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Edited by G.M Power

The Ussher Society

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

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Conference of the Ussher Society held at Exeter, January 1982

CHAIRMAN'S REPORT

At the 1981 Conference it was decided that the 'theme' for 1982 should be aspects of the re-mapping of the 'Tavistock Sheet' (No 337) by members of the Department of Geology at Exeter on contract to IGS, some results of this work having been described that year. A conference centre convenient for this purpose was therefore sought but it was found that all the most promising establishments close to the area had either gone out of business or become too expensive and so the Society was glad to be able to make use of Exeter University's facilities once again. This was its sixth visit to the city (or the eighth if we include the 'South Western Conferences' and their historic inaugural gathering in 1956). Accommodation this time was in Mardon Hall and the meetings were held in the Department of Geology, the Society being once more indebted to Professor Murray and his staff for all their customary hospitality and help. Special thanks are due to Mr M.C. George whose work as Conference Secretary was much appreciated.

Exeter has several times offered a very wintry welcome - 1963 and 19.79 are memorable - but this time it provided something of a refuge from Arctic conditions elsewhere. These may have been responsible in part for fewer attenders at the Conference, although I think it more likely that we are again moving away from that part of the research cycle when, as I mentioned last year, everybody wants to talk about what they have been doing. Nevertheless, with over 65 members present the Conference was an active one.

A full day excursion was held on Sunday, 3 January, and led by Messrs K.P. Isaac and P.J, Turner. When fewer than ten participants set off from Mardon Hall and were joined by only another eight or ten at the Department it seemed unlikely that the trip would be at all successful, but this small group was met at the first exposure by a crowd of impatient enthusiasts whose greetings were as colourful as their anoraks, and for most of the day the party was about 45 strong. It was shown important exposures in ECC's Greystone Quarry south-east of Launceston, on Brent Tor and in the stream section near Wheal Betsy and had explained to it the newly-recognized extensively thrust structure of the country west of Dartmoor. Strong winds and driving rain after lunch failed seriously to reduce enthusiasm but did succeed in causing the abandonment of a visit to the East Okement. The Society expresses its gratitude to leaders, drivers and landowners for providing a thoroughly worthwhile day's geology.

On Monday, 4 January, papers were chiefly devoted to detailed aspects of the mapping of Sheet 337 and its interpretation and this was set against a broader background by Dr Wolfgang Franke of the Geological and Palaeontological Institute of Gottingen University, who gave the Invited Address on 'The Tectonic Setting of Wildflysh Sequences in Europe'. Dr Franke. who is a member of the Society, was making his first visit to a Conference and members not only greatly enjoyed his comradeship, but also found themselves envying his fluent mastery of their own language!

Tuesday's papers concentrated on mineralization, stratigraphy, weathering, and allied topics and included a late addition about structures in the Culm of Iberia.

Over the two days there were 19 papers by 30 authors (only four papers fewer than at Fowey), and as usual there were as many discussions outside the lecture room as in it. These, of course, are one of the Society's most vital activities.

The AGM was held after the papers on Monday and before proceeding to business members stood in silence as a mark of respect to Professor Scott Simpson who had died in October after a very long illness. More than any other individual, Scott Simpson was the 'Founding Father of the Society and the AGM decided to commemorate him both by making a contribution to the memorial fund being organized in Exeter University and by naming the Invited Address the 'Scott Simpson Lecture'. An obituary appears in this Part of the Proceedings but I should like to pay a personal tribute here to a man whose company I always enjoyed, especially in the field, who always had something to teach me, and who honoured me by asking me to be the Society's first Treasurer.

The Treasurer's report showed that, largely as a result of the printers' bill for the most substantial part of PUS so far produced, but also in view of other rising costs, it would be wise to raise the subscription from January 1983 and the AGM agreed to an increase to £7. Among other matters, the Secretary reported that membership numbers remained stable, which is encouraging in these hard times, although I wish, as I hinted last year, that other workers in S.W. England would join us.

Again, despite my urgings, no nominations other than the Committee's were offered for the Committee elections. Three Officers were replaced: myself as Chairman by Mr I.H. Ford of Bristol University, Dr J.M. Thomas as Treasurer by Mr R.C. Scrivener of IGS, and Dr R.A. Edwards as Editor, by Dr G.M. Power of Portsmouth Polytechnic. (The last two retirements were forecast last year). In addition, Mr G. Bisson was elected an Auditor *vice* Mr T.R. Wilson, and Dr E.C. Freshney (IGS) and Dr D. Robinson (Bristol) were appointed to the Committee instead of Mr Scrivener and Dr K. Atkinson. To all those retiring, but especially to the Officers and Auditor, who have worked so hard for so many years, the Society offers its grateful thanks.

On relinquishing the Chair, I am glad to add my personal thanks to those of the Society for all the efforts made by the Officers and the Committee during my term of office, and I am delighted to welcome as my successor Ian Ford who has been a staunch supporter of the Society from its earliest days.

C.S. Exley
January 1982 .

Obituary

Scott Simpson 1915-1981

The first page of the initial volume of these *Proceedings* (1962) bore a preface by Scott Simpson, setting out something of the background to the new publication and, indeed, to the new Society itself. This was most appropriate because Scott himself had been one of the foremost to bring together the many individuals who were active in the geology and geomorphology of the South West of England. It began in the mid 1950's and from then until illness prevented his participation in the Society's affairs, he was to devote much of his time to Cornubian geology and to the Ussher Society.

He was born in India and retained a life-long interest in that subcontinent, even though he left it at the age of five. In the 1930's he was a student at Clare College, Cambridge, where he showed himself aware of and concerned about the economic and political turmoil that was rife then in Europe and elsewhere. After taking his B.A. in 1937 he went to Frankfurt in Germany, there to study under Professor Rudolf Richter at the Senckenbergsinstitut. This was undoubtedly one of the more important phases in his life and it moulded his geological interests for the years to come. Intellectually he was well prepared and suited for the training at Frankfurt and the field work in the Rhineland. There he became fluent in German and also devoted to the stratigraphy and palaeontology of the Devonian system. Something of the rigorous discipline that the Richters, Rudolf and Emma, applied to their studies and their fieldwork rubbed off onto their British student. Despite, from all accounts, very bad weather, he resolutely carried out his field work on an old motor cycle and that impressed even the Richters! His doctorate and subsequent work showed the same objective questioning approach and careful assessment of data.

Shortly before the outbreak of war he took up the post of assistant lecturer at Marischal College in Aberdeen. The geology department there was then renowned for its interest in hard-rock geology and Scott had the somewhat daunting task of sustaining the teaching of palaeontology and stratigraphy and had to shoulder other responsibilities as well. He was during these years and for some time afterwards lame: it kept him out of the forces but never prevented him from doggedly persisting with fieldwork. His childhood interest and enthusiasm for fossils was passed on now to students who otherwise would have perhaps heard little of them, and he lectured frequently to the W.E.A. in Aberdeen. It may not be widely known, but he was interested in the history of geology and in Aberdeen, and later, contemplated writing a book on James Hutton.

In 1949 Professor W.F. Whittard invited Scott to a Lectureship in Geology at the University of Bristol and to stimulate research in the Upper Palaeozoic rocks of the west and south west of the country. The opportunity to live so near to the marine Devonian outcrops and to indulge in his chosen field of study was entirely appropriate and immediately put to good use. Within a very short time Scott's interests and work were known to others in this part of the world. In 1956 he received a Garwood Award from the Geological Society of London. He was to make his mark at Bristol until 1959, teaching, supervising graduate research and conducting his own investigations. A Readership was awarded in 1959.

In 1953 Scott Simpson was able to visit both Frankfurt and Würzburg to lecture on Palaeozoic stratigraphy. Then in 1954 a visit to the Ardennes and Eifel areas of West Germany by British geologists interested in Devonian geology was organised, Scott being the essential link-man between the British and their hosts and guides, the Richters and colleagues from Frankfurt. It was a resounding success in all respects.

In 1956 and again in 1958 Scott was a prime instigator of informal conferences held at the University of Exeter for geologists and geomorphologists interested in all aspects of the natural terrain of south-west England. These were well-attended, highly productive meetings. A third followed at Bristol in 1960 and a fourth in Camborne in 1961. At these gatherings the breadth and depth of Scott's knowledge of the topics under discussion was immediately impressive. Abstracts from these meetings were published by the Royal Geological Society of Cornwall and were much sought after.

The conferences established that there was sufficient interest to set up a new regionally concerned geological society. For various reasons the Cornish society was not able to take on the formal organisation of this and in 1961 the Ussher Society was inaugurated. Its first Chairman was Scott Simpson, who by this time was Professor of Geology at the University of Exeter.

Scott's appointment at Exeter was made in 1959; he was to remain there until ill-health forced his early retirement in 1975, During his tenure of the chair the Department: expanded in size, increased in stature and reputation and moved to its present pleasant quarters. University expansion saw the Department well-placed within the community of geology institutions across the country and its researches became recognised for significance and vigour. Most notable too was the arrangement negotiated with the Institute of Geological Sciences for the mapping of the Teignmouth Sheet (New Series 339) by a team of graduate students. This was a pioneer arrangement, so successful as to prompt other university departments to seek the same. The setting-up of the IGS regional office in Exeter was attended by the growth of very cordial, lasting, and productive relationships with the department.

Scott impressed all who knew him as friend, colleague or correspondent as a gentle, warm-hearted scholar. His father was similarly intellectual and it was perhaps natural that Scott should take to science. His interest in geology as a boy had been encouraged by W.D. Lang of the British Museum (Nat. Hist.) and he had a great love of the outdoors. He was modest, not to say self-effacing, and he was immensely thorough in his search for scientific truth or accuracy. Disagreement with others was tempered by kind words but sharpened by a real grasp of the issues involved. Tolerance and personal freedom were closely held principles and in university affairs he functioned by persuasion and personal example. He was anything but an autocrat. He would no doubt hard preferred to be a scholar and teacher only but he did not shirk administrative chores or responsibilities. It was natural that he had many other interests- art and literature, the outdoor world of nature and the garden. He was also devoted to his family and took joy in their activities always. During the last nine years of his life he suffered a slow decline with never a complaint and he retained his interests in history and literature to the end.

The twenty-three published papers show the development of Scott Simpson's interests, beginning with a major work in German on the Devonian of the S.E. Eifel area, published in 1940. His second paper, also a substantial contribution, was concerned with glacial deposits in the Bay of Nigg, Scotland and he subsequently never lost interest in geomorphology, as his papers on south-west England show. He assisted W.F. Whittard as an Editor of the England Wales and Scotland Fascicule 3a of the *Lexique stratigraphique international* and was instrumental in arranging and editing (with J. Robson) the collections of abstracts that are the direct forebear of these Proceedings. Thereafter followed works on structure and Palaeozoic stratigraphy in south-west England - not voluminous, but perceptive and stimulating.

He personally negotiated the agreement with IGS to re-map the Teignmouth Sheet and would undoubtedly have taken delight in the results achieved by Brian Selwood, who took over the project, and by the graduate students who participated. The memoir to accompany this map will contain a posthumous contribution from Scott.

The loss recently sustained by Scott's family is one shared by this Society, and by his many friends. Had he not been overtaken by illness he would undoubtedly have added much to our *Proceedings,* to the life of our Society and to our sciences.

D.L. Dineley

List of Publications by Scott Simpson

1940 Stratigraphie und Tektonik mit einem Beitrag zur Hunsruckschiefer-Frage. (in German), *Abh.senckenb, naturf Ges. 447.* 1-81.

1948 The Glacial Deposits of Tullos and the Bay of Nigg, Aberdeen. Roy. Soc. Edin. 61 pt. 3 (No. 23),687-698, *I pl., 12 text-figs.*

1949 Pleistocene deep weathering in north-east Scotland. *Nature. 164,* 318.

1950 The Tunnelling Stream and the Melt-Water Channel at Muchalls. Kincardineshire. *Trans. Edin. Geol.Soc., ll.* 396-400, 2 figs. (with G.K. Townsend).

1951 A new Eurypterid from the Upper Old Red Sandstone of Portishead. *Annals & Magazine of Natural History, Ser. 12, 4,* 849-861.

1951 Some solved and unsolved problems of the stratigraphy of the Marine Devonian m Great Britain. *Abh. senckenb, naturf. Ges. 485.* 53-66.

1953 The development of The Lyn drainage system and its relation to the origin of the coast between Combe Martin and Porlock. *Proc. Geol. Assoc. 64.* 14-23.

1954 Field Meeting, Whitsun 1953 at Lynton, North Devon, *Proc. Geol, Assoc,. 65,* 178-181.

1955 A re-interpretation of the Drifts of North-east Scotland. *Trans. Edin. Geol. Soc., 16,* 189-199.

1957 On the trace-fossil *Chrondrites. Quart. J. Geol. Soc, Lond., 112.* 475-500, pls. XXI-XXIV.

1959 Devonien. *Lexique Stratigraphique International. I. Fasc. 3a VI.*

1959 Culm stratigraphy and the age of the mare orogenic phase in Devon and Cornwall. *Geol. Mag., 96,*201-208.

1960 *Abstracts of the Proceedings of the Third Conference of Geologists and Geomorphologists working in the South-West of England. Bristol, 1960.* (eds. J. Robson & S. Simpson).

1962 Variscan Orogenic Phases. *In:* Coe, K. (ed.). *Some aspects of the Variscan Fold Belt. Geol. Congr.,* Manchester Univ. Press, 65-73.

1962 The Devonian-Carboniferous boundary and the problem of the British and Ardennes-Rhineland successions from the upper Famennian to the Namurian. *Compte Rendu du Quatrieme Congres pour l'avancement des etudes de stratigraphie et de geologie du Carbonifere, Heerlen, 15-20 septembre 1958,*

Tome 3, 1962, 629-633.

1962 *Chomatichnus,* a new Ichnogenus, and other trace-fossils of Wegber Quarry. *L'pool Manchr. Geol. J., 3,*73-81.

1962 Structures of Devon and Cornwall. *Geol. Mag. 94,* 284-285.

1964 The supposed 690ft marine platform in Devon. *Proc. Ussher Soc, 1,* 89-91.

1964 The Lynton Beds of North Devon. *Proc. Ussher Soc. 4,* 121-122.

1965 Fold terminology. *Geol. Mag. 102,* 179-180.

1965 Time of emplacement of dykes in Bigbury Bay. *Proc. Ussher Soc. 1,* 168-169.

1966 Kink-bands of Bigbury Bay. *Proc. Ussher Soc., 1,* 224-225.

1967 Problems of the geology of the Geological Survey One-inch Sheet Teignmouth (339). *Proc. Ussher Soc., 1,* 272-273.

1967 Devonian of southern Britain. *In: Internat. Symp. Devonian Systems, 1,* 1-14. Alberta Soc. Petrol. Geol. Calgary. (with R. Goldring, M.R. House, E.B. Selwood & R. St.J. Lambert)

1967 Obituary of W.F. Whittard. *Proc. Geol. Assoc. 78,* 383-5.

1969 Obituary of F.H.W. Holwill. *Proc. Geol. Soc. No,* 1651, 226.

1969 Geology. In: Barlow, F. (ed.). *Exeter and its Region.* University of Exeter (on behalf of British Association), 5-26.

1970 The structural geology of Cornwall: some comments. Proc. Geol. Soc. Lond.. No. 1662, 1-3.

1970 Notes on *Zoophycos* and *Spirophyton. In:* Crimes T.P. and Harper J.C. (eds.). *Trace Fossils,* Geol. Journal Liverpool Spec. Issue No 3.

1971 The Variscan structure of north Devon. *Proc. Ussher Soc.* 2, 249-52.

1975 Classification of Trace fossils. *In:* Frey, R.W. (ed.). *The Study of Trace Fossils.* 39-54. Springer, N.Y. in press. Geology of the country around Newton Abbot. *Mem. geol. Surv.* (with others).

(R.J.G. Savage and E.B. Selwood kindly emended the list of publications for me. D.L.D.)

Address of the Guest Speaker
Read at the Annual Conference of the Ussher Society, January 1982

Variscan Sedimentary Basins on the Continent, and relations with south-west England

WOLFGANG FRANKE
WOLFGANG ENGEL

W. Franke and W. Engel 1982. Variscan sedimentary basins on the Continent and relations with south-west England. *Proc. Ussher Soc., 5,* 259-269.

The evolution of the main Variscan basins on the continent is summarized. The crystalline spine of the Variscides (also a zone of divergence) is flanked by the Mediterranean and the Saxothuringian Zones, which are characterized by nappe-tectonics and wild-flysch sedimentation. The more external areas to the north (south-west England, Rheinisches Schiefergebirge, Harz Mts.) have since long been regarded as belonging to one "Rhenohercynian" Zone. Recent research in south-west England and Germany confirms this view. Apparent differences in the development of these regions may have been conditioned by pre-Devonian structures and events. The important features common to both regions relate to Devonian and Carboniferous horizontal tectonism.

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Introduction

The Variscan Belt of Europe has survived only in the form of scattered fragments. Any attempt to reconstruct its internal organization requires evidence from all possible sources. Recent interpretations are mainly based upon metamorphic and structural features. The present paper is chiefly concerned with the main sedimentary basins. Special attention is given to the record of synorogenic (flysch) sedimentation, since flysch basins display characteristics of both the "geosynclinal" and the orogenic stages of mountain belt formation. The Mediterranean and the Saxothuringian basins are briefly surveyed and the Rhenohercynian Zone is treated in greater detail. The purpose of this paper is to (i) review recently acquired facts and also hypotheses pertaining to Variscan geology on the continent, and (ii) to discuss, against this background, connections with south-west England.

General Setting

The outline of the main Carboniferous basins which contain synorogenic clastics (flysch) is shown in Fig. 1. Arrows indicate the principal orogenic polarity, reflected in the directions of clastic discharge, of folding and thrusting, and of the displacement of orogenic fronts. The Variscan Belt displays a clear bilateral symmetry. The zone of divergence lies within a broad central Variscan crystalline zone, which also contains, nuclei of pre-Variscan origin (Bohemian Massif, Armorican Massif, parts of north-west Spain).

Accounts of the pre-Variscan development may be found in Zwart & Dornsiepen (1978) and Cogné & Wright (1980). The Devonian through Carboniferous tectono-sedimentary history is described in Behr, Walliser & Weber (1980), Engel & Franke (in press), and Engel, Franke & Langenstrassen (in press).

To the north of the crystalline spine, sediments and volcanics of early Palaeozoic to Carboniferous age are present in the Saxothuringian and in the Rhenohercynian Zones where orogenic polarity is towards the north. In the Palaeozoic outcrops set around the Mediterranean, the main vergence is to the south. Westwards, the Variscan Zones curve round to form the vast Ibero-Armorican arc. A similar arc may have existed to the east where the Variscan zones meet the Russian Platform, but this is strongly debated (Dvorak, 1973). Directional changes in the structural trend may have been effected by dextral wrench-faulting along the western margin of the platform (Lorenz, 1976).

The large-scale tectonic zonation used in this paper goes back to proposals of Suess (1888), Kossmat (1927) and Lotze (1945). As will be laid out below, it has since been confirmed by petrological, radiometric, structural and sedimentological data. As already stated by Brouwer (1978), the consistency which is now well-established along the strike allows the Variscan orogen to be considered a "belt", which strongly argues against vertical tectonic models such as the one proposed by Krebs & Wachendorf (1973).

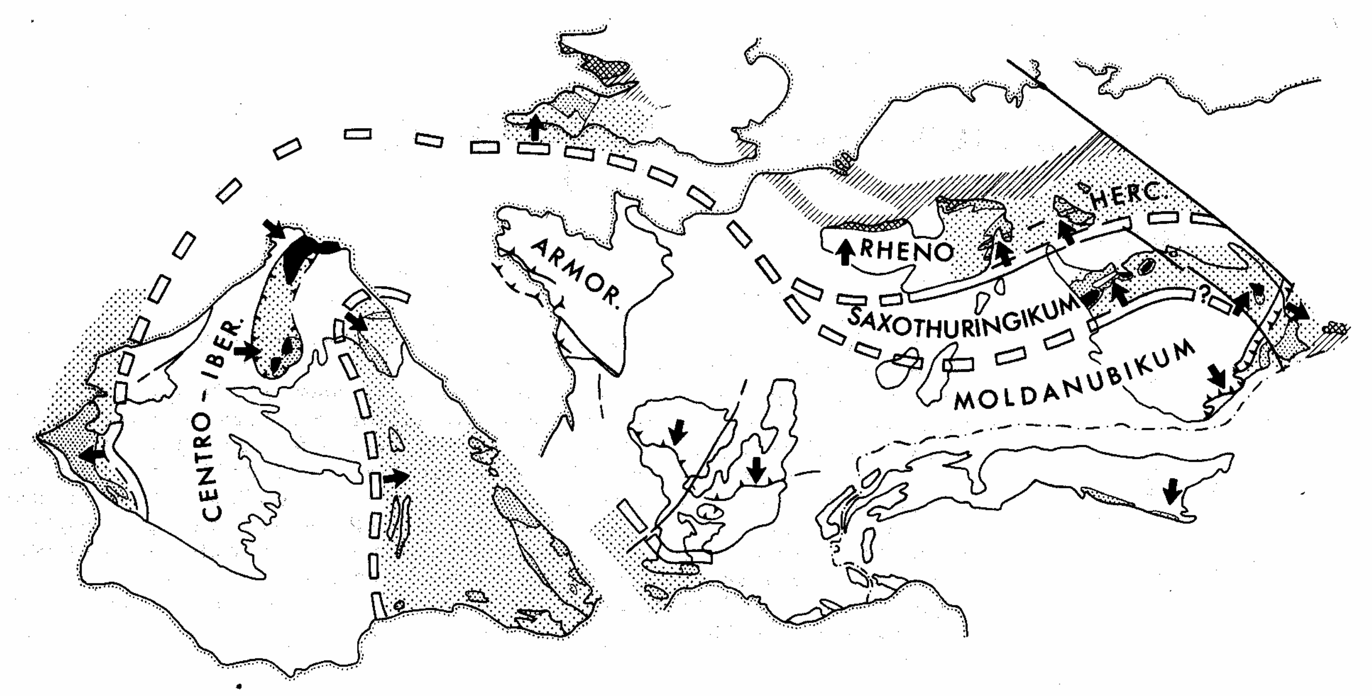

Figure 1
Structural map of the European Variscides, during the time of synorogenic deformation (Devonian and Carboniferous). Devonian and Carboniferous flysch, at outcrop (close stipples), and presumed extent (spaced stipples). U. Carboniferous paralic molasse, at outcrop (cross-hatched), and presumed extent (hatched). Arrows: orogenic polarity, Black patches: tectonic klippen of metamorphic rocks.

As will emerge from the discussion, Kossmat's zoneography is only valid for the present array of structures, which was achieved in the Upper Carboniferous. The structural trends delineated in Fig. 1 increasingly lose their importance, if one goes backward in time from the Devonian.

The Palaeozoic basins of north-western France (Chateaulin, Laval, Ancenis) are not considered here.

These areas represented limited, intra-montane basins, situated within the central-Variscan crystalline zone. They have individual sedimentary records, and do not display any orogenic polarity (Dvorak et al., 1977). The main flysch basins (Rhenohercynian, Saxothuringian, Mediterranean), in contrast, were developed at important thrust zones, which were active throughout most of the Devonian and Carboniferous.

Mediterranean Zone

The area referred to as the "Mediterranean" basin comprises the Palaeozoic outcrops of the Eastern Alps, the Montagne Noire and the Massif of Mouthoumet in southern France, the Pyrenees, the Cantabrian Mts., the Celtiberian Chain, and the Catalonian Coastal Ranges.

Though widely scattered, these areas have a number of important common characteristics:-
(i) The Palaeozoic is mainly composed of neritic sediments, which in part may be described as epicontinental. The Cambro-Ordovician is characterised by thick clastic successions; The Devonian is thin (l000m) and essentially composed of carbonates. Shallow-water carbonates are dominant in the early Devonian, and later give over to nodular limestones with pelagic faunas (cephalopod limestones, or "griotte"; Neumann & Schumann, 1974; Tucker, 1974; Vai, 1980).
(ii) Volcanism is almost entirely restricted to the Ordovician and Silurian, and of bimodal character. Devonian and Carboniferous volcanics are nearly absent from the western Mediterranean. Some Carboniferous activity has been reported from the Alps (see survey of Castellarin & Vai, 1981).
(iii) The ubiquitous Tournaisian to mid-Viséan cherts are succeeded by a conspicuous cephalopod limestone member (e.g., the "Alba Griotte" of the Cantabrian Mts., see compilation in Engel & Franke, in press).
(iv) The Carboniferous flysch (late Viséan to early Westphalian) is characterized by deep-sea fan clastics with frequent disorganized conglomerates and overbank sands, and by displaced blocks of coeval shallow-water carbonates and pre-Carboniferous rocks. These may attain the areal extent of small gravity nappes (10km^2). This association may be referred to as "wildflysch". The flysch clastics are derived from northerly sources (in Celtiberia: from the south-west). The best example of Mediterranean flysch sedimentation is that of the Montagne Noire in southern France (Engel, Feist & Franke, 1978, 1982), which has no Alpine overprint.

(v) There is no subsequent paralic molasse. Late-orogenic shallow-water elastics occur only in intra, montane basins, which are separated from the underlying flysch by angular unconformities.
(vi) Tectonic deformation is polyphase throughout. The main phase involves recumbent folds and nappe-thrusts directed towards the south and (in Celtiberia) towards the north-east (Arthaud, 1970; Julivert 1978; Castellarin & Vai, 1981; Engel & Franke, in press). The displaced blocks set within the flysch were probably derived from the front of nappes driving toward the basin.

Pre-Carboniferous orogenic activity is documented in the more internal, crystalline areas. Important southward thrust and nappe tectonics has been reported from within the French Massif Central (Burg & Matte, 1978). The ultramafic complexes of Cabo Ortegal, Braganca and Moraes are interpreted by some authors as nappes thrust toward the north-east (Bard et al., 1980). These events are inferred to be Devonian A younging of orogeny toward the Mediterranean is well documented in the cross-section Massif *Central/Montagne* Noire/Mouthoumet/ Pyrenees (Engel & Franke, in press).

Palaeozoic sequences containing Carboniferous wild-flysch have also been reported from Tuscany (Cocozza; Lazzarotto & Vai, 1974). However, it seems probable that these should not be put into direct association with the Montagne Noire/Eastern Alps. They are more likely related to the Carboniferous occurrences in Sardinia and Menorca (Bourrouilh et al., 1980) which are not treated here.

Saxothuringian Zone

In the type region, the Saxothuringian Zone is bound to the south by the Moldanubian gneisses of the Bohemian Massif(see Fig. 1, 2), which at least in part, had already suffered Assyntian deformation. During the Devonian and Carboniferous the north-western margin of the basin was formed by the metamorphic rocks of the mid-German Crystalline Rise (see next section). Equivalents of the Saxothuringian are seen in the surroundings of the Sowy Gorie ("Eulen-Gebirge" of the Western Sudeten Mts., western Poland) and in the northern parts of the Black Forest and Vosges.

The most conspicuous element of the Saxothuringian is a series of medium- to high-grade metamorphic inliers, lined up along the "Zentralsächsisches Lineament". These inliers, also known as the metamorphic "Zwischengebirge" of Munchberg, Wildenfels, and Frankenberg, were originally interpreted as tectonic klippen (Suess; I912; Kossmat, 1925; Wurm, 1926), and, later, as diapir-like metamorphic uplifts. Recently, the nappe-concept has been revived, on the basis of new findings in the Münchberg area, by Behr, Engel & Franke (1980, 1982). A further metamorphic inlier, the "Granulitgebirge" (immediately north-west of Frankenberg, not shown in Fig. 2!) indubitably represents a mantled gneiss-dome.

The Münchberg gneisses occur in the core of a broad synform. The metamorphic suite comprises acidic ortho-"augen"-gneisses and clastic meta-sediments ("Liegend-Serie"), and a structurally higher sequence ("Hangend-Serie") of banded hornblende gneisses, amphibolites and eclogites. The high-grade rocks are underlain, at least at the margins of the synform, by bimodal volcanics and sediments in greenschist facies, and these, in turn, overly a lithologically similar sequence of very low metamorphic grade which has produced Ordovician fossils.

