders are also found on the beaches for some distance to the south, as at Pen Voose.

2. Rodingite veins

At Enys Head, 800 metres NE of Cadgwith, the peridotite is cut by two types of intrusion: dark grey dykes, similar to the basic dykes occurring elsewhere along the coast; and thin white veins which were described by Flett (1946) as "saussurite-gabbro". Both types of rock contain rodingite mineral assemblages. The dykes are interpreted as rodingitised amphibolites, and the lighter coloured rocks as discrete rodingite veins.

The light-coloured veins are variable in thickness from about 5 to 30 cm, typically about 15 cm wide. They have been somewhat disrupted by movements in the surrounding peridotite. Some have been torn apart and deflected; some unite or diverge; some are preserved only as isolated angular joint blocks surrounded by peridotite. Individual veins can be traced for ten metres or more in the well exposed lower part of the headland. The veins are separated from the peridotite at their margins by a 2-3 mm band of dark chlorite-rock, which is often weathered out into a groove.

Internally the light veins are variable in character. They commonly have a fine saccharoidal texture, but in places are brecciated. The mineral assemblages which have been found are:-

garnet-serpentine
garnet -serpentine-chlorite
garnet -serpentine-chlorite- ilmenite-zoisite
garnet -serpentine-calcite

The garnet-rich specimens are a pure white colour, and the serpentine-rich material is white with a pale greenish or greyish tinge. The garnet is colourless, with a cell dimension close to that of the grossular end-member (a = 11.85 Å). The serpentines are chrysotile, lizardite, or a mixture of the two, but never antigorite. Chlorite, where it occurs, is colourless, and fills the interstices in an aggregate of anhedral garnet crystals. In the brecciated specimens, fragments of garnet, or garnet + chlorite, are separated by a serpentine matrix arid cut by serpentine veins. Ilmenite occurs as large (2-5 mm) irregular concentrations and black streaks.

They grey dykes are a much less uniform group of rocks. There are some which are coarse-grained and resemble the gabbro dykes found at various places on the east coast of the Lizard. Many are dark, fine-grained, granular rocks similar to the epidiorites which are very abundant on the east coast. Some are a lighter grey and very fine grained, and have no obvious affinities among other Lizard rocks. All of these rocks are variable in thin section, and all show severe rodingitic alteration, but they differ from the white veins in the complete absence of garnet. The mineral assemblages which have been found are:-

prehnite-serpentine
prehnite-amphibole
prehnite-serpentine-amphibole-chlorite
prehnite-serpentine-amphibole- ilmenite
serpentine-amphibole- ilmenite
serpentine-chlorite-ilmenite
serpentine-amphibole
serpentine alone.

The white veins at Enys Head are sometimes parallel to the altered basic dykes and sometimes not. A number of the veins and a number of the dykes strike approximately north-south, and dip steeply to the west, but this orientation is not consistently maintained and there are examples of both types of body aligned in other directions.

3. Discussion

The only previous record of rodingite in the Lizard complex is a passing mention of rodingitic alteration of banded peridotite at Polbream Point (Green 1964, p. 138). Most examples of rodingites that have been described in the literature are altered basic igneous rocks, and the principal chemical changes involved in rodingite formation are calcium and magnesium metasomatism and desilication. Coleman (1967) has discovered that acid igneous rocks and sediments may also undergo a similar type of alteration where they come into contact with serpentinized peridotite, and it seems that rodingitic alteration may be responsible for some previously unexplained features of Lizard geology.

The most interesting of these is the occurrence of talc at Gew Graze. Although talc is a common mineral in metamorphosed ultrabasic rocks, the talc at Gew Graze occurs not in the serpentinite but in a granitic vein cutting through the serpentinite. This is rather puzzling since the chemical changes required to form talc from granite are much greater than those needed to form talc from serpentine, and can only be explained by severe magnesium metasomatism. Unfortunately a complete cross section from serpentinite to talcified granite is difficult to find in situ. A more accessible though less extreme example occurs at Kennack Sands, where the granitic component of the banded Kennack gneiss sends veins into an overlying mass of serpentinite. In the well known locality at the west end of Kennack Sands (Flett 1946, fig. 15; Hall 1974, fig. 14) the acid component of the Kennack gneiss is a quartzofeldspathic rock of broadly granitic composition, but its offshoots into the serpentinite have been desilicated. Quartz is entirely absent from some specimens and a small amount of serpentine is present.

The source of the metasomatizing solutions, and of the material deposited in the discrete rodingite veins, is not certain. Bilgrami and Howie (1960) reviewed the occurrences of rodingites, pointed to their universal association with serpentinites, and suggested that the metasomatically introduced material was released from the original peridotite in the course of serpentinization. Rodingitic alteration is certainly a low-temperature process. It has recently been discovered in basic igneous rocks of the modem ocean floor (Honnorez and Kirst 1975), and authigenic grossular has even been found in deep sea sediments (Easton and others 1977). It is possible that the Lizard rodingite formed while the complex was still apart of the pre-Variscan oceanic crust.

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5. Discussion

Mr C.M. Bristow asked what kind of alteration process had affected the rocks; was it analogous to kaolinisation or pyrophyllitisation, or was it more of a metamorphic process?

The Author replied that the Lizard chrysotile assemblage suggested that alteration had taken place at temperatures lower than about 400°C. Garnet, as was now known, could form at a very wide range of temperatures: it was known to have formed in deep sea sediments at temperatures below 10°C. Thus the garnet provided no evidence about the temperature of alteration. Similarly, there was no oxygen isotope evidence yet available which would give an idea of the temperatures involved. The rodingites contained no potassic minerals which might enable them to be dated and determine the time of alteration. Thus one could only speculate on the temperature and time of alteration. An examination of the literature on rodingitic alteration and rodingite veins showed that there were almost as many explanations as occurrences, since each occurrence had its own individual features.

Dr J.P .N. Badham asked if the rodingite veins cut the black dykes at Kennack Sands.

The Author replied that the relationships of the rodingite veins and the black dykes were somewhat obscure. At Enys Head, where rodingites were best developed, white veins and grey veins were present; many were parallel to black dykes, but some were at variable angles to the dykes. However, the black dykes themselves were not all consistently oriented, although there was a very common N-S trend.

Dr Badham responded that he and his co-workers considered the Lizard complex to be ophiolitic, and the black dykes to be oceanic tholeiite in character, being comparable to the Coverack gabbro or the sheeted dykes at Porthoustock; that interpretation would imply that the dykes were generated on a mid-oceanic ridge, so that if the alteration cut the dykes it would imply that it was very early in age. It was the experience of Southampton University workers that the black dykes had usually acted as channelways for later processes, such as the injection of the Kennack Gneiss, which they regard as a partial melt generated during stacking of the ophiolite before it was finally obducted. It would appear that the alteration post-dated the Kennack Gneiss, because it was confined to the margins and appeared to have affected the gneiss as well as the serpentine; that could be seen at Kennack Sands; at Kynance; and all along Coverack Beach.

The Author said that he considered that the alteration post-dated the formation of all the Lizard rocks, and was a late low-temperature process.

Dr Badham remarked that in that case the author's conclusion that the alteration might have been a sea-floor process was perhaps less valid, because it seemed as if the Kennack Gneiss, which carried fairly well established Upper Devonian ages, must have been a syn-emplacement phenomenon of the Lizard ophiolite and not produced on a submarine ridge.

The Author agreed, and said that whatever the origin of the Lizard complex, if any of the rocks in the complex were continental in origin, the rodingitic alteration would almost certainly have taken place when the Lizard ophiolite was already emplaced into the continent. The fact that rodingites had been recorded from modern ocean floors was, however, interesting by comparison.

PALYNOLOGICAL EVIDENCE FOR THE AGE OF THE MYLOR SLATES, MOUNT WELLINGTON, CORNWALL

by R.E. Turner [1], R.T. Taylor [2], A.J.J. Goode [2], and B. Owens [1].

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Abstract. Palynomorph assemblages from the Mylor Slates, Mount Wellington, Cornwall, contain both acritarch and miospore populations which indicate a Famennian age for the sediments. The relative abundance of acritarchs in samples supports the marine origin of these sediments. The results enable a revision of the stratigraphical succession in West Cornwall.

1. Introduction

The area defined by the maps of the Institute of Geological Sciences as Mylor Slates contains dark-grey to black slates, silty-banded slates and some thin sandstones. In some areas the slates have been disturbed by contemporaneous slumping. The sequence contains basic volcanic rocks, with pillow lavas and agglomerates. Polyphase folding during the Variscan orogeny has rendered the establishment of a succession in the Mylor Slates a major problem.

The stratigraphical position of the Mylor Slates has long been the subject of conjecture. They were included in the Grauwacke Group by De la Beche (1839), who considered them to be of Lower Palaeozoic age but was hesitant in applying the name Cambrian. The subsequent interpretations of the stratigraphical position of the Mylor Slates were summarised by Simpson (1969), ranging from the early proposal of a possible Ordovician age by the Geological Survey (Flett and Hill 1912), to the Lower Devonian age proposed by Hendriks (1937). A Lower Devonian age was also suggested by Wilson and Taylor (1976), on the basis of some similarities between the Mylor Slates and the Lower Devonian succession in the Roseland area (Fig. 1) described by Sadler (1973). Simpson (1969) suggested that the Mylor Slates might be of Upper Devonian to

Lower Carboniferous age, and further that the adjacent Gramscatho Beds might be Namurian and rest uncomfortably on the Mylor Slates and Lower Devonian Meadfoot Beds. Lacy (1958) also suggested an Upper Devonian age for the Mylor Slates, considering that with their associated volcanics they could be equivalent to the Upper Devonian slates and lavas of the Padstow-Pentire successions (House 1956; Gauss and House 1972). The works of Hendriks and others (1971) and Sadler (1973) indicate that the Gramscatho Beds are mainly Middle Devonian in age.

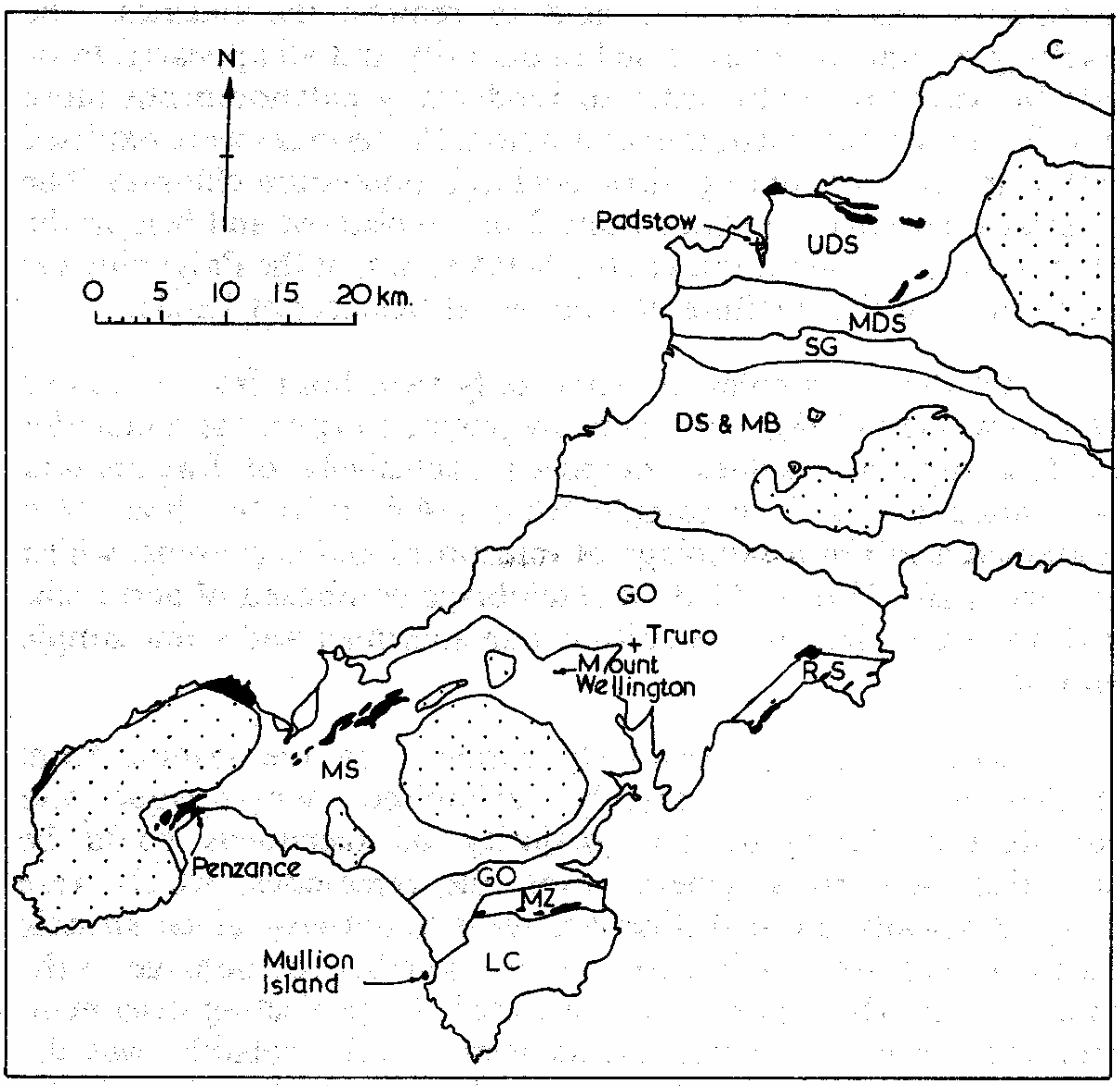

Figure 1. Outline of the geology of North and West Cornwall

MS Mylor Slates (Famennian at Mount Wellington)
GO Gramscatho Beds (Middle Devonian)
RS Roseland Succession (Gedinnian -Emsian)
MZ Meneage Zone (Lower Devonian -Emsian in part)
DS and MB. Dartmouth Slates and Meadfoot Beds (Siegenian-Emsian)
SG Staddon Grit (Emsian)
MDS Middle Devonian slates
UDS Upper Devonian slates (Frasnian-Famennian)
LC Lizard Complex (Precambrian?)
Black: Basic volcanic rocks Stipple: Granite

2. Palynology

During the examinations of exploratory cores drilled at Mount Wellington Mine during 1977, 33 samples were collected for palynological investigation. Selection of samples from these cores of highly disturbed and tectonised sediments was difficult but where possible only the relatively less disturbed and more carbonaceous sediments were chosen. Conventional techniques were used in sample preparation, hydrochloric acid being used to digest the carbonates and hydrofluoric acid to remove the silicates. The resulting organic residues varied in quantity and all appeared to be variably carbonised. In order to render any palynomorphs more translucent for microscopic examination, the residues were oxidised with a mixture of fuming nitric acid and potassium chlorate. The illustrated specimens (Plates land 2) are registered and held in the MPK series, and all samples in the MPA series, of the Palynological Collections of the Institute of Geological Sciences at Leeds.

Of the 33 samples prepared only two, both from borehole 77/6 (SW 7758 4128), contained any palynomorphs, the remainder yielding organic residues composed exclusively of fragmentary carbonised debris. The sample from 184.6 m in borehole 77/6 contained a mixed assemblage of miospores and acritarchs, whilst that from 209.75 m yielded an assemblage composed of acritarchs with the exception of one chitinozoan specimen and a few simple miospores.

Miospores were relatively common in the sample from 184.6m but all were variably carbonised, semi-opaque and considerably damaged. The majority of specimens could be identified only to a generic level; the remainder, which were morphologically more distinctive, were tentatively given specific status. It was not possible to establish whether the damage to the spore exines which particularly affected the projecting ornament, occurred during deposition or, as seems more probable, was the result of post-depositional metamorphism and alteration of the sediments. Representatives of the following taxa were identified:

Punctatisporites spp.
Calamospora spp.
Retusotriletes semizonalis McGregor 1964
Retusotriletes spp.
Apiculiretusispora spp.
Granulatisporites spp.
Cyclogranisporites spp

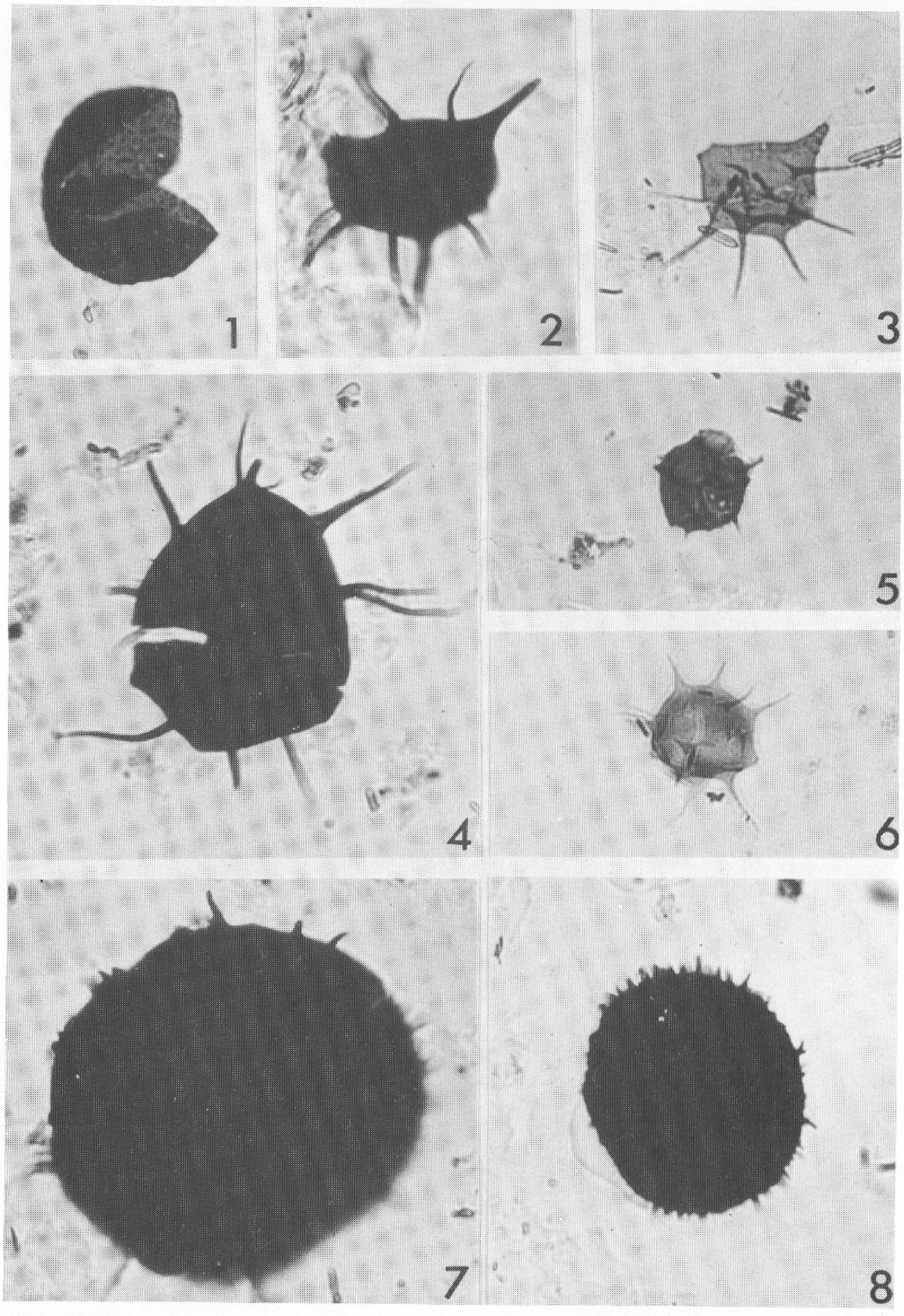

Plate 1

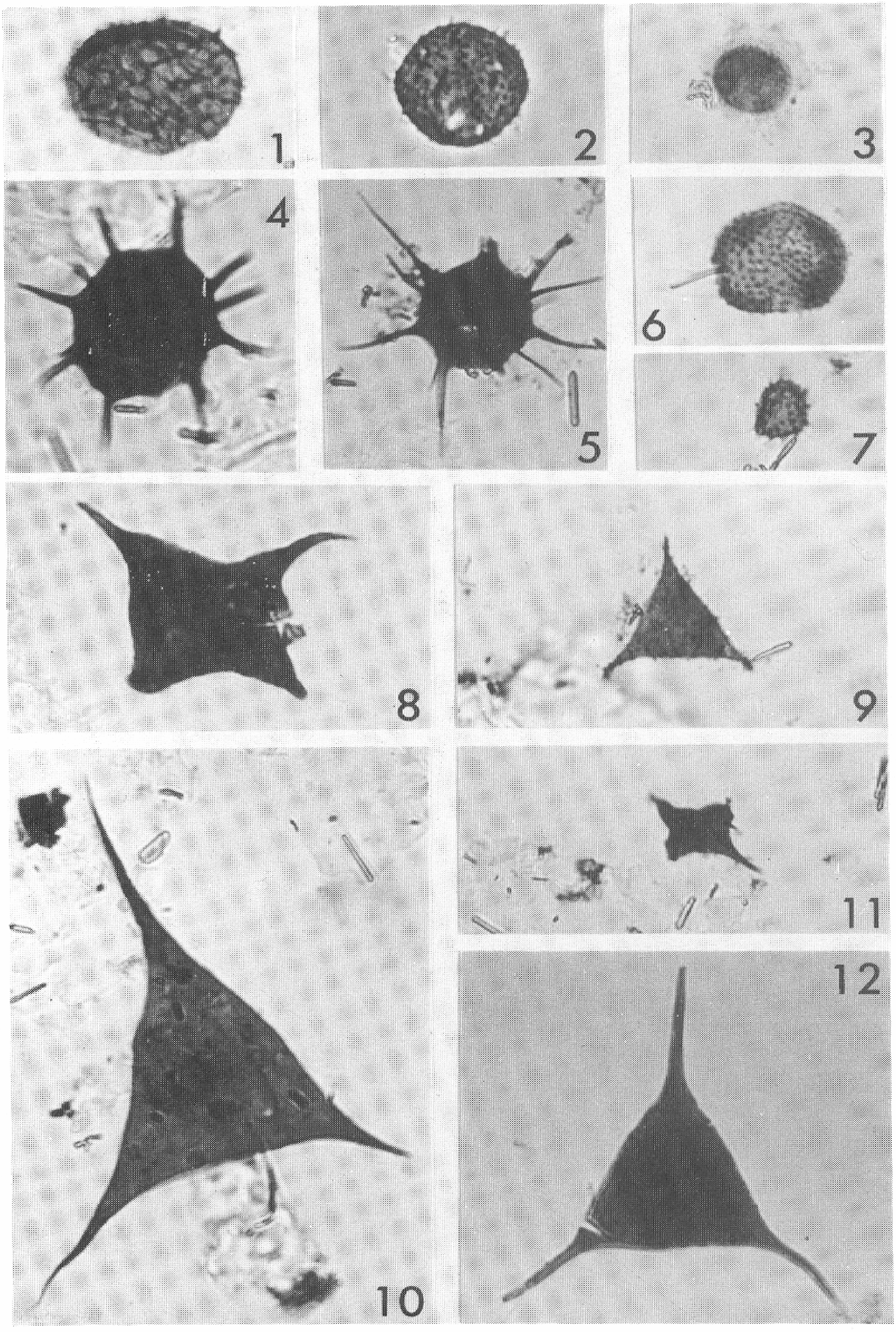

Plate 2

Plate 1
all magnifications x 1200

1.	*Lophosphaeridium cf. papillatum*	MPA 5985-2 MPK 2543
2.	*Unellium winslowae*	MPA 5985-2 MPK 2544
3.	*Unellium winslowae*	MPA 5985 IA MPK 2545
4.	*Baltisphaeridium medium*	MPA 5985-2 MPK 2546
5.	*Cymatiosphaera polonica*	MPA 5984-2 MPK 2547
6.	*'Baltisphaeridium' nanum*	MPA 5984-2 MPK 2548
7.	*Baltisphaeridium simplex*	MPA 5985-2 MPK 2549
8.	*Baltisphaeridium cf. echinodermum*	MP A 5985-2 MPK 2550

All figures in bright-field illumination.

