PROCEEDINGS
OF THE
USSHER SOCIETY

VOLUME TWO
PART THREE

Edited by
E. B. SELWOOD

REDRUTH, OCTOBER, 1970

PRICE: 7/6

THE USSHER SOCIETY

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The following paper was also read :

The Nag's Head landslip, Cullompton. By F. W. Sherrell.

CONFERENCE OF THE USSHER SOCIETY HELD AT BRISTOL, JANUARY, 1970

CHAIRMAN'S REPORT

The ninth Conference of the Society was held, by kind invitation of Professor D. L. Dineley, at Manor Hall, University of Bristol, on the 6th and 7th January. This year the invitation address on *Carboniferous faunas and palaeogeography in the South West England region* was given by Dr. W. H. C. Ramsbottom of the Institute of Geological Sciences. On Monday, 5th January, Professor Scott Simpson led an excursion to the Quantocks and the meeting ended on Thursday, 8th January, with Dr. Crosbie Matthews demonstrating some aspects of the Mendip region and Portishead.

Adverse weather and illness affected the meeting, with some 45 members attending, but even so a full program of papers was presented.

The 1971 Conference will be held at Hoopern House, Exeter, the District Office of the South-Western Unit of the Geological Survey of Great Britain, by kind invitation of the Director and the District Geologist, Mr. George Bisson.

W. R. Dearman, May, 1970.

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CARBONIFEROUS FAUNAS AND PALAEOGEOGRAPHY OF THE SOUTH WEST ENGLAND REGION

by W. H. C. Ramsbottom

Abstract. The main Dinantian lithologies, each with a distinctive fauna, are outlined, and a series of facies maps at successive levels in the Lower Carboniferous is presented. In the late Visean there appears to have been an eastern edge to the south-west England basin. A facies map of the Namurian is given together with some comments on various goniatite migrations into the region in the Namurian and Westphalian.

1. Introduction

Most of the factual knowledge about the Carboniferous faunas in Devon and Cornwall has been splendidly summarised by House and Selwood (1966), and it seems appropriate now to set this knowledge in a regional frame mainly from a palaeogeographical point of view. It need hardly be said that this is like trying to put together a jig-saw in which about 90% of the pieces are missing, but in spite of this (or perhaps because of this!) I hope to show that an integrated picture is emerging, and that events happening further north in the South Wales and Bristol districts often had their effects also in Cornwall and Devon. The area considered therefore includes not only South Wales and the Bristol district, but also a part of Southern Ireland where the recent researches of Naylor (1969, with references) have been most fruitful.

In considering the Carboniferous palaeogeography of the area it is necessary to make some attempt to remove the effects of the Hercynian earth movements. These comprise one or more extensive thrusts, and folding which is often more or less isoclinal. With regard to the main thrusting Waterschoot van der Gracht (1935) estimated the south to north movement in northern France as about 25 km. In Belgium, Fourmarier (1954 : 674) suggests that 25-30 km. is probably an underestimate. Bott and others (1958) estimated that in the Exmoor area the movement may have been about 14 km. In Ireland, R. T. Wingfield tells me that the main thrust near Killarney may have moved at least 25 km. There is some general agreement therefore in all these areas, and in the outline geographies used on the maps here presented the effects of

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these movements have been removed. Of course, apart from this main thrust zone (Fig. 1) there are in all areas numerous minor thrusts both to the north and south of it. South of the main thrust zone the folding is very marked and a figure of 20% shortening has been taken as the effect of such folding and distances on the maps adjusted accordingly. This figure may be too high or too low, but its affect is in any case rather slight. The resulting outline maps may not be very accurate, but these corrections do seem to be worth making. In Figure 6 the palinspastic geography of the Atlantic coasts has been based largely on Webb (1968).

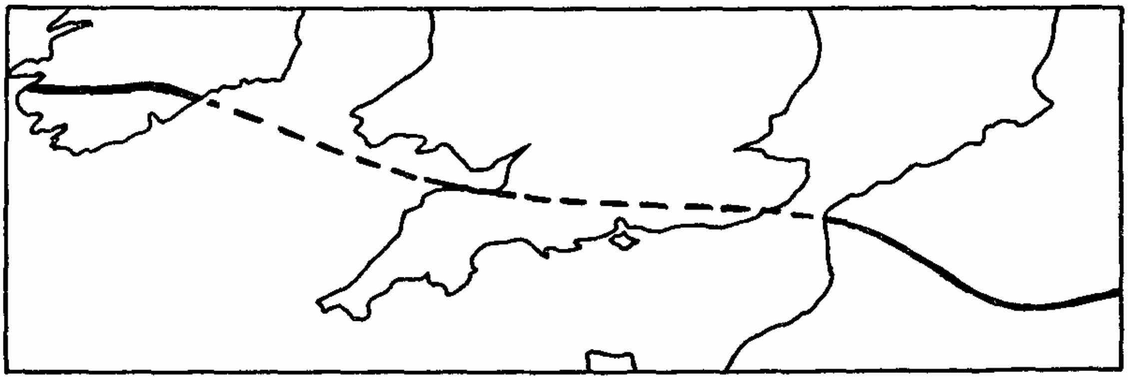

FIGURE 1. Course of the main Hercynian thrust zone of north-west Europe.

2. **Lower Carboniferous**

(a) Lithologies and faunas

The main rock types, each with its characteristic faunal association, are shown in the lower part of Figure 2, which represents an ideal sequence not always achieved. One or more steps in progressing away from a coast may be missing. Moreover the boundaries between facies are not always as sharp as the diagram suggests, and in constructing the facies maps (Figs. 2-3) a good deal of generalisation has been necessary. In some localities there are many variations of lithological (and hence faunal) type within quite small thicknesses, implying continually changing conditions. The facies boundaries interdigitate, but on the maps a line has had to be taken based on the predominating facies in each area. The maps can only be generalisations too, for another reason - the lack of reliable dating marker horizons in the Dinantian (in complete contrast to the Namurian and Westphalian), so that it is hardly yet possible to construct maps on any single individual time-plane.

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Green (*in* Green and Welch 1965 : 21-23) has given a useful summary of the limestone facies and their faunas, which is applicable to the whole South-West Province and it is unnecessary to repeat this here. The more shaly facies, however, require some further comments. The calcareous shale facies includes all shales (not always highly calcareous) containing a benthonic fauna. Sometimes, and this is often apparently on the shoreward edge of the facies, the shales become so calcareous as to be in fact limestones. These limestones, which are thicker-bedded, finer-grained and more shaly than the bioclastic dark limestones proper, are included here in the calcareous shale facies, though it might have been possible to have mapped them separately. The non-calcareous shale facies is characterised more by the lack of benthonic fossils than by the actual chemical composition of the shales.

In the South-West chert is commonly found in both the calcareous shale facies (when benthonic faunal elements will be present) and in the non-calcareous shale facies (when only goniatites and pectinoids, if any macrofossils, will occur). The predominance of chert in the region is presumed to be due to the abundance of silica derived from the local vulcanicity, with the consequent flourishing of radiolaria, and the distance from any shore line, which meant that not much sediment was reaching the areas of silica deposition. Another factor which may have affected the absence of macrofossils in some of the cherts is the solution of calcite at depth, leaving only the siliceous fossils preserved, a suggestion made to me by Professor M. R. House.

(b) Zonation

It has for many years been clear that Vaughan's zonal scheme has many imperfections especially at around the Tournaisian/ Viséan boundary. It is known for example that undoubted Viséan fossils such as *Michelinia megastoma* (see Reynolds 1921: 224 as *M. grandis), Palaeosmilia murchisoni* (see George 1933: 238 as *Yalaeosmilia* Φ), and *Levitusia humerosa* (see Mitchell 1969: 97) occur in the Gully or *Caninia* Oolite, lying within Vaughan's C_1 zone which is commonly regarded as being of Tournaisian age. The situation has arisen in which different meanings have been applied to C_1 and C_2 in the North of England and the South of England.

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For the purposes of this paper a different scheme, devised in collaboration with M. Mitchell, has been adopted, though the detailed reasoning behind this approach and the requisite definitions will appear elsewhere. The Lower Carboniferous is divided into seven zones, intended as chronozones, Zone 1(at the base) to Zone 3 being of Tournaisian age, Zone 4 to Zone 7 (at the top) being of Viséan age. For present purposes the following are the approximate equivalents.

Zone	7	D_2 and P_1, P_2
	6	D_1 and B_2
	5	S_2 and B_1
	4	Upper part C_1, and C_2S_1 (base at base of Visean as defined in Belgium)
	3	Lower part of C_1
	2	Z
	1	K (base at base of Carboniferous on Heerlen definition)

In Devon and Cornwall accurate dating even into these broad divisions often presents a problem, but since there is rarely, if ever, any evidence of actual non-sequence in spite of the extreme thinness of some sequences, a reasonable estimate of facies at any place and time can usually be made.

(i) *Zone 1.* The Lower Limestone Shale of the Bristol district and South Wales is largely of calcareous shale facies, but a considerable amount of limestone is developed and the different types have the distribution shown. In south Cornwall and around Chudleigh, the facies appears to be that of the non-calcareous shales with cherts developed near Winstow and in the Teign valley. The calcareous shale facies is represented by the Yeolmbridge Beds near Launceston, California Quarry with its fauna of trilobites and other benthonic fossils (Selwood 1961), the Wilsey Down borehole, and the Pilton Beds further north. In southern Ireland there is not sufficient evidence for reliable correlation and this area has been omitted from the map.

(ii) *Zone 2.* In Cornwall and Devon conditions seem to be essentially similar to Zone 1, except that the non-calcareous shales are found around Boscastle indicating a slight northward movement

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of this fades in that area. Further north the Tournaisian transgression, which eventually covered most of Southern England at least as far as Cambridge', caused a general deepening of water with consequent movement of the fades belts to the north. Noncalcareous shale fades reappears in Ireland, where there was also a brief influx of sandstone from the western landmass at this time.

No separate map is given for zone 3 when conditions were generally similar to zone 2.

(iii) *Zone 4.* The area with non-calcareous shale fades has now further extended from south Cornwall, and cherts are still developed at Launceston, Okehampton and Chudleigh. The calcareous shale fades has been taken to include the Lower Westleigh Limestone and the Lower Codden Hill Cherts, and this onset of limestone deposition seems to be connected with the clear evidence from further north than the fades belts have moved southwards, and there is a large area of calcite mudstone fades in South Wales. The Irish area also shows evidence of this regression, for calcareous shale fades has replaced non-calcareous shale fades in south Co. Cork. Reef development began both around Cork and in south Pembrokeshire. This may be regarded as evidence, since reefs commonly develop on the edges of basins (Ramsbottom 1969a) that deep water lay not far to the south of those areas. Reef development in the Bristol region is unlikely since there is no evidence of a big development of deep water to the south. What may be the southern edge of the basin of deposition at this time is seen in north-west France around Montmartin-sur-Mer where a shoreline facies is indicated by the presence of much oolite (Sainsaulieu 1962).

In late Zone 4, following the earth movements constituting the ‘mid-Avonian break’ (which gave evidence in the development of *Modiolus* Phase calcite mudstones of extreme, though temporary, shallowing) there was a more or less general shallowing of the sea and also the first incoming of sandstone from the North in the

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[1] Evidence from the fauna found in the Cambridge and Gayton boreholes (Ramsbottom 1969b) suggests that these places were to the south of any Wales - Brabant island rather than to the north of it as recently stated by Kent (1968 :81).

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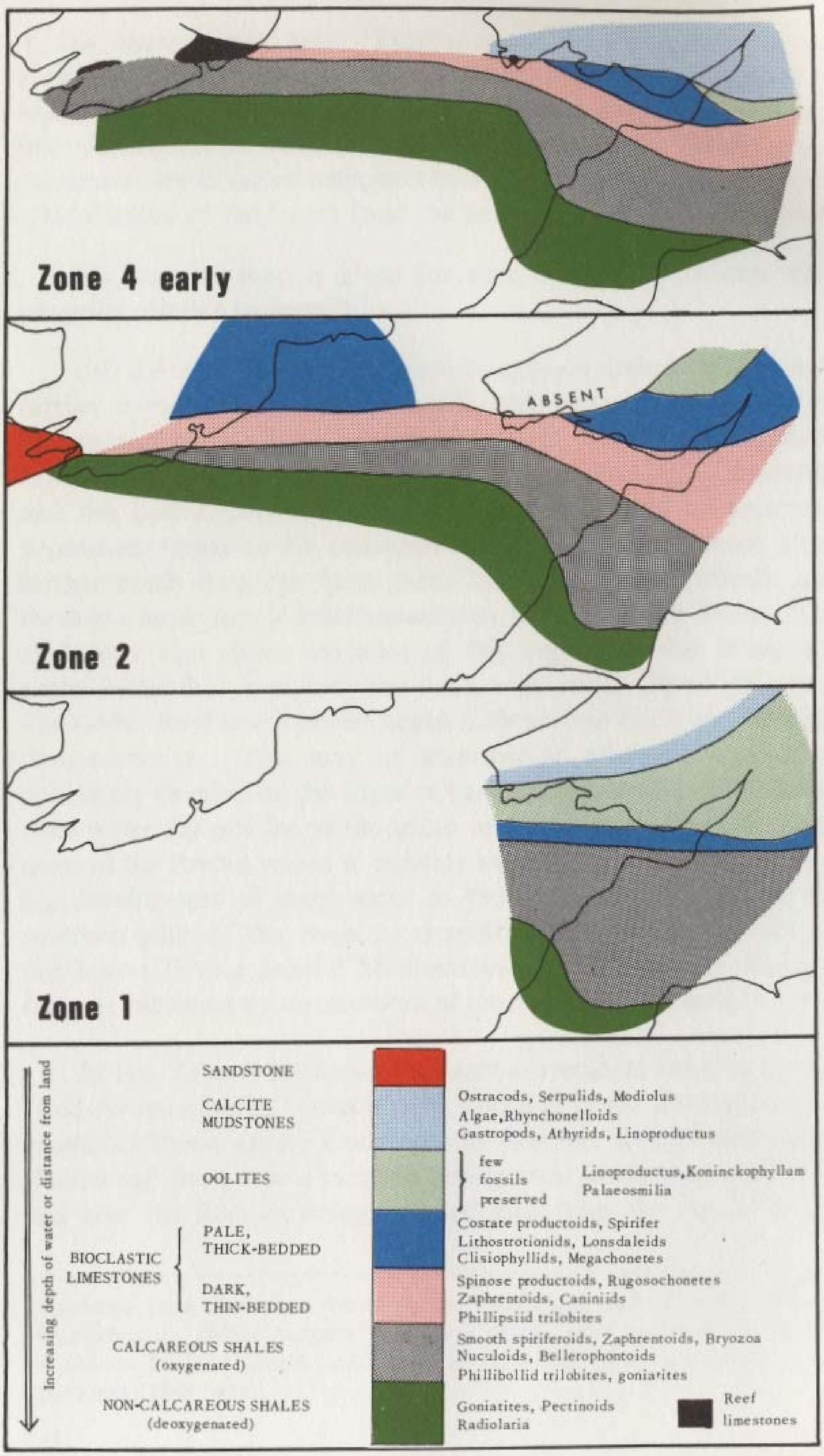

Figure 2

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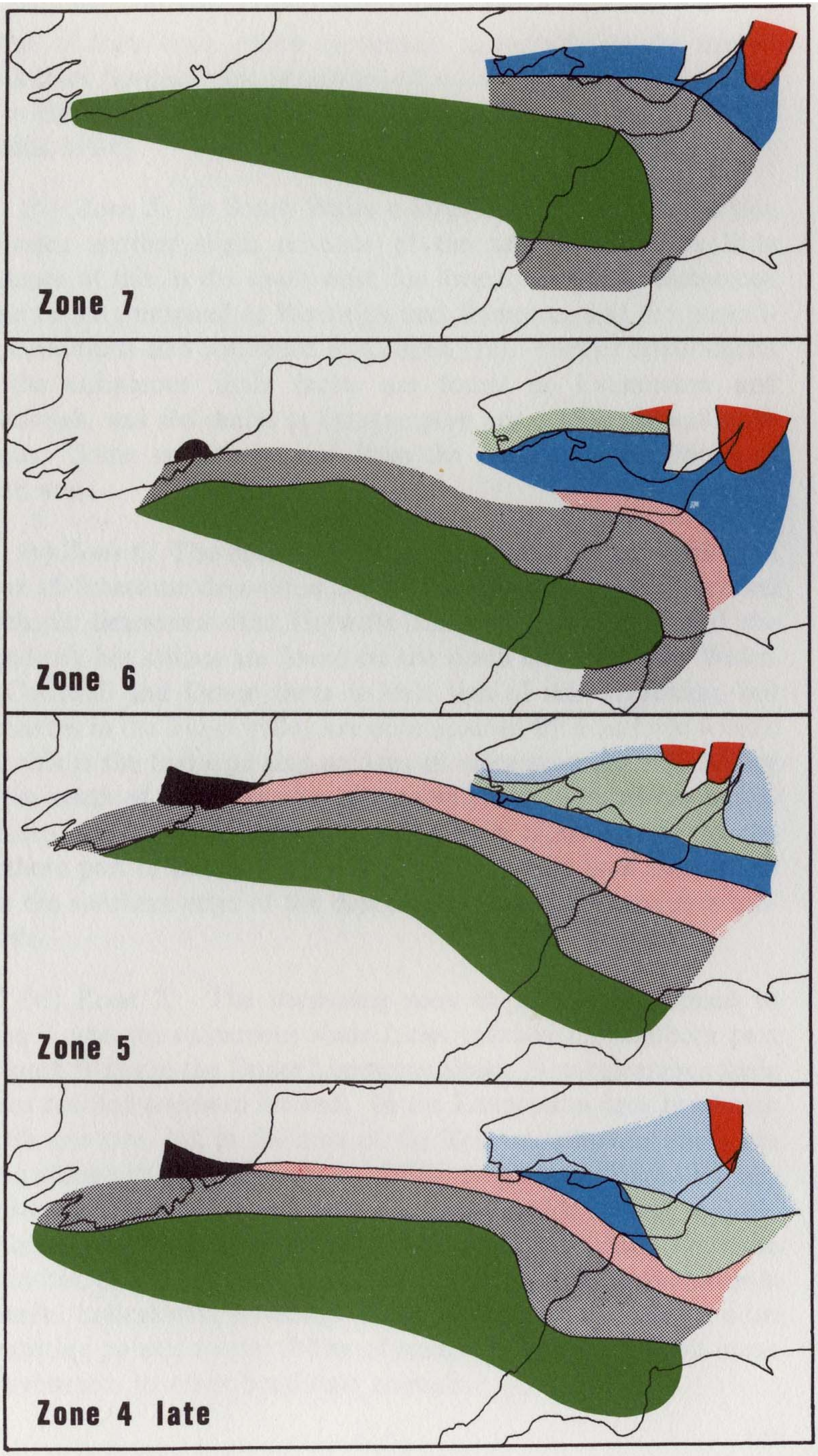

Figure 3

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Forest of Dean area. Such movement, apparently on the line of the Lower Severn Axis, is connected with the great development of oolite which reached as far south-west as Cannington Park (Wallis 1924).

(iv) *Zone 5.* In South Wales a large area of oolite deposition indicates another slight advance of the sea, but there is little evidence of this in the south-west, for limestones of the calcareous shale facies continued at Westleigh and Bampton, and the prevailing conditions also continued at Codden Hill. Further south cherts of the calcareous shale facies are found at Launceston and Chudleigh, and the shales at Okehampton are apparently unfossiliferous. Some sandstone came from the north into the Forest of Dean area.

(v) *Zone 6.* The base of this zone is commonly well marked in areas of limestone deposition by the development of thick-bedded bioclastic limestones (the Hotwells Limestone of Bristol and the Mendips), but oolites are found on the north crop in South Wales. **In** Cornwall and Devon there is little sign of this deepening, but goniatites in the Teign valley are accompanied by benthonic fossils, and this is the first sign that an area of calcareous shale facies lay to the south of the main non-calcareous shale facies of the south-western area. There seems to have been a shallowing of the southern part of this district - the first of several later indications that the southern edge of the depositional area was moving northwards.

(vi) *Zone 7.* The deepening seen in Zone 6 continued in Zone 7, and the calcareous shale facies reached the southern part of South Wales as the Upper Limestone Shale. Non-calcareous shale facies reached southern Ireland. In the Launceston area benthonic fossils are rare, but in the area of the Teignmouth sheet there are three distinct faunal associations. In the north (and around Exeter) goniatites are found alone (non-calcareous shale facies), a little further south Phillibolid trilobites are found associated with the goniatites, and still further south brachiopods join the fauna. This is a useful indicator of a change in facies southwards, and also an interesting pointer to the ability of some trilobites to inhabit areas unfavourable to other benthonic animals.

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(c) General

These facies maps contain, as is evident, a good deal of subjective interpretation and interpolation, especially in those parts for which there is no evidence. This form of prediction about unknown areas is a justifiable, though hardly a safe, geological activity. For example, should the Carboniferous beds presumed to underlie the Devonian in the North Quantocks ever be drilled the maps will provide a guide as to what might be expected at each level. But it is perhaps fortunate that the forecasts of geologists are not found out quite as quickly as those of meteorologists.