According to radiometric data (Gebauer and Grünenfelder, 1978; Söllner, Köhler & Müller-Sohnius, 1981), the higher-grade rocks were formed, from upper Proterozoic and Lower Palaeozoic events, before 380m.y; Since the gneisses are surrounded on all sides by unmetamorphosed Cambrian through Carboniferous sequences, they are best explained as a tectonic klippe. The *Palaeozoic* is well-known, thanks to the thorough studies by members of the geological institute at Wurzburg (see the classical review by Wurm, 1961; or, in English, v. Gartner et al., 1960, and Gandl & Mansourian, 1978 for the Carboniferous). The Palaeozoic surrounding the Munchberg block exhibits a special ,'Bavarian" facies, with bimodal volcanics, sandstone turbidites and shales in the Ordovician, and radiolarian cherts and few pelagic limestones in the Devonian. The normal, "Thuringian" facies surrounds, in turn, the exotic Münchberg Gneiss/Bavarian Facies complex. It contains Ordovician neritic clastics, and in the Devonian, an association of basaltic volcanics, pelagic limestones, ostracod-bearing shales, and (locally) embryonic reefs with corals and stromatoporoids. According to Behr et al. (!980, 1982), the Bavarian facies has been imported, together with the metamorphic rocks, from a root-zone to the south-east of the Fichtelgebirge (at the boundary towards the Moldanubian, see Fig. 2), and represents a bathymetrically deeper part of the basin.

The Bavarian "halo" around the metamorphic block also contains Carboniferous flysch, which closely resembles that of the Mediterranean Zone (proximal deep-sea fan clastics, displaced blocks of Carboniferous shallow-water limestones, sedimentary klippen of pre-Carboniferous Palaeozoic rocks in Bavarian facies, see Behr et al., 1980, 1982). The "Thuringian" Carboniferous, to the north-west of the Bavarian realm, represents outer-fan and basin plain environments. The general array of Carboniferous facies, together with palaeocurrent data, suggest that the Saxothuringian flysch was derived (like the nappes) from south-easterly sources.

Current studies of the tectonic structures in the Palaeozoic (Franke, in prep.) reveal a polyphase deformation. The first phase has produced recumbent, tight to isoclinal folds, vergent towards the north-west, and a set of related thrusts, whose activity outlasted the Y folding. The Münchberg /Bavarian pile of nappes was

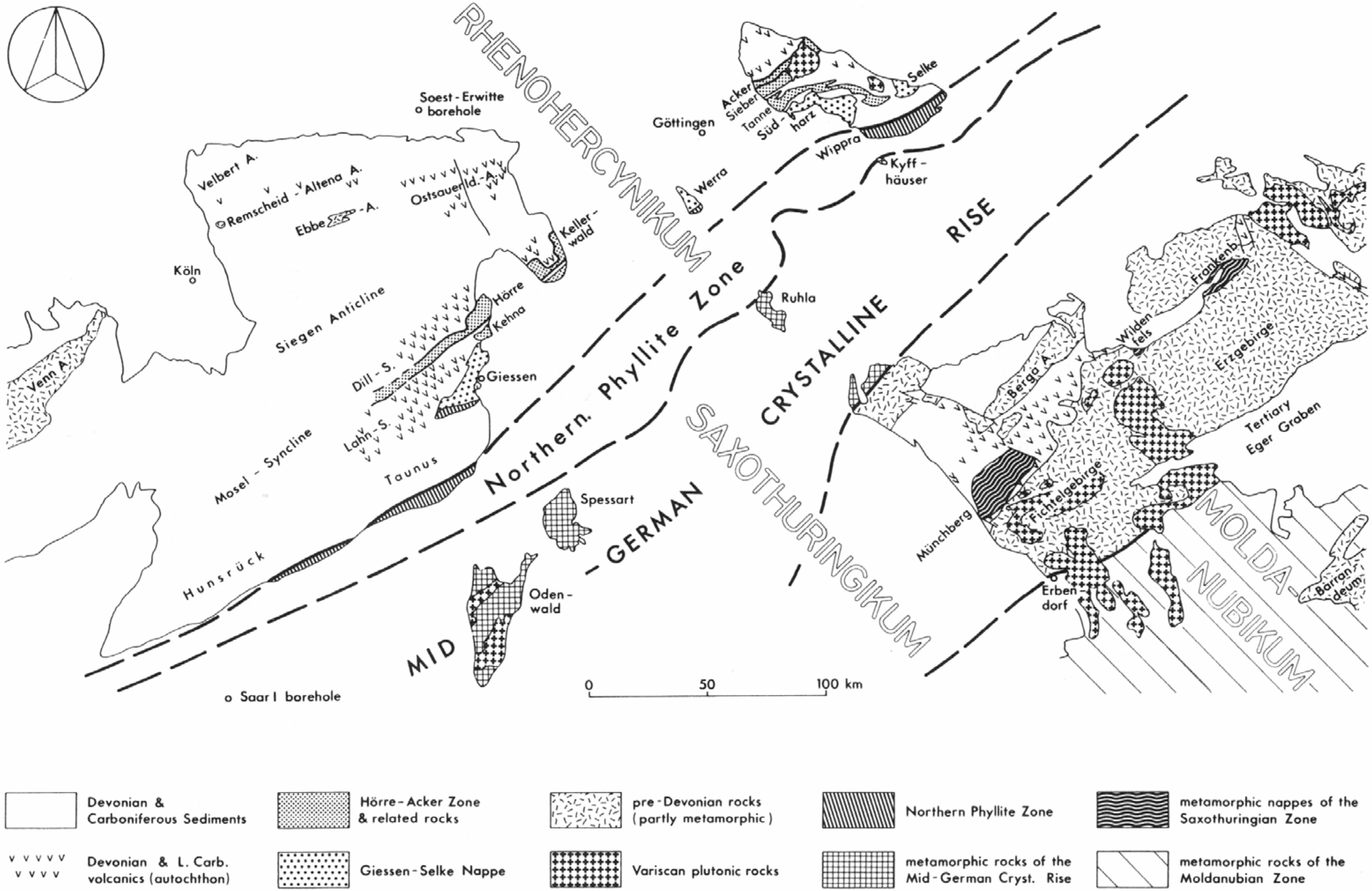

Figure 2
Structural map of the Saxothuringian and Rhenohercynian Zones in Central Europe.

emplaced on the Bavarian Carboniferous, in a late stage of the F1 development. The Bavarian wildflysch, which had originally been deposited in front of the moving nappes, was dragged along at the base of the tectonic pile, intensively sheared, and thrust northwestwards over "Thuringian" (autochthonous) Devonian and Carboniferous sequences. An F2-refolding has produced upright and south-east facing, open folds. A variety of F3 structures mainly occurs in connection with post-tectonic] granites (in the Fichtelgebirge and in a transverse horst-zone west of the Berga Anticline). The updoming of the Fichtelgebirge/Erzgebirge Antiform is essentially a F3 feature, and was enhanced by the rise of the late Carboniferous-Lower Permian plutons (see Richter & Stettner, 1979 for ages and igneous petrology).

Rhenohercynian Zone

The Rhenohercynian Zone can he traced from the Flechtingen Hills over the Harz Mts., the Rheinisches Schiefergebirge, the Ardennes and the Boulonnais into south-west England and southern Ireland. Southwest England and its equivalents on the continent are linked by a number of well-known, fundamental similarities (Stille, 1951; Matthews, 1977a, b; Franke, Eder, Engel & Langenstrassen, 1978):-

(i) The great importance, at an early stage of basin development, of clastic sediments derived from Caledonian uplifts (ORS and marine equivalents, receding northwards through time).

(ii) Growth of Givetian/Frasnian reefs on shoals from which clastic sedimentation had withdrawn.

(iii) Northward encroachment of a pelagic regime (the "bathyal lull" of Goldring, 1962) over the neritic foundation.

(iv) Important volcanism (essentially basaltic), with pronounced peaks in the Givetian/Frasnian and Toumaisian to mid-Viséan.

(v) Invasion of flysch clastics (mainly turbidites), derived from metamorphic terranes to the south, which start early in the Devonian and reach the northern margin of the Rhenohercynian basin during the Namurian.

(vi) Establishment of paralic molasse basins on the northern (external) foreland.

(vii) Dominance of northward directed tectonic vergence.

Matthews (1975, 1977a b, 1978) has pointed out, however, a number of important differences:-

(i) Restrictions of the distribution of ORS facies in south-west England, possible due to trapping of clastics in sinks bounded by east-west trending fractures.

(ii) The different character of the Belgian succession, which intervenes between south-west England and Germany (absence of geosynclinal volcanism, switch-over to a carbonate regime already in the topmost Lower Devonian, possibly also absence of flysch),

(iii) The accommodation of intra-montane Westphalian clastics (Bude Fm.) within a marginal sink adjacent to the rising Cornish batholith.

(iv) More widespread development of flat-lying folds in England.

(v) Importance, in south-west England, of an east-west trending structural grain, superimposed on an earlier, north-east/south-west set of structures.

(vi) Occurrence of south-east facing, younger folds in the Culm Synclinorium of Devon and in the Start area.

(vii) The heterogeneous nature of the set of structures referred to as one "Variscan Front".

Before the common features and differences can be balanced, it is useful to consider some new facts and hypotheses pertaining to the southern part of the Rhenohercynian Zone in Germany. We present these data in following a SE-NW cross-section through the eastern Rheinisches Schiefergebirge (see Fig. 2).

Mid-German Crystalline Rise

The mid-German Crystalline Rise is composed of a variety of metamorphic and plutonic rocks. On the basis of lithological comparison with Saxothuringian sediments, the mid-German Rise is thought to comprise metamorphosed Cambrian to Ordovician clastic and volcanic rocks (Fluck, Maass & v. Raumer, 1980). It would, in this case, originally have been part of the Saxothuringian basin, and was, therefore, included by Kossmat (1927) in his Saxothuringian Zone. Radiometric ages of the events are only known for some ortho-gneisses ("Rotgneise"), which gave Rb/Sr ages of 398 to 419m.y., interpreted as intrusion-ages (Kreuzer et al., 1973; Lippolt et al., 1976). Since cooling ages (Hellmann et al., 1982; Kreuzer & Harre, 1975) give 370m.y. and younger ages, the climax of metamorphism must have been attained between 380 and about 400m.y., i.e. in the early Devonian. As indicated by undeformed Givetian limestone resting on granite in the Saar I borehole (Krebs, 1976), uplift was already well-developed in mid-Devonian time. Eastern parts of the crystalline uplift continued to rise, and produced greywacke turbidites at least from the Eifelian onwards (see review in Engel & Franke, in press). Metamorphism, crustal thickening and uplift are best explained in the horizontal tectonics model of Weber (1978, 1981) and Behr (1978), Weber & Behr (in press).

Northern Phyllite Zone

A "northern Phyllite Zone" is set between the high-grade rocks and the unmetamorphosed sediments of the main Schiefergebirge. In the Harz Mts. (Zone of Wippra), the Phyllite Zone has been shown to comprise Ordovician through Famennian sediments (see Mohr, 1978 for the most recent and comprehensive treatment of the Harz Mts). Metamorphism in the Phyllite Zone ranges between very low and greenschist grade, Unmetamorphosed greywacke turbidites occur near the southern margin of the zone, to the north of Frankfurt.

Hunsruck-Taunus Anticlinorium

The Hunsruck-Taunus Anticlinorium mainly consists of Gedinnian through Emsian clastic sediments. It is uncertain, whether these clastics represent material derived from "Caledonian" sources to the north, or relate instead to the mid-German Crystalline Rise. Most of the folds are upright or vergent toward the south-east, probably due to backward rotation along listric thrust surfaces (Weber, 1978). Middle through Upper Devonian reef- and pelagic limestones are locally preserved in minor synclines. The Stromberg Syncline, at the southern margin of the Hunsruck, also contains some Frasnian and Famennian greywacke turbidites (Meyer, 1970). There are virtually no volcanics.

Lahn Syncline

The Taunus is set off against the Lahn Syncline by a high-angle thrust (the steep frontal portion of a listric overthrust; Weber, 1981). The Lahn area comprises Emsian through Lower Carboniferous rocks in a northward-younging succession. Except for Givetian/ Frasnian reefs, pelagic shales and limestones are dominant from the Eifelian onwards: The Lahn Syncline is characterized by abundant Givetian and Lower Carboniferous volcanics. The tectonic structure is dominated by low-angle thrusts and tight, north-west facing cleavage folds with axial planes dipping gently south-eastwards.

Gießen Greywacke

The volcano-sedimentary sequences of the Lahn Syncline are unconformably overlain, in the south-east, by the Gießen Greywackes, which have produced Frasnian conodonts (see Engel, Franke, Grote & Weber, in press) but possibly range into the Lower Carboniferous. The Frasnian to early Carboniferous sequence of the Lahn Syncline immediately to the west of the Gießen Greywacke is totally devoid of sand-grade clastics. The greywackes are laid into north-west facing, tight recumbent folds. A mylonite zone is developed at the base of the greywacke unit (formerly interpreted as a Viséan transgression). These observations are best explained by a nappe concept (Engel, Franke, Grote & Weber, in press, which rehabilitates proposals of Schwartz, 1925; Dufour, 1925; and, once again, Kossmat, 1927).

The Gießen Nappe has imported, at its base, numerous *slices of exotic rocks.* At the southern margin of the greywacke area, a sheet of "Solmsthaler Phyllite" is reminiscent of the Northern Phyllite Zone. The "phyllites" (or rather phyllonites) are associated with intensely sheared basalts. In a north-south traverse leading from the northern Schiefergebirge through the Dill- into the Lahn Syncline, there is a marked change in the composition of the Devonian and Carboniferous basaltic volcanics, which can be explained by a southward increase in the degree of partial melting of the parental mantle rocks (Wedepohl, Meyer & Muecke, in press), i.e. a tendency toward ocean-ridge basalts. The age of the basalts at the southern margin of the Gießen Nappe is not known, but, in terms of REE contents, they are the clearest expression of the above trend. They are clearly distinguishable from the rest of the Lahn volcanics, which underlines their exotic tectonic position. An equally significant suite of tectonic slices exists at Gießen, at the eastern margin of the Gießen Greywacke (see Fig. 2): the "Palaozoikum der Lindener Mark" (Kegel, 1953). It contains Ordovician quartzites with trilobites, Silurian and Lower Devonian pelagic limestones, and neritic clastics of Emsian age with rich benthonic faunas. There is also one tectonic lens of Lower Carboniferous quartzite, which exactly matches the H6rre/Acker quartzite found farther north (Bischoff & Stoppel, 1957).

Equivalents of the Gießen Greywacke can be seen in the Frasnian to lower Famennian *Werra Greywacke* (a steppingstone between Schiefergebirge and Harz; Wittig, 1968, 1974) and the Famennian *Sudharz and Selke Greywackes* of the Harz Mts. It is generally accepted that the Sudharz-Selke units are nappes (Schwab, 1979). Gießen, Werra, Sudharz, and Selke greywackes can be regarded as parts of one major nappe or nappe system (Engel, Franke, Grote & Weber, in press). The slabs of phyllites at the base of the Gießen and Werra units, and unmetamorphosed greywackes at the southern margin of the Northern Phyllite Zone suggest a root-zone to the south-east, at the northern margin of the mid-German Crystalline Rise. This would imply a minimum distance of transport of 60km. Sheared volcanic rocks underlying the Werra and Sudharz- Selke units still await geochemical investigation.

Kehna-Southern Kellerwald-Sieber-Tanner Greywackes

To the north of the Gießen -Selke system, there is a further series of greywacke units lined up along the strike. The bulk of these greywackes is younger than the Gießen -Selke clastics (Kehna: cdIIIalpha?, Bender, 1978; southern Kellerwald: Frasnian through Lower Carboniferous, Jahnke & Paul, 1968; Sieber and Tanner Greywackes of the Harz: Famennian through Lower Carboniferous, Schuffler, 1978; Solanwar, 1978). At the northern margin of the Kehna and Southern Kellerwald Greywackes, a thrust zone contains slices of radiolarian chert (?Frasnian), Silurian through Upper Devonian pelagic limestones, Emsian clastics ("Erbsloch-Grauwacke", and one Emsian conglomerate (Jahnke, 1971; Bender, Jahnke & Ziegler, 1974). Lithology, faunas, and ages of these rocks closely resemble the Lower Devonian rocks at Gießen. It is possible that the Kehna Greywacke and its eastern equivalents represent outliers of the Gießen -Selke nappe system.

Hörre/Acker Zone

The Hörre -Acker Zone was recognized by H. Schmidt (1931) as the most conspicuous link between the Schiefergebirge and the Harz Mts. It is characterized by Famennian to mid-Viséan greywacke turbidites, Lower Carboniferous quartzites (the farmous Hörre - Kellerwald-Acker (Kamm-) Gommem-Quartzit), and by a general absence of volcanics (Bender, 1978; Bender & Homrighausen, 1979). In addition, there are thrust sheets which contain non-clastic facies (cephalopod limestones or radiolarian cherts). Though it is generally accepted that the Hörre clastics are derived from the mid-German Crystalline Rise, no time-equivalent clastics have been detected to the south (in the Lahn Syncline). The tectonic structure is dominated by low-angle thrust sheets, with minimum displacements known to attain 8km.

The style of deformation, the isolated position of the Hörre clastics, and the presence of Kellerwald-Quartzit at the base of the Gießen -Nappe (see above) could be readily explained, if the Hörre -Acker rocks were part of a nappe (Engel, Franke, Grote & Weber, in press). In the absence of sufficient topographic relief or deep boreholes to expose the deeper structure, this concept remains hypothetical. One has still to consider the model of Meischner (1968, 1971), who envisaged, in the Hörre -Acker Zone, a major mid-geosynclinal rise, subdivided into individual basins (cherts, greywackes) and minor rises (limestones, sandstones, and quartzite).

The array of greywacke units in the Schiefergebirge and Harz clearly exhibits a northward younging, which starts with Devonian clastics in the south-east and eventually leads to the Namurian turbidites at the north-western margin of the Schiefergebirge. This well-known trend is not incompatible with the suggestion of nappes, since a succession Of nappes may have conserved much of the pre-existing palaeogeographic order.

Dill Syncline and north-western Schiefergebirge

The Dill Syncline, to the north of the Hörre (and the Harz to the north of the Acker) has essentially the same range of facies as the Lahn Syncline, but contains, in addition, sandstone turbidites derived from the north-western shelf. The close affinities between the Lahn and Dill Synclines would be readily explained, if the intervening Hörre were a nappe.

To the north of the "Sackpfeife thrust", which forms the north-western limit of the Dill Syncline, one reaches solid (i.e. indubitably autochthonous) ground. The palaeogeographic reconstruction of the northwestern Schiefergebirge (clastic shelf, succeeded by reef carbonates, bathyal lull and, eventually, flysch) is well-established (see the reviews by Meischner, 1971; Behr, Walliser & Weber, 1980; Franke, Eder, Engel & Langenstrassen, 1978; Engel, Franke & Langenstrassen, in press).

Problems concerning the Harz Mts.

Underneath the known and presumed nappes of the Rheinisches Schiefergebirge, there exists a fairly orderly succession of tectonostratigraphic units (laid out above). The interspace between the allochthonous greywacke units in the Harz Mts. is rather chaotic. A matrix of shales and slates contains countless lenses of various sedimentary and volcanic rocks: Devonian basaltic volcanics, Silurian and Devonian radiolarian cherts and shales, cephalopod limestones, neritic limestones and clastics (equivalents of the Erbsloch Grauwacke in the eastern Schiefergebirge), and greywacke turbidites. Most sections display strong tectonic shearing, but there is also evidence of sedimentary mass-flows (referred to as olistostromes). The origin of the chaotic assemblages is debated (tectonic me1ange versus olistostrome, see Reichstein, 1965; Lutke, 1978; Lutzens, 1978; Schwab, 1979; Alberti & Walliser, in press). An oasis of autochthon exists in the Elbingerode area (east of the large Brocken granite, see Fig. 2), probably an equivalent of the autochthonous Lahn Syncline (reef limestones on volcanic mounds).

Relations with south-west England

The Mediterranean and Saxothuringian Zones, which are characterized by extensive nappe tectonics and related wildflysch sedimentation, are the closest approach to alpinotype conditions to be found in the Variscan edifice. Though a discussion of plate-tectonic models is not in the scope of this paper, it may be stated that sutures, if ever they existed in the Variscan Belt, should be sought for in these zones (see also Bard et al., 1980).

The Mediterranean and Saxothuringian are fundamentally different from south-west England and the mid-European Rhenohercynian. From this point of view, the affinities between these northerly, external areas appear still more appealing than ever.

In addition, there are a number of recently acquired facts and hypotheses, which can be added to the list of features common to both south-west England and the Rheinisches Schiefergebirge. In England, the detection of Famennian and early Carboniferous flysch sediments (Isaac, 1981; Whiteley, 1981) has bridged the gap between the Gramscatho and the Crackington greywackes. The record of Devonian to Namurian flysch sedimentation is now fairly complete and matches the German conditions.

It is also noteworthy that the early Carboniferous successions, in England, contain a possible equivalent of the "Hörre/Acker-Quarzit", and that they occur, as in Germany, within subhorizontal thrust sheets of nappes (Isaac, Turner & Stewart, 1982). Recent accounts of tectonic deformation in south-west England have stressed the importance of northward directed tectonic transport (Rattey, 1980; Isaac, Turner & Stewart, in press; Coward & McClay, in press), south-facing structures being related to later and minor deformation phases, although in the central part of the fold-belt southwards directed tectonic transport is considered by some authors (Sanderson, 1979) to be more fundamental.

In south-west England and in Germany, there is now good evidence of "thin-skinned" tectonics (Isaac, Turner and Stewart, 1982; Shackleton, Ries & Coward, 1982; Meissner, Bartelsen & Murawski, 1981, Engel, Franke, Grote & Weber, in press).

Synorogenic sedimentation is characterized, in both areas, by "non-wild" sequences, mainly composed of classical turbidites. It is also possible to recognize, at the base of the Gießen Nappe in Germany, equivalents of the

Ordovician Gorran Quartzite and the Devonian Roseland-type lithologies described by Sadler (1973, 1974). Though the structural situation of the Roseland/ Lizard sediments is still controversial (compare Barnes, 1981 and Sadler, 1973), it is agreed that the position of these rocks involves some distance of transport, and that they are derived from some unknown, southern part of the basin. Such derivation is also likely for the German counterparts.

In both areas, there is now also evidence of basaltic rocks with ocean-ridge affinities, which are in allochthonous positions, mainly near the southern margins of the Variscan outcrops (Floyd, 1981; Wedepohl, Meyer & Muecke, in press). Lastly, metamorphic rocks from the Lizard complex have yielded metamorphic ages, which are very similar to those obtained from the mid-German Crystalline Rise (see Styles & Rundle, 1981; Fitch et al.. 1981, and the summary in Weber & Behr, in press).

No purpose is served, however, by neglecting the points of Matthews (1975, 1977a, b, 1978), which argue against a straightforward, "long-strike" connection between south-west England and Germany. It was Matthews himself (1978) who has shown a possible way out of that controversy, in suggesting that many peculiarities of the Hercynian development in Europe were predisposed by earlier ("Caledonian") events. One salient example is the limitation of thick ORS sequences to the neighbourhood of the British Caledonides. One may add, that Assyntian/ Cadomian after-effects were equally important. This is reflected, e.g. in the alignment of Assyntian/Cadomian "nuclei" along the Variscan zone of structural parting. The special character of the Ardennes (tectonic stability from the late Lower Devonian onwards and absence of volcanism) might also have been conditioned by some early Palaeozoic or late Precambrian consolidation.

In elaborating on Matthew's proposal, it can be stated that pre-Variscan processes have created, in Europe, a complex overlap of different structural grains. When so heterogeneous a segment of crust is subject to Devonian through Carboniferous compression, one is not entitled to expect well-defined linear structures. Variscan geology does not readily lend itself, therefore, to comparisons with plate-margin orogens, the more because it is set in the interspace' between three major plates (North America, Russia, Africa; Walliser, 1977; Brouwer, 1978). Nevertheless, the (roughly) north-south directed compression known as the "Variscan" deformation has demonstrably managed to superimpose, on the earlier segments, a new structural pattern, which is delineated in Kossmat's zonation and justifies the notion of a Variscan "belt".

The interplay of pre-Variscan structures with Variscan events is also reflected in the sedimentary record (Engel, Franke & Langestrassen, in press). Differences and common features in the development of Rhenohercynian-type basins can be reconciled, in that the differences relate to pre-Variscan events, and the common features, such as vulcanicity and orogenic polarity, are brought about by the "new wave".

Though this line of argument may be helpful, the Variscan connections within Europe are still far from being completely understood. We therefore conclude our review with a number of questions, which still have to be answered by English and German workers (if possible, in unison).

(i) What was the original setting of the mid-ocean-ridge type basalts in SW-England and in Germany? "Rhenohercynian" ocean (e.g. Johnson, 1973)? Southward increasing heat-flow in an intra-continental basin (Wedepoht, Meyer & Muecke, in press)? Minor areas of oceanic crust generated at a dextral shear-zone (Badham, 1981)?

(ii) What happens to the Saxothuringian Zone, to the west of the Vosges? In an account of basement rocks underneath the Paris basin produced by Noiret et al. (1972, Fig. 1), it appears that the Saar coal basin (developed within the mid-German Crystalline Rise) extends someway south-westwards of Metz, and is eventually truncated by a north-west trending zone of metamorphic rocks (the "cordilliere parisienne" of Debelmas, 1974, Fig. 1). It is possible that the important thrust structures identifiable at the southern margins of the Rhenohercynian and Saxothuringian Zones merge with one another. Alternatively, the Saxothuringian thrust might represent the more important feature, truncating the Rhenohercynian thrust and extending northwestwards into the British Channel. A Channel-Saxothuringian thrust system might relate to the northern limit of Cadomian/Assyntian deformation.

(iii) The allochthonous clastic facies now recognized within the Hercynian outcrops points to two kinds of rises, which have to be accommodated in a tectonic model: A tectonic land is required as the source for the Devonian through Carboniferous greywacke turbidites. Some more stable tectonic high is needed to produce the relatively thin "clastic rise facies" of Isaac et al., in press, the neritic "Erbsloch-Grauwacke", and the Carboniferous quartzites (recycling from Ordovician clastics?). Do all these "clastic rise" sediments relate to one and the same structure, and what is their relationship with the flysch-producing uplift?

(iv) What were the sources of the early Devonian Meadfoot and Hunsruck/Taunus clastics? In Germany, the Upper Devonian Gießen /Selke greywackes were probably rooted between the mid-German Crystalline Rise and the Taunus, and in England, the Gramscatho turbidites are inserted between the Lizard-Dodman and Meadfoot regions. It appears, that a major Devonian flysch basin was set between metamorphic terranes to the south and a clastic shoal to the north. The neritic clastics would, in this case, probably be north-derived, and most of the flysch basin would have been closed by extensive tectonic shortening. A derivation of the Meadfoot material from a source to the south of the Gramscatho unit would, on the contrary, set relatively narrow limits to the amount of shortening involved.

(v) May all Devonian and Carboniferous greywackes which are now contained in thrust sheets (Tredorn, Petherwin and Heathfield Nappes, Hörre /Acker Zone a.o. in Germany) be referred to one and the same basin to the south, from which they were later expelled? Or is it still possible to envisage a series of individual basins, separated by rises, which were successively filled up with flysch (Meischner, 1968, 1971)?

In spite of these problems, it seems plausible to regard south-west England as the north-westward continuation of structures within Central Europe, modified by the persisting influence of pre-Variscan structures. The tie-lines are major thrust-zones with important northward displacement. In the absence of extensive ophiolite nappes and talc-alkaline volcanics, these horizontal tectonic features may be explained with a model of "subfluence" or "A-subduction" (Behr, 1978; Weber, 1978, 1981; Weber & Behr, in press), which involves subduction of continental lithospheric mantle.

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References

Alberti, H. and Walliser, O.H. Nappes, Flysch and Olistostromes of the Harz Mountains. *In:* Intracontinental Fold Belts: Case Studies in the Variscan Belt of Europe and the Damara Belt in Namibia. Schweizerbart, Stuttgart (in press).

Arthaud, F. 1970. Etude tectonique et microtectonique de deux domaines hercyniens: les nappes de la Montagne Noire (France) et *l'anticlinorium* de l'Iglesiente (Sardaigne). *USTELA, Ser. Geol. Struct., Montpelier, 1, 175p.*

Badham, J.P.N. 1981. A new tale for the Lizard - the last wag. *Tectonic Studies Group Meeting, The Lizard Complex, London (abstract).*

Bard, J.P., Burg, J.P., Matte, Ph. and Ribeiro, A. 1980. La chaine hercynienne d'Europe occidentale en termes de tectonique des plaques. *Int. Geol. Congr. 1980, Paris, Coll. C6 (Geologie de l'Europe),* 233-246.

