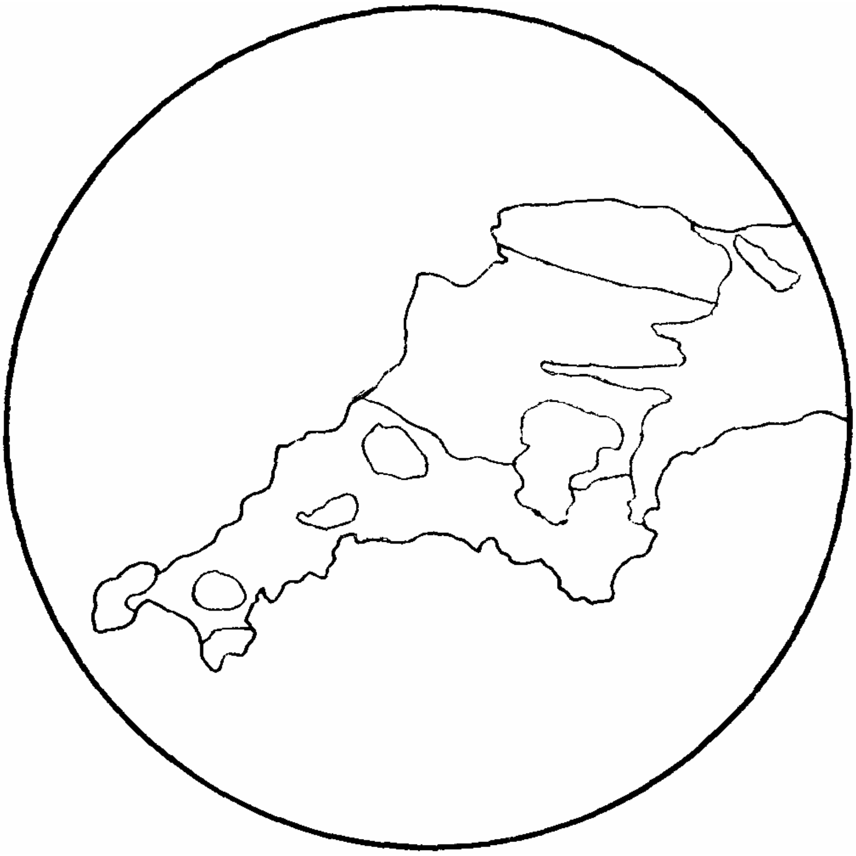
PROCEEDINGS
OF THE
USSHER SOCIETY

VOLUME THREE
PART THREE



1976

THE USSHER SOCIETY

Membership of the Ussher Society is open to all on written application to the Secretary and payment of the annual subscription (£4 ordinary members, £2 students and retired members) due on January lst each year. Cheques should be made payable to the Ussher Society.

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VOLUME THREE

PART THREE

Edited by
A. WHITTAKER

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CONTENTS

Conference of the Ussher Society held at Torquay January 1976

Chairman's Report

Yet again, Torquay proved a happy venue for the Society's Annual Conference. Appropriate to this setting, the proceedings got under way in good nautical style with a fascinating Invited Address from Mr. J.E. Wright on the "Geology of the south-western continental shelf", which demonstrated recent advances made in the exploration of our local offshore geology.

Members' contributions this year covered a breadth of topics ranging from electron microscopy to plate tectonics and a scenario from St. Just to South Wales. This diversity of interest surely guarantees the continuing strength of our Society.

By Sunday the stormy weather had abated and, with undampened enthusiasm, a hardy band followed Drs. Selwood and Thomas through the intricacies of the geology of the Ashburton area. Support for the field excursions remains encouragingly high - sometimes embarrassingly so in the region's narrower by-ways!

The success of our Conference is essentially a corporate achievement, but the Society's thanks are due especially to the Conference Secretary, Dr. R.T. Taylor, the Guest Speaker and the excursion leaders.

In the past year the Society's financial position has been sorely dented by increases in printing costs. The situation had been reached where annual subscriptions no longer covered the cost of the *Proceedings*. At the Annual General Meeting the membership voted overwhelmingly to accept a major increase in annual subscription to maintain the standard of our publication. To contain costs somewhat, it has been necessary to change printers; the Editor has been in touch with Phillips & Co. of Crediton who can offer similar type face and format to ensure continuity in Volume 3.

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By unanimous agreement Professor Scott Simpson was elected as our second Honorary Member. Professor Simpson was a founder member of the Ussher Society, an active Committee member, former Chairman and a regular contributor at the Annual Conference. In appreciating his valuable services the Society wishes him well in his years of retirement.

After some debate over the venue for next year's meeting it was widely approved that the Society should return to the Queen's Hotel, Torquay and Dr. Taylor kindly volunteered to act as conference secretary.

This year's meeting saw the retirement from office of Professor Dineley and Dr. Floyd. Dave Dineley was, with Professor Simpson, the instigator of the forerunner of this Society and Chairman in 1972 and 1973. We are grateful to him for his enthusiastic support and work on behalf of the Society. Peter Floyd's dedicated and invaluable service as the Society's Treasurer has been appreciated by successive Chairmen and Committees. His careful financial control has been a major factor in permitting the expansion of our *Proceedings* to its present form. In thanking him for his unswerving devotion to our interests I am sure that the traditions he has established will be ably carried forward by his successor, Dr. Mike Thomas.

Finally, on a personal note, I should like to thank the two Committees with which it has been a pleasure to work during my term as Chairman. In particular I would mention 'the Secretary, Treasurer and Editor, who do most of the chores and yet remain ever cheerful. It gives me particular pleasure to welcome Professor Michael House as our next Chairman; another founder member of the Society, he edited our first volume of *Proceedings.* I am sure he will enjoy his two years of office and that the Society will benefit greatly from his energy and wisdom.

K.E. Beer
June 1976

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The geology of the south-west U.K. continental shelf (Abstract):

by J.E. Wright

Much of Devon and Cornwall comprises a massif of Palaeozoic and older rocks which is surrounded by Mesozoic and Tertiary outcrops both on land and offshore. Much information on the offshore geology of the South-West has come from commercial seismic exploration, but the results of this work are confidential at present. There has also been a considerable amount of commercial offshore drilling in the Irish sector of the Celtic Sea, but these results have not been made public either. However, in parts of the Bristol Channel, the Celtic Sea and the English Channel, a great deal of evidence has been obtained about the outcrop geology by universities and I G S, utilising shallow seismic surveys, gravity coring and shallow drilling.

In the Celtic Sea and the western English Channel, the younger strata of importance in hydrocarbon exploration probably range in age from Permian to younger Tertiary. Locally they occur in deep troughs, such as the North and South Celtic Sea basins and the South-West Approaches Basin, which are probably major crustal features related to sea-floor spreading, and comparable in size to those of the North Sea. Outside of these troughs the Mesozoic and Tertiary rocks form a relatively thin cover over older massifs which lie at comparatively shallow depths.

Hydrocarbon prospects have not yet been fully tested. There are limited, but commercial, finds of natural gas in the Irish sector of the Celtic Sea south of Cork. So far, only two wells have been drilled in the UK part of the Celtic Sea and none in the South-West Approaches to the English Channel. The French have recently completed one well north-west of Ushant but the results are not available.

The size of the sedimentary troughs and the probable nature of the sedimentary infill suggests that the South-Western area has a potential for further exploration.

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THE STRUCTURE OF THE DARTMOUTH ANTIFORM

by D.M. Hobson

Abstract. In south Devon and Cornwall, a succession of Lower Devonian slates and sandstones crop out in the core of the Dartmouth Antiform. This is a compound structure comprising east-west trending FI folds, modified by a later coaxial open antiform, and also by a large fault. This fracture may have had a long history from initiation during the FI deformation, to final post-orogenic movement in the Permian.

1. Stratigraphy and tectonic history

It has long been recognised that Lower Devonian rocks occupy the core of an antiformal structure, the "Dartmouth Anticline", in south Devon and adjacent Cornwall. Dearman (1971) pointed out that this large fold is one of several in the Variscan fold belt which deform slaty cleavage, and hence are, at least in part, composite structures. The Dartmouth Antiform is well exposed in a series of coastal sections, many of which have been described in recent years. In particular, Ripley (1964, 1965) reports on that part of the structure in north Cornwall, Lane (1966a, b; 1970) has described' the geology around Looe, while Richter (1968) and Hobson (1976) have discussed different areas of south Devon. It is now possible to synthesise the available information and to present the details of the geometry of the Dartmouth Antiform.

The axial trace of the Antiform, as depicted by Dunning (1966) on the Tectonic Map of Great Britain, cuts through the outcrop of the continentally deposited Dartmouth Beds, which are locally the oldest known Devonian rocks (Dineley 1961). This formation is composed mainly of purple, grey and green interbanded slates and siltstones, but in south Devon it is somewhat arenaceous, and pyroclastic rocks are also present (Dineley 1966). Although the base of the Dartmouth Beds is not exposed, the formation is about 3100 m in thickness south east of Plymouth (Hobson 1976). However, south of the present exposures of the Dartmouth Beds, Sadler (1974) has recognised a rapid facies change to a thin deeper water Lower Devonian sequence.

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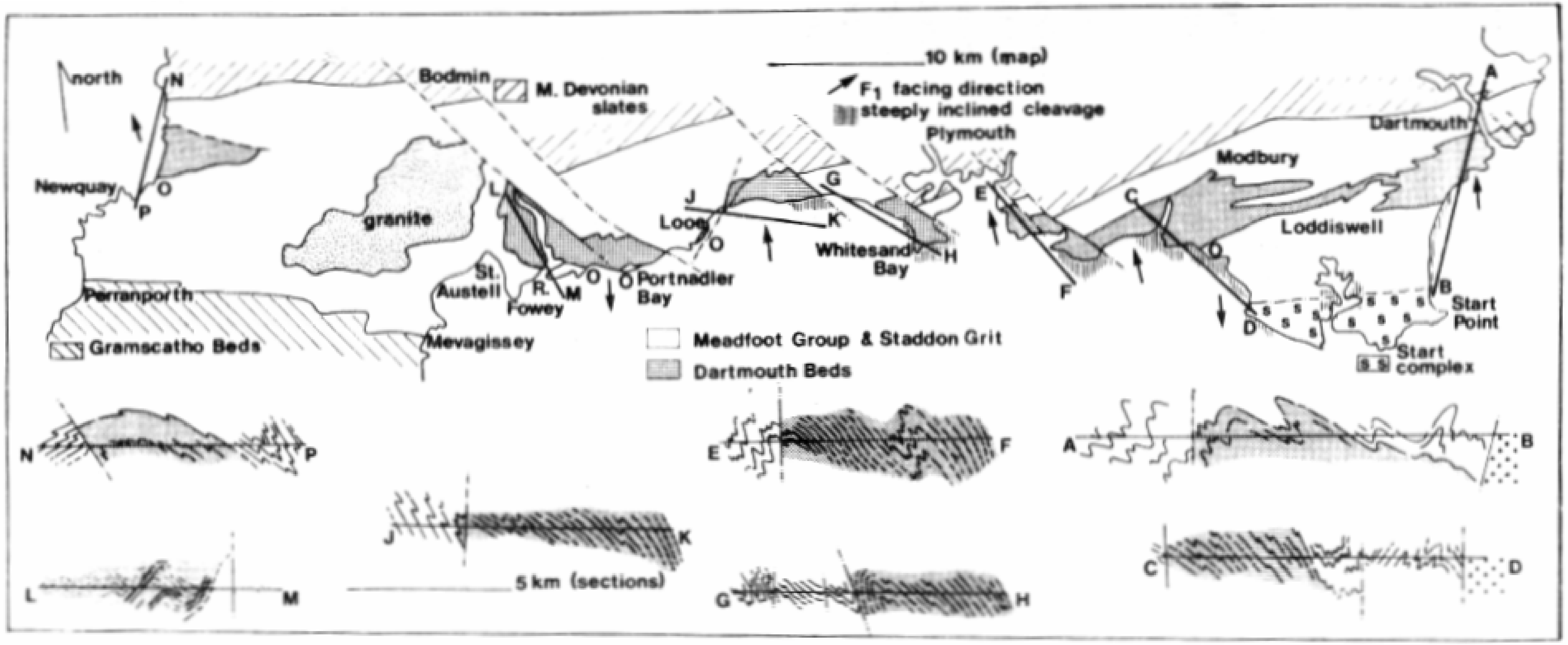

FIGURE 1. Geological map and diagrammatic sections through the Dartmouth Antiform. The map is based on the 1" :1 mile Geological Survey sheets 346, 347, 348, 349, 350, 355 & 356. The sections are based on various authors acknowledged in the text.

O-- localities where a conformable boundary between the Dartmouth Beds and the Meadfoot Group is exposed.

On the flanks of the antiform, the Dartmouth Beds are overlain by other Lower Devonian rocks - the Meadfoot Group and the Staddon Grits (Ussher 1890). In many places the boundary is not exposed or it is faulted, but a normal contact can be examined at 5 localities (Fig. 1). In general, the purple, grey and green slates pass up into a grey slate sequence containing marine fossils - the Meadfoot Group. The transitional boundary zone may include interbanding of both Dartmouth Beds and Meadfoot Group lithologies. Near Looe, Lane (1966a) recognised this zone as a separate formation (his "Transition Beds").

On the northern flank of the Dartmouth Antiform, the Meadfoot Group is overlain by the Staddon Grit (a formation mainly comprising sandstones), which has been mapped across Cornwall and south Devon. The Staddon Grit is absent from the southern flank of the Antiform. This may be a consequence of the southern boundaries of the Lower Devonian rocks being tectonic, corresponding to the Start line and the Perranporth - Mevagissey line (Fig. 1). However near Newquay, Ripley (1964) has argued the case for a facies change across the Dartmouth Antiform, and that the Staddon Grit is represented by an argillaceous unit in the south (his "Holywell Slates"). A rather better documented facies change across the Antiform is known from the Middle Devonian (Edmonds et al. 1969); the slate succession of north Cornwall, and the slate - limestone sequences in south Devon are represented in south Cornwall by the Gramscatho greywacke facies.

Thus the Dartmouth Antiform may lie close to important local facies changes, where variations in thickness and iithology may have controlled the development of the structure.

The chronological development of the minor tectonic structures as inferred by different workers is broadly consistent along the trace of the Antiform (table 1). The earliest F1 folds trend approximately ENE-WSW although some anomalous directions occur, Ripley (1964) has described F1 cross folds near Newquay and some of the folds in south east Cornwall exhibit anomalous trends (Fig, 2d). Most F1 folds face towards the north, although again there are some exceptions where the facing direction is towards the south, such as west of Portnadler Bay (Lane 1970) and near the Start boundary (Hobson 1976) (Fig. l). The FI folds visible in the cliffs are locally parasitic on the limbs of larger FI structures. On the longer normal limbs of large FI folds, the smaller parasitic folds are widely spaced, successive hinge zones being about 100m apart. However the shorter inverted limbs of large FI folds are usually formed of many closely spaced small parasitic folds (see for instance the sections south of Plymouth, Fig. l section EF). All the folds are cut by a sub axial planar fabric, which is spaced cleavage in the psammites, and a slaty cleavage in the pelites (Fyson 1962).

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TABLE 1 Correlation of local fold phased along the trace of the Dartmouth Antiform

	Newquay	Looe		Whitesand Bay	Plymouth	Start Bay
		West of Portnadler fault	East of Portnadler fault			
	Ripley (1964) Sanderson (1971)	Lane (1966a)	Lane (1966a)	this paper	Hobson (1976)	Richer (1968)
F1 trend	NE-SW to WNW-ESE	E-W	ENE-WSW	ENE-WSW	ENE-WSW	ENE-WSW
F1 facing	NW to NNW	S	NNW	NNW	mainly NNW	mainly NNW
F2 trend	E-W	E-W	E-W	E-W	E-W	E-W
F2 direction of overturning	N and S	N and S	N and S	N	S	S
F3 trend	not recognised	not recognised	not recognised	E-W	E-W	E-W
F3 direction of overturning				S	S	S
F4 trend	NNW-SSE folds NNW-SSE kinkbands	NNW-SSE	NNW-SSE	NNW-SSE kinkbands	NNW-SSE kinkbands	N-S kinkbands
F5	late irregular kinkbands	not recognised	not recognised	not recognised	not recognised	not recognised

Small F2 folds of cleavage are also recognised along the trace of the Antiform. They are almost coaxial with the F1 folds and are frequently developed in narrow zones in argillites. They occasionally exhibit an axial planar crenulation cleavage. In south Devon, the majority of these folds are overturned to the north (Richter 1968; Hobson 1976), but in Cornwall both northward and southward overturned F2 folds have been described (Lane 1966a; Sanderson 1971). Sanderson (1971) has argued that there is a large F2 fold south of Newquay, and has described small parasitic folds which are overturned to the north on the steeper limb, and overturned to the south on the more gently inclined northern limb. Henley (1973), however, considers that this structure formed after the F2 movements and is related to the formation of a nearby fault, the Perran Iron Lode.

There are no large F2 folds present in south Devon or south east Cornwall. However, local, open, monoformal folds of cleavage are visible in the cliffs. Small F2 folds are overturned to the north on both limbs of these monoforms. This is interpreted as evidence that the small F2 folds have been refolded by the monoforms, which are here referred to the F3 deformation phase (Richter 1968; Hobson 1976). The monoforms are coaxial with the F1 and F2 folds. A large monoformal fold of cleavage in south Devon and south east Cornwall, also coaxial with F1 and F2 folds is here interpreted as a large F3 structure.

Throughout the district under study, the final fold phase is expressed as a series of NNW-SSE - trending kink bands, normal to the axes of the earlier structures (table 1). The kink bands are especially common close to major wrench faults.

2. A tectonic map of the Dartmouth Antiform

Seven sections through the Dartmouth Antiform are shown in Figure 1. All are derived from previously published research except section GH through Whitesand Bay in south east Cornwall which is based on the author's own mapping. The detailed geology of the Whitesand Bay area is summarised in Figure 2.

The sections accompanying the map (Fig. l) suggest that there are four main features of structural interest which are widespread along the trace of the Antiform:

1. The southern boundary of the Dartmouth Beds is everywhere a conformable contact with the Meadfoot Group.

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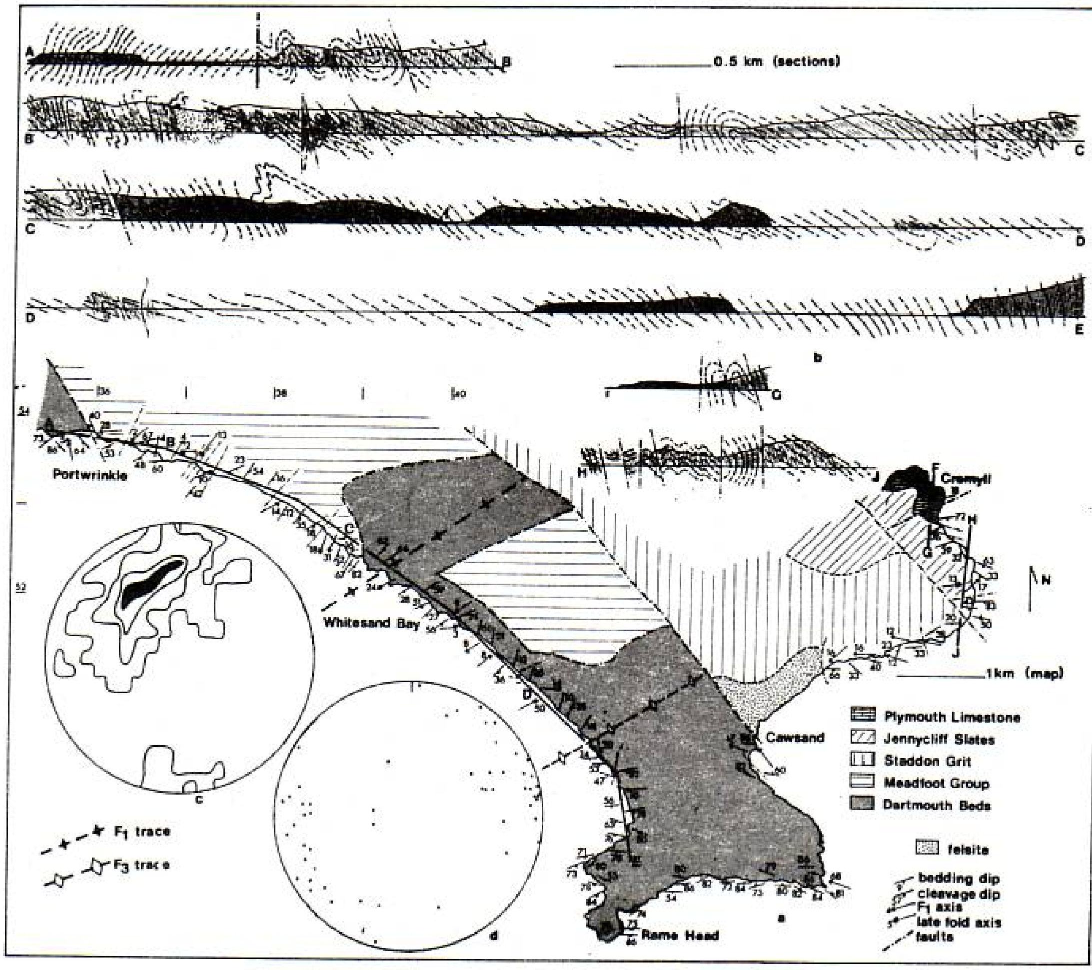

FIGURE 2. Geology of the Rame peninsula in East Cornwall.

(a) Structural map of the area. The geological boundaries inland are based on the Geological Survey sheet 348, with modifications by the author.

(b) Sections to show the structure in the cliffs.

(c) Equal area projection to the poles of slaty cleavage; 195 points; 1, 3, 5 and 7% contours.

(d) Equal area projection to the poles of small F1 fold axes and bedding-cleavage lineations: 56 points.

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2. At many localities, the northern boundary of the Dartmouth Bed is either a NW-SE - trending wrench fault or a roughly E-W trending fault.

3. In south Devon and south east Cornwall, there is a large Fl anticline near the northern boundary of the Dartmouth Beds.

4. In all the sections, bedding and cleavage become more steeply inclined and locally dip to the north on the southern flanks of the Antiform. In south Devon and south Cornwall this is interpreted as an F3 structure. In north Cornwall, large F2 folds (Sanderson 1971) and possibly later formed structures contribute to the formation of the steep zone of cleavage.

Thus there are three major elements which achieve a regional distribution along the trace of the Dartmouth Antiform: a large F1 anticline; a major late formed antiform; and a large fault zone along the northern boundary of the Dartmouth Beds.

Figure 3 is a structural map which shows the distribution of these three elements. Some of the inland sections which are moderately well exposed have been examined by the author, in particular outcrops in the Fowey valley, and near Loddiswell in south Devon. However in many places exposure is poor, and evidence available from the relevant 1" Geological Survey maps has been used.

The large Fl anticline is not completely preserved in any of the sections. South east of Plymouth, the steep limb is formed in the Meadfoot Group and Staddon Grit (Hobson 1976), and the Dartmouth Beds lie on the long normal limb. There is a similar situation near Loddiswell in central Devon, where small isolated exposures of Dartmouth Beds indicate that the normal limb is steeply inclined to the south.

Near Dartmouth, in Whitesands Bay, and also near Looe, the inverted limb of the anticline is formed in the Dartmouth Beds and Meadfoot Group, but much of the hinge zone is cut out by boundary fault. As in south Devon, the Dartmouth Beds are exposed mainly on the southern limb of the anticline. To the west of Portnadler Bay, Lane (1966b, 1970) has recognised a major south- facing anticline with a longer southern inverted limb. This is here interpreted as the main F1 Dartmouth anticline, which is refolded on the southern flank of the large, late-formed fold (see below). Near Fowey, it is not possible

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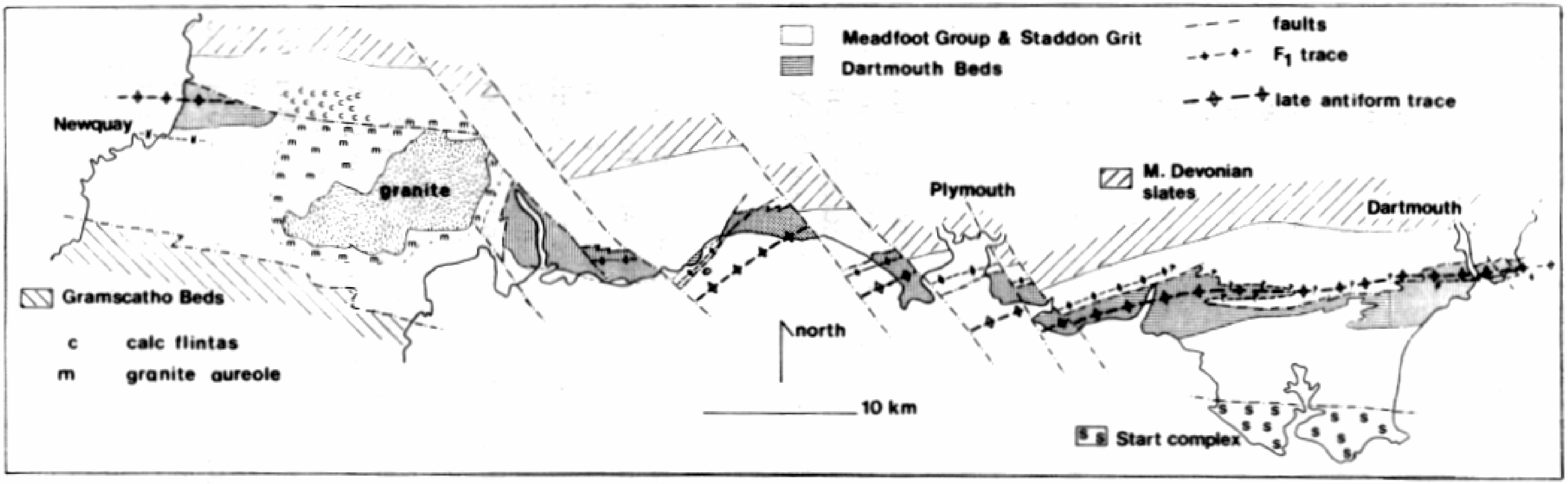

FIGURE 3. Tectonic map of the Dartmouth Antiform, showing the traces of the large F1 fold plus late-formed folds, and major faults.

to trace the anticline through the poorly exposed countryside; neither does it appear to be developed in the Dartmouth Beds near Newquay (Ripley 1964).

It is possible that the anticline is exposed in rocks other than the Dartmouth Beds along the north Cornish coast. Ripley (1964) has illustrated an F1 syncline to the south of Newquay, and also described a series of folds facing gently downwards to the north of the town. It is possible that either of these fold systems represents the western extension of the Dartmouth anticline.

Thus although it is possible to be reasonably certain that a large F1 anticline lies close to the northern boundary of the Dartmouth Beds in Devon and south east Cornwall, its extension to the north Cornish coast is less sure. The inverted limb of the fold is nowhere completely preserved, being cut by large faults.

The second tectonic element of the Dartmouth Antiform is the large late-formed open fold of cleavage which has a monoformal shape in south Devon and south east Cornwall. The Dartmouth Bed outcrop in north Cornwall is flexed into an open upright antiform, which may be the western extension of the monoform. Alternatively, this antiform may have developed at the same time as the large F2 folds (Sanderson 1971) south of Newquay.

This late-stage folding has formed a zone of steeply inclined rocks along the southern flanks of the Dartmouth Antiform. There are areas where cleavage is inclined to the north, and hence the folds face towards the south (e.g. Fig. 1 sections AB, CD). The zones of steeply inclined rocks and the axial trace of the late fold are displaced dextrally across the NW-SE-trending wrench faults (Fig. 3). Lane (1970), who examined rocks west of Portnadler Bay in isolation from other sections, attributed the south facing folds there to rotation adjacent to the Portnadler wrench fault. It is possible that some rotation about this fault has occurred because the cleavage west of Portnadler Bay is inclined at 40° or less to the north. Elsewhere in south Cornwall and Devon, the cleavage on the southern limb of the antiform is inclined at more than 60° to the north. The widespread distribution of the zones of northward-dipping cleavage on the southern flank of the Dartmouth Antiform indicates that the deformation is mainly due to regional folding of the fabric, rather than to local pivot faulting as envisaged by Lane (1970). The observation that the northward cleavage dips are gentler than normal in Portnadler Bay may indicate that the monoform is tightest in this area.

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The third tectonic element of the Dartmouth Antiform is the large fault zone which forms the northern boundary of the Dartmouth Beds. In some places the boundary is formed by NW-SE trending wrench faults. Elsewhere the fault zone trends roughly E-W and is steeply inclined. It is possible to trace a major fault across much of Cornwall and south Devon. Near Newquay, the faulted northern boundary of the Dartmouth Beds lies adjacent to an E-W trending line which separates calc flintas from other rocks of the St. Austell granite aureole. (1" Geological Survey Sheet 347) (Fig. 3). This line is here interpreted as an extension of the major E-W fault zone. A continuation of the same line runs across the northern boundary of the St. Austell granite and then into a wrench fault near Bodmin recognised by Dearman (1963). The E-W trending boundary of the Dartmouth Beds, north west of Portnadler Bay, may represent a continuation of this large fault, but exposure is too poor to be certain. East of Looe, and near Rame Head, the northern boundary of the Dartmouth Beds is irregular, and in places trends NE-SW. This may be due to offset of the boundary fault (which is here locally within the Dartmouth Beds (Fig. 1)) by other smaller faults.

The major fault can be traced in an ENE direction from Plymouth Sound as far as Modbury (Hobson 1976). East of Modbury, its trace cannot be determined accurately. South of Loddiswell, the northern boundary of the Dartmouth Beds is interpreted as a fault. Because of the narrow outcrop width of the Dartmouth Beds here, the throw of the fault may be small. The sinuous outcrop of the fault indicates that it may be locally gently inclined.

Richter (1968) did not recognise a fault east of Dartmouth where cliff exposures in the Dartmouth Beds are inaccessible. However, examination of sections near Dartmouth by the present author indicates that the hinge of the F1 anticline is only about 0.5 km south of the northern Dartmouth Bed boundary. In order to account for a considerable thickness of Dartmouth Beds missing from the northern limb of the anticline, it seems likely that there is a fault along, or close to, the boundary.

There is evidence for variation in throw along the trace of the fault zone. Near Plymouth, the vertical movement along the steeply inclined fault is about 3700 m down to the north (Hobson 1976). It must be of the same order elsewhere in south Cornwall (Figs. 1,2). However, south of Loddiswell in central Devon, the throw may be much smaller (of the order of 100m) and the fault may be more gently inclined. Because the

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fault is here exposed at a higher structural level than elsewhere, this may be responsible for its change in orientation: The fault may be steeply inclined at depth in theAntiform, but traced upwards, the throw may decrease and the-fault becomes more gently inclined.

This fault may have had a long history. Because it developed along the northern boundary of the Dartmouth Beds and also close to the hinge of the large F1 fold, the fracture may have been initiated during the F1 episode of deformation. This argument is supported by the observation that the fault is locally reversed (e.g. at Newquay and Whitesands (Fig. 1)). The fault zone is also locally a clean cut fracture not accompanied by breccia (to the east of Looe).

There is some evidence suggesting that the last movement along the fault may postdate the main orogenic deformation. At Bovisand, south east of Plymouth, the fault zone is marked by a breccia of angular sandstone fragments in a red sandy matrix. The breccia is thought to be a sedimentary deposit because it lies in beds which dip gently towards the north. These rocks, which are not cleaved, are similar in appearance to others mapped as Permian elsewhere in Devon. It is faulted against the Staddon Grit and lies unconformably above the Dartmouth Beds. If the breccia is indeed of Permian age, then the fmal movement along the fault at least locally postdates the main deformation.

3. Regional structural pattern

The Dartmouth Antiform has a long and complex history. It formed close to the site of facies and thickness changes in the sedimentary successions, and both early and late-formed large folds are involved in the structure. The observation that there are three separate coaxial fold phases regionally developed indicates that the principal finite strain axes remained constant in orientation throughout much of the deformation period, although the deformation may have been pulsatory in action. The consistent asymmetry to the north of both F1 and F2 folds may indicate that the rocks were deformed in a large belt of simple shear, characterised by subhorizontal, northward-directed overturning.

The horizontally directed deformation was followed by a phase in which vertical movements which downthrow to the north predominated. The fault close to the northern boundary of the Dartmouth Beds trends roughly east - west, and thus may have formed under the same stress system that was responsible for the folds.

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Steeply inclined, east - west-trending faults may play an important role in controlling the outcrop pattern of other Devonian rocks in south west England. Taylor (1951) recognised a steeply inclined fault along the northern boundary of the Plymouth Limestone. The east - trending Perranporth - Mevagissey line is exposed at Pentewan in south Cornwall, where it is a reversed fault inclined at 45ºN. Sadler (1974 Fig. 2) has shown steep east-west and NE-SW faults bounding the Lizard complex.