3. Namurian

(a) Lithology and faunas

Although the truly littoral limestone facies are rare in the Namurian, there are a few such occurrences of limestone, now usually reduced to rottenstone, known in South Wales, especially in the Kidwelly district (Archer 1968:13-15). They are also known to the north of the Wales - Brabant Island in Lincolnshire (Ramsbottom 1969:225). More usually, south of this island, the rocks consist of mudstones of various shades of grey, and the faunal changes on approach to a coastline are shown in Figure 4A. Again the facies tend to merge into one another, but are on the whole very distinctive.

(b) Bristol district

A special facies comprising mainly quartzitic sandstones with occasional more shaly layers occupies the discrete basins in the Bristol and probably also the Chepstow areas. The sediments came from the north, from an area of erosion of Old Red Sandstone (Dearnley *in* Kellaway 1967:129). The Bristol basin was delineated on the north-west by the Lower Severn Axis (Namurian is absent just north of Nailsea), and on the north-east by the Bath Axis (Namurian is absent in boreholes at Luckham and Westbury on Trym). In the centre of the basin, between Bristol and Wick the Namurian is about 600 feet thick. To the south on the Mendips it thins to 150-175 feet (Green and Welch 1965). It is known that the Mendip Axis was active in Dinantian times as shown by isopachs (Green and Welch 1965: 16). It seems possible, though there is no direct evidence, that the Namurian dies away almost completely

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not far south of the Mendip Axis, and it seems likely that contemporary movement along one of the east-west folds south of the Mendips confined the Bristol basin on its south side.

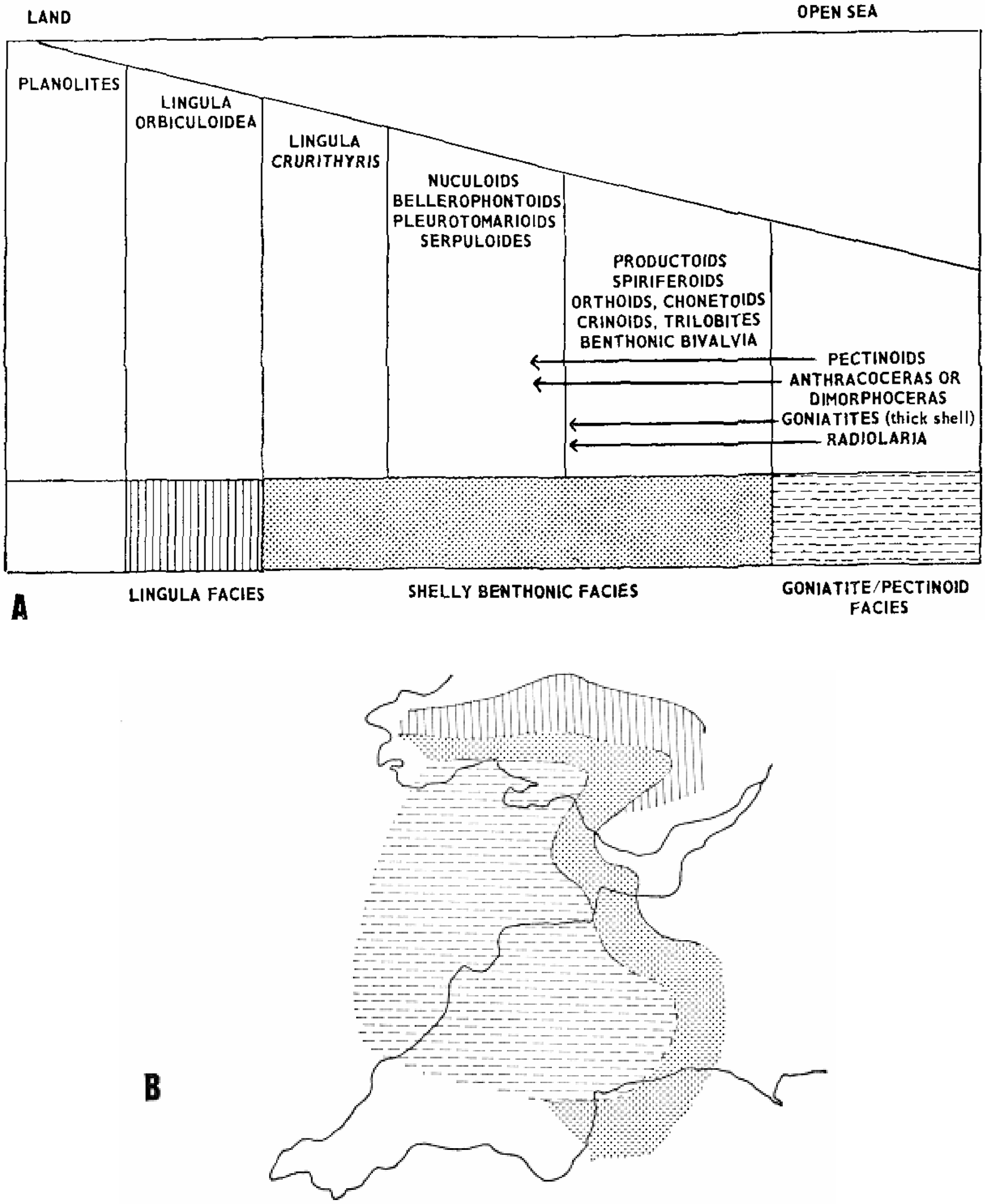

FIGURE 4. A. Facies and faunal changes on approach to a shoreline in the Namurian. B. Generalised facies map of Namurian of the South West England region. The 'shelly benthonic facies' of the Namurian corresponds to the 'calcareous shale facies' of the Dinantian, and the 'goniatite/ pectinoid facies' of the Namurian is equivalent to the 'non-calcareous shale facies' of the Dinantian.

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Confined it appears to have been, for the typical Namurian marine faunas did not enter the district (except at the extreme base). Other evidence such as the presumed absence or thinness of Westphalian south of the Mendips (Brooks *in* Green and Welch 1965: 155) also suggests a separation, by shallow waters or by land of the Bristol and Devonshire Namurian.

It is worth noting that sandstones derived from the Wales - Brabant Island are reduced in thickness in the upper part of the Bristol sequence, above the supposed top of $E_{Z\ i}$, at the 'plant break' of Kellaway (1967). This is confirmation of the low-lying nature of this island in the upper Namurian (Ramsbottom 1969: 226, 228). The Chepstow basin, about which little is known, appears to be similar to the Bristol basin, and was confined to the north-west by the Usk Axis.

(c) Cornwall and Devon

Researches by the Institute of Geological Sciences since 1963 in the Okehampton, Holsworthy, and Boscastle sheets have revealed many goniatite occurrences in the Namurian. The goniatites often occur at the bases of beds of thin turbiditic sandstones possibly in the manner of shell pavements of Kuenen (1964). Although the tectonics are complicated, the distribution of goniatites indicates a general younging northwards of the rocks in the main outcrop between the Boscastle coast and Exeter and a map (Fig. 5) can now

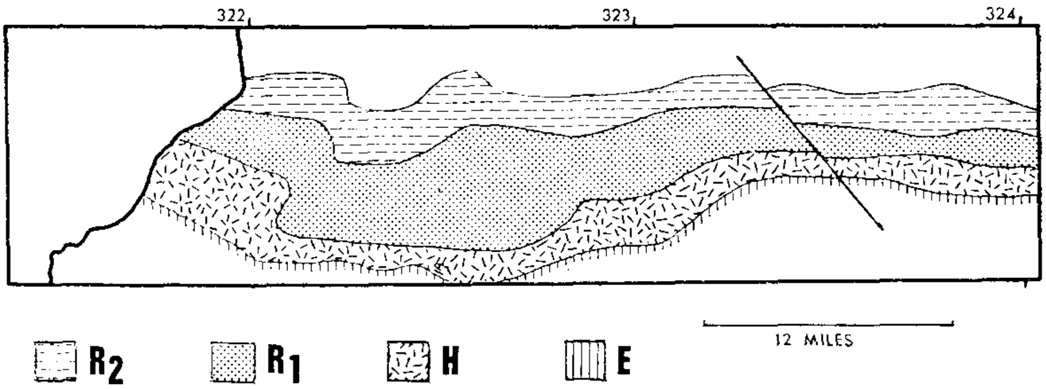

FIGURE 5. Sketch map of the Namurian stages in the main outcrop of the Namurian rocks in the Boscastle, Holsworthy and Okehampton Geological Survey sheets. This map, although agreeing with the available evidence probably provides an oversimplified view of what actually occurs.

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be constructed of the distribution of the main Namurian goniatite stages. Deposition was slight up to E_2, but in H and above the incoming of turbidite sandstones makes the succession thick. Further north, around Barnstaple, the turbitites did not arrive until R_2 times.

The goniatite succession is normally identical to that in northern England, and it would appear that the only thing preventing really detailed structural analysis by means of goniatites is the lack of exposure inland. More work on these lines could certainly be done along the coast.

(d) *Facies distribution*

All the Namurian faunas in the area so far studied by I.G.S. belong to the goniatite - pectinoid phase (with virtually no benthonic fossils), and the same is true of the records in the northern outcrop near Barnstaple. The only significant record of benthonic fossils in Devon is the occurrence of a trilobite in E or H beds at Chudleigh (House, unpublished), and this is the only evidence that the southern side of the basin of deposition is approached. In west Somerset spiriferoid brachiopods have been recorded (Thomas *in* House and Selwood 1966: 75) in the Bampton area in E_2, and this seems to indicate an easterly edge to the basin. The general facies distribution suggested (Fig. 4B) allows for the discreteness of the Bristol and Chepstow basins and for evidence in South Wales previously published (Ramsbottom 1969:227), but for lack of information this is a generalised and not a detailed map on a time plane. In general it shows that the deepening, already noted towards the close of the Visean, continued.

4. Westphalian

The distribution of marine fossils in the south western area has already been given by Calver (1969). It shows a continuation of the Namurian story except that the various structural axes had less effect. The only comment required here is that the general advance towards the north of the base of the Pennant sandstones (already recorded in South Wales by Woodland and others 1957: 8), from Somerset into Bristol and the Oxford region (Kellaway *in* Poole 1969:29) had engulfed the Somerset district by the time of the *Anthracoceras cambriense* Marine Band (cf. Calver 1969, fig. 14).

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5. General

Although in the early part of the Carboniferous it is highly likely that the sea covered all of southern England and provided free passage between south-west England and northern France and Belgium, this passage may well have been interrupted in the Upper Carboniferous (or even probably, a little earlier as is evidenced by the apparent eastern edge to the late Visean basin). There is no direct evidence on this point since none of the boreholes in central southern England has reached Carboniferous rocks. But it seems likely that there was uplift in early Namurian in north-west France and parts of the English Channel area including Kent, and that this uplift provided the sediments which reached south-west England from late E_2 times. The basin seems to have been filled, mainly from southern or south-eastern sources, at progressively later horizons on passing northwards, culminating in the northward advance of the Pennant already mentioned. It may well not be a coincidence that the influx of sediment into south-west England corresponds to a general diminution of sedimentation further north off the coasts of the north-western continent, as in Scotland, Northern England, and large parts of North America (but not in western Ireland) at about the same time (Ramsbottom 1969:231).

6. Goniatite distribution

In the Upper Carboniferous of the west European region there were two main faunal provinces - those of north-west Europe and the Mediterranean. Reasons have been given elsewhere (Ramsbottom 1970) for supposing that the main British early Namurian goniatite fauna came to us from the East, via Poland. In south-west England only one Namurian fauna is alien to that from the rest of Britain. Near Drewsteignton a fauna has been recorded (Ramsbottom *in* Edmonds and others 1968:22) which includes probable *Delepinoceras* and other fossils of E_2 age, and is considered to have come from northern Spain.

Higher in the sequence, at the horizon of the Margam Marine Band (Westphalian A) at Sandimouth 2 miles north of Bude and at nearby localities in Devon and also in South Wales, and the Bristol district, there is another goniatite *(Anthracoceratoides cornubiensis)* different from anything known elsewhere in Britain,

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and which is most closely related to a form from America (Ramsbottom 1970a). Still higher in horizon there is another influx of American species known in the Cefn Coed Marine band in South Wales (Ramsbottom 1952) and some of these forms have also been found in the Bristol district. Some goniatites known only in Scotland and Cumberland at the same level and recorded by Currie also represent this same influx. These various migrations and some others are shown in Fig. 6.

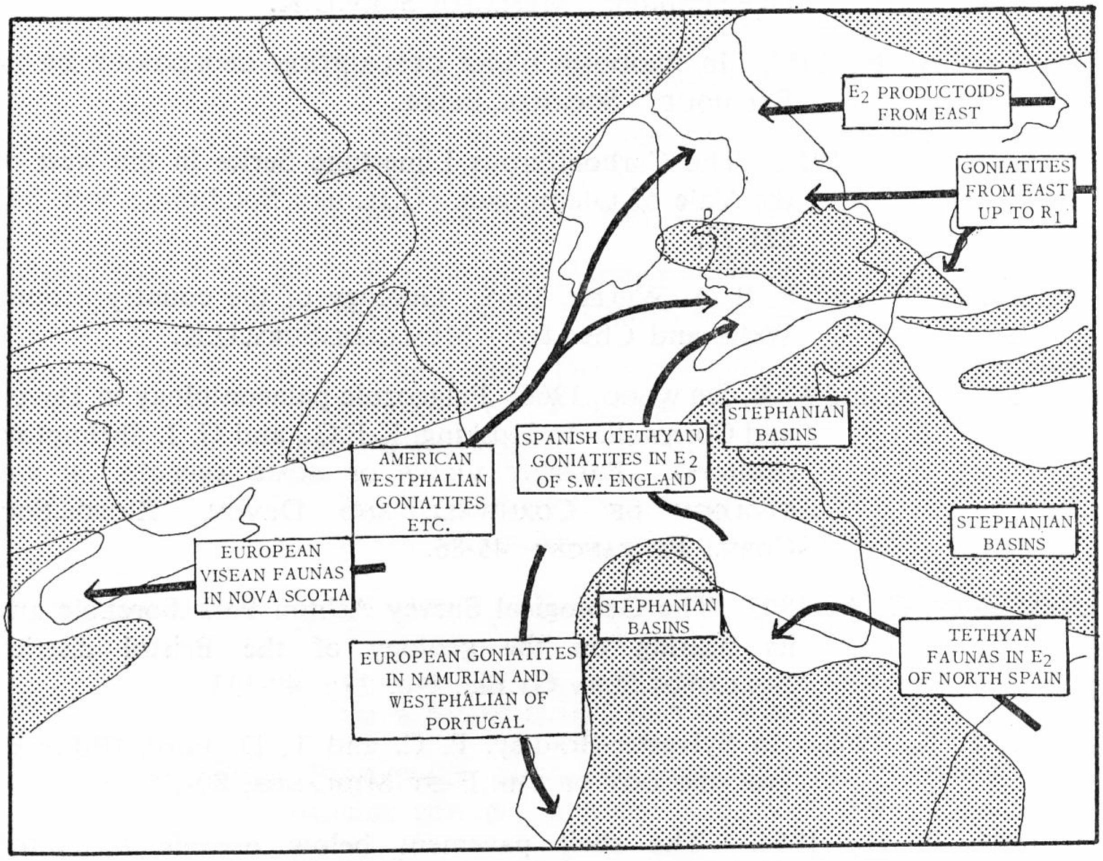

FIGURE 6. Carboniferous faunal migrations.

ACKNOWLEDGMENTS. I am grateful to my colleague Murray Mitchell for many helpful comments and discussions, and I thank Professor Claude Pareyn and Madam A. Pelhate for assistance with French localities, and Professor Michael House for unpublished information about the Chudleigh area.

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Stratigraphy of the Ilfracombe Beds of the North Devon coast (Abstract) : by K. Jeffery.

The Combe Martin-Ilfracombe area has been mapped on a 1:2500 scale as a preliminary to a study of deformation and its relation to geological structures.

An interim succession has been proposed for the Upper Ilfracombe Beds on the basis of eight alternating slaty and sandy units, which vary from 5 to 25 m in thickness. The succession of the Middle Ilfracombe Beds proposed by earlier workers has been confirmed.

The Combe Martin Valley Fault cuts the outcrop of the Lower Ilfracombe Beds into an eastern and a western outcrop. The base of the western outcrop is below sea level, and the top of the eastern outcrop is concealed inland. The general correlation of the two outcrops made by earlier workers, has been refined by detailed measurements of stratigraphic successions. It has been calculated that, in the eastern outcrop, the uppermost 35 m of the Lower Ilfracombe Beds are not exposed.

The origin of calcareous nodules in Upper Devonian Slate near Newton Abbot (Abstract) : by B. W. Riddolls.

Famennian slate with calcareous nodules, containing conodonts of the *Palmatolepis quadrantinodosa* and *Scaphignathus velifera* Zones, is present in core from the I.G.S. borehole at Rydon Ball Farm, Newton Abbot. The nodules may be compared with the *Knollenkalk* of the German Devonian, which is thought to be primarily the product of diagenesis in unconsolidated sediment. Tectonic processes are subordinate in the formation of *Knollenkalk* and appear entirely responsible for the formation of the nodules in this Newton Abbot occurrence.

The nodular slates occur in the borehole at depths from 93 m to 108 m. The upper parts of this section of core are characterised by thin alternating layers of grey slate and fine-grained limestone.

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Other sections of the core suggest that the nodules were formed by the disruption of similar interbedded limestone and slate through the effects of folding and cleavage.

Nodular slates are commonly considered to be transitional between shallow and deep water deposits. The suggested tectonic origin of some nodules indicates that such interpretations should be approached cautiously.

This contribution has been approved for publication by the Director of the Institute of Geological Sciences.

Conodonts from the Upper Devonian of the Saltern Cove-Elberry Cove area (Abstract) : by M. E. Tucker and P. van Straaten.

Conodonts have been obtained from several red micritic limestone bands and blocks associated with the shales and tuff succession about the classic Saltern Cove goniatite bed. Blocks in, and immediately to the south of the goniatite bed, blocks within the limestone conglomerate, and in the first limestone band to the north of this conglomerate, have yielded conodonts of lower *quadrantinodosa* zone (to IIβ) together with older Givetian conodonts in the conglomerate. Conodonts include : *Palmatolepis distorta* Branson & Mehl, *Palrnatolepis glabra elongata* Holmes, *Palmatolepis glabra pectinata* Ziegler, *Palmatolepis quadrantinodosa inflexoidea* Ziegler and *Palmatolepis quadrantinodosa marginifera* Ziegler.

The goniatites indicate an Upper Frasnian age (to Iδ) (House 1963). This surprising occurrence of Upper Frasnian goniatites with upper *Cheiloceras* zone conodonts could be due to 1). tectonic complications, 2). miscorrelation of the ammonoid and conodont chronologies when applied to south-west England or 3). to re-working of the goniatites and conodonts. Other work suggests that the first two possibilities are unlikely; it is thus tentatively suggested that the goniatites (and probably other elements of the main fauna) are derived.

To the east of Elberry Cove, conodonts show that only the Frasnian is represented, up to lower *triangularis* zone (to Iδ), slightly younger than House (1963) obtained from goniatites below.

(Samples are preserved in the Dept. of Geology, University of Reading)

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CONODONTS AND FACIES ON THE CHUDLEIGH SCHWELLE

by M. E. Tucker and P. van Straaten

Abstract. Age determinations from the Chudleigh area S. Devon are presented, which show that the Kiln Wood Beds are equivalent in age to the Lower Dunscombe Goniatite Bed. The Kiln Wood Beds are interpreted as being deposits of a local deeper part of the Chudleigh Schwelle. Conodonts and facies are also considered for the lower part of the Mount Pleasant Series (Lower Famennian).

1. Introduction

For a consideration of facies changes, accurate dating is essential, and we are fortunate in the Upper Devonian that exact correlations can be made through conodonts, which are very common at this time. Good conodont faunas have been collected from Kiln Wood Quarry (SX 861779), the section in the road running past the quarry, and from the track leading to Winstow Cottages (Fig. 1). Other conodonts have been obtained from outcrops above Palace Quarry in the Riding Parks (SX 869787), and from the old quarry at Lower Dunscombe Farm (SX 886791).