Plate 2

all magnifications x 1200

1.	*Diclotidium fairfieldensis*	MPA 5984-2	MPK 2551
2.	*Micrhystridium dangeardi* (phase-contrast)	MP A 5984-2	MPK 2552
3 .	*cf. Dasypilula storea*	MPA 5984-2	MPK 2553
4 .	*Micrhystridium spiniglobosum*	MPA 5985-2	MPK 2554
5.	*Micrhystridium vulgare*	MPA 5985-2	MPK 2555
6.	*Micrhystridium nannacanthum*	MPA 5984-2	MPK 2556
7.	*Micrhystridium ambergris*	MPA 5985-2	MPK 2557
8.	*Veryhachium lairdi*	MPA 5984-2	MPK 2558
9.	*Veryhachium ceratioides*	MPA 5985-2	MPK 2559
10.	*Veryhachium trispinosum*	MPA 5985-1A	MPK 2560
11.	*Veryhachium minutum*	MPA 5985-2	MPK 2561
12.	*Veryhachium downiei*	MPA 5984-2	MPK 2562

All figures in bright-field illumination unless otherwise indicated.

Acanthotriletes tenuispinosus Kedo 1963
Acanthotriletes cf. rugatus Naumova 1953
Acanthotriletes spp.
? Microreticulatisporites sp.
?Hystricosporites sp.
Hymenozonotriletes spp.
Ancyrosporo sp.
Geminospora cf. lemurata Balme 1960
?Geminospora spp.

The miospore components of this association, beyond indicating positively a Devonian age, do not permit a detailed .stratigraphical assessment. The presence of representatives of ?Hystricosporites, Ancyrosporo and Geminosporo does however favour a Middle or Upper Devonian age.

Considerably more evidence is available from the acritarch assemblages from the above sample and that from 209.75 m. Both assemblages are sufficiently similar in composition to be considered as one for interpretative purposes. The acritarch populations are in general terms better preserved than the miospores, although some individuals do appear to be extensively carbonised. Nineteen species have been identified and these are listed below together with their previously known stratigraphical ranges.

Baltisphaeridium cf. *echinodermum* of Stockmans & Williere 1974
(Frasnian -Famennian)
Baltisphaeridium medium Stockmans & Williere 1974 (Famennian)
Baltisphaeridium simplex Stockmans & Williere 1962 (Frasnian)
'*Baltisphaeridium' nanum* (Deflandre 1942) Martin 1965
(Ordovician -Famennian)
Cymatiosphaera polonica Gorka 1974
(late Famennian - Tournaisian)
cf. *Dasypilula storea* Wicander & Loeblich 1974
Dictyotidium fairfieldensis Playford 1976 (Famennian - Tournaisian)
Lophosphaeridium cf. *papillatum* (Staplin 1961) Martin 1968
(Ordovician - Devonian)
Micrhystridium dangeardi Stockmans & Williere 1974
(Frasnian - Famennian)
Micrhystridium embergerii Stockmans & Williere 1974 (Famennian)
Micrhystridium nannacanthum (Deflandre 1942) Deflandre 1945
(Ordovician - Devonian)
Micrhystridium spiniglobosum Staplin 1961 (Emsian - Famennian)
Micrhystridium vulgare Stockmans & Williere 1962
(Frasnian - Dinantian)

Protoleiosphaeridium sp.
Unellium winslowae Rauscher 1969 (?mid or late Devonian – Dinantian)
Veryhachium ceratioides Stockmans & Williere 1962 (Emsian - Frasnian)
Veryhachium downiei Stockmans& Williere 1962 (Ordovician – Devonian)
Veryhachium lairdi (Deflandre 1946) Deunff 1954- ex Downie 1959 (Ordovician -Famennian)
Veryhachium minutum (Downie 1958) Downie 1959 (Ordovician – Famennian)
Veryhachium trispinosum (Eisenack 1938) Downie 1959 (Ordovician -Famennian)

Of the species recorded. eight can be seen to have ranges which are restricted to the Upper Devonian or Dinantian whilst a ninth. *Unellium winslowae*, has only been unequivocally recorded from this level, a single Middle Devonian record being questionable (Rauscher 1969). Four of these species have been recorded only from Famennian or Dinantian horizons. i.e. *Baltisphaeridium medium*, *Cymatiosphaera polonica*, *Dictyotidium fairfieldensis* and 2Micrhystridium embergerii.

Previous records of Upper Devonian acritarchs in Great Britain are limited to those recorded from the IGS Steeple Aston Borehole in Oxfordshire by Downie (*in* Owens and others 1977). Since only five of the acritarch species recorded from the Steeple Aston sequence were encountered in the Mount Wellington assemblages. it is necessary to rely on comparisons of the ranges of species reported from the Belgian successions by Stockmans & Williere (1962. 1969. 1974) and to a lesser extent on records from Australia (Playford 1976) and the eastern United States (Wicander and Loeblich 1977). These comparisons suggest that a Famennian. and possible a late Famennian. age may be attributed to the enclosing sediments. The relative abundance of acritarchs in the samples would further suggest that open-water marine conditions were established at least at times. if not continuously. During deposition of these sediments. This view is supported by the presence of a crinoidal limestone band containing an unidentifiable spiriferid in a borehole (CGF3. SW 7766 4287) at the Wheal Jane Mine adjacent to Mount Wellington.

3. Conclusions

Rearrangement of the stratigraphical succession of West Cornwall on the evidence of an Upper Devonian age from a single locality within the Mylor Slates must be speculative. The local sequence now appears to be: Mylor Slates (slates and volcanic rocks), Upper Devonian; Gramscatho Beds (slates and sandstones), Middle Devonian; Roseland succession (Sadler 1973) and Meneage Zone (Stubblefield 1939), Lower Devonian.

The general equivalence of the Mylor Slates and the Upper Devonian slates and volcanics of the Padstow-Pentire successions proposed by Lacy is confirmed. On this basis the lavas within the Mylor Slates, like those of Pentire Head, could be of Frasnian age, The probable Frasnian age of the pillow lavas of Mullion Island (Hendriks and others 1971) supports this view.

The relationship of the differing facies of the Lower and Middle Devonian across the broadly anticlinal regional of central Cornwall remains problematical.

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UPPER DEVONIAN GONIATITE ENVIRONMENTS IN BELGIUM

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Abstract. Within the Middle and Upper Frasnian sediments of the Dinant Basin of southern Belgium, three main environmental facies can be recognised. These are characterized by three different types of goniatite preservation: calcareous nodular specimens (argillaceous nodular limestones); recrystallized calcium carbonate specimens (blue-black limestones); and small pyritized specimens (black shales). These contrasting goniatite occurrences are discussed in relation to the biohermal reef- complexes and deeper, basinal facies with which they are closely associated.

1. Introduction

This study is confined to the Middle and Upper Frasnian goniatite-bearing sediments of the Dinant Basin of southern Belgium. A number of sections have been examined, mainly in the vicinity of Frasnes and Nismes on the southern flank of the basin, where the Middle Frasnian (F2) Assise de Frasnes and the Upper Frasnian (F3) Assise de Matagne (Fig. I) are exposed. During this period, changes in the Upper Devonian environment are reflected in the lithological and faunal character of the rocks, and in the mode of preservation and size of their goniatite content.

2. Regional environment

The most complete Upper Devonian sequences were laid down in the Dinant Basin, which formed part of the Hercynian (Variscan) Geosyncline. The basin itself showed two contrasting environmental settings: to the north there was a relatively stable shelf on which biostromes and barrier reefs formed, near to the Brabant Massif; while in the deeper, subsiding southern part, biohermal reef-complexes developed (Fig. 2). By the end of the Frasnian, subsidence of the shelf ended reef development in the north, and an influx of shales (F3 Matagne Shales) choked the bioherms to the south.

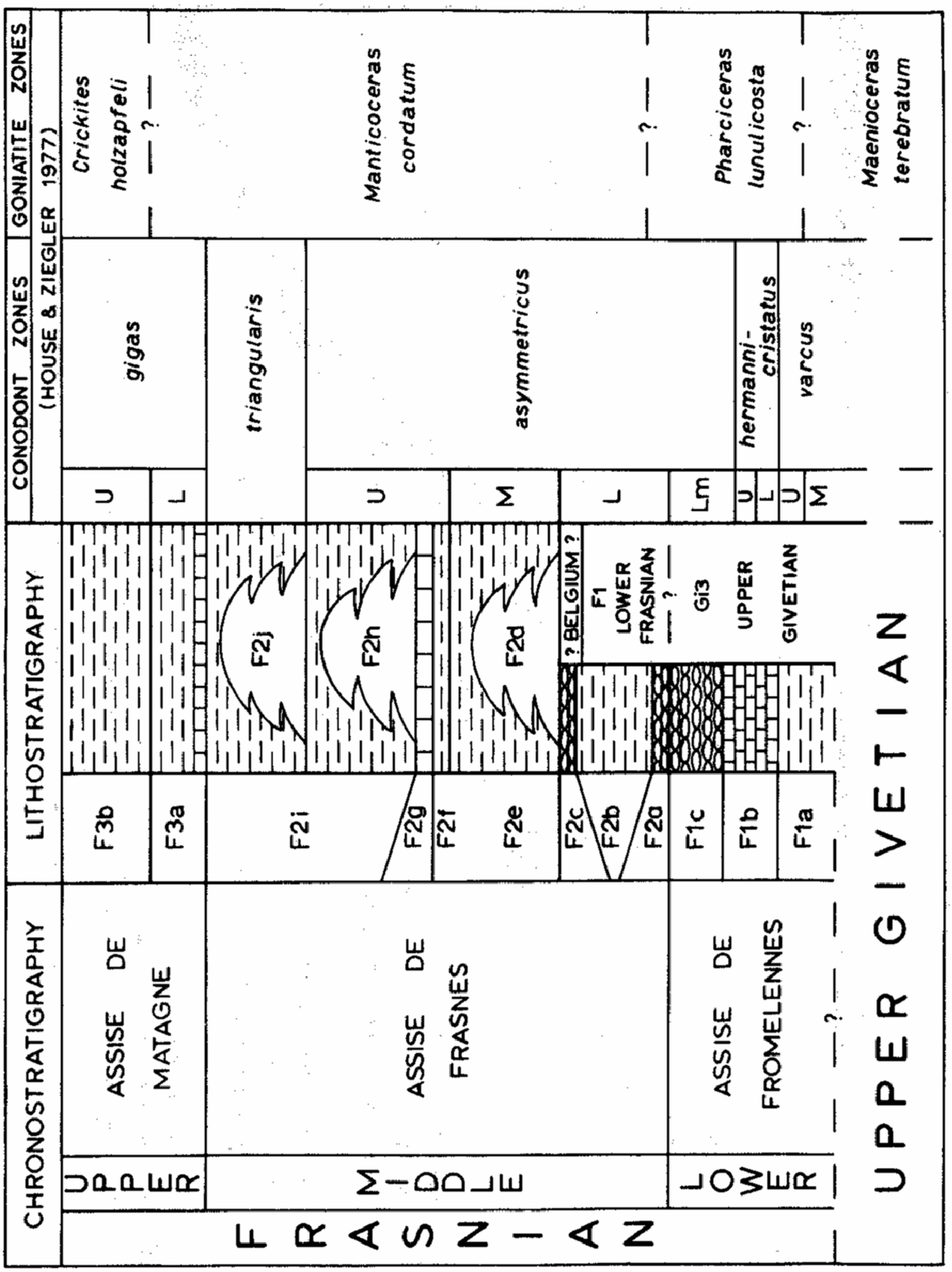

Figure 1. Lithological and faunal correlations within the Frasnian of Belgium (based on Tsien, table 1).

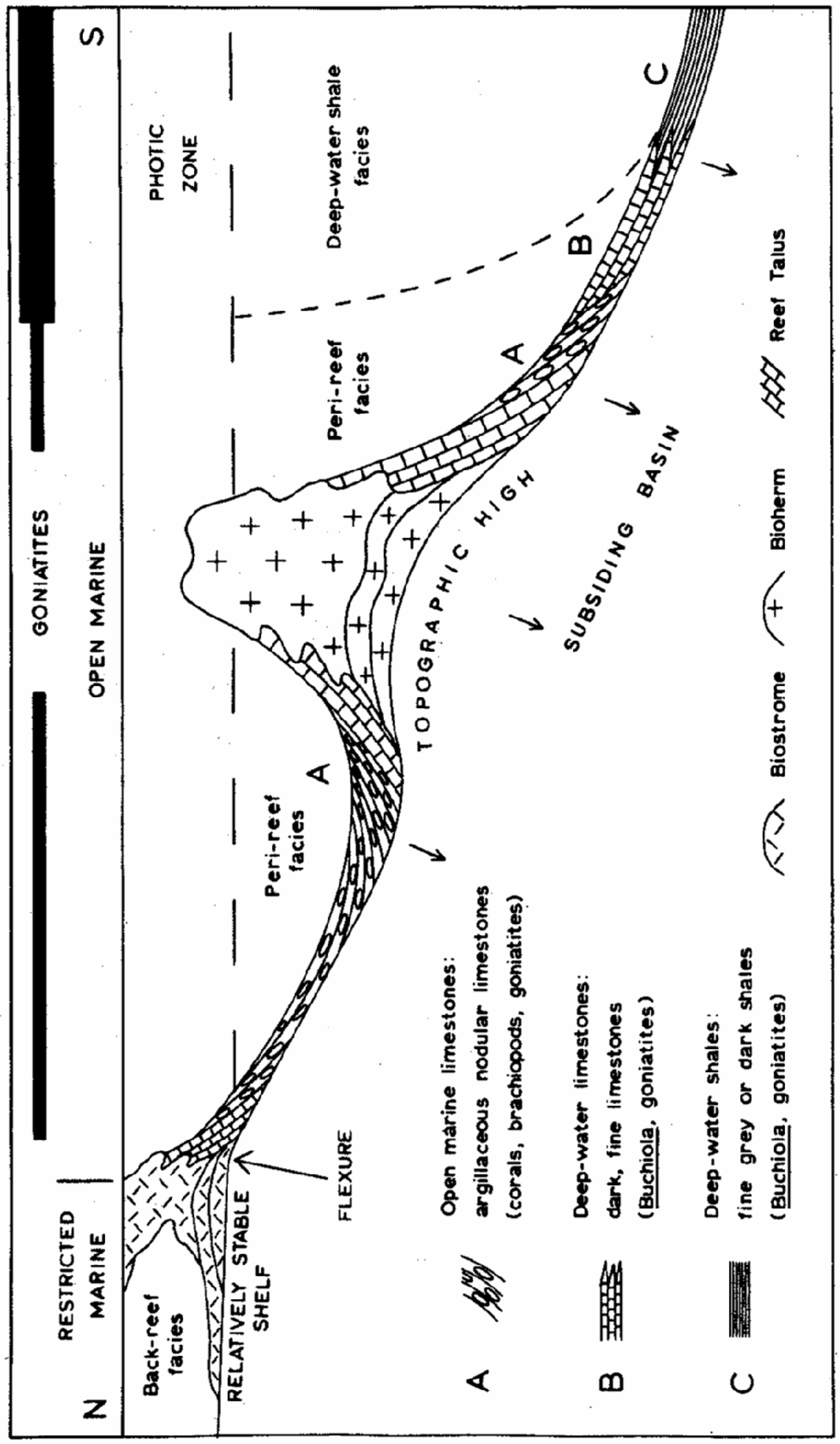

Figure 2. Diagrammatic cross-section through the Dinant Basin, showing a typical reef-complex and associated goniatite environments (based on Tsien 1971, fig 2).

3. Goniatite environments

As a part of the free-swimming nektonic fauna, goniatites inhabited off -reef waters near the shelf and also the deeper, pelagic waters of the basins around the bioherms (Fig. 2). These could develop only in places where reef-building organisms were favoured, such as on topographic highs (Tsien 1977, p. 193), and goniatites probably inhabited the surface irregularities of the reef flanks. This colonization of reef slopes and other seamount environments must have played an important role in the evolutionary diversity of goniatites (House 1975, p. 482).

The lithologies and associated faunas of the Frasnian goniatite sequences are described in stratigraphical order below, but the three main types of goniatite occurrences (and their related environments) recognized within them (Tables I and 2) can be summarized as follows:

A calcareous nodular specimens (argillaceous nodular limestones)

B recrystallized calcium carbonate specimens (blue-black limestones)

C small pyritized specimens (black shales)

4. Assise de Frasnes: F2d,e sequence

The F2d,e sequence is the oldest part of the Assise de Frasnes in which goniatites have been found in the present study. It is well-exposed in the disused quarry, 200m E of the cemetery at Nismes (Olloy-sur-Viroin sheet, G.R. 636852) where 34m of vertical, well-bedded massive F2d limestones have been partly worked out. These are overlain by 6.5m of well-bedded, F2e yellowish-brown nodular limestones intercalated with brown nodular shales.

Goniatites, referable to the genus *Manticoceras*. Occur together in limited numbers (Table 2) within certain nodular limestone beds and shale horizons of F2e (Mouravieff and Bouckaert 1973, p.94). Most are worn and rounded with signs of deformation, and are preserved in the same argillaceous limestone as the other nodules, from which they are often hard to distinguish. Complete specimens reach a maximum diameter of about 120mm (to the last septum), but more commonly, smaller fragments of smoothed body chamber are found. They occur in close association with large orthocones (up to 80mm in length and 35mm diameter), brachiopods such as *Cyrtospirifer Cyrtina* and productellids, small rugose and

	GONIATITE PRESERVATION	ROCK TYPE	HORIZON AND LOCALITY
A	ISOLATED CALCAREOUS NODULES, SHOWING SOME WEAR AND DEFORMATION	ARGILLACEOUS NODULAR LIMESTONES	F2e, E.G NIMES QUARRY F2i, E.G LION QUARRY FRASNES RAILWAY CUTTING
B	CALCIUM CARBONATE SPECIMENS, SHOWING CALCITE CRYSTAL-LISATION AND OCCA-SIONAL REPLACEMENT BY PYRITE	BLUE-BLACK FINE-GRAINED LIMESTONES	F2/F3 LIMESTONE BED E.G NISMES-MARIEM-BOURG RAILWAY CUTING, FRASNES N5 ROAD CUTTING
C (i)	DWARFED PYRITIZED OR HAEMATIZED SPECIMENS, WITH PERIPHERAL ALTERA-TION TO GOETHITE	CONCENTRATED IN "POCKETS" OR DISCRETE HORIZONS IN BLACK SHALES	FF3 MATAGNE SHALES E.G "POCKET" 3M ABOVE F2/F3 BOUNDARY IN FRASNES N5 ROAD CUTTING
C (ii)	FLATTENED FERRUGINOUS SPECIMENS AND OCCASIONAL C (i) TYPES	SCATTERED THROUGH-OUT BLACK SHALES BETWEEN RICH HORIZONS	FF3b MATAGNE SHALES E.G. CHURCH CUTTING BOUSSU-EN-FAGNE

Table 1. Summary of goniatite preservation and associated lithologies in the Middle and Upper Frasnian of Belgium.