Barnes, R.P. 1981. Ma1ange stratigraphy in South Cornwall and its relation to the Lizard ophiolite. *Tectonic Studies Group Meeting, The Lizard Complex, London (abstract).*

Behr, H.J. 1978. Subfluenz-Prozesse im Grundgebirgs-Stockwerk Mitteleuropas. Z. Dt. Geol. Ges., 129, 283-318.

Behr, H.-J., Engel, W. and Franke, W. 1980. Munchberger Gneismasse und Bayerischer Wald. *Guidebook, Int. Conference on the Effect of Deformation on Rocks, Gottingen 1980, l00p.*

Behr, H.-J., Engel, W. and Franke, W. 1982. Variscan wildflysch and nappe-tectonics in the Saxothuringian Zone (NE-Bavaria, W-Germany). *Amer. J. Sci.* (in press).

Behr, H.-J., Walliser, O.-H. and Weber, K. 1980. The development of the Rheno-hercynian and Saxo-thuringian zones of the mid-European Variscides. *Int. Geol. Congr. 1980, Paris, Coll. C6 (Geologie der Europe),* 77-89.

Bender, P. 1978. Die Entwicktung der Hörre-Zone im Devon und Unterkarbon. Z. *Dt. Geol. Ges., 129,* 131-140.

Bender, P. and Homrighausen, R. 1979. Die Hörre-Zone, eine Neudefinition auf lithostratigraphischer Grundlage. *Geol. Palaeontol., 13,* 257-260.

Bender, P., Jahnke, H. and Ziegler, W. 1974. Ein Unterdevon-Profil bei Marburg a.d. Lahn. *Notizbl. Hess. L.-Amt Bodenforsch, 102,* 25-45.

Bischoff, G. and Stoppel, D. 1957. Zum Alter des Wollenberg-Kellerwald-Quarzits (Rheinisches Schiefergebirge). *N. Jb. Geol. Palaont. Mh,,* 1957, 14-24.

Bourrouilh, R., Cocozza, M., Demange, M., Durand-Delga, M. Gueirard, S., Guitard, G., Julivert, M., Martinez, F.J., Massa, D., Mirouse, R., and Orsini, J.B. 1980. Essai sur revolution paleogeographique, structurale, et metamorphique du Paleozoique du Sud de la France et de l'Ouest de la Mediterranee. *Int. Geol. Congr. 1980, Paris, Coll. C6 (Geologie de l'Europe),* 159-188.

Brouwer, A. 1978. Die europaischen Variszicien als Teilstucke des nordatlantischen Palaozoikums. *Z. Dt. Geol. Ges., 129,* 557-563.

Burg, J.P. and Matte, P.J. 1978: A cross section through the French Massif Central and the scope of its Variscan geodynamic evolution. Z. *Dt. Geol. Ges., 129,* 429-460,

Castellarin, A, and Vai, G.B, 1981. Importance of Hercynian tectonics within the framework of the Southern Alps. *J. Struct. Geol., 3,* 477-486.

Cocozza, T., Lazzarotto, A. and Vai, G.B. 1974. Flysch e molassa ercinici del Torrente Farma (Toscana). *Boll. Soc. Geol. It., 93,* 115-128.

Coward, M.P. and McClay, K.R. Thrust tectonics of South Devon. *J. Geol. Soc. Lond* (in press).

Cogne, J. and Wright, A.E. 1980. L'orogone cadomien. Vers un essai d'interpretation paleogeodynamique unitaire des phenomenes orogeniques fini-precambriens d'Europe moyenne et occidentale, et leur signification a l'origine de la crofite et du mobilisme varisque puis alpin. *Int. Geol. Congr. 1980, Paris, Coll. C6 (Geologie de l'Europe),* 29-55.

Debelmas, J. 1974. *Geologie de la France, vol. 1, 293p.,* Doin (Paris).

Dufour, J. 1925. Die Grube "Königsberger Gemarkung" und ihre Beziehung zur Stratigraphie und Tektonik der 6stlichen Lahnmulde. *Unpubl Dissertation, Gießen,*

Dvorak, J. 1973. Problems concerning the north eastern closure of the Variscan orogene. *N. Jb. Geol. Palaont. Mh, 4,* 449-454.

Dvorak, J, Mirouse, R., Paproth, E., Pelhate, A., Ramsbottom, W.H.C., and Wagner, R.H. 1977. Relations entre la sedimentation eodevono-carbonifere et la tectonique varisque en Europe centrale et occidentale. *In:* La chaine varisque d'Europe moyenne et occidentale, *Coll. intern. CNRS, Rennes, no. 243, 1977,* 241-273.

Engel, W., Feist, R. and Franke, W. 1978. Synorogenic gravitational transport in the Carboniferous of the Montagne Nolte (S-France) *Z. Dt. Geol. Ges., 129,* 461-472.

Engel, W., Feist, R. and Franke, W. 1982. Le Carbonifere ante-St6phanien de la Montagne Noire: rapports entremise en place des nappes et s6dimentation. *Bull. du B.R.G.M., 2eme serie, section I, no. 4, 1980-1981,* 341-389.

Engel, W. and Franke, W. Flysch sedimentation: its relation to tectonism in the European Variscides. *In: Intracontinental Fold Belts: Case Studies in the variscan Belt of Europe and the Damara Belt in Namibia.* Schweizerbart, Stuttgart (in press).

Engel, W., Franke, W. and Langenstrassen, F. Palaeozoic sedimentation in the northern branch of the mid-European Variscides - essay of an interpretation. *In: Intracontinental Fold Belts: Case Studies in the Variscan Belt of Europe and the Damara Belt in Namibia.* Schweizerbart, Stuttgart (in press).

Engel, W., Franke, W., Grote and Weber, K. Nappe tectonics in the south-eastern part of the Rheinisches Schiefergebirge. *In: Intracontinental Fold Belts: Case Studies in the Variscan Belt of Europe and the Damara Belt in Namibia*. Schweizerbart, Stuttgart (in press).

Fitch, F.J., Forster, S.C., and Miller, J.A. 1981. The 40Ar/39Ar spectrum of a rock from Gerrans Bay, Cornwall. *Tectonic Studies Group Meeting, The Lizard Complex, London (abstract)*

Floyd, P.A. 1981. Geochemical comparison of basaltic rocks in the Lizard ophiolite and the Cornubian troughs. *Tectonic Studies Group Meeting, The Lizard Complex, London (abstract)*

Fluck, P., Maass, R. and yon Raumer, J.F. 1980. The Variscan units east and west of the Rhine graben. *Int. Geol. Congr. 1980, Paris, Coll. C6 (Geologie de l'Europe),* 112-131.

Franke, W, Eder, W., Engel, W. and Langenstrassen, F. 1978. Main aspects of geosynclinal sedimentation in the Rheno-hercynian Zone. *Z. Dt. Geol. Ges., 129,* 201-216.

Gaertner, H.R. von, Horstig G. yon, Stettner, G. and Wurm, A., with parts of Gandl, J., Greiling, L., Ludwig, V., Raschka, H. and Sdzuy, K. 1968. *Guide to excursion C34, Int. Geol. Congr., XXIII session, Prague 1968, 160p.*

Gandl, J. and Mansourian, E. 1978. Neue Daten zur Entwicklung des Unter-Karbons ina Frankenwald (NE-Bayern). *Z. Dt. Geol. Ges., 129,* 99-108.

Gebauer, D. and Grunenfelder, M. 1978. U-Pb zircon and Rb-Sr mineral dating of eclogites and their country rocks. Example: Munchberg Gneiss Massif, Northeast Bavaria. *Earth Planet. Sci. Lett., 42, 35-44.*

Goldring, R. 1962. The Bathyal Lull: Upper Devonian and Lower Carboniferous sedimentation in the Variscan Geo-syncline. *In:* Coe, K. (ed): Some Aspects of the Variscan Fold Belt. Manchester, Univ. Press, 75-91.

Hellmann, K.N, Lippolt, H.J. and Todt, W. 1982. Interpretation der Kalium-Argnn-Alter eines Odenwailder Granodiorit-porphyritganges und seiner Nebengesteine. *Aufschluss, 33,* 155-165.

Isaac, K.P. 1981. The Hercynian geology of Lydford Gorge, north-west Dartmoor, and its regional significance. Proc. *Ussher Soc., 5,* 147-152.

Isaac, K.P., Turner, P.J. and Stewart, I.J. The evolution of the Hercynides of central south-west England. *J. Geol. Soc. Lond. 139,* 521-531.

Jahnke, H. 1971. fauna and Alter der Erbslochgrauwacke (Brachiopoden and Trilobiten, Unter-Devon, Rheinisches Schiefergebirge und Harz). *G6ttinger Arb. Geol. Palaont., 9, 105p.*

Jahnke, H. and Paul, J. 1968. Das Alter der Grauwacken im suidlichen Kellerwald (Oberdevon und Unterkarbon, Rheinisches Schiefergebirge). *Notizbl. hess. L.-Amt Bodenforsch, 96,* 68-84.

Johnson, G.A.L. 1973. Closing of the Carboniferous sea in western Europe. *In:* Tarling, D.H. and Runcorn, S.K. (eds.): Implications of Continental Drift to the Earth Sciences, 2, 845-850, Academic Press, London.

Julivert, M. 1978. Hercynian orogeny and Carboniferous palaeogeography in Northwestern Spain: a model of deforma-tion/sedimentation relationships. *Z. Dt. Geol. Ges., 129,* 565-592.

Kegel, W. 1953. Das Palaozoikum der Lindener Mark bei Giessen. *Abh hess. L-Amt Bodenforsch., 7, 55p.*

Kossmat, F. 1925. Erscheinungen und Probleme des Uberschiebungsbaus im varistichen Gebirge Sachsens und der Sudetenlander. *Centralbl. Min. Geol. Paldont., B., 1925,* 348-359.

Kossmat, F. 1927. Gliederung des varistischen Gebirgsbaues. *Abh. Sdchs. Geol. L.-Amt, 1, 39p.*

Kreuzer, H. and Harre, W. 1975. K/Ar-Altersbestimmungen an Hornblenden und Biotiten des kristallinen Odenwaldes. *Aufschluss, Sonderband 27 (Odenwald), 71-77.*

Kreuzer, H., Lenz, H., Harre, W., Matthes, S., Okrusch, M. and Richter, P. 1973. Zur Altersstellung der Rotgneise im Spessart, Rb/Sr-Gesamtgesteins-Datiernngen. *Geol. Jb., A,9,* 69-88.

Krebs, W. 1976. Zur geotektonischen Position der Bohrung Saar *1. Geol. Jb. A,27,* 489-498.

Krebs, W. and Wachendorf, H. 1973. Proterozoic-Palaeozoic Geosynclinat and Orogenic Evolution of Central Europe. *Geol. Soc. Am. Bull., 84,* 2611-2630.

Lippolt, H.J., Barany, J. & Raczek, J. 1976. Rb/Sr chronology of orthogneisses in the eastern Odenwald and southern Spessart (Germany). *ECOG IV, Amsterdam (abstract).*

Lorenz, V. 1976. Formation of Hercynian subplates, possible causes and consequences. *Nature, 262,* 374-377.

Lotze, F. 1945. Zur Gliederung der Varisziden der Iberischen Meseta. *Geotekt. Forsch., H. 6,* 78-92.

Lutzens, H. 1978. Zur tektogenetischen Entwicklung und geotektonischen Gliederung des Harzvaristikums unter besonderer Berucksichtigung der Olisthostrom- und Gleitdeckenbildung. *Hall. Jb. f. Geowiss, Leipzig, 3 (1978),* 81-94.

Lutke, F. 1978. Grundzuge der faziellen und palaogeographischen Entwicklung im sudlichen Unter- und Mittelharz. *Senckenbergiana Lethaea, 58 (6),* 473-513.

Matthews, S.C. 1975. Exmoor Thrust? Variscan Front? *Proc. Ussher Soc., 3,* 82-94.

Matthews, S.C. 1977a. The Variscan foldbelt in southwest England. *N. Jb. Geol. Paldont. Abh, 154,* 94-127.

Matthews, S.C. 1977b. Carboniferous successions in Germany and in Southwest England. *Proc. Ussher Soc., 4,* 67-74.

Matthews, S.C. 1978. Caledonian connections of Variscan tectonism. Z. *Dt. Geol. Ges., 129,* 423428.

Meischner, D. 1968. Stratigraphische Gliederung des Kellwaldes *Notizbl. hess. L. -Amt Bodenforsch, 96,* 18-30.

Meischner, D. 1971. Clastic sedimentation in the Variscan Geosyncline East of the River Rhine. *In:* G. Miller (ed.) Sedimentology of parts of Central Europe. *Guidebook VIII. Int. Sediment. Congr. 1971, Heidelberg,* 9-43.

Meissner, R., Bartelsen, H. and Murawski, H. 1981. Thin-skinned tectonics in the northern part of the Rhenish Massif; reflection profiling of the Hohes Venn/Aachen area. *Nature, 290,* 399-401.

Meyer, D.E. 1970. Stratigraphie und Fazies des Palozoikums im Guldenbachtal/SE-Hunsruck am Sudrand des Rheinischen Schiefergebirges. *Dissertation, 307p., Bonn.*

Mohr, K. 1978. *Geologie und Minerallagerstiitten des Harzes.* 387p., E. Schweizerbart, Stuttgart.

Neumann, N. and Schumann, D. 1974. Zur Fossilerhaltung, besonders der Goniatiten, in roten Knollenkalken vom "Ammonitico Rosso"-Typ. *N. Jb. Geol. Paldont. Mh., 5, 294-314.*

Noiret, G., Montigny, R. and Allegre, C.J. 1972. Rb^{87}/Sr^{86} systematics in Bassin de Paris basement complex rocks. *Geol. Soc. Am. Bull., 83,* 3003-3006.

Rattey, R.P. 1980. Deformation in south-west Cornwall. *Proc. Ussher Soc., 5,* 39-43.

Reichstein, M. 1965. Motive und Probleme erneuter Deckenbauvorstellungen fur den Harz. *Geologie, 14,* 1039-1076.

Richter, P. and Stettner, G. 1979. Geochemische und petrographische Untersuchungen der Fichtelgebirgsgranite.*Geologica Bavarica, 78, 144p.*

Sadler, P. 1973. An interpretation of new stratigraphic evidence from South Cornwall. *Proc. Ussher Soc.,* 2, 535-550.

Sadler, P. 1974. Trilobites from the Gorran Quartzites, Ordovician of south Cornwall. *Palaeontology, 17,* 71-93.

Sanderson, D.J. 1979. The transition from upright to recumbent folding in the Variscan foldbelt of S.W. England; a model based on the kinematics of simple shear. *J. Struct. Geol., 1,* 171-180.

Schmidt, H. 1931. Die urspringlichen Zusammenhange zwischen Harz und Rheinischem Schiefergebirge. *DieNaturwissenschaften, 19,* 911-916.

Schuffler, S. 1978. Geologische Untersuchungen im westlichen Tanner Hauptzug nordstlich von Bad Lauterberg (Harz).*Dissertation, 136p, Erlangen.*

Schwab, M. 1979. Zum Deckenbau in den Varisziden (Harz - Rheniden - Sudwestural). *Z. Geol. Wiss., Berlin, 7 (1979) 9,*1131-1155.

Schwarz, H.J. 1925. Geologische Untersuchungen in der Umgebung von Rodheim a.d. Bieber und Krofdorf (westlich von Gießen) mit besonderer Berficksichtigung der Gruben-aufschlfisse. *Ber. Oberhess. Ges. Natur-u. Heilkunde, N.F., Natuwiss. Abt., 10,* 1-68.

Shackleton, R.M., Ries, A.C. and Coward, M.P. An interpretation of the Variscan structures in SW England. *J. Geol.Soc. London. 139,* 535-541.

So11ner, F., Köhler, H. and Muller-Sohnius, D. 1981. Rb/Sr-Altersbestimmungen an Gesteinen der Munchberger Gneismasse (MM), NE-Bayern - Teil 1, Gesamgesteinsdatierungen. *N. Jb. Miner. Abh., 141,* 90-112.

Solanwar, R. 1978. Zur Geologie des Lonauer Sattels und der angrenzenden Gebiete des Acker-Bruchberg-Zuges und der Sieber-Mulde (Harz). *- Dissertation, 213p., Erlangen.*

Stille, H. 1951. Das mitteleuropuische variszische Grundgebirge im Bilde des gesamteuropischen. *Beih. Geol. Jb.,* 2. 138p.

Styles, M.T. and Rundle, C.C. 1981. A whole rock Rb/Sr isochron for the Kennack Gneiss. *Tectonic Studies Group Meeting, The Lizard Complex. London (abstract).*

Suess, E. 1888. *Das Antlitz der Erde. vol II, 703 p.,* Tempsky (Wien).

Suess F.E. 1912. Vorlaufige Mitteilungen fiber die Munchberger Deckscholle. Sitzungsber. d.k. Akad.d. Wiss.,math.-nat. Kl.,Bd. 121, Abt. 2a, H.X. 253.

Tucker, M.E. 1974. Sedimentology of Palaeozoic pelagic limestones: the Devonian Griotte (Southern France) and Cephalopodenkalk (Germany). *Spec Publ. Int. Ass. Sed., 1,*71-92.

Vai, G.B. 1980. Sedimentary environment of Devonian pelagic limestones in the Southern Alps. *Lethaia, 13,* 79-91.

Walliser, O.H. 1977. Probleme der geotektonischen Einordnung der Varisziden. *Z. Angew. Geol., Berlin, 23,* 459-463.

Weber, K. 1978. Das Bewegungsbild im Rhenohercynikum Abbild einer varistischen Subfluenz. *Z. Dt. Geol. Ges., 129,249-281*.

Weber, K. 1981. The structural development of the Rheinische Schiefergebirge. *In:* Zwart, H.J. and Dornsiepen, U.F. (eds). The Variscan Orogen in Europe. *Geol. Mijnbouw, 60,* 149-159.

Weber, K and Behr, H.-J. A geodynamic interpretation of the Variscides. *In: lntracontinental Fold Belts: Case Studies in the Variscan Belt of Europe and the Damara Belt in Namibia.* Schweizerbart, Stuttgart (in press).

Wedepohl, K.H;, Meyer, K. and Muecke, G.K. Chemical composition and genetic relations of meta-volcanic rocks from the Rheuohercynian Zone. *In: Intracontinental Fold Belts.' Case Studies in the Variscan Belt of Europe and the Damara Belt in Namibia.* Schweizerbart, Stuttgart (in press).

Wittig, R. 1968. Stratigraphie und Tektonik des gefalteten Palaozoikums im Unterwerra-Sattel. *Notizbl. Hess. L. -Amt Bodenforsch., 96,* 31.67.

Wittig, R. 1974. Tiefoberdevonische Grauwacken unter der Hessischen Senke. *Notizbl. Hess. L. -Amt Bodenforsch., 102,* 46-57.

Whiteley, M.J. 1981. The faunas of the Viverdon Down area, south-east Cornwall. *Proc. Ussher Soc., 5,* 186-193.

Wurm, A. 1926. Uber den Bauplan des Variskischen Gebirges am Westrand der Buhmischen Masse. *Geol. Rdsch., 17,* 241-257.

Wurm, A. 1961. *Geologie yon Bayern. 2 Auflage, 555p.,* Borntraeger (Berlin).

Zwart, H.J. and Dornsiepen, U.F. 1978. The tectonic framework of Central and Western Europe. *Geol. Mijnbouw, 57,* 627-654.

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The anatomy of a thrust: a study of the Greystone Thrust Complex, east Cornwall.

P.J. TURNER*

P.J. Turner 1982. The anatomy of a thrust: a study of the Greystone Thrust Complex. east Cornwall. *Proc. Ussher Soc., 5,* 270-278.

The development of Greystone Quarry over the last five years has permitted detailed observations on the three dimensional structure of the quarry to be recorded. Direct observation within the quarry has been supplemented by 88 boreholes. Five principal thrust surfaces have been recognized, the highest of which, the Greystone Thrust, marks the base of the Petherwin Nappe. This thrust carries Upper Devonian slates over Lower Carboniferous siltstones and slates, mostly altered to chert and intruded by Viséan dolerite sills. The thrust surfaces exposed in the quarry are highly undulatory and cross cutting relationships indicate at least two principal phases of thrusting. The first (DI) is represented by thrusts in the Lower Carboniferous rocks which were displaced by structures associated with the (D2) northward overthrusting of the Petherwin Nappe. The lithologies of the Lower Carboniferous sequences exerted a marked control over the geometry of the overthrust Sheet. In particular, competent dolerites facilitated ramping of thrusts both parallel and perpendicular to movement directions. The thinning and complex deformation in the intercalated sediments reflects highly variable strain through the sequence.

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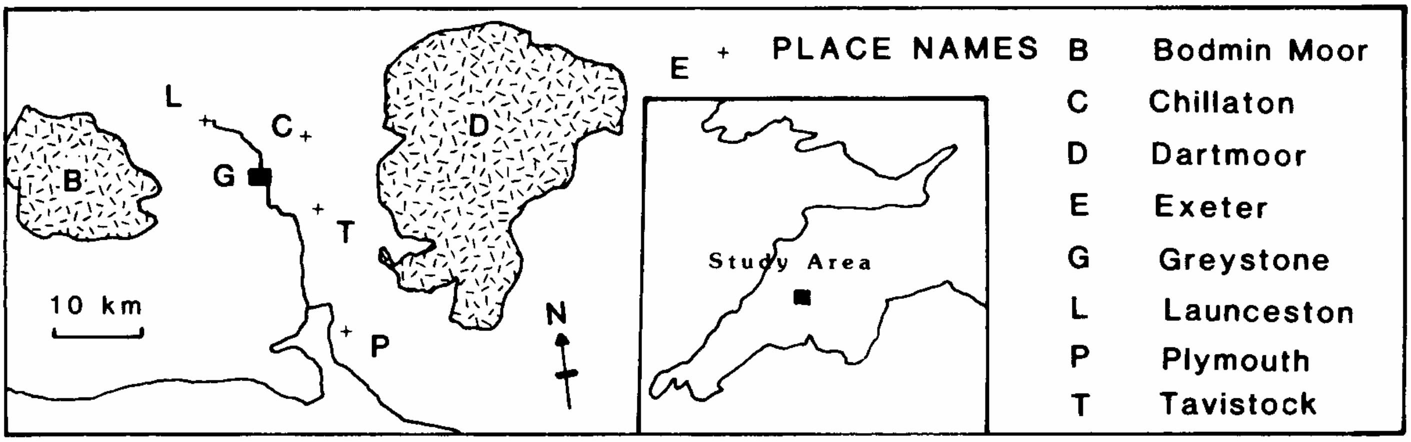
Introduction

During the past five years the author has recorded in detail the development of the English China Clay Company's Greystone Quarry (365806) on the west bank of the River Tamar, Cornwall (Figs. 1 and 2). The geology of the area is dominated by thrust tectonics and the workings have exposed a thrust complex over a 0.4 x 0.5km area and to a depth of 55m. Eighty-eight boreholes, some exceeding a depth of 1 l0m, have supplemented surface exposure and a detailed, three dimensional analysis of the nature of the geology has been possible. A simplified version of the geology of the area surrounding the quarry is given in Fig. 7. The detailed map of the quarry (Fig. 2) illustrates the principal thrust surfaces; contours have been omitted for clarity, but the topography can be simply outlined. The ground rises abruptly from the flood plain of the River Tamar, at some 40m above sea level, to an undulating surface at 100m beyond the quarry workings (see Fig. 8). The quarry is cut into the valley side and exposes successively higher tectonic levels.

Five principal thrust surfaces have been recognised in the Quarry, the most striking of which is the highest (T 1), the Greystone Thrust (Isaac, Turner and Stewart, 1982). This introduced Upper Devonian rise deposits over Lower Carboniferous rise-slope and basinal facies in D2a *(sensu* Isaac and others, 1982) and was the major overthrusting episode of the regional tectonic history. At Greystone Quarry this thrust transported green Upper Devonian slates over a Lower Carboniferous sequence intruded by dolerites. The latter were injected into a series of black siltstones and slates with mudstone layers generally less than 15cm thick, which in the quarry have been mostly altered to form cherts. Sections across the quarry (Figs. 5 and 6) show that the thrust planes are highly undulatory. These sections do not show the topography at the time of measurement since they include data recorded as the quarry was developed. All the lines in the sections were drawn from direct observation and no interpretation has been added; lines have been discontinued where information is not available.

The earliest structures recorded in the quarry are bedding parallel compaction fabrics and crenulation cleavage developed prior to the emplacement of a series of late Visean (Chandler and Isaac, 1982; Isaac and others, 1982; Turner, 1982) sills up to 40m thick. The early fabrics are best preserved in xenoliths (Isaac and others, 1982) seen in fingers *(sensu* Pollard and others, 1975) pods and apophyses of the intrusions. At some intrusive contacts the sediments are "welded" to the igneous bodies through narrow zones of partly recrystallized chert, which also preserve the early fabrics. Beyond such contacts small scale folds, faults and crenulation cleavage foliations and locally developed kink bands reflect complex variation in strain through the sequence prior to the initiation of brittle thrusting (see Table 1). This change in deformation style, which was to develop into the dominant tectonic feature of the area, is manifest as brittle and brittle-ductile shear zones *(sensu* Ramsay, 1980) cutting both intrusions and sediments and by crenulation cleavages developed below thrusts. Within the strain zones crenulation cleavage, microfaults and veins indicate several stages of movement.

Figure 1. Location map of study area



The geometry of the principal thrusts

T5

The surface is flat lying to the south of the quarry and ramps steeply in the central part of the present quarry (Fig. 4). Where it climbed northwards, however, it also developed lateral ramps (Fig. 5). The displacement of the dolerites by less competent material suggests that they were already discontinuous, possibly thrust bounded, prior to the development of TS. Overall the thrust surface dips approximately 20° to the west (Figs. 5 and 6) and is undulose on a metre scale. To the west of the quarry it is truncated by the Greystone Thrust and to the east is bounded by cognate high angle structures. The latter (Fig. 5) are complex DI structures, clearly developed in the south east of the quarry as west dipping listric normal faults. These faults have been recently exposed at depth and pass into shallow to 60° west dipping structures with N/S slickensided surfaces. Small scale folds show both parallel and oblique movement phases across these surfaces with northward transport sense. To the north east of the quarry a high angle NW-SE fault, with normal displacement, downthrows all the thrusts to the east and is a D2 structure related to the Tamar Fault Zone (Turner, 1982). In Fig. 4 T5 is illustrated as a single surface. In detail the thrust zone is immensely complex and consists of a steep (60°-70°) south dipping component with a (10°-20°) shallower imbricate zone developed beneath. The base of the imbricate zone where chert abuts against the dolerite is used to delimit T5 on the larger scale sections. From a conceptual point of view these structures are accreted horses in the footwall and are therefore below the principal thrust for structural considerations.

Table 1. Deformation chronology in Greystone Quarry and its relationship to the regional deformation history established by Isaac and others (1982).

Regional Defor-mation	Greystone Quarry	
D1	d1	Compaction, pressure solution cleavage (S1) and layer parallel quartz veining.
	d2	Folding and crenulation cleavage (S2).
	d3	Intrusion of igneous bodies as fingers and sheets with fluidized and welded contacts, accompanied by autobrecciation and local development of kink bands. Early thrusting.
	d4	Recumbent folding, monoclinal flexures, axial planar slip generating restricted S3. Boudinage. Quartz veining post dates local brecciation. High angle faulting.
early D2 (D2a)	d5	Greystone Thrust and associated shear zones. Styolites, second crenulation cleavage in cherts. First cleavage in dolerites (S4). Brecciation and sub-vertical quartz veins with renewed movement on lower thrusts. (Crenulation cleavage and kink bands above the Greystone Thrust).
late D2	d6	Microfaulting and crenulation cleavage in D2 shear zones and below thrusts (S5). Styolites and quartz veining outlast renewed movement along existing thrusts.