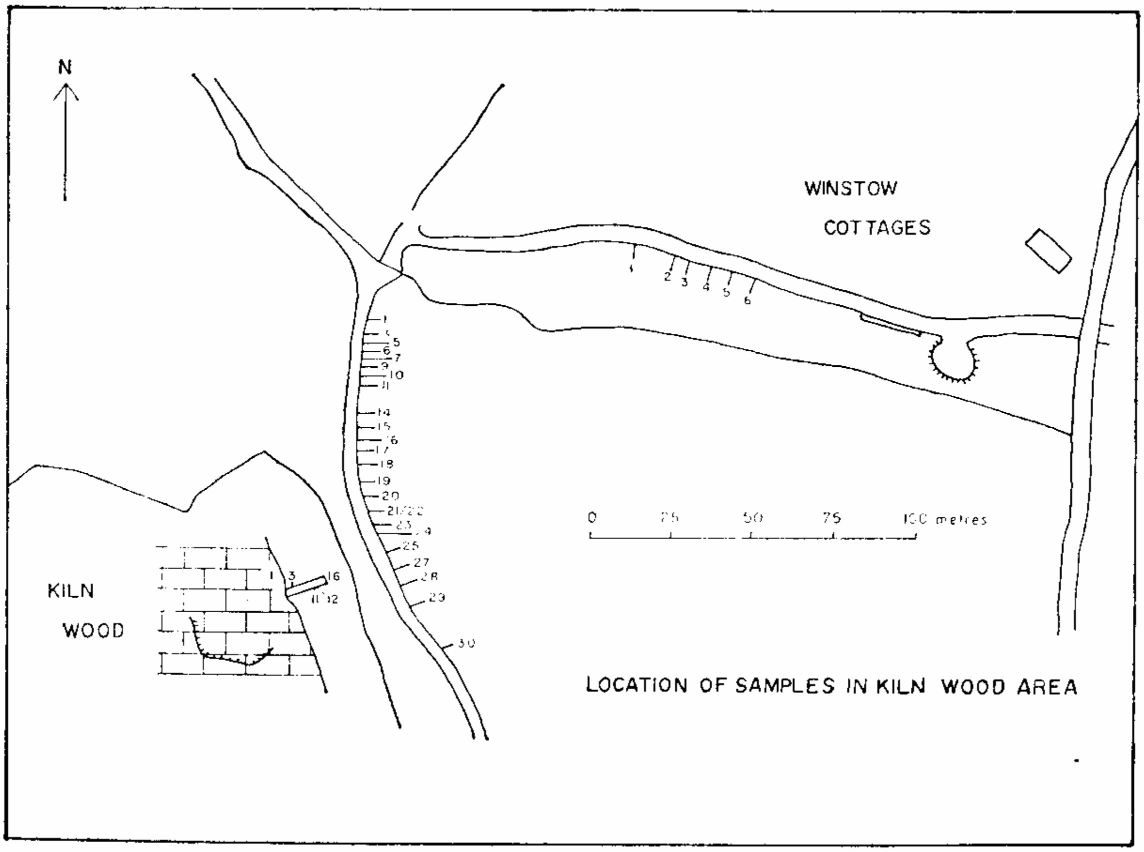

FIGURE 1. Map showing location of conodont samples in the Kiln Wood area, Chudleigh, South Devon.

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A continuous but much reduced Upper Devonian sequence (House and Butcher 1962) of nodular limestones and shales occurs in the Chudleigh area on top of massive limestone, which is in part Frasnian in age. The thickness given for the Famennian is 53 m and it has been termed the Mount Pleasant Series by House (1963). House has described the ammonoid succession in the Chudleigh district and shown that all the German ammonoid *Stufen* are present, and that many of the species zones can be recognised too. House also shows that the Mount Pleasant Series is of *Schwellen* type (Schmidt 1926), that is a succession of condensed limestones, nodular limestones and shales with calcareous nodules thought to have been deposited on a submarine rise. In the Chudleigh case, the *Schwellen* sediments occur above Middle and lower Upper Devonian coral/ stromatoporoid limestones. In contrast to the

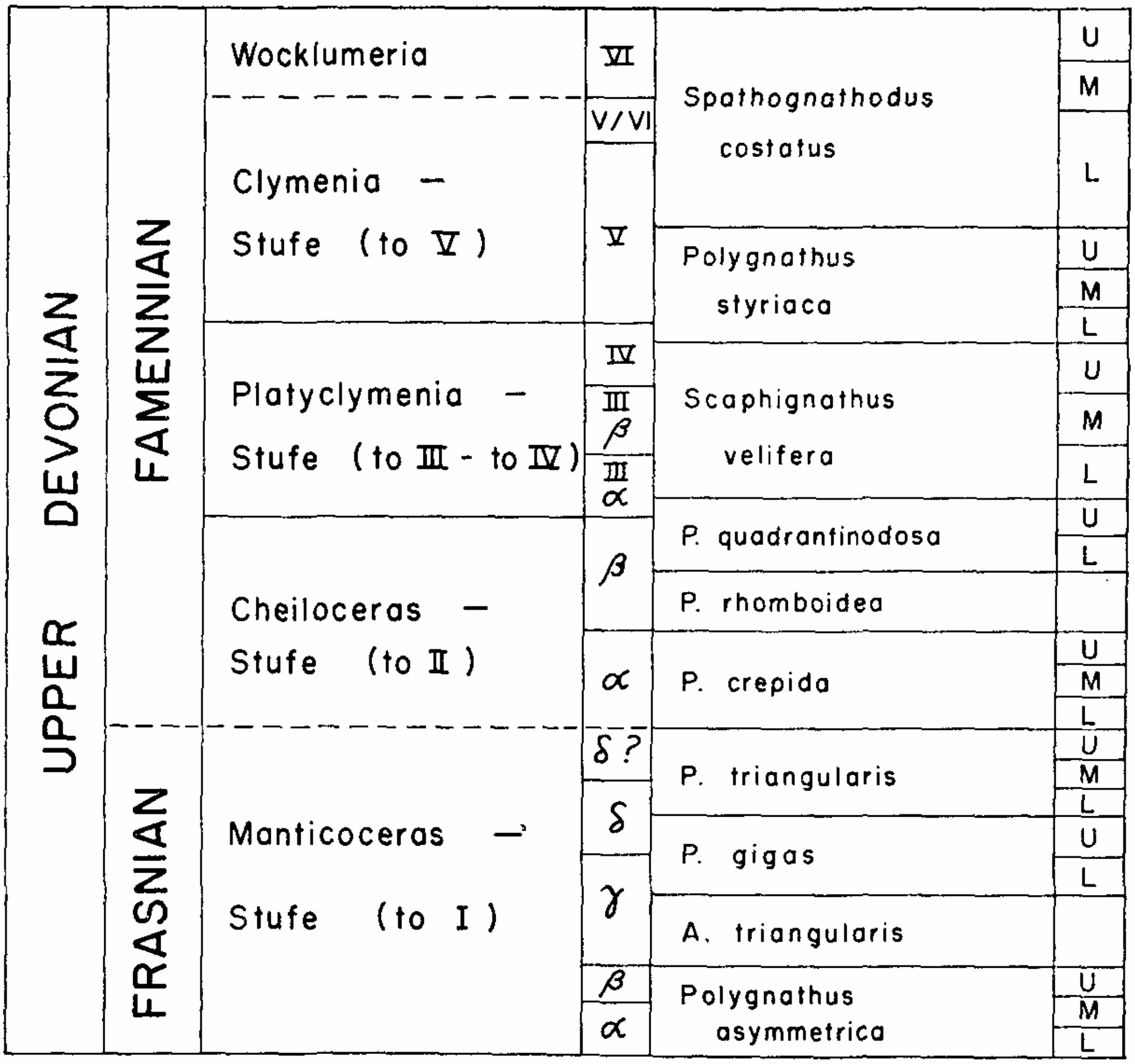

FIGURE 2. Chart showing correlation of ammonoid *Stufen* and conodont zones for the Upper Devonian (after Klapper 1966). "P." is abbreviation for *Palmatolepis*.

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Schwellen facies, *Becken* sediments consist of ostracod shales sometimes with volcanic horizons and turbidites, and were deposited in deeper water (basinal) areas. These are also present in South Devon and occur in the Newton Abbot and Torquay districts (House and Selwood 1964). Scrutton (1969) has shown that the coral faunas in the early Frasnian massive limestone indicate a gradually deepening environment. This trend continues throughout the rest of the Upper Devonian.

In this paper the conodont zonation of Ziegler and others for the Upper Devonian is used, and a full list of the references employed in the determinations is appended. Conodont zones and their relation to Upper Devonian orthochronology is shown in Figure 2.

2. Conodonts and Facies

Conodonts show that the Kiln Wood Beds (Goldring et al. 1967, fig. 4) of Middle/Upper Frasnian, are equivalent in age to the Lower Dunscombe Goniatite Bed, which contains (House 1963) the zone fossil *Manticoceras cordatum.* These two units both occur above massive limestone but are very different lithologically. They represent deposition in quite different environments, though both related to *a Schwelle.* In the field, the two facies occur only 1 ½ km apart, though there is probably some horizontal movement between the quite incompetent Kiln Wood Beds and the underlying massive limestone.

The nodular limestones of the Lower Dunscombe Goniatite Bed (1.7 m thick) are typical *Schwellen* carbonates, greyish-pink micritic limestones with many pressure solution planes and very thin irregular shaly horizons. These sediments yield a rich and varied fauna of goniatites, brachiopods, trilobites, rare corals *(Syringaxon* sp., identified by Dr. C. T. Scrutton) and bivalves including *Buchiola* sp. The dominantly pelagic fauna and restricted benthos suggests deposition at greater depth than in the case of the underlying limestone. There is evidence of small-scale sedimentary dyke formation. Dyke fillings consist of a coarse grained red carbonate containing crinoids.

Conodonts obtained at Dunscombe Farm show that the massive limestone (sample 1) below the goniatite bed is also Middle Frasnian in age (Table 1). Sample 4 from the top of the goniatite limestone shows that the upper *gigas* conodont zone is present, which is equivalent to the lower part of the *holzapfeli* goniatite zone of Upper Frasnian age (to Iδ).

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TABLE 1. Conodonts from Lower Dunscombe Farm and Kiln Wood Quarry. Location of samples for Kiln Wood shown in Figs. 1 and 2. For Dunscombe Farm, samples 0 and 1 from bottom and top of massive limestone respectively. Samples 2, 3 and 4 from the goniatite limestone. Sample 4, 15 cm from top of quarry. (o=cf. determination).

Age of samples

Lower Dunscombe Farm

Sample 0: middle *asymmetrica* to lowermost *gigas* zone. 1: upper *asymmetrica* to lowermost *gigas* zone. 2: lowermost part of upper *gigas* zone. 3: lower part of upper *gigas* zone. 4: upper part of upper *gigas* zone.

Kiln Wood Quarry

Sample 1: as sample 1, Dunscombe Farm. 3: as sample 1, Dunscombe Farm. 11: *Ancyrognathus triangularis* to lowermost upper *gigas* zone. 12: lower to lower upper *gigas* zone. 16: *crepida* zone.

	Dunscombe					Kiln Wood				
	0	1	2	3	4	1	3	11	12	16
Ancyrodella curvata		x	x	x	x	x	x	x	x	
A. gigas		x					x			
A. ioides									x	
A. lobata	x					o				
A. nodosa							x		x	
Ancyrodella sp. indet. . . .					x					
Ancyrognathus asymmetrica .			x	x	x		o			
A. triangularis			x	o				x	x	
Icriodus symmetricus . . .			x						x	
Icriodus sp. indet.	x	x		x	x	x	x			
Palmatolepis crepida linquiformis					x					
P. gigas				x					x	
P. hassi								x		
P. minuta minuta										x
P. punctata	x	x				x	x			
P. punctata var. transitans .							x			
P. quadrantinodosalobata . .										x
P. subrecta				x	x		x	x	x	
P. tenuipunctata										x
P. unicornis					x				o	
Palmatolepis sp. indet. . . .			x							
Polygnathus sp. indet. . . .	x				x	x	x		x	

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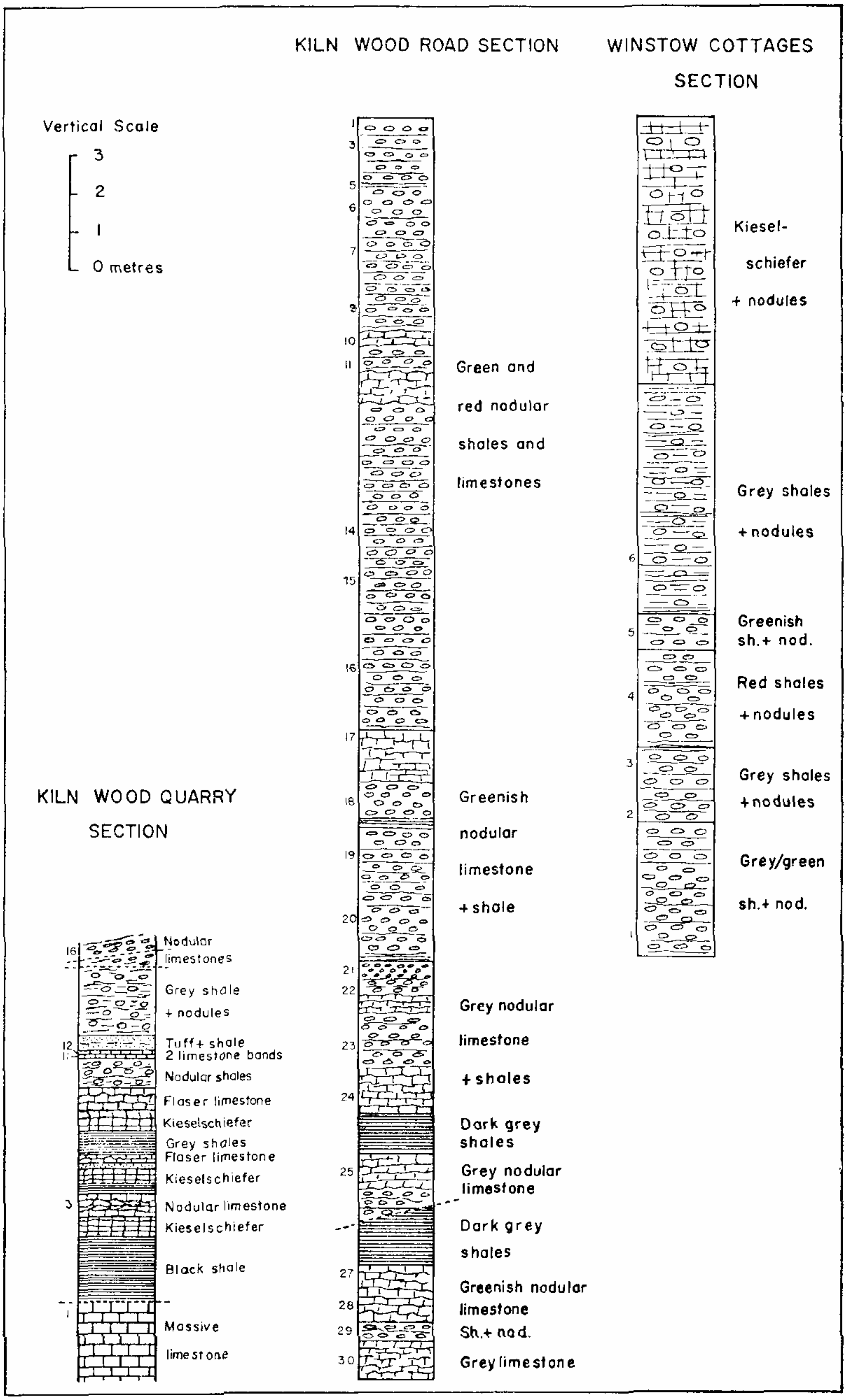

FIGURE 3. Upper Devonian succession in the Kiln Wood area, Chudleigh.

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The Kiln Wood Beds (9 m thick) exposed in Kiln Wood Quarry consist of black and dark grey micaceous shales which contain siliceous horizons *(Kieselschiefer)* and three flaser limestones (Fig. 3). A flaser limestone is a relatively pure (85-95% calcium carbonate) sometimes nodular limestone containing irregular streaks or 'veins' of clay material at all angles to the bedding (*Flaserkalk* of Grundel and Rosler 1963). The dark shales containing pyritised fossils indicate deeper water sedimentation of pelagic material under anaerobic conditions. The flaser limestones, which have been partly silicified, contain many small bivalves, mostly disarticulated, and crinoid ossicles, probably brought in by bottom currents. Fixosessile arenaceous foraminifera occasionally occur attached to the lamellibranch valves and attest to the presence of aerated bottom waters. Two tuff horizons are also developed. Conodonts show that most of the Kiln Wood Quarry succession is Middle Frasnian, including the top of the massive limestone (Table 1). At the top of this section the grey nodular limestone (sample 16) is not *in situ;* conodonts give a *crepida* age (to IIα).

It is suggested that the Kiln Wood Beds represent deposition in a localised deeper part of the *Schwelle.* Similar 'special basins' occur along the Diabas-Schwelle in the Oberharz, Germany (Straaten 1969). Here, sediments traditionally regarded as basinal, occur with shallower water *Schwellen* limestones in local depressions on the volcanic rise. Local areas of lower relief were sites of accumulation of fine grained terrigenous material, though periods of higher and more widespread carbonate precipitation over the *Schwelle* gave rise to flaser limestones in the special basin succession. In the Chudleigh area, tectonics and lack of exposure do not permit an elucidation of the shape of the basin.

In the road running past Kiln Wood Quarry, there is a continuous outcrop for 150 m of Famennian nodular limestones and shales, belonging to the Mount Pleasant Series. This *Kalkknollenschiefer* succession dips and youngs north. The conodonts obtained belong to the *Cheiloceras Stufe* (to II), conodont zones *crepida, rhomboidea* and the lower part of the *quadrantinodosa* zone (Table 2). Rocks of this age and lithology also crop out in the Riding Parks above Palace Quarry, 1 km north-east of Kiln Wood, and yielded conodonts of the *crepida* zone. The conodonts from this nodular limestone group agree with ages obtained from ammonoids by Prof. M. R. House.

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TABLE 2. Conodonts from the Kiln Wood road section. Location of samples shown in Figs. 1 and 2.

Age of samples

Samples 30 to 24: *crepida* zone. 24 to 21: lower to middle *crepida* zone. 18 and 17: upper *crepida* zone. 11 and 10: *rhomboidea* zone. 6 to 1: lower *quadrantinodosa* zone.

	30	29	28	27	25	24	23	22	21	20	19	18	17	16	15	14	11	10	9	7	6	5	3	1
Ancyrognathus sinelamina		x										x	x											
Icriodus sp. indet.		x				x	x	x			x						x		x					
Palmatolepis crepida crepida	x			x	x			x	x															
P. glabra elongata																					x			
P. glabra glabra											x	x	x	x	x							x		
P. glabra pectinata												x		x			x				x			x
P. gracilis gracilis																	x				x			x
P. minuta minuta	x		x	x	x	x		x	x	x	x	x	x		x	x	x		x	x	x	x		x
P. quadrantinodosalobata	x	x	x	x	x	x	x		x				x											
P. cf. regularis								x	x															
P. rhomboidea																		x						
P. subperlobata subsp. a Helms												x		x										
P. tenuipunctata	x	x	x	x	x	x	x	x	x											x				
P. termini						x	x		x															
Polygnathus glabra glabra												x	x					x			x			
P. nodocostata s. l.		x																	x				x	
Polygnathus sp. indet.								x			x				x			x	x	x	x	x		
Spathognathodus sp. indet.																	x							x

Samples taken from outcrops along the track to Winstow Cottages (Fig. 1) yielded conodonts of the *styriaca* zone (Table 3). A more argillaceous succession occurs here containing less carbonate than the underlying *Kalkknollenschiefer,* and consisting of larger calcareous nodules (up to 10 cm across) in grey or green shales. Towards the top of the Upper Devonian *(Wocklumeria Stufe) Kieselschiefer* are present (House 1963), which continue into the Carboniferous (Matthews 1969).

TABLE 3. Conodonts from outcrops along track to Winstow Cottages. Location of samples shown in Figs. 1 and 2. (o=cf. determination). All samples are of *styriaca* zone.

	1	2	3	4	5	6
Palmatolepis distorta manca .				x		
P. gracilis gracilis	x		x	x	x	x
P. gracilis sigmoidalis . .				x	x	o
P. helmsi				o	x	
P. maxima					x	
P. perlobata schindewolfi .	x		x	x		
P. perlobata sigmoidea . .				x		
P. schleizia				o		
Palmatolepis sp. indet. . .		x	x			
Polygnathus styriaca . . .	x			x	x	
Polygnathus sp. indet. . .		x				
Spathognathodus stabilis . .			x		o	
Spathognathodus sp. indet. .	x	x		x		x

The conodont work in the Chudleigh area illustrates that the conodont chronology employed in Germany can be applied with confidence in south-west England. In the 55 samples taken from the area, only two anomalies were encountered. 1) In the Winstow Cottages section, samples 4, 5 and 6 yielded a good fauna of the lower/middle *styriaca* zone (to IV-V), together with the species *Palmatolepis gracilis sigmoidalis* Ziegler. In Germany this conodont begins in the lower *costatus* zone, the conodont zone above.

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2) Sample 7, of the *rhomboidea*/*quadrantinodosa* zone from Kiln Wood road section contained specimens of *Palmatolepis tenuipunctata* Sannemann. This species is normally found in the zone below (*crepida* zone), but could have been reworked into these beds of younger age.

3. Formation of Calcareous Nodules and Flaser Limestones

Calcareous nodule formation is best explained by diagenetic migration of carbonate very soon after deposition. In the reduction zone, a low pH (less than 7.8) causes the solution of the microcrystalline calcite which is disseminated throughout the muddy sediment. The dissolved carbonate is carried upwards by pore fluids into the oxidation zone, where the higher pH causes the calcium carbonate to be precipitated (Gründel and Rösler 1963). Field evidence shows that the size of the nodules and the distance apart of nodule bands both increase with decreasing carbonate content. From this and the process of formation outlined above, it follows that the size of the nodules is proportional to the rate of sedimentation, and that the distance apart of nodule bands is proportional to the amount of carbonate present in the original sediment. More continuous limestone bands and flaser limestones, representing periods of high carbonate production, are primary limestones which have been modified by early or late diagenesis, and/or tectonics. The shale streaks in flaser limestones can be formed in three ways (a) compaction, where the shaly material is injected into the surrounding, partly lithified limestone, (b) pressure solution (diagenetic or tectonic) where the flasers are residual seams, and (c) flasers produced by cleavage.