Thus it is possible that large east-west faults are more widespread in this area than has been realised to date. The fractures exert a fundamental control on the pattern of outcrop throughout the area. The maps of the Geological Survey show a succession which becomes younger as it is traced to the north, yet the rocks are usually inclined to the south. This paradox is probably related to the steep east - west fractures acting as step faults. Such a model is in accord with Sadler's (1974) interpretation of the Lizard - Start area: basement, represented by the Lizard and Start complexes, is faulted down to the north. The fracture at the northern boundary of the Dartmouth Beds marks the hinge zone of an earlier large fold. It is possible that other east - west faults have also formed along the line of important earlier tectonic structures.

Acknowledgements. I would like to thank Dr. S.C. Matthews for his critical appraisal of this paper and Dr. P.L. Hancock for reading and correcting the manuscript.

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THE STADDON GRITS - OR MEADFOOT BEDS?

by G.M. Harwood

Abstract. The lithologies of Devonian rocks exposed along the east coast of Plymouth Sound are discussed. Sequences in both the Bovisand Beds and the Staddon Beds are characteristic of Meadfoot Beds lithologies elsewhere and only a small proportion of the Staddon Beds comprise massive sandstones. These sandstones may only be of local extent and correlation between different outcrops may produce diachronous boundaries. It is suggested that the Staddon "Grits" be included in the Meadfoot Group, the upper limit of which is marked by the disappearance of sandstone/siltstone alternations from the sequence.

1. Introduction

On geological maps of south Devon and east Cornwall the Staddon "Grits", striking east-west, are shown to the north of the Meadfoot Beds and to the south of the Middle Devonian (Jennycliff) Shales. Their outcrop is discontinous and often offset by NW-SE faults. Away from the coast exposure is poor, so that boundaries of the Staddon "Grits" cannot be mapped precisely. Outcrop of the "grits" is usually taken to follow the run of the more resistant hills. At the coast on the east of Plymouth Sound, however, exposure is almost continous and detailed study is possible.

The oldest rocks present, the Wembury Siltstones (Dineley, 1966) of the Dartmouth Group, are terminated by a fault north of Andurn Point and are succeeded northwards by the Bovisand Beds, Staddon Beds (the Staddon Grits of other authors), Jennycliff Shales and Plymouth Volcanic Series, before the Plymouth Limestone is reached at Mountbatten Point (Fig. 1A).

2. Detailed Geology

a) Bovisand Beds

The lowest Bovisand Beds exposed occur in the south of Crownhill Bay, (Fig. 1B). Here they are partially obscured by a breccia, currently thought to be of Permian age, which also covers the fault between the

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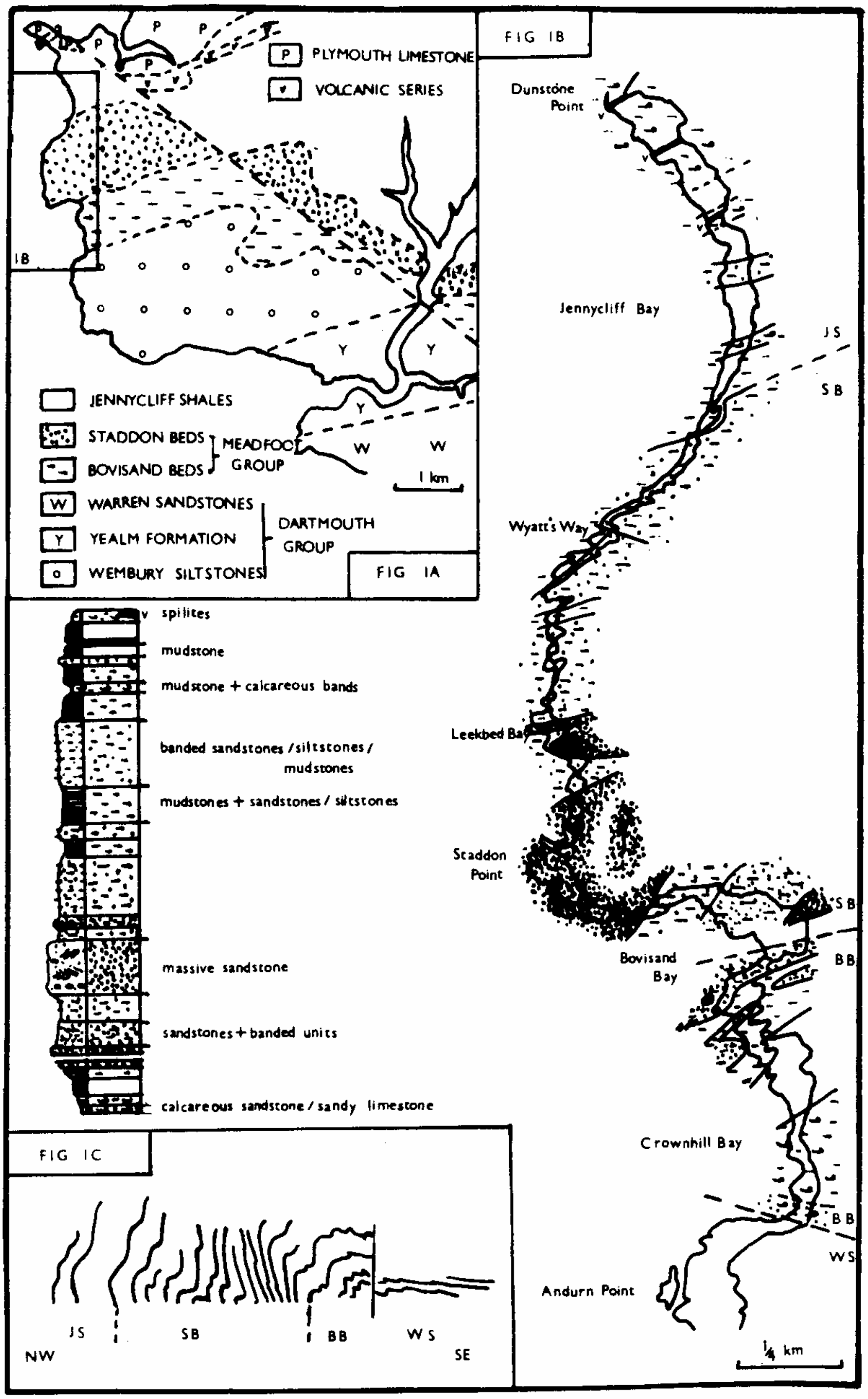

FIGURE 1A. Geology east of Plymouth Sound.

B. Detailed stratigraphy of coastline and stratigraphic column (total thickness 920m).

C. Simplified structure across the area.

JS; Jennycliff Shales, SB; Staddon Beds, BB; Bovisand Beds, WS; Wembury Siltstones.

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Dartmouth Group and Bovisand Beds. Three main types of facies are developed in the Bovisand Beds, gradations being evident between each type. The oldest facies is partially affected in the south by intense red staining, which makes the earliest shales of the Bovisand Beds virtually indistinguishable from the Wembury Siltstones to the south of the fault. North of the breccia, interbedded, red-stained, calcareous sandstones and sandy limestones appear in the shales. Further along the beach the staining disappears, the mudstones becoming black in colour. The sandstones soon disappear, but thin calcareous bands persist throughout the southern half of Crownhill Bay (Fig. 1B). Large ramose thamnoporoids occur in the calcareous sandstones and sandy limestones and are found isolated on rare occasions in the mudstones. Single corals, other colonial corals, bryozoans, crinoids, bivalves and brachiopods are also present, both in the calcareous bands and in the mudstones. All fossils are generally well preserved and are obviously very close to, if not in, their growth position. Crinoids here are rarely associated with corals and, near the centre of Crownhill Bay, there are two beds of limestone debris, composed almost entirely of crinoid calyxes.

In the second facies (fig. 1B), black mudstones predominate with only a few thin calcareous horizons in the older beds. Occasional isolated fossils occur, including *Streptelasma,* a coral species that could apparently tolerate muddy conditions, a few complete crinoids and some bryozoans. Higher in these mudstones are phosphatic nodules, the phosphate replacing bryozoan and coral skeletons, and hematite nodules.

Between Crownhill Bay and Bovisand Bay the third facies of the Bovisand Beds is developed, (Fig. 1B). This comprises mudstones alternating with siltstones and sandstones. the sandstone content gradually increasing higher in the sequence. Some fossils and calcareous horizons occur near the base of this facies but these decrease upwards, bioturbation becoming the main indication of organic activity.

The thicknesses of these three facies have been estimated at 15 m, 30 m and 30 m respectively. Further east, in the Yealm estuary, the Bovisand Beds are thinner (Fig. IA), although this may partly be due to folding and faulting.

b) Staddon Beds

The outcrop width of the Staddon Beds varies across the area shown in Fig. 1A. Although a portion of this variation may be due to folding and faulting, the thickness is less than 30 m in the Yealm

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estuary but over 600 m along the coast of the Sound, in the outcrop from Bovisand Bay to the south of Jennycliff Bay, (Fig. 1B), where the beds are folded into tight anticlines and synclines.

The choice of a junction between Bovisand Beds and Staddon Beds is fairly arbitrary and is taken here as the old mapped line between Meadfoot Beds and Staddon "Grits", which may be another fault boundary, the line being lost beneath the beach in Bovisand Bay. The lowest Staddon Beds exposed north of the beach are sandstones, showing planar cross stratification. They are followed by alternating sandstones, siltstones and mudstones, with the sandstones predominating, as in the Upper Bovisand Beds.

These alternations form most of the Upper Bovisand and Staddon Beds. Units are between 30 cm and 4 m thick but each shows only slight lateral variation. The base of a unit is a muddy sandstone, often with climbing ripple cross-stratification, followed by mudstones. The mudstones contain interbeds of lenticular or irregularly laminated thin silty sandstones or siltstones, which become fewer, thinner and finer upwards. The top centimetre or so of each unit is predominantly mudstone. Dewatering structures occur beneath the sandstone/siltstone layers, but these are often obscured by pressure solution. Burrows occur, filled with muddy sandstone or siltstone, and become more numerous towards the top of each unit. Single ramose trace fossil tracks are seen on the base of some muddy sandstone beds.

To the north of Bovisand Beach individual sandstone beds, often showing climbing ripple cross-stratification, occur between many units, but further west the succession becomes much muddier with some intervening mudstones (Fig. 1B). There are throughout this sequence rare sandy conglomerates with calcareous and phosphatic debris.

Near Staddon Point, sandstones occur on the overturned limb of a major anticline (Fig, 1C); they are often truncated by tectonic slides. The sandstones are rarely clean and may show washouts, scour and fill structures and trough cross-stratification. Trace fossils again occur, including some double ramose tracks.

Three types of sandstones are present. The first is a very sandy equivalent of the earlier units with some ripple lamination. Massive sandstones follow, showing large scale cross-stratification and often wedging out laterally, some evidently being channel fills. The third type comprises sandstones with mudflake breccias and minor conglomerates

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whose clasts have been reworked from preceding sediments. The mudflake breccias generally grade upwards into dirty sandstones and, although an individual breccia never has a great lateral extent, several may be developed as a sandstone bed is traced along its strike. In places beds up to 40 cm thick consist almost entirely of mud clasts. The total thickness of these sandstones, each type being developed several times, is perhaps 100 m.

Higher in the succession thick sandstone beds occur only near Leekbed Bay (Fig. 1B), where they outcrop in a synclinal core. The remaining Staddon Beds comprise variations of the basic alternating unit, with overall sandstone content decreasing northwards. More bands of calcareous and other debris occur here, and several from near Wyatt's Way have yielded *Icriodus,* a conodont which ranges throughout the Devonian and which is thought to be relatively abundant in restricted environments. The calcareous content of. the mudstones increases upward in the succession, with bivalves, bryozoans, corals and crinoid stems being found in the south of Jennycliff Bay (Fig. 1B).

The upper limit of the Staddon Beds is taken at the top of the last of the thick sandy units. Fig. 1B shows that alternating siltstones and mudstones continue into the Jennycliff Shales and that thin sandstones do occur in that unit higher in these strata, so there is no absolutely clear boundary.

c) Jennycliff Shales

These beds are predominantly mudstones, very similar to the lower Bovisand Beds, and they contain isolated corals and bryozoans which increase in abundance upwards. Spilites also occur at various horizons, often intimately associated with limestone bands. From the limestone band at Dunstone Point, M.J. Orchard (pers. comm.) has obtained conodonts of lowest Middle Devonian age, suggesting that the Staddon and Bovisand Beds, a total of perhaps 700 m of strata, are of Lower Devonian age.

3. **Correlation with other areas**

The type locality of the Meadfoot Beds is in an infaulted block at Meadfoot Bay, Torquay, where alternating sandstones, siltstones and mudstones similar to those mentioned above are found, the only

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difference being the more common occurrence of bands of calcareous debris. This same lithology is developed elsewhere in the Meadfoot Beds of south Devon and east Cornwall, and less common are lithologies similar to the Middle and Lower Bovisand Beds. Thus, away from the east coast of Plymouth Sound, the lithology used to recognise the Meadfoot Beds is almost identical to that used here to denote the Staddon "Grits".

It seems reasonable, therefore, to include both Staddon and Bovisand Beds in the Meadfoot Group, and to regard the development of thicker sandstones in the Staddon Beds as perhaps of purely local occurrence. In a nearshore environment the distribution of sediment influx can alter dramatically with time and developments of these sandstones cannot be used to make correlations from one area to another.

The junction between the Meadfoot Group and the Dartmouth Group, when exposed, is a fault boundary throughout south Devon and, as both groups have a Lower Devonian age, it seems possible that some of the Dartmouth Group may be the lateral equivalents of a part of the Meadfoot Group. This suggestion is not new, (cf. Dineley, 1966), but recent structural evidence by D.M. Hobson (pers. comm.) shows that in this area, it is the oldest member of the Dartmouth Group, the Wembury Siltstones, that is faulted against the Bovisand Beds (Fig. 1A). Perhaps, then, correlation of the Bovisand and Staddon Beds with the Yealm Formation and Warren Sandstones of the Dartmouth Group may now be worth some consideration.

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DINELEY, D.L., 1966. The Dartmouth Beds of Bigbury Bay, South Devon. *Q. JI. geol. Soc. Lond.,* **122**, 187-217.

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Notes on the Hangman Sandstones (Middle Devonian) of North Devon (Abstract): by Ian P. Tunbridge

These Couvinian deposits represent an incursion of continental facies into the north Devon area. They pass up conformably from the shallow water marine Lynton Beds into sub-littoral and intertidal facies. The latter consist of lenticular and ripple-bedded very fine-grained grey sandstones, with planar laminations increasing in abundance upwards. Asymmetrical ripples, reactivation surfaces and occasional burrows are found.

The overlying Trentishoe Formation exhibits sequences of fine to medium fine-grained sandstones, usually planar-laminated with basal intraformational conglomerates, and commonly with signs of sedimentary deformation. The finer-grained sediments show climbing ripples, ripple-laminations, plane beds and suncracks. Calcretes are uncommon. These sequences may be the product of periodic sheet floods.

The Rawns Beds which follow are coarser-grained with a pebble assemblage including acid tuff and lava types, many of which are notably angular. Plane bedding and large scale cross-bedding predominate. A relatively nearby northerly source is inferred for this formation.

Fine-grained intertidal and sublittoral deposits follow in a complex association of grey lenticular bedded units and cross-laminated sandstones, passing to fossiliferous sands, planar and cross-bedded units, and further lenticular and faser beds. A series of minor transgressive and regressive events may be represented here, culminating in the establishment of marine conditions.

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The stratigraphy and structure of the South Brent Area

(Abstract): by Alan D. Willcock

The poorly exposed ground between Brent Hill and the Dartmoor Granite comprises two areas where the rocks are relatively inverted. A succession of rocks is present which is similar to other Lower Carboniferous sequences in South-West England. It is possible to interpret the presence of 'right-way-up' and 'wrong-way-up' limbs of a much-sheared, north-facing, recumbent structure in Lower Carboniferous rocks. This has been thrust from the south-east by volcanics, limestones and Gurrington slate on the Bickington Thrust. This in turn has been overridden by the Nordon slate on the Forder Green Thrust, which obscures the Bickington Thrust towards the south-west.

The area has been disrupted by approximately east-west vertical faults of probable late Variscan age, and later by north-west/south-east faults.

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BRITISH TRIASSIC PALAEONTOLOGY
by G. Warrington

Abstract. British Bunter deposits contain few fossils but the Keuper and, more especially, the Rhaetic, are fossiliferous. The sporadic remains from the Bunter are inadequate for dating and correlation purposes. Macrofossils from the Keuper and Rhaetic, though more abundant, are facies-related and thus of limited value for the correlation of British sequences. Plant microfossils are abundant and widespread in the Keuper and Rhaetic and, particularly in the former, facilitate correlation between different facies within Britain.

1. Introduction

The customary description of British Triassic deposits as "unfossiliferous" is invalid as the fossiliferous nature of the Rhaetic is well known and diverse fossil assemblages also occur in the Keuper; the Bunter, however, contains only sparse remains. In comparison with those of the Rhaetic, assemblages from the Bunter and Keuper are non-uniform in character and distribution, a factor which, in conjunction with their scattered documentation may contribute to the lack of appreciation of these biota and the belief in an "unfossiliferous" Bunter and Keuper. The rather disproportionate amount of attention devoted to the Rhaetic in publications may have compounded this misconception and, in an attempt at redress, the Rhaetic biota are therefore treated summarily in this account, emphasis being placed upon those of the Bunter and Keuper.

Many of the more important assemblages of British Triassic macrofossils were discovered before 1908 and are noted in the reports of the Committee for the Investigation of the Fauna and Flora of the Trias of the British Isles (*in* reports of the British Association, for 1903 to 1909 inclusive); these records are here updated. Space limitations preclude the provision of a comprehensive bibliography and only important records, revisions and useful reviews are cited, emphasis being placed on more recent work.

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In this account "Bunter", "Keuper" and "Rhaetic" are used as currently applied in Britain. The British Bunter and Keuper do not, however, correspond with units of the same name elsewhere in Europe. The British Keuper, for example, includes deposits equivalent in age to those from the upper Bunter to the middle Keuper of Germany. Also, "Rhaetic" refers to a lithostratigraphic unit and must not be confused with "Rhaetian", the youngest Triassic stage (a chrono-stratigraphic unit). The Bunter is conventionally regarded as Triassic in age but, in the absence of biostratigraphic evidence, the position of the Permian -Triassic time boundary in the relevant lithostratigraphic sequences cannot be defined objectively in Britain (Pattison, Smith and Warrington 1973). The horizon used by Smith *et al*. (1974) for the base of the Triassic is followed in this account with the reservation that the position of this boundary is arbitrary and potentially subject to modification. The top of the Triassic is taken at the base of the Hettangian *planorbis* Zone (vide George *et al.,* 1969, *Proc. geol. Soc. Lond.,* No. 1656, pp. 159-160).

2. Palaeontological content of the Trias of the British Isles

(i) The Bunter

The following fossils are known from the Bunter: branchiopod crustacea *(Euestheria)* from Staffordshire (e.g. Cantrill *1913)* and Northern Ireland (Fowler and Robbie 1961); palaeoniscoid fish *(Dictyopyge catoptera)* from Northern Ireland (Egerton 1850) and a fragment of a perleidid (actinopterygian) from Worcestershire (White 1950); ichnofossils (mainly vertebrate footprints) occur in Cheshire and Worcestershire (Sarjeant 1974).

A mudstone in sandstones overlying the Zechstein at Kingscourt, Co. Cavan, Eire, has yielded a microfossil assemblage of marine affinity comprising foraminifera, tintinnids, miospores and acritarchs (Visscher 1970).

(ii) The Keuper

The British Keuper comprises two main facies, the arenaceous Keuper Sandstone and the argillaceous Keuper Marl. The majority of the macrofossils from this unit have been obtained from the Keuper Sandstone, from arenaceous variants of a poorly defined unit ("Waterstones") transitional between the Keuper Sandstone and Keuper Marl and from relatively atypical minor facies within the Keuper Marl, the bulk of which contains few macrofossils. Palyno-morphs, predominantly miospores, are, however, widespread and fairly abundant in both the arenaceous and argillaceous facies.

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The Keuper Sandstone and arenaceous variants of the Waterstones have yielded the following: inarticulate brachiopods *(Lingula)* are known from the Nottinghamshire Waterstones (Rose and Kent 1955) and the Keuper Sandstone of the Withycombe Farm Borehole, Oxfordshire *(Ann. Rep. Inst. Geol. Sci.,* for 1974, p. 123). Bivalves assigned, tentatively, to *Modiolus* and *Mytilus* occur, in the Keuper Sandstone of the Withycombe Farm Borehole *(loc. cit.)* and at Bromsgrove, Worcestershire (Wills 1910) respectively. Arachnids *(Mesophonus* and *Spongiophonus,* members of the Scorpionida) occur in Warwickshire and Worcestershire (Wills 1910, 1947). Ostracods are present in the Keuper Sandstone of the Withycombe Farm Borehole *(loc. cit.)* and *Euestheria* occurs sporadically in the Keuper Sandstone and Waterstones of the Midlands, Cheshire and south Lancashire.

Fish remains from the Keuper Sandstone include dipnoan *(Ceratodus)* teeth from Warwickshire (Woodward 1893) and Worcestershire (Wills 1910), a selachian spine (? *Acrodus)* from Bromsgrove (Wills 1910), a perleidid *(Dipteronotus cyphus)* from Bromsgrove (Egerton 1854) and scales and cranial bones of the palaeoniscoid *Gyrolepis* from Warwickshire (Walker 1969, p. 472). A catopterid holostean *(Woodthorpea wilsoni)* and a lepidotid *(Semionotus metcalfei)* are known from the Nottinghamshire Waterstones (Newton 1887; Swinnerton 1925, 1928).

Amphibia are recorded from the Keuper Sandstone of Staffordshire, Warwickshire and Worcestershire and from an analogous unit, the Otter Sandstone, in Devon. This material (recently revised; Paton 1974) comprises remains of capitosaurid labyrinthodonts *(Cyclotosaurus leptognathus, C. pachygnathus* and *Mastodonsaurus lavisii* from the Midlands and *M. lavisii* from Devon).

Reptilia are known from the Keuper Sandstone of Salop, Staffordshire, Warwickshire, Worcestershire and Devon. The status of much of this material has been reviewed by Walker (1969) who considers that the Midlands assemblages comprise lepidosaurs *(Rhynchosaurus articeps* and a macrocnemid), archosaurs (a primitive prosauropod, a large thecodont and a form comparable with *Poposaurus)* and a sauropterygian (nothosaur); *Rhynchosaurus is* also recognised from Devon.

Determinable plant remains occur in the Keuper Sandstone at Bromsgrove, Worcestershire (Wills 1910) and indeterminate planty material in the Keuper Sandstone and Waterstones from Gloucestershire to south Nottinghamshire and south Lancashire. The Bromsgrove

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material comprises sphenopsids *(Equisetites, Schizoneura)* and conifer-opsids *(Voltzia, Yuccites);* these taxa are represented by macrofossils but the presence also of lycopsids, pteropsids and cycadopsids may be inferred from the composition of associated miospore assemblages.

Palynomorphs are widely distributed and locally abundant in the Keuper Sandstone and Waterstones from Gloucestershire and Oxfordshire to Nottinghamshire and south Lancashire (Clarke 1965; Warrington 1970a; Smith and Warrington 1971; Fisher 1972a; *Ann. Rep. Inst. Geol. Sci.,* for 1974, p. 123). The assemblages are dominated by miospores but acritarchs and tasmanitids occur in the Waterstones at Bromsgrove (Warrington 1967, 1970a) and the Keuper Sandstone at Stratford-upon-Avon (Warrington 1975).

Vertebrate and invertebrate trace fossils are known from most outcrop areas of the Keuper Sandstone and Waterstones. The vertebrate tracks are the subject of an extensive literature which has recently been reviewed (Sarjeant 1974) but the invertebrate trace fossils have received little attention and are probably commonly overlooked or ignored.

In the dominantly argillaceous Keuper Marl macrofossils have been principally obtained not from the red mudstone lithologies typical of the facies but from distinctive minor units such as coarse marginal deposits, the thin but widespread Tea Green Marl and the more localised Arden Sandstone and Grey Marls. Elsewhere in the Keuper Marl sequence macrofossils, comprising sporadic *Euestheria,* a euplecopteran insect wing (from Cheshire, Thompson 1966), indeterminate plant remains and invertebrate ichnofossils, have originated principally from thin dolomitic sandstones ("skerries") though *Euestheria* and ichnofossils are observed sporadically in the mudstones. Palynomorphs are, in contrast, widespread and abundant in the Keuper Marl up to and including the level of the Arden Sandstone (Clarke 1965; Warrington 1970a, b, 1971, 1973, 1974; Smith and Warrington 1971; Fisher 1972b; Warrington and Harland 1975). The assemblages are dominated by miospores but acritarchs and tasmanitids have been recorded in Cheshire, west Lancashire, Northern Ireland and Arran (Warrington 1970c, 1973, 1974; Warrington and Harland 1975).

The biota of the Arden Sandstone of Warwickshire and Worcester-shire, and similar, possibly correlative, units in the Keuper Marl of Leicestershire, Gloucestershire, Somerset and Devon, are broadly analogous with those of the Keuper Sandstone and Waterstones.

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Bivalves (tentatively assigned to *Nucula, Pholadomya* and *Thracia)* are known from Warwickshire (Newton 1894) and *Modiolus* is recorded from a comparable horizon in Somerset (Green an& Welch 1965, p. 71). The crustacean *Euestheria* is widespread at this level as also are fish remains; the latter are predominantly selachian spines and teeth assigned to *Acrodus* (Wills and Campbell-Smith 1913) though other fish occur sporadically. The dipnoan *Ceratodus* is known from Worcestershire (Miall 1878-1907) and the actinopterygians *Dictyopyge superstes* and *Semionotus brodiei* from Warwickshire (Egerton 1858; Newton 1887). An actinopterygian *(Saurichthys)* is recorded from a comparable horizon in Somerset (Green and Welch *loc..cit.).*

Amphibian (labyrinthodont) material is recorded from Warwickshire (Brodie 1856). Some vertebrate tracks are known (Sarjeant 1974) but invertebrate trace fossils and locally intense bioturbation are a feature of the sediments of the Arden Sandstone and analogous units.

Plant macrofossils from the Arden Sandstone include representatives of the same sphenopsid and coniferopsid genera as occur in the Keuper Sandstone and elements in associated miospore assemblages imply the existence of lycopsids, pteropsids and cycadopsids also.

Above the level of the Arden Sandstone, the main occurrences of fossils are near the top of the Keuper Marl (in or near to the Tea Green Marl and the Grey Marls). At this level *Euestheria,* fish (including the palaeoniscoid *Gyrolepis* and the perleidid *Colobodus)* and indeterminate plant debris are widespread but occur sporadically. Palynomorphs are scarce but miospores, acritarchs and dinoflagellate cysts are known from the Nottinghamshire Tea Green Marl (Morbey 1975). The Grey Marls, restricted mainly to Devon, Somerset and Glamorgan, have yielded foraminifera, bivalves, gastropods, a belemnoid (?), fish, amphibia, reptiles, an early mammal, plant remains, palynomorphs (including miospores, acritarchs and dinoflagellate cysts) and ichnofossils (Boyd-Dawkins 1864; Storrie 1894; Orbell 1973; Stevenson and Warrington 1971; Warrington 1971, 1974).

Towards the depositional margins the dominantly argillaceous lithology of the Keuper Marl is gradually, superseded by one of arenaceous or rudaceous character; such infinitely variable marginal deposits (commonly termed "Dolomitic Conglomerate") are developed mainly in South Wales, Somerset, Avon and at the concealed margin of the Trias around the London Platform. Algal masses (Ivimey-Cook 1974,

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p. 303), reptilian remains (Riley and Stutchbury 1840) and vertebrate tracefossils (Sarjeant 1974; Bassett and Owens 1974) have been recorded from such marginal facies at outcrop. The reptilian remains (from Bristol) were referred to *Palaeosaurus, Rileya* and *Thecodontosaurus* by von Huene (1908) but, according to Halstead (*in* Warrington 1970a, p. 216; Halstead and Nicoll 1971) also include *Clevosaurus (sic.).*

(iii) The Rhaetic

The British Rhaetic has yielded representatives of the following: foraminifera, coelenterates, inarticulate brachiopods, gastropods, bivalves, crustacea (branchiopoda, ostracoda, cirrepedia), insecta, ophiuroids, echinoids, fish, amphibia, reptilia, plants, palynomorphs (miospores, acritarchs, tâsmanitids and dinoflagellate cysts), scolecodonts and ichnofossils.

British Rhaetic macrofossil occurrences are documented in the appropriate Institute of Geological Sciences memoirs and borehole accounts. In addition to these items (and the numerous works cited therein) the following may be noted as dealing with specific areas or groups of fossils: Anderson 1964 (ostracods); Hamilton 1961 (algae); Sykes, Cargill and Fryer 1970 (Nottinghamshire fauna); Orbell 1973, Morbey 1975, Warrington 1974, Harland, Morbey and Sarjeant 1975, Warrington and Harland 1975 (palynomorphs).

(iv) Stratigraphically or geographically isolated assemblages.

a. Elgin and Lossiemouth, Scotland

The Elgin fauna, from the base of this famous succession, comprises dicynodonts *(Geikia, Gordonia),* the pareiasaur *Elginia* and a procolophonid and is tentatively regarded as of *Lystrosaurus* Zone (earliest Triassic) age (Walker 1973). The Lossiemouth fauna, from near the top of the sequence comprises a procolophonid *(Leptopleuron),* lepidosaurs *(Brachyrhinodon, Hyperodapedon)* and archosaurs *(Erpetosuchus, Ornithosuchus, Saltopus, Scleromochlus, Stagonolepis);* this fauna, partly described in detail by Walker (1961, 1964), is regarded by him as late Triassic in age (Walker *in* Warrington 1970a, pp. 217-218).

b. Avon, Somerset and South Wales

Unusual fossil assemblages are contained in deposits occupying former cave systems and fissures in patches of Carboniferous Limestone which formed karst uplands during the latest Triassic times and early

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Jurassic times but which became submerged during the Jurassic. Robinson (1957a, 1971) has indicated that two groups of fissure deposit exist. One contains reptilian remains and, sporadically, *Euestheria* and is considered to be late Triassic (late Norian; Robinson 1971) in age. The reptilian material includes archosaurs (Kermack 1956; Robinson 1957a), trilophosaurs *(Tricuspisaurus thomasi* and *Variodens inopinatus;* Robinson 1957b), an anapsid (procolophonid; Robinson 1971) and lepidosaurs including *Glevosaurus hudsoni* (a sphenodontid; Swinton 1939; Robinson 1973), *Kuehneosaurus latus* and *Kuehneosuchus latissimus* (lacertilians; Robinson 1962, 1967). Infillings of the second group are considered by Robinson (1971) to postdate the Rhaetic marine transgression. These deposits, of Rhaetian or early Liassic age, contain, in addition to reptiles, the remains of plants and of early mammals and mammal-like reptiles. As infillings in this category include possible post-Triassic deposits it will suffice to note only that the material of mammalian affinity obtained from them includes a triconodont *(Morganucodon;* Kühne 1949) and a pantothere *(Kuehneotherium;* Kermack, Kermack and Musset 1968).

3. Summary

Although the British Trias has yielded a wide range of organisms the existence of strong facies control on the distribution of macrofossils (as evidenced by the relative abundance and diversity of such remains in the Keuper Sandstone, Arden Sandstone and Rhaetic compared with the scarcity in the Bunter and bulk of the Keuper Marl) limits the value of these fossils for correlation of different sequences within Britain. Certain macrofossils (notably reptiles) are, however, invaluable for the dating of particular facies at certain localities (e.g, the Elgin and Lossiemouth sandstones) and contribute towards the correlation of British deposits with sequences elsewhere. Many of the macrofossils (e.g. the fish and the reptiles from the Dolomitic Conglomerate at Bristol) require restudy having been neglected for decades; revision of such material could enhance the stratigraphic utility of British Triassic macrofossils.

In contrast to macrofossils, palynomorph assemblages are widespread, varied and often profuse in the Keuper and Rhaetic and are therefore of value for correlation of different facies within these units in Britain. The study of miospore assemblages from the Keuper Sandstone and Keuper Marl has made possible, for example, the demonstration that the former passes laterally northwards from the Midlands into the lower part of the latter in the Irish Sea area (Warrington 1970c), a situation which would be impossible to demonstrate from macropalaeontological evidence.

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Ammonites, conodonts and other fossils used for correlation in and between other European Triassic sequences are either absent from British assemblages or, as in the case of foraminifera and ostracods, usually occur so infrequently as to be of little value for correlation within Britain though Anderson (1964) has used ostracods in a correlation of Rhaetic sequences. Miospores, which form the basis for the correlation of large parts of the British Triassic are also, apparently, the only widely applicable means of establishing biostratigraphic correlations between the British Keuper and Rhaetic and deposits of equivalent age elsewhere in Europe but the British Bunter may remain intractable and an enigma in this respect.