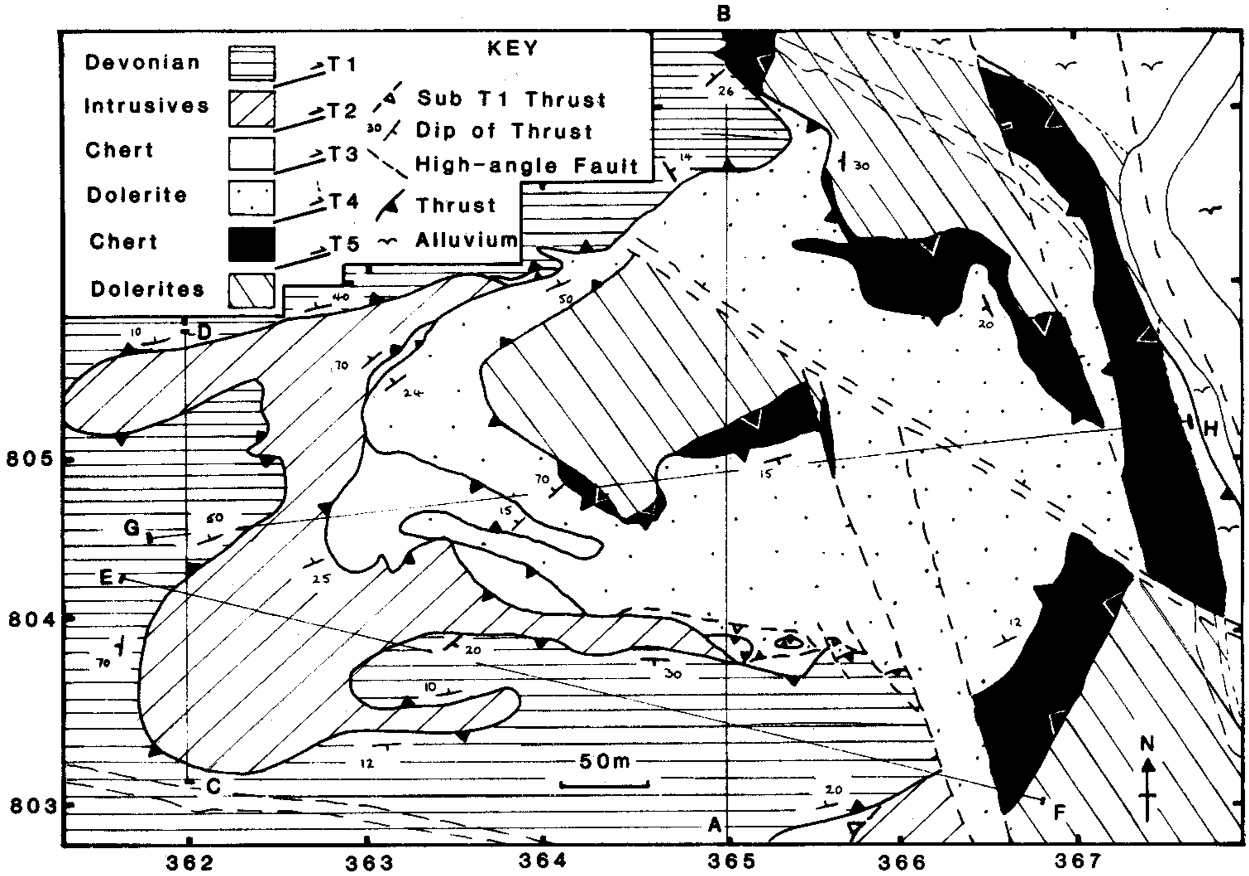


Figure 2. Simplified map of the geology of Greystone Quarry. (Section lines for figures 4 and 5)

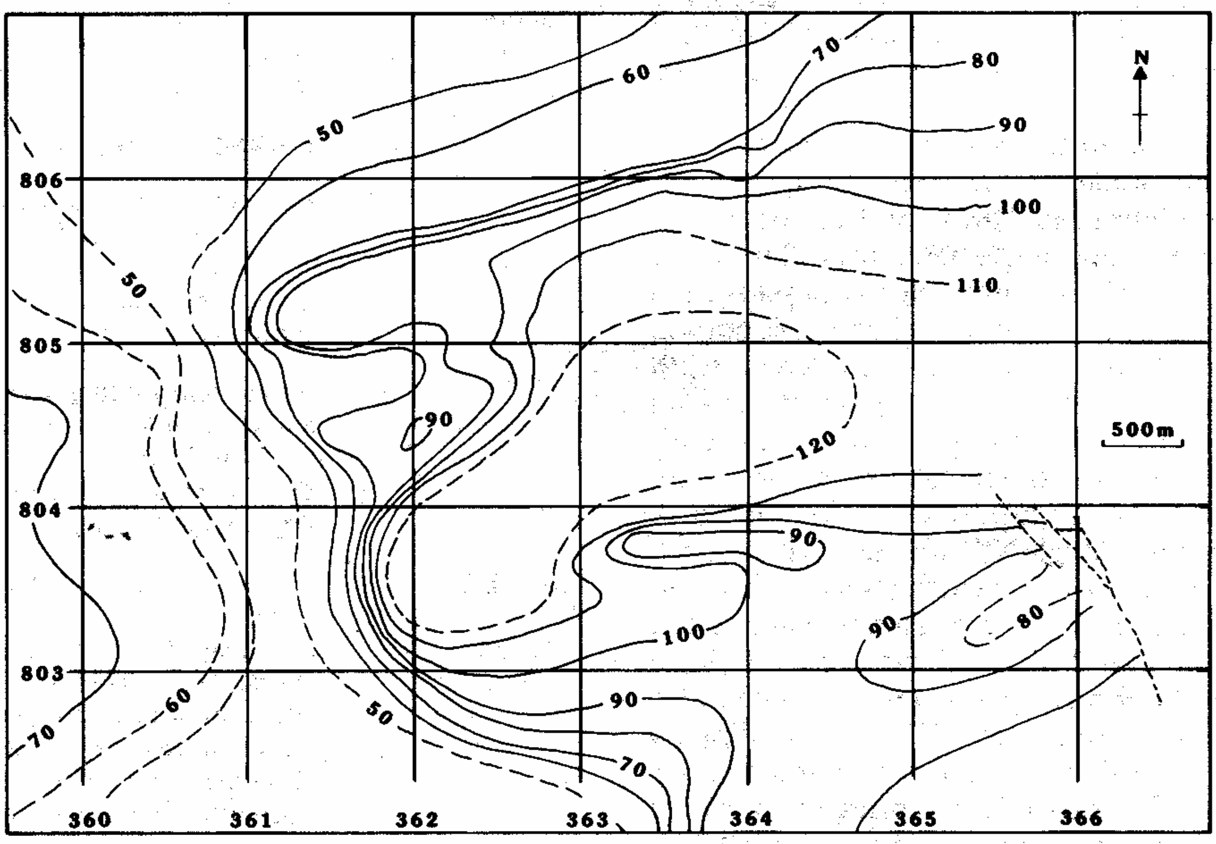


Figure 3. Contour map of the T1 thrust surface (Greystone Thrust). Contour heights are in meters (above O.D.) Broken lines indicate that contours have been derived by extrapolation.

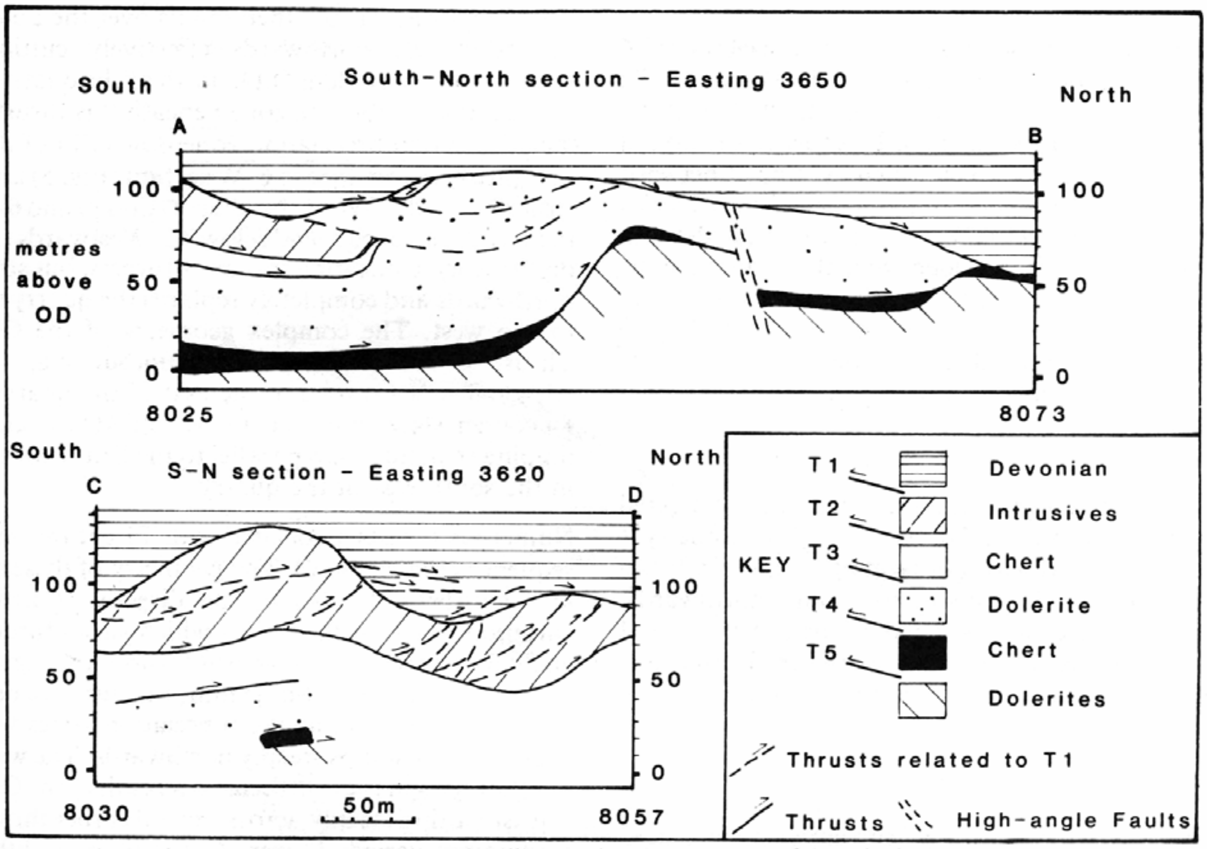


Figure 4. Cross sections illustrating the geometry of the principal thrust surfaces parallel to the transport direction. (Horizontal as vertical scale)

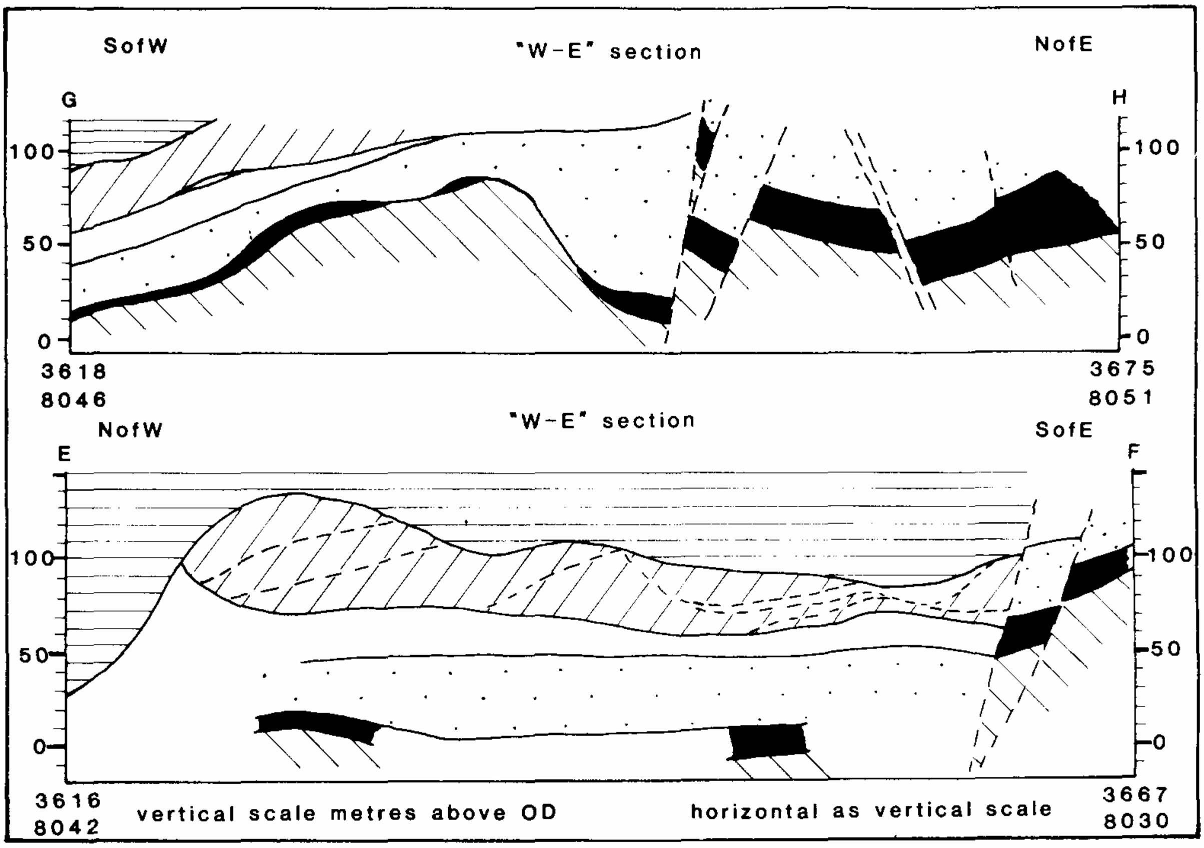


Figure 5. Cross sections illustrating the geology of the principal thrust surfaces perpendicular to the transport direction. (Key as Fig. 4).

T4
It is evident from Figs. 4, 5 and 6 that the geometry of T4 is closely associated with that of T5. Much of the deformation produced by overthrusting thick dolerite on T4 is in the underlying sediments. This thrust is regarded as the roof thrust to a duplex which developed between T4 and T5. Second and third order faulting below T4 was described by Turner (1982). East of the west dipping listric faults (Fig. 5) it is evident that the thrusts can be recognised as discrete structures separated by a thicker chert dominated sequence. South of the quarry (Fig. 8) the geometries of the two thrusts are dissimilar. For these reasons the two surfaces are considered as distinct structures.

T3
This thrust and the higher structures, have been dissected by the younger Greystone Thrust and its D 1 geometry is only preserved at surface in the west of the quarry. From borehole data it is known to ramp northwards, immediately south of the back wall of the quarry (Figs. 4 and 8). Westwards, as in the underlying thrusts, this feature diminishes and the surface dips gently (200-30°) to the west in the central part of the quarry (Figs. 5 and 6). To the south the thrust is flat lying (Figs. 5 and 8).

T2
This surface is poorly exposed currently, having been largely excavated in the south and west of the quarry. To the east it was truncated by the Greystone Thrust and the nature of the surface is best examined in boreholes. In the west of the quarry (Fig. 4) the surface closely parallels T 1 and has been largely modified during D2. South of the quarry the thrust shows a restricted ramping (Fig. 4) and from the centre of the quarry has been traced dipping westwards like the other DI thrusts (Fig. 5).

TI (Greystone Thrust)
The Greystone Thrust (T1) is distinguishable as a discrete interface where the Upper Devonian overlies the Lower Carboniferous lithologies. It displaces, and therefore post-dates, at least in part, the lower thrusts and also truncates high-angle strike slip faults. The penetrative (D1) slaty cleavage of the Upper Devonian slates is crenulated and offset by D2 structures and pre-dates thrusting.

The geometry of this base1 thrust to the Petherwin Nappe (*sensu* Isaac and others, 1982) can be directly related to the form of the underlying Greystone Nappe. South of the quarry (Fig. 8) the thrust ramps northwards over a thick sequence of intrusives between T2 and T3. Rather than climbing up sequence in a classic "staircase" form, the thrust dips northwards and fills a depression in the underlying nappe. During this process cherts from below T2 and dolerite below T3 were transported in the imbricate zone and accreted onto the footwall (Fig. 5) now exposed in the back face of the quarry.

The Greystone Thrust then ramps over the dolerite and dips shallowly northwards effectively cutting down sequence to below 30m O.D. north of the quarry (Fig. 4). The complex imbricate zone beneath this thrust (Fig. 4) includes a 10m brecciation zone down dip of the ramp. The thrust is undulose in E°W section (Fig. 5) and ramps strikingly to the SW of the quarry (Figs. 5 and 6) over the mixed intrusive sequence below T2. Westwards the thrust dips steeply, truncating the lower thrusts, but still moved northwards and completely replaces the quarry sequence to the west. The complex geometry of the Greystone Thrust is summarized on a contour map (Fig. 3). Although not exposed in the east of the quarry, Upper Devonian slates are seen to be introduced along west dipping structures sub parallel to the listric normal faults in the south east of the quarry.

Numerous thrusts associated with T1 cut the underlying sequence (Fig. 4 and 6). The geometry of these synthetic and antithetic faults can be directly related to the variation in the surface of T1 which varies through 70m and cuts northwards, down succession, through most of the quarry exposure. Some minor thrusts are developed in the hanging wall above brecciation zones where the principal thrust dips steeply northwards. The wide range of lithologies in these breccias is a result of the Greystone Thrust cutting steeply across several earlier thrust sheets containing varied Lower Carboniferous lithologies. Lateral slopes in these surfaces cut through more than 60m of succession, at angles up to 60° (Figs. 4 and 5).

In E-W section the undulations in the Greystone Thrust are of a similar magnitude (up to 70m) to those in N-S section. The undulating nature of the thrust surfaces results in a striking juxtaposition of contrasting rock types in both the quarry and the surrounding ground (Fig. 7). The Greystone Thrust dips steeply (50°-70°) west, cutting through 110m of sequence at the western end of the present quarry. Thus, although Devonian slates replace the Lower Carboniferous lithologies at this level, they have the same relationship to them at deeper levels to the west. The Devonian is, in turn, overthrust by Lower Namurian flysch and Visean cherts lkm west of the quarry along a thrust surface of similar undulose form (Fig. 8).

Minor structures associated with the (D2) Greystone Thrust

Fig. 6 illustrates the variety of orientations of minor thrusts and joints below this thrust, normal to the transport direction, while Fig. 4 illustrates similar structures parallel to transport and also includes cognate features above the thrust. The orientation of these structures can be regarded as a direct reflection of the geometry of the Greystone Thrust.

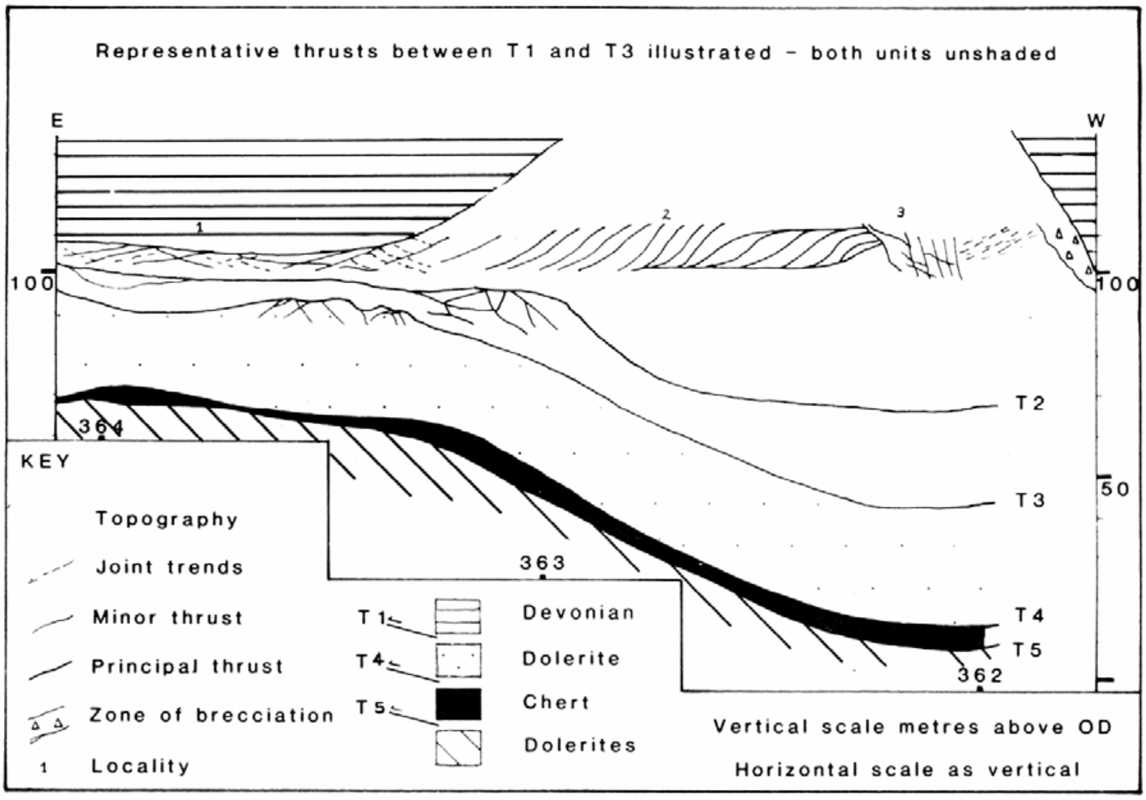


Figure 6. Cross section illustrating the small scale structures associated with principal thrust surfaces perpendicular to the transport direction and currently exposed in the quarry. Locality numbers refer to locations mentioned in the text and illustrated in Turner (1982).

The underlying intrusive has been dissected into lozenge shaped blocks. Most of the surfaces are slickensided with dolomite, quartz and amphibole assemblages and are highly strained. The ramifying network of thrusts and joints form low angle features at Loc. 1 (Fig, 6). As the thrust steepens westwards the high strain zones similarly steepen up to 70°. The lateral duplex west of Loc. 2 (Fig. 6) does not reflect W-E movement but exemplifies the variability within the intrusives below the thrust. West dipping thrusts cut this structure (Loc. 3, Fig. 6) and are deflected into high angle fault zones within the thrust sheet. The movement of the western block northwards relative to the east between each of these faults has produced deflection of the thrusts and associated fabrics into the fault zone (Turner, 1982; Isaac and others, in press). These structures are developed where the Greystone Thrust dips steeply westwards to replace the Lower Carboniferous sequence. Adjacent to the thrust, east dipping joints and thrusts developed. These surfaces are normal to the principal thrust and are "saucer" shaped surfaces in three dimensions. The brecciation diagrammatically indicated on Fig. 6 is representative for the E-W section. In the quarry it is exposed where the thrust dips northwards. Cherts, slates, dolerite and green slates, all variably deformed, are incorporated in this intensely thrusted 10m zone. As the zone directly overlies picritic dolerite it is evident that translation of material in the imbricate zone is very significant locally. The dolerite from below T3 (Fig. 4) is represented in the imbricate zone in the back wall of the quarry and must have been translated a minimum of lkm.

The direction of displacement on all the minor faults is not demonstrable other than the consistent N-S constraint of the slickensided surfaces. It is possible that some of the faults are antithetic structures, certainly their form bears strong resemblance to those described by Rodgers and Rizer (1981).

Minor structures associated with D1 thrusts

A remarkable heterogeneity in the geometry of D 1 minor thrust has been recorded in the quarry (Turner, 1982). A hierarchy of thrusts has been identified between the principal thrusts. Second order thrusts between the steep south dipping thrusts form discrete lozenge shaped geometries in three dimensions. The complexity of the duplex between T4 and T5 is attributable to the accretion of horses in the hanging wall as T5 ramps over the lower dolerites. Complex strains are not solely a function of the mixed rheology in these zones, i.e. complex dolerite fingers with chert xenoliths in a pelitic host. The lateral constraints to the thrust surfaces will result in changes in length of the hanging wall which must be accommodated

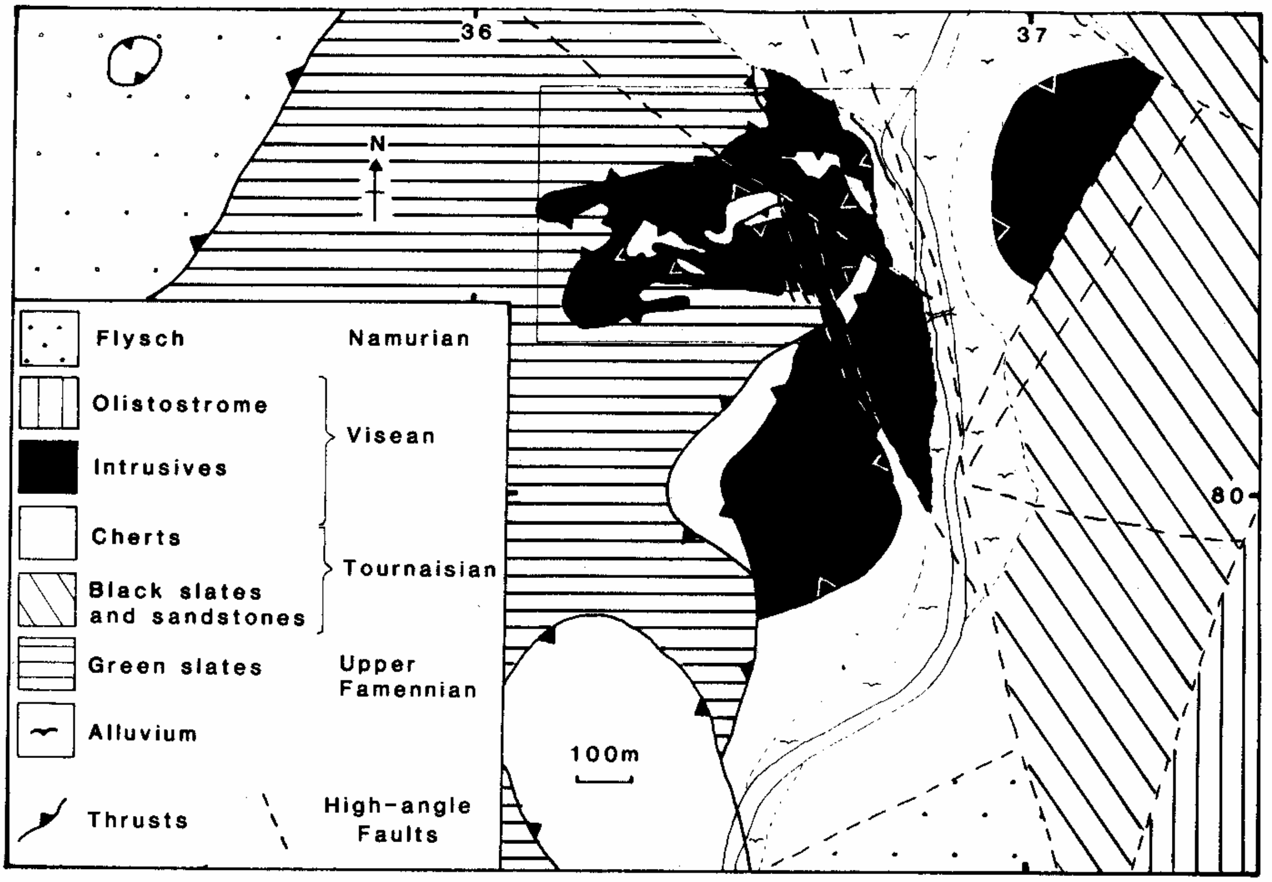


Figure 7. Simplified map of the geology of the area around Greystone Quarry. The location of Fig. 2 is illustrated.