Trace fossils in carbonate nodules have been recently discovered by one of the authors (M.E.T.) in the Harz Mountains, in sediments of similar lithology and age to the ones described above. This find substantiates a very early diagenetic origin for the nodules. The trace fossils, a simple worm-burrow type of 1-3 mm diameter, occur at all angles to the bedding, but are mainly perpendicular to it. The bioturbation is rarely observed in the shales.

ACKNOWLEDGEMENTS. We are grateful to Prof. M. R. House for constructive comments in the field and subsequently. Thanks are also due to Prof. M. R. House and Dr. R. Till for reading the manuscript.

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CONODONTS FROM THE LUMMATON SHELL BED (MIDDLE DEVONIAN, TORQUAY)

by S. C. Matthews

The Lummaton Shell Bed is a frequently cited source of well-preserved palaeontological material. In the last ten years its fossils have received attention from a number of palaeontologists. Elliot (1961) described an alga, *Palaeoporella lummatonensis,* and identified certain hypothyridinid brachiopods as being of Givetian character. House (1963) confirmed Elliot's estimation of age and took the evidence of ammonoids to indicate that the main Lummaton Shell Bed belongs in the *terebratum* Zone. Selwood (1966) described trilobites from the Shell Bed. He observed that the goniatites are found usually in a black bituminous bedded limestone rather than in the Shell Bed itself; but both lithologies

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EXPLANATION OF PLATE 1

FIGS. 1-6. *Polygnathus linguiformis*. BU 20098-20103.
FIGS. 7-9. *Polygnathus varca*. BU 20104-20106.
FIG. 10. *Polygnathus* cf. *decorosa*. BU 20107.
FIGS. 11, 12. *Belodus* sp. BU 20108-20109.
All x 45. Specimen numbers refer to the Geology Museum, University of Bristol.

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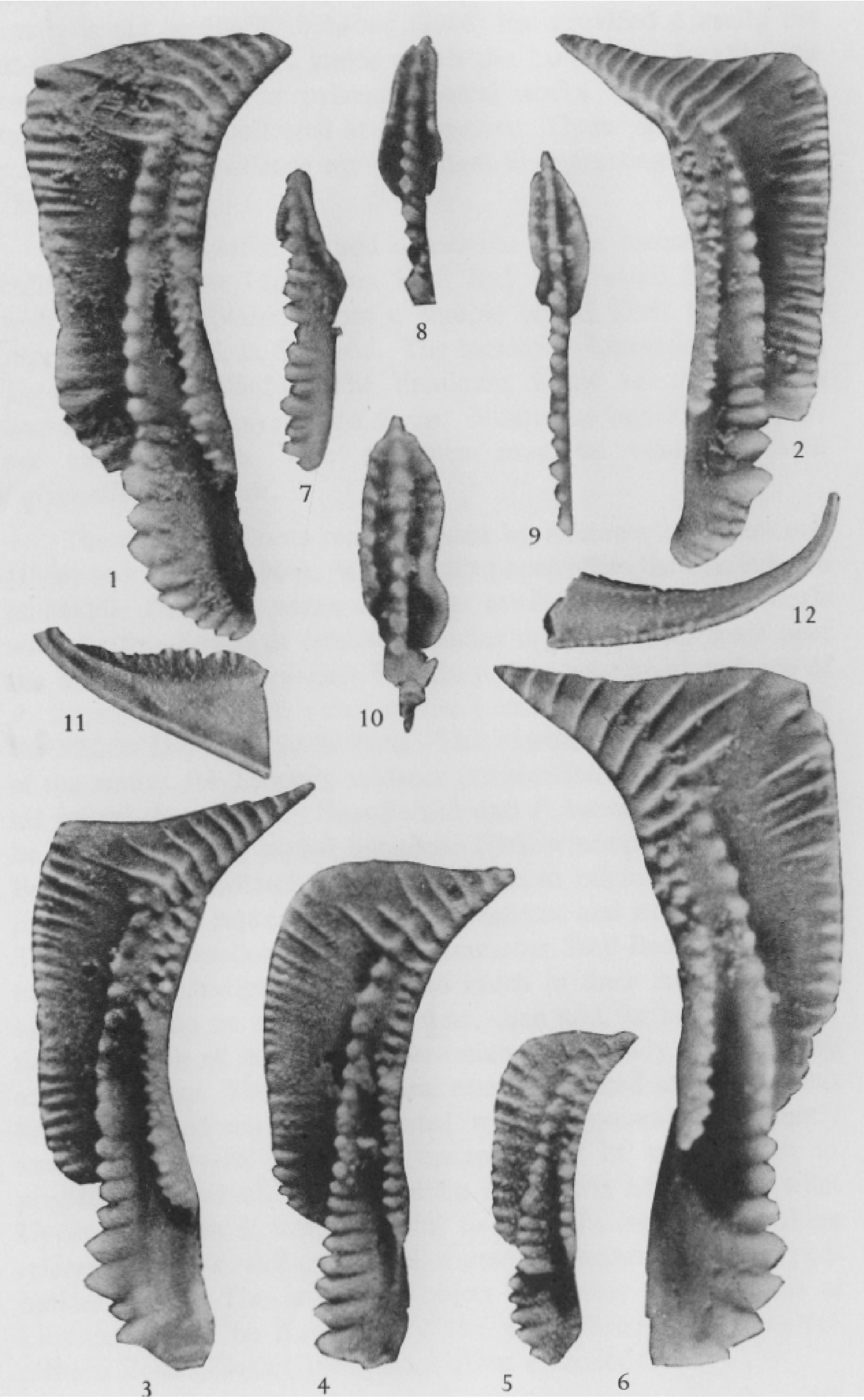

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produce subspecies of *Scutellum costatum,* and their contemporaneity is not in doubt. Selwood (1966) has provided a useful list of the variety of names under which the Lummaton locality has been treated in earlier palaeontological works. Scrutton (1968) referred to corals collected at Lummaton. These various lines of palaeontological evidence are consistent in suggesting late Middle Devonian age.

It is now possible to add conodonts to the record of fossils collected from the Lummaton Shell Bed. The small fauna dealt with here was obtained from a sample of the Shell Bed kindly supplied by Dr. E. B. Selwood. The locality is Lummaton Quarry, Torquay (SX 914665). The dominant forms are *Polygnathus linguiformis* and *Polygnathus varca.* Numerous belodids and bars are also available. One specimen may be compared with *Polygnathus decorosa.*

The conodont fauna may be dated by reference to Wittekindt (1966) and Ziegler (1966). Wittekindt's paper offers the best scheme of Middle Devonian zones at present available, and Ziegler deals with the fine details of conodont faunas taken from horizons near the Middle/Upper Devonian boundary. The relative abundance of *P. lingui formis* and P. *varca* in the Lummaton material suggests the Middle Devonian *varca* Zone. This cannot be a final judgement of the matter, for Ziegler's evidence (summarised in fig. 2, p.662 of his paper) shows that P. *linguiformis* and P. *varca* are both still to be found at slightly higher horizons. Further sampling of the Shell Bed and of immediately succeeding horizons might be expected to produce a fuller representation of *P. decorosa* and its later variants. The value of conodonts from the Lummaton Shell Bed and adjacent levels of the stratigraphy is not so much in their information on age - they do no more, at this time, than add further support to the suggestion of late Middle Devonian age already advanced by several authors. The main interest attaches instead to the fact that here the conodonts are associated with representatives (recently studied) of several groups of macrofossils. In any attempt to produce a conodont-based definition of what is Middle and what Upper Devonian it will be useful to have the means of making reference to this well-accredited source of macropalaeontological indices of age. The immediate object of further investigations at Lummaton will be discovery of the more distinctive *hermanni-cristata* Zone (Ziegler 1966) association of conodonts.

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ACKNOWLEDGEMENTS. The author owes his thanks to Dr. E. B. Selwood, who supplied a sample of rock from the Lummaton Shell Bed, and to Mr. E. W. Seavill, who photographed the conodonts figured here.

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THE TRIASSIC ROCKS OF SOUTH DEVON

by M. R. Henson

Abstract. Formations so far recognised in the re-survey of the Teignmouth (339) Sheet between the Exe estuary and the River Otter are described, and their probable depositional environments discussed. The development of cyclothems in the red sandstone and mudstone succession is thought to be consistent with environments typical of a floodplain complex.

1. Introduction

The upper part of the New Red Sandstone is exposed east of the Exe estuary for 6.5 km between Exmouth and Budleigh Salterton, where cliffs up to 400 ft high provide excellent, almost continuous, exposure. The sediments are rarely cemented, and have a non-uniform dip to the east-south-east of 3 to 8 degrees.

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2. The Breccias

The s tratigraphic ally lowest lithologies seen in the coast section are the sands and breccias. As yet, it is difficult to equate these with divisions recognised by Laming (1968) to the west of the Exe, for a recent seismic survey indicates the presence of a fault along the line of the estuary with a downthrow to the west of at least 400 ft.

The breccias are composed of subangular, coarse and fine gravel size fragments, in a matrix of sand and silt. Sand lenses up to 35 cm thick, are numerous, and commonly show small-scale cross stratification and lenses of breccia. At Lympstone a lenticular sand bed at least 7 m thick, with large-scale dune cross-stratification of probable aeolian origin, is present. The gravel sized fragments are dominantly of a dark grey sandstone, probably of Carboniferous age, with some deep red shale and fine grained porphyries, and some coarse grained granitic rocks containing large red K-feldspar phenocrysts up to 5 cm long. Isolated fragments of white K-feld-spar ("Murchisonite" of Ormerod 1875) thought to have been derived from Dartmoor, also occur. The red phenocrysts are clear and little altered; the white phenocrysts are opaque, sericitised and friable. The source of the former may lie to the south in the English Channel beneath later members of the Trias. The sedimention units are often graded; an erosional base with a concentration of the larger clasts showing imbrication upon it is succeeded by a bed of vertically decreasing grain size. Trough and planar cross stratification is well developed and these sets and cosets cut across the more regularly bedded sequences. The graded units vary in thickness from 15 to 45 cm; they are usually persistent through any one outcrop. There is considerable variation in the thicknesses of individual beds but the thickness of a given bed remains fairly constant. The trough and planar cross-stratified units are composed of finer, better sorted material than the graded units.

These sediments have some of the features characteristic of alluvial fans, formed by the agencies of sheetfloods and streamfloods (Allen 1965a), and these mechanisms are suggested to have operated in a hot semi-arid climate. The dune-bedded aeolian sands formed by aeolian reworking of the fans, concentrating sand grade material in isolated dunes and restricted dune fields.

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3. Exmouth Formation

The formation is composed of red and green sand units and apparently structureless red silts and clays. The sand bearing units, generally persistent for over 200 m, are of three different types. Listed in order of decreasing frequency of occurrence they are :

(a) poorly sorted, locally impersistent green beds, 15 cm to 1.0 m thick, occuring 20 times;

(b) red and green cross-stratified sands with mud lenses, 1.25 to 3 m thick, occasionally showing evidence of erosion into the silts below, occurring 8 times;

(c) two members, in excess of 15 m thick, composed of red and green sands with mudstone beds and lenses and showing large and small-scale cross-stratification.

The bases of all these units are sharp and probably erosional. The thicker units show evidence of exposure, suncracks, and bioturbation.

The silts and clays are moderate reddish brown (hue lOR4/6 Rock Color chart) except when associated with the coarse horizons, where they are pale olive (hue 10Y/2), and vary in thickness from 1 to 15 m X-ray photographs show no evidence of primary lamination but some evidence of bioturbation, indicating that organic reworking was possible in this environment.

The base of the formation is defined as the sharp contact existing between the gravel-free sands and silts characteristic of the formation and the underlying breccias, as seen at Lympstone (SX 98988365).

4. Littleham Formation

The formation consists of red (hue 10R4/6) silts and clays, with variable coarser intercalations generally persistant for over 400m, which are usually green (hue 10Y6/2) or mottled red and green in colour. The red silts and clays are apparently structureless but the coarser intercalations have a variety of sedimentary structures including small-scale cross-stratification, ripples both symmetrical and asymmetrical, contorted lamination and suncracks. The bases of these coarse horizons are always sharp. 90% of the succession is composed of the silts and clays, the coarser intercalations being subordinate.

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The base of the formation is taken as the top of the last well developed cross-stratified sand horizon of the Exmouth Formation, as seen at Straight Point (SY 03957947).

5. Budleigh Salterton Pebble Beds

These "Pebble Beds" are famous for their cobbles and boulders of exotic quartzites, the fauna of which comprises Lower Devonian and Silurian brachiopods and trilobites, typically of French species (Vicary and Salter 1864). The quartzites are of a lithology not seen in England, although they show similarities to quartzites within the Meneage Crush Zone. Cobbles of schorl and some of porphyry also occur. The clasts vary from subangular fine gravel in the matrix through coarse rounded gravels to well-rounded cobbles and boulders up to 45 cm in diameter. Red silt intraclasts up to 70 cm long are present locally. It is notable that many of the cobbles are covered by well-developed chatter marks, which on the coast are rapidly removed by attrition on the shingle beach. The relative abundance of quartzites to schorl and porphyries is 90% : 10%, and the abundance of clasts to matrix 80% : 20%. The clasts are set in a matrix of fine and coarse sand and silt, mica flakes are abundant, and any feldspar present has apparently been subject to *in situ* post depositional kaolinisation. Sand lenses are present and become more frequent towards the top of the formation: they contain stringers and lenses of gravel and are usually cross stratified, the foreset height being in excess of 30 cm. The upper surface of a sand bed is always eroded beneath the base of the overlying cobble bed, the lower surface is conformable with the underlying cobble bed.

The sedimentary structures indicate a fluviatile environment, which at times had competence to carry a coarse bed load. Accumulations of cobble and boulder-size material are common in fan deposits or as the flood gravels of very large rivers.

The top of the formation on the coast is formed by a deflation layer of ventifacts up to 7 cm thick cemented with iron and manganese compounds. Here the uppermost part of the formation is dominantly sandy, and cobbles do not become dominant until approximately 1.5 m below the ventifact layer.

The base of the Budleigh Salterton Pebble Beds is the sharp erosional surface on the Littleham Formation on which the cobbles and boulders of the Pebble Beds lie (SY 05858155).

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6. Otter Sandstone Formation

The formation is composed of a number of sandstone members and is rarely cemented. The geometry of the sand bodies is indeterminable due to the lack of related exposures. Silt lenses are present, generally thin, 30 cm maximum recorded thickness, and impersistent, 2.5 to 10 m long. The total of silts and clay beds in the succession is negligible, however the - 0.063 mm fraction of the sands is rarely less than 8%. The sands are of the fine-medium sand range of the Wentworth Scale, having a mean of about 0.31 mm. Most of the sand members show large and small cross stratification, desiccation cracked mud lenses, cut-and-fill channel lenses, small gravel horizons and have a high proportion of mica in the sand. These members are therefore considered to be of fluvial origin. A few show large scale dune cross-stratification, with no mud lenses or desiccation cracks, the sand grains are noticeably larger and they are mica free. These are considered to be of aeolian origin.

The base of the formation is seen on the coast (SY 06328162) as the layer of ventifacts. In other localities it is possible that the top of the Pebble Beds has been channelled and infilled with fluvial sands and gravels, and in these cases the formational boundary is taken as the top of the last cobble bed.

7. Exmouth and Littleham Formations : origins and characteristics

The most interesting feature of the sand and mudstone succession is the presence of fining-upward cycles, now ascribed to a fluvial origin (Allen 1965b). The cyclothems are characterised by an erosive base underlying a coarse member which gradually fines upwards into a silty clay member. The whole is composed of several or many sedimentation units.

The two 15 m thick members and the 1.25 to 3 m group of the Exmouth Formation show a fining upwards sequence with sedimentary features in the same associations as described by Allen (1964): a scoured basal surface of low relief, large-scale trough and planar cross-stratified sands, local mud pellet conglomerates, flat bedding with a parting lineation fining upwards into small-scale cross-stratification, clay lenses, often with desiccation cracks and sand-filled pipes and burrows. Similar sedimentary structures are characteristic of recent channel deposits, channel bars and point bars (Allen 1965a).

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Features found in the 15 cm to lm thick units of the Exmouth Formation, and the coarser, 20 to 40 cm intercalations of the Littleham Formation are : poorly sorted beds with interbedding of coarse and fine material, small-scale cross-stratification and occasional channelling into the underlying floodbasin deposits. Similar sedimentary structures are characteristic of overbank deposits, levees and crevasse splays (Allen 1965a).

The red silts and clays form a single variable group with no lithological differences defining the bedding. Lamination is rare, and no suncracks, calcretes or ferricretes are present. Organic re-working is widespread. These features are characteristic of flood basin deposits of a flood plain (Allen 1965a). The interbedding of coarse and fine overbank sediments indicates a flood plain of low relief and the absence of concretions, that the nett water movement was downwards.

In summary, the similarity of cyclothems within the Triassic red sandstone and mudstone succession to those of recent alluvial sequences and recognised old alluvial sequences is taken to indicate that these sediments are of alluvial origin and they are interpreted as belonging to a floodplain complex formed by a river of high sinuosity. The coarse sands and occasional silts being point bar and channel bar deposits within a river course, the poorly sorted sands and silts being the coarser overbank deposits, levees and crevasse splays, and the red silts and clays being the fine-grained floodbasin deposits.

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This contribution has been approved for publication by the Director of the-. Institute of Geological Sciences.

Permo-Triassic erosion of the Mendip Hills (Abstract) :
by A. E. Frey.

In the estimated 70 million years of dominantly sub-aerial erosion of the Permian and Triassic, the Mendip Hills survived surprisingly intact. Only at the western end of the Blackdown pericline was the relief reversed, and the remaining three periclines merely show removal of their Carboniferous crests. At maximum, the quantity of sediment removed from these crests could have been 8,000 ft of Upper Carboniferous and 3,500 ft of Lower Carboniferous. These figures must be heavily reduced however to allow for (a) the non-deposition of beds throughout the Carboniferous because of a rising Mendip axis and deepening flanking basins, (b) post-Triassic erosion (especially pre-Albian and late-Tertiary) and (c) the excellent conformity between the late-Triassic drainage pattern and the disposition of the periclinal cores.

The Mendips now average 1,000 ft in height above O.D., to which must be added 2,000 ft of Triassic sediments in the basin to the south, and say 3,500 ft of Carboniferous sediments restored to the eroded crestlines, to produce an amplitude of relief in Triassic time of 6,500 ft over a horizontal distance of 5 or 6 miles. Such steep gradients, an absence of Permian deposits, and the late-Triassic wadi pattern point to Mendip as a strong watershed site which should have been heavily attacked. The removal of 4 to 6,000 ft of sediments from anticlinal crests in 70 million years produces a denudation rate of around ¾ inch per thousand years. It is highly likely however that early Permian and late Triassic erosion was much more rapid than this, but that the long intervening period was mostly highly arid, characterised by deflation, basin filling and quiessance.

Aspects of the Upper Greensand of the Bovey Basin (Abstract) :
by R. A. Edwards.

The Upper Greensand of the Bovey Basin is the most westerly outlier of the Cretaceous in England. In this area, the Upper Greensand comprises a series of very shallow water glauconitic marine sands, often gravelly, cross-bedded in part and with a maximum

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measured thickness of 20m. Their outcrop is restricted to the eastern side of the Bovey Basin, where they rest on Devonian and Carboniferous rocks, and to an area south of Newton Abbot, where they rest mainly on Permian sediments.

Cherts occurring in the sequence are banded, shelly or bioturbated, and show cross-bedding and other primary structures. Limestones occur in the Upper Greensand near Wolborough, Newton Abbot. These limestones are medium and coarse calcarenites, including sandy glauconite *Orbitolina* biosparites and sandy skeletal biosparites. Components include abraded allochems, dominantly molluscan, algal, echinodermal, foraminiferal and polyzoan skeletal material, with rare intraclasts. These elements have a sparite cement. Skeletal allochems often have syntaxial overgrowths. Fossil material is commonly preferentially silicified; it is suggested that many cherts in this Upper Greensand sequence are the product of silica diagenesis of limestones. Textural features of the cherts support this conclusion.

The present distribution of the Upper Greensand of this area is controlled by structures of Tertiary age.

This contribution has been approved for publication by the Director of the Institute of Geological Sciences.

CYCLICAL SEDIMENTATION IN THE PETROCKSTOW BASIN

by E. C. Freshney

Abstract. Deposits of fluviatile and lacustrine origin were laid down in the Petrockstow Basin during Lower Tertiary times. The fluviatile deposits comprise channel and overbank sediments, the distribution of which was controlled by periodic contemporaneous fault movements, which produced a cyclicity in the sedimentation. The bottom of each cycle is marked by a sharp or erosional base followed by a fining-upwards sequence, topped by a seat earth. The nature of the iron compounds in or near the seat earth horizon is related to the position of the water table in the sediments after deposition and to the amount of decaying vegetable matter present.