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Triassic evaporites in south-west England (Abstract):

by G. Warrington

Evaporite minerals in British Triassic deposits include halite, gypsum and anhydrite. The halites, including that of Somerset, occur only in the argillaceous Keuper Marl facies below the horizon of the Arden Sandstone and its correlatives; they form relatively thick, discrete units and commonly appear to be located within graben structures. The sulphates, though less restricted than the halite in their geographic and stratigraphic distribution, are also almost completely restricted to the Keuper Marl facies. In areas where evaporites are, as yet, unproven in the Trias (i.e. in the concealed development of those rocks in Dorset and Hampshire and in offshore areas in the Bristol Channel, Celtic Sea and Western Approaches of the English Channel) the presence of those minerals may be anticipated where the appropriate facies (the Keuper Marl) is developed, particularly where that facies is associated with known or postulated graben structures.

The stratigraphic setting and relationships of the evaporite deposits and the sedimentology, palaeontology and palaeogeography of the host and related sediments, when considered on a regional scale, support derivation of the evaporites from water of marine origin; this water evaporated under arid conditions in an environment dominated by continental influences and the resulting evaporites include minerals possibly precipitated both in water bodies and, from interstitial brines, within sediments.

The extensive graben structures, which appear to have influenced the distribution of the halite deposits, may have originated and been operative in Triassic times during a tensional phase in the initial stages of rifting prior to continental separation in the North Atlantic area later in the Mesozoic.

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NOTES ON THE LIAS OUTLIER NEAR SELWORTHY, WEST SOMERSET

by A. Whittaker

1. Introduction

The Lias outlier near Selworthy, Somerset, is the most westerly, onshore occurrence of Jurassic strata in England. Although Jurassic rocks have been known to crop out in the vicinity for many years, there is little published detail on the Lias, Rhaetic or highest Keuper Marl deposits. Brief mention of the Lias geology was made by Homer (1816, p. 379), Etheridge (1872, p. 37), Ussher (1889, p. 12), Woodward (1893, p. 97), Richardson (1911, p. 11) and Thomas (1940, p. 33), but mostly in a structural context.

The Lias outlier occupies sloping, rather uneven ground just south of Selworthy village, on the northern slopes of the Vale of Porlock. and is about 2 km long and 500 m broad as seen in plan. The mapping of J.H. Blake (Geological Survey archive material) shows the strike of the Rhaetic to be about 110°, more or less parallel to the regional strike of Mesozoic rocks in west Somerset, although individual dip measurements vary in direction from NW to NE and in amount from 8° to 23°. The Lias and Rhaetic of the outlier are separated from the Blue Anchor exposures of the same strata by a distance of about 10 km.

The Vale of Porlock is a 120° to 130°-trending valley, interrupting the high moorland area of eastern Exmoor which is composed of Devonian rocks. The valley is floored by New Red Sandstone deposits and superficial deposits: Thomas (1940) described the New Red Sandstone rocks of the Vale of Porlock and noted that they dip off the Devonian rocks of Dunkery Hill to the south and are faulted into contact with the Devonian strata of North Hill and Grabbist Hill to the north. According to Thomas. the upland regions of this area are fault blocks tilted towards the north or NE. the lowlands being formed of soft rocks which are preserved in the depressions. In early Triassic times, the Porlock depression was an isolated basin, only becoming continuous with other New Red Sandstone areas of deposition in

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Keuper Marl times. A series of breccia beds, with boulder beds and sandstones, rests unconformably on the Devonian strata and represents, essentially, fossil scree deposits. Calcareous sandstones overlie the breccias and pass up into the Red (Keuper) Marls.

Ussher (MS notes) described workings (SS 931 458) near Venniford Cross consisting of "light bluish grey even shales containing *Ammonites planorbis,* with interstratified beds of grey limestone". It is clear from this description that the Lias deposits hereabouts consist of the normal, offshore Blue Lias type.

2. Stratigraphy

During the Primary 6-inch Survey of the Weston-super-Mare (279) Sheet, the whole coastline of north Somerset was mapped from Blue Anchor in the west to Hinkley Point in the east, using aerial photographs of the intertidal area as base maps. As a follow-through from this project it was decided to sink boreholes on the Selworthy outlier to investigate the stratigraphy of the Triassic and Jurassic (to facilitate comparison with the easterly coastal exposure) and to examine the structural relationships between Palaeozoic and Mesozoic rocks.

Prior to drilling, some of the few available exposures were examined, but no systematic mapping was carried out. An old overgrown pit (SS 9216 4632) contained a few loose blocks of typical dark bluish grey argillaceous Lias limestone, one slab of which contains casts of a fairly large (0.10 m diameter), strongly ribbed ammonite, probably *Schlotheimia sp.* from the higher part of the *S. angulata* Zone beds. Another old pit (SS 9243 4633), at East Lynch Farm, contained many typical Blue Lias limestone blocks (loose) and Devonian sandstone fragments of local derivation; some of the Lias blocks yielded the small brachiopod *Calcirhyncia calcarea,* which in north Somerset characteristically occurs in the higher parts of the *S. angulata* Zone strata or in the overlying *M. conybeari* Subzone strata of the *A. bucklandi* Zone. Old workings at Mapleridge (SS 9226 4616) revealed traces of Lias limestone and shale, while those at Pixie (SS 9246 4612) exposed about 1.22 m of dark grey *in situ* shale with abundant *Psiloceras planorbis* and indicative of the *P. planorbis* Zone. Loose, individual specimens of *P. planorbis* were found in nearby old workings (SS 9256 4613) along the strike.

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In 1973, drilling commenced at the Selworthy No. 1 borehole (SS 9244 4630), with surface level about 134 m O.D. The borehole proved alternating Lower Lias limestones and mudstones which, at 17.15 m depth, were faulted against Keuper Marl. Beneath this was a 1.30 m-thick zone of badly faulted strata in contact, at the base, with disturbed purplish red, rather gritty sandstone (Hangman Grit, Devonian).

The Selworthy No. 2 borehole was sited at a place (SS 9244 4618) west of East Lynch Farm, with surface level about 118 m O.D. The borehole proved a Mesozoic succession similar to that exposed in the Watchet area. Mudstones of the *Alsatites liasicus* Zone overlay limestones and shales of the *Psiloceras planorbis* Zone, which, in turn, overlay the Rhaetic. A Grey Marl sequence, with pink and colourless anhydrite veins and layers, overlay a possible, thin representative of the Tea Green Marl which was in contact with a fault zone at the bottom. At the top of the fault zone were brownish red, green-spotted, Keuper Marl traces in juxtaposition with a fault gouge containing purple sandstone and marl fragments. Fractured and disturbed purplish red, medium-grained, cleaved sandstones of the Devonian Hangman Grit were present below the fault zone down to the final depth of 60.5 m.

The Lower Lias strata of the No. 2 bore correlate on virtually a bed-by-bed basis with offshore Lias strata of the coast. Even allowing for dips of up to 15° in the drill cores, the Lias strata of the borehole are slightly thicker than their equivalent at St. Audrie's Bay.

3. Discussion

The results of the project have an important bearing on Mesozoic palaeogeography and on the form of part of the N. Devon massif of Exmoor during those times. The highest Triassic and Jurassic deposits hereabouts are faulted into contact with Devonian strata, bearing out Thomas' (1940) thesis of block faulting for the Vale of Porlock. For the major fault proved in both boreholes to be the same fracture, the structure would have to dip S or SSW at only 20°, which is a much lower angle than the inclinations of normal faults exposed in north Somerset. If the possibility of low-angle reverse faulting is excluded, it seems likely that two or more normal step faults may be involved. This interpretation is also suggested from the general shape of the Lias outcrop, which is uneven and ridge-like.

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The project proves Lower Lias strata of offshore facies to be present at a height of about 131 m O.D. in the Vale of Porlock and faulted down probably from a higher level still. There are no signs of the so-called littoral facies of the Lower Lias in the vicinity of North Hill, Minehead, which rises to over 300 m O.D. at Selworthy Beacon, only 1.3 km north of the Lias outcrop at Selworthy. It is possible for a facies change to take place in this short distance but it is equally possible that offshore facies Lower Lias strata at one time passed over North Hill. Lower Liassic *(bucklandi* Zone) strata are known just offshore from North Hill (Lloyd and others 1973) at levels relative to O.D. of between -9 m and -18 m. This gives a minimum displacement of 140 m for the Bristol Channel Lower Lias near Minehead and a possible maximum displacement of over 300 m.

Liassic thicknesses at Selworthy suggest that this part of Exmoor at least was subsiding at a similar, if not greater rate, than the Central Somerset Basin during earliest Liassic times. The Rhaetic deposits, however, are thinner than those of the Watchet area and suggest that in those times the North Hill area was subsiding at a slower rate. Although the full thickness of Tea Green and Grey Marls is not known at Selworthy, comparison of these deposits with those of the Watcher area suggests that the Selworthy area was subsiding at a slower rate than the main part of the basin. The presence of evaporites, and lithologies like those of the coastal exposures, suggest environmental similarities and point to probable ancient sabkha conditions for the North Hill area in Grey Marl times. (Stevenson and Warrington 1971).

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The distribution of the ammonite *Psiloceras planorbis in* SW Britain (Abstract):

by A. Whittaker

The lowest ammonite-bearing beds of the Lower Lias (Jurassic) crop out across the neck of the south west England peninsula from the Lyme Regis, Dorset, area by Street, Somerset, to Blue Anchor, Somerset. The Beds occur beneath the alluvial lowlands of central Somerset and in South Wales. Throughout the area studied, the strata are in typical Blue Lias offshore facies comprising alternating limestones and shales.

Stratigraphical studies suggest that some thin, but laterally persistent, individual Lower Lias beds can be correlated throughout the area. Ammonites referrable to the subgenus *Psiloceras* range through three shales, vertically, and first appear in great abundance at precisely the same stratigraphical level. The subgenus contains individuals which have been referred to three separate species m the past, but biometrical studies suggest that a single, interbreeding community may be present.

Individual specimens are most numerous in the Bristol Channel - Glastonbury Syncline area eastwards to Street, but south of this they are less common. Present work suggests that there were no physical barriers to migration across the region but that environmental conditions may have been more favourable in the Bristol Channel area.

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POST-HERCYNIAN MOVEMENTS IN SOUTH-WEST BRITAIN AND THEIR SIGNIFICANCE IN THE EVOLUTION OF THE CORNUBIAN AND WELSH "OLDLANDS"

by T.R. Owen

Abstract. Cornubia and Wales, as major palaeogeographical positive elements, date back to the Permo-Trias but were to receive several rejuvenating pulses during Mesozoic and Cenozoic times. One important phase preceded the Upper Cretaceous transgression.

1. Introduction

Studies of the sea floor in recent years have added considerably to our knowledge of the geology of the British area. Previous palaeogeographical reconstructions, based on the geology of only the present land areas, are m need of revision. In Cardigan Bay, Jurassic and Triassic deposits occur, the Lias in the Mochras Borehole being 1305 m thick (the thickest known Lower Jurassic .sequence, in the British area). In Tremadoc Bay the Lias and Trias are overlain unconformably by Tertiary sands, clays and pebble beds, which, at Mochras are 524 m thick. Tertiary deposits occupy the main downfold of the St. George's Channel Basin, resting on Jurassic and (south-westwards) on Cretaceous rocks. The Lower Cretaceous of the North Celtic Sea Basin is the reservoir for the Marathon gas finds south of Ireland. Beyond the WSW-trending Pembroke Ridge, a South Celtic Sea Basin extends eastwards into the Bristol Channel Basin and southwards towards the Cornubian oldland's northwestern edge. Tertiary and Chalk dominate the South Celtic Sea, beds of the latter system showing marked transgression across Permo-Trias on to basement when traced towards Lands End. Lower Cretaceous probably also occurs in the South Celtic Sea Basin (see Naylor and Mounteney, 1975, figs. 16 and 17), with salt structures within the deeper Permo-Trias (as in Cardigan Bay).

The unconformity at the base of the Chalk continues to be the dominant feature of the sea floor geology across the Scillies Ridge into the Western Approaches to the English Channel (see Naylor and Mounteney, 1975, fig. 14). Thick Permo-Trias appears to the south of Cornubia and still farther east the Jurassic members appear in turn from

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beneath the Upper Cretaceous cover. The axial trough of the main Western Approaches downfold is occupied by Tertiary sediments but structural complexity occurs in mid-Channel more especially along the "North Armorican Fault", which is really an ENE-WSW belt of pre-Upper Cretaceous folding and faulting, bringing horizons from Permo-Trias to Lower Cretaceous to the surface. These structures are cut off by the Upper Cretaceous unconformity; their presence (especially if involving Lower Cretaceous sand reservoirs) farther west in the Western Approaches could have considerable economic impact.

2. Post-Hercynian evolution of the area

The Hercynian Orogeny was followed by a time of intense erosion, and Permian sands with local coarse breccias and conglomerates began to blanket the irregular relief. The main uplands were presumably Cornubia and South Wales with possibly a depression along the Bristol Channel (this is suggested by the recent Permian finds in Somerset (Whittaker, 1972)). The westward extension of Permian along the Crediton Trough is a reminder that even more of Cornubia may have been once blanketed, with perhaps subsequent removal following on some westward upthrow along the Sticklepath line. Permian deposits spread over the basin to the west of Cornubia also.

Triassic deposition could also have spread over more of Cornubia and Wales than is "traditionally" claimed. That there were emergent areas is evidenced by the banking of littoral Trias against Mendip, Exmoor and Glamorgan "islands" but one must remember that the hearts of Wales and Comubia have suffered many upwarps since Triassic times and present-day height must not be allowed to confuse the issue. The same warning applies to consideration of the former extent of Jurassic deposition. Coarser Lias deposits are banked against islands in the Vale of Glamorgan and in the counties of Avon and Somerset but once again this can be a localised feature. What is particularly significant here is the generally fine-grained character of the thick Lias sequence at Mochras (with no hint of nearby land) and of the almost complete Jurassic succession in the Bristol Channel, where only in the Oxfordian is there a hint of sand influx (possibly from a southerly source). The diachronous Cotswold to Bridport sands, near the Lower-Middle Jurassic boundary, could again have had a Cornubian (or even a Western Approaches) source. These considerations remind one that intra-Jurassic uplifts of both Wales and Cornubia were a distinct possibility. In fact the probable Jurassic (and even late Triassic) pattern was that whereas subsidence was fairly continuous and

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considerable in (fault controlled?) basins such as the Bristol Channel, the Celtic Seas, Cardigan Bay and the English Channel, areas such as Cornubia and Wales were "loth to subside" and were yet further examples of the now classic Jurassic "swells". Cornubia and Wales were thinly covered with Jurassic (perhaps even Triassic) formations but slight regional uplifts were sufficient to intermittently remove parts of these sequences. The views of Whittaker (1975) are in keeping with this differential movement.

Late in Jurassic times, movements became more exaggerated and extensive and both the positive and negative Jurassic areas became largely emergent, i.e. non-marine. From late in the Purbeck through the Lower Cretaceous, earth movements were widespread. The timing of the climax of unrest varied considerably from place to place with post-Purbeck to pre-Wealden, post Wealden to pre-Aptian, post-Aptain to pre-Albian and even post-Albian "summits" of more intense movement. In mid-channel, folding and fracturing along ENE-WSW lines occurred. In the Weymouth area, folding and fracturing was particularly localised near the Abbotsbury line. The Mere Fault, near Wincanton, moved with appreciable southward downthrow (like the Abbotsbury fracture) before the deposition of the Albian. The combined effect of these Lower Cretaceous movements resulted in a major regional up-warping of Cornubia. This upwarping took place before the main Upper Cretaceous transgression and resulted in the removal of Jurassic, Triassic and Permian from the main heart of Cornubia. In the Haldon Hills, an occurrence of Cretaceous (of later Albian to a Cenomanian age) rests on the Permian. The Culm-Permian boundary lies less than a mile west of the Great Haldon Cretaceous, and hereabouts the Cretaceous oversteps westwards on to the Carboniferous. Internal overlap must however have occurred within this Haldon Greensand.

On the other hand, corresponding downwarps along the English Channel and Bristol Channel basins preserved the Permian to Jurassic sequences (and even Lower Cretaceous in parts of the English Channel). The preservation of the thick Jurrasic sequence in the Bristol Channel is then mainly due to these Lower Cretaceous movements and not to the mid-Tertiary movements (though the latter may admittedly have further accentuated the downwarp). It is also likely that Wales was upwarped (to the north of the Bristol Channel basin and to the east of the Cardigan Bay basin) by the same Lower Cretaceous movements. Along the easten edge of Cardigan Bay, the differential movements were probably more violent with large fault movements along the Mochras and Bala fractures. Fracturing may also have influenced pre-Chalk outcrops to the west of Cornubia.

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The flooding of the British area by the Chalk Sea was one of the great events of Phanerozoic time and must be directly linked with important opening of the North Atlantic (helped possibly by the removal of the Iberian barrier). The whole of south west Britain was probably covered with Chalk, though considerable lateral variation in thickness and completeness of time-sequence must have occurred with thinner (perhaps also younger) Chalk covers over Cornubia, Wales and southern Ireland. The latter region is unique in still preserving a patch of Chalk (near Killarney), but it is significant that this (collapsed) patch rests on Upper Palaeozoic basement with no hint of earlier preserved Mesozoics.

The next clue in the evolution of Cornubia is supplied by the fortunate preservation of mid-Eocene gravels, again on the Haldon Hills, Both hills are capped with thick gravels made up largely of Chalk flints together with Greensand chert and Palaeozoic fragments. It is obvious that the Chalk and underlying Greensand were being extensively removed at this time. That these Upper Cretaceous sheets were at least pierced in places is shown by the Palaeozoic stones, probably derived from the Permian breccias (Edmonds, McKeown and Williams 1969) The Cornubian granites were certainly at least partially exposed as evidenced by the matrix of the Haldon Gravels-rough granitic sand mixed with whitish clay (decomposed feldspar). A renewal of upwarping of Cornubia is therefore likely between the formation of the Chalk cover and the deposition of the Haldon Gravels.

The importance of these post-Cretaceous and pre-Eocene movements in west Scotland and in Ulster has already been convincingly demonstrated by George (1966 and 1967). In Ulster, the Eocene basalts overstep the Chalk and any underlying Mesozoics and rest discordantly on a variety of deformed Palaeozoic rocks down to Precambrian (George 1974a, p. 347). There are no Eocene sedimentary relics in Wales but there are Eocene dykes in N.W. Wales, implying "an Eocene terrain whose surface was at an unknown level above the present summits of at least some of the North-Welsh mountains" (George, 1974a, p. 348). The presence of the Lundy Granite (intruded about 52 m.y. ago) off the N.W. edge of Cornubia implies a marked uplift of that area in post-Eocene times to allow erosion down to that "plutonic" level' uplift possibly closely linked with movement of the Sticklepath Fault and with the neighbouring Oligocene basin to the east.

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Yet another clue to the evolution of the Cornubian and Welsh "oldlands" is supplied by the now-increasing numbers of outliers of Palaeogene rocks known in S.W. and W. Britain. George (1966, 1967, 1974a, 1974b) has once again stressed the importance of this Palaeogene overstep. Important movements preceded its depositions in Ulster with the complete removal of the basalts in places. In the Mochras Borehole, the Tertiary rests on Lias with no hint of Chalk either in the actual borehole sequence or as fragments (not even flints) in the Tertiary debris. At Flimston in Pembrokeshire, as George has shown, "neither Chalk nor other Mesozoic rock was locally present at the time of Palaeogene deposition" (1974a, p.351, also 1974b. p. 117).

The presumed Oligocene sands and lignitic clays of Petrockstow rest unconformably on Upper Carboniferous and those of Bovey Tracey on Cretaceous Permian, Carboniferous, and Devonian. The Upper Cretaceous (and any Eocene) cover was certainly removed from Petrockstow prior to the Oligocene deposition. The Dartmoor Granite was one of the chief sources of supply for the Bovey beds. On the eastern edge of the newly discovered Stanley Bank basin east of Lundy, the Tertiary beds transgress across Triassic and Jurassic on the southern limit of the Bristol Channel Syncline. Here again there is no intervening Chalk. As George maintains (1974b, p. 116) "the direct evidence thus discourages any hypothesis of the influence of a Chalk cover in the evolution of the Cornubian oldland during mid and later Cenozoic times". The same statement applies for Wales and Ireland. The Welsh and Cornubian ancestral streams never developed on a tilted or warped Chalk cover because that cover had long since been removed-at least in part by Eocene times, almost completely by Oligocene times.

The recognition of important movements in Cretaceous and Palaeogene times in S.W. Britain must lessen the effect of Miocene deformation to a certain extent. No longer does any folding of Mesozoics have to be of Miocene (the traditional "Alpine") age. The same caution applies to faulting though the dextral movements along the NW-SE fractures of Cornubia are notable exceptions, the broact oval form of the Comubian oldland was anticipated in many up-pulses through Mesozoic and Tertiary times, but particularly as a result of Lower Cretaceous, pre-Eocene, pre-Oligocene and Neogene movements. Of these particular pulses, the sea floor evidence gives pride of place to those which preceded the Upper Cretaceous transgression.

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THE GEOMORPHOLOGICAL DEVELOPMENT OF THE PENZANCE AREA

by Anthony J.J. Goode and Alan C. Wilson

Abstract The earliest Pleistocene event was the cutting of the marine surface at about 130 m (430 ft). Subsequently, during several episodes of erosion in the Middle and Upper Pleistocene, streams were cut down to graded base levels during stillstands of the falling sea level. In the latter part of the Upper Pleistocene the development of Head removed most traces of earlier beach and alluvial deposition but the alluvium deposited since the termination of periglacial activity was deposited on previously eroded topographic features. The Flandrian Transgression drowned the submerged forests of the district and resulted in the silting up of most of the streams.

1. Introduction

This paper examines the topography and deposits of Pleistocene to Recent age in the Penzance area and attempts to summarize the evolution of local geomorphology. The area lies to the west of the Cam-menellis Granite, including the Land's End Granite and the slate country to the east between St. Ives Bay and Mounts Bay. Many geomorphological features seen here many be compared with similar features throughout south-west England.

2. Topography

One of the best developed features of this area is the gentle, sea-ward dipping planar surface backed in many places by an old cliff line at about 130 m. It is best preserved on the northern coast of the Land's End Peninsula.

A distinction may be made between the drainage pattern of the higher land of the Land's End district and that of the lower lying slate country to the east. In the former the drainage is closely controlled by NW-SE joints and faults. The north-westerly flowing streams are short in length and flow gently across the 130-m surface before descending rapidly seawards in steep-sided valleys. The south-easterly flowing

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streams are generally longer, displaying more complex longitudinal profiles. The slate country of the latter area is drained by streams of shallow gradient which flow along moderately steep-sided valleys and although partly controlled by faulting they more commonly follow a winding course. The streams examined are only a few metres wide and barely a metre deep and commonly flow in rather broad, deep valleys; thus they are misfits with regard to the valleys in which they flow.

Many of the streams, particularly those on the granite, tend to rise in broad basins with shallow sides, enclosed except for a downstream-tapering channel flanked by bluffs (Wilson 1974, p. 122). Some basins show no similarity in height to those of nearby valleys and may have originated as nivation hollows.

It is believed that the topographical features described can be related to the recent deposits of the area which are reviewed in the following section.

3. Deposits

Raised Beach deposits

Raised Beach deposits consist of gravels and well sorted sands. The clasts are well rounded and commonly of cobble grade. The overall fabric of the rock and the structures of the sands clearly indicate beach deposition.

Old Alluvium

The old alluvium of the broad open basins is generally clayey with a mixture of rounded and angular gravels, occasionally having exotic clasts transported from a distance of several kilometres. The roundness and provenance of some Clasts suggest an alluvial origin at least in part, but the apparent lack of stratification may be the result of post-depositional destruction by periglacial processes.

Head

The Head usually comprises a poorly consolidated melange of locally derived rock fragments bound together by a sandy or clayey matrix. Two separate types have been noted.

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i) Basinal Head

Basinal Head is found inffiling valleys and from a distinct back feature the upper surface grades downslope. It can be up to a few tens of metres thick, comprising layers of sediment which show slight structural and textural changes but are still recognisable as having been deposited by water or debris-flow. Basinal Head is well exposed in low cliffs to the west of Marazion and has been encountered in a borehole at Pendarves near Cambome (IGS. Ann. Rept. for 1972, p. 16). Slight compositional difference between layers suggests movement of material downhill but clasts can be traced to a source not more than a few hundred metres distant.

ii) Blanket Head

Blanket Head has a general thickness of 1 or 2 metres and is fairly widespread throughout the district. There is little difference in thickness between hilltops and valley bottoms, however those variations in thickness that have been observed apparently depend more on the nature of the subsurface lithology than the location. There are no exotic clasts as Blanket Head has been dervied from 'in situ' or almost 'in situ' weathering of the substrate with no evidence of mass transport.

Alluvium

The alluvium consists of rounded gravels, sands, silts and clays, with some associated valley peat. The greatest variations of lithology and sedimentary structure occur in the non-granite area but in places it is difficult to differentiate either topographically or lithologically between alluvium derived from granite and basinal Head derived from granite.

4. The relationships of deposits to topography

Few of the deposits carry any dateable material and consequently it is only possible to attempt a determination of relative ages.

The 130-m surface, with its old cliff line and gentle seaward dip, can be seen throughout the area and it is comparable to many present day near-shore sea bottoms cut by wave action. It is generally accepted that this feature was so formed, probably in early Pleistocene times and

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is certainly Neogene rather than Palaeogene in age (Wilson 1975, p. 291). Some rounded clasts, possibly the remnants of an old beach deposit have been found at this height but the movement of great quantities of modern beach material for agricultural use has cast doubt on this evidence.

The remnants of another wave-cut surface may be seen at many localities around the peninsula, at about 3 m O.D., commonly capped by a few metres of raised beach. No dateable fossils have been found in the latter, probably because acid water has leached out any calcium carbonate, but it appears that it is a good deal younger than the 130 m wave-cut surface.

The old alluvium of the broad open basins was disturbed by periglacial activity, suggesting that the older periglacial and the younger alluvial processes partly coincided in the later part of the Pleistocene.

Where the two types of Head are found together the basinal variety always occurs below the blanket type and is consequently the older. It is likely that a gradual amelioration of the climate, accompanied by a reduction in solifluction processes, would permit the accumulation of in-situ weathered detritus. The Head is clearly a relatively young deposit since it overlies the 3-m raised beach deposits, the old high-level graded reaches of some valleys (below) and some of the earlier well-developed terrace deposits. However it is older than the youngest alluvial terrace deposits of the area, which are dateable (below).

The graded reaches of many of the streams have been extrapolated towards the horizontal and concentrations of levels occur at approximately 98, 82, 61, 52, 42, 30, 21, 10 metres O.D. These heights may represent stillstands of a falling sea level during Middle and Upper Pleistocene times. All deposits which might have formed have long since been removed by periglacial and other erosional processes.

The raised beach deposits which lie on a wave-cut surface at about 3 m O.D. probably equate with Some of the lowest graded stream profiles of the area. If the good preservation of these deposits and of the higher, graded reaches does indicate progressive regression of the sea without intervening transgression during the Middle and Upper Pleistocene, then since the Flandrian Transgression has drowned the extensive low-lying forests around Marazion and Hayle, it is likely that the submerged forest at Penzance (dated at 4278 B.P.) is considerably younger than the raised beach deposits occuring just above sea level.

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SUMMARY TABLE

Recent	B.P.		
	1810	Little deposition of alluvium after Roman times	Marine transgression
	4278	Submergence of forest, reduction in alluvial deposition	
	4919	Alluvial deposition with peat	
		Maximum development of peat around present sea level	
Pleistocene	10202	Alluvial deposition with peat	Most alluvial terrace deposits accumulated at this time
			Sea level below O.D. by a few metres
		Development of blanket Head	Amelioration of climate with little movement by solifluction
	Upper	Development of basinal Head	Solifluction processes prevalent
		Alluvium beginning to be deposited and preserved	
		Cutting of marine surface 3 m O.D.	Accretion of raised beach on this surface
	Middle	Lowering of sea level, stillstands at 98, 82, 61, 52, 42, 30, 21, 10 m and the cutting of graded stream profiles	Marine regression Aggradation of alluvial deposits subsequently removed
	Lower	Cutting of marine surface 130 m O.D.	Possible deposition of raised beach
Plio-cene	Upper	Deposition of the St Erth Beds	Marine transgression

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All the streams are at present flanked by abandoned terraces which by means of radio-carbon dating have been shown to be of late Devensian to Flandrian age (Shotton 1973, Table 1) from 10202-1810 B.P. These later terrace deposits have not been disturbed by periglacial processes and are younger than the latest event of this nature to influence the region. This is partly confirmed by the fact that the terraces are parallel to each other and to the present stream floor and not directly related to the individual graded reaches along which they occur.

The inferred age relationships between the topographic features and the deposits of the area are summarised in Table 1.

Acknowledgements. We are grateful to our colleagues Dr E.C. Freshney and Dr R.T Taylor for their comments on aspects of the paper. The paper is published by permission of the Director, Institute of Geological Sciences.

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PRACTICAL ASPECTS OF PERIGLACIAL EFFECTS ON WEATHERED GRANITE

by W.R. Dearman, F.J. Baynes and Y. Irfan

Abstract. Mapping of the distribution of six grades of weathering in Hingston Down granite quarry, near Gunnislake, Cornwall reveals a discordance between surface topography and the topography of the weathering zones. It can be demonstated that material representing high grades of weathering has been stripped by solifluction from the hill crest and deposited over a complete weathering profile preserved on the hill flanks.

Granite showing various weathering stages has been characterised in terms of the index properties strength and effective porosity. Worked quarry areas are restricted to granite of high strength and high durability, the latter linked directly to very low effective porosity.

1 . Introduction

Opinions on the origin of decomposed granite on Dartmoor, summarized by Brunsden (1964), attribute the deep rotting variously to chemical decomposition by circulating acidic surface waters, to frost shattering, or to hydrothermal alteration. Brunsden finds evidence for all three activities, often in the same exposure, whereas Palmer and Neilson (1962) had earlier ascribed all rotting to hydrothermal alteration with additional frost shattering just below the surface. That chemical decomposition by weathering has, in fact, played an important part in the development of weathering profiles becomes certain when rock types other than granite are studied (Fookes *et al.* 1971, Dearman and Fookes 1972, Dearman and Fattohi 1974).

The age of the weathering profile is difficult to determine, but Brunsden (1964) points out that the deposits are formed within the height range of Middle-Late Tertiary erosion surfaces. Most of the terraces below 800 ft, cut in solid granite, seem to have been little affected by chemical weathering since their formation. Little chemical weathering was accomplished during the Pleistocene, and Eden and Green (1971) relate the formation of Dartmoor 'growan' to the 'sandy weathering' type of Bakker (1967) formed under meso-humid sub-tropical climatic conditions during the Pliocene or Lower Pleistocene.

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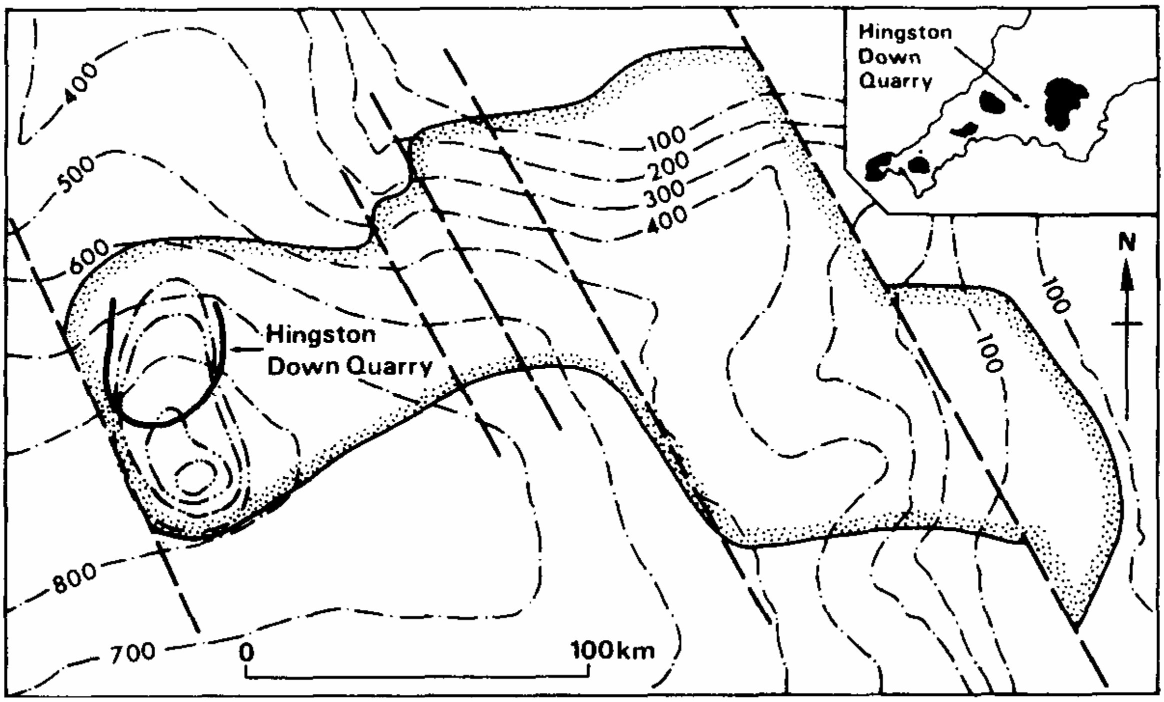

FIGURE 1. The outcrop of the granite at Hingston Down and the main structural features. Inset: location of the quarry in S.W. England. The north-west trending broken lines are wrench-faults; the most easterly is the Great Cross Course, the others are presumed faults on the basis of the outcrop pattern. Weathering zone contours are shown by the double dotted lines, see Fig. 3.