Type	Est. no. of goniatites per m3	No. of specms. sampled	OR (D to last septum in mm)	D	SD	V
A	2	24	40.0 - 120.0	78.1	19.7	370.4
B	530	25	4.4 - 90.0	24.9	24.4	573.6
C (i)	500	25	4.5 - 23.0	11.6	4.2	17.3
C(ii)	130	20	4.6 - 14.0	8.5	2.9	7.8

Table 2. Size and frequency of goniatites (of the genus *Manlicoceras*) found within environments A. B and C of Table I. OR = Ordinary Range; D= Mean Diameter; SD= Standard Deviation. V = Variance.
(Not on the Significance of V: using the Mann-Whitney U-test to compare the four sample variances; A and B belong to different populations at a 0.1% level of significance; B and C (i) are drawn from the same population; and C (i) and C (ii) are drawn from different populations at a 1% level of significance).

occasional tabulate corals, small gastropods, crinoids and bryozoa, the last commonly found encrusting the surface of goniatites and other members of the fauna. Most of the fossils show a similar preservation, of calcareous mudstone, to the goniatites.

The underlying F2d massive limestones are the age equivalent of F2d bioherms seen in nearby localities (e.g. in the Arche Quarry at Frasnes), but no reef morphology is apparent in the Nismes Section. However, the corals found in the nodular limestone and shale horizons are not in life-position and may represent fallen reef debris. The large size of the goniatite individuals of F2e also suggests their original colonization of a topographic high, or at least the upper slopes of a reef-complex, above the zone of aragonite (goniatite shell) dissolution. Transportation from a higher part of the reef, and redeposition amongst these lateral nodular limestones would account for the worn and rolled nature of the goniatites. They always occur as internal moulds, the outer shell having been dissolved before the post-mortem colonization by encrusting bryozoa.

Towards the top of this 6.5m of strata, the nodular limestones give way to about 8m of greenish-grey shales, containing some discontinuous calcareous horizons and occasional limestone nodules. A few isolated goniatites, mostly of the genus *Tornoceras*. occur in these shales as small (10-20mm diameter) pyritized individuals. Rugose corals, brachiopods, orthocones, crinoids and bryozoa are still found, and in addition, small phacopid and other trilobites showing a calcareous preservation, occur in abundance in the shales.

The pyritic preservation of the goniatites suggests a deeper-water reducing environment, but some Devonian trilobites inhabited peri-reefal waters as well as the deeper basins (House 1975, p.475). As there appears to have been sufficient iron sulphide for goniatite preservation only, these shales were probably formed under just slightly deeper conditions than the nodular limestones; perhaps a little further away from the envisaged nearby reef or topographic high.

5. Assise de Frasnes: F2i,j sequence

Higher in the stratigraphical sequence, F2i,j nodular limestones containing occasional goniatites, are exposed at a number of localities around Frasnes. In the three entrances to the Lion Quarry, 300m SE of the cemetery at Frasnes (Couvin sheet, G.R. 602845), they total about l0m in thickness and are seen flanking the F2h bioherm out of which the main quarry has been cut. A short distance to the east, they are exposed again along the Frasnes Railway section, 200m S of the Frasnes cemetery (Couvin sheet, G.R. 599845), where they reach about 16m in thickness. They consist of thick beds of nodular limestones and limestone layers, alternating with shales containing discrete calcareous nodules. Interpreted as reduced successions, they are thought to have been laid down during the same period of time that the adjacent 300m of Lion bioherm was being builtup. The vast numbers of conodonts found per unit kg in these off-reef limestones, supports the idea of their slow deposition in a deep-water, open-sea environment below at least 200m depth (pers. comm. Dr A.N. Mouravieff).

As in the F2d,e sequence, goniatites are fairly uncommon and occur as large (about 100mm diameter), well-worn nodules, again indicating reworking. They are virtually always confined to discrete bedding planes parallel to thin (20mm) seams of very soft, weathered yellowish-brown material of unknown origin. These off-reef nodular limestones and shales show signs of compaction (and distortion of goniatite nodules is common), with much jointing and calcite veining throughout the section, which is separated from the edge of the Lion bioherm by a fault. This has been interpreted as the result of differential compaction between a reef-capped topographic high and its lateral deposits (Tsien 1977, p.199).

The yellowish-brown seams commonly lie along joint planes and they may just be the weathered residues of calcite veins. The close proximity of the goniatite nodules to them suggests that movements causing the jointing may also have dislodged the goniatites from a higher part of the bioherm, resulting in their redeposition in this deeper, off-reef sequence. These beds also contains specimens of 2Hexagonaria, which must have similarly been derived from the reef. A less likely explanation for the concentration of goniatites near these weathered zones is that they represent thin seams of volcanic material, and that associated epeirogenic disturbance caused the reworking of the goniatites: however, there is no other evidence for volcanic activity in the Dinant Basin during this period.

6. The F2 Frasnes/F3 Matagne boundary

The boundary between the F2 Assise de Frasnes and the F3 Assise de Matagne marks a change to deeper water conditions within the Dinant Basin, shown by an influx of black shales which ended reef development of the Lion bioherm and of the other F2h reef-complexes. In several localities, the boundary is easily recognized as a goniatite-rich limestone bed of about 0.3m thickness, the upper part of which marks the base of the Assise de Matagne, on conodont evidence (the entry of *Palmatolepis gigas*).

In the Frasnes N5 Road section, about 300m N of the junction with the Nismes road (Couvin sheet, G.R. 604858), the change to deeper water is apparent from about one metre below the boundary, where the underlying F2j greyish-blue limestones and shales quite suddenly give way to darker blue-black limestones and black shales. The boundary bed and several other overlying limestone horizons are fine-grained and homogeneous in texture, and contain a well-preserved fauna of goniatites, orthocones and brachiopods. Goniatites in the boundary bed include fairly large individuals (50-100mm diameter), which usually show the external shell and some of the inner chambers preserved in white sparry calcite, while the body chamber and outer phragmacone are infilled with the same dark calcium carbonate of the matrix. Some of the smaller goniatites (less than 30mm), as well as having a calcified inner phragmacone, show partial pyritization which is usually confined to the periphery. Calcite precipitation may have commenced in the inner chambers from trapped sea-water, resulting in complete infilling of the early, closely-spaced chambers, and a lining of pyrite, internal to the shell (now dissolved) formed in the outer whorls, after burial in the deep-water limestone environment.

The overlying F3 dark limestones, which are much thinner than the boundary bed, contain a few, small pyritized fossils, similar to the dwarfed fauna found in the interbedded Matagne Shales. Placoderm bones, well-preserved in black phosphate, are also known from these horizons. Such limestones may be the equivalents of the dark, organic-rich limestones of the Kellwasserkalk facies recognized in Germany and other parts of Europe. The Lower Kellwasserkalk occurs at this same level elsewhere, in the upper part of the Frasnian (the Lower gigas conodont zone), and is commonly developed within basinal facies where the reducing environment produces the high proportion of pyritic preservation within dark shales and limestones (Buggisch 1972, p.47).

7. The F3 Matagne Shales

The black Matagne Shales, which are interbedded with the dark limestones, become the dominant lithology upwards in the succession, and contain just a few discontinuous and isolated nodule horizons. They are characterized by their dwarfed pyritized fauna, mostly of goniatites, which are confined to certain levels parallel to the bedding within the shales (Table 2), including localised "pockets" where they occur in great abundance (as many as 100 individuals in 0.3m3 in one example). Throughout the intervening shales, ill- preserved, flattened ferruginous specimens are the main evidence of goniatite remains.

The pyritized goniatites rarely exceed 30mm, and mostly average 10mm in diameter, the dimensions referring to the maximum diameter of the phragmacone. This is nearly always a well-preserved internal mould showing the sutures, whilst the body chamber is seen as an outer zone of flattened, ferruginous shale. In most cases the phragmacone has lost the bronze lustre of the pyrite which infilled the original shell, as a result of superficial oxidation to goethite which forms a dull yellowish-brown coating. Other specimens are preserved in haematite, which may be after pyrite (Krauskopf 1967, p.5l4), or which may have directly replaced the original infilling of the goniatite shell. The unusually high proportion of pyritization must have necessitated a deep, reducing environment in which there was plenty of available sulphur and organic material for the replacement and infilling of the fossil material.

Associated with this goniatite fauna are orthocones, brachiopods including *Caryorhynchus* and abundant *Leiorhynchus*, and most commonly, the bivalve, *Buchiola*. The latter is always pyritized and occurs in a dwarfed form, rarely exceeding 10mm in length, whilst the brachiopods are preserved in calcium carbonate and attain normal adult size. *Buchiola* has been interpreted as living pseudoplanktonically on floating algal groves (Schmidt 1935, p.138), and *Leiorhynchus* is similarly assigned to a planktonic mode of life, attached to floating weed (Ager 1962, p.185). Buggisch (1972, p.47) postulated, as one of many ideas on the possible origin of the Kellwasserkalk horizons, that they may have formed beneath such a cover of sea-weed, but in relatively shallow water rather than in a deeper basin as required in the Belgian case: he also suggested deep water conditions (with no weed) for their formation. Finger-print ostracods, of the genus *Entomozoa*, reach a length of about 1.5mm in these shales, and are also thought to have been planktonic in habit (House 1975, p.480).

8. Size and distribution of goniatites

During Devonian times, the free-swimming goniatites would have enjoyed a fairly ubiquitous distribution throughout basinal waters, and post-mortem drifting would have increased the chances of universal deposition. The notable absence of large individuals from the deep water shales could be explained by the fact that dissolution of the aragonite shell would have occurred at such depth, if rapid burial did not take place. Large individuals are found in the deep water limestones, but it is possible that faster sedimentation of these beds resulted in their preservation.

Perhaps more significant is the restricted distribution of the small goniatites. The size of the pyritized fauna of the Matagne Shales would suggest that either they are all immature forms, or that an environmental factor imposed a restriction on growth. House (1975, p.482) envisaged the black shale environment as the breeding-ground and site for juvenile goniatites, and this may also have been the case for the dwarfed *Buchiola*. The adult-sized brachiopods could have drifted in from surface waters to be quickly covered by shales. The concentration of goniatites in “pockets" within the shales might suggest colonies of young ones, rather than the chance accumulation of drifted material in sea-floor hollows.

Alternatively, if the goniatites are interpreted as small adults, an environmental reason for the dwarfing must be sought. It could be assumed that these were deep-water forms (nekto-benthonic), and that their reducing environment limited shell growth, and also resulted in the diagenetic alteration to pyrite after rapid burial of such small specimens. The larger sizes attained by goniatites colonizing reef flanks in shallower waters, could be attributed to the greater availability of calcium carbonate, for precipitation both as sediment and as the goniatite exoskeleton.

If the "small adults" were not restricted to deep waters, but enjoyed the same distribution as their larger counterparts, sexual dimorphism would seem to be the only explanation for such a striking size difference. Small specimens would also be expected in nodular form amongst the off-reef nodular limestone sequences, although they would be less conspicuous than the large goniatite nodules.

9. Concluding remarks

Goniatites are not always found in the sediment-type associated with their original environment, because of post-mortem drifting. However, in general, the three main relationships observed between goniatite preservation and lithological character are a combination of; (i) the size permitted by environmental conditions during the life of the goniatite, and (ii) the preservation imposed upon it by its environment after death.

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11. Discussion

Dr C. T . Scrutton asked whether the author had noted any differences in the specific make-up of goniatitic faunas from the different environments A, Band C. which might suggest that depth communities had existed; did the author consider that the goniatites were possibly nektobenthonic rather than simply nektonic?

The Author, in reply, said that the goniatites would have been swimming ubiquitously in the waters. and post-mortem drifting would also have increased the chance of their almost universal deposition. It was difficult to decide whether the goniatites had been closely associated with the environment in which they were now found. or whether they had drifted into position.

Dr Scrutton questioned the importance of the drifting mechanism. Was it not the case that goniatites were rare in the bioherms themselves?

The Author replied that goniatites were indeed absent from the bioherms.

Dr J.M. Thomas asked whether the fact that suture lines could be observed in many of the author's specimens showed that the pyrite was like that seen in many Mesozoic ammonities, where it was not a replacement of the shell, but an early pyrite lining of the body chamber present before any later fill took place.

The Author agreed that the shell could not have been replaced at all, but must have been dissolved after infilling took place.

Dr Thomas continued by asking the author about the preservation of the large ammonoids in the more calcareous facies, which the author had said were encrusted with bryozoa. He would like to know whether the bryozoa were encrusting the goniatite shell, or whether the encrustation was present on specimens which showed sutures and from which the shell had been dissolved.

The Author replied that all the larger nodules were internal infillings, all of which showed suture lines; the encrust ration by bryozoa must have occurred after dissolution of the shell, possibly long after the goniatites had been reworked.

Mr E.C. Manley asked whether the figures the author had given for the mean diameter of the specimens (quoted under four zones) referred to the same species. or whether they were four different species within the same genus.

The Author replied that all the goniatites studied were specimens of the genus 2Manticoceras, and probably included two or three species. which had not been differentiated.

Dr Thomas asked whether the yellow-coloured weathered seams were rich in ammonoids. The author had discounted a volcanic origin; the questioner wondered what the possibility was of the seams being major solution planes in which the ammonoids were less soluble residuals; did the seams show features of considerable solution?

The Author responded that she had mentioned in her paper the possibility of the seams being volcanic horizons. They did not appear to show features of considerable solution, and the goniatites were comparable to the calcareous nodule found throughout the other nodular limestones. The subject was worthy of further investigation; perhaps analysis of the weathered material might throw light on its origin.

British Triassic Palaeontology: supplement 3

by G. Warrington

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Since the submission of the writer's previous supplement *(Proc. Ussher Soc.,* 4, 156; 1978) to his paper on British Triassic palaeontology the following works dealing with or including aspects of that subject have appeared:

CAVE, R. 1977. Geology of the Malmesbury District. *Mem. geol. Surv. U.K.,* viii + 343 pp.

DUFFIN, C.J. 1978. The Bath Geological Collections. The importance of certain vertebrate fossils collected by Charles Moore: an attempt at scientific perspective. **2**, 59-67.

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A DERIVED LATE PERMIAN PALYNOMORPH ASSEMBLAGE FROM THE KEUPER MARL (LATE TRIASSIC) OF WEST SOMERSET

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Abstract. An assemblage of late Permian palynomorphs has been recovered from the late Triassic Keuper Marl sequence at St Audrie's Bay, west Somerset. The provenance of this material, which is regarded as derived from late Permian deposits undergoing erosion during late Triassic time, is not known.

Assemblages of derived Palaeozoic (Devonian and Carboniferous) miospores have been recorded from several horizons in the ‘New Red Sandstone' sequence of South Devon (Warrington 1971; Owens 1972). A further instance of such reworking concerns an assemblage of late Permian palynomorphs recovered from the Keuper Marl sequence exposed on the eastern side of St Audrie's Bay (c. ST 110 431) on the west Somerset coast. This occurrence is, in the absence of 2in situ palaeontological evidence of Permian age in sequences in southern Britain, of greater than usual interest.

The assemblage concerned was recorded from an horizon 48.09 m below the base of the Westbury Beds ('Rhaetic') during examination of palynological preparations from the late Triassic sequence exposed at St Audrie's Bay (Warrington 1974, 1978). It occurred 3.05 m below the lowest indigenous (late Triassic) palynomorph assemblage recovered from the Keuper Marl at that locality; three samples from the intervening sediments, and a further 16 from the 43.51 m of the Keuper Marl sequence examined below the horizon which yielded the late Permian specimens, were devoid of palynomorphs.

The assemblage (held in the IGS palynology collection, Leeds; preparation number SAL 1604) comprises approximately 250 palynomorphs; determinable specimens are referable entirely to late Permian taxa. Specimens in the assemblage display variable but generally poor preservation; many are ruptured or otherwise damaged (e.g. by internal growth of pyrite) and all are moderately dark yellow-brown in colour. The specimens nevertheless have a general uniformity of appearance, and, whether determinable or not, are regarded as members of a homogenous palynomorph association which originated from a detrital lithic clast of late Permian age incorporated in deposits which accumulated during the late Triassic.

The following taxa have been recognised in the assemblage:

Miospores

a) Monosaccate:

Perisaccus granulosus (Leschik) Clarke 1965

b) Bisaccate:

Lueckisporites virkkiae Potonie & Klaus emend. Clarke 1965

'Taeniaesporites' sp.

'T' labdacus Klaus 1963

Protohaploxypinus chaloneri Clarke 1965

P. cf. jacobii Jansonius emend. Hart 1964

Jugasporites delasaucei (Potonie & Klaus) Leschik 1956

Labiisporites granulatus Leschik 1956

Klausipollenites schaubergeri (Potonie & Klaus) Jansonius 1962

Paravesicaspora splendens (Leschik) Klaus 1963

Falcisporites zapfei (Potonie & Klaus) Leschik 1956

Acritarcha (organic-walled microplankton)

cf. *Micrhystridium microspinosum* Schaarschmidt 1962

The assemblage is closely comparable with those of late Permian (Kazanian -Tatarian) age obtained from Zechstein sequences throughout much of northern Europe and includes specimens (the acritarcha) indicative of a marine facies. In the British Isles, late Permian palynomorph assemblages are known from the Zechstein sequences of Cumbria, Lancashire, Yorkshire and Nottinghamshire (Clarke 1965; Warrington in Arthurton and Hemingway 1972, in Pattison and others 1973, in Smith, D.B. and others 1974, in Smith, E.G. and others 1974) and from the Kingscourt outlier in counties Cavan, Meath and Monaghan in the Republic of Ireland (Gardiner and Visscher 1971; Visscher 1971). However, late Permian palynomorphs have not been reported from deposits presumed to be of that age south of, approximately, latitude 53°N in the British Isles. The recovery of such material from the upper part of the Keuper Marl sequence in west Somerset therefore poses a problem of provenance.

Although units in the Devon New Red Sandstone sequence below the Budleigh Salterton Pebble Beds (Ussher 1913; Edmonds and others 1969) or, lower, below the Exmouth Sandstone and Mudstone Formation (Henson 1970, 1972, 1973) have been identified as Permian, that designation is, in the absence of *in situ* palaeontological evidence, entirely arbitrary .The derived palynomorphs, however, form indirect evidence of the existence and erosion of deposits of that age in or around southern Britain during the late Triassic. Whether any vestige of such deposits remains is conjectural but the potential implications, for palaeogeographical syntheses, of these, albeit derived, late Permian palynomorphs should not be overlooked.

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Discussion

Dr J.M. Thomas asked if there were any lithological differences between the horizons that yielded the forms described by the author and any other part of the sequence.

The Author replied that all the palynological samples were collected from very green horizons which were usually rather more dolomitic, or even slightly silty or arenaceous. than other parts of the sequence. In general, he preferred to collect from argillaceous or silty lithologies, and to avoid arenaceous beds.

THE CLAY MINERALOGY OF THE RHAETIC TRANSGRESSION IN DEVON AND SOMERSET - ENVIRONMENTAL AND STRATIGRAPHICAL IMPLICATIONS

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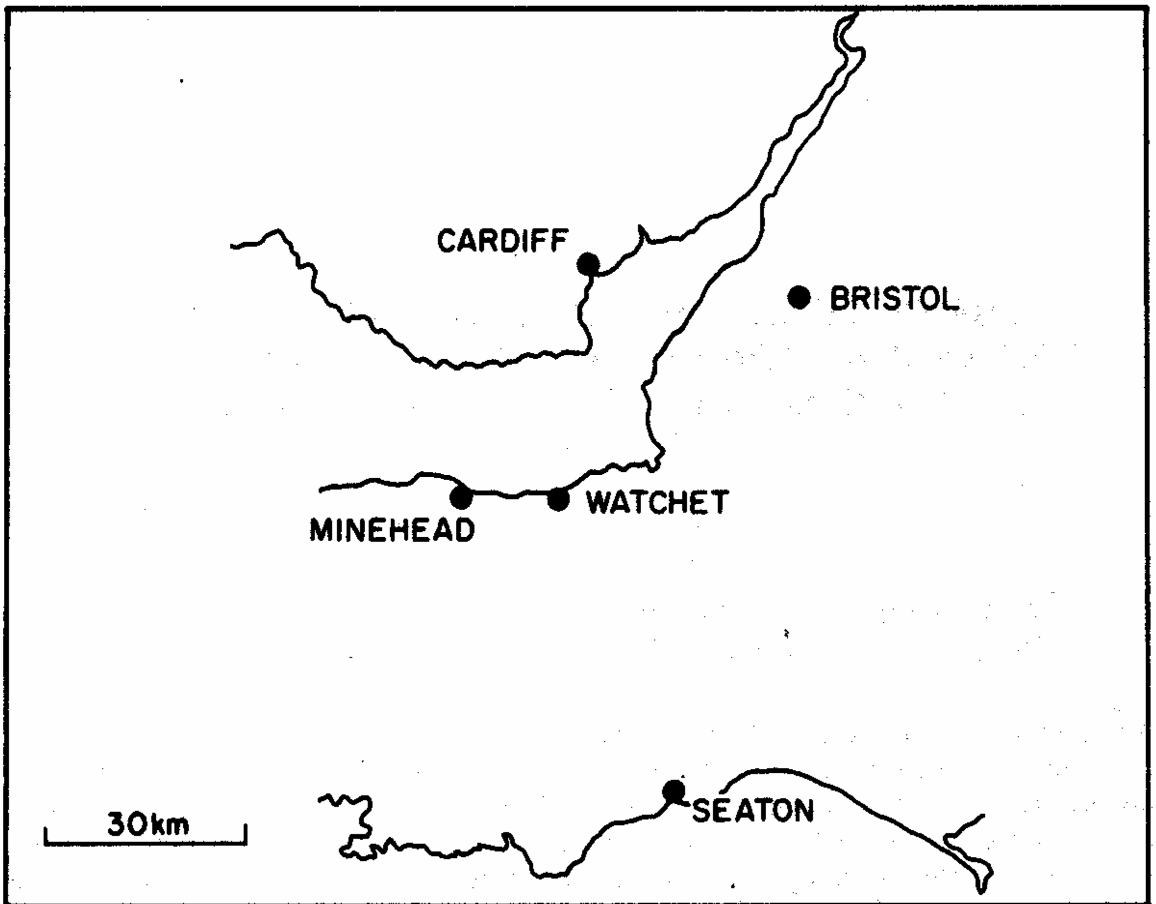
Abstract. In Devon the Grey Marls contain a detrital assemblage of illite and chlorite. In Somerset this same association additionally contains corrensite which indicates a northward increase in the salinity gradient. The base of the Westbury beds in Devon is marked by a sudden increase in the mixed layer illite-smectite and smectite contents. This is interpreted as being due to a climatic change and indicates that a substantial hiatus separates the Westbury Beds from the Grey Marls. Kaolinite first appears in the Cotham Beds of Devon and the Watchet Beds of Somerset suggesting that these beds may be time equivalents.