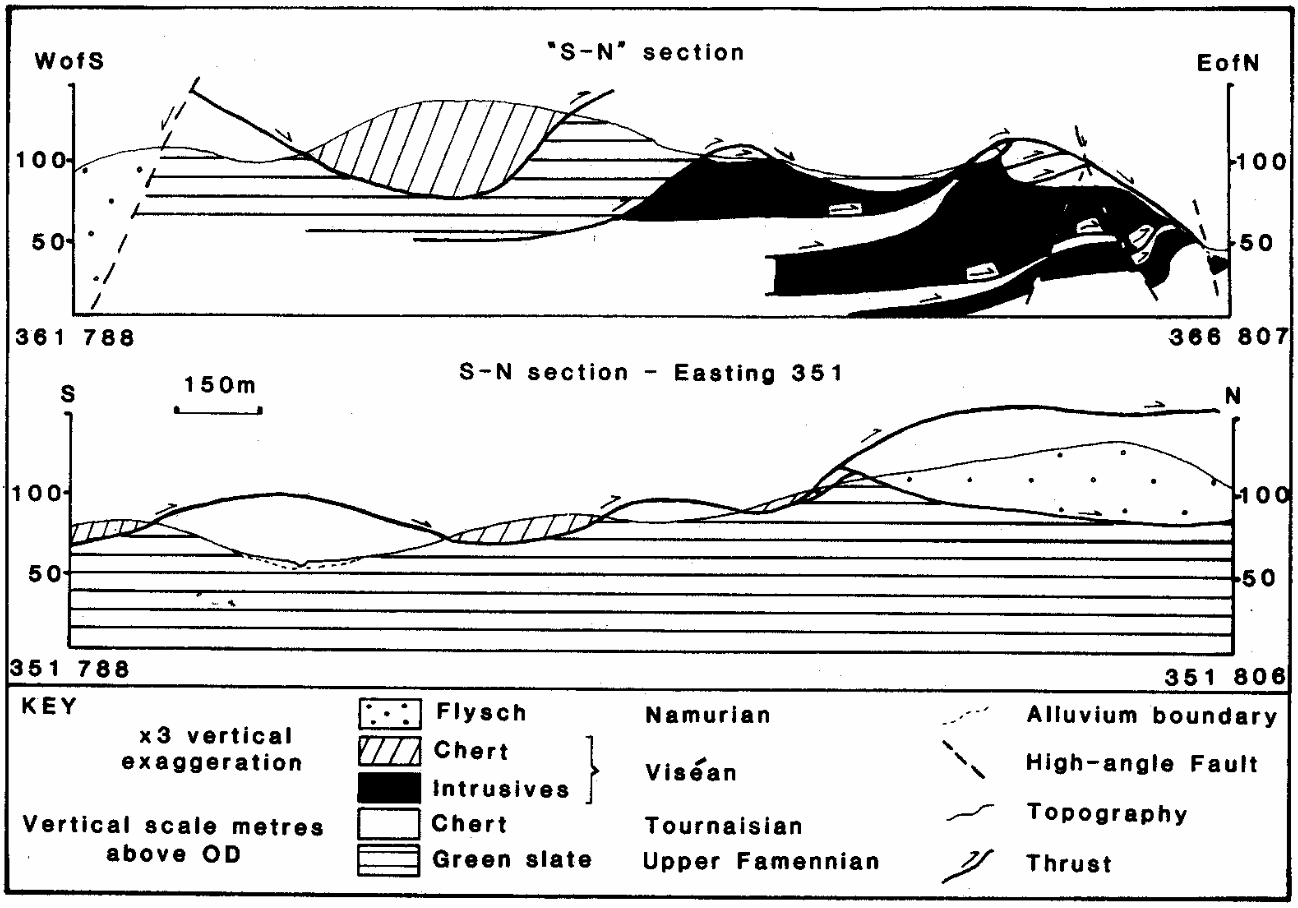


Figure 8. Cross sections illustrating the geology of sections, parallel to the transport direction, through the quarry and 1km to the west.

internally. In the Moine Thrust Zone, Butler (1982) has shown that horse accretion will result in extensional strains initially normal to movement direction. This will be followed by folding as more horses are accreted laterally onto the thrust sheet, and compression of rocks above the hanging wall will result. In Greystone Quarry a complex history of extensional and compressional strains has developed in the hanging wall during thrust displacement, However, folding of the type described by Butler, for the hanging wall situation, is not seen. Complex pressure solution and buckling has accommodated the strain in the deforming sequence. Monoclinal flexures and highly variable folds with axial planar slip were generated during the thrusting to accommodate the thrust geometry seen. The emplacement of the dolerite during early thrusting in the section undoubtedly exerted a marked influence on the nature of the deformation. Effects on stress and chemical gradients would be exerted locally affecting solution deposition processes of dissolution, diffusional transfer and crystallization. The presence of discrete fingers of dolerite in a deforming pelite host is seen to produce highly variable local strains.

Butler (1982) noted that, statistically, the probability of lateral variations in structure is increased with the number of ramps. It is possible that the striking contrasts in rheology in this mixed sequence are in part responsible for the extreme variability in the thrust geometry observed. Horses are readily generated where pelite dominated successions carrying discontinuous bodies of dolerite, ramp over more competent, thick intrusives.

Boudinage axes in the horses, trending E-W, indicate that extension was perpendicular to movement in these sections. Boudinaged early D 1 fabrics which lie higher in the sequence, however, indicate extension parallel to the movement direction. Fig. 6 illustrates minor structures below T2 and T3 in the zone of extension parallel to transport.

In the sequences below the Greystone Thrust D1 structures are seen to be related to complex variations in stress through the deforming pile. Complex accretion patterns seen in the lower parts of the sequence prevent the reasonable projection of structure onto cross section lines. It is important to note that where the three dimensional geometry of such surfaces cannot be established, great care must be exercised in the interpretation of the larger structure.

Movement directions

The orientation of folds, the deflection of fabrics into high strain zones and the orientation of linear features such as slickensides have been used as an indication of thrust transport direction. The so called "Bow and Arrow" Rule (Elliott and Johnson, 1980), which states that poles to bedding within horses have a symmetrical distribution about the tectonic transport direction, is not applicable. The rule assumes that thrust surfaces cut up stratigraphic section with displacement and that there is a symmetrical distribution of lateral ramps, Clearly neither of these criteria are satisfied in the Greystone Complex. Correlatable markers are not available for measuring displacements throughout the quarry. Individual displacements seldom reflect the overall relationships of thrust displacement in the section. The generation of a lateral duplex below T1 in the back wall (Fig. 6) might be taken to suggest a degree of accretion perpendicular to the transport direction of the thrust. However slickensides on these shear surfaces reflect movement consistently along S-N and NW-SE lines. This is further supported by the deflection of fabrics into cognate high angle fault zones within the thrust sheet (Fig. 6).

The vergence of thrust cogenerated folds is used to assess movement direction, being generally overturned in the direction of upper plate motion (Oldow, 1981). This relationship is valid for D2 folds associated with the Greystone Thrust and the earlier principal thrusts. Folded quartz veins and D 1 fabrics reflect the fold age of these D2 folds. E-W axes are abundant in north overturned folds ranging from 070° to 090° and plunge rarely exceeds 10°. These are consistent for DI folds in the thrusted sediment between T4 and T5 and for folds immediately adjacent to steep west dipping listric faults in the south east part of the quarry. On these faults and on all the structures in the back wall (Fig. 6) the slickensides are orientated within 4° of north. This is true for all the lateral ramps and minor surfaces. Where thrust lozenges are developed below T1 the slickenside striations curve around the surface but are N-S orientated, north and south of the lozenge, and remain undeflected over the NS axis. An earlier generation of NW-SE orientated slickensides is seen at the base of the Greystone Thrust along the ramp behind the back face of the quarry. In the east dipping thrusts of the west face the early 004° slickensides are deflected by a 330° later set. In the west dipping high angle faults in the southeast of the quarry (Fig. 5) the second set trend to 030° and indicate that oblique movement occurred across these surfaces. This feature reflects the accretion of horses onto the footwall below the Greystone Thrust early in D2 and the subsequent ramping of the thrust unit over these structures which are reflected in oblique movements in sidewall ramps.

The deflection of early D2 shear zones into high angle fault zones reflects movement of the west side of these faults northwards relative to the right. This led to the deflection of the shear zone fabrics northwards in the east wall. This feature and the cognate folding with thrusting provide consistent northward sense of movement. Locally deflection of slickensides can be used as a corollary but no porphyroclast trails have been identified at the thrust surfaces.

Concluding remarks

In the Greystone area the nature of the Lower Carboniferous succession evidently exerted a marked control over the geometry of the overthrust sheets; in particular, thick, competent intrusive rocks facilitated ramping of the thrusts. Thinning of the intercalated, less competent, pelitic and semi-pelitic lithologies, accompanied by extensive solution, were responsible for many minor features. The distinctive variability in thrust surface geometry perpendicular to the general transport direction (Figs. 5 and 6) reflects both the interaction, laterally, of the thrust sheets and the character of the underlying lithologies. The geometry of the T2-T5 surfaces predominantly reflect deformation in the Greystone Nappe prior to the overthrusting of the Petherwin Nappe along the Greystone Thrust (T1).

These surfaces are, accordingly, attributed to the D1 gravity sliding event of Isaac and others (1982). Displacements along these surfaces were small compared to the overriding Upper Devonian sheet but brought about significant thinning of the Greystone Nappe by extension.

The structures described in this study reflect a continuum of deformation from the generation of folds and fabrics of an essentially ductile nature before and during intrusion, to more brittle displacements associated with the overthrusting of the Petherwin Nappe.

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References

Butler, R.W. 1982. A structural analysis of the Moine Thrust Zone between Loch Eriboll and Foinaven. N.W. Scotland. *J. Struct. Geol. 1,* 73-80.

Chandler, P.C. and Isaac, K.P. 1982. The geological setting, geochemistry and significance of Lower Carboniferous basic volcanic rocks in central South-West England. *Proc. Ussher Soc. 5, 000-000.*

Elliott, D. and Johnson, M.R.W. 1980. Structural evolution in the northern part of the Moine Thrust belt, N.W. Scotland. *Trans. R. Soc. Edin,'71,* 69-96.

Isaac, K.P., Turner, P.J. and Stewart, I.J. 1982. The evolution of the Hercynides in central S.W. England. J. *Geol. Soc. Lond. 139,* 521-531.

Isaac, K.P., Chandler, P. Whiteley, M.J. and Turner, P.J. An excursion guide to the geology of central south-west England: report on the field meeting to W. Devon and E. Cornwall, 28-31st May 1982. *Proc. Geol. Assoc.* (in press).

Oldow, J,S. 1981. Kinematics of late Mesozoic thrusting, Pilot Mountains, West-central Nevada, U.S.A.J. *Struct. Geol. 3,* 39-49.

Pollard, D.D., Muller, O.R. and Dockstader, D.R. 1975. The form and growth of fingered sheet intrusions. *Bull. Geol. Soc. Am. 86,* 351-363.

Ramsay, J.G. 1980. Shear zone geometry: a review. *J. Struct. Geol. 2,* 83-99.

Rodgers, D.A. and Rizer, W.D. 1981. Deformation and secondary faulting near the leading edge of a thrust fault. *In:* McClay, K.R. and Price, N.J. (eds.) Thrust and nappe tectonics. *Spec. Publ. Geol. Soc. London No 9,* 65-77.

Turner, P.J. 1982. Aspects of the evolution of the Hercynides in central South-West England. *Unpubl. Ph.D., Thesis, Univ. of Exeter.*

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Read at the Annual Conference of the Ussher Society, January 1982

The geological setting, geochemistry and significance of Lower Carboniferous basic volcanic rocks in central south-west England.

PAUL CHANDLER
KEVIN P. ISAAC

Paul Chandler and Kevin P. Isaac 1982. The geological setting, geochemistry and significance of Lower Carboniferous basic volcanic rocks in central south-west England. *Proc. Ussher Soc., 5,* 279-288.

Lavas, pillow lavas and volcanogenic sediments in the area between Dartmoor and Bodmin Moor are largely restricted to rocks of latest Tournaisian to mid-Viséan age and represent a phase of basic magmatism lasting for about 19 million years. Spatially associated dolerite intrusions, that exhibit a similar geochemistry, also relate to this phase of activity. Both intrusive and extrusive volcanic rocks suffered carbonatisation and albitisation during very low grade metamorphism and the major oxide contents and calculated norms are consequently highly variable. Most of the trace elements were also mobile during alteration with the possible exception of Ti, Y, Zr and Nb. Using these four elements, and following the scheme of Pearce and Cann (1973), the sampled rocks are found to have ocean floor affinities. It is suggested that the Lower Carboniferous basic magmatism occurred in a restricted pelagic zone, bounded to the south by a neritic carbonate platform, in a small ocean basin setting.

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Introduction

The basic igneous rocks of the central part of south-west England, between Bodmin Moor and Dartmoor, have received considerable attention in early papers and memoirs (see Reid and others, 1912) but in more recent times only brief lithological or petrographical descriptions have appeared in stratigraphical and structural papers (e.g. Dearman and Butcher, 1959). Much geochemical and petrological work has been carried out on basic volcanic rocks elsewhere in southwest England (Floyd, 1972 a, b, 1976; Floyd and Lees, 1973; Floyd and AI-Samman, 1980)but no modern geochemical or petrological research has been carried out on samples from central south-west England. The purpose of this paper is to present major oxide and selected trace element data from an initial study of eighty-one samples of exclusively lower Carboniferous volcanic rocks from central south-west England and to comment on their regional setting and environment of formation.

Geological setting

Recent revision of the Institute of Geological Sciences 1:50,000 Sheets 337 (Tavistock) and 338 (Dartmoor Forest) by a team, working under contract to I.G.S., at the Geology Department of the University of Exeter, has shown that the area is dominated by a thin skinned thrust . and nappe tectonic regime developed in Upper Devonian and Carboniferous rocks (Isaac, Turner and Stewart, 1982). (Fig. 1). Four allochthonous nappe units and probable autochthon have been recognised. The allochthon is believed to have a southern origin (Stewart, 1981a; Isaac, Turner and Stewart, 1982) and, although no root zone has been identified, translation of the nappes from at least the Dartmouth Anticline (Hobson, 1976), a distance of some 25km, is envisaged.

Included within the allochthonous nappe pile are numerous occurrences of intrusive and extrusive basic igneous rocks which form the subject of this contribution. With the exception of rare examples of vesicular lavas and sheared dolerites in the Upper Devonian Kate Brook Slate, (Table 1 and Fig. 1) (Whiteley, pers. comm.) no occurrences are known from the autochthon. Within the allochthon by far the greater proportion of the basic igneous rocks are contained within the Greystone Nappe (terminology of Isaac, Turner and Stewart, 1982) and this is emphasised by the distribution of sampled localities (see Table 1 and Fig. 1).

In the past, insufficient faunal evidence for the age of enclosing sediments led to many volcanic rocks in the area being tentatively identified as Upper Devonian in age (e.g. Selwood, 1974). However, recently recovered conodont faunas (Stewart, 1981b, 1981c) indicate that most of the volcanic rocks of the study area are late Tournaisian to late Visean in age.

CATEGORIES AND FIELD RELATIONS OF BASIC IGNEOUS ROCKS IN CENTRAL SOUTH WEST ENGLAND			No. of samples
INTRUSIVE	DOLERITES	1) intruded into post-typicus Zone chert-shale facies	42
		2) intruded into Lower Carboniferous basin facies	4
		Upper Devonian basin facies: 3) Tredorn Slate (allochthon)	4
		Upper Devonian basin facies: 4) Kate Brook Slate (autochthon)	2
	GABBROS AND PERIDOTITES	5) intruded into Tredorn Slates	
		6) as tectonic clasts in thrust melange	
EXTRUSIVE	BASALTS (lavas and pillow lavas)	7) post-typicus Zone chert-shale facies	5
		8) post-typicus Zone basin facies	14
		9) post-typicus Zone neritic rise slope facies	7
		10) Lewannick Lavas	
		11) Tintagel Volcanic Group	
	VOLCANOGENIC SEDIMENTS	12) post-typicus Zone pillow breccia	3
		13) Tournaisian pillow breccia	
		14) Lower Carboniferous flysch	
		total	81

Table 1. Table showing the categories and field relations of the samples used in this study.
The field relations categories (1), (2), (7), (8), (9), (12), and (13), belong to the Greystone Nappe; categories (3), (5), (6), (10), (11) and (14) belong to the higher nappes; category (4) to the autochthon.

The association of dolerite intrusions with the volcanic rocks and the similar restriction of the bulk of the intrusions to the Greystone Nappe is thought to indicate a temporal association between the two. More specifically the phase of basic magmatism these two groups represents is contained with allochthonous sediments between the lower part of the *typicus* Zone and top of the *texanus* Zone, a period of about 19m.a. from 357 to 338m.a. (estimated from Paproth 1969; Lane and others 1980; and from radiometric data given in George and others, 1976).

Field relations and sampling

The location of sampling points and geological setting of the study area is shown in Fig. 1. The field relations of the sampled lithologies is shown tabulated in Table 1. Conodont zones and facies relationships are shown in Isaac, Turner and Stewart (1982, Fig. 2).

Metamorphism and alteration

Both the intrusive and extrusive igneous rocks have undergone, along with the surrounding sediments, very low grade regional metamorphism. Clay mineral assemblages in the Lower Carboniferous metasediments of the Greystone Nappe indicate that the higher part of the ordered mixed-layer zone (Zone III of Velde 1977, Fig. 5I) and the lower part of the illite-chlorite zone was reached (Isaac, 1982). This represents temperatures of about 250°C and very low pressures, less than 2 Kbar, and corresponds approximately to the prehnite-pumpellyite zone in igneous and volcanogenic sedimentary rocks. We have tentatively identified pumpellyite in thin sections of vesicular lavas from southeast of Launceston but overall both the intrusive and extrusive lithologies are dominated by phyllosilicates (chlorites with minor illite), albite and carbonate minerals (calcite, ankerite, siderite).

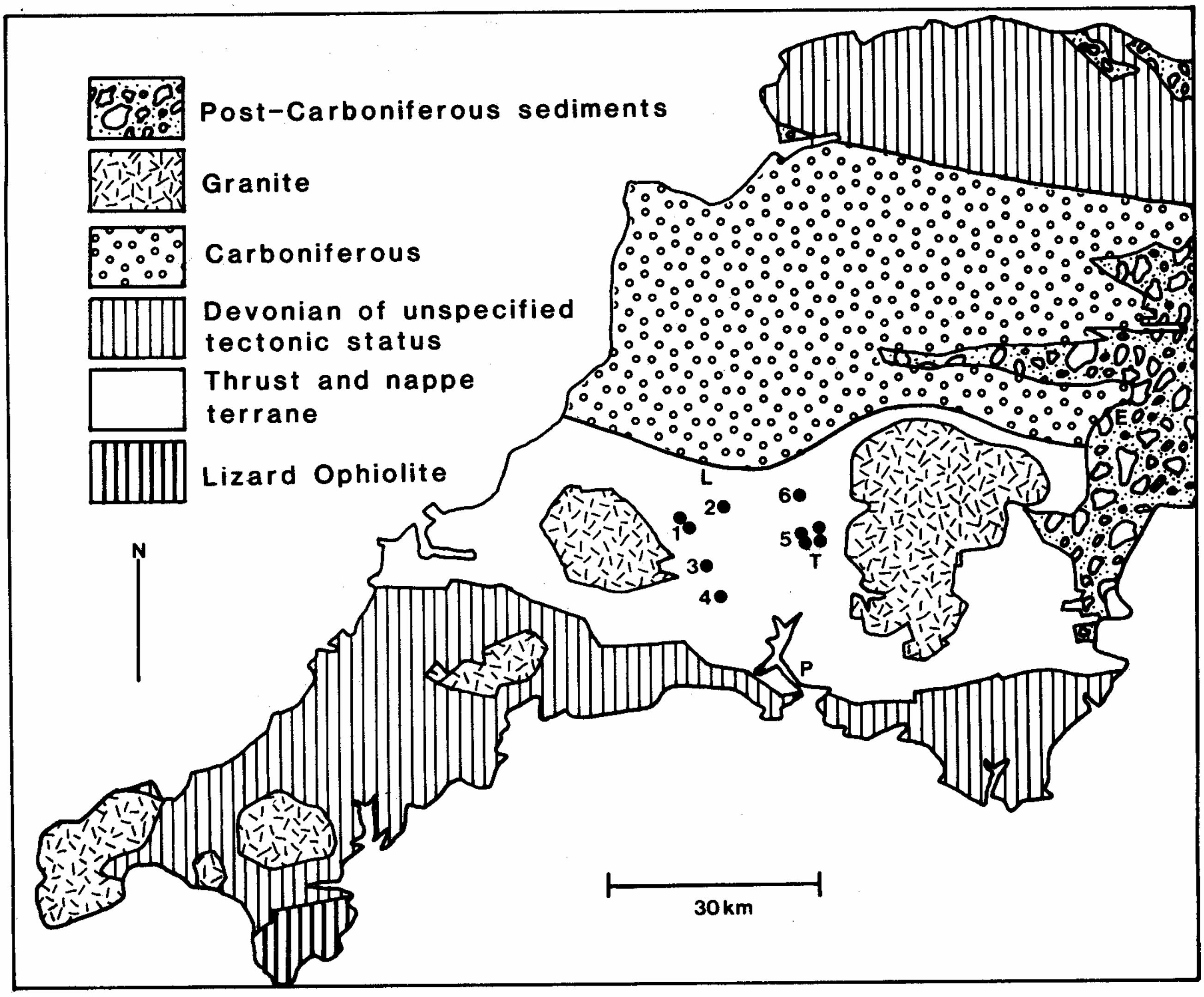

Figure 1. Map showing tectonic setting of sampled localities. L=Launceston, T=Tavistock, P=Plymouth and E=Exeter. Sample localities (all grid references lie within National Grid 100km square SX); 1) Trewinnow Plantation (303788) and Lower Larnick (307780), 2) Greystone Quarry (365806), 3) South Hill (330723), 4) Newbridge (346697 and 347681) 5), Tavistock (478745, 478747, 485745 and 493756) and 6) Asheltor (475827)

It has been inferred that the fluid phase evolution of the surrounding sediments was dominated by conditions in which PH O was considerably less than P_{fluid} (Isaac, 1982). Many of the sediments are rich in graphite and contain metamorphic carbonate porphyroblasts suggesting that they were originally rich in organic matter which has undergone degradation during diagenesis and metamorphism. The degradation of Organic matter in the sediments may have played a key role in the carbonatisation and albitisation of the interbedded and intruded igneous rocks during metamorphism.

Thin beds or intrusions of igneous rocks are invariably pervasively altered to calcite-chlorite-albite rocks, whereas larger bodies, for example sills in Greystone Quarry (Turner, 1982), are most altered at their margins and are only pervasively carbonatised near the contact with the sediments. We believe that this is evidence that the carbonate was introduced from outside the intrusions and that the carbonatisation process was effected by a reaction between the igneous rock and the fluid phase evolved from the surrounding sediments.

Methods

Eighty-one whole rock samples have been analysed using a Philips PW 1220 X-ray spectrometer using standard X-ray spectroscopic procedures. Samples were prepared for 1 analysis of major oxides using the method of Harvey and others (1973), and for trace elements using the pressed , powder method of Norrish and Hutton (1964). Calibration was made using U.S.G.S. standards (Flanagan, 1970). Ferrous iron was determined using a wet chemical technique (French and Adams, 1972).

Major oxide geochemistry

The brief appraisal above of the effects of very low grade metamorphism demonstrates that these rocks have suffered extensive alteration. A large loss on ignition (>2%) was found in all the samples analysed and reached values of 21%. Work in progress indicates that the largest component of the loss can be attributed to CO2. The values of loss on ignition are related to the high degree of carbonatisation and hydration as indicated by the presence of carbonate minerals and hydrous phyllosilicates in the metamorphic mineral assemblages.

The major oxide compositions of both the intrusive and extrusive rocks are extremely variable. A plot of Na_2O + K_2O against SiO_2 for all samples (Fig. 2) shows no recognisable distribution patterns and a complete spread of points into the alkali and tholeiitic basalt fields of Macdonald and Katsura (1964). This is further emphasised by an examination of the CIPW norms calculated from selected analyses (Table 2). All these analyses are from a single sill and have olivine tholeiite, tholeiite and alkali basalt normative compositions. This variation cannot be explained by different magmatic sources but must be due to the effects of the very low grade metamorphism and associated carbonisation and hydration. This large variation in the major oxide compositions is seen throughout all the samples analysed and it is suggested that the major oxide compositions cannot be used here as an indicator of original petrologic type.

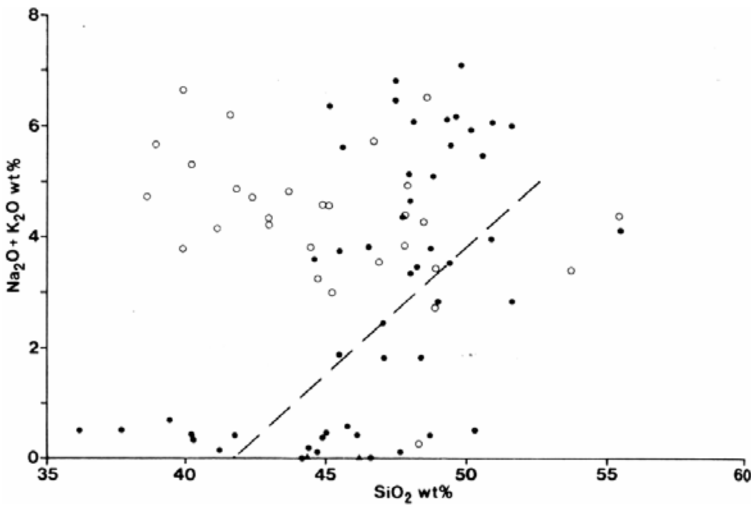

Figure 2. Bivariate diagram, after Macdonald and Katsura (1964), showing plots of basic volcanic rocks from central southwest England. Closed: circles are intrusive dolerites from the Greystone Nappe. Open circles are extrusive basalts from the Greystone Nappe. Closed triangles are intrusive dolerites from the autochthon.

Trace element geochemistry

All the samples were analysed for 18 trace elements. However, only data for titanium (Ti), yttrium (Y), zirconium (Zr), niobium (Nb) and strontium (St) are considered here. Four of these elements, (Ti, Y, Zr and Nb) are generally regarded as being immobile and consequently are unaffected by such processes as weathering and greenschist facies metamorphism (Cann, 1970). Our analysis of the trace element data follows the scheme of Pearce and Cann (1973) and Pearce (1975) who devised a series of graphical plots on which the tectonic setting of the samples could be identified according to their position on the plot. These diagrams have been widely used by other authors. The principal criticism of the method lies in the assumption that Ti, Y, Zr and Nb have remained immobile during subsequent alteration (Hynes, 1980; Williams and Floyd, 1981) and this aspect will be considered below.

	PC8039	PC8040	PC8041	PC8042	PC8043	PC8044	PC8045	PC8046	PC8047	PC8051
SiO_2	48.69	48.28	47.03	47.55	45.84	48.2	48.43	45.81	44.91	45.33
TiO_2	2.14	1.91	1.73	1.54	3.26	2.6	3.43	3.01	3.16	3.44
Al_2O_3	19.38	17.45	16.45	16.41	19.82	20.65	18.14	22.14	20.03	21.82
Fe_2O_3	1.4	2.6	2.84	0.68	3.18	1.76	2.36	1.33	2.15	8.13
FeO	10.57	8.85	10.35	11.1	7.4	7.55	10.4	9.14	10.35	6.21
MnO	0.19	0.17	0.19	0.18	0.26	0.23	0.26	0.26	0.43	0.18
MgO	9.11	11.02	14.87	11.8	4.99	4.56	5.68	5.1	5.56	4.73
CaO	4.7	6.49	6.28	8.77	8.97	7.9	7.3	8.48	9.05	3.13
Na_2O	3.45	1.79	0	0	2.69	2.8	1.97	1.42	1.65	3.39
K_2O	0.03	0.01	0	1.82	2.96	2.35	1.37	2.34	1.97	2.99
P_2O_5	0.34	0.34	0.26	0.15	0.62	0.5	0.67	0.67	0.75	0.65
Sr	281	245	191	187	271	306	192	269	261	177
Y	35	37	34	27	43	42	51	47	45	43
Zr	149	144	118	98	180	200	221	206	224	207
Nb	23	22	19	14	34	32	36	36	36	33
Q	-	3.26	5.58	-	-	-	4.04	-	-	0.39
C	5.85	3.49	5.63	-	-	-	1.72	3.42	0.49	7.3
Or	0.18	0.06	-	10.76	17.51	13.9	8.1	13.84	11.65	17.69
Ab	29.16	15.14	-		16.25	23.66	16.65	12	13.95	28.65
An	21.31	30	29.48	39.34	33.2	36.78	31.87	37.73	40.04	15.54
Ne	-	-	-	-	3.52	-	-	-	-	-
Di	-	-	-	1.28	2.9	0.98	-	-	-	-
Hy	33.58	38.78	51.31	35.59	-	5.37	26.14	22.39	12.9	11.83
Ol	3.14		-	7.43	11.31	9.93	-	2.26	10.13	-
Mt	2.03	3.78	4.12	0.99	4.61	2.55	3.42	1.93	3.12	10.62
Hm	-	-	-	-	-	-	-	-	-	0.8
Il	4.07	3.63	3.29	2.93	6. 19	4.94	6.52	5.72	6	6.54
Ap	0.68	0.74	0.57	0.33	1.35	1.09	1.46	1.46	1.64	1.42

Table 2. Table showing the whole rock major oxide analyses (recalculated to 100%), selected trace element analyses and CIPW norms of ten samples from a single dolerite still within Greystone Quarry (SX 365806).