Much of the interest in decomposed granite has centred on the origin of tors (Linton 1955, Palmer and Neilson 1962) and it is becoming evident (Eden and Green 1971) that geomorphological processes active during the Pleistocene stripped the early formed saprolitic cover, modified the Tertiary elements in the topography, and disturbed the weathering profile (Waters 1964).

It is within this context that the distribution of weathering grades and engineering properties of the granite at Hingston Down Quarry near Gunnislake, Cornwall, has been studied.

2. Geological Setting

Hingston Down Quarry is situated at the western end of the outcrop of the Gunnislake granite.The granite is known to be faulted at its eastern end by the Great Cross Course (Fig. 1) which has a dextral offset of 650 ft (Dines 1956); the outcrop pattern suggests that other NNW cross courses may be present. East to west trending quartz-tourmaline veins, mineral lodes and elvans also cut the granite.

The granite is grey, medium-grained with scattered porphyritic crystals of varying grain size (Reid *et al.* 1911).

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3. **Weathering grades in the granite**

A sequence of weathering effects can be recognised spreading inwards from joints in the joint-bounded granite blocks:

(a) Fresh grey granite with some iron-staining on joint surfaces

(b) Deep brown discolouration penetrating into the rock as a selvedge to discoloured joints

(c) Complete light brown discolouration of the granite

(d) Granular disintegration developing along joint planes giving core stones of discoloured rock in soil.

(e) Complete granular disintegration; all the rock converted to soil.

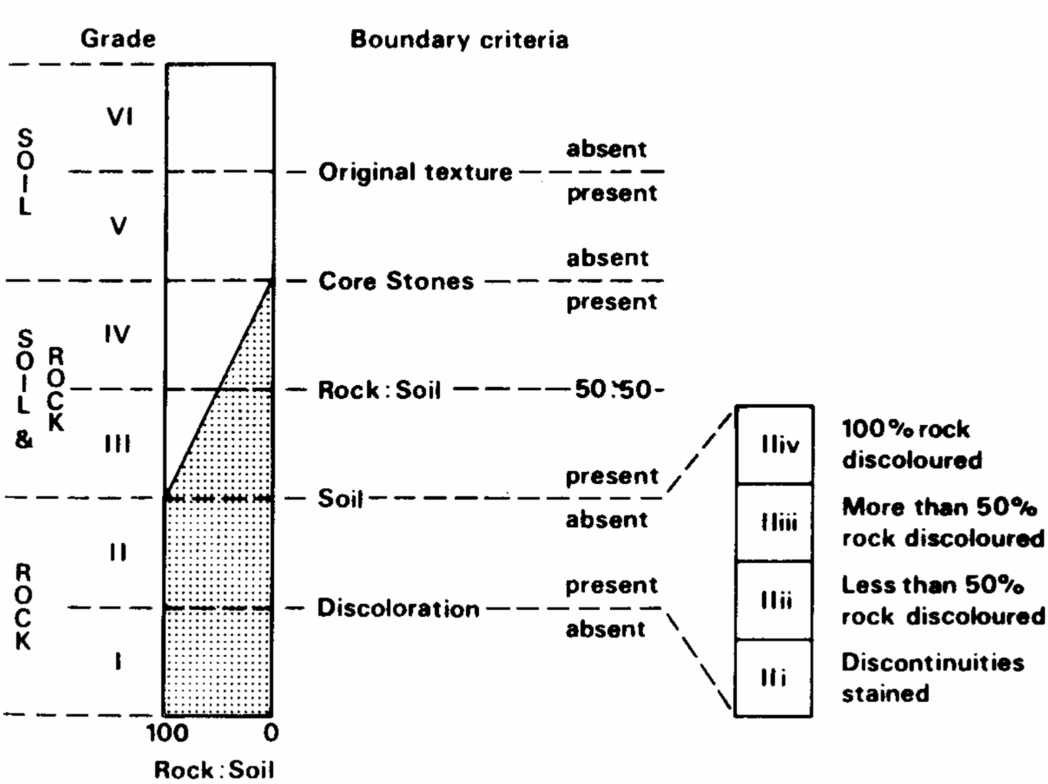

FIGURE 2. Sequence of weathering grades used in mapping Hingston Down Quarry

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The terms ‘soil’ and ‘rock’ are used in the engineering sense (Anon. 1972), and the sequence (a) to (e) in which rock material is converted to soil by chemical weathering is similar in broad outlines to the weathering classifications adopted by Moye (1955) for the Snowy Mountains Scheme in Australia, and by Ruxton and Berry (1957) for the granite of Hong Kong.

For practical mapping purposes on the scale of a quarry face various characteristic stages of the weathering process are defined as weathering grades applicable to the jointed granite mass. Grades are determined by the amount of discolouration, the rock: soil ratio, and the present or absence of the original granite fabric in the soil (Fig. 2). A reasonable number of mapping units is the six grades represented in Fig 2, but additional mapping units may be established by, for example, subdivision of Grade II, which is based on rock discolouration, into Grades IIi, IIii, IIiii and IIiv depending on the degree of penetration of discolouration.

Weathering grades were mapped on to a series of Polaroid photographs by visual assessment; the grade boundaries were then transferred to accurate plans and elevations of the various quarrying levels. Structure contours of the surfaces between various grades were sketched on the plans and from these it was possible to assess the general three-dimensional form of the weathering profile in relation to the present day surface topography (Fig. 3). It is clear that a complete weathering profile is present only on the east and west flanks of the quarried area, whereas in the centre Grade II material crops out at the surface beneath a thin cover of soliflucted debris. If it is assumed that a complete weathering profile was formerly present over the whole area, then the present day topography has to be modified to fit the model of a weathering profile developed on a convex hill proposed by Ruxton and Berry (1957, fig. 9). This early convex hill suffered erosion of the higher parts by solifluction during the Pleistocene, with resultant deposition downhill of the more weathered material, and the later incorporation in the upper parts of the solifluction mantle of less and less weathered material. This picture of the formation of an inverted weathering profile on the lower hill slopes (Brunsden 1964) is borne out by the presence of Grade V completely weathered granite passing up into the same material disturbed by creep with overlying sandy/clayey soil, ‘head’, with large angular relatively fresh granite boulders.

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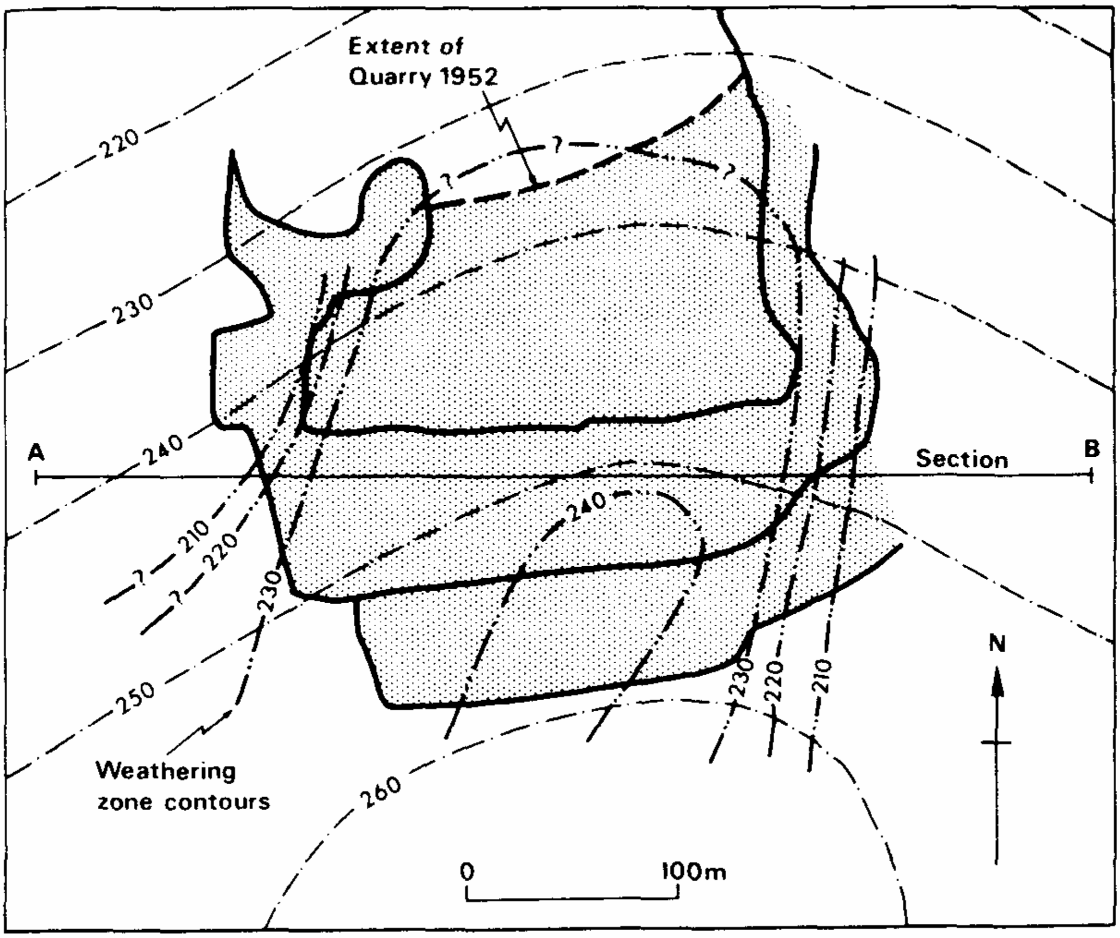

FIGURE 3. Plan of Hingston Down quarry showing the surface topography and the contours on the boundary of weathering grades I and II.

4. The influence of weathering on quarrying practice

Hingston Down Quarry provides crushed stone for roads and concrete. For both uses the required qualities are high strength and durability which may be assessed by index tests on specimens of the rock material. It is possible to characterize the different types of rock material, for example, fresh granite, discoloured granite, and soil making up each weathering grade, and so arrive at a practical assessment of the value of each mass weathering grade.

The index tests used were:

(i) Strength. This can be assessed by the point load test (Franklin *et al.* 1971) which gives a value of tensile strength directly correlatable with unconfined compressive strength (D'Andrea *et al.* 1965). The results of uniaxial compressive strength quoted here are those determined in the laboratory on prepared cylinders in order to relate field with laboratory results.

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(ii) Durability. Resistance of rock to weakening and disintegration in use is a meaure of durability (Fookes *et al.* 1971, p. 152). One of the chief controls influencing durability is the ability of the rock material to resist penetration of weathering agents; high effective porosity is the chief cause of penetration and may be regarded as a durability index.

Effective porosity is determined by the quick absorption test in which a specimen, oven dried for 2 hours, is weighed, immersed in water for 2 hours and then reweighed. The increase in weight is a measure of porosity. The results for various kinds of rock material are:

		Uniaxial Compressive Strength (KN/m^2)		
Grade	Material	Dry	Saturated	Effective Porosity %
I	Fresh Granite	246	228	0.11
Iiii	Partly discoloured	219	154	0.57
IIiv	Completely discoloured	165	93	1.52
V	Intact Soil	3.5	not determinable	9.98

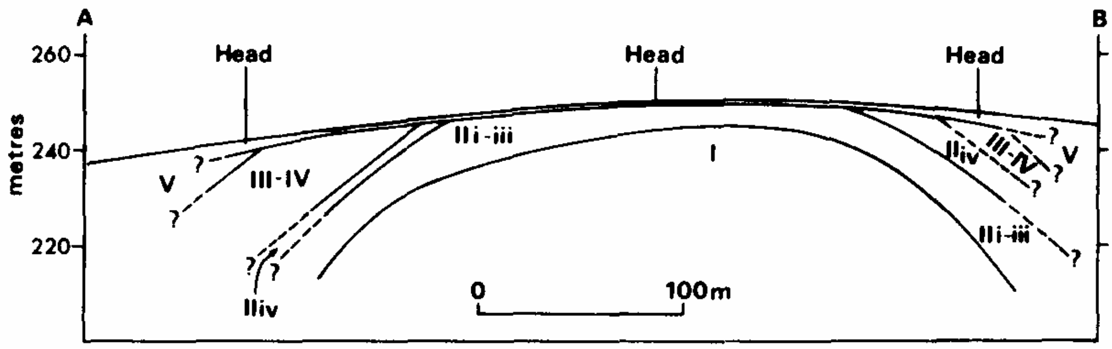

FIGURE 4. Cross-section through Hingston Down quarry, along the line A-B marked on Figure 3, showing the distribution of weathering grades and head deposits.

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From the results it is apparent that as the rock material becomes more weathered the strength decreases and the effective porosity increases (i.e. durability decreases). In quarrying practice, the cut-off point for acceptable material is complete discolouration; material of this and lower grades is dumped to waste or utilised as fill-material.

5. Discussion and conclusions

The weathering profile preserved at Hingston Down has been shown to dip more steeply away from the crest of the hill than the present day topography. Consequently, the hill crest comprises relatively unweathered granite which formed the core of a small convex hill on which a complete chemical weathering profile had been developed in early Tertiary times (Fig. 5a). The early topographic configuration is likened to the Hong Kong model proposed by Ruxton and Berry (op. cit.); during the Pleistocene the saprolitic cover on the top of the hill was stripped off by solifluction and deposited further down the slope as `head', producing Brunsden's inverted weathering profile (Fig. 5b).

The controls on the original topography, and hence the original weathering profile, may well have been the presence of NNW-trending wrench faults. Such faults may have had associated with them more closely spaced jointing (Fookes *et al.* 1971, fig.. 18b), thus opening the ground to penetration by weathering agencies and increasing mechanical erosion. This aspect still has to be investigated.

Although the weathering profile was investigated by classifying it into various rock mass edges, only the physical properties of various stages of weathering of the rock material could be assessed by the use of index tests. These tests show that as weathering intensity increases there is an associated reduction in strength and an increase in effective porosity, reducing the durability of the rock. As high strength and durability are important properties of aggregates, the rock material must be regarded as unsuitable for use when it is weathered beyond a certain stage. In practice this is assessed visually as being at the IIiii/IIiv boundary, i.e. material that is completely discoloured or even more weathered is dumped or used as fill. Degree of preservation of the complete weathering profile coupled with the addition of head on the hill flanks, determines the amount of overburden which has to be stripped off before the unweathered rock can be extracted. This study has shown that to the west and east of the present quarry the combined depth of this overburden increases because of the

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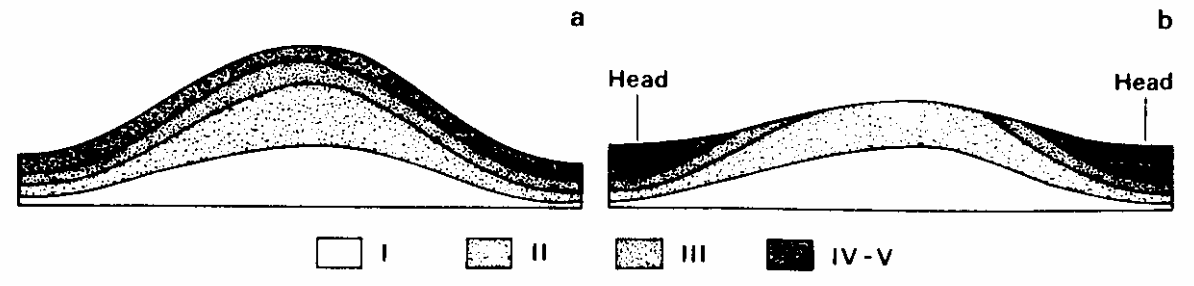

FIGURE 5. Idealized model of the Pleistocene modification of the presumed Tertiary topography and distribution of weathering grades at Hingston Down. (a) Tertiary, (b) Pleistocene and present.

preservation of a complete chemical weathering profile beneath head derived from the adjacent hill crests. Thus the extraction of unweathered rock from these areas becomes uneconomic, and the workable reserves lie south of the present quarry within the exposed core of unweathered rock.

Acknowledgements. This work has been continued with the aid of a NERC research award which is gratefully acknowledged, as is the interest shown by the owners and management of Hingston Down Quarry who readily provided access to the quarry faces.

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ASPECTS OF THE HYDROGEOLOGY OF ST. MARY'S, SCILLY ISLES

by W.G. Burgess, U.R. Clowes, J.W. Lloyd and J.M. Marsh

Abstract. A preliminary investigation of the hydrogeology of St. Mary's in the Scilly Isles is described. The aquifers are defined and the groundwater flow pattern is established. A study of geophysical aspects of the granite aquifer is discussed, and a recharge assessment indicates the approximate groundwater flow volumes moving into areas where groundwater abstraction is at present occurring.

1. Introduction

The Scilly Isles are located west-south-west of Land's End at general co-ordinates 49° 55'N and 6° 18'W. The largest island is St. Mary's which has an area of 6.5 km^2 and supports a permanent population of about 2000 inhabitants. Winter water supplies pose no problems but during the summer a large influx of tourists significantly increases the water demand.

To clarify the water resource situation the study discussed below was initiated by the South West Water Authority as a prelude to detailed long-term investigations.

St. Mary's obtains its entire water supply from granite rocks and their derivates. In this respect it has an uncommon hydrogeological environment and provides an unusual opportunity for hydrogeological study.

2. **Geology**

The geology of St. Mary's is shown on Figure 1 and is based on the work of Dollar (1957). The geological succession is as follows:

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Recent	Alluvium and blown sand
Pleistocene - Pliocene (?)	Head, loess and conglomerate
Permo-Carboniferous	Quartz-porphyry dyke, pegmatites and aplites
	Fine-grained and coarse grained granite

Hydrogeologically only the granites and the Recent alluvium are of significance. Two types of muscovite-biotite granite are present differing essentially in grain size, with the fine-grained granite intruded into the coarse-grained variety. The granites are well jointed with a system of inclined conjugate joints and sub-horizontal pressure relief joints. The conjugate joints trend generally north-west, and north-east to east-north-east.

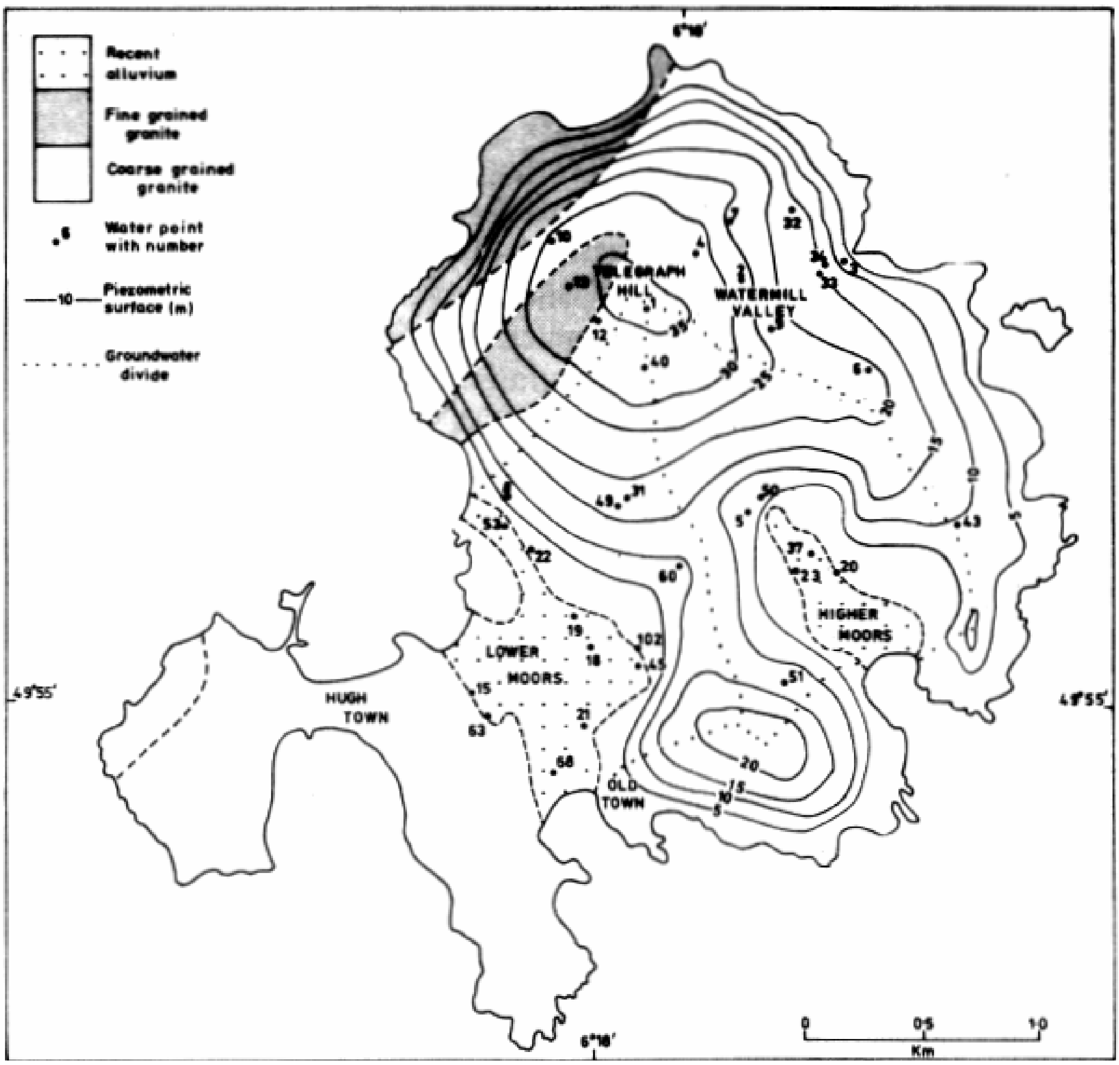

FIGURE 1. General geology and aquifer piezometric surface of St. Mary's

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The Recent alluvium is located in the two lowland areas known as the Higher and Lower Moors (see Figure 1). The upper levels of the alluvium are fine-grained and consist predominantly of clays and silts. These overlie a coarser unit of sands and sandy grits which directly overlie the granite.

3. Hydrology

The Scilly Isles experience warm, damp summers and mild wet winters. The mean annual rainfall for St. Mary's (Telegraph Hill) is 881 mm (1941-74).

The runoff conditions are unusual in that few well-defined valleys are present. Normally most of the rainfall over the granite areas passes into the soil profile either to be evaporated, move coastwards as interflow, or recharge the aquifer. In the Moors, marsh conditions exist as a result of the low permeability of the top layers of the alluvium. Base flow of a very low order is present only in the Watermill valley and in the lower levels of the Moors, but no long term records are available.

For the present study direct recharge calculations were carried out using soil moisture balance concepts. Owing to the absence of runoff records an estimate was made at 10% of actual precipitation based on runoff values for south-west England (Devon River Authority, 1972) and the local evidence of low volumes. Rainfall data for Telegraph Hill were used and evaporation was computed from the meteorological data for the same station on a ten-day basis. Values of 58 mm and 92 mm were used for the crop factor and soil moisture respectively.

The recharge values are shown in Table 1 together with annual rainfall, throughput and abstraction.

4. Hydrogeology

The aquifers consist of the secondary permeability granite system and the primary permeability sandy units in the Moors which are in hydraulic continuity with the granites feeding the alluvium. The granite system is unconfined, although head variations have been recorded during drilling due to differential pressures in different fissures and the local absence of hydraulic continuity. In the Moors, confined or partially confined conditions occur as a result of the low permeability top layer in the alluvium.

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Table 1. Approximate recharge, throughput and abstraction

	1971	1972	1973	1974
Rainfall (mm)	794	987	794	1125
Recharge (m)	0.165	0.426	0.249	0.504
Lower Moors catchment				
Recharge ($10^3 m^3$)	132	319	199	404
Throughput ($10^3 m^3$)	-	-	-	237
Abstraction ($10^3 m^3$)	-	-	-	85
Higher Moors catchment				
Recharge ($10^3 m^3$)	171	441	258	526
Throughput ($10^3 m^3$)	-	-	-	310
Abstraction ($10^3 m^3$)	-	-	-	97

The piezometric surface for the island is shown in Figure 1 with the main recharge mound centred on Telegraph Hill. The piezometric surface shows the presence of a very steep groundwater gradient in the north-west where the main fine-grained granite masses occur. It is considered therefore that open joints are poorly developed in this intrusive with consequent low permeability. The main groundwater flow occurs in the coarse-grained granite. Three dominant directions are important, two relate to the movement into the Moors with the third along the Watermill valley. These flows account for the bulk of the recharge and are each directly or indirectly related to structural control. The Moors occupy structurally disturbed zones along the north-west alignment which have been eroded lo low elevations and the Watermill valley has formed along a highly jointed zone on the east-north-east alignment.

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In the coarse-grained granite, surface and borehole geophysical studies were carried out to determine if any significant differential zones of permeability occur.

Surface resistivity methods were limited by poor current penetration due to the high resistivity in the granite. In the recharge mound area no marked resistivity differences were recorded. The indications, therefore, are that joints are regularly developed and significant zoning with resultant high permeability is not present. Some changes of resistivity with depth occur in the Watermill valley where marked jointing is present. The narrowness of the valley, however, introduces problems in interpretation so that it is unlikely that surface resistivity techniques will reliably distinguish high permeability zones.

Various borehole logging methods were tested to discern measurable differences in the granite. As most holes are shallow, multi-point resistivity proved unfeasible and reliance was placed on single point logging. Differences were detected in all holes logged, notably in Watermill valley where a broad horizontal correlation was obtained. Fissure flow was easily identified using temperature and electrical conductivity probes. In the deepest hole, Decca (B.H. 10), fissures are located throughout the borehole whilst in the shallower holes it is clear that only one or two fissures have been penetrated which have produced adequate yields for local requirements. No correlation of fissures between neighbouring boreholes is apparent.

From the geophysical studies it may be concluded that minor local differences are,present in the vertical resistivity of the granite which may be related to differential weathering along the major pressure relief joints. Although conjugate joints have governed Watermill valley geomorphologically, the lateral correlation of single point resistivity indicates that differences exist that are more in accord with horizontal jointing.

In the Moors, surface resistivity was successfully used to obtain the configuration of the top of the granite below the alluvium. Lithological control was obtain from auger holes. The interpretations of both areas are shown in Figure 2.

With respect to aquifer characteristics standard pumping-test analysis techniques were discounted on the basis of the secondary permeability nature of the granite and the absence of observation wells. Specific capacity data for wells in the granite indicate a wide range

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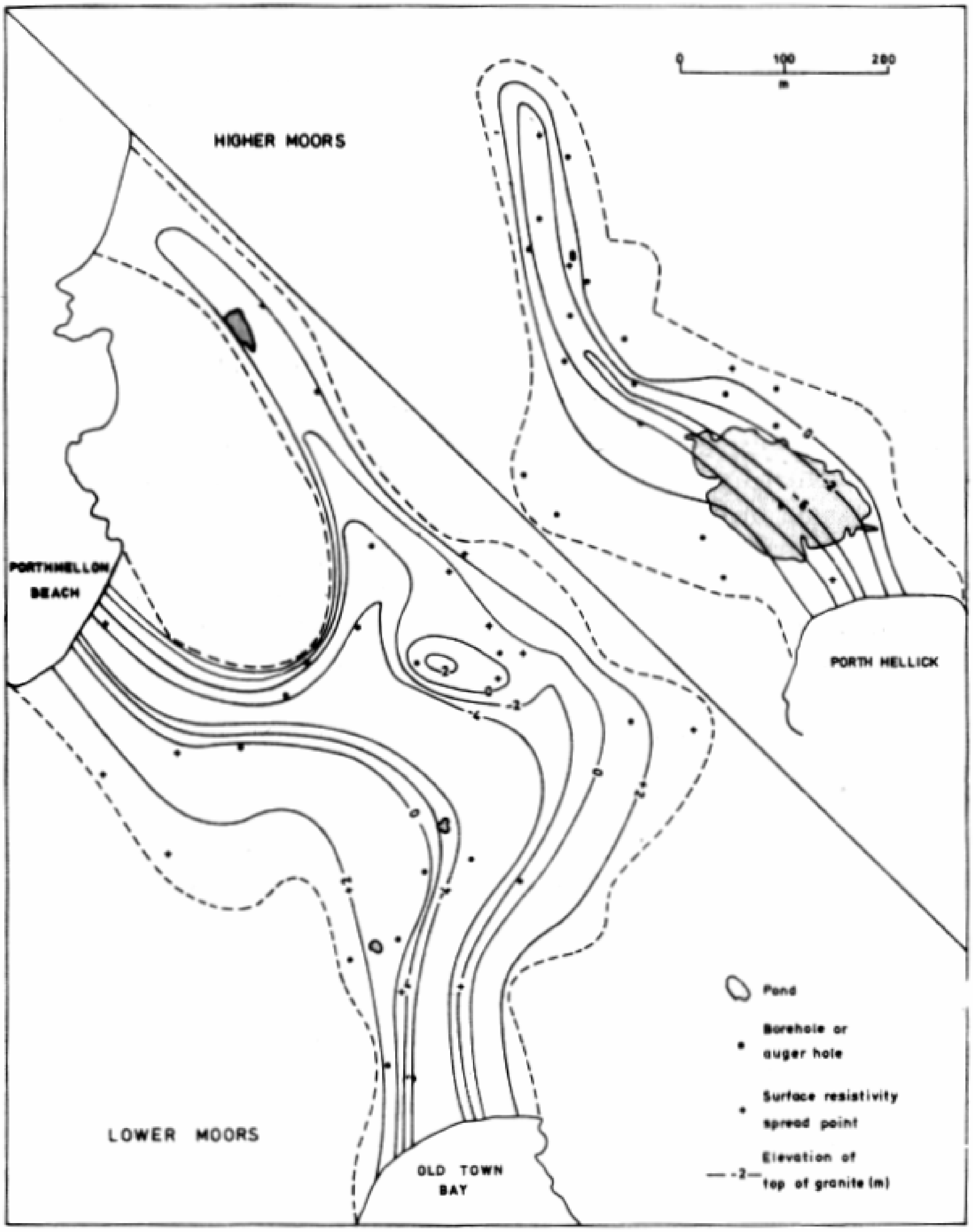

FIGURE 2. Structure contours of the top of the granite under the areas of the Moors

(0.39 to 5.4 m^3/day/m) which makes the regional allocation of permeability very difficult. Further, from the point of view of transmissivity the base of the aquifer is not known.

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From the specific capacity data (3_0 to 5.2 m^3/day/m) it is apparent that the wells in the granite in Watermill valley have penetrated the highest permeability zones so far drilled in this aquifer. Although no throughput analysis is possible the recharge estimate for the valley has been calculated to be $110.10^3 m^3$/year which is in excess of the present abstraction.

In the Moors, pumping-test analyses were carried out on the main abstraction wells. The most reliable data were obtained from Venn's well (B.H. 37) in the High Moors where a permeability value of 100m/day was established which was extrapolated for all the alluvium and used in the throughput analyses. Throughputs were computed using the 1975 summer hydraulic gradients (see Table 1), and although they are of the same broad order of magnitude as the recharge estimates, they are about 40% less. The discrepancy may be due to various reasons. Undoubtedly the throughput is underestimated for the steeper winter gradients and some overestimation of recharge may have been made owing to the absence of runoff data. However, the omission of any allowance for the throughput of groundwater flowing in the granite beneath the alluvium is believed to be the main discrepancy. The recharge indications are, therefore, that these flows are important.

Finally, although St. Mary's is an island, no saline water encroachment has been recorded. The main abstraction wells are some distance from the coast in the alluvium, but abstraction is a significant proportion of throughput in the summer months so that a deterioration in quality would not be surprising in such a thin aquifer. This absence of encroachment may well be another indication of important groundwater flow occurring in the granite beneath the alluvium. Groundwater gradients are, however, shallow, so care must be exercised to avoid reversal of gradients to the abstraction wells.

5: Hydrochemistry

The groundwater of St. Mary's is a corrosive, low pH water, undersaturated in carbonate minerals. Marine salts introduced into the aquifer by infiltration from oceanic rainfall are estimated to comprise 80% of the dissolved solids content of the water, the remaining concentration is derived from solution in the soil zone and in the aquifer.

The acidic nature of the water results in corrosion of metals in wells and distribution systems. The trace elements zinc and copper occur in relatively high concentrations as a result of corrosion. The levels, however, are within potable limits.

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There is no significant variation of groundwater chemistry with depth and no evidence that the quality of groundwater will deteriorate at present rates of abstraction.

6. Conclusions

The study has established the nature of the aquifer and the pattern of the groundwater distribution. Geophysical evidence on the granite in the recharge area has revealed no significant differences in its physical character. Water level and specific capacity data, however, indicate that the aquifer has a non-homogeneous permeability and it is apparent that quantitative analysis of groundwater in the granite involving normal Darcy principles is not feasible. Therefore attention should be paid to refining the recharge estimates possibly on a daily balance basis. Reliable evaporation figures exist, but data on runoff are essential and more data are required on the soil profile characters.