1. Introduction

The uppermost Triassic sediments of Britain have been divided into a series of lithostratigraphical units (Richardson 1906, 1911 ; Whittaker 1974). Fig. I shows the thickness variations of these units in N. Somerset and S. Devon. There are many problems of correlation between these units and, to date, biostratigraphical attempts are incomplete. In this study the upper limit of the Rhaetic has been taken at the appearance of *Psiloceras planorbis* but the lower limit has been more arbitrarily drawn where the Grey Marls pass into the red marls of the Keuper .

The clay mineralogy of sequences from St Audries Bay (ST 105432) near Watchet in Somerset, and from near Seaton (SY270895) in Devon have been studied (Fig. I). The results have aided environmental interpretation of the sediments and may be of some stratigraphical value.



STRATIGRAPHIC UNITS	THICKNESSES (METRES)	
	DEVON	SOMERSET
PRE-PLANORBIS BEDS	2·37	5·00
WATCHET BEDS	0	0·45-0·10
LANGPORT BEDS OR WHITE LIAS	~8·00	1·00
COTHAM BEDS	1·74	1·40-1·70
WESTBURY BEDS	~6·00	10·20-11·20
SULLY BEDS	0	3·10-2·05
GREY MARLS	~34·00	~30·00

FIG. 1. RHAETIC STRATIGRAPHY & LOCATION MAP

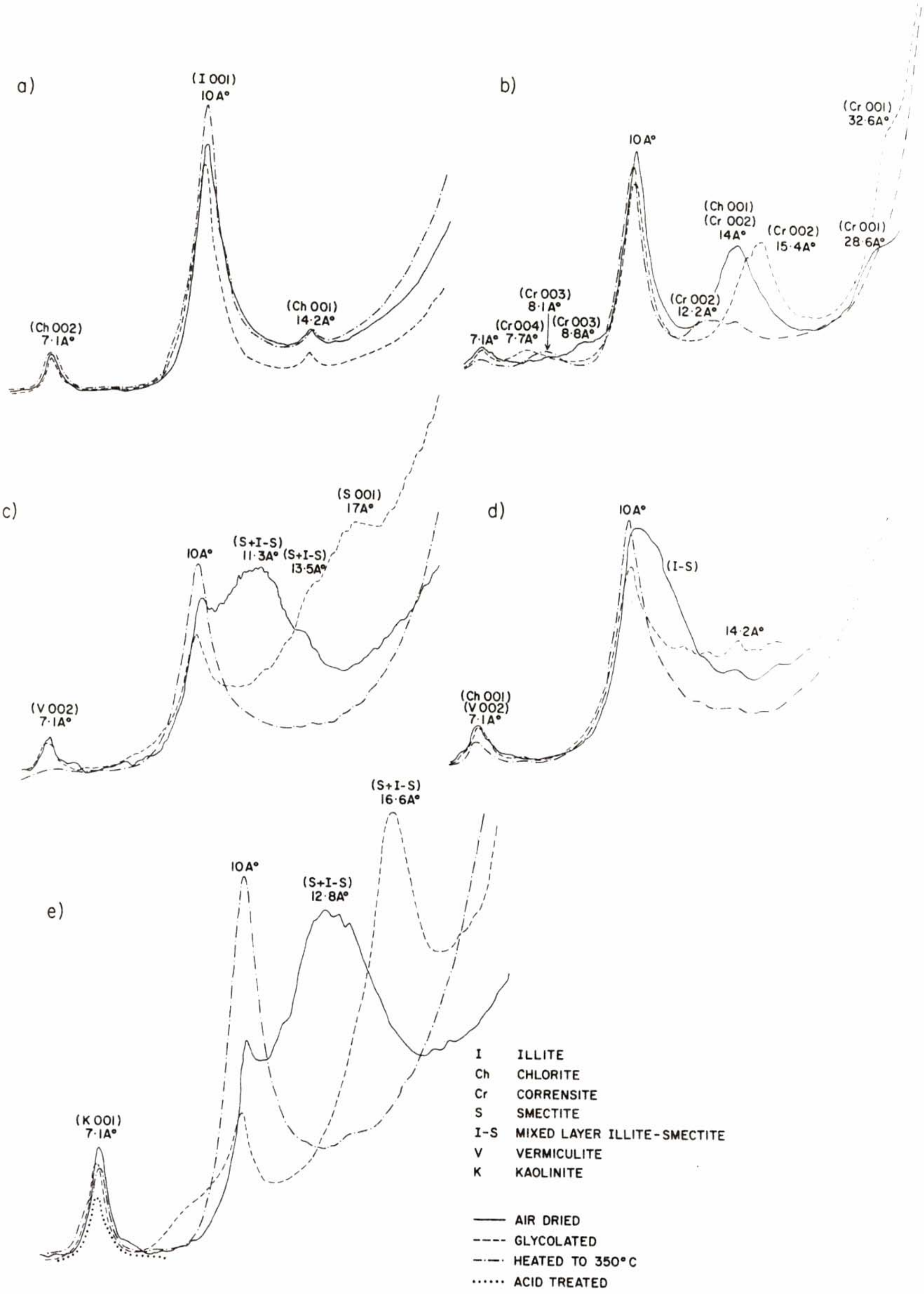


FIG. 2. TYPICAL RHAETIC CLAY MINERALOGY TRACES. NOT ALL THE MINERALS FORMING THE PEAKS ARE INDICATED IN EACH EXAMPLE SEE FIG. 3. FOR THE STRATIGRAPHIC POSITION OF THE SAMPLES.

a) GREY MARLS, S. DEVON b) GREY MARLS, N. SOMERSET
c) WESTBURY BEDS, S. DEVON d) WESTBURY BEDS, N. SOMERSET
e) UPPERMOST COTHAM BEDS, S. DEVON.

2. Analysis

The less than 2 µm effective settling diameter fraction was analysed using a Philips PW 1280 horizontal goniometer with a PW 1130 2K W generator. Clays were run air dried, glycolated, heated to 350°C, in some cases to 550°C and some were treated with warm HCl to detect the presence of kaolinite.

Semi-quantitative analysis was carried out using the method of Bradshaw (1975). In addition corrensite was interpreted as a regular interstratified chlorite-smectite as described by Jeans (1978). However, because of background interference at low angles it was often difficult to detect the 001 peak of corrensite at 29Å and peak height measurements were taken on the 002 peak at about 15.4Å (Fig. 2b). The regularity of the structure could be seen from a series of air dried peaks at about 29Å, 14Å, 9Å.and 7Å, and glycolated peaks at about 32Å, 15Å, 10Å. and 7.7Å. (Fig. 2b).

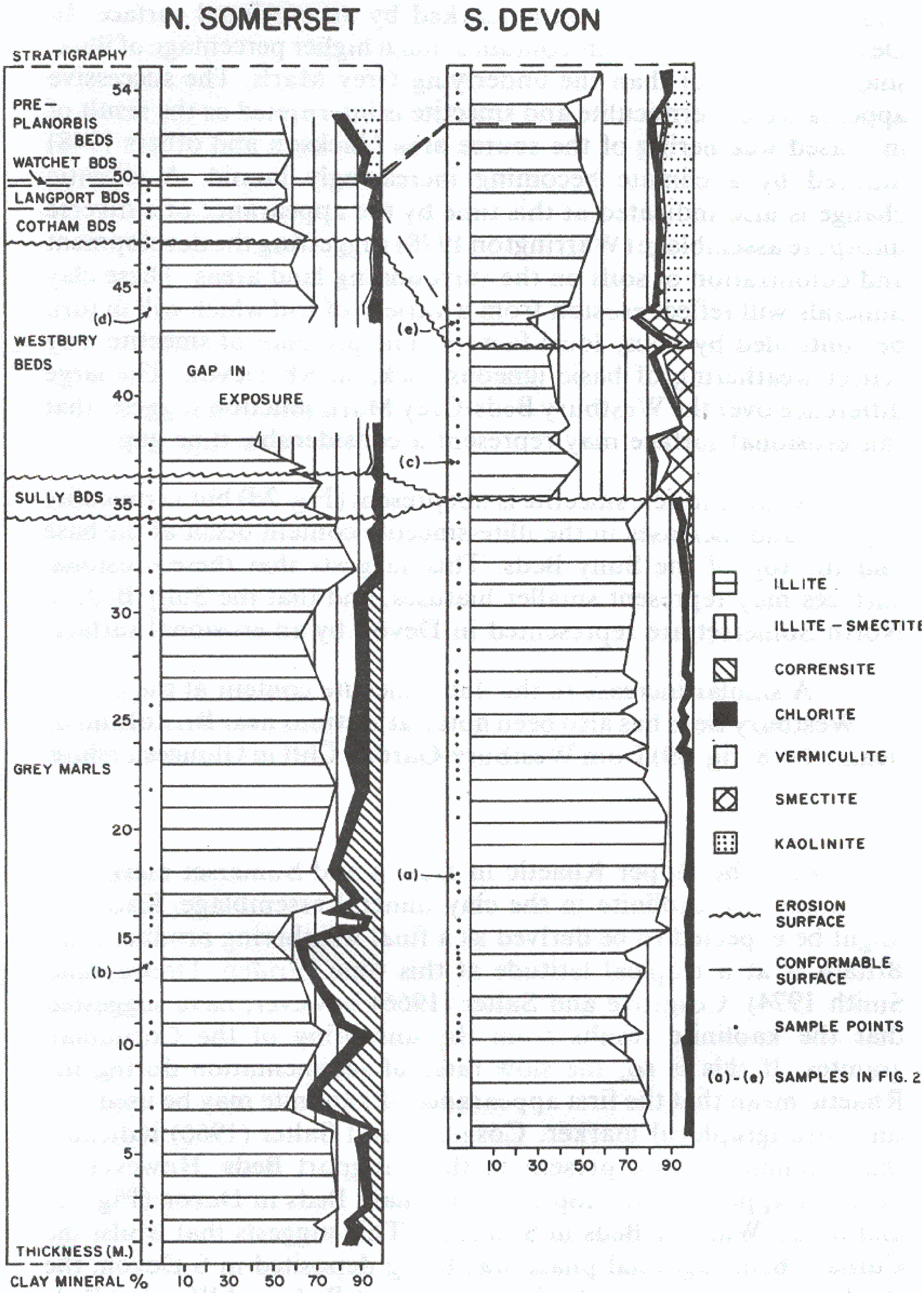
3. Results

The results of the analysis are given in Fig. 3. Variations occur both laterally and vertically, the most important of which are discussed here.

(i) The presence of corrensite in the St Audries section (Fig. 2) indicates a marked lateral variation in the clay mineralogy of the Grey Marls. These sediments with their association of ripples, mudcracks and evaporites are interpreted as a sabkha deposit (Sellwood, Dunkin and Kennedy 1970; Stevenson 1970).

Jeans (1978) has recognised two clay mineral assemblages from the Trias, a detrital assemblage of illite and chlorite and a neoformed assemblage of high magnesium clays including corrensite. Corrensite has commonly been associated with evaporite deposits (e.g. Kopp and Fallis 1974). However, evaporites occur in both sections so that there is no intimate association between evaporite-bearing horizons and Mg-rich clays. Instead, as Jeans has , shown, there are broad regional associations. The presence of corrensite in North Somerset suggests that this area lay towards the margin of the evaporitic basin with the salinity gradient decreasing towards the south. The presence of celestite in Devon and gypsum and halite in Somerset is consistent with the clay mineral-evaporite associations found by Jeans (1978) in the earlier parts of the Trias.

FIG. 3. RHAETIC CLAY MINERALOGY



(ii) The junction between the Grey Marls and the overlying units shows a significant change in clay mineralogy. In both Devon and Somerset this junction is marked by an erosional surface. In Devon the Westbury Beds contain a much higher percentage of illite-smectite (Fig. 2c) than the underlying Grey Marls. The successive appearance of vermiculite and smectite is interpreted as the result of increased weathering of the source area (Jackson and others 1948) induced by a climate becoming increasingly humid. A climatic change is also indicated at this time by the appearance of a diverse miospore assemblage (Warrington 1978) suggesting the development and colonization of soils on the surrounding land areas. These clay minerals will reflect erosion from a variety of soil which will in turn be controlled by many local factors. The presence of smectite may reflect weathering of basic igneous rocks in SE Devon. The large difference over the Westbury Beds-Grey Marls junction suggests that this erosional surface may represent a considerable time gap.

At St Audries, smectite is not present (Fig. 2d) but vermiculite appears and increases in the illite-smectite content occur at the base and the top of the Sully Beds. This suggests that these erosional surfaces may represent smaller hiatuses, and that the Sully Beds in North Somerset are represented in Devon by an erosional surface.

A similar increase in the illite-smectite content at the base of the Westbury Beds has also been noted at sections near Bristol and by Jeans (1978, fig. 59) from Westbury-Garden Cliff in Gloucestershire.

(iii) The Upper Rhaetic in Devon and Somerset marks the appearance of kaolinite in the clay mineral assemblage. Kaolinite might be expected to be derived as a final weathering product since Britain is at a tropical latitude at this time (Briden, Drewey and Smith 1974). Cosgrove and Salter (1966) however, have suggested that the kaolinite results from the unroofing of the Cornubian granites. If this is so, the slow rates of sedimentation during the Rhaetic mean that the first appearance of kaolinite may be used as a time stratigraphical marker. Cosgrove and Salter (1966) indicated that kaolinite is first present in the Langport Beds. However, in detail, it appears in the top of the Cotham Beds in Devon (Fig. 2e) and in the Watchet Beds in Somerset. This suggests that whilst the Cotham Beds lagoonal phase was being deposited in S Devon, the shallow marine lime muds of the Langport Beds and Watchet Beds accumulated in North Somerset.

However, because of the difficulties of detecting small amounts of kaolinite these results must be treated with some caution and used along with other sedimentological and stratigraphical evidence.

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5. Discussion

Mr C.M. Bristow asked whether the kaolinite present in the samples was a disordered type, or one showing good crystallinity.

The Author replied that. owing to the small percentage (14 per cent at most) of kaolinite present. it had proved difficult to carry out further work; the x-ray diffraction patterns showed that the kaolinite had a sharp peak, suggesting that it was fairly well ordered.

Mr Bristow wondered whether it would be possible to determine how much kaolinite was present in the sediments, and then to calculate how much kaolinised granite would have to be eroded to provide that amount of kaolinite. He suggested that there might be a quantitative discrepancy between the two results.

The Author replied that it would be an almost impossible calculation. His results provided the relative percentages of clay minerals present in the rocks, but he could not see how it would be possible to determine the absolute abundances of clay minerals present. It had not been his suggestion that the kaolinite had been derived from kaolinised granite, but it was interesting to note that others who had studied Rhaetic clay mineralogy in sections outside SW England had not found kaolinite, which supported the notion that it had come from the Cornubian area.

Professor J. W .Murray said that he had noticed that in the north Somerset section there were greater changes in the clay mineralogy within the Grey Marls than there were between the Grey Marls and the Sully Beds. He asked whether the author would comment on the changes occurring within the Grey Marls.

The Author replied that the changes within the Grey Marls and the changes at the top of the Sully Beds occurred for two different reasons. The changes in the Grey Marls were due mainly to the changes in the relative abundance of corrensite, which was a neoformed mineral created by the reaction of existing minerals with hypersaline solutions, or by direct precipitation from solution. The change at the top of the Grey Marls was related to increased weathering of the source area.

Dr M.B. Hart asked whether the conspicuous kink in the middle of the south Devon profile was due to the occurrence of argillaceous limestones such as those that occurred within the Westbury Beds on the north Somerset coast.

The Author replied that he had not sampled the limestones owing to the likelihood of their clay mineralogy being changed by the passage of fluids.

Dr Hart remarked that, in the Lilstock section on the north Somerset coast he had observed limestones which could be seen to grade into black clays; there appeared to be some evidence that the limestones were being lost by solution.

The Author said that he had observed the same phenomenon, but he had formed the impression that the limestones were being built up by precipitation of carbonate, rather than being dissolved.

Dr E.C. Freshney. returning to the problem of the source of the kaolinite in the Rhaetic, remarked that one had to consider the possibility of there having been granitic rocks exposed in the English Channel area during the Permo-Trias, which might have provided a source of kaolinite.

Mr Bristow said that kaolinite very often simply reflected the presence of feldspar in the original material, from which kaolinite could have formed as a neoformed mineral it a much later date.

The Author replied that it was possible, but he had not detected appreciable amounts of feldspar in the remainder of the sequence.

Dr L.H.N. Cooper asked whether corrensite was treated as one phase or two when applying Gibbs's Phase Rule.

The Author replied that it was treated as two phases.

MICROFAUNAL INVESTIGATION OF SHAPWICK GRANGE QUARRY, EAST DEVON

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Abstract. Samples from Shapwick Grange Quarry, east Devon, have been investigated for their microfaunal content, with limited success. Within the Upper Greensand succession Ostracoda and Foraminiferida are very rare and/ or badly preserved, and the faunas are not diagnostic. The Foraminiferida appear to be of Cenomanian aspect, while the Ostracoda present could be either Albian, Albian-Cenomanian, or Cenomanian, in age.

1. Introduction

In a recent account of the Upper Greensand stratigraphy of the Haldon Hills, Hamblin and Wood (1976) described an important, Albian, ammonite fauna from the uppermost Upper Greensand of Shapwick Grange Quarry (SY 31189180), immediately north-west of Lyme Regis, in east Devon. In that account they used this fauna as evidence of an Albian age for a large part of the Upper Greensand on the Devon coast, as well as a guide (via. lithological correlations) to the likely age of a part of the Haldon Hills succession. The presence of a diagnostic uppermost S. *dispar* Zone ammonite fauna in the Upper Greensand clearly has an important bearing on the local stratigraphy and as this quarry was not visited by Carter and Hart (1977) in the preparation of their account of mid-Cretaceous microbiostratigraphy this present survey was initiated.