The deposits of the Petrockstow Basin consist of Lower Tertiary unconsolidated clays of varying silt content, silts, sands, gravels and lignites, deposited in a partly fault-controlled sediment basin which is thought to be a relic of a river system which probably flowed from a south-easterly direction, mainly following the line

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of the Sticklepath Fault Zone and entering the sea in the Bristol Channel area (Freshney and Fenning 1967). In the Petrockstow Basin sedimentation appears to have been controlled by contemporaneous fault movements, mostly along north-west to south-east lines. This faulting divides the basin axially into a deep central trough around 2,200 ft deep, with flanking shelf areas to the north-east and south-west. The trough sedimentation is characterised by silts, sands, gravels and extremely silty clays with some lenticular developments of strongly laminated brown silty clays containing undisturbed leaf remains. In the marginal shelf areas gravels and coarse sands are almost absent and clays, often brown, with a variable silt content are dominant; lignite occurring chiefly as fragments within brown clays is common but no laminated brown clays with undisturbed leaf fragments are found.

It is thought that during the earlier part of the deposition the river course was mainly confined to the central trough area of the basin by contemporaneous fault movements, and the sands and gravels represent mostly channel sands deposited either as channel lag deposits, channel bar deposits, or point bar deposits, with a relatively restricted development of overbank silty clays and silty sand. During the later part of the deposition the central trough faulting became less active and the river deposition extended over a wider area. The channel sands and gravels still tended to be restricted to the area of the trough but the overbank deposits became much more extensive, particularly in the shelf area to the west of Merton village and in the Wooladon shelf area south-east of Petrockstow. The internal trough fault was still active to the south-west of Merton, where the upper beds of the deposit are folded into a monocline along the line of the fault. Slumping and highly disturbed bedding is commonly found in these upper beds adjacent to the monoclinal line.

Three boreholes were sunk for the Institute of Geological Sciences at the locations shown in Figure 1, all within the down-faulted trough area. During the examination of the cores from these boreholes it was apparent that the deposition was cyclical, particularly in the case of the most north-westerly borehole (No. 2). Figure 2 shows examples of the types and variations in the cycles occurring in the three I.G.S. boreholes. The cycles characteristically commence with the deposition of coarse sand or even sandy gravels

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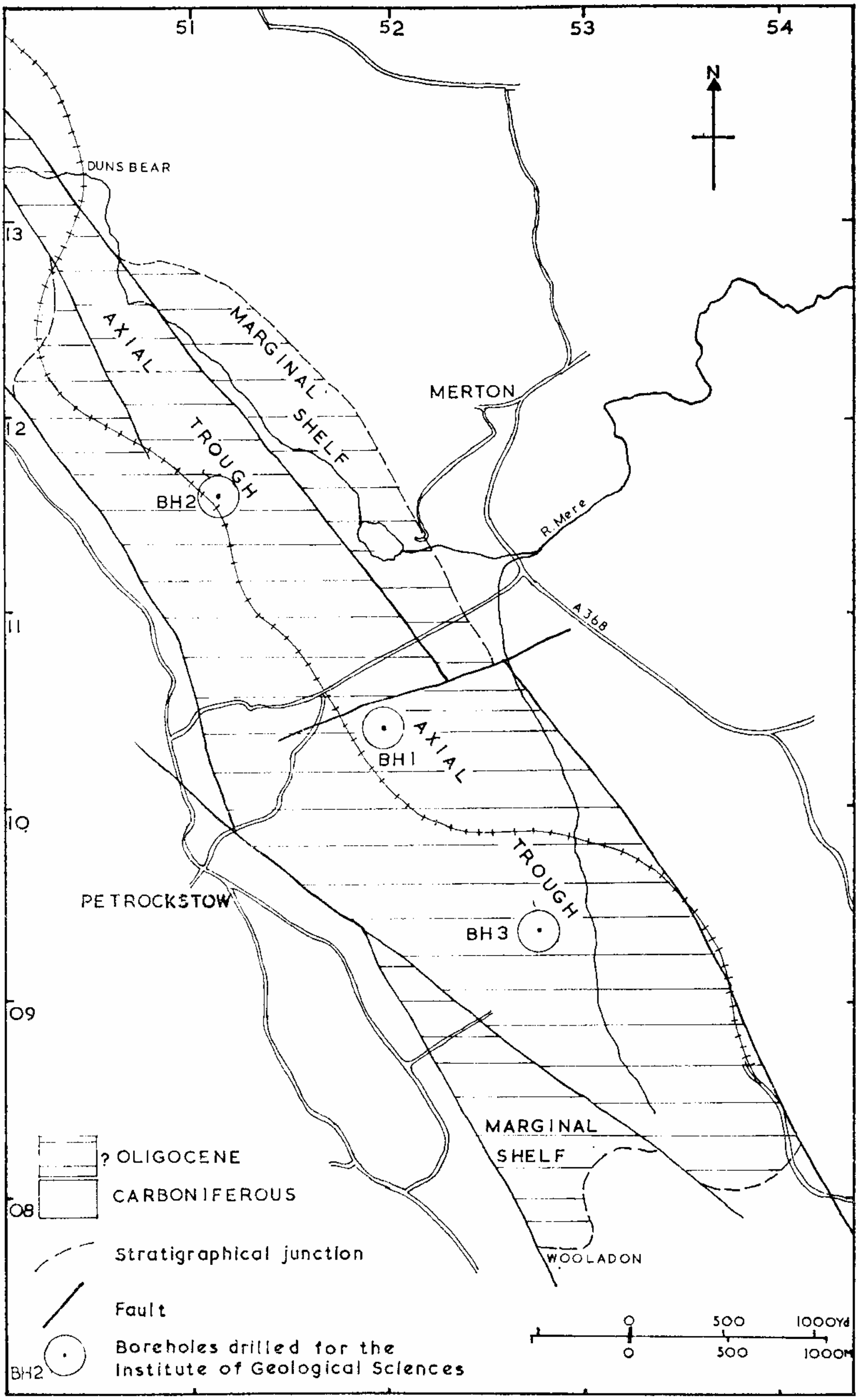

FIGURE 1. Geological map of the Petrockstow Basin showing the relative positions of the axial trough and the marginal shelves with their dividing faults.

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on an erosive base whose attitude may dip as steeply as 45' with respect to the dip of the bedding. The sands fine upwards and become increasingly clayey and silty towards a rootlet horizon which is typically brown or brownish grey in colour. The sands themselves are usually grey and brown and occasionally beds of deep reddish brown, lignitic, irregularly laminated sands and silts occur in the fining-upwards sand sequence. These brown sands frequently show small erosional channels and micro-faults attributable to compaction and in some cases a very rough cross-lamination can be seen. For the most part, however, no large-scale cross-bedding or cross-lamination can be detected in the sands; this may be chiefly due to the restricted size of the borehole cores and natural exposures of these sands are not very common. One exposure in Wooladon Ball Clay Pit showed grey and brown sand occupying a large erosional channel, with a smaller subsidiary channel to the side, cut into silty and smooth clays. These sands are generally well sorted, between 0 and 3 Φ in particle size, but are heavily skewed with a large poorly sorted tail below 3 Φ. The silts and silty clays which continue to fine upwards above the sand commonly contain rootlets towards the top and are frequently stained with dark finely disseminated iron sulphide which sometimes forms haloes round the rootlets. In some cases the iron in this seat earth sequence is not in the form of a sulphide but may occur as siderite spherules, occasionally in a massive form but more commonly as scattered grains. Iron may also occur at this horizon in the form of an oxide causing a bright red stain. Towards the top of the seat earth the silty clay becomes increasingly brown and the topmost few inches are commonly brecciated with abundant rootlet and other vegetable debris. This horizon is then usually succeeded by a brown, often dark brown, clay, which is silty in the bottom few inches but which becomes smooth to slightly silty above this. On some occasions solid lignite also occurs at this position associated with the brown clays, on others fragmental lignite is contained within the clays. Within the brown clay section above the seat earth there may be a repetition of rootlet beds and further lignite and brown smooth clay above this. In some instances very regularly laminated brown clays and silty clays occur above the seat earth and these frequently contain perfectly preserved leaf remains and thin lignite bands. The top of the cycle is then marked above by the erosional base of the succeeding coarse sand or gravel.

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Figure 2A shows a typical cycle from Borehole No. 2. This commences with coarse brownish grey sand which fines upwards and becomes more grey in colour with an increasing clay content. A rootlet horizon occurs in the beds immediately below the first lignite and the clay also becomes brown in this area. Resting on the slightly silty to silty clay of the seat earth horizon there is a lignite 1 ft 9 in thick, followed by further slightly silty to silty clays with more rootlet horizons and some worm burrows. This is succeeded by a further lignite bed, on top of which there are regularly laminated brown silty clays which are followed by a repeated sequence of silty clays with some rootlet horizons and more laminated brown silty clays. The cycle is closed by the brown sand of the following cycle. In Borehole No. 1, near the centre of the deposit, the cycles appear to occur at more frequent intervals, but the brown clay horizon with lignite above the seat earth is usually absent. Figure 2B shows three cycles in this borehole. The erosive bases are still clearly marked below the sand which fines upwards in the case of the lowest cycle through a very silty clay into silty clay. The succeeding cycle rapidly fines up into a very silty clay, above which there have been deposited very silty brown clays with some lignite and rootlets. The topmost complete cycle fines upward into grey silty and slightly silty clays. In the most southerly borehole, No. 3, the cycles are marked by an abundance of rootlet horizons, although brown clays and lignites are rare. One thick cycle (Fig. 2C), commencing on an erosive base, continues upwards in coarse gravelly brownish grey sand, becoming brown higher up with a band of brown lignitic laminated sand about half-way up the fining upward sequence. The sequence then fines upwards into a silty and sandy clay with rootlet beds and continues with much repetition to the top of the cycle. Besides the occurrence of rootlets, worm burrowing is common. Iron, in the form of finely disseminated dark sulphide is abundant in the repetitive silty clay sequences, but also occurs as a red oxide stain at other horizons. Figures 2 D, E and F, show examples of cycles found in shallow boreholes in the shelf areas of the deposit. Figure 2 D shows a perfect fining-upwards sequence, from a fine sand with a sharp but non-erosional base, upwards into very silty and then silty grey to brownish grey clays. Within these clays iron occurs chiefly as the form of red oxides, but some dark sulphide stain is also present.

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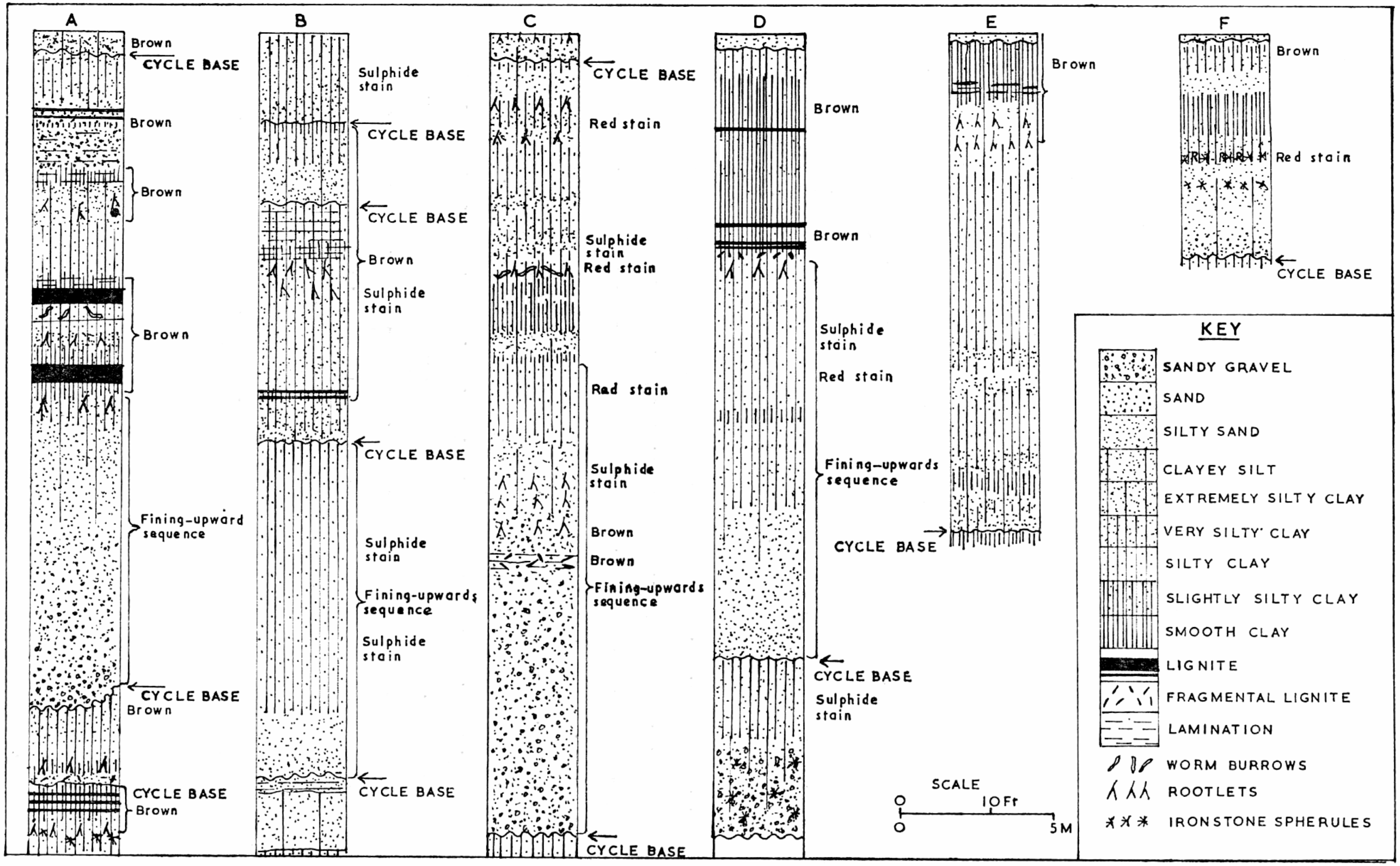

FIGURE 2. Examples of cycles, A, B and C from I.G.S. Boreholes Nos. 2, 1 and 3 respectively; D, E, and F from clay company boreholes (Merton marginal shelf).

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A seat earth with rootlets is developed at the top of these silty clays, and resting upon it are smooth to slightly silty clays, brown to brownish grey in colour with thin seams of lignite, chiefly at the base. This smooth clay sequence is succeeded by silty clays once again up to the base of the following cycle. Figure 2E, shows a cycle in which extremely silty clay with a sharp base rapidly fines upwards into a repetitive sequence of silty to extremely silty greyish brown clays with a seat earth at the top. This seat earth is succeeded by brown smooth to slightly silty clays containing lignitic material which concludes the cycle. In Figure 2F, the cycle commences in clayey silt with a sharp base which fines upwards into a very silty clay; both the top of the clayey silt and the extremely silty clay contain siderite spherules as well as iron in the form of red oxide, but no rootlets were seen. This is followed by brownish grey smooth clays with further slightly silty to extremely silty clays to the top of the cycle.

Conditions of **deposition**

The sands and gravelly sands making up the bottom parts of the cycles in the axial trough region are well sorted, have eroded and channelled bases, and were probably deposited within the channel of a meandering river. Fining-upwards sequences are also thought to be suggestive of an alluvial environment (Allen 1965: 229-46). The gravels sometimes found at the bottom of a cycle would constitute a lag deposit, while the coarser sands more frequently found, together with some gravelly sands, fining upwards into silty sands, probably represent part of the point bar and swale-fill deposits of the river. The finer sediments above this were deposited during the filling of an abandoned channel, the vertical accretion being finally sufficient to allow the establishment of a vegetation cover with the consequent production of a soil with rootlets. Within the seat earth beds there were developed a variety of iron compounds, the chemical composition of which depended upon the elevation of the water table, and also on the amount of decaying vegetable matter. In swampy conditions, with the water table at or close to the surface, and in the presence of organic matter, finely divided iron sulphide was probably deposited within the sediments. Frequently this dark iron sulphide stain is oxidised to a yellow oxide or iron giving a patchy, yellow stain around the darker sulphide-stained areas. It is possible that this situation arose when a small fall in the water table allowed the entry of

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oxygen to the sediments. Iron sulphide also occurs in the form of marcasite nodules within the lower sand part of the cycle, probably indicating acid anaerobic conditions after deposition, due to the presence of vegetable matter. According to Curtis and Spears (1968: 260), the growth of siderite within a sediment is possible only in conditions of low Eh value, zero sulphide activity, and severely restricted water circulation. Within the seat earth horizons at Petrockstow this situation may have arisen with a high water table giving a low Eh, a lack of organic material possibly resulting in a low sulphide activity, and restricted water circulation in the silty clays and clayey silts in which the siderite chiefly occurs. Siderite spherules also grow within the Lower Tertiary weathering zone found below the clay deposits in highly altered and kaolinised Carboniferous shales, siltstones and sandstones (Bristow 1968: 29-35). Upon exposure to air the siderite rapidly oxidises to a reddish brown or yellow colour with the formation of lepidocrocite, and in some instances this alteration has taken place prior to present-day exposure, oxide stain being commonly associated with spherulitic siderite. This situation probably arose when a lowering of the water table permitted oxidation of the siderite. A final common form for the iron within seat earth horizons is red, lilac and brownish yellow coloured oxides; this staining can occur in the form of patches, as fine laminae, probably picking out an original sedimentary lamination, or as differential staining of rootlet networks and worm burrows. In some cases the matrix around the worm burrow is stained red, the worm burrow itself being left grey, and in other cases the worm burrow is stained red with the matrix grey. As yet no definite name can be given to the mineral which forms these red stains, but it is possibly hematite, goethite or lepidocrocite, or a mixture of all three. The occurrence of the iron in this oxidised form is thought to be due to the sediments being in a relatively elevated position, with a low water table and consequent aeration of the sediments.

The presence of lignite, sometimes up to 2 ft thick above the seat earth, indicates that a vegetable cover was established for some considerable time prior to the deposition of any further sediments, but in most cases the seat earth is succeeded rather abruptly by smooth to silty brown clay, frequently with some small lignitic development. It is thought that these clays overlying the seat earth are overbank deposits which, when they are smooth to slightly

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silty, indicate deposition at some considerable distance from the river channel. Within the succeeding overbank deposits there may be repeated seat earths and thin lignitic beds with attendant sulphide, siderite or iron oxide stain. For the most part the cycles in the axial trough area of the deposit do not contain very smooth clays due to the proximity of the river channel, but in cycles examined in the marginal shelf areas thicknesses of up to 20 ft of smooth silt-free clays occur because these areas were up to 4 mile away from a possible river channel position. For the most part channelling and channel sands are absent in the marginal areas and although the clayey silts and extremely silty clays found at the bottom of the cycles in these marginal areas have sharp bases, they are not markedly erosional and merely indicate proximity of the river channel with a consequent periodic discharge into the adjacent flood plain of coarser silt and fine sand. The coarser silty sand beds occurring occasionally within the cycles in the shelf areas are probably levee or crevasse splay deposits. One such sand which occurs in the shelf area about 1 mile west of Merton village has a large areal extent, is laminated, and sometimes shows signs of cross-lamination. It has a sharp, but non-erosive base, and is most probably a crevasse-splay sand.

The finely laminated reddish brown silty clays and silts usually found intercalated within the part of the cycle above the seat earth, are almost restricted to cycles found in No. 2 Borehole in the northern third of the axial trough, although some were found in No. 1 Borehole in the centre of the basin. These clays contain disturbed and perfect leaf remains, thus indicating either very gentle current conditions or a complete absence of currents. Such deposits are very probably of lacustrine origin and the lake appears to have occurred at intervals, in the northern part of the axial trough area only.

Figure 3 is a composite diagram showing how the various cycles occurring in the axial area and in the shelf flanking areas of the deposit may be related one to another. The diagram illustrates the vertical and horizontal variability of the deposit, a feature which causes grave difficulties when correlation is attempted between boreholes, even when these boreholes are as close together as 50 ft.

The strong evidence of contemporaneous tectonic movements during the deposition of these sediments provides at least one factor which probably influenced the cyclicity of deposition together with

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geomorphological factors such as the periodic migration of the meanders of the river. During most of the time of deposition the accumulation of sediments within the axial trough seems to have kept pace by and large with the rate of sinking of the trough between its bounding faults. When the faults defining the axial trough allowed the ground between them to descend marginally faster than normal, then a lake became established within this area. During the latter part of the deposition in the Petrockstow Basin the internal faults bounding the axial trough became less active and movement appears to have been concentrated on more widely spaced faulting, thus permitting the establishment of a broader flood plain with consequent deposition of thicker beds of silt-free clay, a fact which now tends to restrict the extraction of such clay by ball clay producers to the marginal shelf areas.