The recharge study indicates that important groundwater flow probably exists in the granite under the Moors and it is suggested that these areas should be further investigated. The Moors and Watermill valley are regarded as having the highest potential for groundwater resources development.

Obviously saline intrusion must be considered in any further development. In the Moors this does not pose such a problem as in Watermill valley, as they are comparatively wide areas and abstraction heads can be distributed throughout a number of wells.

Acknowledgements. The authors would like to thank the staff of the Council of the Scilly Isles and the South West Water Authority for their assistance during the study.

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Heavy element accumulations in the Teign Estuary (Abstract);

by J.R. Merefield

Recent studies of stream sediments from the Middle Teign Valley of South West Devon revealed high concentrations of Ba, Pb and Zn related to local mineralization. In the present work, active river and estuarine sediments from Teign Head to Teignmouth have been analysed for heavy elements in order to examine their modes of transport. Sediments were collected from 30 sampling stations and analysis carried out by X.R.S. on the $< 250\mu$ fraction.

As expected, highest concentrations of Ba, Pb and Zn occur in the Middle Teign River adjacent to orefield-feeding streams. However, peak values discovered in the fresh/salt water mixing-zone, at the head of the estuary, prove particularly interesting. Estuarine highs attain values of eight times for Ba, eight times for Pb, and twice for Zn, threshold levels.

Hydrous Fe and Mn precipitates contain up to 86% of the Ba, 99% of the Pb and 99% of the Zn found in the sediments. Fe/Mn scavenging appears, therefore, to have taken place where local pH and Eh changes cause Fe precipitation. Additional major controls on element accumulations in the estuary are clay flocculation and mechanical sediment sorting. The source area of the estuarine highs is essentially the same as that of the river anomalies.

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SUPRA-BATHOLITHIC VOLCANISM OF THE SOUTH WEST ENGLAND GRANITES

by M.E. Cosgrove and M.H. Elliott

Abstract. Geochemical and petrographic comparisons axe made between rhyolites cutting and resting on deformed Devonian strata occurring marginally to the S,W. England batholith and those now occurring in red bed Conglomerates of Stephanian-Lower Permian age. Evidence for the comagmatic origin of both sets of rhyolite is presented including extrusive phases (in both cases) showing enrichment of K, Rb, Sr, As, Ni, Cu and Zn as compared with their associated intrusive phases. The element distribution patterns axe related to metasomatic and mineralisation events, and the rocks axe interpreted as remnants of a once extensive rhyolite capping of the granite batholith.

1. Introduction

Over the years many references have been made to the theoretical existence of Dartmoor volcanoes as extrusive expressions of the underlying batholith. The presence of abundant feldspar crystals (sanidine-previously recorded as murchisonite) in the St. Cyres Beds of the Crediton Trough, and rhyolite boulders and cobbles in the red bed conglomerates (Hutchins, 1963; Laming, 1966) have been used as evidence to support such a theory.

The apparently rapid erosion of this volcanic cap has left no direct evidence of its existence. However, it would seem reasonable to expect that there might also have been marginal volcanoes, whose products could have been less prone to erosion. With this in mind, the Withnoe-Kingsand igneous rocks (SX 4050) (possible marginal representatives of the volcanic event) have been compared petrochemically with some of the cobbles from the red bed Conglomerates (possible derivatives of the original capping volcano), to test the thesis that feeders and volcanics in the *in situ* marginal phase are similar to rhyolitic debris in molasse from the granite capping. In making this comparison, some chemical variations between the central and marginal examples would be expected, as would textural and chemical differences between extrusive and intrusive phases at each locality.

2. Geological setting

In the Withnoe-Kingsand area of Cornwall (Fig. 1) some 18 km to the southwest of Dartmoor there are *in situ* occurrences of intrusive and extrusive rhyolites both cutting and overlying deformed Devonian sediments. They are believed to be post-orogenic and subaerial and were

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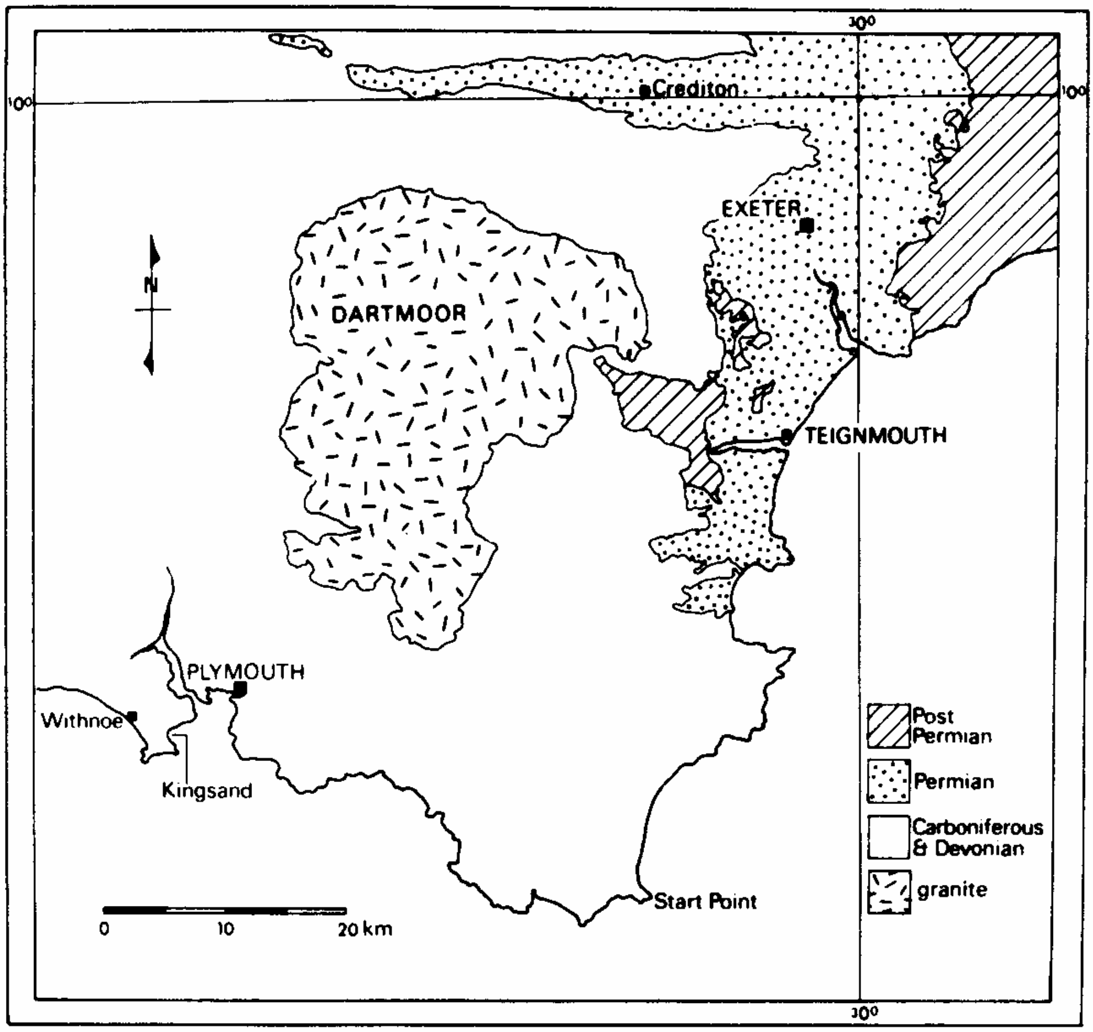

FIGURE 1 Map of central Devonshire showing general geology and localities.

subjected to a "red bed type" weathering environment immediately after formation. The Withnoe rocks, believed to be intrusive, occur in a roughly circular outcrop some 200-250 m across, and are well exposed in an old quarry (SX 404517). The Kingsand rocks, believed to represent the extrusive phase, outcrop on a prominent wave-cut platform stretching for about 1 km along the shore and up to about 500 m inland (SX 438508). The petrochemical characters, described later in this paper, indicate consanguinity between the two outcrops.

In the Teignmouth area of Devonshire (Fig. 1), some 15 km to the southeast of the nearest outcrop of the Dartmoor granite, "porphyry" boulders and cobbles occur commonly in the Stephanian/Lower Permian red bed conglomerates which rest with marked unconformity on deformed Devonian rocks. These porphyritic rhyolite boulders were

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derived from the Dartmoor uplands (Laming, 1966) and deposited as alluvial fans spreading eastwards from the newly emergent Cornubian highlands. The samples were collected from the Teignmouth Breccias and the Ness Beds of Lower Permian and Stephanian age respectively (Laming, 1968).

Sample Pr27 represents the Kingsand flow which has a remarkably constant chemistry over its entire outcrop. The Withnoe quarry intrusive rhyolite is represented by Pr35 and Pr38, the freshest material from marginal and central phases respectively. Three cobbles (V2, V3, V4) from the red bed conglomerates represent the derived rhyolites from the Dartmoor region. All six samples have been studied petrographically and Chemically analysed. The chemical analyses were obtained using a Philips PW1212 automatic X-ray spectrometer on rock powder pellets. Water was determined gravimetrically.

3. Petrography

Withnoe-Kingsand rocks (Pr2 7, Pr35, Pr38)

Table 1 gives petrographic details of the three rocks from this area. All are porphyritic with phenocrysts of a few mm size set in a cryptocrystalline groundmass showing devitrified glass and palimpsest spherulitic texture. They are typical of felsic volcanic suites with ample evidence for fluidization as an important factor in their formation. Very rapid chilling from quite high original temperatures is event from the presence of such phases as sanidine and possibly tridymite. The marginal phase of the Withnoe plug shows flow-banding as does much of the Kingsand flow, although on the scale of the hand specimen the particular sample studied (Pr27) showed no banding. All three samples are classified as rhyolites.

Teignmouth rocks (V2, V3, V4)

Table 1 also gives petrographic details of the three cobbles of porphyritic fine-grained acid igneous rock collected from the red bed conglomerates. Samples V3 and V4 are interpreted as extrusive. Both show relict spherulites, with V3 probably having been originally extruded as a glass, and V4 (banded and strongly fragmented) probably having been extruded as a tuff flow. Both also contain embayed hexagonal quartz, indicative of initial crystallisation at depth of a phase which was unstable on extrusion. The presence of a fringe to these quartz crystals is evidence of reheating on extrusion. The occurrence of sanidine as the alkali feldspar phase indicates very rapid cooling, preventing the exsolution of the Na-rich phase. Both samples again are rhyolites.

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Table 1 Petrographic details of the six samples

	Pv 27 Kingsand lava flow	Pv 35 Withnoe plug - marginal	Pv 38 Withnoe plug - central
Colour Texture	Pink, porphyritic. Not banded.	Dark-grey, porphyritic. Banded	Pink-grey, porphyritic. Not banded
Phenocrysts	Feldspar (3 mm) 60%, fragmented, Carlsbad twinning. Features of both Sanidine and Orthoclase. Biotite (1 mm) 35%, varying degrees of alteration to chlorite and Fe-oxides. Quartz (1.2 mm) 5%, fragmented with groundmass inclusions. Some have developed an optically continuous fringe.	Feldspar (1 mm) 60%, fragmented. Carlsbad twinning sometimes poly-synthetic. Orthoclase except for one zoned phenocrvst - Albite. Varying degress of alteration to mica. Biotite (0.8 mm) 40%, some crystals completely pseudomorphed by Fe-oxides, other chloritised.	Quartz (2 mm) 50%, fragmented. Common outgrowths into ground mass not optically continuous. Feldspar (2 mm) 35%, fragmented. Carlsbad twinning - Orthoclase. Outgrowths into groundmass common. Biotite (0.6 mm) 15%, show some alteration to chlorite and Fe -oxides.
Groundmass	Cryptocrystalline and vague due to much Fe-oxide staining and alteration. Much of it occurs as spherical patches of intergrown material about 0.2 mm diameter indicating a partially devitrified glass.	Cryptocrystalline, a little glass, relict spherulites. Granular quartz and feldspar, some micaceous alteration. Common Fe-oxides.	Cryptocrystalline, a tittle glass, relict spherulites. Orthoclase feldspar and interstitial quartz, some possible tridymite. Discrete patches of Fe oxide.
	V2 Teignmouth Breccias	V3 Ness Beds	V4 Ness Beds
Colour Texture	Pale dull green, porphyritic	Red, porphyritic	Green/purple, porphyritic. Banded.
Phenocrysts	Feldspar (40 mm x 10 mm) down to about 10 mm length, 20%. Incipient alteration to sericite along cleavages. Orthoclase. Quartz (7 mm) 80%. Rounded and embayed. Some relict hexagonal forms indicative of inverted ~- quartz	Feldspar (6 mm) 60%. Altered to secondary mica. Sanidine. Quartz (3 mm) 35%. Corroded-embayed and rounded. Optically continuous fringe in groundmass. Biotite (2 mm) 5%. Altered to Fe-oxides and chlorite.	Feldspar (6 mm) 45%. Altered to secondary mica. Sanidine (Carlsbad twinning). Also probably some oligoclase. Quartz (2 mm) 30%. Rounded and embayed with an optically continuous fringe. Many appear in groups and appear to be hexagonal outlines. Biotite (1.5 mm) 25% Minor alteration to chlorite.
Groundmass	Average grain size 0.15 mm. Quartz orthoclase and oligoclase/albite. Some crystals appear fragmented. Abundant sericite with tourmaline patches often pseudomorphing feldspar-greisenization. Groundmass composition approx. - 30% sericite, 30% feldspar, 30% quartz, 9% tourmaline, 1% opaques.	Microcrystalline with a maximum grain size of 0.05 mm. Heavily stained with Fe-oxide. Small interstitial quartz crystals and small relict altered areas of feldspar. Much of the groundmass consists of discernible relict spherulites.	Microcrystalline (max. size 0.04 mm). Microgranular, although some relict spherulites. Quartz, feldspar and biotite are visible. Patches of sericite common.

In detail sample V2 is quite unlike the previous pair. It exhibits features indicative of a slower cooling rate (the presence of orthoclase and inverted quartz phenocrysts with no fringe). The rock also shows incipient greisenization and tourmalinization. It is interpreted as a high-level intrusive, the fragmentary nature of some of the crystals suggesting that it may have been emplaced as a fluidized crystal mush. The rock is a quartz-feldspar porphyry, typical of the elvans so common in the granitic terrain of southwest England.

4. Geochemistry

The two samples from the Withnoe plug (Pr35 and Pr38) have a very similar chemical composition closely resembling that of typical rhyolites (Table 2). The Kingsand flow (Pr27) differs from these mainly in being richer in K_2O and poorer in Na_2O; not an unusual relationship in a plug-flow situation. However, far greater variation is seen among the trace elements, with As, Rb and Sr being notably enriched in the flow material. The Rb and Sr enrichment is concomitant with the higher K_2O value, but As is more probably related to hydrothermal mineralisation which is ubiquitous in the area. The flow also tends to be richer in Ni, Cu and Zn, a point which is discussed more fully later.

In the samples from the red bed conglomerates, V3 and V4 have closely similar chemical compositions, V3 being somewhat richer in Fe, and V4 being comparatively rich in Mg and Ca. Both rocks have been interpreted petrographically as rhyolites, although they are richer in K_2O and lower in Na_2O than the Withnoe-Kingsand group. Sample V2 (petrographically identified as a partially greisened elvan), in comparison with average elvan analyses, shows the relative loss of alkalies and enrichment of SiO_2 and $A1_2O_3$; chemical trends consistent with the effects of greisenization. Again the high K_2O values in the rhyolites are reflected by high Rb and Sr. Arsenic, Ni, Cu and Znare also relatively enriched in these rocks as compared with the elvan.

It is important to note the variation in Sn values which appear to be areally controlled. The Withnoe-Kingsand rocks are consistently low in Sn compared with the cobbles from the Stephanian/Lower Permian conglomerates; the latter shows values about three times higher at an average of 15 ppm. This value is in close agreement with Henley's (1974) average Sn value for elvans of the Perranporth area.

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Table 2 Chemical analyses of the six samples and some selected analyses for comparison

	V3	V4	Pv27	Pv35	Pv38	V2	A.H.	S.H.	Ave. Rhy.
%									
SiO_2	69.1	71.7	72.3	70.6	71.6	75.1	72.0	73.3	73.7
TiO_2	0.42	0.41	0.36	0.37	0.32	0.42	0.22	0.19	0.22
Al_2O_3	14.4	14.9	14.1	14.9	14.3	16.1	14.4	15.1	13.5
Fe_2O_3	4.5	2.3	2.0	1.5	1.9	1.2	1.3	1.9	1.3
FeO	0.07	0.86	0.42	0.84	0.87	0.3	1.3	-	0.75
MgO	0.18	0.69	0.43	0.69	0.47	0.95	0.39	0.00	0.32
CaO	0.08	0.20	0.27	0.82	0.30	0.26	0.58	0.21	1.1
Na_2O	0.30	0.32	0.97	2.4	1.9	0.12	0.66	0.30	3.0
K_2O	8.2	7.6	6.9	5.3	5.6	4.0	7.4	6.3	5.4
H_2O	2.4	2.0	2.1	1.9	1.8	2.4	1.3	-	
Total	99.65	100.98	99.85	99.32	99.06	100.85	99.55	97.30	99.29
P	670	353	432	457	482	678	1266	960	-
S	130	69	20	8	21	44	-	101	-
Cl	520	710	201	260	185	591	-	92	-
V	70	85	-	-	-	74	-	-	-
Mn	34	477	117	211	89	83	387	155	-
Ni	33	15	11	4	9	8	-	8	-
Cu	20	15	14	12	9	9	-	16	-
Zn	86	71	51	41	23	23	-	74	-
Ga	16	19	22	23	23	19	-	35	-
As	39	24	42	6	3	5	-	14	-
Rb	649	757	549	402	420	277	-	839	-
Sr	554	178	191	107	74	27	-	104	-
Y	46	35	45	36	37	29	-	31	-
Zr	123	150	180	187	169	137	-	84	-
Nb	17	12	11	13	13	15	-	-	-
Sn	16	13	5	6	6	17	-	16	-
Ba	276	413	439	461	350	203	-	446	-
La	34	30	39	47	15	22	-	-	-
Ce	67	47	110	120	77	39	-	68	-
Nd	36	10	42	64	30	19	-	-	-
Pb	15	98	40	38	41	9	-	75	-
Th	16	14	19	22	16	24	-	41	-
U	7	5	4	8	5	5	-	17	-

A.H. - Average 'elvan' from A. Hall (1970). S.H. - Average 'elvan' from S. Henley (1974). Ave. Rhy. - Average rhyolite from Wedepohl (1969).

5. Discussion

It has been demonstrated that the red bed conglomerates of the Teignmouth district contain extrusive rhyolite cobbles which are closely similar, both petrologically and chemically, to the Kingsand lava. The Teignmouth rocks were, in all probability, derived from capping rhyolites of the Dartmoor batholith. The Withnoe-Kingsand rocks are interpreted as comagmatic, but were emplaced marginally to the batholith. All the extrusive rocks are enriched in K, Rb; Sr As, NJ, Cu and Zn and depleted in Na as compared with the associated intrusive phases. Sample V2 is somewhat anomalous, a consequence of the mild greisenization and tourmalinization.

The enrichment of K, Rb and Sr and the depletion of Na in the extrusive phases is probably partly due to normal differentiation processes, but it is unlikely that this represents the complete picture. Table 3 shows the K_2O and Na_2O distribution in the rocks investigated along with related rocks from southwest England. If the average alkali values for Dartmoor granite are taken as a probable starting point, the trend from granite to marginal intrusive (feeder) to rhyolite (Withnoe-Kingsand) can readily be seen. Further, taking Hall's (1970) average

Table 3 K_2O and Na_2O values for rhyolites and associated rocks of S.W. England

	Ave* granite	Ave. Withnoe	Ave. Kingsand	Ave.** elvans	Ave. rhy.cobbles
Na_2O	3.0	2.2	1.0	0.7	0.3
K_2O	4.9	5.5	6.9	7.4	7.9

(all values in percentage rounded to two significant figures)

* From Brammall and Harwood (1932)

** From Hall (1970)

elvan values as typical for the central batholith intrusives (feeders) their trend to capping rhyolites (the red bed cobbles) show an even more enhanced K-rich Na-poor relationship. It is suggested that this is corroborative evidence for the K (Rb and Sr) metasomatism of other workers (e.g. Exley and Stone, 1964); the K enrichment is more strongly developed over the central regions of the batholith than in marginal phases.

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A related factor is the relatively high Sn values for the central batholith rocks (V series as compared to the marginal Pv series). The former are well within the tin zone of mineralisation while the latter are well beyond it. In this case the Sn appears to have been fixed equally in both intrusive and extrusive rocks and it is presumably therefore in silicates and not in oxide/sulphide form. The elements As, Ni, Cu and Zn (also probably fixed in silicates since there is no correlation with S) are relatively enriched in the extrusives in both sets of samples. This group of elements can be identified with a higher zone of primary mineralisation and a later mineralisation phase whose ore minerals are normally found above and beyond the tin zone. The mineralising fluids presumably found passage up the feeders relatively easy but tended to be trapped in the capping rhyolites while passing through them (Ypma and Simons, 1969).

The suggested model for the petrogenesis of the rhyolitic rocks is that they formed a substantial extrusive expression of the underlying granite, which itself had reached a very high tectonic level. The rhyolites were fed through channelways which occupied faults formed during the upwelling of the batholith. They were concentrated over the highest points of granite emplacement, although marginal expressions also occurred. Textural evidence from the rhyolites and elvans (Stone, 1968) indicates that an important process affecting their emplacement was fluidization, which probably resulted from pressure release of volatile-charged magma during hydraulic fracturing of the granite (Phillips, 1972). The high K (Rb and Sr) enrichment was due to ion-exchange between consequent K-rich volatiles and magma, and the primary distribution of Sn, As, Ni, Cu and Zn was enhanced by slightly later hydrothermal episodes, the zonation being determined by position, both vertical and horizontal, with respect to the batholith roof. Greisenization and tourmalinization must have been closely associated events (sample V2 had been subjected to both processes), and intuitively it is believed that kaolinization followed quickly (Exley, 1959) although in the present study there is no direct evidence as to its precise timing.

These events all took place towards the end of the granite emplacement period, some 290 m.y. ago (Dangerfield and Hawkes, 1969; Badham *et al,* 1975). The newly uplifted "Dartmoor Uplands" were immediately subjected to intense weathering, probably in an alternating wet and dry season climate producing typical red bed conglomerates

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(Cosgrove, 1973) now preserved to the north in the Crediton trough and to the east in the Torquay-Teignmouth-Exeter belt. By 280 m.y. ago when the basic Permian volcanics were extruded (Miller and Mohr, 1964), most of the upland capping volcanics had been removed and probably the granite itself was being eroded. It is perhaps worth commenting that the trigger for the generation of these basal Permian volcanics of high-K basalt type (Cosgrove, 1972) may well have been isostatic sinking of cool (solid) granite resulting in deep fractures leading to pressure release in the upper mantle and thereby magma generation (Badham, 1975).

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REVIEW OF GEOCHEMICAL DATA ON ROCKS FROM THE LIZARD COMPLEX, CORNWALL

by P.A. Floyd

Abstract A summary of published geochemical data on rocks from the Lizard complex is presented and reviewed to obtain estimates of the pressure-temperature environment of the various units and their petrogenetic relationships. Geochemically, the Lizard peridotite is a Iherzolitic mantle residue that equilibrated at high temperature and moderate depth. Because of limited geochemical data the possibility of a cogenetic relationship between the Crousa gabbro, the Landewednack hornblende schists and spilitic volcanics (that is, representing an ophiolite suite) cannot be ruled out, although it appears unlikely.

1. Introduction

The close association of ultramafic and mafic rocks in deformed orogenic belts has been recognised for a long time. This is particularly true in the Alps, such that they are generally termed alpine complexes. These complexes are predominantly composed of peridotite, serpentinite, gabbro and spilitic lavas (commonly pillow lavas), and are collectively called the ophiolite suite. The "Steinmann Trinity" of serpentinite-spilite-chert is one closely associated group of rocks that typify ophiolitic suites.

Consideration of the petrogenesis of ultramafic rocks led Wyllie (1969) to group the alpine-type peridotite-serpentinite associations together and classify them broadly on the metamorphic facies of the associated metamorphites. For example, the ophiolite suite typically occurs in a low-grade (greenschist, blueschist) terrain. Also in this alpine type association are included small, high temperature peridotite intrusions, apparently unrelated to any associated mafic rocks.

2. **Re-interpretation of the Lizard complex**

The Lizard complex of south Cornwall contains closely associated ultramafic and mafic rocks in a low to medium grade environment, and as such might be a tectonically dismembered remnant of an ophiolite suite. Certainly, Flett (1946) considered the Lizard serpentinite, the

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Crousa gabbro and dykes, and possibly the Landewednack hornblende schists to have a common origin. However, on remapping the Lizard area, Green (1964a) considered the serpentinite to be a high temperature peridotite intrusion with an associated narrow contact aureole (Green, 1964b and c). The divorce of the Lizard peridotite from the adjacent gabbro, and its existence as a separate entity, was criticized by Thayer (1967), who re-emphasized the close association of such rocks in alpine complexes and in particular in the Lizard area.

With the recognition that ophiolite suites have a pseudostratigraphy of lithological units similar to models of the oceanic lithosphere (Dietz, 1963; Coleman, 1971; Thayer, 1969; Gass *et. al.* 1975), the Lizard complex has been re-interpreted in such terms (Bromley, 1973, 1976; Strong *et. al.* 1975).

Thus, due to the different emphasis put on the associated Lizard rocks, two interpretations have been developed concerning the Lizard peridotite - (a) that it is a high temperature intrusive diapir, and (b) that it is a segment of oceanic (upper mantle) lithosphere. At first sight the two interpretations may not be mutually exclusive, because tectonically emplaced peridotites may form part of the oceanic crust.

3. Objectives

This paper brings together published geochemical data on the Lizard rocks and attempts to determine the temperature-pressure environment of the different units and their respective origins. Apart from the mineral and whole rock data of Green (1964b & c) and Frey (1969), there is a general paucity of suitable geochemical material from the Lizard rocks, although Floyd *et al.* (1976) have evaluated preliminary new results in terms of magma type and tectonic environment.

4. Lizard peridotite

Green (1964b & c) considered that the Lizard peridotite was a high temperature intrusion that metamorphosed the adjacent hornblende schists to high-grade contact granulites. Three peridotitic assemblages were recognised and consisted of a central primary core (olivine + Al-orthopyroxene + Al-clinopyroxene + spinel) surrounded by a recrystallized anhydrous margin (olivine + orthopyroxene + clinopyroxene + spine) + plagioclase), parts of which had undergone hydrous

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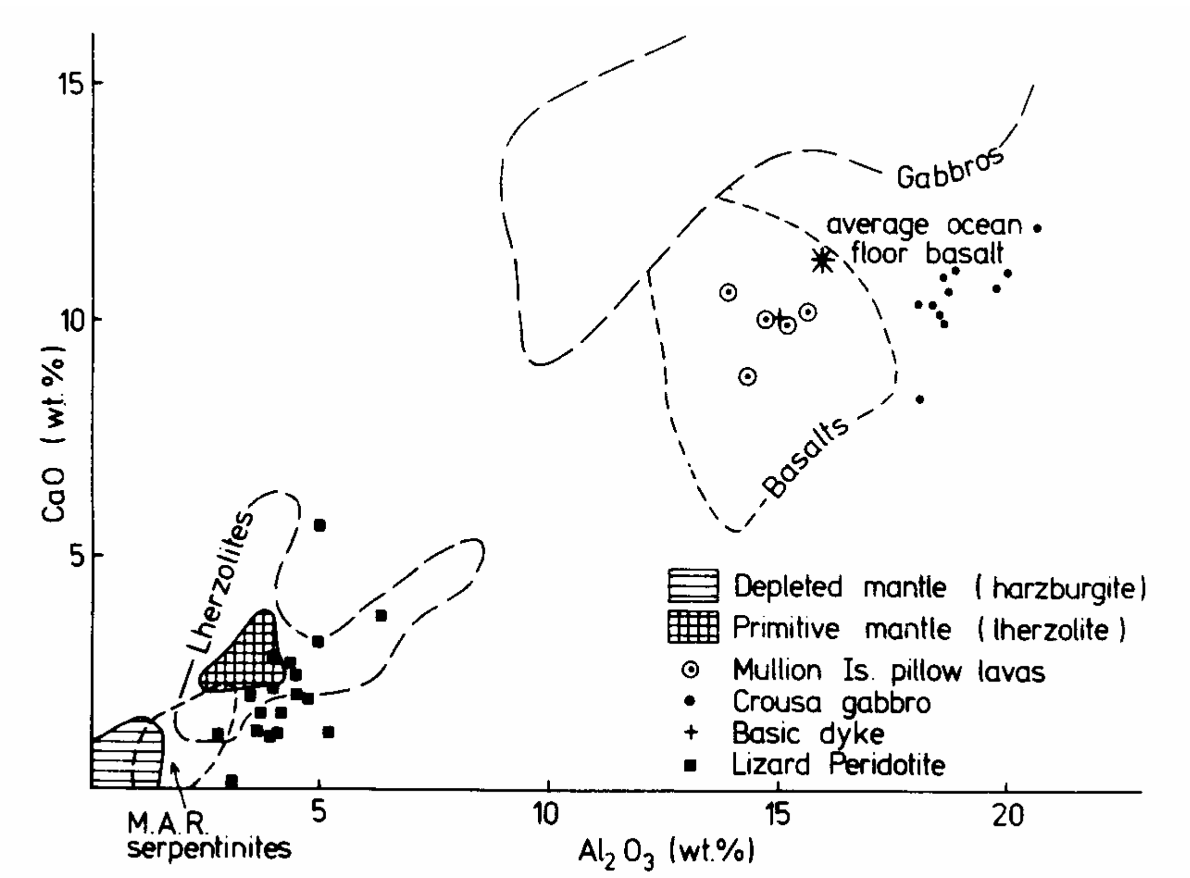

FIGURE 1. Distribution of CaO and Al_2O_3 in Lizard complex rocks compared with ophiolitic lherzolites, gabbros and basalts (delimited fields from Coleman, 1971), primitive mantle lhenolite and depleted mantle harzburgite, and Mid-Atlantic Ridge (MAR) serpentinites (Miyashiro *et al.* 1969). Ocean floor basalt average from Cann (1971).

recrystallization with the development of a pargasitic amphibole. Serpentinization (typically lizardite-chrysotile) is common throughout.

On the ophiolite/oceanic lithosphere model, the peridotite is interpreted as depleted upper mantle (Strong *et al.* 1975) of relatively shallow origin; in contrast to the deep-seated origin proposed by Green (1964b). From the geochemistry and phase assemblages of the peridotite it should be possible to distinguish between these two depth environments.

The highly aluminous nature of the pyroxenes of the primary assemblage relative to the recrystallized assemblages suggests that the former had formed under a higher pressure environment than the secondary assemblages (Green, 1964b). The relative pressure (or depth) environment can be evaluated from the sub-solidus equilibrium assemblages found experimentally to be stable under a range of mantle conditions (O'Hara, 1967a; Wyllie, 1971). The primary assemblage is representative of an intermediate pressure (10 - 25 kb) spinel peridotite while the recrystallized assemblages are low pressure (0 - 10 kb) plagioclase peridotites. Using the distribution of Ca, Mg and Al in

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clinopyroxenes, O'Hara (1967b) has constructect a petrogenic grid whereby the P-T conditions of equilibration for per idotite assemblages can be evaluated. The estimated equilibration conditions for the primary assemblage are about 15 kb (50 km depth) and 1250° - 1300°C, whereas the recrystallized anhydrous assemblage is 7.5 kb (27 km depth) and 1075°C (O'Hara, 1967b) - both of which confirm the respective pressure environments given above and support the hypothesis of tectonic emplacement of hot peridotite from depth (Green, 1964b).

Strong *et al.* (1965) refer to the Lizard peridotite as harzburgite and, as such, representative of the depleted or residual layer of the upper mantle under the oceanic crust. However, the modal composition when plotted on the peridotite classification triangle (olivine, orthopyroxene, clinopyroxene) is that of an olivine-rich lherzolite. Similarly the CaO and A1203 contents are higher than typical harzburgites or indeed serpentinites dredged from the ocean floor (Miyashiro *et al.* 1969) and are clearly more akin to lherzolites (Fig. 1). As harzburgites are typical of both oceanic lithosphere and ophiolite complexes rather than lherzolites (especially those of high pressure origin), it is considered that the Lizard peridotite is not representative of depleted upper mantle or indeed the ultramafic accumulates of the basal oceanic crust

This leaves the possibility that the Lizard lherzolite represents (a) primitive mantle, (b) residual mantle left after partial melting, or (c) a deep-seated accumulate from a basaltic melt. Green (1964b) was of the opinion that the primary assemblage was akin to peridotite nodules found in basalts rather than a representative of an ultrabasic accumulate. Rare earth element (REE) data of all the peridotite units (Frey, 1969, 1970a) show that (a) the primary assemblage is markedly depleted in the light REE relative to both chondrites and primitive mantle of lherzolite composition (see Schilling 1971, fig. 17), and (b) that although the distribution pattern remains similar (with light REE depletion) the absolute abundance of REE increases from the primary assemblage to the recrystallized assemblages. Fig 2 illustrates these features and also clearly shows the distinction between oceanic spinel peridotites from St. Paul's Rocks (Mid-Atlantic Ridge) and the Lizard peridotites (cf. Frey, 1970b). The Lizard peridotite REE distribution pattern is interpreted by Frey (1969) as either a residue left after partial melting or possibly a mantle accumulate. This conclusion is supported by Masuda *et al.* (1971) who consider the peridotite to be a "secondary solid-type" material which was once in equilibrium with a primary melt.