2. Lithological succession

In their account, Hamblin and Wood (1976) only outlined the ammonite fauna found at Shapwick, and did not describe, or figure, the lithological succession. The quarry is still worked and the succession available for study varies from time to time. During 1978 the succession shown in Fig. 1 was compiled by the authors during the course of three visits. The greater part of the quarry is an old

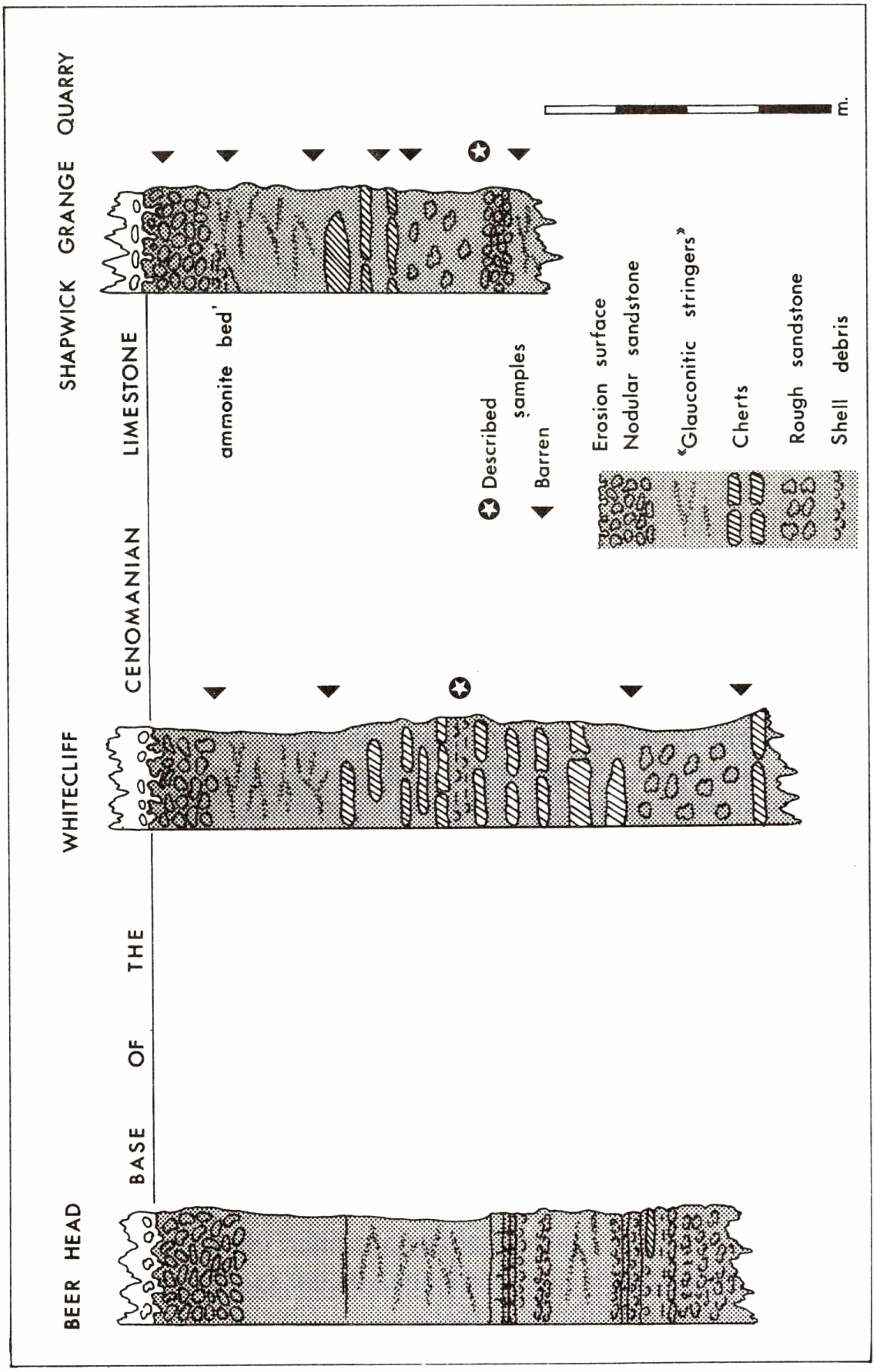

Figure 1. Lithological succession of the upper Greensand immediately below the Cenomanian limestone succession at Shapwick Grange Quarry, Whitecliff, and Beer Head.

chalk pit, although the present interest centres on the Upper Greensand, exposed near, and to the right of, the quarry entrance. The Turonian chalk, which contains a fauna dominated by planktonic Foraminiferida (including *Praeglobotruncana helvetica* (Bolli), can be equated with the succession at Beer, described by Hart and Weaver (1977). Immediately below the white nodular chalk is an interesting development of the Cenomanian limestone succession with Beds A -C all being developed. Bed C displays its usual, rich, phosphatised fauna while Beds A and Bare readily comparable with the succession at Whitecliff (Seaton). The base of Bed A rests on an irregular, piped surface of the Upper Greensand. The Upper Greensand above the first course of cherts is readily separated into two units; an upper, nodular, glauconitic sandstone, and a lower, 'green-streaked' yellowish, finer-grained sandstone. These two units -generally termed the Top Sandstones -can also be detected at Whitecliff, near Seaton (see Fig. 1). At Beer Head the same general succession is found to be much expanded, with cherts first appearing in the succession some 7 m below the top of the Upper Greensand succession. A lithological correlation based on either the first appearance of the cherts, or the highly variable grain size of the sediments was found to be generally unreliable, even over the short distances involved. A preliminary sedimentological examination of the environments represented by this succession has indicated that the upper levels of the Upper Greensand succession at Beer Head is a complex series of overlapping cross-stratified units, the grain size variations of which could be potentially misleading if used in regional correlation.

3. Microbiostratigraphy

The all-important ammonite level is shown in Fig. 1, located in the succession by C.J. Wood (pers. comm.), as ammonites were not found by the present authors. This lens of shelly debris has yielded a fauna that indicates (Hamblin and Wood 1976; H.G. Owen pers. comm.) a level high in the S. *dispar* Zone. Unfortunately none of the samples from the critical levels of the succession yielded any microfauna. The only sample that contained identifiable Ostracoda and Foraminiferida is that indicated in the section, some distance below the dated ammonite level.

The Ostracoda recovered include:-

*Neocythere vanveeni M*ertens.....................Albian-Cenomanian

Isocythereis sp. indet.

Curfsina (?) sp. nov. C. (?) *donzei* Weaver MS 1978)

U. Cenomanian (U.K)

Cornicythereis sp.
Cornicythereissp.cf. C. *corneuli*(Deroo) ....U. Albian (N. France)
*Bairdiapseudoseptentrionalis*Mertens.........................U. Albian Cenomanian
Cythereis hirsuta (?) Damotte and Grosdidier ....U. Albian Cenomanian
Veenia sp. cf. *V.florentensis* Damotte and Grosdidier................ M.-U. Albian (?)

The Foraminiferida in the sample were:-
Marssonella oxycona(Reuss)..................... Albian-Cenomanian
Arenobuliminasp. cf. A. obliqua(d'Orbigny) ....Albian Cenomanian
Arenobulimina sp. cf. A. depressa(Perner)......................Albian Cenomanian
Lenticulina sp. indet.
Patellina trochiformis(Schacko)................ Albian-Cenomanian

The overall impression of this fauna is one very close to the Albian - Cenomanian boundary with few really diagnostic species that provide the detail necessary for a definitive statement. There is therefore no microfauna that allows a correlation with the Upper Greensand of the Dorset coast where Carter and Hart (1977) describe a Lower Cenomanian fauna from the matrix of the 'ammonite bed' seen at Durdle Door and Holworth House. In that case Carter and Hart (1977) compared the Dorset 'ammonite bed' fauna to that seen derived in the Cambridge Greensand, but at Shapwick Grange Quarry there is insufficient evidence on which to base any judgement. However, the assignment of an Albian -Cenomanian boundary age for such a level high in the Upper Greensand succession might cast some doubts on the conclusion reached by Carter and Hart (1977) on the dating of the Chert Beds. Unfortunately the dating of the present fauna is not even that precise, with all the species recorded having either long ranges or rather imprecisely known ranges, especially in marginal facies.

4. Summary

The lithological succession of the Upper Greensand in Shapwick Grange Quarry has been described, and its correlation with nearby coastal sections attempted on lithological grounds. The microfaunal investigation of the succession has yielded an undiagnostic fauna of uppermost Albian or Lower Cenomanian age in a sample coming from well below the ammonite horizon described by Hamblin and Wood (1976).

Acknowledgements. The authors wish to thank the owners of Shapwick Grange Quarry for access to the succession. C.J. Wood and H.G. Owen are also thanked for their advice and assistance.

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A BIOMETRIC ANALYSIS OF AN ORBITOLINA FAUNA FROM THE CRETACEOUS SUCCESSION AT WOLBOROUGH, S. DEVON

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Abstract. During the excavation of a trench through the Upper Greensand near Wolborough Church in November 1974 (by the Institute of Geological Sciences) richly fossiliferous. glauconitic, limestones were recorded. They contain a microfauna dominated by *Orbitolina* sp., that can be shown to be either latest Albian or earliest Cenomanian in age.

1. Introduction

The Upper Greensand exposure at Wolborough was discovered by Dr R.A. Edwards during the IGS -Exeter University (1966-69) remapping of the 1 :50,000 Newton Abbot (339) Geological Map. At that time only a few blocks of coarse-grained, glauconitic, sandy limestones were available for study, as reported by Carter and Hart (1977). Even so, a rich *Orbitolina* fauna was obtained and described (Carter and Hart 1977, p.105). In 1974 a trench (SX 855700) was dug 400 m south of Wolborough Church to expose a more complete succession of the Upper Greensand. Eventually 9 m were excavated resting on Devonian shales (Fig. 1). The most interesting feature of the succession is the highly fossiliferous, glauconitic, sandy limestone. This contains an abundant molluscan fauna, but the whole rock is dominated by layers of densely packed *Orbitolina*.

In their discussion of the mid-Cretaceous stratigraphy of the Haldon Sands Formation, Hamblin and Wood (1976) refer the Wolborough limestones to the Woodlands Sands Member, although little evidence for that assignment was presented. This Member has been equated with the Chert Beds of the Devon coast, and placed in the Upper Albian (S. *dispar* Zone). This as noted by Hamblin and Wood – conflicted with the micropalaeontological evidence

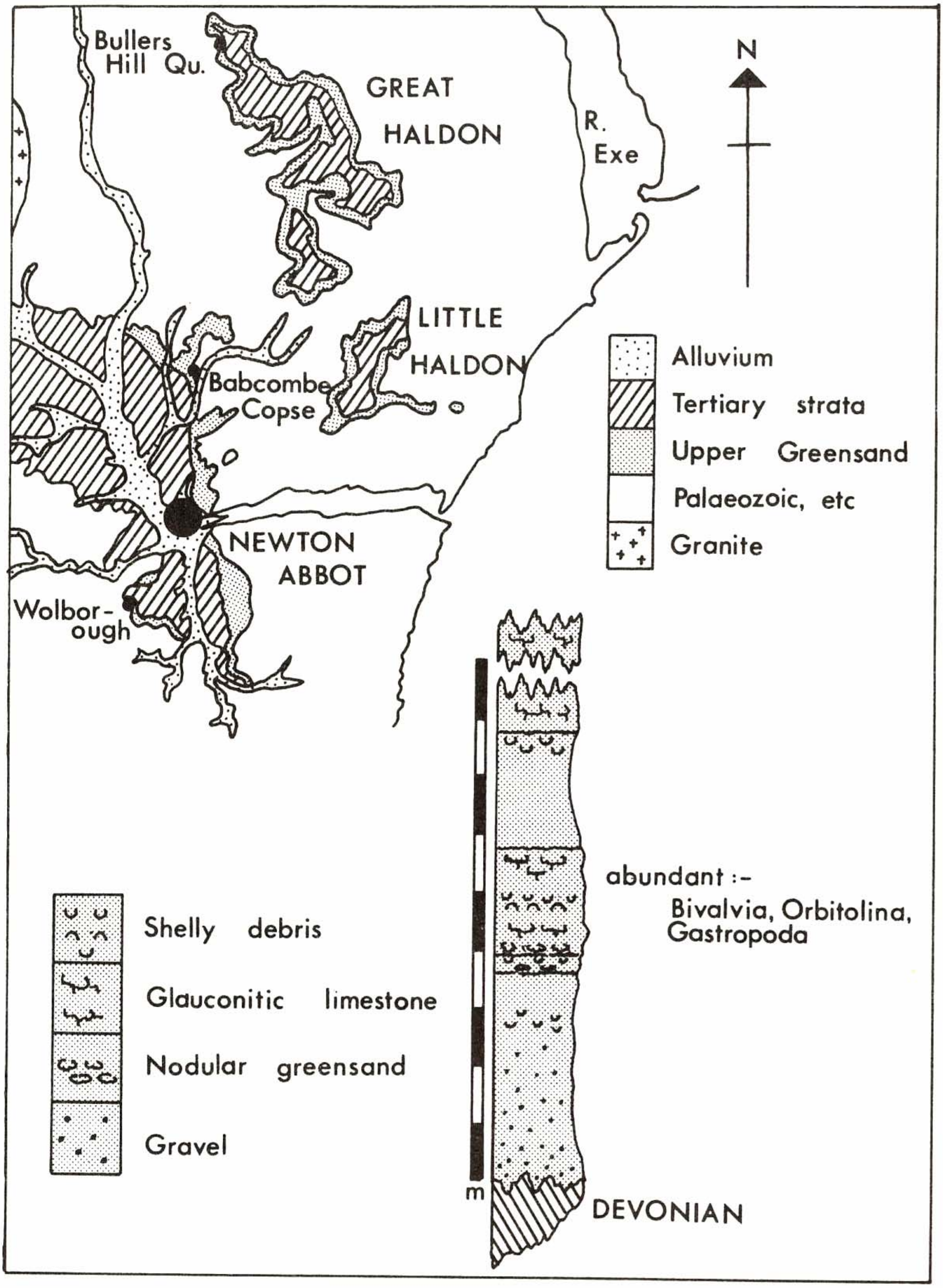

Figure 1. Locality map of the Haldon Hills, with details of the upper Greensand succession of the Wolborough trench.

presented by Carter and Hart (1977). Part of the information used in that account came from a study of the *Orbitolina* fauna, which was claimed to be of Early Cenomanian age by comparison with material - from the type Lower Cenomanian ('Marnes à Ballon') from the Sarthe, France.

The *Orbitolina* fauna of north-west Europe during the Albian - Cenomanian interval is limited in extent and definite comparisons are difficult. Schroeder (1962) has provided a detailed account of the evolution of the European Cenomanian *Orbitolina* species/subspecies, while Rey and others (1977) have recently described a succession of *Orbitolina* spp. from the Albian and Lower Cenomanian of Portugal. In the Upper Albian the nearest, described, *Orbitolina* faunas to the U.K. are those of the Iberian Peninsula (Fig. 2), and generally accepted palaeo-geographical reconstructions show no migration routes to the U .K. at that time other than through the Paris Basin, where no such faunas are known. Following a eustatic change in the Early Cenomanian (Hancock 1976; Cooper 1977) the Orbitolina fauna spread northwards (Fig. 3) through the Paris Basin, and has been described in the Sarthe and in Cotentin (Rioult and Juignet 1965).

In the English Channel Basin/ South West Approaches Basin Andreieff and others (1975) record 'advanced forms' of *Orbitolina* sp. at two localities in glauconitic sandstones, and assigned a Lower Cenomanian age, although no evidence for that dating was given. Curry and others (1970) have also recorded *Orbitolina* sp. of Albian - Cenomanian age in glauconitic sandstones west of the Scillies. The majority of localities south of the U.K. have therefore been assigned to the Lower Cenomanian, and it is difficult to see how this accepted 'Tethyan' genus could appear in the U.K. earlier than in these more southern localities.

Carter and Hart (1977) attempted to show, by bivariate analysis, that the *Orbitolina* faunas of the Upper Greensand were comparable to those from the Marnes à Ballon. The further material recovered from the Wolborough trench has now been incorporated into that analysis.

2. Statistical treatment of the *Orbitolina* fauna

Three samples were used in the following analysis. One was collected (under the guidance of Prof. P. Juignet) from the type locality of *Orbitolina concava concava* (Lamark 1816), which is within the type

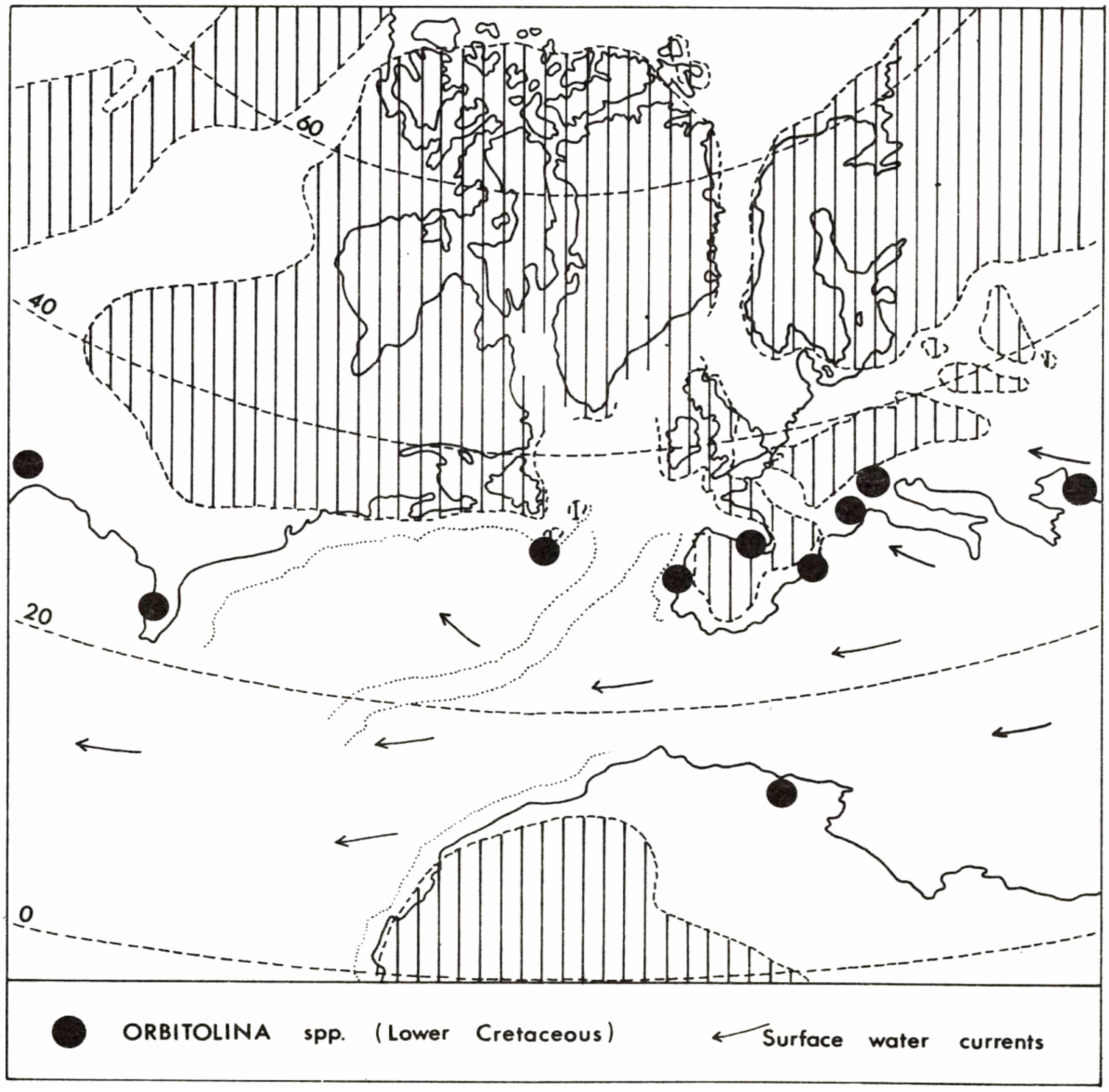

Figure 2. Albian palaeogeography and Lower Cretaceous *Orbitolina* occurrences of the European/Atlantic area.

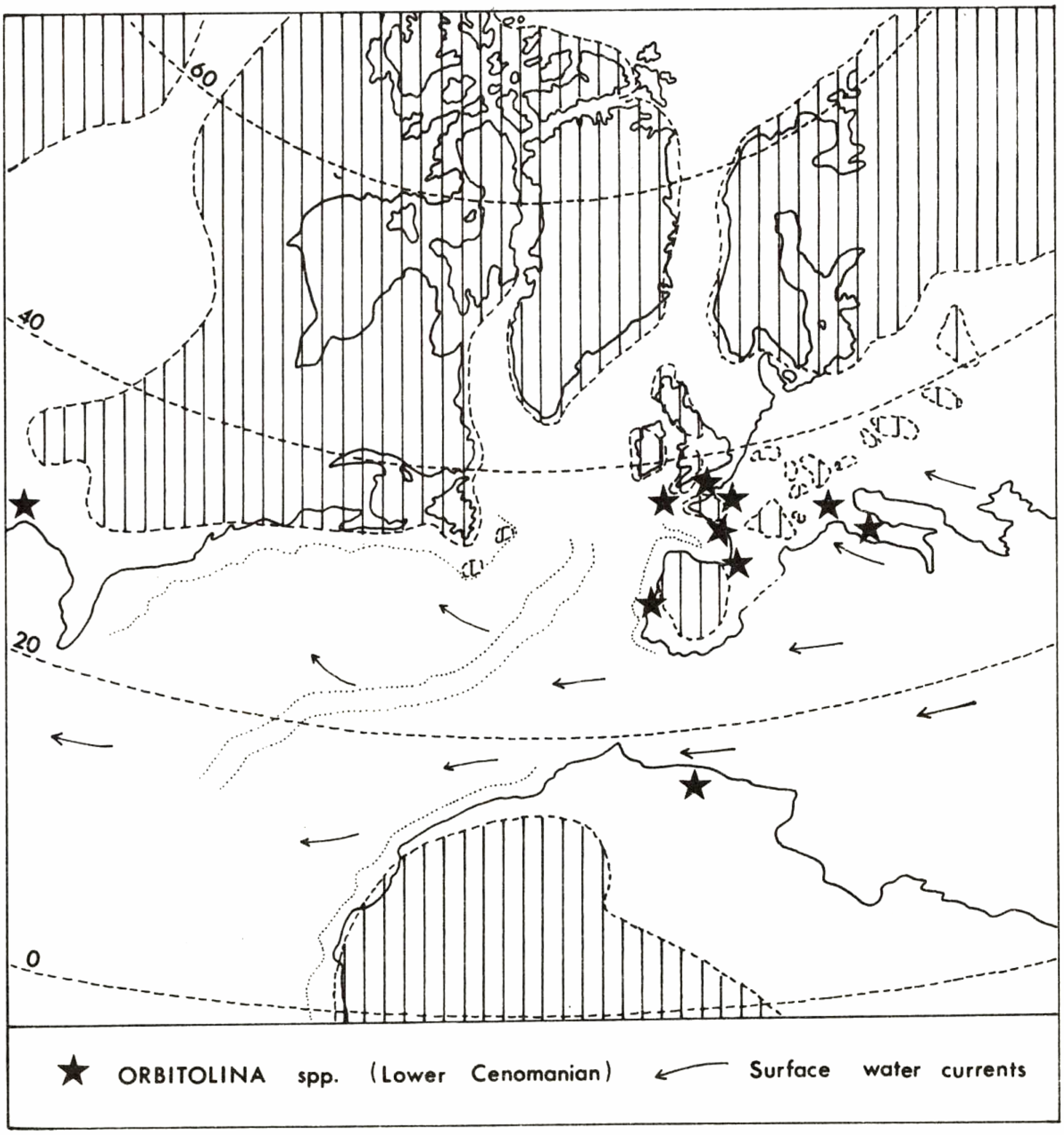

Figure 3.Lower Cenomanian palaeogeography and *Orbitolina* occurrences in the European/Atlantic area.