Yttrium/niobium ratio

Pearce and Cann (1973) suggested that the Y/Nb ratio can be used as an indication of basalt magma type even where substantial post-magmatic alteration of the basalt has occurred. The sampled volcanic rocks have a wide range of Y/Nb ratios (Fig. 3). There is no systematic variation in this ratio with respect to any other chemical feature of the rocks. The spread of data and the lack of systematic variation may be a result of the difficulty in accurately measuring low *concentrations* of Nb. However, values of between 1 and 2, inclusive, predominate with 58% of the samples falling in this range, suggesting possible alkali ocean floor basalt affinities for these rocks.

Titanium-yttrium-zirconium diagram (Fig. 4a)

When plotted on a Ti-Y-Zr discriminant diagram (Pearce and Cann, 1973) 71% of the samples fall in the ocean floor basalt field whilst 22% fall in the within-plate basalt field.

Titanium-strontium-zirconium diagram (Fig. 4b)

The ratio of Ti to Zr is relatively constant whilst the ratio of Sr to Ti or Zr varies considerably. This indicates a much greater mobility of Sr with respect to Ti and Zr and is probably reflecting redistribution during alteration and carbonatisation. Pearce and Cann (1973) state that this diagram should not be used on samples in which calcium loss or gain can be demonstrated. However, 66% of the points fall in the ocean floor field in agreement with all the other diagrams.

Titanium-zirconium diagram (Fig. 5)

Sixty-four percent of the samples plot in the ocean floor basalt field in this diagram. Points falling outside this field can be attributed to samples representing residual liquids enriched in Ti and Zr formed during progressive differentiation of the dolerites and basalts.

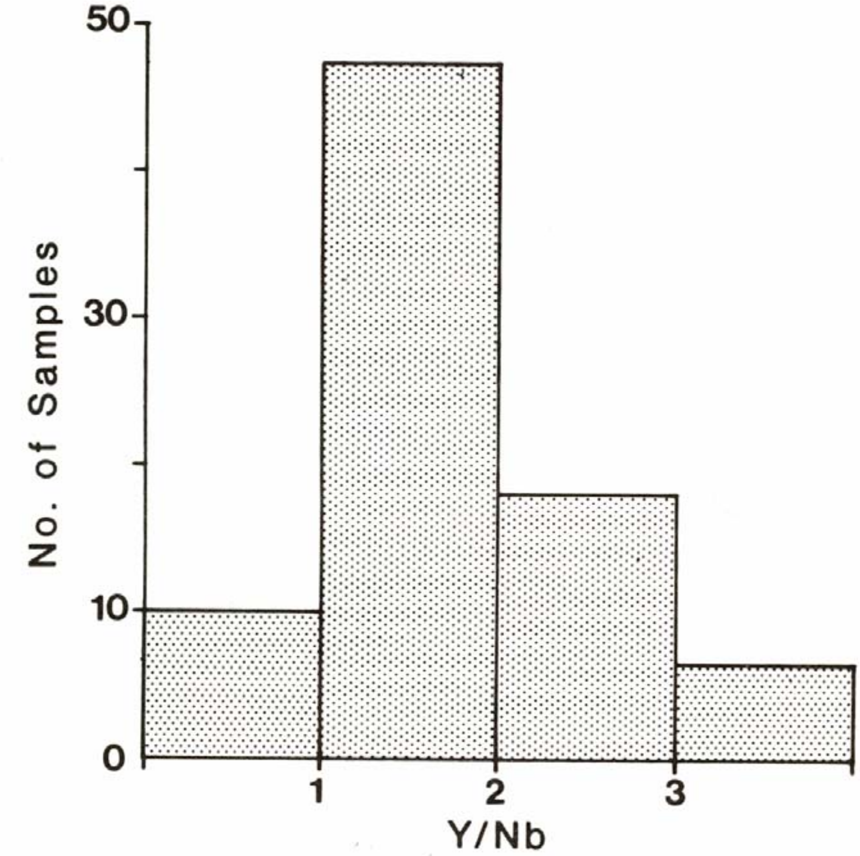

Figure 3. Bar diagram showing the Y/Nb ratios of all the sampled basic volcanic, classes from Pearce and Cann (1973)

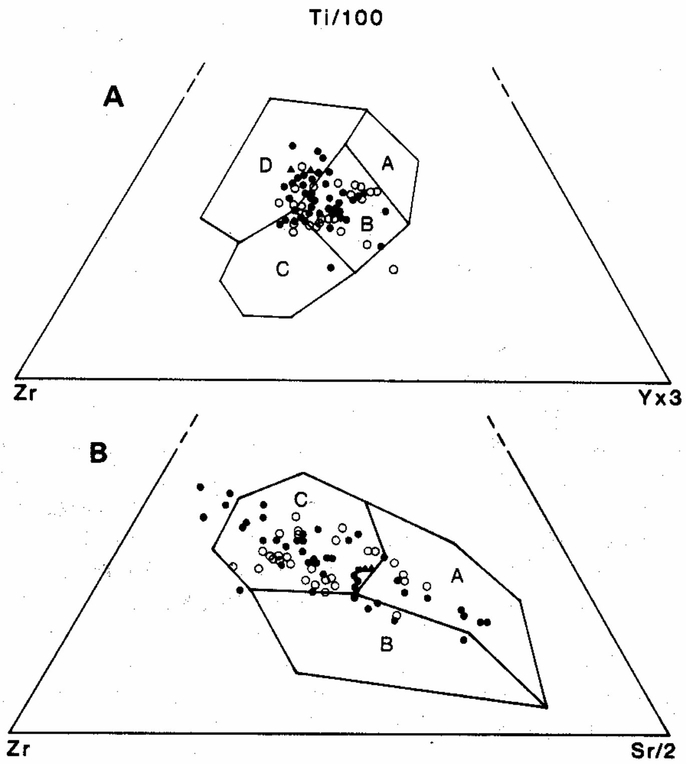

Figure 4. Discriminant diagrams (Pearce and Cann, 1973). a) Ti-Y-Zr: Within-plate basalts plot in field D, ocean-floor basalts in field B, low-potassium tholeiites in fields A and B, and calc-alkali basalts in fields C and B. Symbols as for fig. 2. b) Ti-Sr-Zr: Ocean-floor basalts plot in field C, low-potassium tholeiites in field A, and calc-alkali basalts in field B. Symbols as for fig. 2.

Interpretation

To what extent the so called "immobile" elements Ti, Y, Zr and Nb, can be regarded as immobile is uncertain. Hynes (1980) studied a series of carbonatised metabasalts from the Ascot Formation in south-east Quebec and concluded that the Ti, Y and Zr variation patterns were not primary in origin. Evidence for mobility of these elements was not found in our data because, a) the range of values is considerably less than an order of magnitude, b) no unusually low values of Ti or Zr are present and c) comparison of Figs. 4 and 5 with Hynes's diagrams shows that our data has a markedly closer grouping.

Consideration of the geochemistry of individual sills in relation to the setting of each sample (Chandler in prep.) shows that whilst major oxides and other trace elements show considerable metasomatic variations, either losses or gains, approaching the boundary of the intrusion, Ti, Y, Zr and Nb show no statistically significant loss or gain right up to the contact with the sediments. Thus we believe that in our samples the rocks have behaved as closed systems with respect to these elements, despite considerable alteration and disturbance of the major oxides. Hence we believe that use of the Pearce and Cann (1973) discriminant diagrams is probably valid in this case.

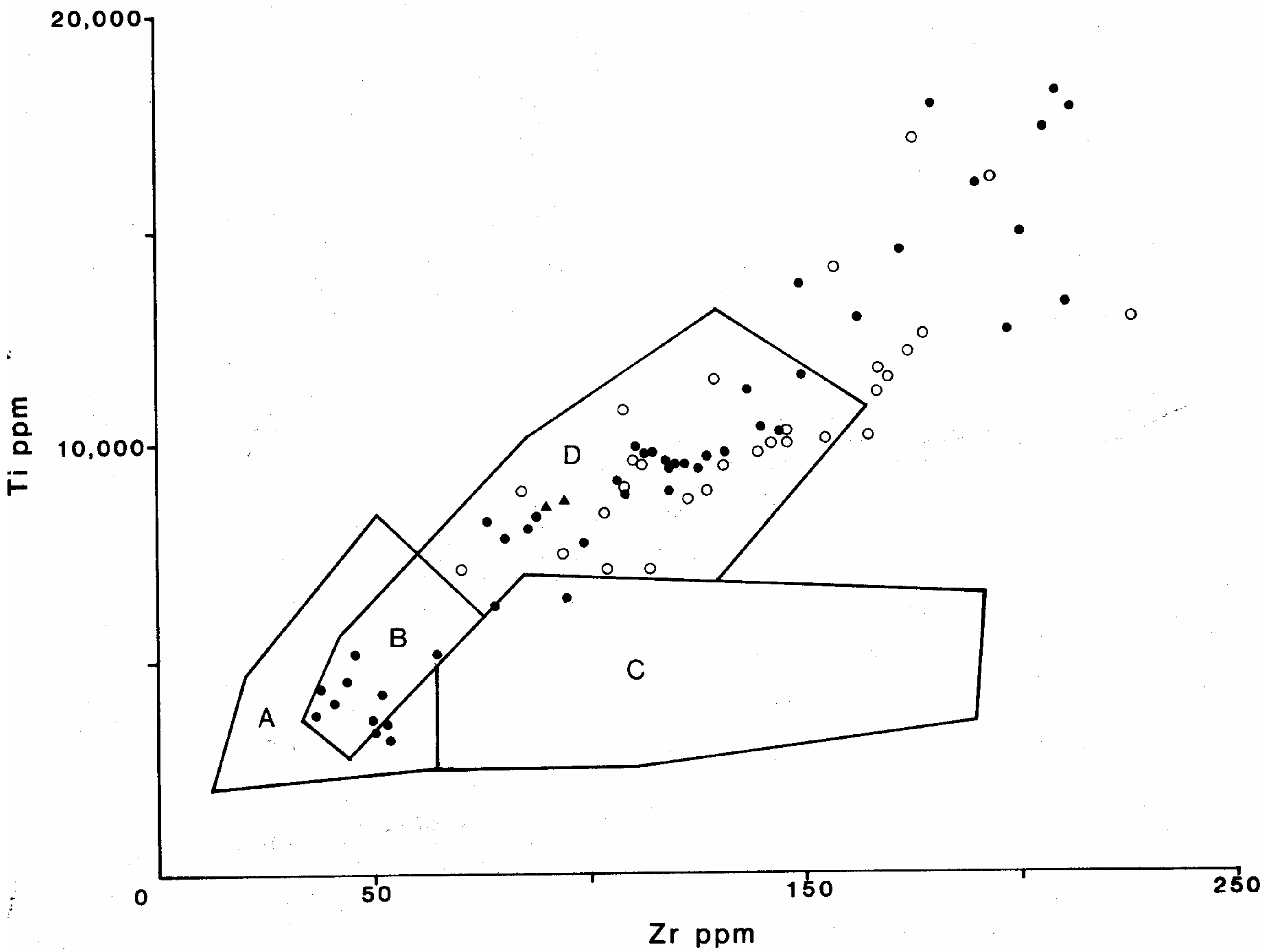

Figure 5. Ti-Zr discriminant diagram (Pearce and Cann, 1973). Ocean-floor basalts plot in fields D and B, low-potassium tholeiites in fields A and B, and calc-alkali basalts in fields C and B. Symbols as for fig. 2.

The complete overlap of the intrusive and extrusive basic volcanic rocks on all the figures may suggest a common magmatic source with, perhaps, the intrusive rocks forming the feeders to the extrusive basaltic volcanism. The two analyses from autochthon plot within the main group of samples, likewise the four samples from the higher Tredorn Nappe, (Isaac, Turner and Stewart, 1982), inferring that they are probably part of the same phase of igneous activity.

In conclusion, it is suggested that more than half the Lower Carboniferous basic volcanic rocks of central south-west England sampled show ocean floor basalt affinities. These are the first results from central southwest England which show ocean floor affinities and this contrasts with previously published data from the majority of basic volcanic rocks of Devonian age in West Cornwall (e.g. Floyd and A1-Samman, 1980) which suggests within plate basalt affinities.

Discussion

The ocean floor geochemistry for the basic igneous rocks of exclusively Lower Carboniferous age in central south-west England permits a speculative but nevertheless useful interpretation of the rocks of the Greystone Nappe. Lithologies represented include cherts, pillow lavas, olistostromes and flysch. These lithologies are typical of ophiolite associations. In addition, intruded into Upper Devonian slates of the Tredorn Nappe, is the Polyphant Complex which consists of peridotites (mostly lherzolites) and gabbros with intercalated dolerites and sediments. In the model of Isaac, Turner and Stewart (1982) for the evolution of the Hercynides of central south-west England, these rocks were immediately, beneath the Greystone Nappe rocks prior to thrusting. It is possible, therefore, that the peridotite and gabbros are not only spatially but also temporally related to the igneous rocks described in this paper, Regardless of the original position of the basic and ultrabasic rocks they are now part of the same tectonic terrane and therefore part of an ophiolite association.

While some authors would argue that an ophiolite is an association of basic and ultrabasic rocks showing an ocean crust stratigraphy, many units presently called ophiolites no longer show such an ordered stratigraphy. It is pertinent to note that with the exceptions of the Oman and Troodos ophiolites, Tethyan ophiolites of the 'croissant ophiolitique' are tectonically dismembered (Ricou 1971). The dismemberment has in some cases proceeded to the point where the term "ophiolitic melange" is used to describe the ophiolite unit and the more general term "ophiolite-flysch complex" is used to describe the whole association (e.g. Hall 1980).

The Greystone Nappe is always the basal tectonic unit of the allochthon; a thin sliver of exotic ophiolitic lithologies separating normal shelf and flysch sediments in the allochthon from similar but autochthonous rocks beneath. The Greystone Nappe is rootless, that is, no autochthon of similar lithology and age is known. Despite this, field relationships of the igneous rocks provide valuable evidence as to their original setting.

(1) The intrusion of the dolerite bodies ranges over a period of time with respect to deformation. In Greystone Quarry for example some bodies were intruded into incoherent, wet sediments yet post-date and cut early compaction and burial fabrics. These early fabrics were deformed by gravity sliding (D1 of Isaac, Turner and Stewart, 1982) before the dolerites were intruded. This relationship indicates that the period of basic magmatism and the commencement of deformation overlap.

(2) Pillow lavas, pillow breccias and, to a lesser extent, the dolerite intrusions frequently contain numerous clasts, up to boulder size, of sediments. The lithology of these clasts is varied, but includes abundant limestones as well as shales and cherts. The limestones contain faunas indicative of shelf environments (Stewart, 198 lc). This is at odds with the geochemical and sedimentological evidence suggesting an ocean floor origin. This apparent paradox can be resolved if the rifting environment, producing these basic volcanic rocks, was in close proximity to an area of shelf carbonate sedimentation.

(3) Many of the extrusive volcanic rocks are either interbedded with or included within olistostromes or conglomeratic slumps (Isaac, Turner and Stewart, 1982). Stewart (1981b) envisaged one such slump, the West Petherwin Conglomerate, forming on the margins of a pelagic rise. It seems reasonable to interpret the volcanogenic olistostromes which contain limestones as forming in a similar situation either on the slope beneath, or on the margins of a carbonate platform or rise. Other slumps involving only cherts with volcanics could have originated within rifted basins beneath the rise slope.

It seems, therefore, that the site of extrusion and intrusion was very close to a platform or rise on which neritic sedimentation was proceeding in close proximity to pelagic sedimentation in a rifting environment. It is possible to draw widespread analogies from regions elsewhere in the world. In particular it is pertinent to note that Tethyan ophiolites show clear evidence of development immediately adjacent to a continental margin (Othris Ophiolite in western Greece, Smith and others, 1979; Haybi Complex beneath the Oman Ophiolite, Searle and others, 1980; Neyriz Ophiolite in southern Iran, Hall, 1981; Stoneley, 1981).

In south-west England the Lizard Complex of possible Devonian age is generally regarded as being an ophiolite (Thayer, 1967; Strong and others, 1975). Kirby and Styles (1980) reviewed the evidence for an ophiolite origin for the Lizard Complex and concluded that certain aspects of the petrology and field relations of the igneous rocks and the close association with continental sediments were different from other well known ophiolites. They envisaged a short-lived ocean which formed temporarily along a transform fault close to a continental margin.

The field relations of the igneous rocks indicate that intrusion and extrusion occurred in a restricted pelagic zone bounded on one side, presumably the south, by a neritic carbonate platform. Both the platform and the pelagic zone were buried firstly by gravity nappes of Viséan flysch (Isaac, Turner and Stewart, 1982) and then by Namurian flysch deposition. The basic magmatism appears to have immediately preceded and indeed heralded the beginning of overthrusting and deformation.

It is concluded that the Lower Carboniferous ophiolite *association* of the Greystone Nappe developed in a short-lived rifting and spreading centre in an ocean basin setting. The field relations of the ophiolite association lithologies allow the ocean basin a life of about 20 million years before it was destroyed in late Viséan to Westphalian deformation. Further support for the existence of a small Lower Carboniferous ocean in the south-west England area is found in palaeomagnetic continental reconstructions (Tarling 1979) which infer an east-west trending ocean about 300-400km wide between the North American-European plate and the group of micro-plates to the south during the Lower Carboniferous.

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Reference

Cann, J.R. 1970. Rb, Sr, Y, Zr and Nb in some ocean floor basaltic rocks. *Earth Planet, Sci. Lett., 10,* 7-11.

Chandler, P. The Petrology, Geochemistry and Geophysics of some Basic and Ultrabasic Igneous Rocks in Central S.W. England. *Thesis, Univ. Exeter, in preparation.*

Dearman, W.R. and Butcher, N.E. 1959. The geology of the Devonian and Carboniferous rocks of the north west border of the Dartmoor Granite, Devonshire. *Proc. Geol. Assoc. Lond., 70,* 51-92.

Flanagan, F.J. 1970. Sources of geochemical standards - II. *Geochim. et Cosmochim. Acta., 34,* 121-125.

Floyd, P.A. 1972a. Geochemical characteristics of spilitic greenstones from S.W. England. *Nature, Phys. Sci., 239,* 75-77.

Floyd, P.A. 1972b. Geochemistry, origin and tectonic environment of the basic and acidic rocks of Cornubia, England. *Proc. Geol. Assoc. Lond, 83,* 385-404.

Floyd, P.A. 1976. Geochemical variation in the greenstones of S.W. England. *J. Petrol., 17,* 522-545.

Floyd, P.A. and Al-Samman, A.H. 1980. Primary and secondary chemical variation exhibited by some west Cornish volcanic rocks. *Proc. Ussher Soc., 5,* 68-75.

Floyd, P.A. and Lees, G.J. 1973. Ti-Zr characterization of some Cornish pillow lavas. *Proc. Ussher Soc.,* 2, 489-494.

French, W.J. and Adams, S.J. 1972. A rapid method for the extraction and determination of Iron (II) in silicate rocks and minerals. *Analyst. 97,* 828-831.

George, T.N., Johnson, G.A.L., Mitchell, M., Prentice, J.E., Ramsbottom, W.H,C., Sevastopulo, G.D. and Wilson, R.B. 1978. A correlation of Dinantian rocks in the British Isles. *Geol. Soc. Lond., Special Report No. 7*

Hall, R. 1980. Unmixing a me1ange: the petrology and history of a disrupted and metamorphosed ophiolite, S.E. Turkey. *J. Geol. Soc. Lond., 137,* 195-206.

Hall, R. 1981. Ophiolite-related contact metamorphism: skarns from Neyriz, Iran. *Proc. Geol. Assoc. Lond., 92,* 231-240.

Harvey, P.K., Taylor, D.M., Hendry, R.D. and Bancroft, F. 1973. An Accurate Fusion Method for the Analysis of Rocks and Chemically Related Materials by X-ray Spectrometry. *X-ray Spectrometry,* Z 33-34.

Hobson, D.M. 1976. A structural section between Plymouth and Bolt Tail, South Devon. *Proc. Geol. Assoc. Lond., 87,* 27-43.

Hynes, A. 1980. Carbonatization and mobility of Ti, Y and Zr in Ascot Formation Metabasalts, S.E. Quebec. *Contrib. Mineral. Petrol., 75,* 79-87.

Isaac K.P. 1982. Hercynian regional and contact metamorphism in Upper Devonian and Lower Carboniferous metasediments in the Launceston and Lydford area of South West England. *Trans. Roy. Geol. Soc. Cornwall, XXI,* (in press).

Isaac, K.P., Turner, P.J. and Stewart, I.J. 1982. The evolution of the Hercynides in central south-west England. *J. Geol. Soc. Lond., 139,* 521-531.

Lane, H.R., Sandberg, C.A. and Ziegler, W. 1980. Taxonomy and phylogeny of some Lower Carboniferous conodonts and preliminary standard *post-siphonodella* zonation. *Geologica et Palaeontologica 14,* 117-164.

Macdonald, G.A. and Katsura, T. 1964. Chemical composition of Hawaiian lavas. *J. Petrol., 5,* 82-133.

Norrish, K. and Hutton, J.T. 1964. Preparation of Samples for Analysis by X-ray fluorescent Spectrography. *Divl. Rep. Div. Soils CSIRO, 3/64*

Paproth, E. 1969. Die Parallelisierung von Kohlenkalk und Kulm. *C.R. 6th Congr. Int. Strat. Geol. Carb. (Sheffield 1967)* 1. 279-292.

Pearce, J.A. and Cann, J.R. 1973. Tectonic setting of basic volcanic rocks determined using trace element analyses. *Earth Planet. Sci. Lett., 19,* 290-300.

Pearce, J.A. 1975. Basalt geochemistry used to investigate past tectonic environment on Cyprus. *Tectonophysics. 25,* 41-67.

Reid, C., Barrow, G., Sherlock, R.L., Macalister, D.A. and Dewey, H. 1911. Geology of the country around Tavistock and Launceston. *Mem. Geol. Surv. G.B.*

Ricou, L.F. 1971. Le metamorphisme au contact des p6ridotites de Neyriz (Zagros interne, Iran): developpement de skarns a pyroxene. *Bull. Soc. Geol. Fr., 13,* 146-155.

Searle, S.J., Lippard, S.J., Smewing, J.D. and Rex, D.C. 1980. Volcanic rocks beneath the Semail Ophiolite nappe in the northern Oman mountains and their significance in the Mesozoic evolution of the Tethys. *J. Geol. Soc. Lond., 137,* 589-604.

Selwood, E.B. 1974. The age of the Upper Palaeozoic volcanics between Bodmin Moor and Dartmoor. *Proc. Ussher Soc., 3,* 63-70.

Smith, A.G., Woodcock, N.H. and Naylor, M.A. 1979. The structural evolution of a Mesozoic continental margin, Othris Mountains, Greece. J. *Geol. Soc. Lond., 136,* 589-603.

Stewart, I.J. 198 la. The Trekelland Thrust. *Proc. Ussher Soc., 5,* 163-167.

Stewart, I.J. 1981b. Late Devonian and Lower Carboniferous conodonts from North Cornwall and their stratigraphical significance. *Proc. Ussher Soc., 5,* 179-185.

Stewart, I.J. 1981c. The structure, stratigraphy and conodont biostratigraphy of the north eastern margin of Bodmin Moor and adjacent areas. *Unpubl. Ph.D. thesis Univ. of Exeter.*

Stoneley, R. 1981. The geology of the Kuh-e Dalneshin area of southern Iran, and its bearing on the evolution of southern Tethys. J. *Geol. Soc. Lond., 138,* 509-526.

Strong, D.F., Stevens, R.K., Malpas, J. and Badham, J.P.N. 1975. A new tale for the Lizard. *Proc. Ussher Soc., 3.* 252.

Styles, M.T. and Kirby, G.A. 1980. New investigations of the Lizard complex, Cornwall, England and a discussion of an ophiolite model. Ophiolites. proceedings International
Ophiolite Symposium Cyprus 1979. Cyprus Geol. Surv. Dept.

Tarling, D.H. 1979. Palaeomagnetic reconstructions and the Variscan Orogeny. *Proc. Ussher Soc. 4,* 233-261.

Thayer, T.P. 1967. Chemical and structural relations of ultra-mafic and feldspathic rocks in Alpine intrusive complexes. *In:* Wyllie, P.J. (ed). *Ultramafic and related rocks.* Wiley,
New York. 222-239.

Turner, P.J.T. 1982. The anatomy of a thrust: a study of the Greystone Thrust Complex, East Cornwall. *Proc. Ussher Soc. 5, 000-000.*

Velde, B. 1977. *Clays and clay minerals in natural and synthetic systems.* Elsevier, Amsterdam, 217pp.

Williams, C.T. and Floyd, P.A. 1981. The localised distribution of U and other incompatible elements in spilitic pillow lavas. *Contrib. Mineral. Petrol.. 78.* 111-117.

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Read at the Annual Conference of the Ussher Society, January 1982

An introduction to the geology of the area between Buckfastleigh and Ivybridge.

A.D WILLCOCK

Willcock, A.D., 1982. The geology of the area between Buckfastleigh and Ivybridge. *Proc. Ussher Soc., 5,* 289-295.

Between Buckfastleigh and Ivybridge on the southern flanks of Dartmoor, three separate successions lie within three tectonically juxtaposed structural units. The Beacon Hill and Buckfastleigh Successions are closely comparable with successions established by workers on IGS sheet 339 (Newton Abbot), Selwood *et. al.* (in press). The Kate Brook Succession contains a sequence of lithologies referable to the Lower Carboniferous which overlies the Kate Brook Slate and which occupies a complex, sheared synclinal core to the north of Brent Hill. Major thrusts separate the three structural units. The early deformation within all three units is characterised by recumbent to reclined tight folds with a well-developed, axial-planar slaty cleavage (S_1) which dips gently southeast. Second folding is open and is restricted to the vicinity of fracture-zones within the slaty lithologies where a crenulation cleavage dips steeply south-east deforming bedding and slaty cleavage.

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Introduction

The ground between Buckfastleigh and Ivybridge to the south of Dartmoor is covered by Geological Survey Sheet 349. Sheet 339 lies to the north-east and has recently been re-mapped by workers on the Exeter University/Institute of Geological Sciences mapping contract; some elements of the structure and stratigraphy pass south-westward onto Sheet 349.

The geology of the area was first described by de la Beche (1839) who included the rocks in his Grauwacke Group. Ussher's re-mapping of Sheet 349 for the Geological Survey (Ussher 1912) indicated that an area occupied by black shales and sandy hornfelses lay surrounded by slaty lithologies referred to the Upper Devonian between Brent Hill and the Dartmoor granite. Ussher (1912) compared the sandy lithologies with his Ugbrooke type Culm (Ussher 1901) because of their immature aspect, and also clearly envisaged the Middle and Upper Devonian volcanics, limestones and slates of Brent Hill and Buckfastleigh to be thrust over the Upper Devonian and Carboniferous lithologies to the north of Brent Hill. Fitch (1933) interpreted the geology north of Brent Hill as a block of Carboniferous lithologies downfaulted into Upper Devonian slates.

Detailed mapping of the area indicates that between Buckfastleigh and Ivybridge three distinct successions occupy three structural units which are separated by major thrusts (Fig. 2a and 2b). The southernmost unit, the Denbury Unit, contains the Beacon Hill Succession and this has been thrust northward over the Bickington Unit on the Forder Green Thrust, a fracture originally described by Riddolls (1970) from Sheet 339. The Bickington Unit contains the Buckfastleigh Succession, this has been thrust northwards over the Kate Brook Unit on the south-westerly extension of the Bickington Thrust; T_4 of Waters (1970). To the north of Brent Hill the Kate Brook Unit contains a much-sheared synclinal infolding of lithologies of Lower Carboniferous affinity which lie within an envelope of Upper Devonian Kate Brook Slate.

Stratigraphy

The Beacon Hill Succession

The Beacon Hill Succession (Fig 2A) was named and described by Riddolls (1970) from the area west of Newton Abbot; on Geological Survey sheet 339 it is illustrated as forming the older part of the Bickington/Beacon Hill Succession. The Beacon Hill Succession is comprised of an unknown thickness of Nordon Slate which contains interbedded clastic limestones and local volcanics. The succession ranges in age from the Eifelian in the Newton Abbot area (Riddolls 1970) to the base of the Frasnian, the youngest rocks in both the Newton Abbot and South Brent areas. In the area to the south-west of Newton Abbot the Nordon Slate forms an argillaceous base to, and lateral equivalent of, the Chercombe Bridge and East Ogwell Limestone, Riddolls (1970), Scrutton (1977). A comparable relationship between limestone reefs and basinal slates has been described by Orchard (1978)from the Plymouth area.