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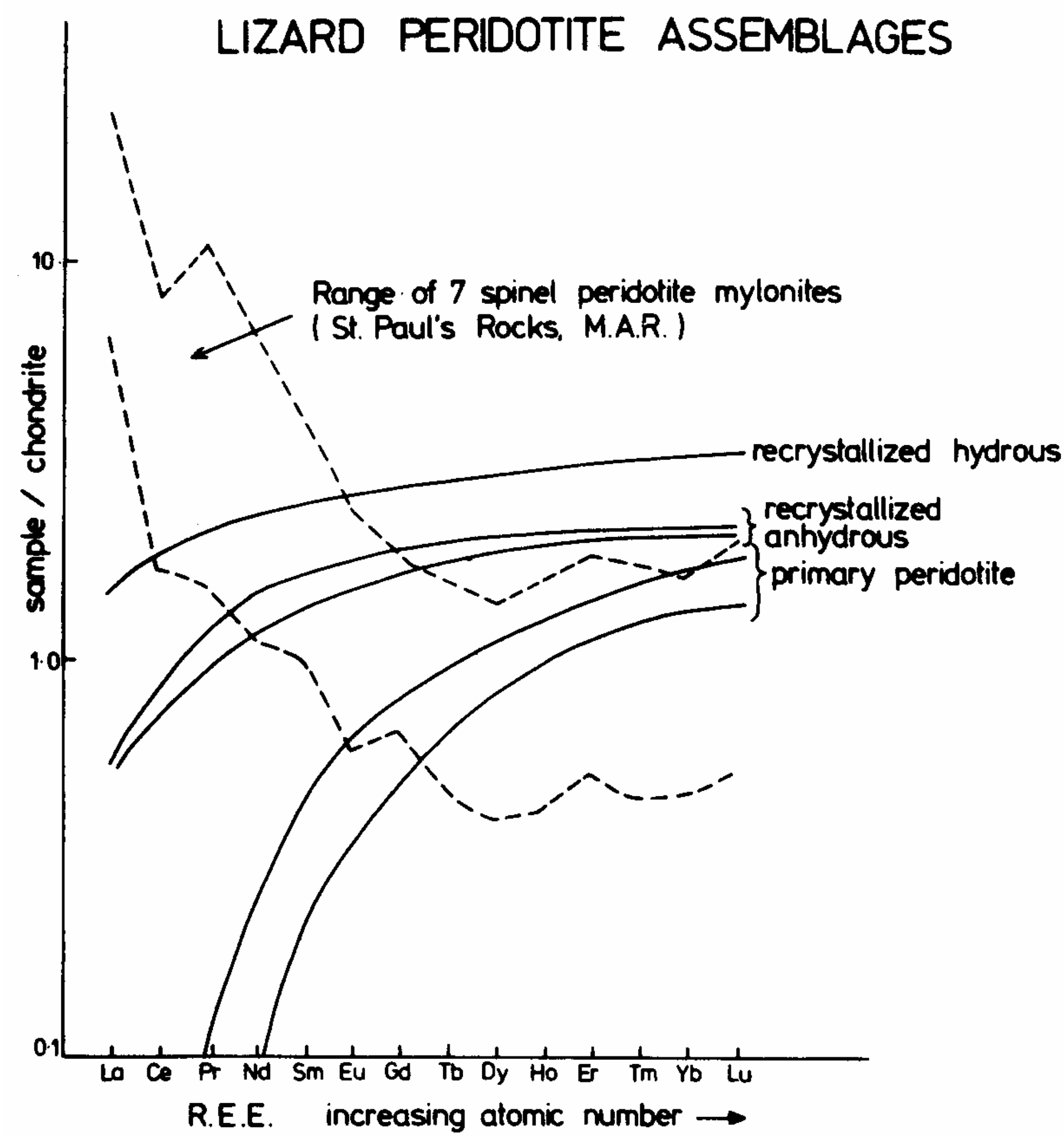

FIGURE 2. Rare-earth element distribution pattern for Lizard peridotite assemblages (data taken from Frey, 1969) compared with oceanic peridotites from St. Paul's Rocks, Mid-Atlantic Ridge (Frey, 1970b).

In summary, the published data support a deep-seated origin for the Lizard peridotite as a mantle residue depleted of its basaltic liquid. It was tectonically emplaced in the upper mantle from its source region as a hot, largely solid, crystalline mass. Certainly the fabric is highly tectonized and relict primary features confirm the high pressure origin (Rothstein, 1976).

Serpentinization would have taken place below the upper stability limit for serpentine, 400-500°C at less than 10 km depth (Scarpe & Wyllie 1967), and probably at a high level in the crust. Oxygen, carbon and hydrogen isotope studies on carbonates and serpentines associated

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with ultramafic complexes have shown that the serpentinization process takes place via the agency of meteoric water at shallow depths (O'Neil & Barnes, 1971; Wenner & Taylor, 1974). Wenner & Taylor (1973) demonstrated that there are distinct differences in the oxygen and hydrogen isotopic ratios between modern oceanic serpentines (antigorite) and ophiolite serpentines of the lizardite-chrysotile type. This is interpreted as reflecting the presence of different types of water during the serpentinization of ophiolitic (mixed meteoric and/or connate water) and oceanic (heated marine water) ultramafic rocks. The Lizard serpentine minerals are lizardite and chrysotile (Green, 1964b) and were probably formed via the agency of meteoric ground water or brines. Using the serpentine-magnetite geothermometer, Wenner & Taylor (1971) have estimated that continental lizardite-chrysotile minerals were formed at about 85-115°C. For the Lizard peridotite (as with other ultramafic complexes) this implies that serp-entinization took place after it had been tectonically emplaced high in the (continental) crust.

5. Crousa gabbro

This body is a highly tectonized and slightly metamorphosed olivine gabbro with troctolitic variants. It is cut by numerous basaltic and gabbroic dykes which Bromley (1973) considers represents the root zone of an ophiolitic sheeted dyke complex.

The few whole rock analyses available (Flett 1946, Butler 1953) show that the gabbro is characterized by a very high $A1_2O_3$ and low TiO_2, K_2, Zr and Rb contents -features confirmed by Parker (1970). The commonly developed secondary amphibole is, however, Al-poor and low in Ga and F (Butler, 1953). The REE distribution pattern of the olivine gabbro is atypical of gabbros generally and shows a strong light REE depletion relative to chondrites (Frey, 1969). On the other hand, a troctolite sample exhibits an REE distribution pattern that is characterized by a strong positive Eu anomaly and a generally low total REE abundance and suggests an accumulate origin (Frey, 1969).

In view of the residual nature of the Lizard peridotite and the similar REE distribution pattern of the gabbro, these two units may represent an equilibrium residual-liquid pair and thus indicate a genetic relationship between them. The REE data do not rule that possibility out, although Frey (1969) suggests that the characteristics of the gabbro REE pattern can best be explained by generation from some

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pre-existing residue. Experimental work on basaltic systems (Green & Ringwood, 1967) suggests that high-alumina basalt liquids will be generated in a relatively shallow pressure regime (9 kb) and leave on fractionation, plagioclase-bearing ultramafic accumulates. If this is the case, the Crousa high $A1_2O_3$ gabbro may not necessarily be related to the Lizard peridotite as the pressure conditions at equilibrium are so different. Any liquid produced in equilibrium with peridotite at a pressure of about 15 kb would be low-alumina tholeiite (unlike the gabbro here), although it is possible that it could undergo fractionation at higher levels (lower pressures) to produce a high-alumina liquid.

6. Dykes

The one published analysis on an epidiorite dyke in the gabbro (Guppy & Sabine, 1965) shows it to be dissimilar to the host rock in having higher TiO_2 and K_2O and much lower Al_2O_3

7. **Landewednack hornblende schists**

According to Green (1969c) the amphibolite facies Landewednack hornblende schists were contact metamorphosed to high-grade granulites by the peridotite intrusion. Evidence for a high thermal gradient over a narrow zone is illustrated by the progressive change in metamorphic assemblage (and amphibole composition and colour) similar to that seen in the regional granulite facies. The amphiboles of the contact granulites are Al-poor pargasites.

Based on the temperature-dependent distribution coefficient for the Fe/Mg ratio between coexisting clinopyroxene and orthopyroxene, Green (1969c) suggested that the granulites crystallized at temperatures between 700^0 - 800°C and possibly up to 1000°C. However, using the calculated distribution coefficients and the approximate temperature calibration employed by Engel *et al.* (1964, fig. 8) for the Adirondack amphibolites and granulites, a range of temperatures are produced from a minimum of 675°C to 875°C at the contact. The temperature of the peridotite is similarly calculated at 1225°C, which is rather high if it was entirely solid.

On the basis of major element geochemistry, Green (1969c) considered the contract granulites (and the parental Landewenack hornblende schists) to be meta-tholeiitic basalts; this is supported by REE data (Frey *et al.* 1968; Frey, 1969) which show a distribution pattern similar to data from submarine ridge basalts.

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8. Old Lizard Head Series

The Old Lizard Head series are pelitic and semipelitic meta-sediments and meta-basic rocks closely associated with the Landewednack hornblende schists. Few analyses have been published (Guppy & Sabine, 1965).

The presence of andalusite-cordierite-bearing assemblages in the north and garnet-kyanite-sillimanite-bearing assemblages in the south at Lizard Point, indicates the presence of both a low-pressure and medium-pressure series in the amphibolite facies of regional metamorphism- developed at about 500° - 700°C and 3 - 6 kb (Turner, 1968).

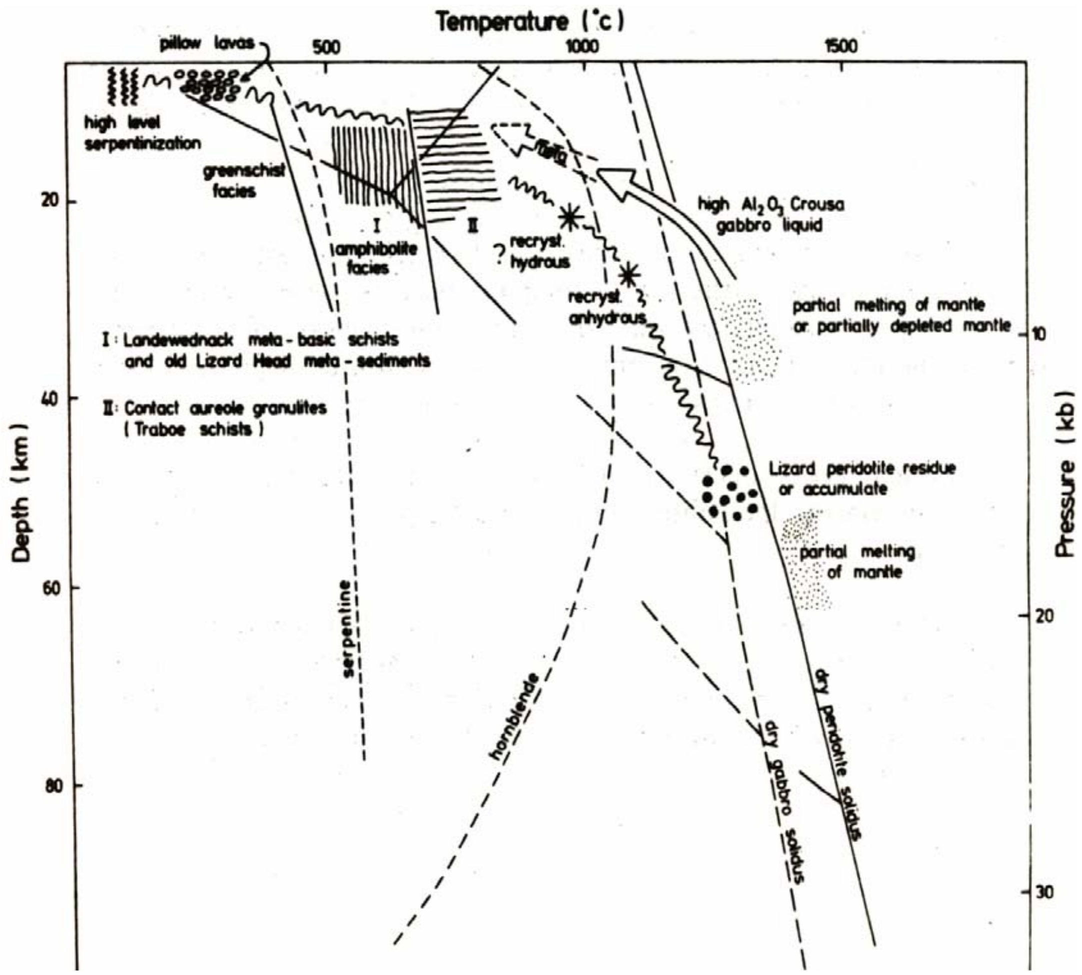

FIGURE 3. Estimated P-T environment for Lizard complex rocks; details in text. Peridotite, gabbro solidi and hornblende stability curve from Wyllie (1971), serpentine stability curve from Scarfe and Wyllie (1967) and amphibolite facies boundaries from Turner (1968).

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9. Volcanic rocks

In the Meneage zone, to the north of the Lizard peridotite, are spilitic lavas associated with sediments (Veryan Formation) of supposed Upper Devonian age (Edmonds *et al.,* 1969). Similarly, on Mullion Island are well preserved pillow lavas of the same age (Hendricks *et al.,* 1971). Both groups have been subjected to a lower greenschist facies metamorphism. The Mullion Island pillow lavas were considered by Floyd & Lees (1973) to be alkaline basalts on their Ti and Zr contents although more extensive (unpublished) geochemical data clearly show them to be tholeiitic.

It is difficult to know what relationship the Mullion Island pillow lavas and Meneage volcanics bear to the rest of the Lizard rocks (in particular the higher grade Landewednack hornblende schists), as the tectonics are complex and as yet the geochemical data are lacking.

10. Conclusions

1. Based on mineral assemblages and phase relations, estimates of the P-T environment of the Lizard complex rocks can be determined. Fig. 3 attempts to summarise the points mentioned above. Note in particular the tectonic emplacement of the hot peridotite diapir from deep levels eventually to a near surface environment.

2. Present geochemical data indicate that the Lizard peridotite is a high-temperature lherzolite residue left after partial melting of mantle material.

3. On the basis of limited geochemical data it is not possible to say definitely whether the peridotite, gabbro, hornblende schists and volcanics are contemporaneous (ophiolite model), although each group does apparently have distinctive features that set them apart.

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A PRELIMINARY GEOCHEMICAL TWIST TO THE LIZARD'S NEW TALE

by P.A. Floyd, G.J. Lees and A. Parker

Abstract. Based on the distribution of elements that are immobile during secondary alteration and metamorphism (Ti, P, Zr, Y, Nb & R.E.E.) the basaltic units of the Lizard complex can be divided into three chemically distinct groups: (a) Landewednack hornblende schists and the peridotite "contact granulites" (Traboe schists), (b) Crousa gabbro and dykes within both gabbro and peridotite, and (c) lavas from Mullion Island and the Meneage zone. Only the Landewednack schist group have immobile element compositions similar to ocean floor basalts, whereas the lava group represent "within-plate" volcanism. The gabbro and dyke group *may* represent the deep-seated part of an island arc, although this is by no means conclusive on chemical grounds. The chemical data do not support a simple ocean crust model for the Lizard basaltic units.

1. Reinterpretation

The Alpine-type ultrabasic-basic association of the Lizard complex has recently been interpreted as an ophiolite suite remnant and as such represents a segment of ancient oceanic lithosphere (Bromley, 1973, 1976; Strong *et al.*, 1975). In terms of a new tectonic reconstruction for south Cornwall, the whole assemblage was carried laterally as part of a spreading oceanic plate and obducted onto continental crust (Badham and Halls, 1975).

This reinterpretation of the Lizard complex as ancient oceanic lithosphere contrasts with the model proposed by Green (1964a and b) who considered the Lizard peridotite to be a diapir of high P-T origin and unrelated to the adjacent basic intrusives and volcanics. If the reinterpretation is correct then the various units of the Lizard complex can by lithological comparison be assigned to different parts of the modern oceanic lithosphere - as speculatively suggested in Fig. 1. Bromley (1976) has also stated that the Lizard displays a similar pseudostratigraphy, although there are clearly many gaps in the sequence.

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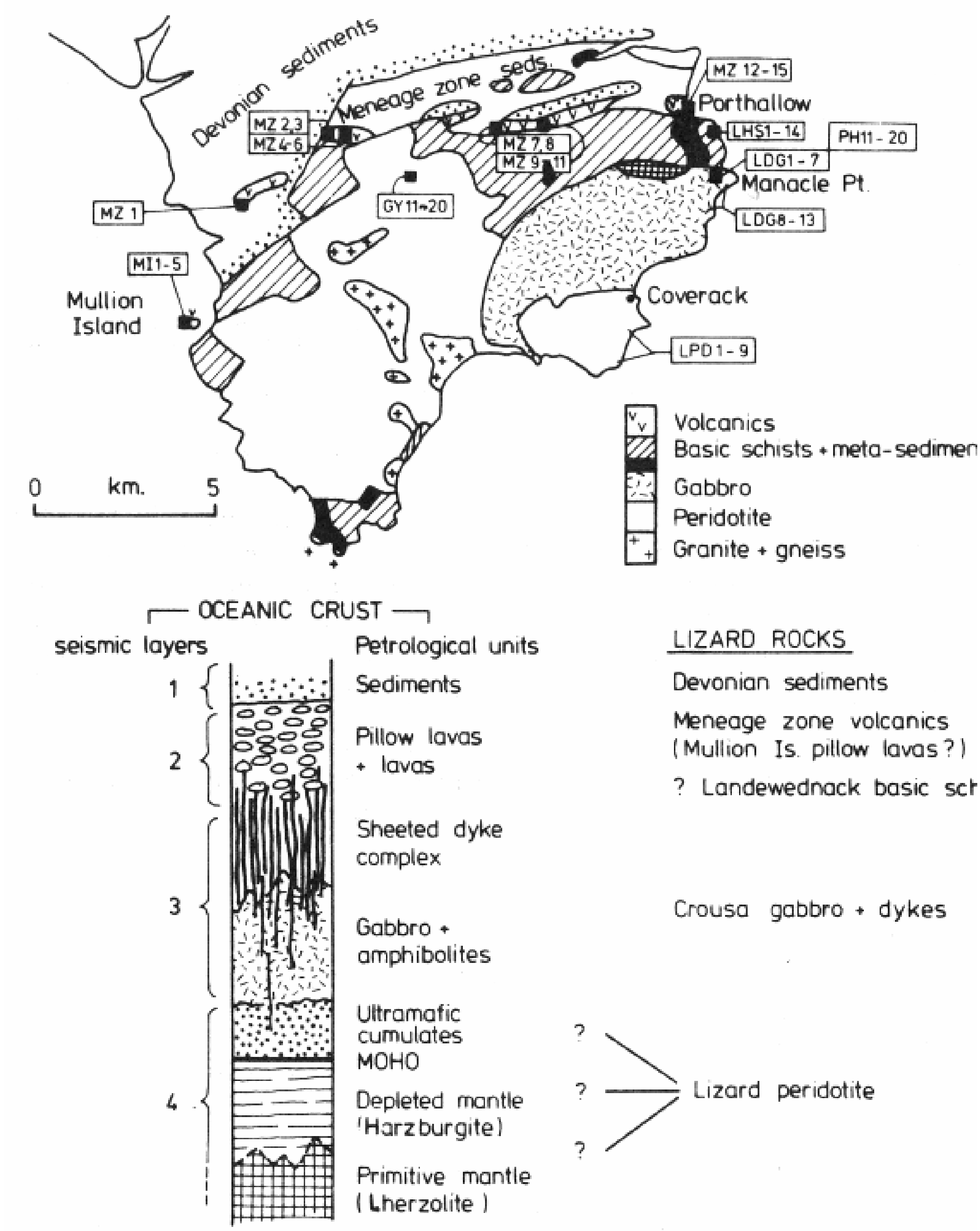

FIGURE 1 Simplified geological map of the Lizard, Cornwall, and a possible comparison of the various lithological groups with that of the oceanic crust. Sampling localities are also shown for Mullion Island pillow lavas (prefix MI), Meneage zone lavas (MZ), dykes intrusive into gabbro (LDG), dykes intrusive into peridotite (LDP), Crousa gabbro (PH), Landewednack hornblende schists (LHS) and Lizard peridotite (GY).

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2. Chemical criteria

The preliminary data presented attempt to identify chemically the different Lizard units and to see if they represent the ocean floor environment in terms of their composition. Because the majority of the rocks involved have suffered some degree of alteration, the initial elements that have been analysed are those considered to be essentially immobile (e.g. Ti, P, Zr, Y, Nb, R.E.E.) during low-grade alteration and metamorphism (Cann, 1970; Herrmann *et al.,* 1974). All analyses were determined by XRF spectrometry (with the exception of the rare earth elements) using a spiked Standard greenstone (KUM-3) for calibration.

In the following discussion of chemical data the Lizard peridotite has been excluded and only the basic rocks considered; that is, pillow lavas from Mullion Island, lavas.from the Meneage zone, dykes from the gabbro and peridotite, Crousa gabbro and also the Landewednack hornblende schists (see localitites in Fig. 1). A review of the Lizard peridotite has been given by Floyd (1976) based on the chemical data published by Frey (1969) and Parker (1970).

If the ophiolite/oceanic lithosphere model is correct then the basaltic units (representing oceanic crust) should exhibit the following chemical features:

(a) If they are all members of an ophiolite suite the basaltic rocks should be related and have essentially the same composition or exhibit varying degrees of differentiation along a common tend (Thayer, 1967).

(b) If they are all representative of oceanic crust the basaltic rocks should have the chemical composition of ocean floor tholeiites with low incompatible elements and light R.E.E. depletion (Engel *et. al.* 1965; Schilling, 1971).

(c) Their trace element chemistry should clearly indicate an oceanic environment on immobile element discrimination diagrams (Pearce and Cann, 1973).

Chemical comparisons based on immobile element data will also be useful in seeing if (a) the Mullion Island pillow lavas are essentially the same as the scattered lava horizons in the Meneage zone to the north of the Lizard complex, (b) whether the Landewednack hornblende schists are the amphibolite facies equivalents of the lower grade pillow lavas.

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Table 1 Partial analyses of Lizard complex basaltic rocks compared with average ocean floor basalt

	Mullion Island pillow lavas	Meneage zone lavas	Dykes in gabbro	Dykes in perido-tite	Gabbro	Horn blende schists	OFB*
TiO_2	1.94	1.91	1.54	1.25	0.81	0.83	1.43
Al_2O_3	14.48	-	(15.06)	-	19.12	(15.03)	16.01
K_2O	0.96	0.74	0.33	0.19	0.70	0.48	0.22
P_2O_5	0.16	0.17	0.22	0.11	0.06	0.05	0.14
Nb	6	4	5	1	16	1	5
Rb	18	13	6	3	20	10	2
Y	30	34	33	25	13	16	29
Zr	195	186	167	122	65	53	96
Zr/Y	6.5	5.5	5.1	4.9	5.0	3.3	3.3
Y/Nb	5.0	8.5	6.6	25.0	0.8	16.0	5.8
Zr/TiO_2	0.010	0.009	0.010	0.009	0.008	0.006	0.006
K/Rb	443	472	457	526	291	398	913
Number of Samples	5	14	13	8	5	12**	-

Major elements in weight %, trace elements in p.p.m. Values in brackets represent averages from literature. Analysts: G.J. Lees and A. Parker.

*OFB = ocean floor basalt average (Cann, 1970, 1971 - except Rb from Condie et al., 1969).

**Excludes "contact granulites"(Traboe schists) of Green (1964b).

3. Average chemical composition

The average chemical composition of the basic rocks of the Lizard complex are shown in Table 1. The assembled data represent rocks of basaltic composition only, that is, rocks with Zr/Ti02, <0.010 (Winchester and Floyd, 1976b), and exclude all subsequent differentiates.

The gabbro, characterized by high Al, K, Rb and Nb, does not appear to have a typical oceanic basalt composition. The high Al coupled with low Ti is typical of high-alumina basalts of island arcs, although the Cr and Ni values (Parker, 1970) are much too high.

Although there are chemical differences between the two sets of dykes and the lavas, immobile element abundance systematically increase from the dykes in the peridotite → dykes in the gabbro → Meneage lavas → Mullion Island pillow lavas. A similar increase in all these elements is seen with progressive magmatic differentiation, but as the average values hide considerable variation these rock units may not necessarily be linked via such a process.

Of all the units the Landewednack hornblende schists have abundance ratios suggestive of basalts from the ocean floor, a feature supported by R.E.E. data (Frey, 1969). The "contact granulites" (Traboe schists) of Green (1964b) have comparatively higher TiO_2 (average 2.2 wt.%), P_2O_5 (0.17 wt.%), Zr (87 ppm) and Y (26 ppm), although Zr/Y (about 3.4) and Zr/TiO_2 (about 0.004) ratios are of the right order and distinct from those of the gabbro.

The uniformly low K/Rb ratios, especially in the gabbro and hornblende schists, cannot be considered a reliable petrogenetic guide due to the relative mobility of these elements with alteration (Hart and Nalwalk, 1970). The very low Nb values (1 ppm) in the dykes from the peridotite and the hornblende schists are at the limit of detection and could be x2 or x3 the value indicated and thus lower the Y/Nb ratio to more normal levels.

Chemical variation between the various basaltic units is illustrated in Fig. 2. Only the Landewednack hornblende schists have Zr and Y values typical of ocean floor basalts and fall on a distinctive and separate trend from all the other units. The dykes from the gabbro and peridotite host rocks cannot be separated and form a trend virtually the same as the gabbro; as seen in Table 1 they also have similar Zr/Y ratios. This feature suggests a close genetic relationship between the dykes and the gabbro with possible derivation from the same magma batch. In a similar manner the Mullion Island pillow lavas and Meneage zone lavas fall together on another (scattered) trend, which is different from that of the previous trend (Fig. 2).

Work on modem basaltic lavas (e.g. Sceal and Weaver, 1971) shows that Zr and Y often exhibit a high degree of correlation for any one suite and that both elements increase with progressive basaltic differentiation within that suite. By comparison, the basaltic units from the Lizard define three separate trends spread over essentially the same Zr and Y ranges and suggest that the rocks comprising these units - Landewednack hornblende schists, gabbro + dykes, pillow lavas + lavas - may not be genetically related.

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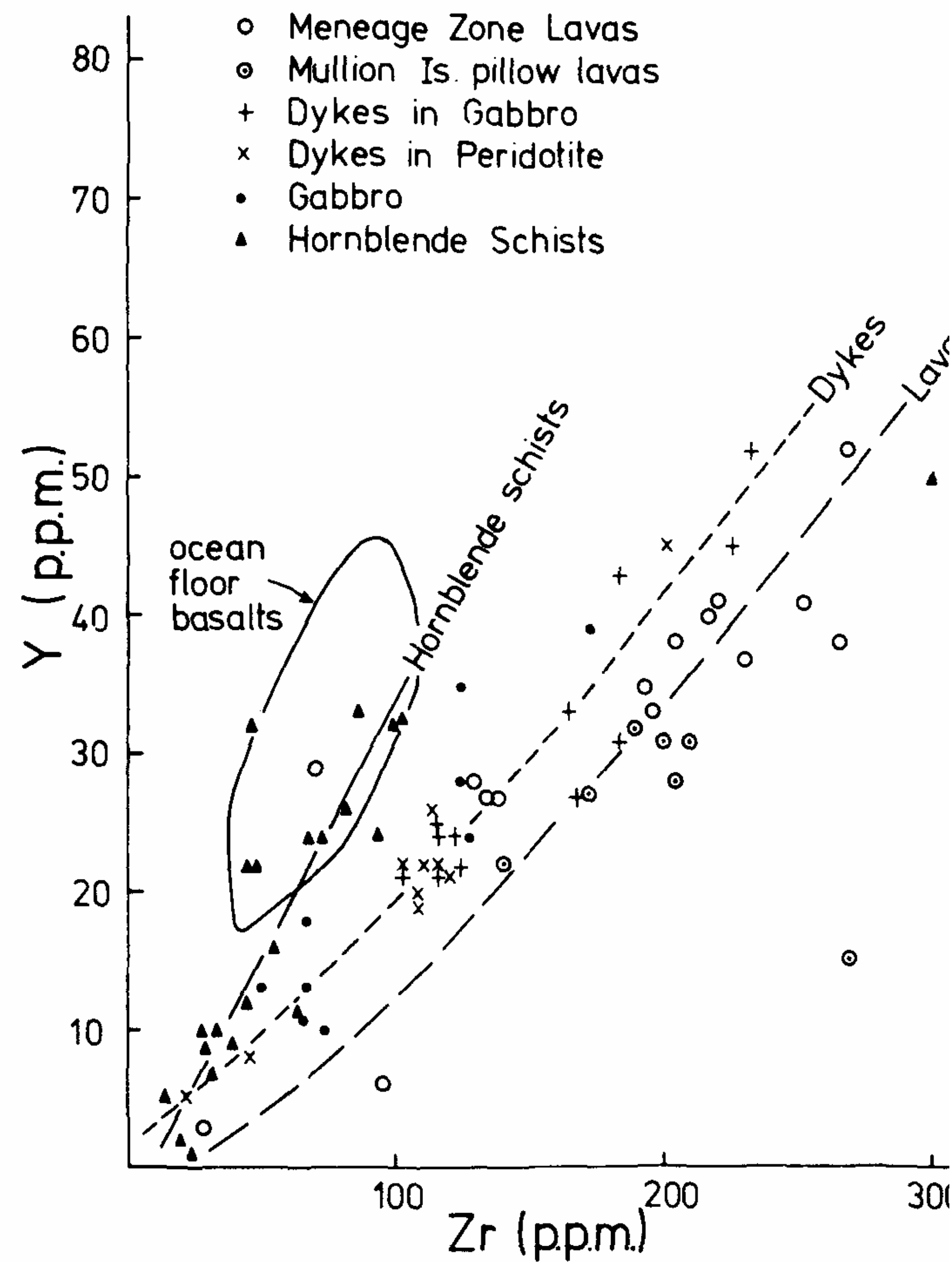

FIGURE 2 Distribution of Zr and Y in the basaltic rocks of the Lizard and the development of three trends. Ocean floor basalt field produced from published analyses in the literature.

4. Magma type characterization

Using immobile elements to discriminate between tholeiitic and alkalic magma types (Floyd and Winchester, 1975; Winchester and Floyd, 1976a) it can be demonstrated (Fig. 3) that all the basaltic units represented are tholeiitic or sub-alkaline in composition. The generally high Y/Nb ratio is also characteristic of sub-alkaline basaltic magmas.