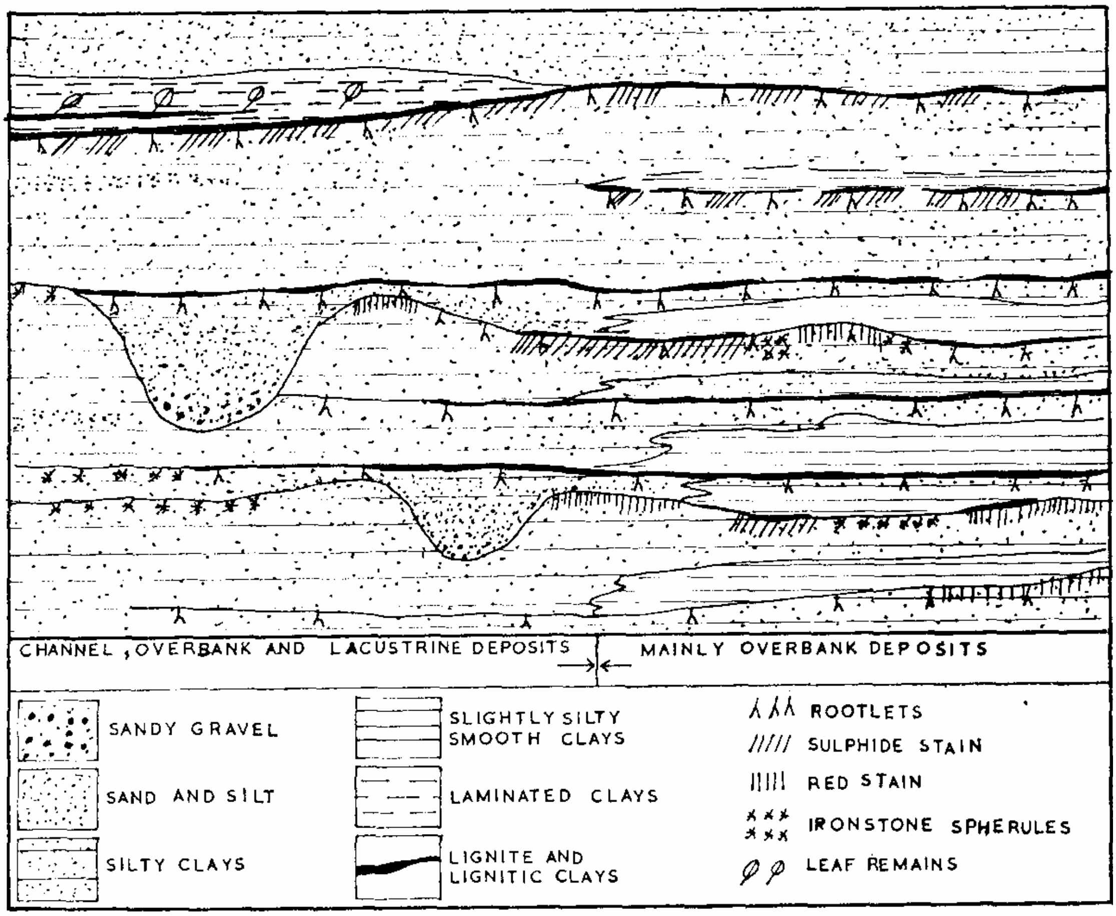

FIGURE 3. Diagram showing the relationship of the various facies found in the basin. Sequences taken at different positions on this diagram demonstrate how the changes in cycle type may occur.

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THE BURTLE BEDS OF SOMERSET

by C. Kidson

A re-examination of the Burtle Beds, during which seven boreholes were sunk and a number of exposures were re-opened in the area between Catcott Burtle and Ottery, has shown that they consist of an upper sand and gravel bed and a lower clay member. Bulleid and Jackson described the sands and gravels in 1937. In the underlying clay, the foraminifera and ostracods show a gradual change from estuarine to marine assemblages.

To the north of the Polden Hills the Burtle Beds lie on the eroded surface of the Lower Lias, while to the south of the ridge they are underlain by Keuper marl. Throughout the area the Recent faunas of the Burtle Clay include a number of Lias 'contaminants'. These faunas suggest a` post-Liassic ' estuary extended by a transgressing sea until full marine conditions obtained. The faunas of the Burtle Sands, dominated by *Macoma baltica* show that they are sand bank rather than beach deposits. The highest level reached by the sands is less than 9m (30 ft) O.D. giving a *high tide* level in Burtle Times of the order of 15m (50 ft) O.D. This allows a depth of 5.5m (3 fathoms) over the sand banks at mean high water, which would be consistent with the very high *Maconia* population and which compares with depths over the higher banks in Bridgwater Bay today. A mean sea level some 9m (30 ft) above that of the present is therefore indicated assuming unchanged tidal ranges.

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The upper surface of the Burtle Sands has undergone a long period of sub-aerial erosion. In places the larger sand banks have been dissected by streams draining to the Rivers Parrett and Brue. Taking this into account, some upward revision is, therefore, necessary of the estimate of sea level in Burtle Times, but there is, at present, no factual evidence on which to base this.

Carbon 14 dates have been obtained for shells from the Burtle Sands as follows -

Cutley	1.2980	$36{,}200 {}^{+\,3{,}600}_{-\,2{,}500}$ B.P.	26. 7ft O.D.
Middlezoy	1.3924	32.750 ± 1,600 B.P.	23.07ft O.D.
Greylake	1.3925	29,000 ± 1,000 B.P.	21. 0ft O.D.

These compare with Wood's (Callow and Hassell 1969) dates from Middlehope of $33{,}240 {}^{+760}_{-700}$ B.P, and $38{,}990 {}^{+1{,}690}_{-1{,}390}$ B.P. (N.P.L. 126A and B), which he accepted as Middle Weichselian (Swallow Cliff). Taken at their face value all these shell dates suggest a high sea level in Mid-Weichselian (Upton Warren) times. While Milliman and Emery (1968) have produced data from the eastern seaboard of the U.S.A. to support such a high sea level, no such high sea level can be supported in Britain. All the other evidence suggests that these shell dates cannot be accepted and that the real age of the Burtle Beds is either Eemian or Hoxnian, probably the former. A date of 34,900 ± 140 B.P. (1- 3914) has been obtained from shells from soliflucted Burtle Beds from a depth of - 35ft O.D. in a borehole at Highbridge and a similar date $33{,}200 {}^{+2{,}300}_{-1{,}800}$ (1 -2981) was obtained from raised beach sands beneath head at Saunton in North Devon. Both these deposits indicate an inter-glacial rather than an interstadial age. The available evidence considered together with the known unreliability of shell dates, therefore, suggests that the Burtle Beds and other similar deposits in the locality, the Kenn gravels (Welch 1955) and the marine Pleistocene beds of the Vale of Gordano (Ap Simon and Donovan 1956), are Eemian.

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THE VARISCAN STRUCTURE OF EASTERN DARTMOOR

by R. A. Waters

Abstract. Five synchronous Upper Palaeozoic successions have been mapped which occur in separate tectonic units. Flat-lying and essentially upright structures are demonstrated to be closely allied to transported and nontransported tectonic units respectively.

1. Introduction and stratigraphy

In the course of the remapping of the 1in Teignmouth (339) sheet under the I.G.S./Exeter University contract and some preliminary investigations by the author on the eastern edge of the Dartmoor Forest (338) sheet, various synchronous Upper Palaeozoic successions have been differentiated on a basis of fauna and lithology. Facies variation is most marked in the Upper Devonian and decreases with time until the Upper Carboniferous which is fairly uniform over most of the area. Facies differences within the Middle Devonian are not well known and are beyond the scope of this paper.

The areas occupied by the different successions are tectonically bounded. Altogether five successions can be mapped, namely :

Teign Valley succession

Liverton succession

Kate Brook succession

Southern successions:

(i) Chudleigh succession

(ii) Newton Abbot succession

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(a) The Southern successions

These range from the Middle Devonian to Upper Carboniferous and it is within the Upper Devonian that the two facies are clearly seen. (i) Chudleigh succession. House and Butcher (1962) established a complete, but reduced, succession from Givetian to probably Namurian. Above the Givetian/Frasnian massive limestones occur purple and green nodular limestones, nodular shales, and shales with a rich fauna of ammonoids, trilobites and ostracods. This Upper Devonian succession is condensed and thought to represent a *Schwellen* type of environment. The overlying Lower Carboniferous consisting of thin-bedded greenish brown radiolarian cherts are also considerably reduced and pass upwards through the *Posidonia* Beds into the overlying and apparently conformable Ugbrooke type Upper Carboniferous which is characterised by horizons of thick conglomerates within the sandstone shale sequence. (ii) Newton Abbot succession. B. W. Riddolls (personal communication) has shown that the Upper Devonian in the wide slate tract lying south of the limestones at Bickington is thicker than that at Chudleigh and moreover contains volcanics and is intruded by dolerite. The succession comprises grey laminated slates with spilitic intrusives, succeeded by purple and green slates. The fauna is sparse consisting mainly of ostracods and bivalves with rare trilobites and ammonoids.

(b) Teign Valley succession

In the middle Teign Valley, Chesher (1968) demonstrated a succession from high Upper Devonian to Upper Carboniferous which is in marked contrast to the Southern successions. The Upper Devonian (zones V-VI only) comprise blackish blue shales with siliceous nodules and bands, passing up into rather silty micaceous green shales. The fauna consists of trilobites, bivalves, and brachiopods, infrequent ostracods and a few indeterminate ammonoids. The Lower Carboniferous shows a thick series (300-500 ft) of black shales underlying the chert beds. This is in marked contrast to Chudleigh, where chert deposition commenced at the end of the Famennian. The chert sequence in the Teign Valley is characterised by thicker chert units between the shale interbeds, packets of blue black shales, beds of manganese and the presence of pyroclastics and extrusives, that may be genetically related to the widespread dolerite sills. The *Posidonia* Beds at the

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top of the chert sequence are thicker than at Chudleigh. The overlying Upper Carboniferous (Crackington Formation) consists of shales with turbidite sandstones; the individual sandstone beds are up to two feet thick and of a grain size typically in the medium sand range.

(c) Kate Brook succession

This sequence consists of greenish, often rather soapy, slates with a sporadic fauna of thick-shelled and coarse-ribbed brachiopods, including *Cyrtospirifer sp.* These slates are seen at Chudleigh, to the south of Holne Bridge and in a small patch to the east of Bickington. All their junctions with other rocks are tectonic and little is known of their stratigraphic range, except that they are at least in part Upper Devonian.

(d) Liverton succession

In the southern half of the Ilsington area and westwards to Holne and the Dartmoor granite the Upper Devonian (zones V-VI) consists predominantly of purple and green slates with occasional thin limestones and contains horizons of calcareous thinly bedded and blocky silt-stones, especially near the top. This Upper Devonian is virtually volcanic free, compared with the purple and green slates of the Newton Abbot area, and carries a rich fauna of ammonoids, ostracods and bivalves. It passes up into Lower Carboniferous cherts with no intervening black shale group such as occurs in the Teign Valley succession. The overlying *Posidonia* Beds are thinner than in the Teign Valley. The Upper Carboniferous is of Crackington type. Thus the succession is rather unusual in having Upper Devonian lithologies and fauna of southern affinities but Upper Carboniferous of northern affinity (Crackington Formation).

2. **Structure**

The successions noted above are limited by tectonic boundaries and are identified in the following tectonic units :

Tectonic unit		Succession present
Foundation unit	. . .	Teign Valley
Ilsington unit	. . .	Teign Valley
Liverton unit	. . .	Liverton
Kate Brook unit	. . .	Kate Brook
Southern unit	. . .	Chudleigh and Newton Abbot

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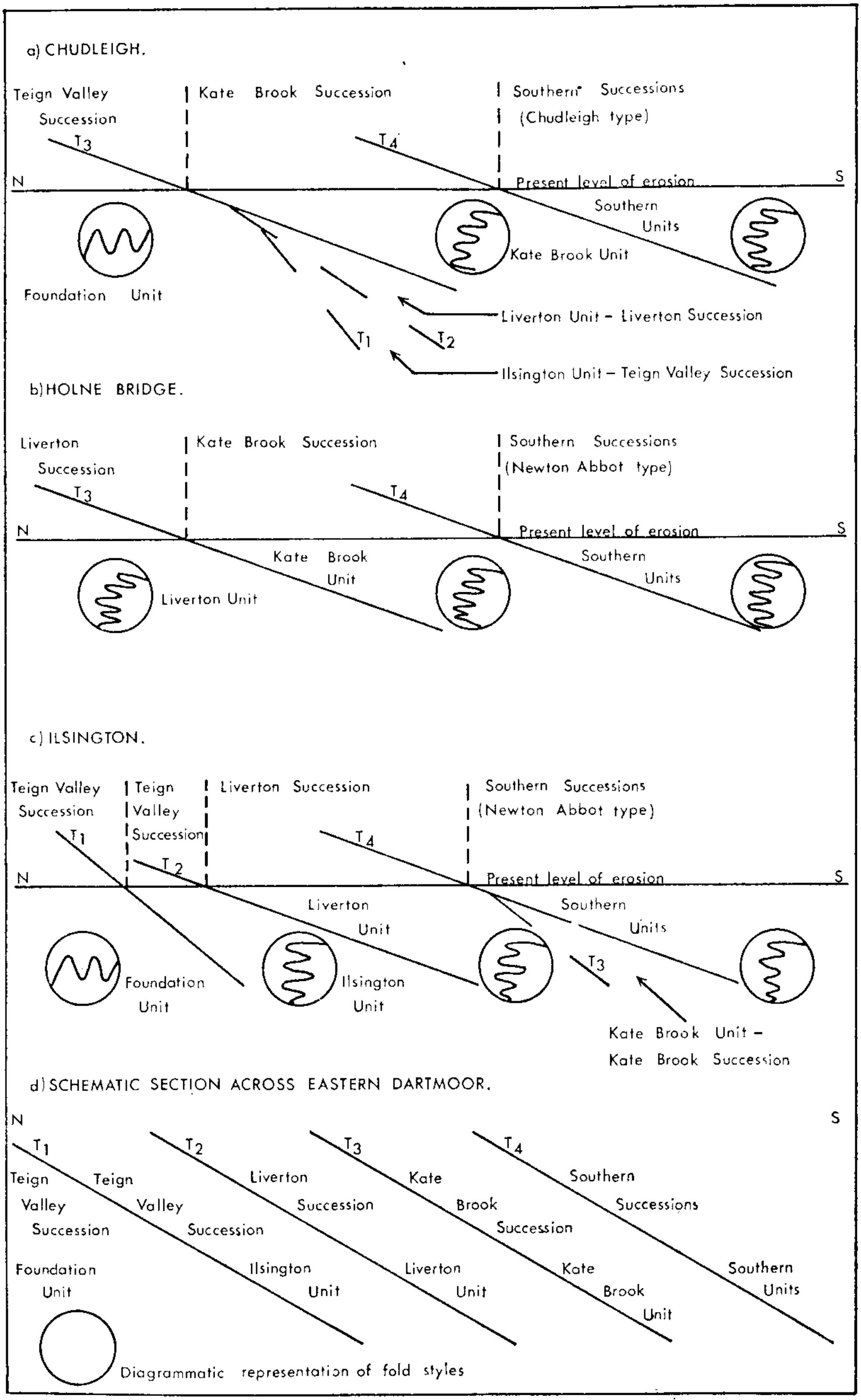

FIGURE 1. Sections at various points across Eastern Dartmoor.

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The relations between these tectonic units are best explained by reference to studies of Chudleigh, Holne Bridge and Ilsington, and of contrasting fold styles.

(a) Chudleigh

At Chudleigh (Fig. la) the Foundation unit is separated from the Kate Brook unit by a thrust T3. The latter unit is in turn bounded to the south by another thrust T4 on which the Chudleigh succession of the Southern unit is riding. The thrust T3 at Chudleigh is overridden by T4 at both ends of the Kate Brook succession outcrop.

(b) Holne Bridge

At Holne Bridge (Fig. lb) the thrusts T3 and T4 are seen as the northern boundaries to the Kate Brook and Southern unit (Newton Abbot succession) respectively. Thus although at Chudleigh T3 is the limit of exotic successions (Kate Brook unit carried over the Foundation unit), at Holne Bridge T3 carries the Kate Brook unit over another exotic succession, the Liverton unit.

(c) Ilsington

The thrusts T3 and T4 can be traced along the southern edge of the Ilsington area, with T3 bringing the Kate Brook unit from the south over the Liverton unit while T4 brings in the Southern unit, here comprising the Newton Abbot succession (Fig. lc). Just to the north of Ashburton T4 overrides T3 and the latter is not seen again until it reappears beneath T4 at the western edge of the Bovey Basin.

At Ilsington the Liverton unit is carried over the Ilsington unit by a thrust T2. A further thrust (T1), possibly a low-angle reverse fault, separates the Ilsington unit from the Foundation unit. So here T2 separates exotic southerly derived units from the Teign Valley succession of the Foundation and Ilsington units, which suggest that at Chudleigh (Fig. la) the thrust T3 must have overridden T2 and possibly T1.

(d) Fold styles

The Foundation unit is characterised, in the Teign Valley, by upright folds overturned to the north in the north (Chesher 1968). The units that are brought in from the south exhibit a sub-horizontal slaty cleavage associated with isoclinal to close recumbent.

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The junction between these contrasting fold styles is everywhere tectonic. Flat lying structures are brought against upright structures by T3 at Chudleigh (Fig. la) and by T1 at Ilsington (Fig. lc). As T1 brings Teign Valley succession onto Teign Valley succession the transport is probably not great, though sufficient to cut out any transition from upright to recumbent folds (if ever such a transition existed). If T1 is present at Chudleigh, overridden by T3 and T2, then it is likely to separate flat-lying from upright folds within the Teign Valley succession, with the first southerly derived exotic succession, riding on T2.

3. Conclusion

Exotic successions of equivalent age have been carried tectonically from a southerly direction by thrusts (Fig. ld), and where the allochthon ajoins the autochthon a change in fold style from flat lying to upright is observed.

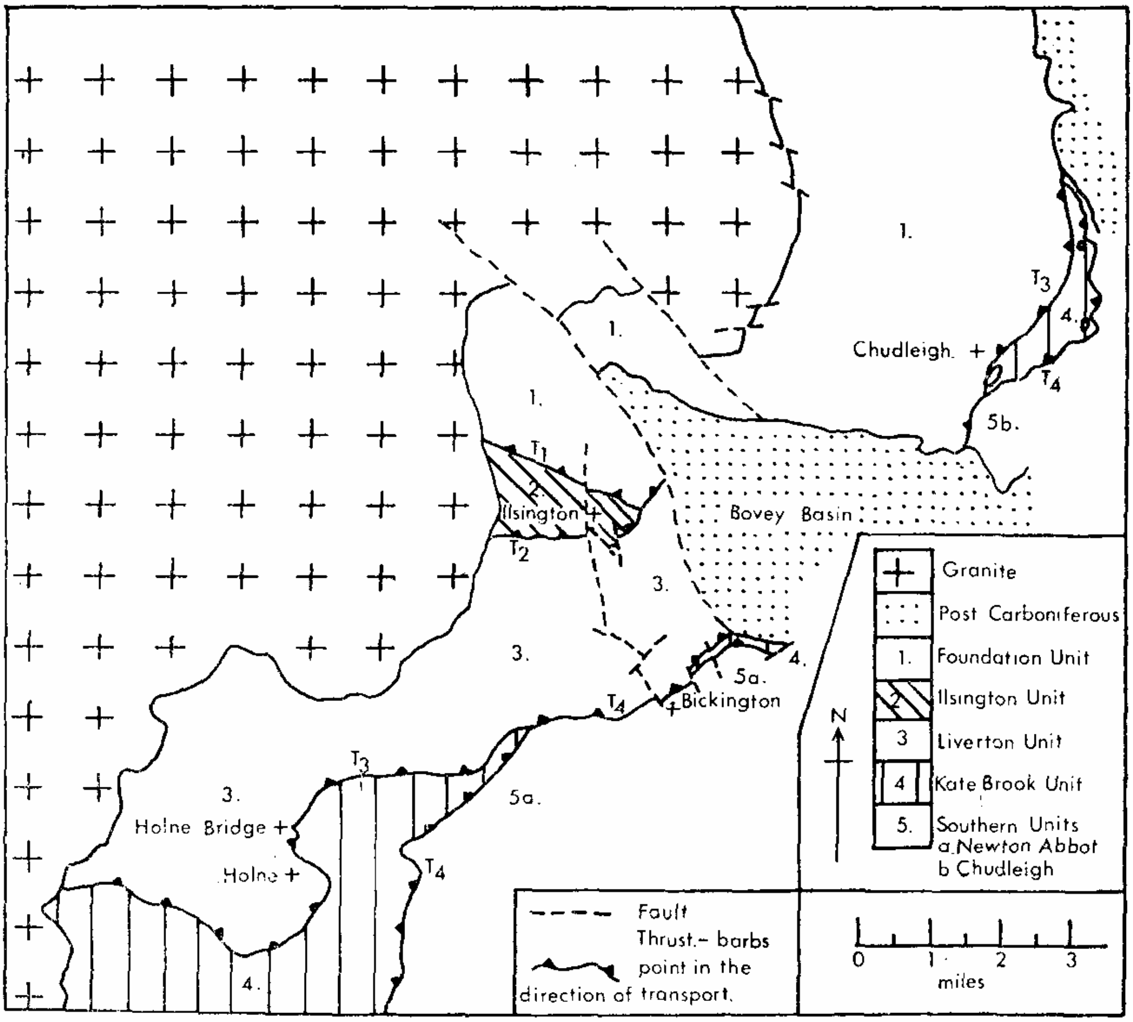

FIGURE 2. The tectonic units and thrusts of Eastern Dartmoor.

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The thrusts are fairly flat-lying and map out as sinuous lines with a NE-SW trend (Fig. 2). This trend however is attributable to the injection of the Dartmoor pluton having caused structures to swing round from the more usual E-W trend to a NE-SW one. Thus the tectonic transport could have been from any southerly direction.