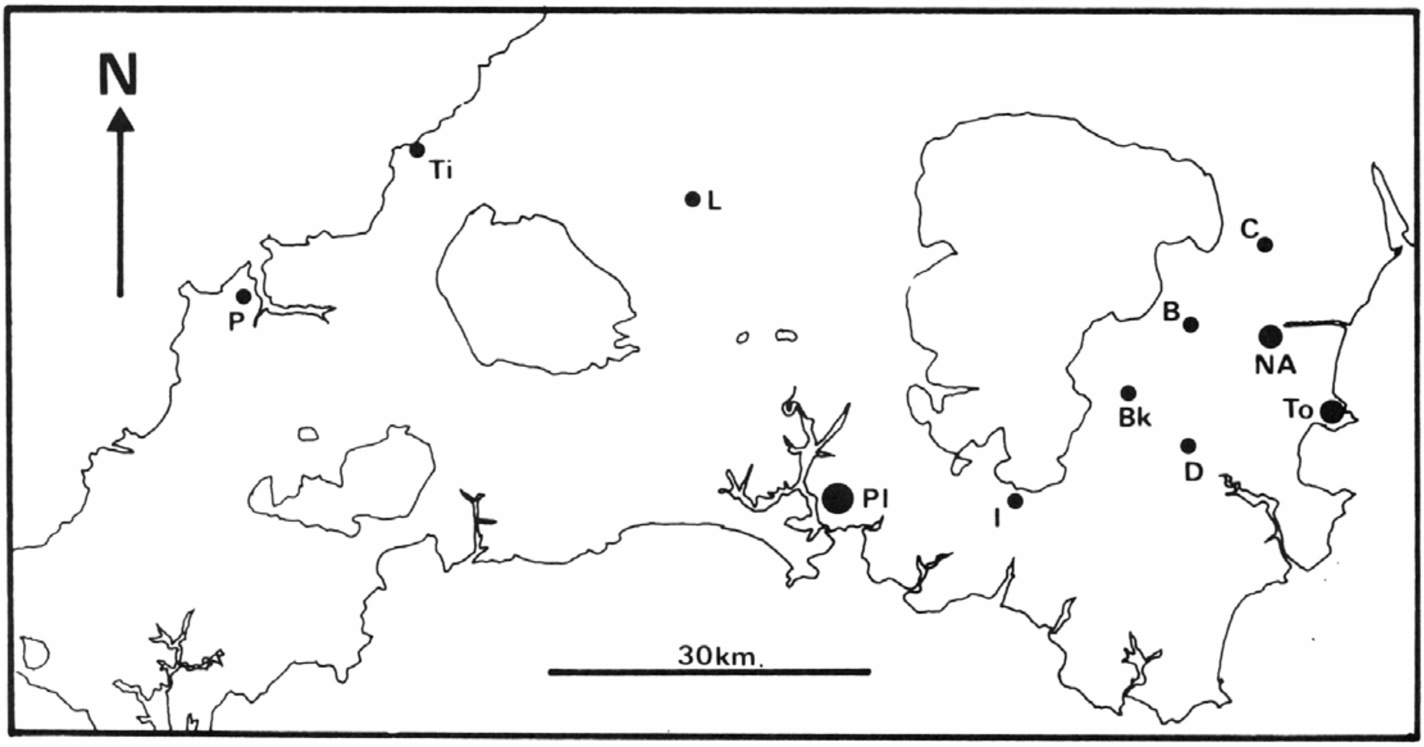

Figure 1. Location Map
B = Bickington, C = Chudleigh, P = Padstow, NA = Newton Abbot Bk = Buckfastleigh, Pl = Plymouth, D = Dartington, Ti = Tintagel, L = Launceston, To = Torquay, I = Ivybridge

The Nordon Slate is a brownish-grey to black calcareous slate, sometimes finely bedded, which forms the bulk of the Beacon Hill Succession. The Nordon Slate is locally fossiliferous; localities beneath the tract of tuffs and spilitic lavas which crop-out at Rattery SX(741617) have yielded stratigraphically useful faunas. An ammonoid referable to the Lower Frasnian has been recovered from slates in the railway cutting at SX(7088 6049), and at SX(7479 6257) near Bulkamore Farm styliolinids and fragmentary ostracods occur within the Nordon Slate, the latter indicative of the *torleyi-Zone,* Gooday (1978). These faunas indicate a Lower Frasnian age for the Rattery Volcanics.

The Rattery Volcanics are a member of the Nordon Slate in which they form an impersistent horizon which crops-out between Ivybridge SX(636 657) and Tor Hill SX (770 656) south of Woolston Green where the volcanics are at least 30m thick. These spilites are typically developed at SX(7413 6174) in Rattery where the Nordon Slate is conformably overlain by 0. lm of slates containing rotten, scoreaceous bombs, these are succeeded by an unknown thickness of lapilli tuffs and basic vesicular lavas. Throughout its outcrop the Rattery Volcanics contains a wide variety of spilitic extrusives interbedded with dark-grey slates, including crystal and lapilli tuffs, bomb-tuffs and spilitic flows with some pillow-lavas: North of Rattery at SX(7494 6310) spilitic lavas 2m above the base of the Rattery Volcanics contain irregular pods of chert and limestone lenses. Whilst a conformable base to the Rattery Volcanics is evident at Rattery the top of the member is only seen in isolated outcrops near South Brent where thin tuffaceous horizons which continue the strike of the Rattery Volcanics lie within the Nordon Slate.

Limestones within the Nordon Slate. Ussher (1912) recognised several small outcrops of limestone between Brooking SX(790 608) and Woolston Green SX(777 658); these are limestone turbidites which lie within the Nordon Slate. Near Woolston Green the turbidite beds are thin (less than 0. lm) and sparsely developed, while at Brooking Quarry SX(765 668) the beds are prominently graded, crinoidal limestone turbidites up to lm thick with thin, black shale interbeds. Conodonts referable to the Lower Frasnian Middle to Upper *varcus-Zone (sensu* Ziegler, Klapper and Johnson, 1976) have been recovered from these beds and indicate a likely age for the turbidity currents. The nearby Dartington Limestone persisted into the Lower Frasnian, Middleton (1960)and could represent a source of detritus for these beds.

Calcareous developments within the Nordon Slate near Marley SX(721 608) have yielded a benthonic fauna of ribbed brachiopods, crinoid ossicles and tentaculitids. A comparable fauna occurs in slates associated with local umber patches (after limestone lenses) within the Nordon Slate south of South Brent at SX(701593). Other localities within the Nordon Slate which have yielded

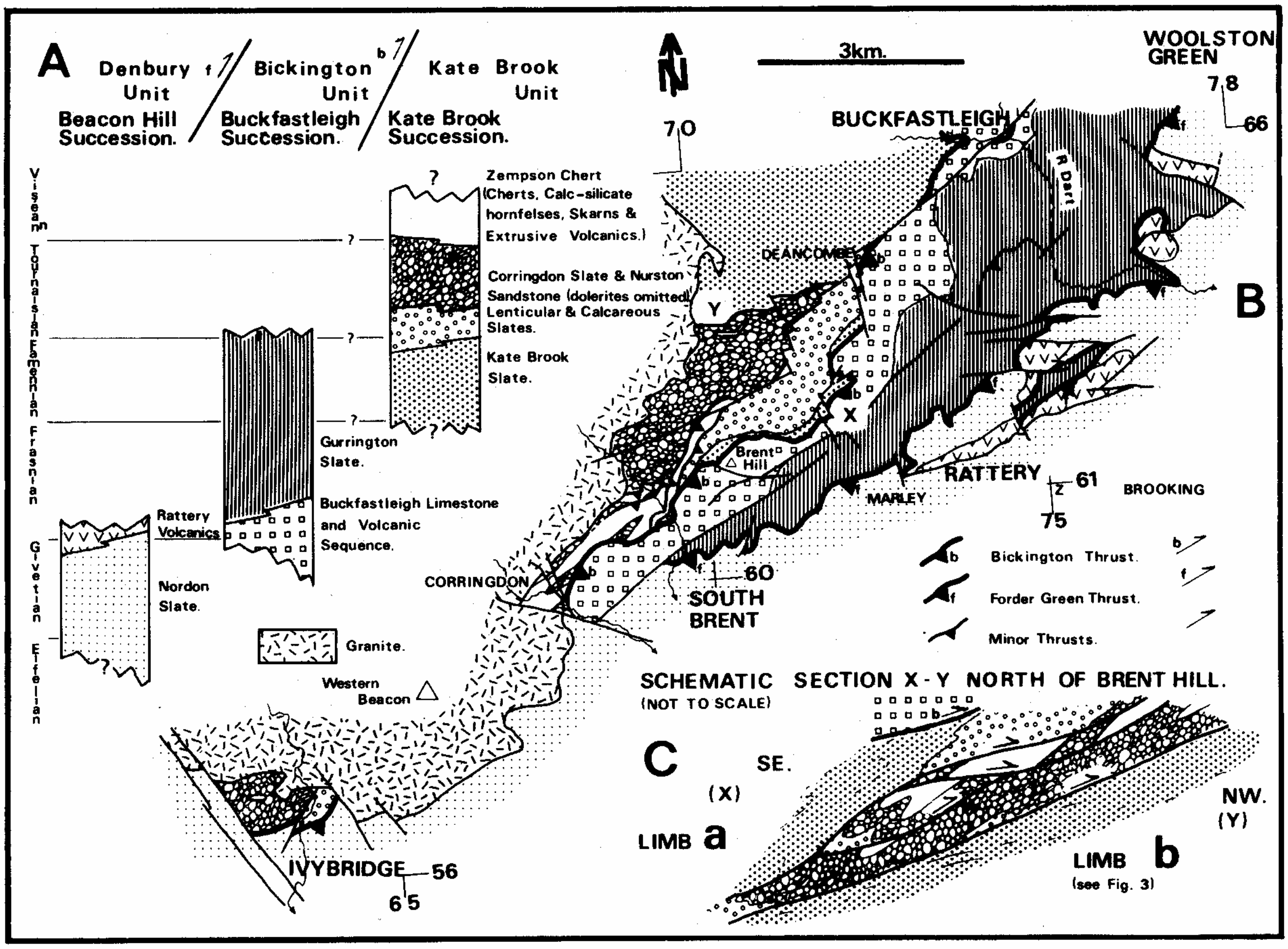

Figure 2. The geology of the area between Buckfastleigh and Ivybridge.

2A: The relationships between the stratigraphic successions, major thrusts and structural units in the area.

2B: A simplified geological map of the area. Numerous small dolerite intrusions, lavas, tuffs and limestones have been omitted for clarity.

2C: A section in the Kate Brook Unit indicating the complex, sheared, synclinal core in which the higher elements of the stratigraphy of the Kate Brook Unit are preserved. Vertical faults have been omitted for simplicity.

benthonic faunal assemblages including isolate pleurodictyid and favositid corals, trilobites and bryozoa were listed by Ussher (1912, pp56-59); Champernowne (1881) compared these slates with the Wissenbach Slates from the Rhenisch Schiefergebierge. In the metamorphic aureole of south Dartmoor, calc-silicate hornfelses continue the strike of these calcareous horizons within the Nordon Slate.

The Buckfastleigh Succession
The Buckfastleigh Succession (Fig 2A) is broadly equivalent to the younger part of the Bickington/Beacon Hill Succession from Geological Survey sheet 339 where Waters (1974) considered the Gurrington Slate and tuffs to be thrust over the Bickington and Ashburton Limestones. Excellent exposures south and east of Buckfastleigh now reveal that a sequence of greyish-green to purple and green slates (Gurrington Slate) overlies and succeeds a base of laterally merging limestones, tuffs, spilitic lavas and slates which form a prominent scarp overlying the Bickington Thrust between Bickington SX(799 726)and Owley SX(677 597).

The Buckfastleigh Limestone and Volcanic Sequence crops-out south-west from Buckfastleigh with the Bickington Thrust defining a tectonic base. Lenticular stromatoporoidal limestones and bedded clastic limestones are overlain by tuffs (Middleton 1960)and are laterally replaced by grey slates, lapilli tuffs and spilitic extrusives; local limestone pods on the south-eastern side of Brent Hill are now represented by skarns. The ages of the limestones and volcanics are not precisely known although they must be older than the Gurrington Slate which is not known to be older than Lower Frasnian throughout its outcrop.

The Gurrington Slate is a lustrous, greyish-green to purple and green, colour-banded slate with local graded beds of calcareous sandstone usually less than 0.03m thick. Tuffs and spilitic flows of varied thickness are common and are scattered throughout the outcrop of the Gurrington Slate.

The Gurrington Slate contains a fauna dominated by ammonoids and pelagic ostracods with rare trilobites the only benthonic element. Ages within this area range from the Middle *Manticoceras Stufe* to the topmost Famennian (Upper *hemisphaerica-dichotoma-Zone)* where the faunas are commonly preserved in indian red, micaceous silts. At Whitecleave SX(731 657) south of Buckfastleigh, silts of this age have been baked against a dolerite which may have been a feeder for intrusions into overlying Carboniferous sediments.

Affinities of the Beacon Hill and Buckfastleigh Successions
The Beacon Hill and Buckfastleigh Successions contain lithologies and lithological associations widely developed in Middle and Upper Devonian slates from Padstow, Gauss and House (1972) eastwards and through the ground north of Plymouth, Gooday (1974), Orchard (1978) to the Newton Abbot area. In this belt Middle Devonian slates comparable to the Nordon Slate were deposited in basinal areas to the north of limestone reefs (e.g. the Plymouth Limestone, Orchard 1978), the sporadic development of benthonic faunas within these slates might indicate local colonisation during periods of shallowing in a basin, otherwise dominated by pelagic faunas, into which turbidites flowed from the limestone reefs to the south, Matthews (1977). Widespread deepening during the Lower Frasnian (Orchard 1978, Matthews 1977) heralded the onset of the deep water Upper Devonian Ostracod Slate Facies widely developed between Padstow and Chudleigh (Gooday 1978) and typified by purple and green slates.

The Kate Brook Succession
The Kate Brook Slate was originally described from the Bickington and Chudleigh areas by Riddolls (1970) and Waters (1974) respectively. Blocks of chert (Lower Carboniferous) and greywacke (referred to the Upper Carboniferous Crackington Formation) crop-out in the Holne Thrust zone (T_3 of Waters 1970) west of Chudleigh: Waters (1974) considered these structurally isolated lithologies to succeed the Kate Brook Slate.

A more complete succession crops-out in the area south-west of Buckfastleigh (Fig. 2A & 2B) and has hitherto not been described. Beneath the Bickington Thrust south-west from Deancombe, a sequence of rocks referred lithostratigraphically to the Lower Carboniferous, crops-out in a complex, sheared synclinal core within an envelope of Kate Brook Slate (Fig 2C). Outcrops to the north of Ivybridge, isolated in the Modbury Wrench Fault Zone of Dearman (1963) are also referred to this succession. Because most of the area north of Brent Hill and around Ivybridge is within the metamorphic aureole of the Dartmoor granite palaeontological control is lacking; however, lithological associations are distinctive enough to allow the establishment of a lithostratigraphy.

The Kate Brook Slate is a well-cleaved, greenish-brown to grey, lustrous slate with some thin silty bands, in adjacent areas it contains a restricted benthonic fauna comprised of spiriferid and crinoidal debris. Volcanic rocks are rare throughout the total outcrop of the Kate Brook Slate and equivalent formations to the west. A stratigraphic base to the Kate Brook Slate is nowhere seen but the oldest ages recorded from the formation are from SX(7360 7544) south of Buckfastleigh where a rare ostracod locality has yielded *Richterina* (?F.) *intercostata,* the index of the Middle Famennian *intercostata-Zone.* Stewart (1981) has recorded an Upper *marginifera-Zone* age (equivalent to the upper part of the Lower Famennian) for the comparable Tredorn Slate north-east of Bodmin Moor; ages older than Lower Famennian have not been recorded from the Kate Brook Slate or equivalent lithologies between Tintagel and Chudleigh. The youngest age recorded from the Kate Brook Slate is the Upper Famennian *costatus-Zone* (Selwood 1971) from SX(3241 6785).

The Kate Brook Slate crops-out beneath the Bickington Thrust to the south of Deancombe (Fig. 2B). Allowing for the inversion of the strata (Fig. 2C) the Kate Brook Slate passes stratigraphically upwards into 30m of unnamed calcareous slates which locally contained thin limestones (now represented by calc-silicate hornfelses and skarns) and greenish-grey nodular slates. This unnamed unit is in turn overlain by restricted outcrops of black silty slate SX(7192 6367), here defined as a new formation, the Corringdon Slate.

The Corringdon Slate is typically exposed in a quarry at SX(7093 6349) south-west of Deancombe. The exposure is comprised of 7m of black, chiastolite-bearing hornfelses. A rude cleavage dips gently south-east, and two prominent, sub-vertical joint sets (on which remobilised sulphides have crystallised) combine to impart a blocky fracture to the outcrop. Bedding is sub-parallel to cleavage and delineated by thin, white, lenticular, fine-grained sandstones. No fossils have been recovered from the Corringdon Slate and intense tectonism does not allow for an estimation of the thickness of the formation.

The Corringdon Slate crops-out between Deancombe SX(722 642) and Corringdon SX(674 604); it also crops-out in the area north of Ivybridge (Fig. 2B). Throughout its outcrop the dark-grey to black silty hornfelses are often chiastolite-bearing and are intruded by many sill-like dolerite pods. Thin sandstones and sandy lenses are common within the formation. Beds of immature, often coarse-grained, open-textured sandstones which are sometimes graded occur as an impersistent member (the Nurston sandstone) within the Corringdon Slate.

The Nurston Sandstone is typically developed in the track section in Thynacombe Wood at SX(7089 6294) where an extensively quartz-veined, composite, graded bed of immature, open-textured sandstone 0.75m thick which dips 40° south-east is isolated, in normal sequence, within a wide outcrop of black, chiastolite hornfelses. Near Nurston Farm SX(719 640) these sandstones contain mica, orthoclase, angular quartz grains and comminuted plant fragments. In the River Avon SX(690 614) massive, clean-washed quartzitic hornfelses crop-out; these are probably the sandstones from which Fitch (1933) recorded pink garnets among the heavy minerals. In the Ivybridge area these sandy hornfelses, sandy micaceous hornfelses, and quartzites predominate over the chiastolite hornfelses in the outcrop.

The Zempson Chert is a mappable formation which succeeds the Corringdon Slate. It consists of siliceous and siliceo-calcareous shales interbedded with true cherts; it contains an horizon of basic tuffs, both lithic and crystal which locally contain volcanic bombs. These rocks have been metamorphosed to calc-silicate hornfelses, skarns, cherts and hornfelsed tuffs. In the type section at Zempson Farm SX(713 629) where the lithology is least metamorphosed, 4m of silicified slate with isolated lenticular beds of pyritous, black, siliceous slate up to 0.5m thick crop-out: a calc-silicate hornfels mineralogy is developed in irregular patches. The contact between the Zempson Chert and the Corringdon Slate is implied by the presence of gradational lithologies between black shales and true cherts in Thynacombe Woods SX(704 636) south-east of Deancombe. A top to the Zempson Chert has not been identified.

The Zempson Chert crops-out between Zempson Farm SX(713 629) and Owley SX(675 597), it is extensively hornfelsed in this tract. In the Ivybridge area a restricted capping of calc-silicate hornfelses on Henlake Down SX(630 572) is referred to the Zempson Chert.

The Affinities of the Kate Brook Succession Greenish-grey slates bearing occasional bands of *Cyrtospirifer* have been identified east of Dartmoor (the Kate Brook Slate), between Dartmoor and Bodmin Moor (Whitchurch Green Slate) and westward towards the coast at Tintagel (Delabole Slate, Woolgarden Slate and Tredorn Slate). The Tredorn Slate is overlain conformably by dark grey and black slates which have yielded a *Gattendorfia Stufe* trilobite fauna at California Quarry, Selwood (1971). The nodular and calcareous slates which lie between the Kate Brook Slate and the black, silty Corringdon Slate south of Deancombe are comparable to members of the Stourscombe Formation of Stewart (1981) and the Upper Petherwin Beds of Setwood (1971), their presence indicates that, in the Deancombe area, the Kate Brook Slate passes upward into facies which are associated with the flanks of topographic highs in adjacent areas.

The Gurrington Slate and its equivalents to the west are, in part at least, coeval with the Kate Brook Slate and its western equivalents. The two facies contrast markedly. Whilst the Gurrington Slate contains an exclusively pelagic fauna and common spilitic volcanics, the Kate Brook Slate is typified by a benthonic fauna and rare volcanics.

The Corringdon Slate and the Nurston Sandstone are intruded by extensive sill-like dolerite sheets and pods which would argue strongly in favour of a Lower Carboniferous age for these rocks. The Zempson Chert is associated with an horizon of extrusive volcanics; the association of cherts and volcanics is common and widespread in Lower Carboniferous successions both east and west of Dartmoor. Where faunas occur an *anchoralis-Zone* age is indicated for the onset of chert deposition. The occurrence of immature sandstones in the succession is reminiscent of the Dinantian sandstones which are abundantly developed in the St Mellion outlier, Matthews (1966), Whiteley (1981).

The Structure of the area

Between Buckfastleigh and Ivybridge the three tectonic units are separated by thrusts (Fig. 2A). The structure of the Kate Brook Unit to the north of Brent Hill (Fig. 2C) is picked-out by the distribution of the stratigraphic elements; an envelope of Kate Brook Slate surrounds a much-sheared core of lithologies referable to the Lower

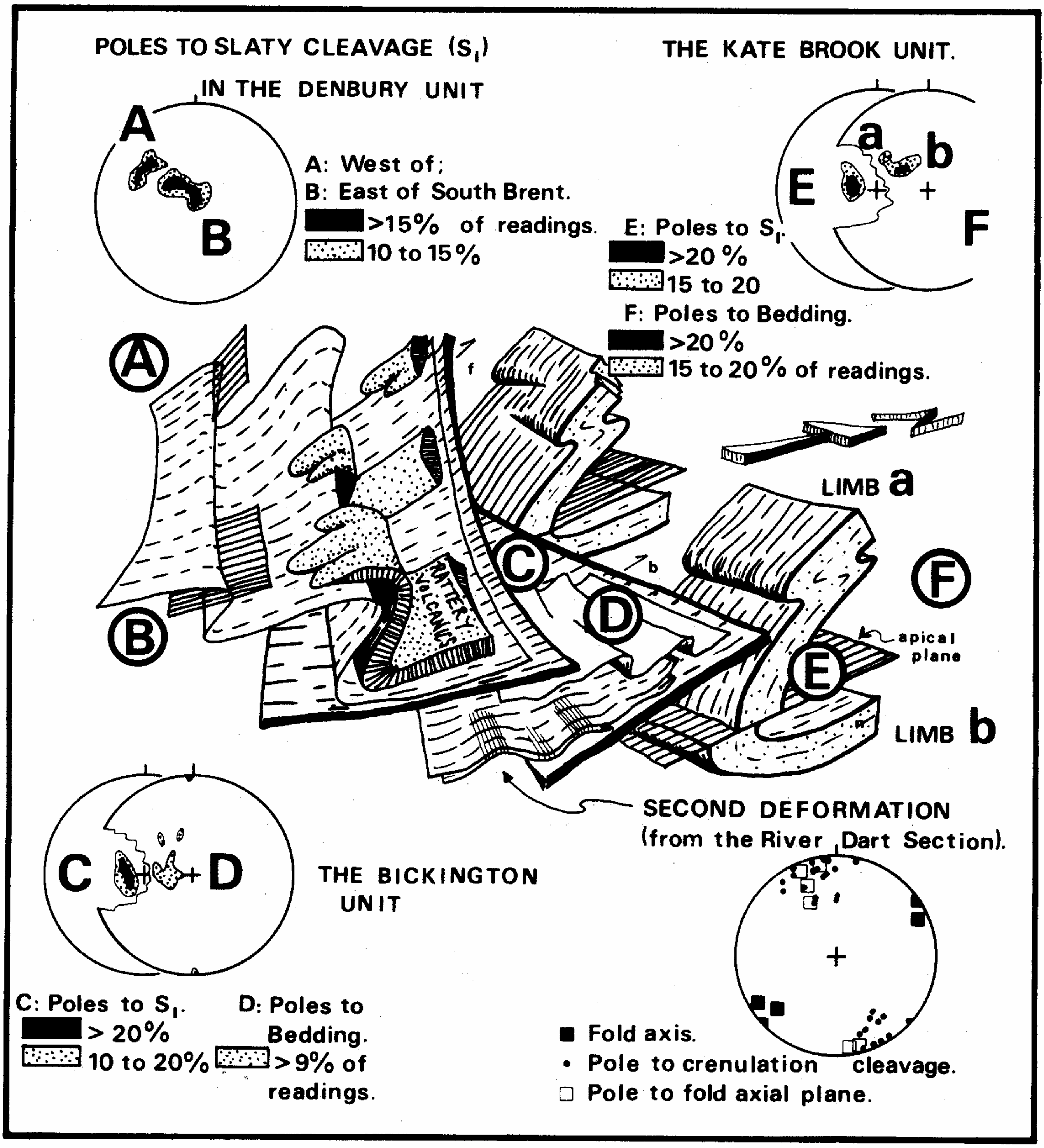

Figure 3. The structural styles and relationships between the Kate Brook Unit, the Bickington Unit and the Denbury Unit between Buckfastleigh and Ivybridge.

Carboniferous. Bedding/cleavage relationships and way-up evidence combined with the structural data (Fig. 3 E and F) indicates that a tight, reclined fold with an axial-planar slaty cleavage (SO dipping gently south-east lies to the north of Brent Hill beneath the Bickington Thrust. This simplified structure is complicated by minor thrusts (Fig. 2B and 2C), and vertical faults.

Interpretation of gross structure within the Bickington and Denbury Units is difficult because of the limited stratigraphic control and the sparcity of marker horizons. Structural data (Fig. 3) and the relationships between thin-bedded turbidites and slaty cleavage (S_1) in the Gurrington Slate indicate that tight, reclined to recumbent, north-facing folds with an axial-planar slaty cleavage dipping gently south-east characterise the first deformation in the Denbury and Bickington Units in the area east of South Brent.

A locally developed crenulation cleavage which dips steeply south-east is axial-planar to small-scale open folds which deform the slaty cleavage; a comparable S_1/S_2 relationship has been described from the Torquay area by Richter (1969). In the River Dart section the second deformation is closely associated with fracture-zones within the Gurrington Slate; this and the variation between the orientations of slaty cleavage maxima in the three structural units east of South Brent (Fig. 3) reflects post St movement on the major thrusts which separate them. To the west of South Brent slaty cleavage in the Denbury Unit dips south-east and steepens along the southern flanks of Dartmoor. This is not thought to be the result of turning against the granite because in the Ivybridge area the steeply dipping S_1 in the Denbury Unit is juxtaposed with the reclined, north-facing synclinal structure of the Kate Brook Unit (and its gently-dipping S_1) across a fracture which represents the westerly equivalent of the Forder Green Thrust or the Bickington Thrust; these relationships are expressed diagrammatically in Figure 3. The Dartmoor granite intrusion was emplaced in the already deformed slate sequences and in this area turning of strata against the intrusion is less than 10°.

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References

de la Beche, H.T. 1839. Report on the Geology of Cornwall, Devon and West Somerset. *Mem. Geol. Surv. G.B.*

Champernowne. A. 1881. The Ashburton Limestone: its age and relations. *Geol. Mag., 8.* 410-416.

Dearman. W.R. 1963. Wrench-faulting in Cornwall and South Devon. *Proc. Geol. Assoc., 74,* 265-287.

Fitch, A.A. 1933. Contact metamorphism in south-eastern Dartmoor. *Quart. J. Geol. Soc. Lond. 88.* 576-606.

Gauss. G.A. & House, M.R. 1972. The Devonian successions in the Padstow area, North Cornwall *Quart. J. Geol. Soc. Lond., 128.* 151-172.

Gooday, A.J. 1974. Ostracod ages from the Upper Devonian purple and green slates around Plymouth. *Proc. Ussher Soc.. 3.* 55-62.