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Note that the different units fall in different parts of the sub-alkaline field (Fig. 3) and develop separate trends. The generally close association of the Meneage zone lavas and the Mullion Island pillow lavas again suggests they may form one group and similarly the dykes from their respective host rocks fall on the same trend. The uniform TiO_2 content of the gabbro appears unusual in this context and is not associated with the dyke trend as might have been expected. The Landewednack hornblende schists again define a different trend to the

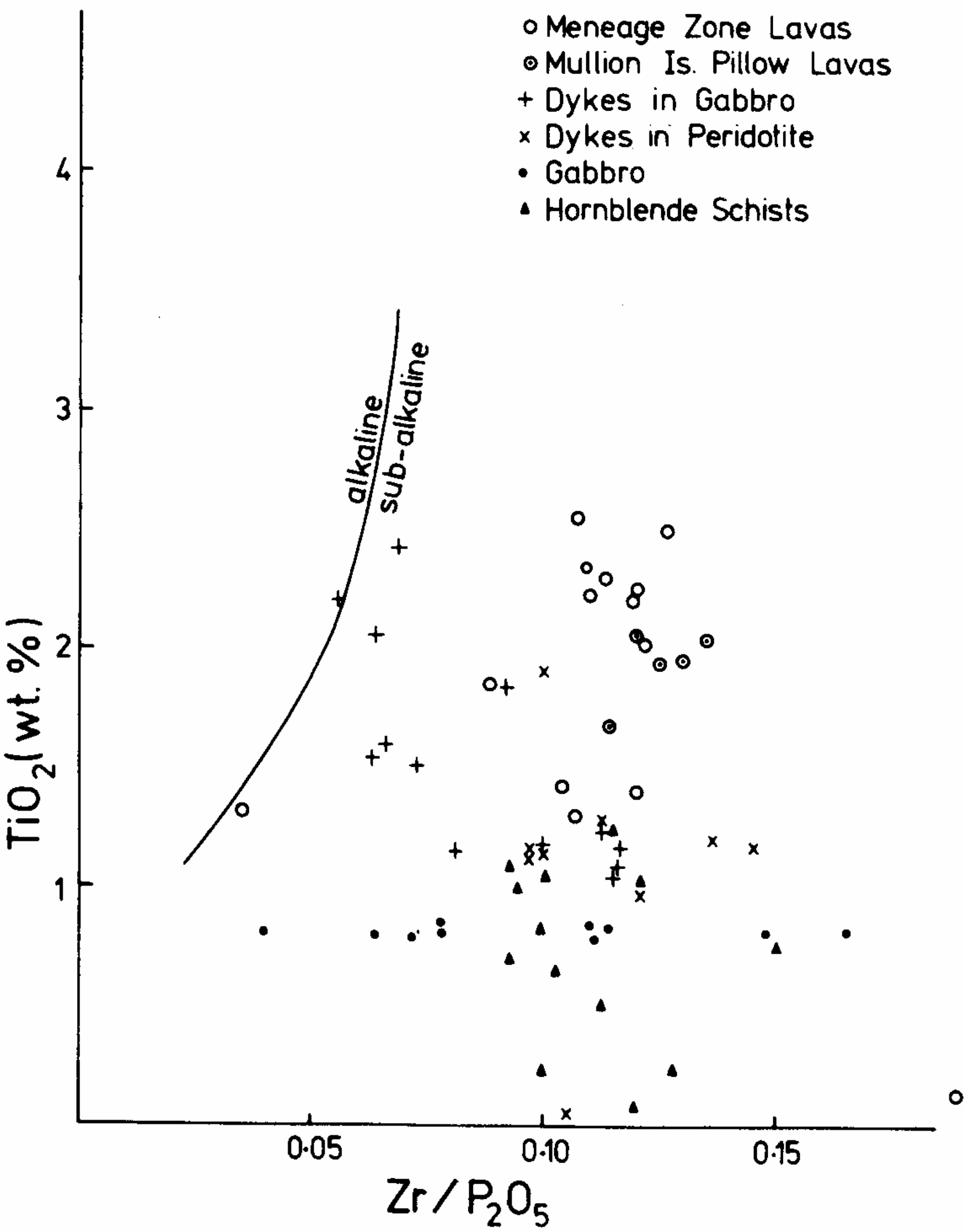

FIGURE 3 Magma type discrimination diagram (Floyd and Winchester, 1975) showing the tholeütic or sub-alkaline nature of the Lizard basaltic rocks.

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other units. If the various low-grade units represented a single differentiated series they would all fall essentially on the same trend in this diagram (see Floyd and Winchester, 1976a, for typical basaltic differentiation trends).

As with Fig. 2 this diagram (Fig. 3) also indicates three distinct groups of rocks based on immobile element variation.

5. Tectonic environment characterization

In order to determine the tectonic environment of the Lizard units in terms of stable or immobile element abundance, two sets of data were used: (a) rare earth element (R.E.E.) data from Frey (1969), including one unpublished analysis of a Mullion Island pillow lava (P.A.F. data), and (b) relative distribution of Ti, Zr and Y in the tectonic discrimination diagram of Pearce and Cann (1973).

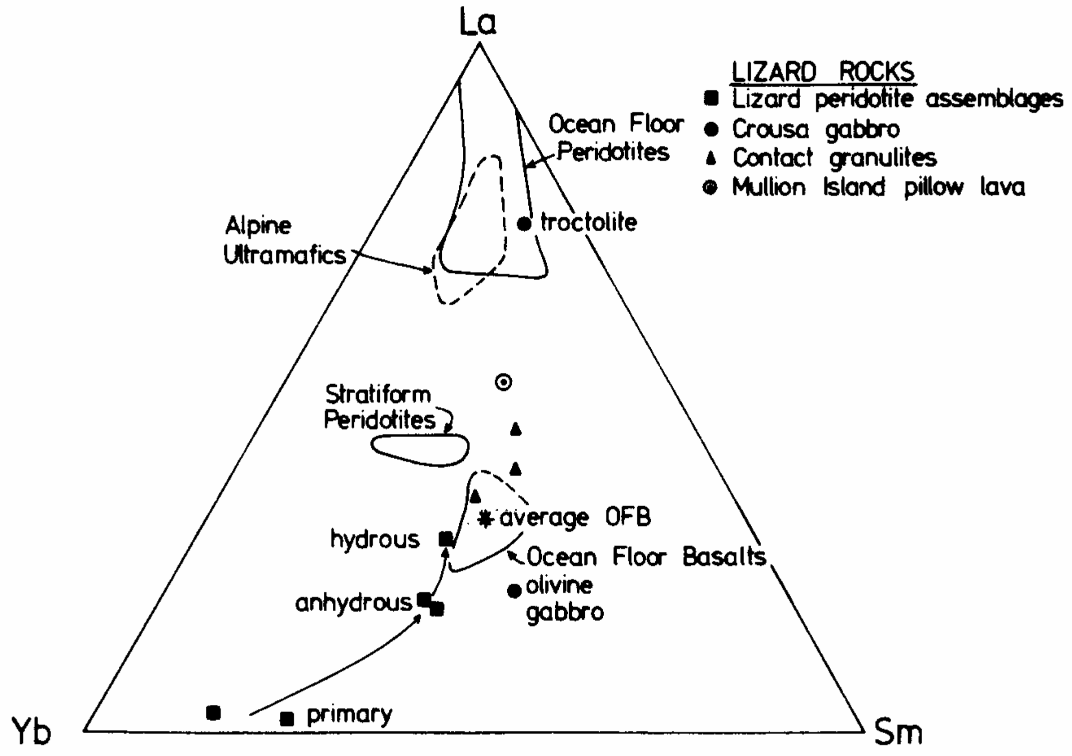

FIGURE 4 Rare earth element triangular diagram for various rocks from the Lizard area. Lizard peridotite, gabbro and "contact granulites" from Frey (1969); Mullion Island pillow lava by Floyd (unpublished data). Ocean floor basalt field data from Schilling (1971); Ultramafic types from Frey (1970a & b) and Frey *et al.,* (1971).

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Fig. 4 shows that the "contact granulites" are the only group to have affinities with ocean floor basalts - a feature that also characterizes the Landewednack hornblende schists proper (Fig. 2) and substantiates their chemical equivalence. The olivine gabbro, as seen on other diagrams, again has a distinctive composition. Note that the Lizard peridotite is La-depleted relative to other ultramafic rocks and is not representative of typical ophiolitic peridotites.

On the Ti-Zr-Y discrimination diagram (not shown) of Pearce and Cann (1973), the majority of the Landewednack hornblende schists plot in the ocean floor field, although the "contact granulites" with higher TiO_2 scatter outside this field. The Mullion Island and Meneage zone lavas plot closely together just in the "within-plate" field, whereas nearly all the dykes and some of the gabbro analyses just spill over into the calc-alkali island arc field.

The chemical distinctions seen previously between the three groups of Lizard basaltic rocks are also reflected in the apparent presence of three different tectonic regimes.

6. Conclusions

Based on the distribution of the immobile group of elements in the basaltic units of the Lizard. complex a number of chemical features emerge :

(a) All the rocks are tholeiitic in character and exhibit some degree of differentiation within the basaltic composition spectrum.

(b) The "contact granulites" of Green (1964b) are chemically equivalent to the Landewednack hornblende schists and distinct from the gabbro.

(c) Three groups of rocks are distinguished which may not be genetically associated :(i) the Landewednack hornblende schists, (ii) the dykes intrusive into both the gabbro and peridotite, together with the gabbro, and (iii) the Mullion Island pillow lavas and Meneage lavas.

(d) Of all the units sampled, only the Landewednack hornblende schists have a composition akin to ocean floor basalts. The gabbro and dykes *might* be representative of the deep-seated part of a calc-alkali island arc, although this interpretation is speculative in view of the relatively high Ti, Cr and Ni contents. The lavas are

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"within-plate" volcanics and in this connection are similar to both the intrusive greenstones and other pillow lavas of South West England (Floyd, 1975).

(e) The peridotite apart, the basaltic units of the Lizard are not all representative of ocean floor rocks and as such do not bear a simple relationship to the pseudostratigraphy of the oceanic crust (Fig. 1).

Acknowledgements. Field work expenses from the University of Keele Research Fund are gratefully acknowledged by P.A.F. and G.J.L.

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Preliminary Isotopic Age Determinations from the St. Just Mining District (Abstract):

by A.N. Halliday and J.G. Mitchell

^{40}Ar - ^{39}Ar stepheating studies (whole rock) suggest that Simm's Lode, Geevor Mine was completely ‘degassed’ by a hydrothermal event at close to 210 Ma. K-Ar age determinations on partial clay separations from traverses across the same lode indicate that the asymmetrical wallrock alteration envelope may also be related to this period of activity, but that a late quartz-tourmaline-cassiterite stringer formed at close to 165 Ma. Ages from a traverse across Coronation Lode suggest that this has undergone a similar hydrothermal degassing at approximately 215 Ma. Age determinations on partial clay separations from the Levant Carbona imply a major metasomatism of the meta-pelites at close to 160 Ma. K-Ar and ^{40}Ar - ^{39}Ar stepheating studies of chlorite, biotite, tourmaline, and hornblende from the skarn mineralization indicate primary formation in Hercynian times (approximately 270 Ma), with major overprinting at 210 Ma and possibly further activity at close to 100 Ma or later. Similar studies of K-feldspars associated with ore minerals indicate that some ore formation took place in late Hercynian times.

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THE LEVANT MINE CARBONA, A FLUID INCLUSION STUDY

by N.J. Jackson

1. Introduction

Intense, disseminated and massive cassiterite-arsenopyrite-chalcopyrite-pyrite replacement and vein mineralisation occurs within a granite sheet complex on the 180 fathom (329 m) level of Levant mine. The ore-body has already been described (Jackson, 1975) but a recently completed fluid inclusion study has revealed some further interesting details about the formation of the ore-body and its cogenetic alteration envelope.

2. **The fluid inclusion study**

Samples were collected from the main types of mineralisation and some metasomatically altered wallrock from the alteration envelope. Homogenisation temperatures (T_h) were determined for primary (P) pseudosecondary (PS) and secondary (S) fluid inclusions in quartz and fluorite, and the results of over 300 measurements are presented in Table 1. A limited number of salinity determinations have also been made. These data suggest that:

1. The main phase of alteration (albitisation) was developed at between 270 - 370°C.

2. Quartz and fluorite associated with vein and massive sulphide mineralisation contain many generations of inclusions which show a large temperature range. The probable temperature of main phase ore deposition was between 270 - 330°C, although cassiterite may have been deposited at slightly higher temperatures.

3. Quartz pegmatites containing inclusions of arsenopyrite, pyrite and chalcopyrite formed between 250 - 310°C. A zoned quartz-fluorite pegmatite shows a continuous temperature decrease from quartz (270°C) to purple fluorite (114°C).

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SUMMARY OF INCLUSION DATA FOR THE CARBONA ORE BODY

SAMPLE DESCRIPTION	TYPE	TH. RANGE	NUMBER
`Unaltered' Granite	P	410-440	6
Quartz	S	200-290	10
Albitised Granite	P	260-370	38
Fluorite	PS		
Albitised Granite	P	270-370	25
Quartz	PS		
Main Fissure Vein	S	230-370	17
Quartz		150-190	3
Massive Sulphide	S	350-410	4
Replacement	P ?	270-330	14
Quartz	S	210-250	11
Massive Sulphide	P	270-330	106
Replacement	S	230-270	6
Fluorite	S	180-210	10
Cassiterite Replacement	P?	210-390	33
Quartz			
Pegmatite 1	P + PS	210-270	11
Quartz	S	130-210	14
Colourless Fluorite	P + PS	170-230	19
	S	110-170	5
Green Fluorite	P + PS	110-170	20
Pegmatite 2			
Quartz	P+ PS	250-310	14

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It is important to note that these temperatures are minimum formation temperatures, uncorrected for pressure. All temperatures (Th) are accurate to within + 8°C.

At the present time only a small amount of salinity data has been obtained. The few data suggest that the initial fluids which produced the albitisation had moderately high salinities 15 - 30 equiv. wt. % NaCl. Inclusions formed at this time frequently contain a small daughter phase which is probably halite. The replacement mineralisation also developed from fluids of moderate salinity 15 - 30 equiv.wt. % NaCl. Inclusions in quartz associated with cassiterite frequently contain a small cubic daughter (halite ?). Inclusions in quartz and fluorite associated with massive sulphides often contain a small prismatic daughter (anhydrite ?). The quartz-fluorite pegmatites formed from fluids with lower salinities <10 equiv. wt. % NaCl.

3. Discussion

Both the field observations and the fluid inclusion study suggest that the main phase of cassiterite and sulphide deposition, both vein and replacement, and the main phase of hydrothermal alteration (albitisation) was produced by a single major hydrothermal event. Main phase ore deposition and hydrothermal alteration was produced from fluids of variable salinity (15 - 30 equiv. wt. % NaCl) in the temperature range 270 - 370°C (uncorrected for pressure). Minor pyrite, chalcopyrite and hematite were deposited at lower temperatures. There is also some evidence for a late stage low temperature hydrothermal event, but whether this is temporally related to the major event or is a younger separate event cannot be distinguished on field evidence or be resolved using the inclusion technique. However, recent K-Ar isotopic age dating of alteration assemblages (Halliday, personal communication) suggests that there were at least two and possibly three distinct and widely separated hydrothermal events.

Acknowledgements. I would like to thank King's College for financial support, Professor Davis for allowing the use of the fluid inclusion facilities in the Mining Geology Division of the Royal School of Mines, Imperial College, and Alex Halliday of the Dept. of Geophysics and Planetary Physics, the University of Newcastle upon Tyne for generously allowing me access to his K-Ar age data.

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FLUID INCLUSION STUDIES AT ST. MICHAEL'S MOUNT

by N.J. Jackson and A.H. Rankin

1. Introduction

St. Michael's Mount is situated in Mount's Bay approximately 3 km east of Penzance (SW 515 298). Lithologically the Mount can be divided into two parts, a small (60 m-diameter) mineralised granite porphyry stock and its pelitic thermal aureole of andalusite and biotite hornfelses. Detailed geological descriptions of the Mount are given by Davison (1920) and Hosking (1953).

W-Sn-Cu mineralisation in the form of sheet veining is developed in a 40-50 m-wide, approximately east-west-trending belt on the southern flank of the stock. The vein system is developed in two sets of subvertical joints trending 070° and 050°, and also in some minor flat (less than 30°) south-west-dipping joints in the extreme west of the mineralised belt. The veins are predominantly tensional structures and show little evidence of shearing. They are usually less than 15 cm wide with continuous strike lengths of less than 50 m. They show typical cavity infill textures-euhedral, vuggy and crustified gangue and ore. The gangue is dominated by quartz with minor apatite, feldspar and mica. The main ore phases are wolframite, cassiterite and stannite, proportionally in that order, with minor pyrite, chalcopyrite and arsenopyrite. Hosking (1953) suggested that the sequence of vein infill was silicates and apatite-wolframite and cassiterite-sulphides. Wallrock alteration is predominantly intense phyllic (greisen) bordering the fissure with an outer weakly sericitised envelope. Occasionally there is an intermediate feldspathised (albitised) zone. However, most of the wallrock alteration was probably pre-ore emplacement (Hosking, 1953).

2. Inclusion studies

The main features which make the Mount ideal for inclusion studies are:

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1. The availability of good material (clear euhedral quartz and cassiterite).

2. Good geological control in a relatively simple ore system.

All the temperatures quoted are minimum formation temperatures and are accurate to $\pm$8°C. To calculate the actual formation temperature a pressure correction is needed. This can be calculated by knowing either the temperature or pressure at the time of formation from independent sources. These data are not well known for south west England. However, the depth of emplacement of the batholith has been estimated to be about 4 km (Floyd, 1971) and temperature estimates of some vein phases by oxygen isotopes (Alderton, personal communication) suggest a general pressure correction of between ½-1 kb. In the St. Michael's Mount hydrothermal system this would require an addition of between - 50-100°C to the quoted homogenisation temperatures assuming a 10 wt. % NaCl solution.

3. Types of inclusion

Primary (P) and pseudosecondary (PS) inclusions in quartz apparently cogenetic with cassiterite and wolframite are usually small, well shaped, 2 phase systems (liquid + vapour). Rare 3 phase inclusions (liquid + vapour + solids) contain combinations of:

1. a small opaque phase (sulphide ?)

2. hexagonal platelets (a mica ?)

3. a fibrous, pale green coloured phase.

P and PS inclusions in cassiterite are simple 2 phase (L + V) systems. P and PS inclusions in quartz associated with stannite are usually 2 phase (L + V) systems, but they sometimes contain a small prismatic birefringent daughter phase, possibly a sulphate. Illustrations of the main types of inclusion are shown in fig 1.

It should be noted that during homogenisation runs these daughters (1-3) failed to dissolve completely within the inclusion fluid even at high temperatures. The possibility that they are 'captive phases', not directly derived from the inclusion fluid cannot be precluded.

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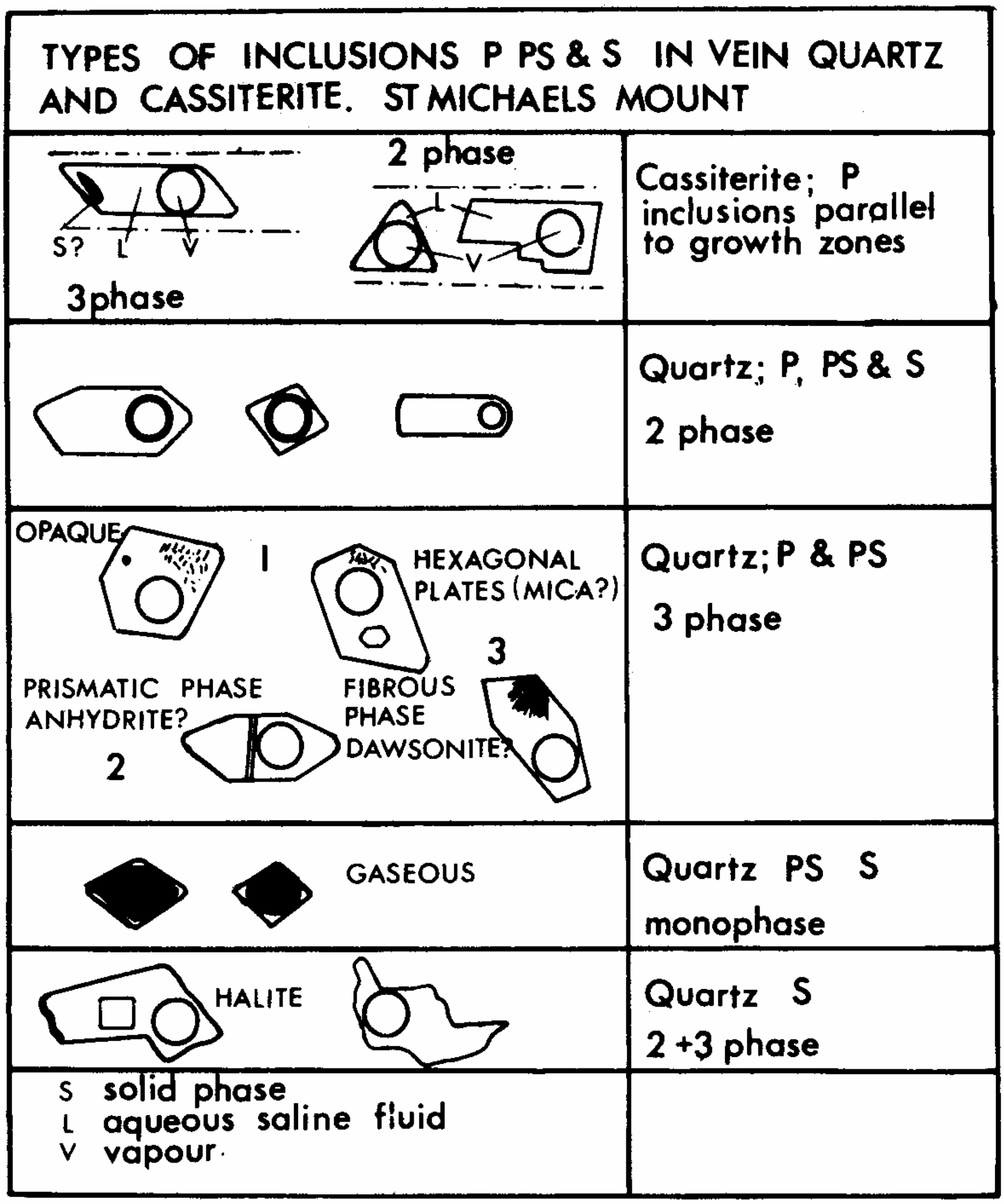

In quartz associated with wolframite, small planes of secondary (S) or pseudosecondary (PS) gaseous inclusions are often present. They were also observed on rare occasions in quartz associated with cassiterite. These trapped portions of a vapour phase suggest that the pressure varied considerably during the history of the vein system. We hope to study these inclusions in more detail with a view to resolving the question of pressure variation during the formation of the vein system.

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4. Results

The homogenisation temperatures (uncorrected for pressure) of over 500 P and PS inclusions show that:

1. Quartz-cassiterite and quartz-wolframite formed approximately in the same temperature range, about 340-400°C; quartz-stannite was formed at a lower temperature 280-300°C.

2. Individual cassiterite crystals show a temperature variation from margin to core of 340-400°C. This is the same as the total range in temperature at which cassiterite was deposited in the whole of the vein system.

3. The maximum concentration of P and PS inclusions in cassiterite homogenise at temperatures approximately 40°C higher than the maximum concentration of primary inclusions in apparently cogenetic quartz. This observation has fundamental implications for earlier inclusion studies, where formation temperatures quoted for opaque ore phases e.g. cassiterite and wolframite, were based on only a few (often less than 5) measurements for the apparently cogenetic transparent phase.

4. Salinity data were difficult to obtain due to the small size of the inclusions. Serious problems of metastability were also encountered. The quoted freezing temperatures are accurate to within t 1°C. Freezing temperatures of P and PS inclusions in quartz intergrown with cassiterite were between -3.6 to 16.5°C (mainly between -5.5 and -9.5°C). This is equivalent to an 8-14 wt.% NaCl solution. Freezing temperatures of P inclusions in cassiterite were also between -5.5 and -9.SoC.

5. Very approximate Na/K values of all inclusion fluids (P, PS and S inclusions) obtained by simple bulk crushing and leaching of samples taken from a traverse across a single vein, suggest that initial fluids had low values (about 2) and later fluids had high values (about 14). The significance of these data is questionable because all generations of inclusions were sampled.

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5. **Conclusions**

The detailed inclusion studies at St. Michael's Mount have revealed some interesting philosophical points regarding the use of fluid inclusions as indicators of the physico-chemical environment of vein deposition in south west England. For an apparently simple vein system, the assemblage of inclusions, their composition and abundance is extremely complex. Previous inclusion studies (Little 1960, Bradshaw and Stoyel 1968, Sawkins 1966, Alderton 1975) are considered to be over-generalised versions of a vastly complex regional hydrothermal system. Detailed studies of inclusions in minerals from individual fissure systems are needed to complement and refine the data of previous workers.

Acknowledgement. We thank NERC for providing a grant to Dr. C. Halls for part of the fluid inclusion facilities in the Mining Geology Division of the Royal School of Mines. N.J. Jackson acknowledges the financial support of King's College and would like to thank Professor G.R. Davis for the use of the inclusion facilities in the Mining Geology Division.

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METATYUYAMUNITE FROM THE URANIFEROUS - VANADIFEROUS NODULES IN THE PERMIAN MARLS AND SANDSTONES OF BUDLEIGH SALTERTON, DEVON.

by E.M. Durrance and M.C. George

Abstract. The presence of metatyuyamunite is recorded as small radiating clusters of thin, yellow plates growing on fracture surfaces. It is considered to have formed by the spontaneous dehydration of tyuyamunite, which, in turn, formed from an original thucolite/coffinite assemblage.

Since Carter (1931) first recorded the occurrence of dark radio-active nodules in the Permian marls and sandstones underlying the Budleigh Salterton Pebble Beds, the character of the material producing the radioactivity has remained an enigma. The nodules are usually roughly spherical in shape and range up to about 25 cm in diameter. Perutz (1939) classifies them according to their morphology into three types: (A) Irregular black concretions, the irregularities being filled with grey clay; (B) Spherical concretions consisting of a black core surrounded by a sheet of grey clay which, in turn, is surrounded by a concentric shell of black material which on its outer surface extends as fins away from the centre of the concretion; (C) Spherical concretions consisting of a black core, which is often irregular, surrounded by successive concentric shells of black material separated by grey clay.

The radioactivity of the nodules is normally sufficiently intense. to allow the production of contact autoradiographs in about 14 days, if a cut, flat surface is placed in contact with the emulsion of ordinary photographic film (such as Ilford EP 4 or HP 4) in a dark room. Such autoradiographs show that the radioactive material is concentrated in the black zones, usually in the central part and at boundaries between the different layers in the composite nodules. In some instances the layers in the composite nodules can be seen to rut across the bedding in the host rock, clearly indicating a post-depositional origin, as shown

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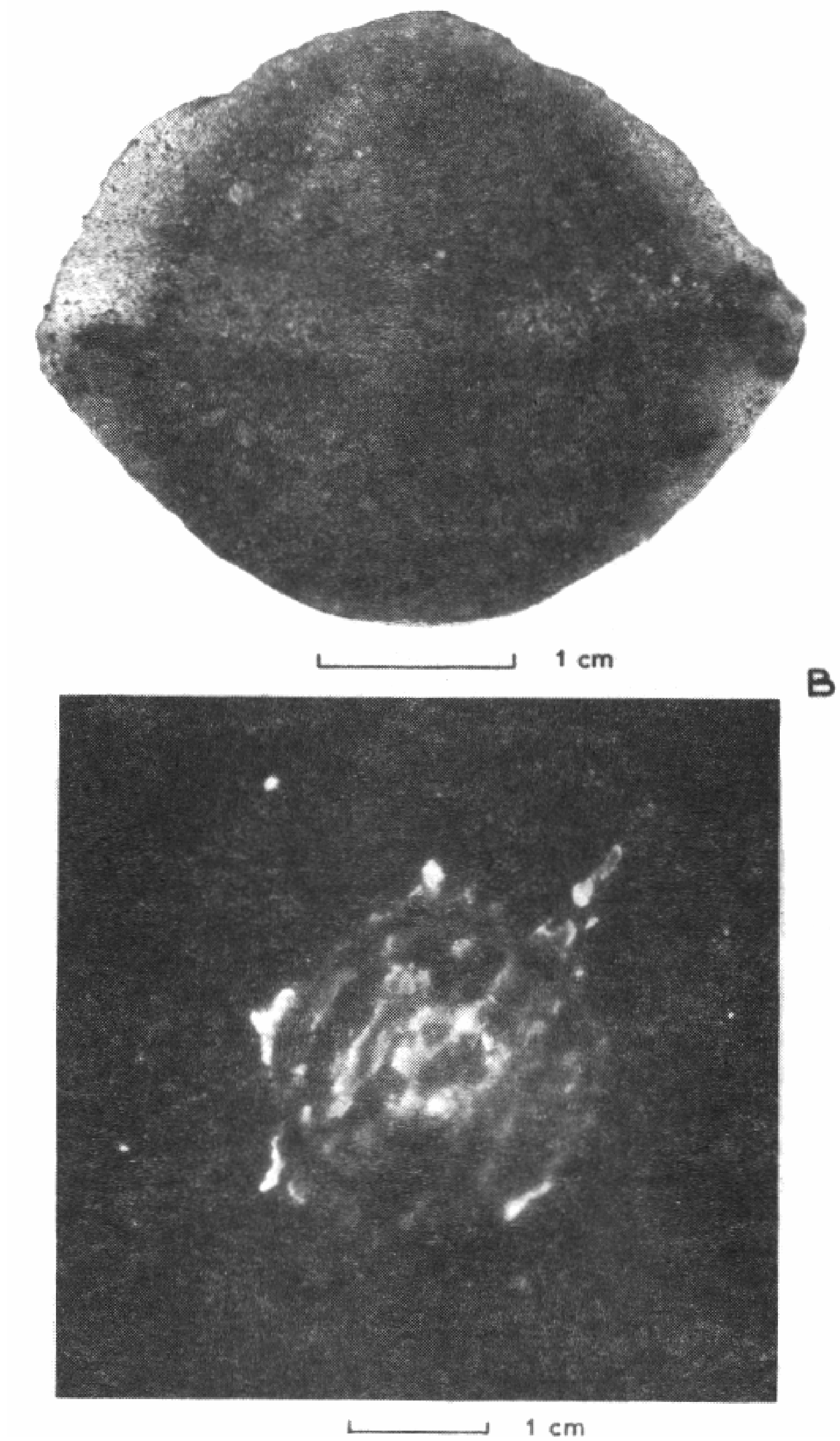

Plate 1

A Small concentrically banded nodule in a sandy unit from the Littleham Marl Formation.

B Autoradiograph (14 day exposure) showing concentric banding of radioactive material with local extensions in bedding direction.

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in Plate 1. The autoradiograph of the nodule shown in Plate 2 also shows that the distribution of the radioactive material cuts across the bedding.

Chemical analysis of the black nodule material (Carter, 193 1) indicates that V_2O_5 may form up to about 14%, but of the other elements with naturally occurring radioactive isotopes no thorium or Rare Earths were found, and U_3O_8 only at the 0.07% level. Although the radioactive isotope V^{50} is therefore present, the total activity associated with this composition is far less than that recorded. Perutz (1939), however, shows that on powdering the black material and heating at low pressure, the radioactive emission is considerably reduced but with time recovers at a rate characteristic of the formation of Rn^{222} in the U^{238} decay series. He therefore concludes that most of the activity is due to the presence of U^{238} and its daughter isotopes, and on this basis calculates that the nodules contain about 0.3% uranium. This he confirms by a new chemical analysis yielding 0.5% uranium. Although failing to identify any specific radioactive minerals by X-ray diffraction or optical study, despite attempts to concentrate the radioactive material by centrifuging powdered nodules in Bromoform, he shows, by autoradiography, that the emissions appear to originate from thin layers coating other minerals. He therefore further concludes that apart from containing uranium, the radioactive material is amorphous, of colloidal origin and variable chemical composition, and suggests the presence of calciocarnotite or rauvite.

Harrison (1975) also records experiencing difficulty in the identification of the radioactive material by optical and X-ray diffraction methods, but electron microprobe analysis has confirmed an earlier suggestion by Harrison (1962) that coffinite is present in the nodules in a finely mixed complex of clay minerals and organic material. He also notes that metatyuyamunite was identified by Wyley (1961), but no account of the associations of this mineral appears to have been published.

New X-ray diffraction work on the nodules has now yielded the presence of alpha cristobalite, which as it has not been recognised in their detrital host material, is probably of secondary origin; and metatyuyamunite. The alpha cristobalite may indicate an association between silicification processes and the formation of the radioactive mineials within the nodules. This would not be unusual, as a similar association is known in the south-western U.S.A. (Witkind, 1956), where tyuyamunite occurs with silicified wood remains. Coffinite is

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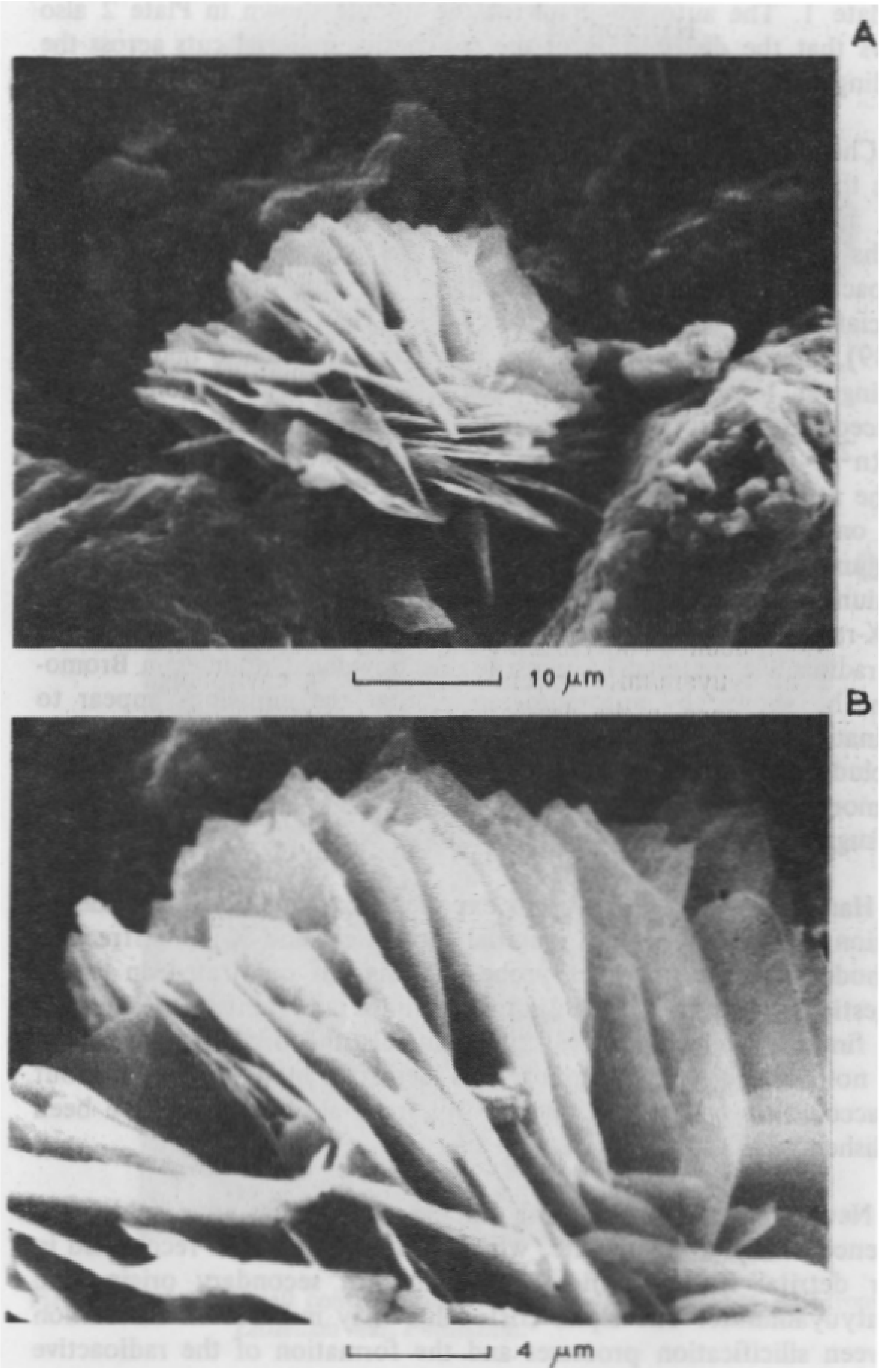

Plate 2 A Radiating cluster of metatyuyamunite.