Lower Cenomanian at Hallon. The two U .K. samples were from the Wolborough Limestones and the cherts found in Hullers Hill Quarry (see Fig. 1).

The material has been investigated both in terms of external shape and internal structure, although only the results of the simpler, external shape investigation are presented here. Further work on the internal structures is progressing in conjunction with Dr R. Schroeder (Frankfurt am Main). As shown in Fig. 4 two dimensions were used for each specimen; the maximum diameter and the maximum height (from the plane of the maximum diameter to the highest point, ignoring any basal concavity). Fig. 4 shows the compound scatter of all these measurements, and on this graph are also included the Means (larger symbol) for each population, and their respective Reduced Major Axis. The numbers of specimens in each sample are clearly too low for any rigorous treatment and the conclusions drawn from this analysis must be regarded as provisional. The data from Portugal come from specimens figured by Rey and others (1977) and are included only to give an impression of where specimens from an ammonite-dated Upper Albian fauna would plot on such a scatter.

The scatters for Hallon and Hullers Hill Quarry have virtually the same Reduced Major Axis, and the Means are in close proximity. The population from Wolborough (with the Mean and Reduced Major Axis also shown) departs sharply from the other two –towards the samples from the Upper Albian of Portugal. It seems reasonably certain that the Hullers Hill Quarry and Hallon specimens can be grouped together, and assigned the same species/ subspecies (?) determination, whilst acknowledging that there is some variation - probably induced by the changing facies. The Wolborough specimens are almost certainly distinct at the species/ subspecies (?) level from the other two localities.

3. Stratigraphical implications

The material from Hallon is accepted as being of Early Cenomanian age and is associated with a classic Lower Cenomanian ammonite fauna (Hancock 1959). The material from the Hullers Hill Quarry is also associated with an ammonite fauna (Wood 1971, p. 100; Carter and Hart 1977, p. 107). The agreement of the *Orbitolina* faunas shown in the bivariate analysis is therefore confirmed by the macrofaunal data.

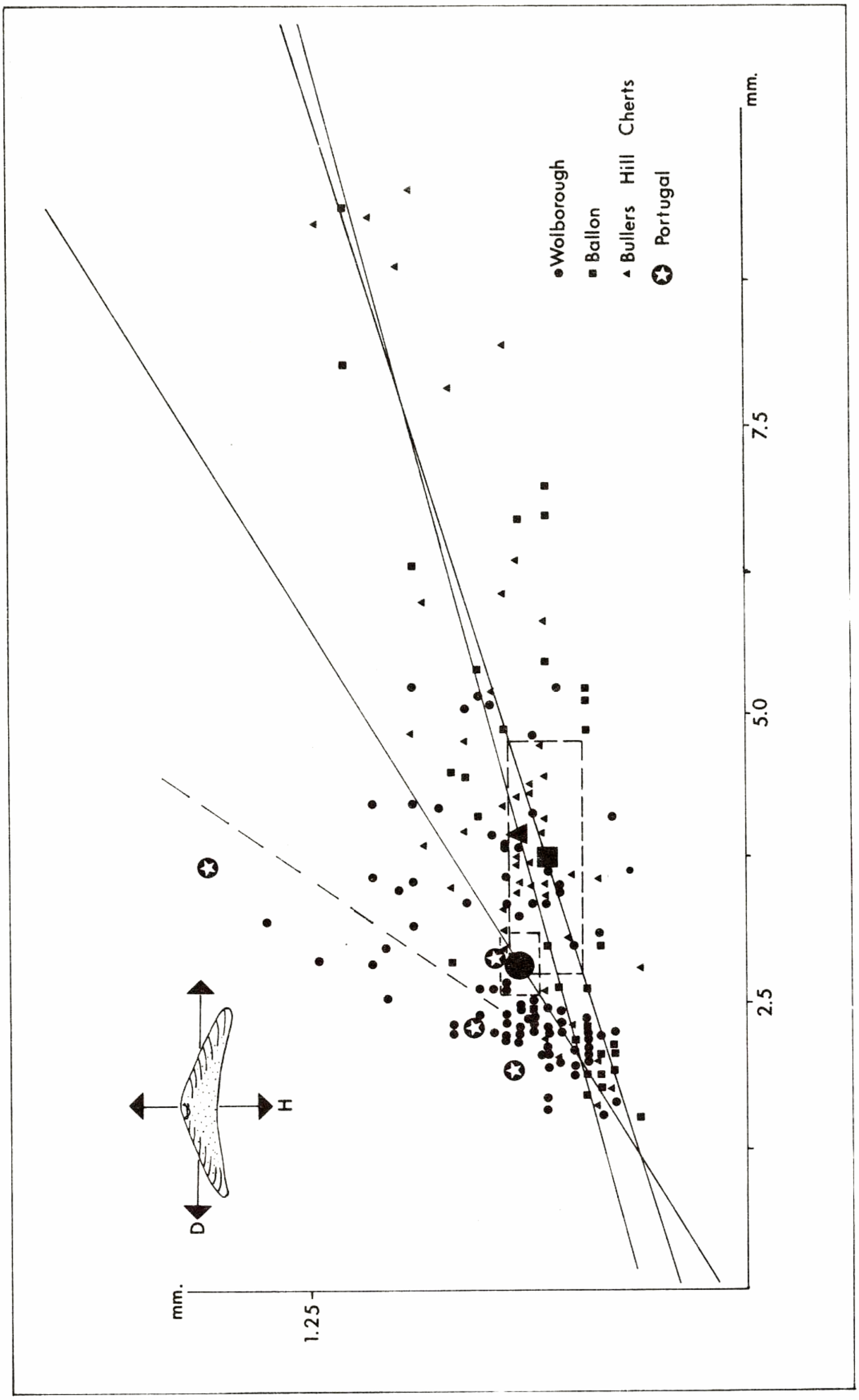

Figure 4. Bivariate analysis of samples of Orbitolina from Bullers Hill Quarry, Ballon, and the Walborough trench. Reduced major axes and Mean (large symbols) are shown, calculated for each sample

If the Portuguese material is of proven Late Albian age then the bivariate analysis suggests that the age of the Wolborough material is intermediate between it and the Early Cenomanian, Hallon fauna. At this stage in the investigation, therefore, the Wolborough fauna has been ascribed to the Late Albian –Early Cenomanian interval.

4. Other microfaunal data

The Wolborough limestones have also yielded a fauna of smaller Foraminiferida and Ostracoda. The Ostracoda include *Loxoconcha* sp. nov. (*L. icknieldensis* Weaver MS, 1978), *Protocythere* speetonensis Kaye, and *Neocythere* sp.. This assemblage could equally well be assigned to the Late Albian or the Early Cenomanian, and this conclusion is supported by the presence of the Foraminiferida (*Palmula cordata* (Reuss); *Lingulogavelinella jarzevae* (Vasilenko), and *Vaginulina* sp. nov.). The Hullers Hill cherts contain an Ostracoda and Foraminiferida fauna that is more typically Cenomanian, including *Oertliella* sp. cf. *0. donzei* Weaver (MS, 1978), *Neocythere* sp., *Imhotepia* sp., and *Netrocytheridea* sp. cf. *N. tenuistriata* Colin.

5. Summary

A bivariate analysis of the *Orbitolina* fauna from the Cretaceous limestones from the Wolborough trench suggests an age of Late Albian -Early Cenomanian, while the *Orbitolina* faunas from Hullers Hill Quarry can be favourably compared to those from the type Cenomanian of the Sarthe. The confirmation of this temporal separation (first indicated by Hamblin and Wood(1976) on the basis of the macrofauna) is very important as it may now be possible to re-assess the stratigraphical position of the *Orbitolina* faunas recorded from Wilmington, Warminster and Dunscombe.

In the Haldon Hills succession of the Upper Greensand it seems clear that the Cullum Sands with Cherts Member is probably Early -early Mid-Cenomanian in age and that the Woodlands Sands Member is possibly latest Albian -earliest Cenomanian on the basis of the *Orbitolina* analysis. If the internal structures of the *Orbitolina* fauna prove useful for stratigraphical interpretation then it may eventually be possible to place the Albian-Cenomanian boundary more precisely in the Upper Greensand succession of the Haldon Hills and adjacent areas.

Acknowledgements. The authors wish to thank D.J. Carter, C.J. Wood, R.A. Edwards. and R.J.O. Hamblin for their assistance during this research into the *Orbitolina* faunas of the Haldon Hills. The Institute of Geological Sciences is thanked for allowing the authors to publish the Upper Greensand succession of the Wolborough trench.

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DIAGENESIS OF LIMESTONES FROM THE UPPER GREENSAND AT WOLBOROUGH, SOUTH DEVON

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Abstract. Limestones in the basal 10m of Upper Greensand at Wolborough. Newton Abbot, are, in ascending sequence, sandy glauconitic *Orbitolina* biosparite; sandy biosparite; and biosparrudites, some with intraclasts. Grains mainly have a calcite cement, but some neomorphic recrystallization of bioclasts and (in intraclasts) of peloids and micrite has occurred. The centres of some bioclasts and intraclasts are silicified. Staining of thin sections demonstrates the following chronological sequence of cements: (i) non-ferroan dogtooth spar, (ii) granular ferroan calcite, (iii) granular non-ferroan calcite. Intraclasts show the first two, or all, or the cements, but outside intraclasts only granular ferroan calcite cement is present. The early cement was possibly generated by the excess calcite resulting from the dissolution of aragonite particles in the subaerial freshwater diagenetic environment, although a marine origin cannot be excluded. The granular ferroan calcite cement probably formed in the freshwater phreatic zone, the source of the cement being uncertain.

1. Introduction

Lenses of impure limestone are locally present in the Upper Greensand (Albian-Cenomanian) around the Bovey Basin (Fig. I), the most notable occurrence being that at Wolborough (SX 855700), 400 m south of Wolborough Church, Newton Abbot. The limestones were described by Edwards (1970), but samples were collected from field brash and could not be accurately related to the local Upper Greensand sequence until an IGS trench was excavated in 1974. The Upper Greensand in the trench was divided into eight beds (Selwood and others, in preparation), limestone constituting beds 6 and 8 (Fig. .1). Bed 6 is a distinctive 1.9m-thick unit of pale greenish-yellow (10Y 8(2) glauconite-speckled rubbly limestone containing abundant tests of the large foraminifer *Orbitolina*, together with bivalves and gastropods. Bed 8 is a more massive, relatively unfossiliferous, yellowish-grey (5Y 7/2) sandy limestone. Coarse-grained limestones occurred some 11 m beyond the NE end of the trench, presumably at a higher stratigraphical level than the bed 8 limestone.

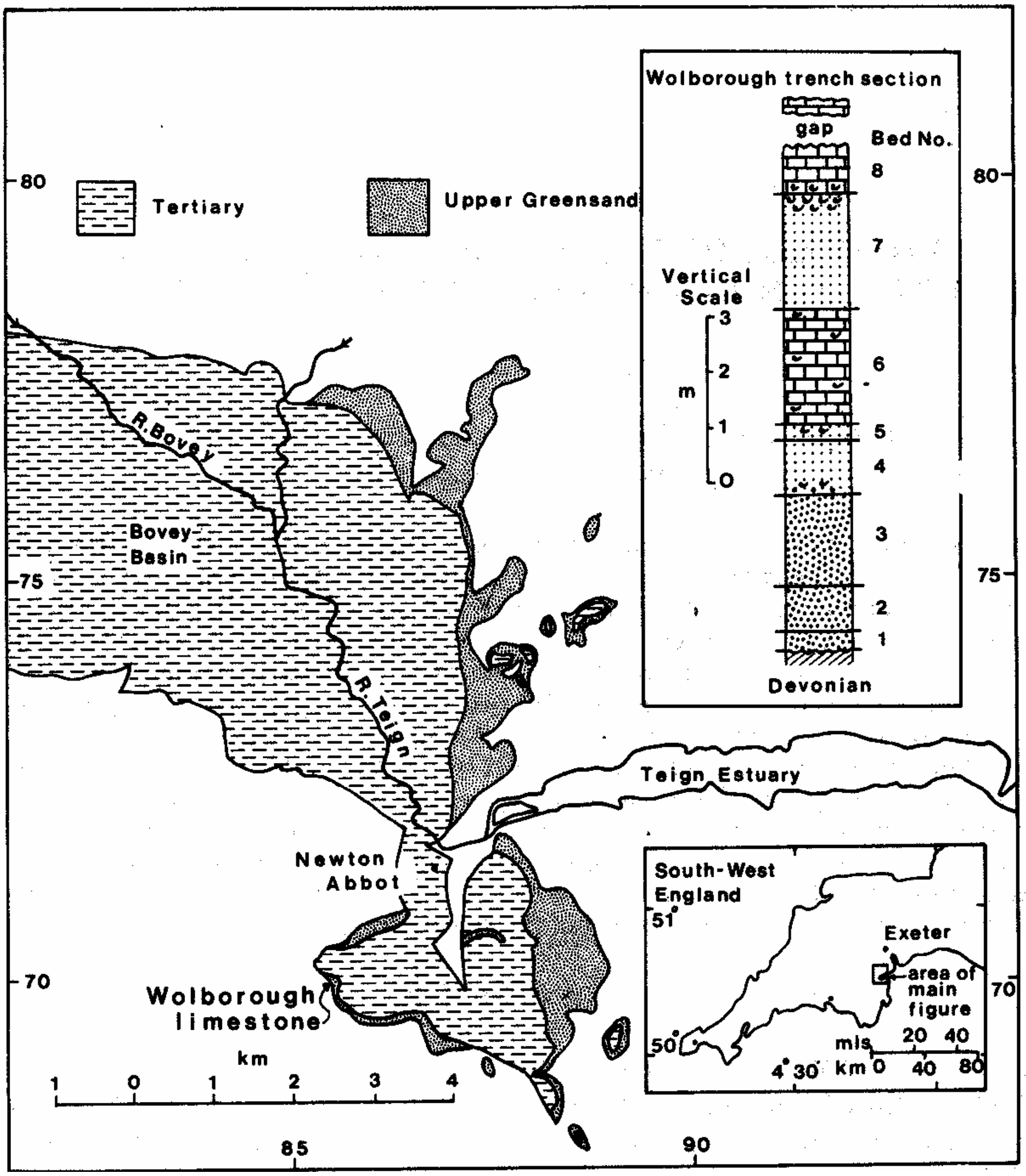

Figure 1. Geological map of the Bovey Basin, south Devon, showing the outcrop of the Upper Greensand, the position of the Wolborough limestone locality, and details of the beds exposed in the Wolborough trench. Beds 1-3: gravel. Beds 4-5: green and reddish-brown glauconitic sand. Bed 7: yellowish-green sand, shelly in top 0.3m. The limestone beds (shown with brick ornament) are described in the text.

The coarse grain size, considerable degree of abrasion of particles, lack of micrite, and presence of intraclasts indicate that the coarse-grained Wolborough limestones were deposited in a high-energy environment. Some of the biosparites consist of well-sorted and rounded grains, with no interstitial micrite, and were subject to intensive winnowing. The *Orbitolina* biosparites contain areas of micrite, suggesting that they were deposited in lower energy areas where winnowing was less pronounced. Thus the limestones are likely to have been deposited near shore, in shallow water subject to powerful waves and currents.

Plate 1. *Orbitolina* biosparite. Allochems, including many tests of *Orbitolina*, and other grains are cemented mainly by sparite, but micrite is patchily present. Negative print from a thin section.

2. Limestone types

(i) Sandy glauconitic Orbitolina biosparite (bed 6)

These limestones comprise detrital quartz, tourmaline and muscovite; glauconite; and bioclasts (some silicified), cemented mainly by sparite, but with patches of micrite (Plate 1). The carbonate content averages 84%. Skeletal particles are the only allochems, and include echinoderm fragments (usually with syntaxial overgrowths), polyzoan material, forams, bivalves and gastropods. Coarse-grained calcite mosaic occurs within geopetal cavities and filling moulds formed by the solution of aragonitic bioclasts.

(ii) Sandy biosparite and sorted biosparite (bed 8)

The dominant grains of the sorted biosparites are detrital quartz and tourmaline, and bioclasts (many with micrite envelopes; Bathurst 1958), cemented by clear sparite; micrite is absent. The carbonate content of one specimen was 75%. The constituent grains show a good degree of rounding and are moderately well sorted.

The dominant grains of the sandy biosparites are well sorted angular quartz, with lesser amounts of indeterminate skeletal debris; some peloids are present. Skeletal particles commonly have syntaxial overgrowths or fibrous rim cement, and some are silicified.

(iii) Sandy intraclastic biosparrudites; sandy non-intraclastic biosparrudites.

Limestones included in these categories were not encountered in the Wolborough trench and probably occur stratigraphically above the bed 8 limestones. The grains of the intraclastic limestones are abraded bioclasts, intraclasts, glauconite, and detrital quartz and tourmaline, cemented by coarse inclusion-free sparite (Plate 2). The carbonate content averages 60%. Bioclasts include echinodermal, algal, polyzoan, gastropod and bivalve material. Intraclasts range from a maximum of 50mm in length to a minimum of a few millimetres, and are commonly somewhat discoidal in shape. Some are pelsparites, composed of sub-rounded grains between 150μ-600μ of microcrystalline material (‘peloids’ of McKee and Gutschick 1969), cemented by sparite; others are similar to the biosparites of bed 8. They are almost certainly intraformational in origin. The limestones in which they are contained represent a period of higher energy deposition during which somewhat earlier partly cemented Upper Greensand sediment was eroded. N on-intraclastic biosparrudites are otherwise similar to the intraclastic limestones, although their cementation history differs (section 4(ii) below)

Plate 2. Intraclastic biosparrudite. containing parts of two intraclasts (top and left-hand side). The intraclasts and other grains are cemented by sparry calcite. Negative print from a thin section.

3. Diagenetic fabrics

(i) Calcite cement

The sparry calcite binding allochems and other grains, and filling cavities, in the Wolborough limestones is nearly always cement, and satisfies most of the fabric criteria listed by Bathurst (1975, pp.417-419). Calcite cement also fills moulds formerly occupied by aragonitic bioclasts. Several moulds show well developed micrite envelopes (Bathurst 1966), these being particularly well developed in the well-sorted biosparites of bed 8. In some cases, parts of the envelopes are broken, and such collapse is additional evidence for the existence of a cavity stage during the replacement of aragonite shells by calcite (Bathurst 1958, p. 367). Certain moulds are apparently lacking micrite envelopes; since there must have been some means of support to prevent collapse of these cavities, it is suggested that either this support was in the form of a cement or micrite envelope which had subsequently been dissolved, or, alternatively, the sediment had achieved such a degree of lithification prior to the solution of aragonitic material that the rigidity of the fabric prevented collapse into cavities. Possibly the 'mucilage envelope' of Talbot (1971) may have played apart in supporting cavities.

Bathurst (1958) described 'rim cementation' as a special case of chemical deposition, applied where calcite is deposited on grains surfaces syntaxially, the resulting fabric being a mosaic of grains each with a detrital core enclosed in a rim of syntaxial cement. Orme and Brown (1963) have used the term 'syntaxial cement rim' to describe this fabric. Syntaxial rim cement is developed in the Wolborough limestones, usually around echinoderm fragments. In some cases, overgrowths from detrital fragments in the Wolborough limestones may become large enough to enclose neighbouring non-monocrystalline fragments in an 'incipient poikilitic' fashion (Evamy and Shearman 1965, p.217).

(ii) Neomorphic fabrics

Owing to the general lack of fine-grained carbonate in Wolborough rocks, neomorphic (Folk 1965) fabrics resulting from the recrystallization of micrite are rare. There is, however, some evidence from intraclasts of the recrystallization of fine-grained fabrics by syntaxial rim replacement, and by coarser calcite mosaics.

Much more common in most Wolborough lithologies are molluscan bioclasts showing *in situ* recrystallization (Bathurst 1964). Fabric evidence from Wolborough limestones shows that these calcite mosaics have grown in situ: they show inclusions inherited from the original shell structure, which cut across intercrystalline boundaries; the crystals are commonly columnar, with their longest axes normal to the margin of the shell wall; intercrystalline boundaries are either consertal, gently curved, or, less commonly, planar; triple junctions with one of the angles equal to 180° are uncommon; the calcite mosaic is commonly pale brown and pleochroic. Hudson (1962) noted that this pseudopleochroism was caused by the scattering of the extraordinary ray by inclusions which outlined the early shell structures.

Examples of other types of recrystallization fabric, i.e. syntaxial neomorphic rims and coarse mosaics, are few and restricted to intraclasts. They have many of the characteristics described by Bathurst (1975, pp. 491-493). Peloids within intraclastic pelsparites are probably very small intraclasts of micritic limestone; they commonly show a dark grey fine-grained narrow marginal area, with a colourless central area occupied by a single calcite crystal in the centre of which is a lath-shaped ?echinoderm fragment. In some cases the central portion has spire-like projections into the marginal zone. The present appearance of peloids is probably a result of the recrystallization of their central part by a process similar to that which produces syntaxial replacement rims.