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This contribution has been approved for publication by the Director of the Institute of Geological Sciences.

POSSIBLE TERTIARY DEFORMATION OF ARMORICAN STRUCTURES IN SOUTH EAST CORNWALL

by A. N. Lane

During the detailed mapping of the coastal belt around Looe in south-east Cornwall, it became apparent that the Portnadler Fault has had a significant effect on the local structural pattern. It is the purpose of this paper to describe these effects and to present some problems that are revealed.

The Portnadler Fault and the nearby Portwrinkle and Cawsand Faults are members of a series of dextral wrench-faults trending north-north-west across the south-west of England. Dearman (1963) considered that the wrench-faults were initiated as tension joints normal to the Armorican fold axes; later Tertiary movement along these fractures displaced dextrally all other structures. The faulting replaces laterally the folding of Alpine age found further east in the Hampshire Basin and the Isle of Wight. As mapped by Ussher (1907 and 1909) the Portnadler Fault follows a general north-north-westerly trend inland where at Bury Down

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it displaces the outcrop of the Staddon Grit dextrally by about one mile. Dearman (*op.cit.*) continues the trace of the fault along the western limit of the Bodmin Moor granite and on to the north coast.

Along the coastal strip of the Looe area a conjugate set of minor wrench-faults cuts all pre-existing structures. Measurements of joint and fault plane attitudes demonstrate that the strike of the dextral component of the system lies parallel to tension joints normal to the Armorican fold axes. The faults do not change their orientation across the Portnadler Fault but become less frequent away from it. The dextral component of the minor faults lies parallel to the general trend of the Portnadler Fault, implying that there is a relationship between the conjugate minor fault system and the Portnadler Fault.

A distinctive feature of the Portnadler Fault is that it strikes west-north-west inland from the coast for about three miles before veering to the north-north-west for the remainder of its detectable course. All other major faults in the same series appear to maintain a more constant strike to the north-north-west. The deflection of the Portnadler Fault as it approaches the coast near Looe could represent terminal splaying. De Sitter (1956) has suggested that wrench-faults can pass into thrust faults and the change of trend of the Portnadler Fault might represent a stage in this process. Alternatively, the Portnadler Fault could have originated locally as an Armorican wrench-fault; later and more extensive slip locally may have followed this west-north-west path.

A second more striking feature of the Portnadler Fault is that it divides the Looe area into two zones of identical structural styles and sequences, but with very different structural orientations. Along the south coast of Cornwall and south Devon Armorican deformation has caused planar structures such as bedding and cleavage to dip generally to between south and east with fold structures facing to between north and west. Such is the case in the block of country to the east of the Portnadler Fault where bedding and cleavage dip to the south-east and folds of all sizes face north-west. However, along the coast to the west of the fault the opposite is true and bedding and cleavage dip north and folds face to the south. Because of its anomalous character within the regional setting, it is concluded that the block of country to the west of the fault must have moved

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after the main Armorican deformation to reach its present attitude. This movement is most likely to have occurred either as some form of rotation or as a strike-slip displacement along the fault plane, thereby introducing into the area a structural zone from a region of different structural attitude.

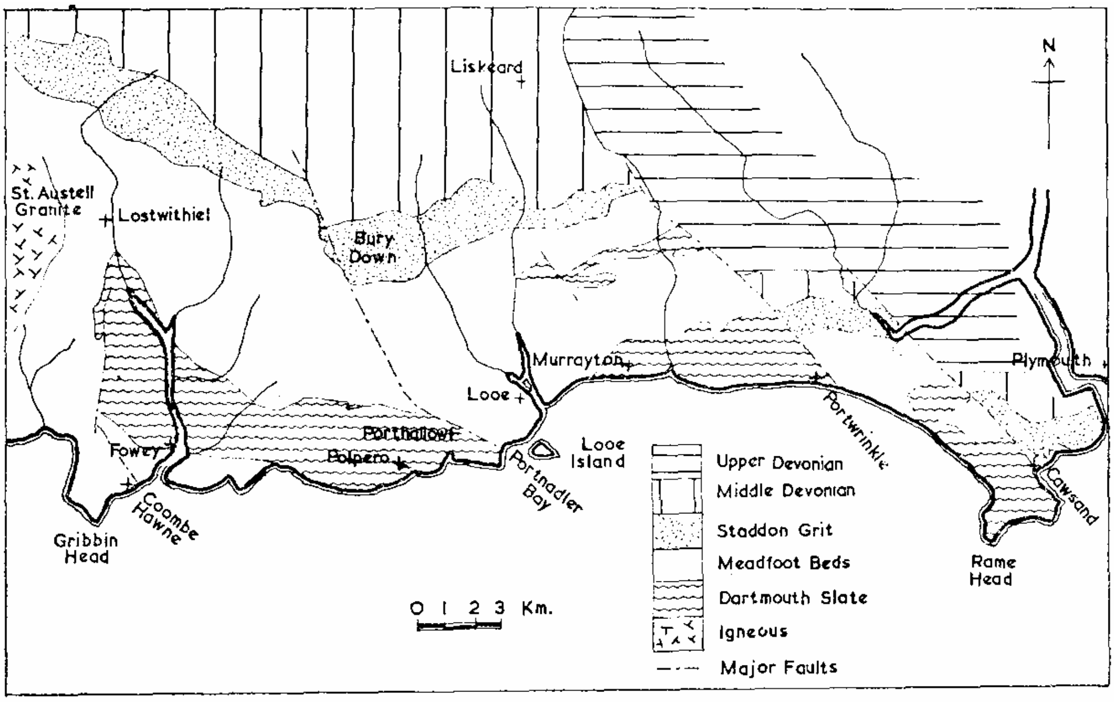

FIGURE 1. Geological map of the south coast of Cornwall from Plymouth to Fowey.

If strike slip displacement is considered first, then the outcrop of the Staddon Grit six miles inland near Bury Down (Fig. 1) is displaced dextrally by about one mile. Dearman (1963) has demonstrated a likely displacement of the order of one mile further to the north-north-west. Recent mapping in the Looe area indicates the presence of a major anticline comparable to the structure shown on the Tectonic Map of Great Britain (Dunning 1966) and across the fault the anticlinal axis is offset dextrally by about one mile.

An apparent displacement of only one mile is unlikely to bring together Armorican structures of strongly contrasting attitudes. Cleavage adopts a slight northerly dip near Liskeard, about seven miles to the north, but folds in this region face north. The introduction from the north of northerly dips to the west side of the fault would in any case require a sinistral movement. Another possibility is that the block west of the fault has moved from the south. Again,

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it is suggested that it is unlikely for two large Armorican folds with such contrasting attitudes to lie so close together before the wrench-faulting. Adjacent coastal sections of south Devon and Cornwall having a greater continuity in a north to south direction show no evidence for any such abrupt regional reversal of attitude.

Evidence for rotation is best presented by briefly considering the structure of the area. In Figure 2 it can be seen that a north-north-westerly facing anticline is present to the east of Portnadler. The lower steeply dipping and inverted limb can be traced east from the Portnadler Fault to a point on the coast by Murrayton farm-house. The upper gently dipping limb lies east of Murrayton and also occupies Looe Island. The upper limb of the anticline is characterized by minor folds which when viewed from the west present an S profile; small thrust faults concave to the south east are common. Thrust faults are rare on the lower limb where minor folds present a Z profile.

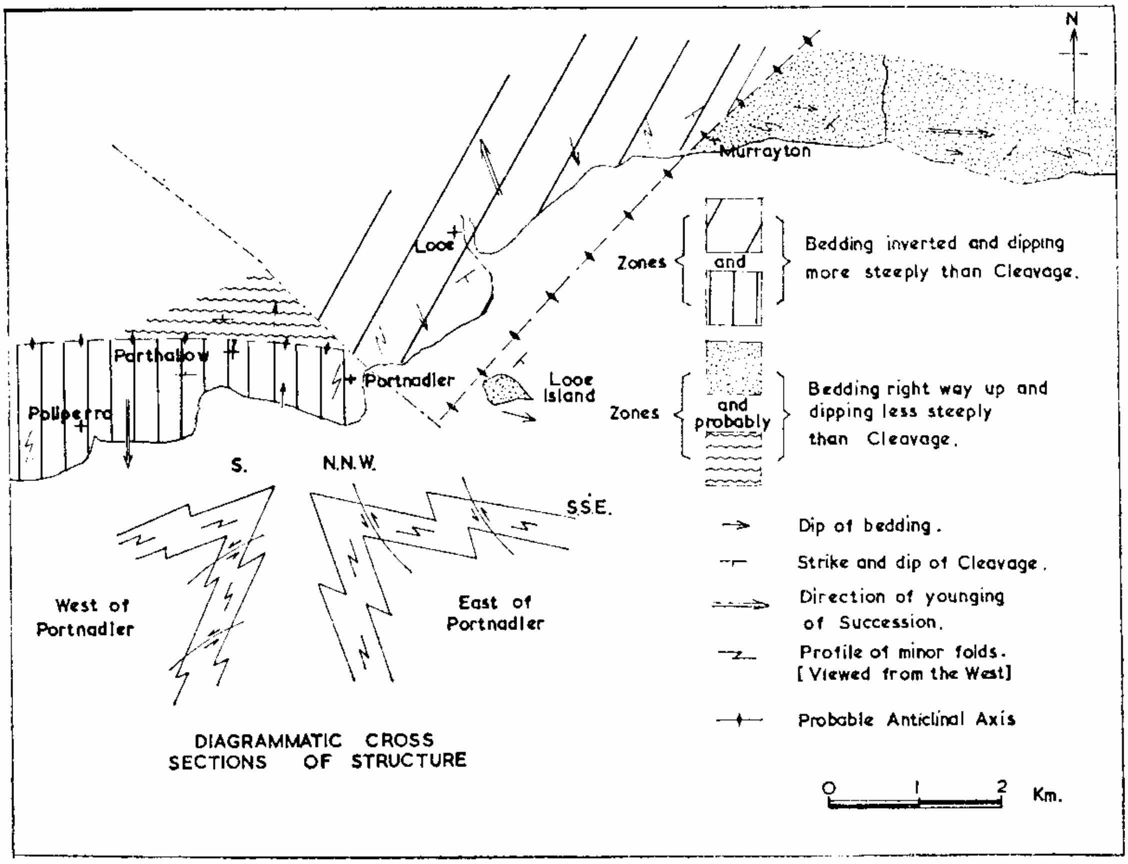

FIGURE 2. Structural zones east and west of the Portnadler Fault. Inset: diagrammatic cross-sections of the major folds east and west of the fault.

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A southerly facing anticline appears to be present to the west of the Portnadler Fault, and the axial trace follows an east-west trend passing through Porthallow (Fig. 2). The coastline west of Portnadler is incised into the steeply dipping inverted limb of the anticline. When viewed from the west the minor folds along the coast present an S profile and small faults abound but, in contrast to those east of Portnadler, are low-angle normal faults which are convex upwards.

On the assumption that the anticline to the east of the Portnadler Fault retains its original attitude then the evidence presented is consistent with the concept of rotation, namely, the coastal belt west of the fault is a continuation of the upper limb of the structure east of the fault, or a segment of it, rotated into its present attitude after the cessation of the Armorican folding.

A view from the west presents a clockwise rotation of the order of eighty degrees in the vertical plane. Rotation is not strictly limited to the block of country west of the fault. The dips of both bedding and cleavage steepen considerably from Looe towards Portnadler and east to west along the north shore of Looe Island. However, both planar elements retain their original angular relationship to each other. This steepening is in a clockwise direction when viewed from the west. The relationship of the rotated block to the regional structure becomes very problematical. The simplest structure produced by rotation would be a monocline (Fig. 3a) imposed on the gently dipping normal limb of a large Armorican anticline. However, the likely occurrence of low northerly bedding dips to the north of Porthallow suggests the complete rotation of a pre-existing anticlinal structure (Fig. 3b).

Although it has previously been assumed that movement within the plane of the Portnadler Fault was dominantly of a strike slip nature, evidence of rotation suggests that oblique slip is present at least in the coastal region. Hence the measurement of the horizontal displacement of the anticlinal axes becomes a rather doubtful quantity.

The association of rotation, that is folding, and strike-slip displacement presents a similar picture to Hills' (1963) concept of tear faults. Hills (*op.cit*) restricts the use of the term 'tear fault' to those strike-slip faults which cut folds forming contemporaneously with the faulting, as is possibly the case of the structure west of Looe.

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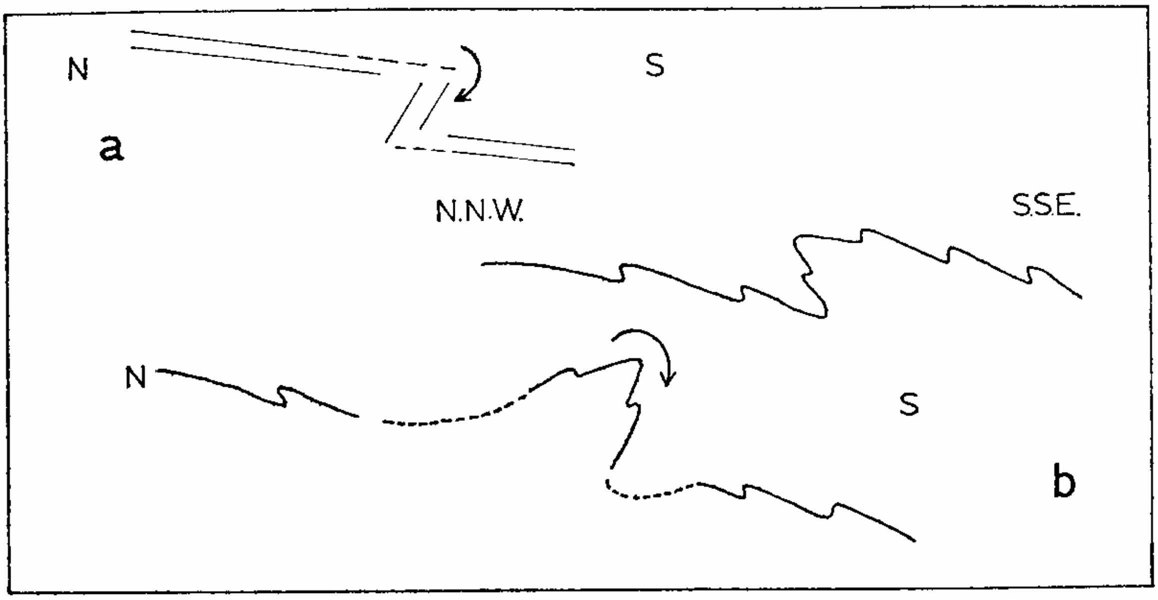

FIGURE 3. Structures produced by rotation (a) a simple monocline on gently inclined beds, (b) rotation of previously existing anticlinal structure, with, above, the structure east of Portnadler and, below, that to the west.

The mechanics of the rotation west of Portnadler are as puzzling as the form of the fold. Dearman (1963) and Shearman (1967) have suggested that the wrench-faulting in the South-West was formed by a stress field within which the maximum compressive stress acted in an approximately north to south direction. This is consistent with the approximate east-west trend of the rotated belt.

The south facing structure to the west of Portnadler suggests a northwards movement of the sub-Devonian basement with overriding of the upper layers to the south and subsequent rotation. This movement may well have commenced over a wide area prior to the faulting, as is implied by the slight rotation east of the Portnadler Fault. Initiation of the faulting may well have mainly relieved the stress east of the fault, other than that represented by the later formation of conjugate minor faults, but to the west of Portnadler the rotation continued to give the present structure.

A movement plane, terminating at its northern limit the zone of rotation and extending south down to the sub-Devonian basement, would conveniently explain a case of awkward structural continuity. Unless the rotation dies out gradually to the west then

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it must be terminated by a structural break similar in nature but opposite in effect to the Portnadler Fault. The evidence at this stage of the investigation suggests that the rotation is terminated at the Coombe Hawne fault zone. (Fig. 1) with an apparent return to south-easterly dips to the west. On the map the faulting at Coombe Hawne can be seen to strike inland initially to the west north west, but then links up with the supposed faulted western limit of the Dartmouth Slate outcrop. Even allowing for the effects of the intrusion of the adjacent St. Austell granite, this faulted junction, striking to just east of north, has an unusual trend for an Armorican structure.

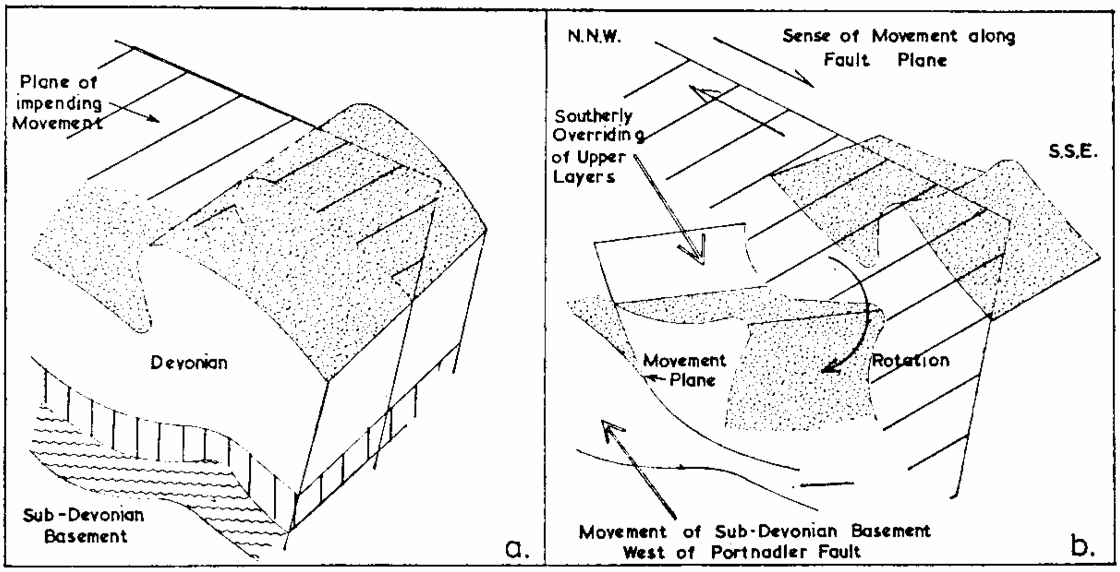

FIGURE 4. Block diagrams illustrating the Portnadler structures, (a) before wrench-faulting and (b) afterwards.

Structural features suggestive of rotation of a similar nature can be found at Rame Head (Fig. 1) and in adjoining areas. For example, there is considerable variation in the attitude of bedding and cleavage along the shores of the Rame Peninsula. More striking, however, is the east-west variation along the strike. Northerly dipping beds at Cawsand revert to a south-easterly dip on the other side of the peninsula between Rame Head and Portwrinkle. That these variations occur within a block of country contained between two large wrench-faults, the Cawsand Fault to the east and the Portwrinkle Fault to the west, probably implies a genetic relationship between the deformation of the slates and the wrench-faulting.

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Finally, some thoughts on why rotation is so strongly developed west of Portnadler. The coastal belt including Portnadler and Coombe Hawne (Fig. 1) is the widest part of a wedge of soft rocks which narrows rapidly to the north between the St. Austell and Bodmin Moor granites. In a tectonic drive to the north, the constriction presented by these two resistant granite bodies may have intensified the effects of the Alpine deformation to the south. The irregularity presented by the marked change in trend of the Portnadler Fault, from an atypical west-north-west direction on the coast to a more north-north-westerly trend inland, might have affected the deformation of the slates brought about by fault movement.

Rotation of the kind described would have some significance in the structural interpretation of the South-West if the effects were found to be widespread. The structure found west of the Portnadler Fault is probably an extreme case. A more gentle deformation of the pre-existing structures could be mistaken for a regional or a later phase variation in the general Armorican pattern, especially as the axis of rotation could lie close to the Armorican trend.

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THE COMPOSITION OF CORNISH QUARTZ-PORPHYRY (“ELVAN”) DYKES

by A. Hall

Abstract. Previously published analyses of Cornish elvans show that they differ considerably from their associated granites. In contrast, a new analysis of elvan from Hingston Down is of normal granitic composition.

Dykes and other minor intrusions of quartz-porphyry, locally known as ‘elvan’, are associated with all the principal granities of Cornwall. Their petrography and mode of occurrence have recently been reviewed by Exley and Stone (1964: 147-149). The petrogenesis of the Cornish elvans presents a problem because on the basis of existing analyses they appear to be chemically dissimilar to the granites with which they are associated.

The quartz-porphyry dykes which have so far been studied do show some general resemblances in chemical composition to normal granitic rocks, as would be expected from their petrographic similarity. Silica contents are in excess of 70%, and only small amounts of iron, magnesium and calcium are present. The chemical features which are anomalous are the very low sodium and very high potassium contents.

The average composition of all previously analysed Cornish elvan dykes is shown in column 1 of Table 1. The total alkali content of 8.1% is not unusual for a granite, but the K_2O/Na_2O ratio of 11.3 is extremely high, and much higher than that of any of the granites of south-west England. For example, Brammall and Harwood (1932) found values of this ratio ranging from 1.1 to 2.5 in different samples of the Dartmoor granite, 1.0 to 1.7 in the St. Austell granite, and 1.8 in the Bodmin Moor granite; Ghosh (1934) found values of 1.3 to 2.7 in the Carnmenellis granite, and Hall (1969) found values of 1.4 and 1.7 in the Cligga Head granite. This difference in alkali ratios between the elvans and the associated granites is difficult to reconcile with a common magmatic parentage for the two rock types.