B Fine detail of individual plates of metatyuyamunite.

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also present in this assemblage (Heinrich, 1958), an additional factor lending support to Harrison's (1975) suggestion that this mineral is present in the Budleigh Salterton nodules. However, in the American material the occurrence of organic remains also results in the formation of uranium hydrocarbons similar to thucolite. The presence of similar uranium hydrocarbons in the Budleigh Salterton nodules would be consistent with the difficulty in obtaining any recognisable X-ray diffraction pattern from most of the radioactive material, especially as an excess weight loss on ignition of 4.4% occurs for the nodule material over that for the host. The metatyuyamunite cannot be considered the original uranium-bearing mineral as it characteristically forms by the spontaneous dehydration of tyuyamunite (Stem *et al.* 1956), a process which can easily occur between field collection and laboratory study. This implies that tyuyamunite is probably the *in situ* mineral. Even so, it is unlikely that tyuyamunite is the original uranium mineral, as in its re-crystallised form it occurs in hemispherical clusters of thin (about 0.1 μm) yellow plates growing on fracture surfaces in the nodules (shown in plates 3 and 4) and its growth is obviously a late stage feature of the mineralogical history. ; Moreover, the formation of thucolite and coffinite requires a reducing environment, while that of tyuyamunite requires an oxidising environment. The most likely sequence in the development of the radioactive minerals is thus firstly the formation of thucolite type complexes and coffinite, possibly accompanied by silicification, in a reducing environment during the decay of organic remains, with a subsequent oxidising environment leading to the formation of tyuyamunite.

Acknowledgements. We would like to thank Mr. R.H. Hoskins for the electron micrographs shown in Plates 3 and 4.

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THE CURVED-CRYSTAL PEGMATITE, GOONBARROW

by J.P.N. Badham and C.W. Stanworth

Abstract. Post-emplacement phenomena can be deduced from exposures in the Goonbarrow pit of E.C.L.P. Ltd. A comb layered pegmatite dyke followed potash metasomatism, intrusion of quartz - tourmaline 'magmas' and the initiation of a master joint system. Pegmatite intrusion was followed by aplites, greisens and mineralisations, and kaolinisation. The pegmatite has a simple mineralogy of K-feldspar, biotite, tourmaline and quartz; the K-feldspar showing curved and branching crystals up to 20 cms long. A mode of crystallisation involving moving aqueous fluid theories is favoured.

1. Introduction

The Upper Carboniferous potash granites of southwest England (and indeed of much of the European Hercynides) are characterised by a great range of post-emplacement phenomena. The full spectrum typically includes metasomatism (K and B) - pegmatites and aplites - greisens, mineralisations and porphyries - kaolinisation(s). The granites are everywhere exposed near to the roofs, and its has been demonstrated that the small amount of cover was removed in the Stephanian and Permian (Dangerfield and Hawkes, 1969. Cosgrove and Elliott. In Prep.). The batholith as a whole must have been intruded effectively as a single event, have risen to near isostatic compensation level, and have cooled uninterrupted by the *major* vertical tectonism that has affected the multi-emplaced 'Andean' batholiths. Consequently the only post-emplacement adjustments were due to cooling and were of relatively small scale. It is this lack of major adjustments that permitted development of the full spectrum of post-emplacement phenomena (see Badham 1975, Badham and Halls 1975 and Badham in prep. for discussion).

The St. Austell granite is, because of its extensive kaolinisation and consequent economic attentions, the best exposed part of the Cornubian batholith. The work of Exley (1958), Bristow (1968) and Dines (1956) has described various of the post-emplacement phenomena, and Badham *et al* (1976) have deduced a paragenesis of these events (figs. 1 & 2).

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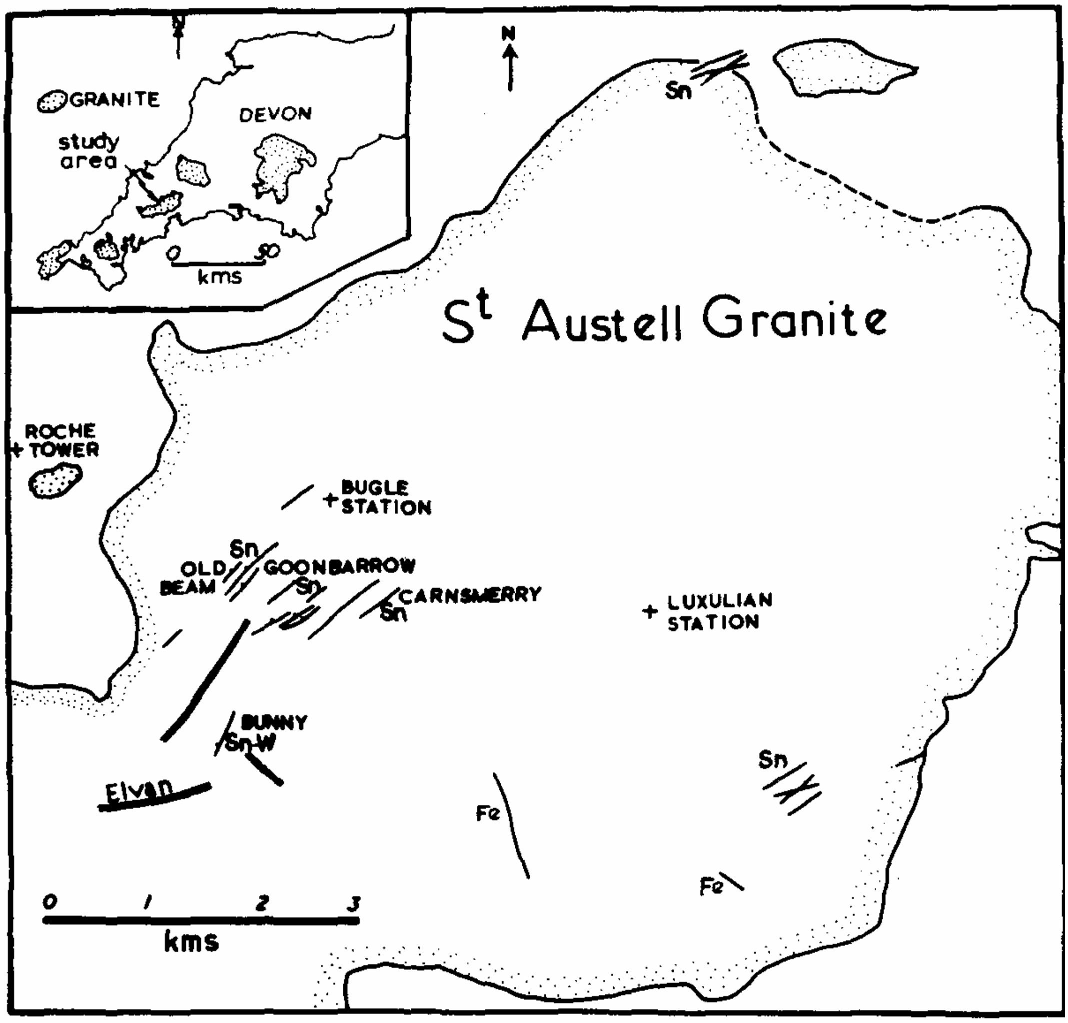

FIGURE 1 Location map of the Goonbarrow pit

A map of the Goonbarrow pit shows the courses of pegmatite, elvan and mineralisations: the joint-control is obvious. The host-granite (the ‘early lithionite’ type of Exley, 1958) is a rather variable rock consisting principally of quartz, orthoclase, plagioclase, muscovite and tourmaline. It has been variably kaolinised, the most intense alteration being along the areas of most intense greisenisation. The granite is commonly fluxion-banded, but this has no consistent orientation. K-feldspar megacrysts are common in zones, but irregular. The same is true for rare miarolitic cavities lined with quartz and tourmaline.

The granite is evenly jointed on three sets (vertical at 065°, vertical at 135° and horizontal) which are coeval. A younger set (dip 60° at 310°) apparently post-dates the initial greisenisation.

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2. The pegmatite

True pegmatites are rare in southwest England (Hosking, 1954) and none has yet been described from the St. Austell granite. The Goonbarrow pegmatite strikes around 140°, is generally vertical, and varies between 2 and 3 metres in thickness. In 1974 it was exposed intermittently over 55 m. along the base of the pit. Recent workings have shown it to extend with little variation another 20 m. or so to the southeast and over 100 m. to the northwest, where it thins markedly (Dr. E.T.C. Spooner, pers. comm. 1976). 20 m. of new (1976) exposure show a 5 m. thick comb-layered sequence (described below) almost on strike with the pegmatite, but separated by 25 m. of no exposure. The margins of the pegmatite are sharp and unsheared, and it clearly generally filled dilatant joints. There is no chilled margin and the adjoining granite is unaltered. The granite on the eastern side is a fluxion-banded megacrystic quartz -feldspar-biotite rock: to the west it is a finer-grained feldspar-quartz-tourmaline rock. In two places the pegmatite bends into the horizontal for a few metres. This change is an original intrusive phenomenon and is not the result of later tectonism; it indicates that the horizontal joint system was extant at the time of intrusion.

The main part of the pegmatite is symmetrical and composite. The outer zone consists of curved fans of pink feldspar that nucleate at a point, expand and ramify inwards and curve upwards. The fans are surrounded by a matrix of quartz, biotite and some tourmaline and are up to 20 cm. long and 2 cm thick. There are no signs that the bending is anything but primary. The inner zone has a 10 cm.-thick wall of massive feldspar, and then again consists of (smaller) curved and branching fans of feldspar. The matrix of the inner zone consists predominantly of quartz and tourmaline, with rare biotite. Splays of tourmaline up to 5cm. long radiate into the centre of the dyke from the ends of the feldspar crystals. There are rare miarolitic cavities (lined with quartz and tourmaline) in the centre. The curved crystals and the zonation are confined to the vertical parts of the dyke: where it turns horizontal, large crystals of quartz, feldspar, biotite and tourmaline are all intergrown, with no consistent orientations. They contain interstitial blebs of chalcopyrite, pyrite, arsenopyrite and rare molybdenite.

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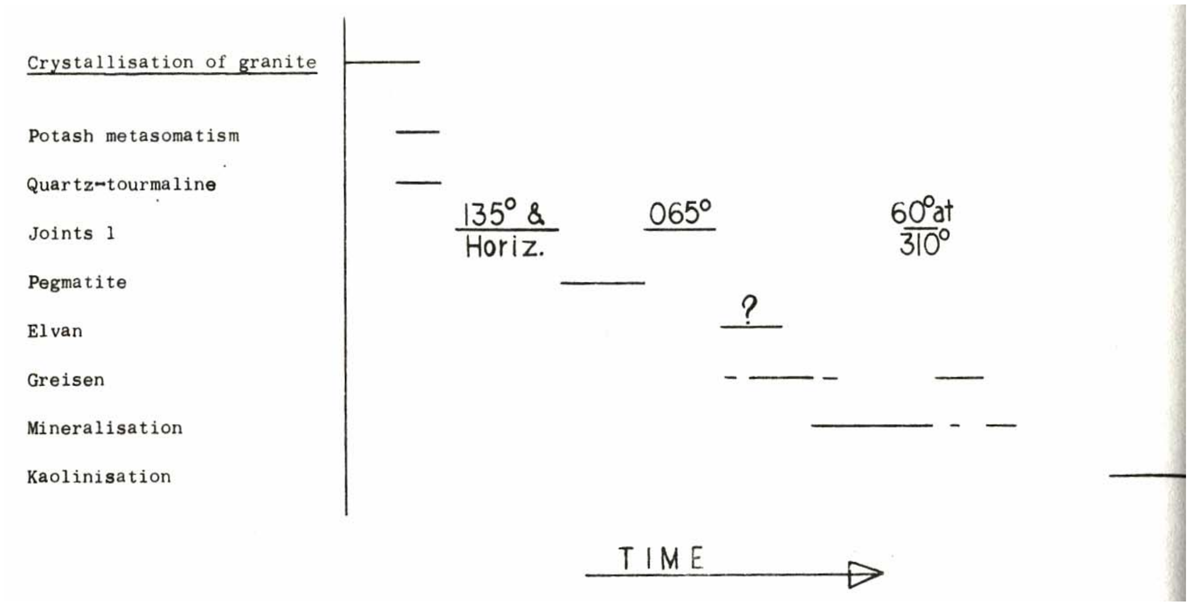

FIGURE 2 Paragenesis of events during the cooling of the St. Austell granite.

The pegmatite has been variably kaolinised along its length, but small 'islands' of astonishingly fresh material have escaped this alteration. Petrographic studies of the feldspar show it to be an orthoclase-albite microperthite, which has been weakly sericitised. The long, curved crystals are in optical continuity and have fractures and simple-twin planes parallel to their length, both are curved. The perthitic intergrowths are aligned perpendicular to the length, and their orientation also swings gently with the curvature. There is no sign of deformation.

The matrix to the feldspars consists predominantly of intergrowths of quartz and tourmaline. The quartz is generally euhedral, with no inclusions. The tourmaline is pale to dark brown pleochroic, and contains numerous pale to dark blue pleochroic zones around radio-active inclusions and cracks. The tourmaline is commonly zoned. Where biotite is present, it occurs as green-brown pleochroic sheaves which are crowded with pleochroic haloes, and some remnants of what appear to be monazite and zircon at the halo cores. Scattered crystals of microcline, albite and muscovite are also present in the matrix. Opaque minerals are uncommon and usually secondary. The sulphide minerals have not yet been studied in polished section. Secondary torbernite, malachite and copper are locally common on fractures,

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especially in the horizontal areas. The torbernite probably derives from the same radioactive mineral that caused the pleochroic haloes in biotite and tourmaline. Malachite and copper were derived from chalcopyrite.

During a brief visit to the pit in April 1976, a new exposure of "pegmatite", slightly separated from the southeasternmost outcrop of "normal" pegmatite, was examined. Here a complex, comb-layered (Moore and Lockwood, 1973) zone 5m. thick dips at 70º to the east. The various layers are between 5cm. and 50cm. thick, and a maximum of 20 separate layers was counted. The outermost layers are both in sharp contact with the granite, but detailed relationships are obscured by pervasive kaolinisation of both granite and pegmatite. The layers alternate between being feldspar rich (90 - 100%) and biotite-feldspar rich (about 50% of each mineral). In all the layers the feldspars nucleate on the hangingwall, expand and ramify inwards, and curve upwards. Biotite, where present, is interstitial. No detailed petrographic work has been performed owing to the intensity of kaolinisation. Each layer is in sharp contact with its neighbours, and no crystals transect the boundaries.

3. Discussion

We consider the "normal" pegmatite liquid to have been a late differentiate of the granite that was emplaced passively into dilatant joints. This implies that the granite was cool enough to undergo brittle failure. It is equally clear that the fluid was not truly magmatic, but was aqueous. The composite nature and variable mineralogy of the dyke may be the result of pulses of intrusion. However, the breakdown of zonation in the horizontal parts, and the lack of chilling and of intrusive breccias (xenoliths), make it more likely that the composite nature is due to gradual changes in a parent fluid which was moving and being variably replenished from a changing reservoir. Movement of fluid is necessary to explain the double appearance of feldspar megacrysts. However, changes from feldspar to tourmaline as the dominant phase may be due to gradual differentiation of the fluid and concomitant sudden changes in mineral stability in the fluid.

If the fluid were moving, it seems logical to interpret the curvature of the crystals in terms of this movement. Lofgren and Donaldson (1975) have shown that curved crystals can result from rapid nucleation after supercooling. While their experimental data cannot be doubted,

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it should be noted that their curved crystals were rarely larger than a few millimetres, and were often of metastable mineral phases. The giant crystals at Goonbarrow and the indications of relatively slow, equilibrium growth (perthitic texture and zonation) militate against such a model.

We feel that the evidence supports the contention that the fluid was moving. Moore and Lockwood (1973) have presented similar arguments for comb layered rocks in the Sierra Nevada batholith. They further argue that the fluids must have been of low viscosity (so as not to have broken the delicate branched crystals) and thus essentially aqueous. There is good evidence from elsewhere in the St. Austell granite for early, supercritical, aqueous solutions (tourmaline breccia pipes and greisens), and we would use the same arguments for the Goonbarrow pegmatite. However, Moore and Lockwood went on to argue that the fluids that cause comb layering probably moved relatively rapidly. The fine textures, lack of xenoliths and ponding in horizontal portions suggest to us that the normal pegmatite parent-fluid was moving quite gently. However, the discovery of classic comb-layering virtually identical to that described by Moor and Lockwood (op. cit.) supports their arguments. The fact that the pegmatite changes from a dyke to a comb-layered sequence might mean that the parent-fluid was moving slowly in dilatant areas (thus forming a dyke), but was moving rapidly, or with more difficulty, in non-dilatant areas (thus forming comb-layers).

A final problem concerns the nature of curvature of the feldspars; were they bent physically as they grew, or did they grow with a curve? The petrographic evidence suggests that they grew with an original curvature. Growth on the centre and uppersurfaces must have been favoured to have caused an upward curvature, i.e. growth was enhanced on the areas in contact with the moving fluid.

Acknowledgements. It is a pleasure to acknowledge the help and encouragement of E.C.L.P. Ltd. - especially Clive Gronow, Colin Bristow, Ian Wilson and Keith Menadue. Discussions with Dr. E.T.C. Spooner have also been helpful.

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CORNUBIAN GEOTECTONICS - LATERAL THINKING

by J.P.N. Badham

Abstract. Traditional models showing perpendicular plate motions as the cause of the Upper Palaeozoic orogens of Europe are invalid in that they fail to explain the lateral inhomogeneity, in time and space, of these orogens. A model for lateral plate tectonics is presented. It is shown that the various geological 'oddities' of Cornubia are better explained on such a model.

1. Introduction

Many attempts have been made to explain the evolution of the Hercynides in plate tectonic terms, and it would *de trop* to review them here. Suffice it to say that most of them are suspect in that their authors assume lateral homogeneity, and apply a cross-sectional template from their own area of expertise to the whole orogenic system. The reviews of Riding (1974) and Badham and Halls (1975) have at least attempted to account for the lateral inhomogeneity, and while there are obvious failings in both works, they both attempt to rationalise all the geological data. For example, palaeomagnetic constraints require that the Upper Palaeozoic motions between Africa and Europe were predominantly lateral, yet many models show cross-sections with perpendicular motions implicit in them. Perpendicular motions require such manifestations of the plate-tectonic pageant as subduction, andesites, continental collision, etc. - manifestations which, despite the protests of arden plate-tectonicians, are simply not seen in Upper Palaeozoic rocks in Europe. It may be that in the attempt to satisfy both palaeomagnetic and often highly contradictory palaeontologic data, Badham and Halls (1975 Fig 2A) have exaggerated what real distances may have lain between Europe, various microplates and cratonic Africa, and that the conclusions of Ager (1975, p. 140) are more valid. Nevertheless, the lateral tectonic model is a far better explanation of the Hercynides than previous models.

I wish to digress for a moment here to discuss the generalities of the lateral tectonic model. In the situation where two plates (at least

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one of them oceanic) are moving parallel to each other, all motion is clearly taken up by strike-slip faults. Transform faults are one example of this; the Alpine fault and Maquarie Rise may be another. However, when the relative motion has some small degree of obliquity; then there must be a net approach of the two plates. This perpendicular motion may combine with the lateral motion in the case of fluent angled subduction, such as is now occurring in the Western Aleutians or at the north end of the Andaman arc. Fluent angled subduction is favoured by fast relative velocities. Conversely, the motions may be taken up by intermittent subduction and strike-slip motion; such a situation has pertained throughout the Tertiary in western North America.

In ideal cases the strike-slip component may be taken up on a single fault. However, where a continental and an oceanic plate are juxtaposed and in relative lateral motion the faulting is usually taken up on a complex-zone (e.g. the San Andreas *system* or Queen Charlotte Islands *system).* This results in fault-bound fragments of the two plates being rotated and translated. The translation of these microplates will continue until they are removed to some point where orientations of plate motions are changed. Western North America provides a fine illustration of this process. The continental margin is at present in shear and in the past has been both in shear and in compression (i.e. subduction) in various places and at various times (cf, the intermittent and spatially restricted volcanism of the Cascades). An excellent synthesis by Beck (1976) has shown that many fault-bound fragments that make up the coast ranges from California to Alaska have been rotated clockwise and translated northwards. Packer and Stone (1975) and Jones *et al.* (1972) have further shown that portions of south Alaska were originally parts of California and Oregon, which migrated northwards until they impinged with the bend in the continental margin at the Aleutian arc.

It is important to note that the translation and rotation of microplates has resulted in: 1) the frequent compression and occasional obduction of ophiolites between fragments; 2) the separation of sediment sink and source areas; 3) emplacement of alkaline or continental tholeiite magmas in the bounding-fault areas; 4) discontinuous deformation of sediment piles, between or on the edge of the microplates; 5) fragmentation of the products of intermittent subduction, such that recognition of complete arc terrains is almost impossible. The discontinuous and irregular nature of the orogen is well shown on the tectonic maps of the U.S.A. and Canada.

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Further complications ensue when the interacting plate margins are continental, with only a small (and vanishing) wedge of oceanic crust between them. Interactions between the continental plates will enhance the 'ball-bearing' effect of the microplates, and will result in a wide, complex and inhomogeneous collision orogen. These processes are occurring now in the Mediterranean - one only has to consider the phenomenal range of geological processes occurring now between Spain and Greece to see some of the complications that could ensue. The elegant synthesis of Dewey *et al.* (1973) describes the same process in the evolution of the Alps, although in places with difficulty and no little controversy. How much more difficult it is to reconstruct the fragmented Hercynides and then to analyse the various microplate movements. As I have said, it is only the works of Riding (1974) and Badham and Halls (1975) which have made any attempt to rationalise the extraordinary variations in time and space in the Upper Palaeozoic orogens of the North Atlantic region.

Finally, before dealing with the relevance of this model to Cornubia let me make another digression - on granites. Having said that the Hercynides are a most variable orogenic system, I should qualify this, for it appears that in the Upper Carboniferous there was for the first time some homogeneity. The Westphalian and Stephanian deformations are similar in style and timing from Spain and Cornwall to Bohemia. The potash granites and their related hydrothermal deposits are identical over the same area. All are epizonal and are now preserved near their roof levels. Such lateral continuity, high-level emplacement and preservation are characteristic of distal Andean situations. There is no way that such granites could possibly have formed as a result of continental collision, with its crustal thickening and partial melting and consequent erosion. These granite magmas may have derived from crust or mantle (and I shall argue neither way) but what is important is that the causative phenomenon must have been subcrustal.

2. Relevance to Cornubia

In figure 1, I show a series of reconstructions (slightly modified from Badham and Halls 1975) of the plate tectonic history of a part of the Hercynian orogenic systems. This is not the place to discuss all the phenomena that occurred because of these motions - they are discussed in the reviews already cited. The relevance of the model to Cornubia can readily be seen. Broadly speaking, Cornubia was an Atlantean margin through the Ordovician and Silurian, suffered inter-

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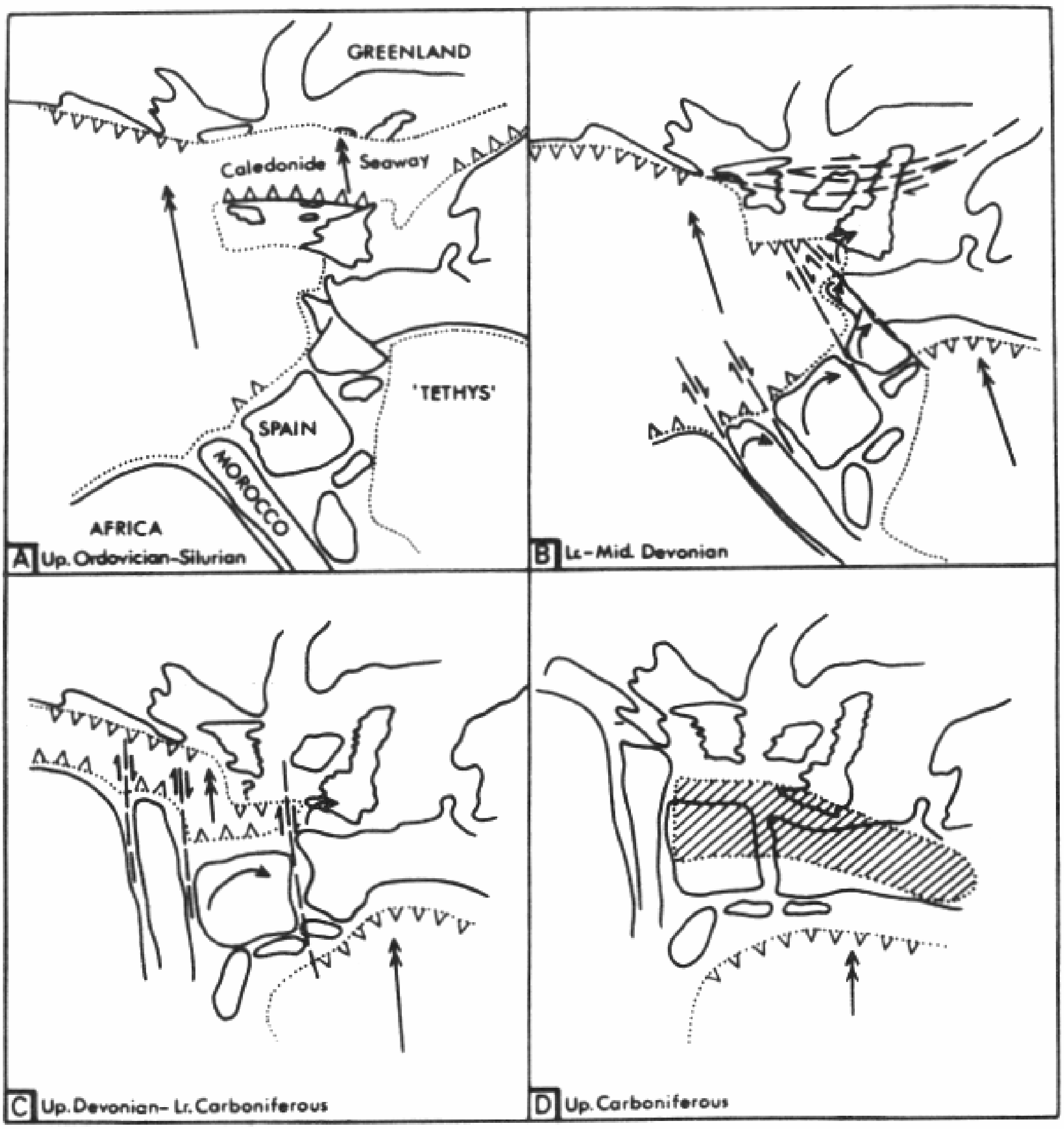

FIGURE 1 A plate-tectonic history of Western Europe in the Upper Palaeozoic. The relative locations of the major cratons follow the suggestions of Smith *et al.* (1973). The microplates are extrapolated from the Permian tectonic map of Dewey *et al.* (1973). The symbols are as follows: Dotted line: continental margin. Toothed line: subduction zone. Double-headed arrow: direction of motion relative to a stationary North America. Single-headed arrow: sense of rotation of microplates between faults (and hence direction of compression of intermittent deformations). Dashed line plus arrows: main strike-slip fault systems and their sense of shear. Striped area: Potash granite - Sn - W zone.

mittent compression and strike-slip motion through the Devonian and into the lower Carboniferous, and underwent uplift and intrusion in the Upper Carboniferous. What special geological features are there in Cornubia that require this model, and not a more `conventional' subduction and/or collision model?

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1. The presence of Ordovician and Silurian shelf sediments (albeit in melange) contrasts strongly with the Upper Palaeozoic sedimentary regimes.

2. Intermittent volcanism and deformation occurred throughout the Devonian and Lower Carboniferous all over Cornubia. The volcanic rocks and their intrusive equivalents were frequently emplaced into wet sediments, and are chemically similar, whether they intrude marginal sediments (Mylor Group), deltaic sediments (Meadfoot-Dartmouth series), basinal sediments (Culm) or reefal limestones. Cornubia is one of the few areas I know where a major deltaic system was pierced by basic volcanic rocks.

3. The magmatic rocks are chemically classified as "continental tholeiite" (Floyd 1972).

4. The intermittent pre-Namurian deformation was directed from SE to NW and involved major thrusting and recumbent folding.

5. The Lizard Complex is a slab of some sort of oceanic crust, obducted into and over the Mylor sediments in Lower and Middle Devonian times. There is absolutely no indication of an associated subduction zone, either in Cornubia, or in Brittany and Galicia, as implied by Riding (1974) and Mitchell (1974) amongst others. The obduction process therefore requires a different tectonic process to that which caused the emplacement of the Troodos or the Bay of Islands complexes.

6. Palaeocurrent indicators, where measurable, show transport from the north (present co-ordinates) in the Lower Devonian, and an increasing contribution from the south (and west?) through the later Devonian and into the Carboniferous. The detritus derived from the south includes ophiolitic and cratonic material, but no arc-type debris.

The presence of Lower Palaeozoic shelf sediments agrees with the plate-situation of Cornubia on a ‘trailing-edge’ (fig. 1 a). With the closure of the 'Caledonide' sea-way, the oceanic crust of Tethys dislocated from the European craton to the north of the South Armorican Shear Zone and Brittany fault, and may have subducted beneath the craton. The various strike-slip faults first became active at this time, causing intermittent compression. The stable margin of Cornubia was disrupted and compressed northwestward (present co-ordinates), while

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the supply of clastic sediment from the north dwindled. The intermittent motion of the French faults ceased with the collision of Armorica with the Grand Banks - Flemish cap area, but a slice of the intervening oceanic crust was shouldered aside over Cornubia. The intermittent tension and torque on Cornubia throughout this time (figs 1b and c) permitted the emplacement of continental tholeüte magma at various times. The obduction of the Lizard complex resulted in a small trapped basin, which was slightly downwarped on the pre-existing faults (Schwelle and Becke facies, with volcanism along the boundary faults) and then rapidly filled from all sides. Subsequently (fig ld), the area was no longer in shear, but, being accreted with the rest of Europe, underwent the same late Palaeozoic evolution - perhaps because of subduction from the south east by dislocation of Tethys from the Afro-Euramerican plate (fig. ld).

3. Conclusions

Geological analysis of the Upper Palaeozoic orogens of Europe is hindered not only by their later fragmentation, but also by political and linguistic barriers. Nevertheless, it is clear that the orogens are highly variable along their length and that these variations (both in geologic processes and in their timing) were not satisfactorily explained by previous models using what might now be called 'classical' plate-tectonic theory. It is felt that the lateral tectonic model presented here provides a more satisfactory plate-framework. The particular problems of Cornubia are better explained using this, than by assuming perpendicular plate motions.

No doubt many European geologists would claim that a platemodel is totally unnecessary (see for example Krebs and Wachendorf 1973). However, it is clear from palaeomagnetic data that plate motions were occurring throughout the Upper Palaeozoic, and the onus is on anti-plate-tectonicians to show how belts such as the Hercynides can evolve independently of plate-tectonic processes. Those who see the complications of the Hercynides as being too great to have resulted from plate-tectonic processes need only look to a section from California through the Colorado Plateau to New Mexico to have their minds set at rest.

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Acknowledgements.I have made no attempt to acknowledge all the papers I have read and must refer the reader to Badham and Halls (1975) for a more complete bibliography. I have also culled indiscriminately from previous papers in the Proceedings of the Ussher Society. I thank Chris Halls, Myrl Beck and many colleagues in the Ussher Society for discussions.

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