(iii) Silica fabrics

Many bioclasts in Wolborough limestones are preferentially silicified, while the matrix is more rarely affected. The silicified portions of bioclasts commonly occupy the central zone, leaving a narrow marginal area of unreplaced material. The clearly replacive nature of the silica is shown by the preservation of original bioclast structures. Silicification of bioclasts appears to have taken place more readily in the coarse limestones.

Some intraclasts show a central zone of chertification, where carbonate grains and matrix have been completely silicified: the resulting textures are similar to those in cherts from elsewhere in the Upper Greensand sequence of the Bovey Basin and Haldon Hills. Edwards (1970) considered that cherts in these areas had originated by the silicification of detrital limestones.

4. Calcite cements

Forty thin sections of Wolborough limestones were stained using the technique of Dickson (1965). An acid solution of alizarin red S and potassium ferricyanide indicates the distribution of ferrous iron and differentiates calcite and dolomite. Ferroan calcite stains mauve, purple or royal blue in the combined stain, while non-ferroan calcite stains very pale pink to red. (Dickson 1965, table 1, p.587).

(i) lntraclastic biosparrudites

Grains in intraclastic Wolborough limestones are bound together only by coarse granular blue-staining ferroan calcite cement. The contained intraclasts have more complex cementation histories; in one group the earliest cement is a pink-staining non-ferroan calcite which rims allochems. Where grains are closely packed, the rim cements of adjacent particles meet and fill the interparticle space, but more commonly the volume of early non-ferroan cement precipitated has been insufficient to fill the initial interparticle pores, and the remaining space is occupied by a later granular ferroan calcite cement. In places it can be demonstrated that the ferroan calcite cement is continuous from intraclasts into the surrounding sediment. The first cement from small radially oriented dog-tooth

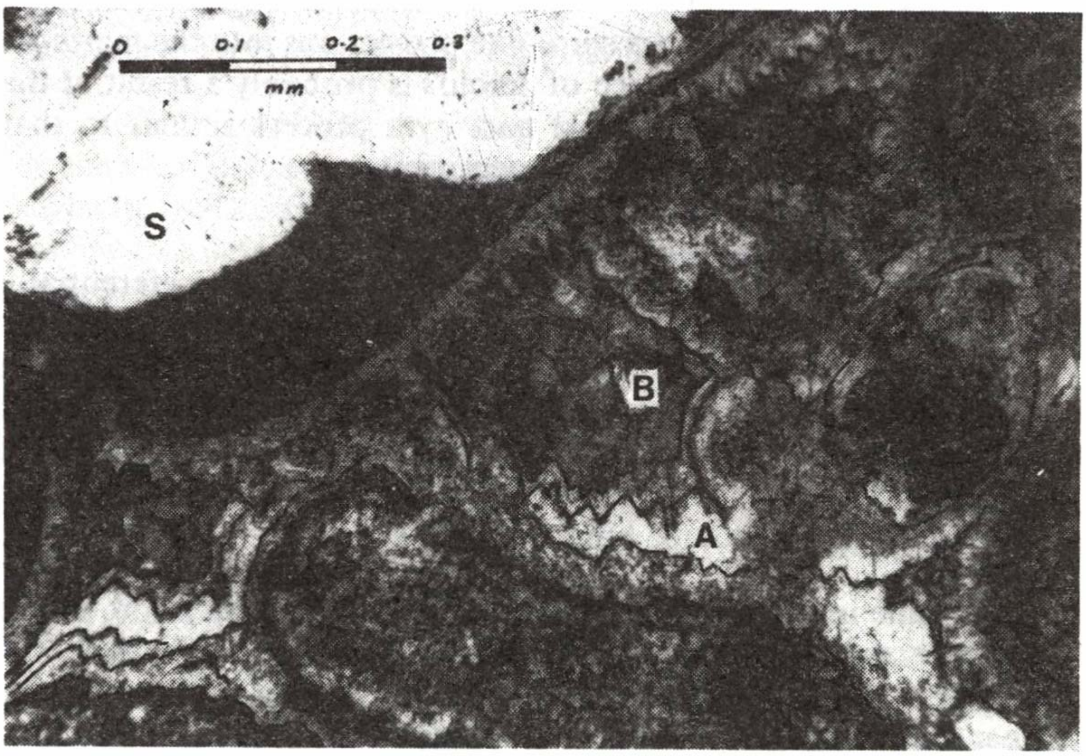

Plate 3. Retouched photomicrograph of a thin section of part of an intraclast from an intraclastic biosparrudite, stained with alizarin red S and potassium ferricyanide to show an early non-ferroan calcite cement (A) [white to pale grey on the photograph] fringing allochems, and a coarse ferroan calcite cement (B) [dark grey on the photograph]. filling the remaining voids. Part of the skeletal fragment at the top left-hand side of the figure has been silicified (S).

crystals, sometimes with zoned inclusions, while the second cement is of large equant calcite (Plate 3). The boundaries between non-ferroan and ferroan cement are crystal faces, suggesting that an interval elapsed between the cessation of non-ferroan calcite growth and the beginning of precipitation of ferroan calcite.

In other intraclasts three calcite cements are present. The first, a pink-staining dog-tooth non-ferroan calcite, rims allochems, and is succeeded by a thin zone of blue-staining ferroan calcite. Finally, non-ferroan calcite was precipitated and occupies the centres of interparticle cavities.

Non-carbonate grains (largely quartz and glauconite) in intraclasts are not rimmed by the early non-ferroan cement, showing the importance of nucleation in governing cement development.

The lack of early non-ferroan cement rimming allochems outside intraclasts indicates that the non-ferroan cement formed before deposition of the intraclastic biosparrudites. The presence of a non-ferroan cement binding particles within intraclasts would mean that the parent sediment was semi-lithified at the time of its erosion; this is borne out by the equal truncation of allochems and cement at intraclast margins, showing that intraclasts were sufficiently consolidated at the time of their erosion for cement and grains to wear equally during transport.

(ii) Non-intraclastic biosparrudites

Three calcite cements are developed in non-intraclastic biosparrudites, the earliest being non-ferroan in composition and consisting of irregularly developed dog-tooth calcite rimming allochems. The remaining voids are filled by coarse granular ferroan calcite and later coarse granular non-ferroan calcite. In places, the early non-ferroan cement is in contact with coarse non-ferroan spar . This may mean that pore space was incompletely filled by ferroan spar before the change in composition of the precipitating solutions.

(iii) Orbitolina biosparites

Allochems in *Orbitolina* biosparites commonly have a rim of small calcite crystals which show two compositional zones after staining. Cavities may have a similar lining. The earlier cement is very pale pink-staining non-ferroan calcite, with which is associated a later mauve-staining ?ferroan calcite. Although these early zones are commonly morphologically distinct, in some cases the change from non-ferroan to mauve ?ferroan to blue ferroan calcite takes place within a single crystal.

Large cavities in *Orbitolina* biosparites, formed by the solution of originally aragonitic fossils, having linings of non-ferroan calcite, the remaining pores being largely filled with coarse granular blue-staining ferroan calcite drusy mosaics. Towards the centres of such cavities non-ferroan calcite may occur, the compositional change taking place within crystals. Where cavities retain a central pore; this is lined with crystals of non-ferroan calcite, showing that the precipitation of non-ferroan calcite is the latest cementation event.

(iv) Other biosparites

The remaining Wolborough biosparites show a similar cementation history, involving the development of an early non-ferroan cement fringing allochems, followed by a coarse granular ferroan cement which fills the bulk of the pore space. Most specimens show the development of a late non-ferroan cement.

(v) Veining

A small number of thin sections show narrow veins of coarse non-ferroan calcite which post-date the ferroan calcite cement. One vein cuts a partially silicified bioclast, suggesting that the veining post-dates silicification. Some intraclasts have a thin outer coat of non-ferroan calcite, probably introduced at a late stage along separation fractures between intraclasts and the surrounding limestone.

5. Discussion

The general sequence of cementation in the Wolborough limestones was (a) precipitation of small non-ferroan calcite crystals on allochem surfaces and in many cavities formed by the dissolution of aragonitic fossils; (b) precipitation (after an interval of time) of coarse ferroan calcite filling most of the remaining pores between allochems, and also much of the remaining moldic porosity; (c) precipitation (without a break) of coarse non-ferroan calcite which lines the few remaining pores. Diagenetic sequences showing an early non-ferroan calcite cement and a later ferroan calcite cement have been described by several authors from limestones of various ages (e.g. Evamy and Shearman 1965; Dickson 1966; Oldershaw and Scoffin 1967; Nea11969; Evamy 1969; Talbot 1971).

The first (non-ferroan) calcite cement formed early in the diagenesis of the Wolborough limestones. This is particularly demonstrated by its abrasion in intraclasts which are enclosed by coarse sediment cemented only by granular ferroan calcite. Talbot

(1971) has also described, from the Corallian Beds, intraclasts with an early non-ferroan calcite cement included in rock with a wholly ferroan calcite cement.

The first cement in the Wolborough rocks lines most cavities originally occupied by aragonitic shells ('moldic porosity' of Friedman and Sanders 1978), but others contain only granular ferroan calcite cement. Possibly certain aragonitic shells and compositions which enabled them to survive dissolution until after precipitation of the first cement was completed (cf. Talbot 1971, pp.266-267).

The presence of moldic porosity in limestones is generally held to be evidence for the dissolution by fresh water or aragonite particles in the subaerial diagenetic environment (eg. Friedman and Sanders 1978). This process produces an excess of about 8 per cent of calcite which could provide the first generation of calcite cements observed in many limestones (Bathurst 1975, pp.329, 434; Pingitore 1971). However, early diagenetic fringing cements are also known to form in the intertidal area (e.g. "beachrock"), or on the sea bottom (see many articles in Bricker 1971). In most beach rock and intertidally cemented carbonates, the cement consists of a uniformly thick fringe of aragonite or high magnesian calcite, which may transform with time into a calcite cement poor in iron retaining only the general form and orientation of the original cement; it will be difficult to deduce the original nature of such transformed cements.

The early cement in Wolborough limestones forms a crust around the allochems showing no distinctive variations in thickness ('even style' type of Müller 1971); this probably reflects the complete water saturation of the rocks during cement precipitation. 'Uneven style' ('gravitational' or 'meniscus') cements which are thought to have formed in the vadose zone, where pores are only partly water filled (Müller 1971; Dunham 1971) are lacking in the Wolborough limestones.

There are no definite petrographic criteria which can be used to determine whether the first non-ferroan calcite cement of the Wolborough limestones formed in the marine or freshwater diagenetic zone. However, it seems most likely, in view of the evidence for dissolution and in situ recrystallization of aragonite particles, that the sediments were exposed early to fresh water which dissolved the aragonite and produced a surplus of calcite for the first cement. The even style of the cement may indicate a phreatic environment of precipitation.

The second (ferroan calcite) cement is volumetrically more important than the first cement, and with its precipitation porosity of the limestones was almost completely destroyed. With small amounts of later coarse non-ferroan spar, it is the only cement binding allochems in the intraclastic limestones. Thus precipitation of the early non-ferroan cement was completed at the time of intraelast formation. Evamy (1969) suggested that the presence of ferrous iron in calcite cement was good evidence for precipitation in reducing conditions in the phreatic zone. Friedman (1975) noted the following products of phreatic diagenesis: (a) former moulds filled with drusy calcite, (b) rim cement that develops as syntaxial growth on echinoderm fragments, (c) a xenotopic mosaic of calcite as a replacement of aragonite shells (paramorphic replacement). All these features are present in the Wolborough limestones and may be taken as evidence that they have spent some period of their diagenetic history in the phreatic zone.

The source of the late ferroan and non-ferroan cements is uncertain; an internal origin is unlikely, since the dissolution of aragonite particles would have provided insufficient amount of calcite for the second generation of cement. The origin of second generation cements has been related by some authors (eg. Oldershaw and Scoffin 1967) to pressure solution, but there is little evidence of extensive pressure solution and pitted and etched calcite grains in the Wolborough limestones, suggesting that the cement was derived from an external source.

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TERTIARY SILCRETES OF THE SIDMOUTH AREA, EAST DEVON

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Abstract. The Tertiary sediments in the Sidmouth area are divided into two lithostratigraphical units. The older of these, the Peak Hill Gravels. is composed of unabraded flints in a matrix of kaolinite and formed by the removal of $CaCo_3$ from the Chalk under lateritic weathering conditions. Faulting and uplift then occurred, with erosion and local redistribution of Peak Hill Gravels in some areas. A new lateritic weathering profile was established. Mutters Moor Gravels were then formed by the aeolian and fluvial reworking of Peak Hill Gravels. Silcretes are locally abundant in the Sidmouth area; a wide range of sediments was silicified. The silcretes formed during possibly two periods by desiccation of the weathering profiles in increasingly arid conditions.

1. Introduction

The hills surrounding Sidmouth form part of the dissected tableland of the East Devon Plateau (Fig. I). They are formed of deeply weathered Upper Greensand. with some Chalk in the east and these dip gently eastwards. Capping the Upper Cretaceous is a sequence of Tertiary residual and flu vial gravels. The fact that there was a complex of sediments in this area. included in the blanket term 'Clay- with- Flints'. was realized early this century by Woodward (Woodward and Ussher 1911).

In this study the succession is divided into two main stratigraphical units, the Peak Hill Gravels and the younger Mutters Moor Gravels. The two units are separated by an unconformity. The deposits are continental and show a sequence of lateritic weathering profiles with the local development of silcretes. Figures 2 and 3 show geological maps of two areas studied in detail.

2. Peak Hill Gravels

The Peak Hill Gravels consist of unabraded flints in a white to

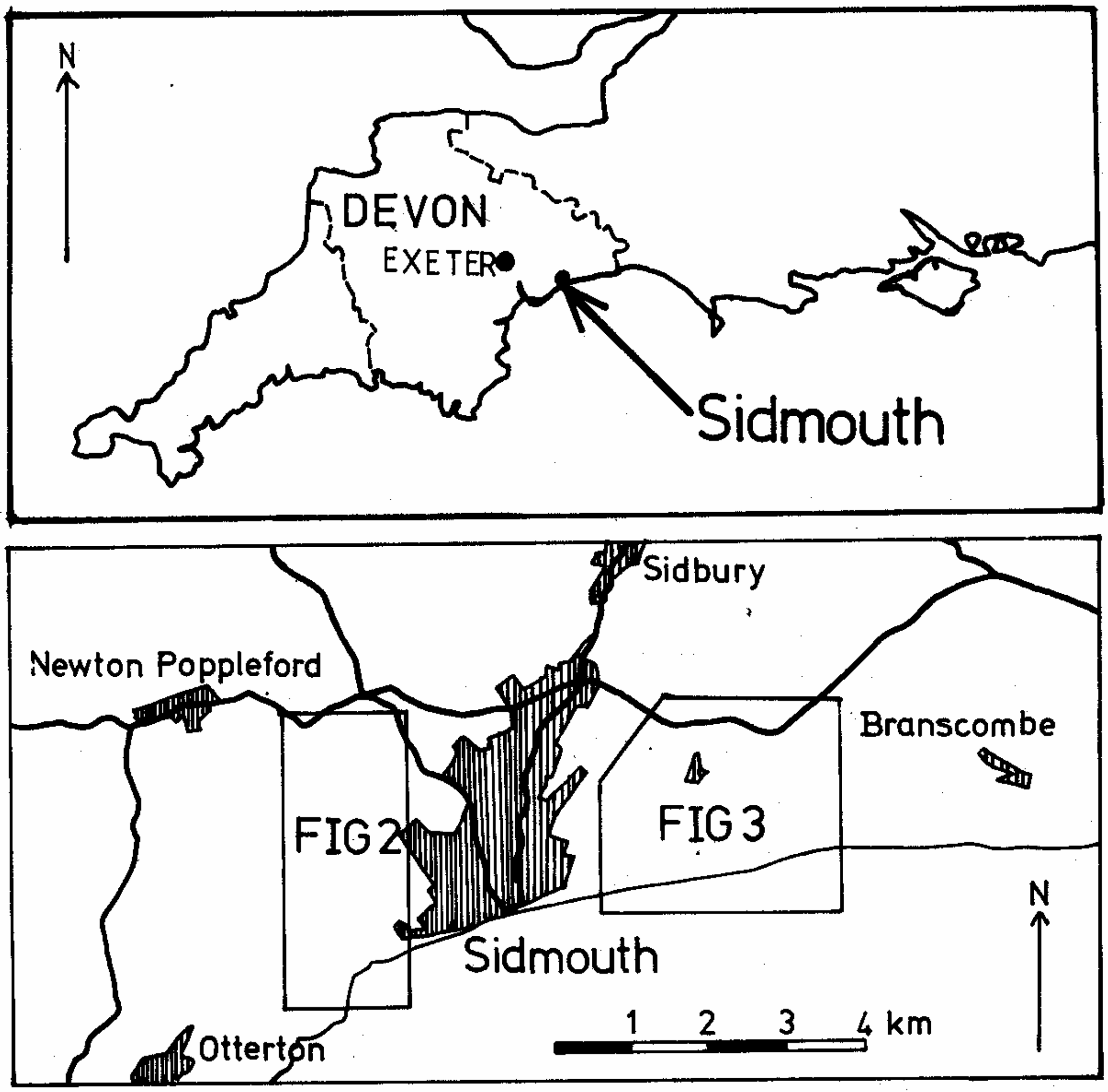

Figure 1. (a) Map showing position of Sidmouth in southwest England.
(b) Map showing position of detailed study areas, Fig. 2 and 3, in relation to Sidmouth.

reddish-brown matrix of moderately fine-grained disordered kaolinite, sand and silt. Nodular flints of variable size are irregularly distributed through the unit. Lines of tabular flints reflect bedding and seem to have been locally let down passively from above as their host chalk was removed by solution. Angular flint chips form a large proportion of the matrix. Two main fabrics are developed. The first, which occurs near the base of the unit, shows tightly interlocking flints with little matrix. In the second, the flints are rarely seen in contact with each other and the matrix forms the bulk of the material. The matrix clay and sand moved down from above by infiltration. The kaolinite was formed by chemical weathering of clay rich sediments overlying the Chalk. These sediments are probably almost wholly incorporated into the Peak Hill Gravels and the later Mutters Moor Gravels.

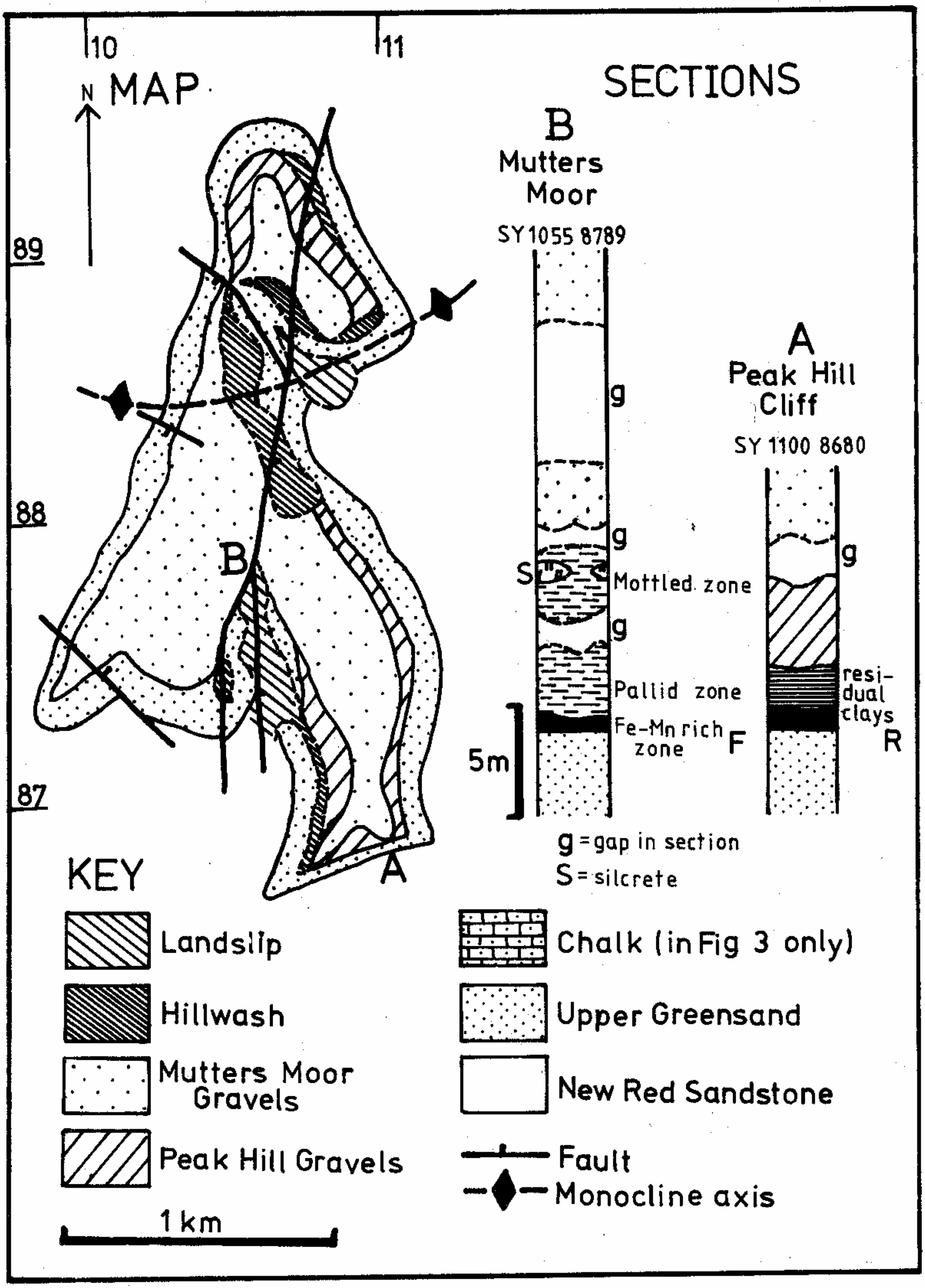

Figure 2. Geological map of the hills west of Sidmouth and section from the type localities of the Peak Hill and Mutters Moor Gravels. The pallid and mottled zones in section B consist of silty kaolinitic clays representing intensely weathered Upper Greensand