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A new analysis by the author of a quartz-porphyry dyke from the Hingston Down granite suggests that not all elvans show the abnormal alkali contents described above. This analysis is given in column 2 of Table 1, together with analyses of the Hingston Down granite in columns 3 and 4.

TABLE 1. Chemical compositions of Cornish elvans and granites

	1	2	3	4
SiO_2	71.95	72.36	73.22	73.15
TiO_2	0.22	0.16	0.06	0.21
Al_2O_3	14.42	14.67	14.67	14.42
Fe_2O_3	1.27	0.46	0.22	0.40
FeO	1.31	0.54	0.54	0.96
MnO	0.05	0.01	0.01	0.02
MgO	0.39	0.40	0.23	0.48
CaO	0.58	0.80	0.45	0.90
Na_2O	0.66	3.41	3.85	2.82
K_2O	7.44	5.16	4.75	5.31
H_2O+	1.28	0.88	0.79	0.61
H_2O-		0.47	0.40	0.48
P_2O_5	0.29	0.17	0.18	0.13
B_2O_3		0.08	0.11	0.08
Li_2O	0.04	0.03	0.03	0.02
F		0.17	0.13	0.07
	99.90	99.77	99.64	100.06
O≡F		0.07	0.05	0.03
Total	99.90	99.70	99.59	100.03

1. Mean of eight previously published analyses of Cornish elvans : one from Praze (no. 11 of Ghosh, 1934), one from Mellanear (no. III on p.335 of Phillips, 1875), two from Tregonning Hill (nos. 5 and 6 on p.149 of Exley and Stone, 1964), and four from Praa Sands (nos. 1-4 of Stone, 1968).
2. Quartz-porphyry dyke, Hingston Down quarry, Chilsworthy, near Gunnislake, Cornwall.
3. Coarse-grained biotite-granite, Hingston Down quarry.
4. Fine-grained biotite-granite, Hingston Down quarry.

Nos. 2-4 are new analyses by the author.

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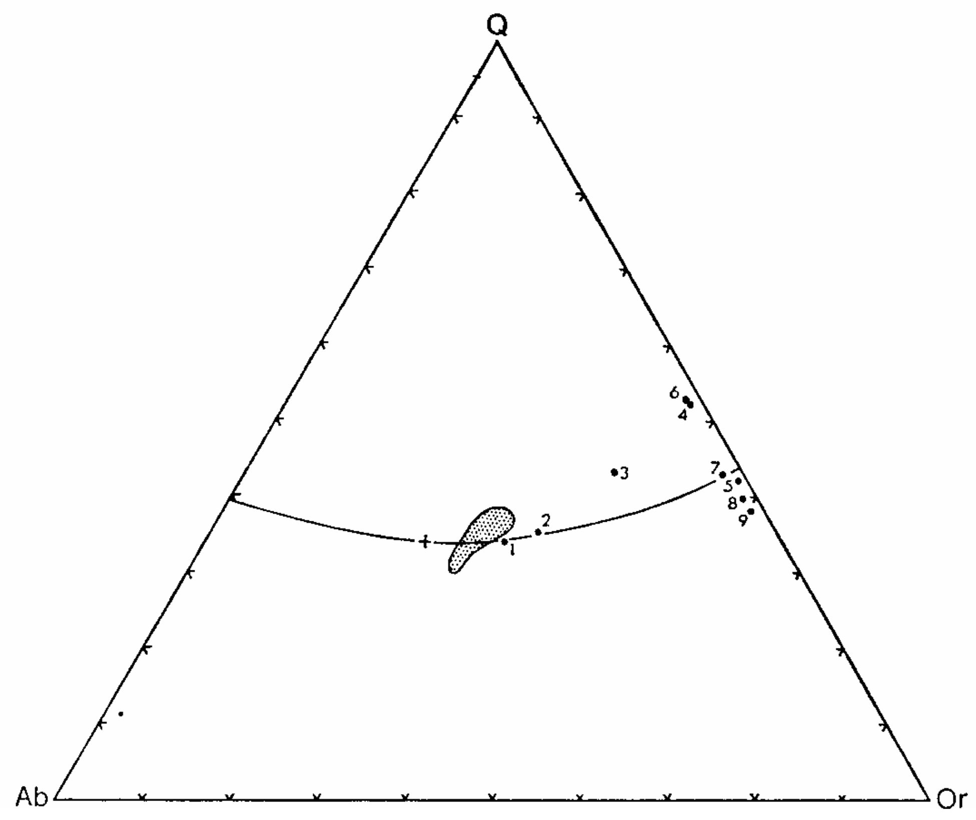

FIGURE 1. The compositions of Cornish elvans in relation to the system Q-Or-Ab-H_2O. The cross marks the position of the 'ternary' minimum at a water pressure of 2000 bars, and the shaded area represents the greatest concentration of compositions of granitic rocks (Tuttle & Bowen 1958). The elvans are numbered as follows : 1 Hingston Down, 2 Mellanear, 3 Praze, 4-5 Tregonning Hill, 6-9 Praa Sands (references to these analyses are given in Table 1).

The analysed elvan dyke is exposed in the north-eastern corner of the Hingston Down granite quarry at Chilsworthy, near Gunnislake, and is one of several elvan dykes associated with this granite intrusion. The rock consists of phenocrysts of quartz, feldspars (orthoclase-microperthite and sodic plagioclase) and reddish-brown biotite, set in a groundmass of quartz, feldspars and muscovite. The dyke shows a fine-grained chilled margin against the granite, into which it is intruded, and contains a few xenoliths of the granite.

The chemical analysis of the Hingston Down elvan corresponds to that of a normal alkali-granite, with the addition of traces of boron, lithium and fluorine, elements which are commonly present in small amounts in the granites of south-west England. The elvan

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is closely similar to the granites of Hingston Down, and for many constituents it is actually intermediate in composition between the two varieties of the Hingston Down granite. The analyses do not suggest in any way that the granite and elvan magmas are unrelated. The granites are themselves quite typical of granites from south-west England.

The petrogenetic significance of these observations may be illustrated by Figure 1. Tuttle and Bowen (1958) have shown that the great majority of granitic rocks are similar in composition to the minimum in the system Q-Or-Ab-H_2O at water pressures of the order of 0.5 to 3 kilobars. The Hingston Down elvan lies close to the 'ternary' minimum, and near the field of maximum concentration of granitic rocks, whereas most of the other analyses of Cornish elvans lie well away from this composition. The Hingston Down elvan may therefore be interpreted as being a normal magmatic rock of granitic composition, but the other elvans, with the exception of that from Mellanear, can not have been derived directly from a granitic magma by the normal processes of magmatic crystallization. A similar conclusion was also reached by Stone (1968), who suggested that the elvan of Praa Sands may have been derived from a biotite-granite magma by alkali ion exchange. The composition of the Hingston Down elvan confirms that the parent magma of the Cornish elvans was of normal granitic composition.

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New isotopic age-determinations, S.W. England (Abstract) :

by R. R. Harding and J. R. Hawkes.

Available K/Ar and Rb/Sr isotope data from biotite and muscovite occurring in the S.W. England granites yield a spread of ages between 306 m.y. and 250 m.y. Using this information with geological evidence, Fitch and Miller reasoned that the plutons were probably intruded during the Stephanian about 295 m.y. ago, the younger dates being indicative of subsequent hydrothermal alteration. ^{206}Pb/^{238}YU and ^{207}Pb/^{235}U isotope data from uranium minerals likewise give a series of ages suggesting that mineralization in this province was not due to a single event. One way of interpreting the latter data is to relate ore genesis to three different processes, namely; dispersed pegmatitic mineralization developed within the fabric of the granites while they were crystallizing, precipitation from fumarolic vapours derived from acid volcanism possibly around 220-230 m.y. (the main lode-mineralization) and, finally, intermittent hot spring activity during the last 170 m.y.

To provide a more rigorous test for these ideas, a project is being carried out using Rb/Sr analyses of selected whole-rock and mineral samples collected from the granites, quartz-porphyry dykes and the lodes. A preliminary whole-rock age is reported here : non-kaolinized, big-feldspar facies, St. Austell Granite (8 samples) 288 m.y. (Mr. C. M. Bristow of English China Clays kindly supplied two of the St. Austell granite samples used in the determination).

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AN APPLICATION OF STATISTICAL METHODS TO THE GEOCHEMISTRY OF AN AREA AROUND PERRANPORTH, CORNWALL

by S. Henley

Abstract. 80 samples of sedimentary rocks have been analysed for 10 major elements and 9 trace elements. Two-dimensional plots give little information even when Niggli transforms are used. Trend surface analysis of the trace elements reveals significant patterns in most cases. 9 factors have been derived by factor analysis which together explain 86% of the chemical variation and have been given substantive interpretations.

1. Introduction

80 samples of slates, siltstones, and greywackes from the area illustrated in Figure la, have been analysed for 10 major elements and 9 trace elements. SiO_2, $A1_2O_3$, TiO_2, total iron, MnO, and P_2O_5 were determined by methods modified from Shapiro and Brannock (1956) and Riley (1958), using a Hilger and Watts spectro-photometer. MgO and the alkali metals were analysed by flame photometry, and CaO by X-ray fluorescence spectrometry, as were all the trace elements (S, Cl, Co, Cr, Sn, Ba, La, Ce, and Nd). These elements were calibrated by spiking a standard slate (Nottingham University standard 1007) with differing amounts of the appropriate spectrographically pure oxide; in the case of sulphur, the standard CAAS sulphide ore was added, while for chlorine, rubidium chloride was used. In the case of calcium, "Analar" calcium carbonate was found to give accurate results.

2. **Results**

The rocks analysed showed a very wide range of composition; significant facts to emerge are the very low content of calcium in all these rocks, the high K_2O/Na_2O ratio, and the very high silica, even in the more argillaceous rocks.

3. **Interpretation**

(a) *Major elements*

Simple two-element plots were at first attempted, to elucidate the relationships between the major elements. However, strong apparent negative correlations occurred between silica and all the other major elements (e.g. with K_2O in Fig. lb). This is as one might expect from a closed data system, particularly when the most important variable, silica, shows such extreme variation.

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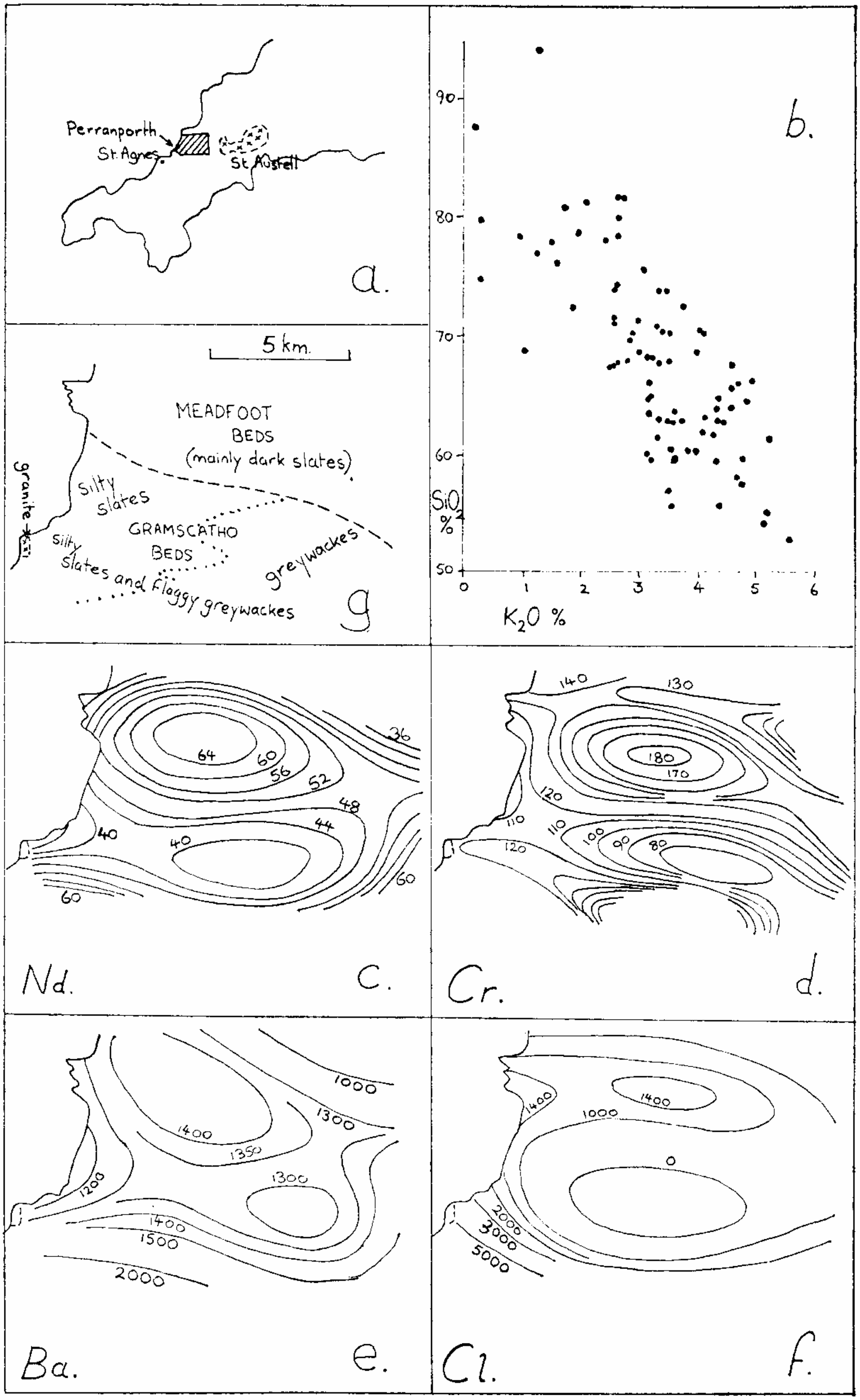

FIGURE 1. (a) Location of the area. (b) Plot of silica against potash. (c) 3-degree trend surface for neodymium. (d) 5-degree trend surface for chromium. (e) 3-degree trend surface for barium. (f) 3-degree trend surface for chlorine. (g) Geology of the area.

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Plotting Niggli numbers in an attempt to avoid this hazard gave little better results however, as no correlations could be seen in the plots produced by this method.

(b) Trace elements

Examination of trace element distributions was initially by polynomial trend surface analysis, to obtain information on their areal variations : this method was employed not as a rigorous statistical tool, but merely as an expedient way of presenting the data. It revealed significant patterns for all the elements determined, with the exceptions of tin and sulphur, for which trend analysis accounted for very little of the variation.; a six degree equation only gave a 6.4% fit in the case of tin, and for sulphur a four degree equation accounted for only 10.6%.

The rare earth elements lanthanum, cerium, and neodymium all give very similar patterns, with maxima in the northern part of the area, and in the south-east, and a trough of low values across the centre (Fig. lc, neodymium). Chromium and barium also give strikingly similar trend maps (Figs. ld, e) with low values just south of the Meadfoot/Gramscatho boundary (Fig. lg), and high values in the area of the Meadfoot Beds. In the area studied, the Meadfoot Beds consist principally of dark slates, occasionally tuffaceous, frequently with small fossiliferous lenticles of iron carbonate, and usually quite intensely sheared, with much quartz veining. The Gramscatho rocks, on the other hand, include greywackes, siltstones, and slates, the latter predominating in the west, while the coarser rock types are more important in the east. The difference in trace element contents between the two groups is not due solely to the difference in silica content of the rock types, which is not particularly great : some other factor must be sought.

The trend maps for barium and the rare earths show an increase in the south-east, where the Gramscatho rocks become coarser along the strike, and conglomerates begin to appear. These increases in value may thus be 'due to the abundance of detrital constituents such as microcline (observed in thin sections of these rocks) and rare earth-bearing minerals.

The chlorine trend map shows high values, as might be expected, along the coast, with a maximum around the Cligga Head granite, which is possibly a result of metasomatism associated with the granite.

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TABLE 1. Varimax rotated factor matrix. Loadings less than 0.21 are omitted

Factor	1	2	3	4	5	6	7	8	9
Element									
SiO_2			0.72	-0.48		0.26			
Al_2O_3	-0.22		-0.81	0.32					
TiO_2			-0.43	0.64					-0.29
Fe_2O_3		-0.38	-0.33	0.38	0.31	-0.51	-0.29		
MgO		-0.39		0.76				0.27	
CaO								0.92	
Na_2O	-0.27			0.52				0.59	
K_2O			-0.91						
MnO		-0.91							
P_2O_5						-0.96			
SiO_2					0.91				
Cl							0.92		
Cr	-0.23		-0.25	0.84					
Co		-0.65		0.47	0.24	-0.26			
Sn					0.22				0.86
Ba			-0.83			0.23			-0.23
La	-0.79		-0.26				-0.22		-0.31
Ce	-0.86								
Nd	-0.84								

Chromium shows a similar map to that exhibited by the rare earths, with the exception that there is a prominent maximum across the southern edge of the area. It seems likely that chromium, as well as the rare earths, is associated with a detrital constituent, in this case illite or muscovite. Gad *et al.* (1969) quote evidence that chromium is strongly adsorbed on to detrital phyllosilicates during transport, and is only weakly desorbed after deposition. Such a process could partly explain the distribution of this element in the present study, since flaggy siltstones, with large flakes of probably detrital mica, occur in, and are almost confined to the area of high Cr values.

(c) Factor Analysis

Principal components analysis, followed by varimax rotation of the factor matrix, was carried out on the complete data matrix, and the resulting rotated factor matrix is given in Table 1. The factor-vectors in this matrix (the columns) can be given physical interpretations representing the main sources of variation in the analysis, either actual mineralogical constituents of the rocks, or processes which have acted on them. 9 factors account for 86.6% of the total variance, factor loadings above 0.21 in this analysis are significant at the 95% level, and those below this are omitted from the table.

Factor 1 has significant loadings on Al_2O_3,Na_2O, and Cr, and high loadings on the rare earths. This is difficult to explain, but may be due to an association of detrital rare earth minerals with detrital micas which possess adsorbed Cr, as previously suggested.

The second factor, with high loadings on ferromagnesian constituents, and in particular on MnO, appears to represent the contribution made by iron and manganese oxides, which are abundant in many of the samples.

Factor 3, with high loadings on Al_2O_3, K_2O, TiO_2 and total iron, probably represents the mica minerals. The fact that most of the samples are essentially bimineralic mica-quartz rocks, accounts for the presence of silica in this factor, with opposite sign, reflecting its negative correlation with all the other elements. The high loading on Ba reflects its almost universal substitution for potassium, and the presence of a significant La loading in this factor may indicate that this element also substitutes for potassium, despite the

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difference in ionic charge of 2. The ionic radius of K^+ is 1.33, while that of La^{+++} is 1.14. The other rare earths studied, Cc and Nd have ionic radii of 1.07 and 1.04 respectively and so would not substitute for K to the same extent.

Factor 4, with significant loadings on total Fe, MgO, ALO, $Ti0_3$ and Cr, indicates the importance of chlorite : apart from the ubiquitous fine grained chlorite, coarse-grained penninite is also commonly seen in thin sections of these rocks, often associated with the lenticular quartz veins in both the Meadfoot slates and the Gramscatho rocks.

Factor 5, with high loadings only on S, Fe, Co, and Sn, is interpreted as due to sulphide mineralisation. Factor 6, in which P_2O_5 is the most important constituent, with significant loadings on only Fe and Co otherwise, indicates that in the lack of appreciable quantities of CaO, the phosphorus present is combined with iron.

Factor 7 represents simply the addition of chlorine, perhaps largely due to sea-water attack. The negative loadings on iron and lanthanum, however have not yet been explained.

Factor 8 contains significant loadings on MgO, CaO, and Na_2O, and may possibly be interpreted as the loss of these elements in chemical weathering, since it is these three elements which are leached most rapidly from silicate rocks under normal circumstances (Krauskopf 1967).

The ninth factor, with a high loading on tin, represents cassiterite mineralisation. The presence of tin in factor 5 may be due either to spatial coincidence of the tin and sulphide deposits, or possibly to the presence of some of the tin in sulphide minerals such as stannite.

4. Conclusions

The geochemistry of the sediments in this area is too complex for simple statistical methods such as correlation analysis (comparing two elements at a time) to reveal the underlying causes of variation, and recourse must be made to the more advanced methods, of trend analysis and factor analysis. When these methods are employed, even, the conclusions which emerge can only be given tentative interpretations in this study, and more definite results await the addition of further samples and the analysis of 15 more trace elements.

Acknowledgments. Thanks are due to Dr. P. K. Harvey for much helpful advice and discussion. The research was carried out during the tenure of a N.E.R.C. Research Studentship.

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THE USSHER SOCIETY

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To promote research into the geology and geomorphology of South West England and the surrounding marine areas ; to hold Annual Conferences at various places in South West England where those engaged in this research can meet both formally to hear original contributions and progress reports and informally to effect personal contacts ; to publish proceedings of such Conferences or any other work which the officers of the Society may deem suitable.

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