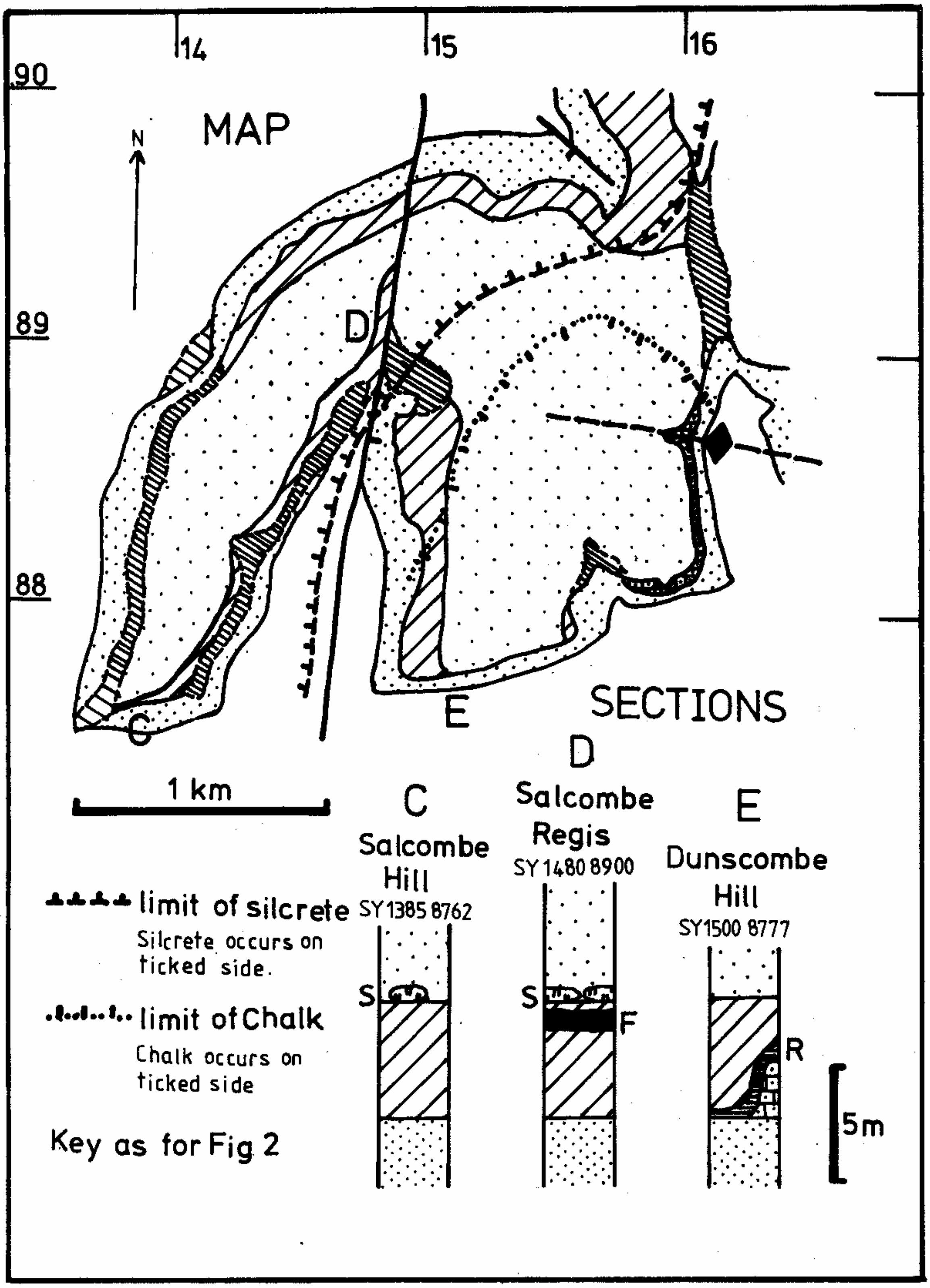

Figure 3. Geological map and sections from the hills east of Sidmouth.

Fine-grained residual deposits derived from the underlying Upper Cretaceous appear as a thin band of well laminated black –or chocolate-coloured clays at the base of the Peak Hill Gravels. Where underlain by chalk, this band is relatively thin and pure, but over the Upper Greensand a bed of clayey sand with lenses of well-rounded quartz pebbles is frequently developed. This resembles the basal horizon of the Haldon Gravels described by Hamblin (1973, p. 463). Evidence given by Chartres and Whalley (1975) indicates that truly residual clays may form at any time by dissolution of underlying chalk.

The type locality of the Peak Hill Gravels is Peak Hill Cliff, (SY 8680 1107) where a 0.1 m-thick band of gritty but well-laminated fine-grained sand with small quartz pebbles is overlain by about 0.2m of laminated, stiff, chocolate-coloured clays. Overlying these are 1-2m of the tightly interlocking fabric of the Peak Hill Gravels and about 2 -3 m of the more open fabric. In places the clay shows a mottled staining by sesquioxides. The underlying strata is decalcified Upper Greensand.

Associated with the Peak Hill Gravels, where the underlying strata has been decalcified, are large blocks of silcrete which are locally very common in the Sidmouth area. The silcrete commonly consists of shattered but unabraded flints in a compact, pale pink to grey matrix of irregularly distributed, often tightly packed, silt-sized quartz and flint clasts cemented by cryptocrystalline silica and opal. The pale pink colour is due to finely divided haematite, irregularly distributed through the cement. The silcrete formed at, or near the surface as many blocks show root structures and features such as reddening of the flints at the clast-cement interface. This latter feature indicates aerial exposure in a semi-arid to arid environment immediately prior to silicification (Stephens 1971, p. 25). More rarely the Peak Hill Gravels occur indurated as a ferricrete.

In addition to the silicification of Peak Hill Gravels, silicified bioclastic limestones, probably Upper Cretaceous, are found as occasional large blocks and pebbles in later silcretes. Silicification of chalk in association with the formation of 'Clay-with-Flints' is known from others areas (Van den Broeck and Van den Waals 1967) and is thought to be contemporaneous with lateritic weathering. The Peak Hill Gravels are interpreted as being formed by removal of $CaC0_3$ from the chalk by dissolution. The silcretes are duricrusts and represent a period or periods of desiccation of the profile (Watts 1978).

Post-Palaeocene weathering, the establishment of later deep weathering profiles, and finally Pleistocene cryoturbation, have done much to alter the Peak Hill Gravels. The two fabrics are frequently mixed and may have been produced by solifluction, the finer constituents being concentrated and the large flints being left behind. It is likely that some of the flint chips were formed by frost shattering during the Pleistocene. However, as the silcretes contain angular flint chips, a proportion of the shattering must have occurred at an earlier time prior to silicification. The silcrete duricrust and patches of silicified limestone were broken up and incorporated into later deposits.

3. Mutters Moor Gravels

The Mutters Moor Gravels appear to have been derived principally by the reworking of the Peak Hill Gravels, from which they can be distinguished by the rounding of the flints. The degree of roundness varies from well-rounded cobbles to comparatively unworn flints with rounded horns only. Silcrete blocks, cobbles and angular fragments are common, these being absent from the Peak Hill Gravels; on Mutters Moor, for example, the ratio of flint to silcrete may be as low as 1 :3. Less common are clasts consisting of coarse to fine-grained, often quite angular quartz sand with a ferruginous cement.

The matrix clay of the Mutters Moor Gravels is very fine-grained disordered kaolinite with variable amounts of illite. Clay lenses are commonly present within the gravel The sand content varies but is always high and sand lenses occur locally. At certain horizons the coarse components of the gravels are close-packed and have suffered much post-depositional shattering.

The type locality of the Mutters Moor Gravels is a stream section (SY 10558789) on Mutters Moor, west of Sidmouth, where 3m of the Gravels lie directly on deeply weathered Upper Greensand. The Upper Greensand has been altered to a 2-3 m thick zone of pallid, silty kaolinitic clay containing various iron sesquioxides, overlain by 2- 3 m of kaolinitic clays with a patchy mottled staining. This weathering profile was developed after the removal of the Peak Hill Gravels by erosion and before the deposition of the Mutter~ Moor Gravels. Silcrete also occurs as pallid zone accumulations and silicified bedrock as well as a surface duricrust.

The base of the Mutters Moor Gravels is a generally planar surface modified by broad flexures which are not tectonic in origin but represent the original topography developed by fluvial erosion of the emerging surface on which the Peak Hill Gravels had formed. The base of the Mutters Moor Gravels, which closely parallels the present topography, suggests that the present Sidmouth landscape is quite an ancient one. In the immediate area of the Sid Vale the drainage system was of a similar pattern to that of the present day. A shallow valley 5 -6 km wide and having the same trend as the present Sid Vale is envisaged. The relief was less than at present.

Certain horizons showing intensely shattered flints and silcrete, compacted and with little interstitial clay matrix, are interpreted as palaeo-deflation surfaces. These may be Pleistocene in age. On Mutters Moor it is suggested that such a surface has become exhumed so that the present gravel plane exposed at about 180 m above sea level is of a similar composition to the ancient land surface. At Salcombe Hill Cliff, (SY 1385 8762) a deflation surface lies directly on Peak Hill Gravels and is taken as the base of the Mutters Moor Gravels there.

Silicification of the weathering profile had ceased by the time the Mutters Moor Gravels were deposited. Lateritic weathering had also ceased and it seems that much of the kaolinite of the Mutters Moor Gravels was derived from the reworking of the older kaolinitic weathering profiles.

4. Structure

Pre- Tertiary folding is revealed by the configuration of the base of the Upper Greensand north of Sidmouth. This horizon can be readily mapped for it is unaffected by cambering. Most apparent are east-west trending synclines; in the anticlinal areas the Upper Greensand thins or is almost cut out by the Tertiary unconformity. At Weston Coombe and Bulverton Hill east-west monoclines may reflect basement structures. On the Bulverton Hill monocline, dips steepen considerably so that near Mutters Moor an amplitude of 30 m is represented. There is no evidence in the Sidmouth area for periclines as described by Durrance and Hamblin (1969) in the Haldon Hills.

These folds are cut by NNE-SSW trending normal faults showing well-developed splay structures. The best known fault is that which cuts the coast at Jacobs Ladder, Sidmouth and continues northwards to beyond Pinn Hill Farm (SY 1445 9500). A comparable structure passes through Salcombe Regis. These faults probably represent Tertiary reactivation of Armorican structures in a direction conjugate to the Sticklepath fault. Reactivation occurred on these faults after an interval, during which the Peak Hill Gravels were formed. The resulting uplifted blocks were subject to erosion and the Peak Hill Gravels rapidly removed, to expose the Upper Greensand. The Mutters Moor Gravel which postdates this faulting, succeeds the Peak Hill Gravel unconformably and locally rests on Upper Greensand. Thus west of the Mutters Moor fault, the Mutters Moor Gravels lie directly on the Upper Greensand. East of this fault Peak Hill Gravel thins westerly to nothing along the line of the fault (Fig. 2).

5. Silcretes

Silcretes commonly consist of over 97 per cent SiO_2. Silcrete genesis is basically a process of replacement and cementation following mobilization of silica from outside the silcrete horizon (Watts 1978). Their classifiable characteristics are therefore very much the characters of the silicified parent rock. Surface duricrusts, pallid and mottled zone accumulations and silicified bedrock are all represented by silcretes in the Sidmouth area.

The dominant cement in the Sidmouth silcretes appears to be cryptocrystalline silica, probably chalcedony. Amorphous and possibly crystalline (Jones and others 1964) opal is often common. The opal usually occurs as an early cement or infill of pore space and characteristically shows colloform structures indicative of deposition from a colloid in the form of a gel.

The evidence suggests that in the Sidmouth area there were at least two discrete periods of silcrete formation. Silcrete genesis was initiated with the emergence of the Tertiary land surface. Senonian bioclastic limestones were silicified contemporaneously with the formation of the Peak Hill Gravels. These were subsequently eroded and incorporated into later deposits. Cryptocrystalline silica chalcedony, fibrous chalcedony and quartz characterise these silcretes. In contrast with the later silcretes of the area, opal is absent

In situ silicification of Peak Hill Gravels is frequently recorded. Several isolated blocks show that a shallow soil supporting vegetation, occurred on top of the weathering profile. Later silcretes developed in weathering profiles on Upper Greensand where the Peak Hill Gravels had been removed by erosion show slightly different characteristics. Finely laminated clays, fine-grained sands and silts are the commonest sediments silicified producing a texture called porcellanitic by many authors. Well-rounded flints and silcrete clasts indicate silicification of fluvial gravels. Some silcretes consist entirely of earlier silcrete pebbles in a new matrix. The overall emphasis is of repeated episodes of silicification and disintegration.

Where the profile lies directly on the Upper Greensand silcretes were thicker and more extensively developed, which suggests that the permeability of the Upper Greensand had some controlling influence on the movement and deposition of silica in the weathering profile. Over the Peak Hill Gravels the silcretes tended to be thinner and less continuous.

Solution features are commonly seen in the silcretes; however, the indications are that much of the secondary silica originated outside the silcrete horizon (Watts 1975). Associated with silcrete samples and as separate clasts, are poorly cemented sandstones which, in thin section, show impressive solution features. Following dissolution, which is indicated by dramatically embayed grain margins, a sequence of haematite and then goethite cements is seen. Repeated deposition and solution of the cements occurred.

Studies in Australia (Watts 1976; 1977; 1978) indicate that silica is derived by dissolution of detrital quartz above the silcrete horizon and that this moves downwards in solution before precipitating into a colloid and then a gel as desiccation of the weathering profile proceeds. These poorly cemented sandstones may represent the horizon from which the silica for the Sidmouth silcretes was initially derived.

Veins of ferricrete commonly cut the silcretes. A complex sequence of replacement of silica, fracturing of the new matrix, disintegration and then recementation by silica, haematite or goethite, is seen. These accumulations of iron oxides in the silcretes are thought to represent concentration of iron from the heavy mineral fraction of the silica source sediments. In thin section the heavy mineral fraction of the poorly cemented sandstones is dominated by tourmaline which is absent in the silcretes, having apparently been completely dissolved. Occasional zircons are seen in the silcretes, these being highly resistant to dissolution. The role of

TiO_2 in the formation of silcretes is important and well known (Watts 1977). Unfortunately no information on its occurrence in the Sidmouth silcretes is available although it is present as anatase in the source sediments and has tentatively been identified in association with colloform structures in the silcretes.

6. Discussion

Watts (1977) used geochemistry to establish the most likely process of accretion and found that silcretes were formed during periods of relative aridity when silica, mobilised during intense leaching, was deposited as desiccation of the profile occurred. In Australia, conditions of lateritic weathering profile formation were followed by rather more arid conditions during which silcretes developed. Such a history is envisaged for the Sidmouth deposits where at least two major periods of desiccation occurred with the formation of silcretes.

Watkins (1967) showed that climate was the main control of the distribution of contemporaneous duricrust types in north-eastern Australia. He found that silcrete is formed between a mean annual rainfall of 40-65 to 75-90 cm and above a minimum mean annual temperature of between 10 and 15.5°C. Where rainfall and also perhaps temperature is higher, laterites form in the usual lateritic weathering profile. How applicable these figures are to the early Tertiary is uncertain but they are useful when considering the degree of climatic change implied. It is evident however from other studies (Stephens 1971; Watts 1978) and from the Sidmouth area that other factors may be locally important in determining silcrete occurrence and distribution. Silica may not always be available from leaching and transport in the weathering profile as is suggested by the absence of silcrete in areas east of Sidmouth. West and north of Sidmouth the permeability of the bedrock is seen to be important.

The succession of the Sidmouth area is comparable to that established in the Haldon Hills by Hamblin (1973). Hamblin recorded no silcrete or lateritic weathering profiles however, and interpreted the clay matrix of the Tower Wood Gravels as being derived from the granite mass of Dartmoor, the kaolinite having a hydrothermal origin. Green (1974) questioned this interpretation and implied that production of kaolinite by weathering processes was more plausible. Present evidence suggests that this is the case and the Tower Wood and Peak Hill Gravels have a common origin by lateritic weathering of the Chalk and its overburden.

Lateritic weathering profiles are found at many localities in south-west England and Bristow (1968) has shown that kaolinitic weathering profiles were probably very extensively developed in the past. In Northern Ireland (Wright 1924; Fowler and Robbie 1961) and on the Continent (Van den Broeck and Van den Waals 1967) lateritic weathering profiles are well recorded and have been used as palaeo-temperature indicators (Montford 1970). Silcretes are found over large areas of southern England as sarsens (Kerr 1954) and in France the 'Siderolithique' and' Argille a Silex' is known in some detail, (Millot 1970). That the 'Clay-with-Flints' of East Devon contains more than one sediment group was realised by Woodward (1911). However, since then little work has been published and the area remains little known.

The age of the 'Clay-with-Flints' in Britain is disputed, Most British authors favour a Pleistocene age (Pepper 1973) whereas French authors accept ages within the Lower Tertiary for the equivalent deposits in France. The widespread occurrence of silcretes in the forms of sarsens often in association with the 'Clay-with-Flints' has already been noted. Generally, however, relationships between the 'Clay-with-Flints' and its companion materials have not been properly ascertained. Some deposits are undoubtedly Pleistocene or later, e.g. the residual clays described by Chartres and Whalley (1975). Evidence from other localities is more consistent with the views of workers on the Continent.

In Northern Ireland 'Clay-with-Flints' rests on Chalk and is overlain by basalts (Fowler and Robbie 1961; Wright 1924). These have been dated as spanning 65-66 m.y. (Evans and others 1973), giving the 'Clay-with-Flints' a lowest Danian to Maastrichtian age. Hamblin (1973, p. 461) reviewed the ages given to the Haldon Gravels by various authors and favoured a Palaeocene age for the Tower Wood Gravels. Climatic evidence (Dury 1971) and knowledge of the conditions of formation of silcretes (Watkins 1967; Watts 1978) suggest that a Palaeocene age is appropriate for the Peak Hill Gravels and the accompanying silcretes. This must be a tentative conclusion at present.

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8. Discussion

Dr A. Hall asked whether the author had compared the Sidmouth deposits with other cemented Tertiary deposits father east, for example the famous Sarsen stones or the Hertfordshire Puddingstones, both of which had a siliceous cement:

The Author replied that he had not, but hoped to do so in the future; at present he was examining Tertiary deposits W and NW of Sidmouth. It was his impression that the residual Clay-with-Flints became younger as it was traced eastwards. The Sarsen stones seemed to be simply cemented quartzites. The dominant cements differed geographically; microcrystalline quartz seemed to be predominant farther east, whereas in the East Devon deposits, a common cement was amorphous opal, possibly with some crystalline opal.

Dr R. Edwards asked whether the author had recorded from the Haldon Gravels silcretes comparable to those in the Sidmouth deposits.

The Author replied that there were no obvious silcretes in the Haldon Gravels comparable to those occurring so abundantly in the Sidmouth area. This was not, however an argument against correlation since silcretes could be locally developed at one horizon and absent from the same horizon elsewhere. In the Upper Greensand at Buller's Hill Quarry, on Great Haldon there were cherts; bedrock silcretes rather than surface duricrusts may have formed, and it was possible to speculate that the silicification in the Upper Greensand, which was very deeply weathered and decalcified, might have been contemporaneous with part of the Haldon Gravels.

Dr M.B. Hart asked on what evidence the Senonian dating of the silicified chalks in the Sidmouth area was based.

The Author replied that the dates were tentative based on identification by Prof. Murray of foraminifera in thin sections.

Dr Hart continued by asking if the author had identified any macrofossils in the residual flint gravels of Sidmouth that agreed with the dates given for the Haldon Gravels; that is, Coniacian to Campanian? Also, had the author found and examined any flint meal?

The Author replied that the age range cf the Sidmouth deposits was Coniacian to possibly Campanian. He had not yet examined any flint meal.

Mr Bristow remarked that the source of the silica which formed the silcretes in Australia was the kaolinisation of feldspars, liberating silica which then accumulated near the surface.

The Author responded that that was one theory; the most recent work [Watts(1977). *Geochim. Cosmochim. Acta,* 41, 1164-1167; Watts(1978). J *Sedimentary Petrol,* 48, 987-994] indicated that the silica was derived from above by the intense leaching of detrital quartz during lateritic weathering. He had observed sandstones from the Sidmouth area which probably occurred above silcrete horizons, and which showed intense solution features. However, when it was considered that some of the South African silcretes were up to 80 m thick, there was a considerable problem in deciding on a mechanism by which such thicknesses could accumulate.

Professor J.W. Murray, commenting on the author's suggestion that the Sidmouth deposits might be in part Palaeocene, said that an argument against such a dating was that the Palaeocene was generally thought to be somewhat cooler than the preceding Cretaceous and even the succeeding Eocene; warmer periods were not recorded until mid-Eocene or even late Eocene.