Gooday, A.J. 1978. The Devonian. *In:* Bate, R. and Robinson, E (eds.) *A stratigraphical index of British Ostracoda.*

Matthews. S.C. 1966. Remarks on the Geology of the St Mellion Area. *Proc. Ussher Soc., 1,* 245-24T

Matthews, S.C. 1977. The Variscan foldbelt in southwest England. *N. Jb. Geol. Palaeont. Abh.. 154.* 94-127.

Orchard. M.J. 1978. The conodont biostratigraphy of the Devonian Plymouth limestone, South Devon. *Palaeontology, 21.* 907-955.

Richter, D. 1969. Structures and Metamorphism of the Devonian Rocks south of Torquay, South-east Devon (England). *Geol. Mitt., 9,* 109-178.

Riddolls, B.W. 1970. Devonian and Carboniferous geology south and west of Newton Abbot, Devon. *Unpubl Ph.D. Thesis. Univ. of Exeter.*

Scrutton C.T. 1977. Facies variation in the Devonian limestones of eastern south Devon. *Geol. Mag., 114,* 165-248.

Selwood, E.B. 1961. The Upper Devonian and Lower Carboniferous Stratigraphy of Boscastle and Tintagel, Cornwall. *Geol. Mag., 98,* 161-167.

Selwood E.B. 1971. Successions at the Devonian-Carboniferous Boundary between Boscastle and Dartmoor. *Proc. Ussher Soc., Z* 275-285.

Selwood, E.B., Edwards, R.W., Simpson, S. Chesher, J.A., Hamblin, R.J.O., Henson, M.R., Riddolls, B.W. and Waters. R.A. (in press). The geology of the country around Newton Abbot. *Mem. Geol. Surv. G.B.*

Stewart, I.J. 1981. Late Devonian and Lower Carboniferous conodonts from north Cornwall and their stratigraphical significance. *Proc. Ussher Soc., 5,* 179-185.

Ussher, W.A.E. 1901. Culm Measures Types of Great Britain. *Trans. Inst. Mining Engrs., 20,* 360-390,

Usshers, W.A.E. 1912. The geology of the country around Ivybridge and Modbury. *Mem. Geol. Surv. G.B.*

Waters, R.A. 1970. The Variscan Structure of East Dartmoor. *Proc. Ussher Soc.*, 2, 191-197.

Waters, R.A. 1974. Palaeozoic Successions and Structures Between Little Haldon and Dartmoor *Upubl. Ph.D. Thesis. Univ. of Exeter.*

Whiteley, M.J. 1981. The faunas of the Viverdon Down area, southeast Cornwall. *Proc. Ussher Soc., 5,* 186-195.

Ziegler, W., Klapper, G. and Johnson, J.G. 1976. Re-definition and sub-division of the *varcus-zone* (conodonts Middle? Upper Devonian) in Europe and North America. *Geologiea. Palaeont., 10,* 109-140.

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Chemistry of primary and secondary minerals in titaniferous brown amphibole-bearing greenstones from north Cornwall.

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P.A. Floyd and G. Rowbotham, 1982. Chemistry of primary and secondary minerals in titaniferous brown amphibole-bearing greenstones from north Cornwall. *Proc. Ussher Soc., 5,* 296-303.

Brown amphibole-bearing greenstones (so called "proterobases" or "minverites") from the Padstow area, north Cornwall, are kaersutite-bearing alkali dolerites that have been subsequently metamorphosed in the prehnite-pumpellyite facies. Apart from their primary hydrous nature they are chemically similar to other Devonian alkali dolerites. The relict primary assemblage of clinopyroxene (salite), brown amphibole (kaersutite), biotite (phlogopite-annite), iron ore and apatite is characterized by the highly titaniferous nature of all the mafic phases and salitic pyroxene compositions typical of alkali basalt magmas; High temperature reactions under hydrous conditions produced the crystallization sequence: (olivine)-clinopyroxene-brown amphibole-biotite. Secondary low-grade phases include: Al-pumpellyite, prehnite, chlorite (brunsvigite), epidote, muscovite, sphene. Actinolite is apparently lacking. The aluminous nature of the pumpellyite may reflect the degree of plagioclase breakdown relative to mafic degradation, as well as metamorphic grade.

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Introduction

Brown amphibole-bearing greenstones have been known in south-west England for a considerable time, although occurrences are relatively few compared with the more normal anhydrous types. They are mainly found in and around the Padstow, Polyphant and Plymouth areas (Ussher, 1907; Reid et al., 1910; Reid et al., t911; Dewey, 1914) where they intrude strata of mainly Upper Devonian age. These intrusive rocks are generally referred to as "proterobases" or "minverites" (the later after the type locality at St Minver, N. Cornwall) and have been compared with lamprophyres and essexites (Reid et al., 1910) or considered as members of the "spilite suite" (Dewey, 1914) in the early literature. However, the presence of a number of potassium-rich phases not seen in the majority of intrusive greenstones, led Floyd (1976) to consider the "proterobases"? as a potassic suite of alkali basalts relative to the more normal types of greenstone which represent a sodic alkali lineage.

In view of the paucity of recent data on these particular greenstones, a preliminary chemical and mineralogical study was undertaken on samples from a large sill-like outcrop at Trevone Bay, 3km west of Padstow on the north Cornish coast (grid reference SW890762). The two main objectives of this work relate to the primary and secondary mineral assemblages exhibited by the samples: (1) the petrogenesis of hydrous alkaline basalt magma relative to the dominant Upper Palaeozoic intrusive rocks which appear to have crystallized from anhydrous melts, and (2) determination of the grade of regional metamorphism that affected these rocks during the Hercynian orogeny.

Petrography

The primary and secondary mineral assemblages and their replacement relationships are shown in Table 1. Although olivine has not been observed, its possible existence may be inferred from the presence of small chlorite ovoids often developed within clinopyroxene crystals.

Alkali feldspar, sometimes reported in the early literature (Reid et al., 1910), has not been found. Colourless clinopyroxene occurs as subhedral crystals which are variably replaced by dark brown amphibole around their margins or along the cleavage as well as an occasional patchy internal replacement. Neither of these primary minerals are optically zoned. A few ragged flakes of dark brown biotite are present either growing on brown amphibole, adjacent to clinopyroxene or as isolated grains in mafic-dominated matrix. Grains of titaniferous iron ore are often associated with the brown amphibole and when enclosed within large amphibole prisms are subrounded and appear to have been corroded. Iron ore was clearly precipitated before amphibole and underwent

Table 1. Relationships between primary and secondary minerals in brown amphibole-bearing metadolerite from Trevone Bay, near Padstow. Vertical line connects primary crystallization-reaction sequence; horizontal lines connect secondary breakdown products to primary phases.

Primary assemblage	Secondary assemblage
(Olivine) →	chlorite ovoids in clinopyroxene
(Calcic plagioclase) →	albite, prehnite, pumpellyite, carbonate, epidote, muscovite
Clinopyroxene	
Titaniferous iron ore →	sphene rims
Apatite	
Brown Ti-amphibole →	chlorite, sphene granules
Ti-biotite →	chlorite, sphene granules, epidote

reaction with hydrous fluids in areas of amphibole growth. The subophitic relationship of plagioclase to clinopyroxene indicates early growth of (originally) a calcic plagioclase, although this has now been largely replaced by secondary CaAl silicates and albite. Apatite is an important assessory, occurring as large elongate prisms (sometimes cored) which grew prior to the brown amphibole. The sequence of primary mineral crystallization was as follows:-
(olivine)-calcic plagioclase-clinopyroxene, iron ore and/or apatite-brown amphibole-biotite. Reaction relationships with falling temperature within the hydrous melt are shown by the major mafic phases: (olivine)-clinopyroxene-brown amphibole-biotite.

Of all the major phases clinopyroxene is the only one that has not been altered during low-grade metamorphism. Even clinopyroxene crystals unmantled by brown amphibole have not developed a fringe of secondary actinolite, although this type of alteration is seen in the Launceston area (Reid et al., 1911). Brown amphibole is patchily replaced by pale green chlorite around its margins and along cleavages. Iron ore may develop a thin veneer of sphene 'when not enclosed within brown amphibole crystals. Plagioclase has been the most affected by low-grade hydrous metamorphism with the ubiquitous development of prehnite and varying proportions of pumpellyite, carbonate, epidote and muscovite. All still recognisable plagioclases are now, almost pure albite or variably pseudomorphed by the above secondary minerals. In some cases secondary replacement of felsic areas has been extreme with irregular domains of prehnite, large, colourless, radiate pumpellyite sheaves and minor carbonate, epidote and muscovite. In some of these areas even apatite, which is generally unaltered, has an irregular corroded outline. Biotite is often replaced by pale green to colourless chlorite in association with numerous sphene granules and minor epidote. Both these latter minerals represent by-products of the chloritization process with Ti and Fe from the biotite entering sphene and epidote respectively. Ca was derived from the breakdown of adjacent primary calcic plagioclase. The secondary assemblage developed is typical of low-grade hydrous metamorphism in the prehnite-pumpellyite facies. The complete lack of actinolite and the relatively minor occurrence of epidote group minerals suggests that it represents the lower grade prehnite-pumpellyite subfacies as defined by Schermerhorn (1975).

On the basis of their present mineralogy and textural features these greenstones are metadolerites.

Bulk rock chemistry

Chemical analyses of the brown amphibole-bearing greenstones (or more strictly metadolerites) from the literature and a new analysis of a sample (PA.I) from Trevone Bay are presented in Table 2. These dolerites are characterized by high TiO_2 (reflecting the high proportion of titaniferous ore and the high Ti content of all the primary mafic phases) and high P_2O_5 (indicative of the abundance of apatite). The highly variable K_2O content is to be expected in rocks where the main K phase (biotite) has been chloritized to different degrees. In general terms the dolerites are incompatible element rich alkali basalts as exhibited by the high Ba, Sr and light REE contents of sample PA.I (Table 2). This particular sample, within which many separate mineral phases were analysed, is also well-fractionated as indicated by its high FeO*/MgO ratio and low Ni and Cr contents.

Utilizing TiO_2 and P_2O_5, which are relatively stable during secondary alteration (Floyd & Winchester, 1975), the brown amphibole-bearing dolerites can be compared with other intrusive greenstones from south-west England (Fig. 1). Excluding the dolerites intrusive into Carboniferous strata, the Ti and P distributions define two adjacent, slightly overlapping, areas for Devonian tholeiitic and alkaline dolerites respectively. The brown amphibole-bearing dolerites are chemically related to the Devonian alkaline dolerites and are clearly different to the Permian lamprophyres and high-K shoshonitic basalts. Although the more biotite-rich dolerites of the brown amphibole-bearing suite have been mineralogically compared with some lamprophyre groups (e.g., minettes) the former rocks have far too low, P, Ba, Zr, Y, Nb and light REE contents to be directly related magmatically.

Chemically and mineralogically the brown amphibole-bearing dolerites have features in common with other Devonian alkali basaltic rocks, except that crystallization must have taken place under hydrous conditions such that primary amphibole and biotite were precipitated.

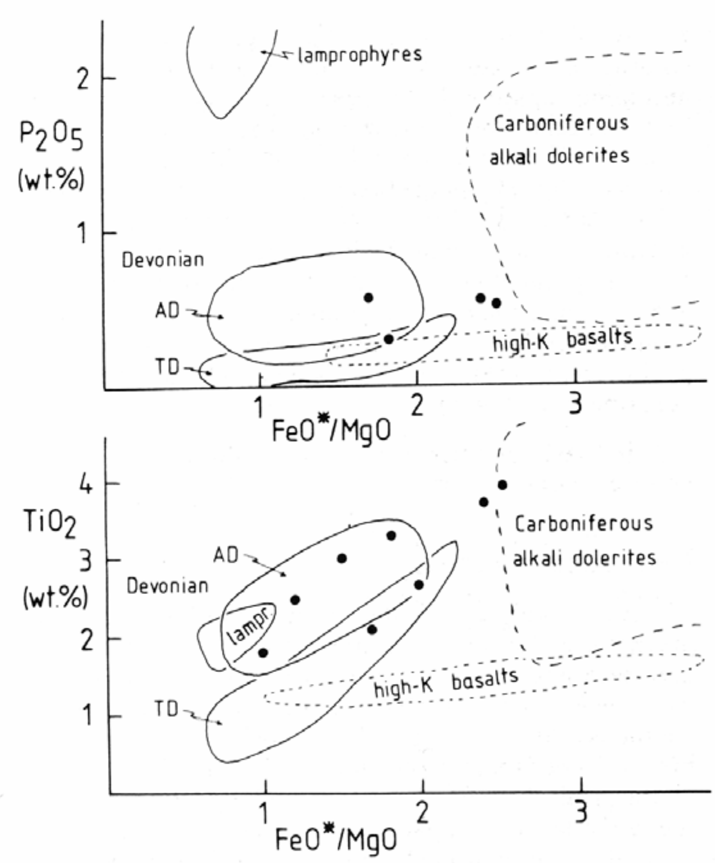

Figure 1. Distribution of TiO_2 and P_2O_5 in brown amphibole bearing metadolerites compared with Devonian tholeiitic metadolerites (TD field) and alkaline metadolerites (AD field), as well as Permian lamprophyres and high-K shoshonitic basalts (data from Cosgrove, 1972) from S.W. England.

Primary mineral chemistry

Examples of the chemical range shown by the main primary phases are listed in Table 3 together with their formulae.

Pyroxene.

All the Padstow clinopyroxenes are very rich in Ca and plot in the salite field of the pyroxene quadrilateral adjacent to the Di-Hd tieline (Fig. 2). Rim and core analyses suggest that intracrystalline chemical zoning is minimal and that the pyroxenes crystallized under equilibrium conditions. Whereas Cr and Mn values are close to the analytical detection limit, the main non-quadrilateral components (Na, Al, Ti) are relatively high (Table 3) and together with the overall salitic composition indicate that these pyroxenes crystallized from an alkaline magma. Apart from their highly calciferous nature they are similar in composition to clinopyroxenes analysed by Morton & Smith (1971) from the Ryecroft alkaline dolerite (Fig. 2). Relatively high levels of Na, Al and Ti were also found in the Mullion Island tholeiitic lavas (Floyd & Rowbotham, 1979), although this feature and the wider range of compositions displayed (Fig. 2) reflect disequilibrium quench crystallization in the lavas. In contrast to the Mullion Island data, the clinopyroxenes analysed here are more uniform in composition and show no Ti enrichment at the rims. Na is systematically higher than the Mullion Island clinopyroxenes reaching a maximum of 0.05 atoms in the structural formula.

All the clinopyroxenes analysed from south-west England greenstones, irrespective of their tholeiitic or alkaline parent magma, show a considerable variation in Ti and Al contents (Fig. 2). The Padstow clinopyroxenes reach a maximum Ti content of 0.085 atoms with 0.32 atoms A1 and have a consistent 1:4 Ti/A1 ratio (Fig. 2). Systematic variation of this type suggests two possible substitutions (e.g. Bence et al., 1970) for incorporating A1 into clinopyroxenes:

(a) $R^{2+} + 2Si \rightleftharpoons Ti + 2AlIV$

(b) $R^{2+} + Si \rightleftharpoons A1VI + AlIV$

where R^{2+} = Mg, Fe, Mn.

Brown amphibole

The analysed amphiboles were both discrete grains and crystals growing on salites and showed little chemical variation either within or between individual crystals. Their compositions were recalculated on the basis of 23 oxygens using the formula: A X_2 Y_5 Z_8 O_{22} $(OH)_2$ where A = K, Na; X = Ca, Na; Y = Mg, Fe^{2+}, Mn, Fe^{3+}, Al, Ti; Z = Si, Al. The "A" sites are almost entirely filled with alkali ions (0.81 - 0.96) with an essentially constant K content of 0.17 - 0.19 atoms. The "X" sites are dominated by Ca with Smaller amounts of Na required to fill the site (0.12-0.18 Na atoms). In the octahedral sites ("Y") there is almost always a-slight deficiency (maximum of 0.076 atoms). Mg and Fe are the most important cations which occupy these sites (the Mg/Mg + Fe ratio varies from 0.55 to 0.62) whereas Mn is exceedingly low and Ti concentrations extremely high (0.52-0.63 atoms). In the tetrahedral sites ("Z") A1 replaces Si to a maximum of 2.09 atoms and no site deficiencies are indicated.

All the amphiboles belong to the calciferous amphibole group and as they contain >0.50 atoms of Ti (Fig. 2) are strictly kaersutites (amphibole nomenclature, Leake, 1978). A number of coupled substitutions have been suggested for the incorporation of Ti into the amphibole structure, several of which involve vacancies in the lattice, e.g. Ti + □ ⇌ Na + A1IV (Giret et al., 1980). As there are only very slight deficiencies in the Padstow kaersutites and the Ti/Al ratio is constant at i:4 (Fig. 2) the most reasonable coupled substitution is:

$R^{2+} + 2Si \rightleftharpoons Ti + 2AlIV$

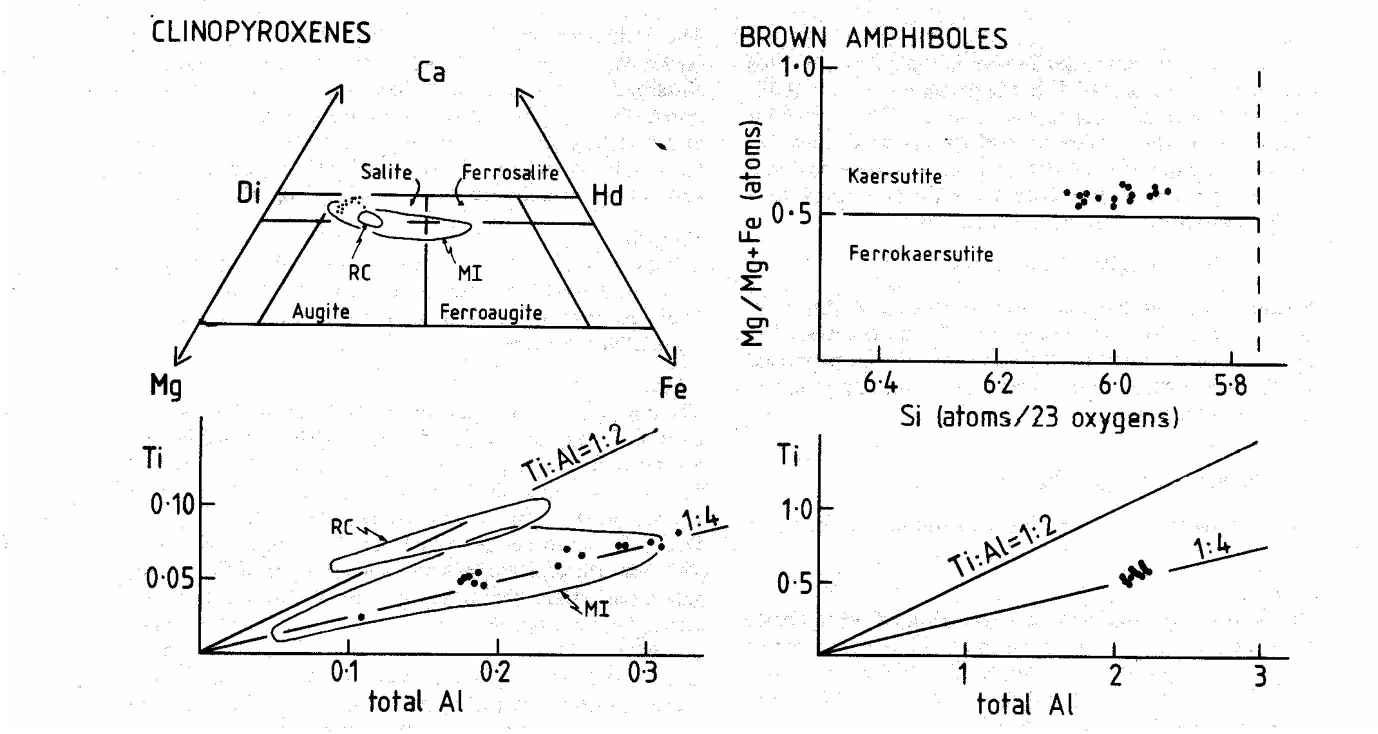

Figure 2, Classification and Ti-A1 relationship in primary clinopyroxene and brown amphibole from an alkaline metadolerite, Trevone Bay, near Padstow (sample PA.1). Enclosed fields for clinopyroxenes: RC = Ryecroft alkali dolerite sill, Teign Valley, E. Devon (Morton & Smith, 1971); MI = Mullion Island, tholeiitic pillow lavas, west Lizard coast (Floyd & Rowbotham, 1979).

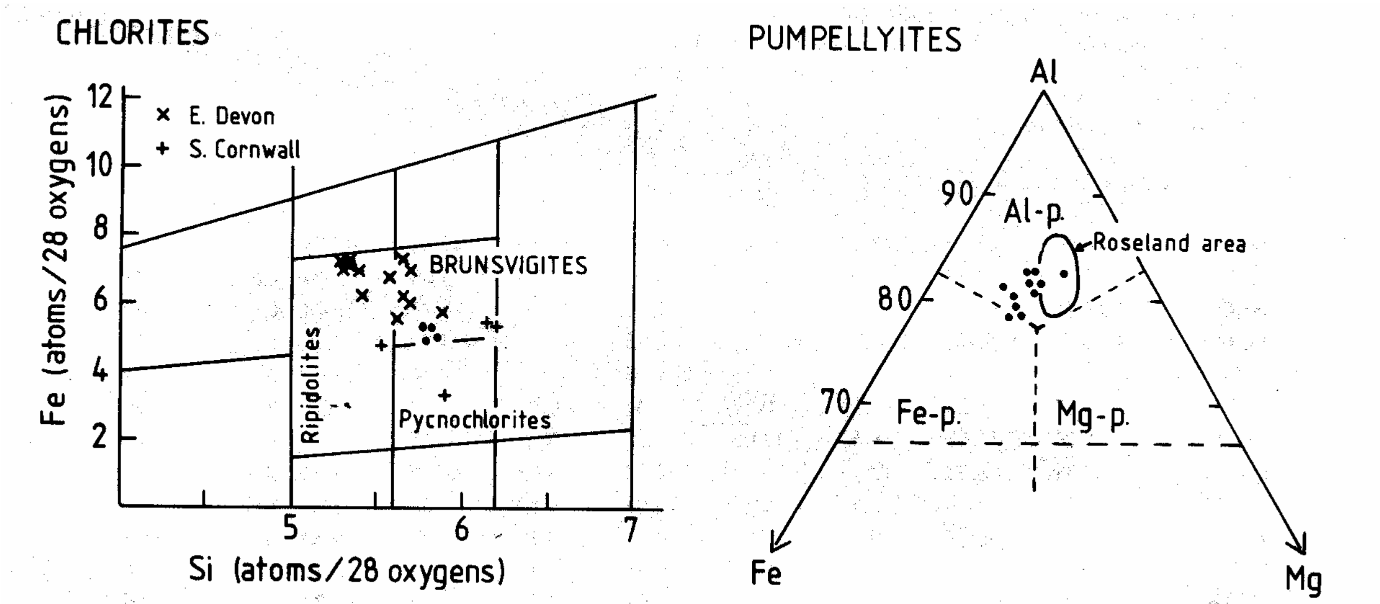

Figure 3. Classification of secondary chlorite and pumpellyite from an alkaline metadolerite, Trevone Bay, near Padstow (sample PA.1). Dots represent new data from this work. Additional chlorite data from E. Devon (Morton & Smith, 1971) and S. Cornwall (Floyd & Rowbotham, 1979; Barnes & Andrews, 1981). Pumpellyite field from the Roseland area, S. Cornwall, are data from Barnes & Andrews (1981). Chlorite classification after Hey (1954) and pumpellyite diagram and classification from Coombs et al. (1976) and Passaglia & Gottardi (1973).

Biotite
The analyses indicate that biotite is highly titaniferous with up to 0.75 atoms of Ti per formula unit and that it is a member of the phlogopite-annite series. There are slight deficiencies in the octahedral and "potassium" sites. On the basis of experimental data, Robert (1976)considered that Ti enters the biotite structure in the octahedral sites and proposed the coupled substitution:

$$R^{2+} + 2Si \rightleftharpoons Ti + 2AlIV$$

A similar scheme has also been suggested by Arima & Edgar (1981) for mantle-derived Ti-phlogopites. The above coupled substitution is the same as that proposed for Ti incorporation into the pyroxenes and amphiboles of the present study.

Secondary mineral chemistry

Selected analyses and calculated formulae are shown in Table 3.

Pumpellyite
The pumpellyite analyses were recalculated on the basis of 16 cations due to the uncertainty of the number of oxygens in the structural formula (Coombs et al., 1976): W_4 $X_2.Y_4$ Z_6 O(20+x) (OH) (8-x) where W = Ca, Mn; X = (Mg, Fe^2+, Mn)$_2$ -x (Fe^3+, Al)x; Y = Fe^3+, Al; Z = Si.

The Padstow pumpellyite data were plotted (Fig. 3) on an A1-Fe-Mg diagram (Coombs et al., 1976) and are classified (after Passaglia & Gottardi, 1973) as aluminous pumpellyites. They have a composition not unlike pumpellyites described from the Roseland area, south Cornwall by Barnes & Andrews (1981), although in general are marginally more Fe-rich (Fig. 3).

Prehnite
Little can be said concerning prehnite as they are all very pure and show little or no substitution of Fe^{3+} for Al. The analysed prehnite flakes were all adjacent to stellate pumpellyite groups.

Chlorite
The compositional variation of the Padstow chlorites are exhibited on an Si-Fe diagram (Fig. 3) using the classification scheme of Hey (1954). They are all brunsvigites and show a very limited compositional range. On the other hand, chlorites from the low-grade Ryecroft metadolerite from E. Devon (Morton & Smith 1971) are ripidolites and show a wide range of Fe content reflecting different bulk compositions within the sill for example, the total Fe content varies from 9.5-13.9 weight % FeO_2. Tholeiitic basalts from Roseland, south Cornwall metamorphosed in the pumpellyite-actinolite facies contain various pycnochlorites (Barnes and Andrews, 1981), whose composition again reflects, in part, variations in bulk rock chemistry.

Table 2. Chemical analyses of brown amphibole-bearing metadolerites from south-west England. Major elements in wt.%, trace elements in ppm. 1-5 from Padstow area (Reid et al., 1910; Juteau & Rocci, 1974), 6 & 7 from Plymouth area (Ussher, 1907) and 8 from Trevone Bay, Padstow area (PA.1 - new analyses, this work).
- indicates not analysed.

	1	2	3	4	5	6	7	8	(traces)	
SiO_2	45.80	40.90	43.10	43.00	42.86	47.19	42.88	45.75	Ba	263
TiO_2	2.67	2.53	3.06	1.81	3.30	2.09	3.68	3.94	Cc	75
Al_2O_3	15.54	13.40	13.75	10.10	13.81	13.96	14.31	16.84	Cr	45
Fe_2O_3	(11.63)	(15.40)	(14.33)	(14.16)	1.93	3.39	4.70	1.18	La	31
FeO	-	-	-	-	11.64	9.01	9.44	10.64	Nb	22
MnO	0.17	0.21	0.23	0.17	0.44	0.47	0.32	0.22	Nd	34
MgO	5.29	11.67	8.57	13.00	7.33	7.10	5.67	4.67	Ni	46
CaO	8.48	8.32	10.17	6.32	12.84	8.08	10.90	9.54	Rb	9
Na_2O	3.57	2.48	3.00	1.13	2.03	4.50	2.52	3.58	Sc	31
K_2O	1.81	0.52	0.82	1.03	0.13	0.70	1.92	0.80	Sr	992
P_2O_5		-	-	-	0.30	0.56	0.54	0.51	Y	24
$H2O^+$	-	-			2.81	2.56	2.52	3.20	Zr	186
$H2O^-$	-	-		-	0.13	0.12	0.25	-		
CO_2		-	-		0.22	0.79	0.13	-		
LOI	4.61	4.29	3.11	5.60	-	-	-	-		
FeO*/ MgO	1.98	1.19	1.50	0.98	1.82	1.70	2.41	2.51		

Table 3. Representative mineral analyses (and calculated formulae) from a brown amphibole-bearing alkali metadolerite, Trevone Bay, near Padstow (sample PA.I). Analyses express maximum range of compositional variation (a and b).
- indicates below instrumental detection limit.

Analyses	Clinopyroxene		Ti-amphibole		Ti-biotite		Plagioclase		Chlorite		Pumpellyite		Prehnite		Muscovite
(wt.%o)	a	b	a	b	a	b	a	b	a	b	a	b	a	b	
SiO_2	49.63	51.59	40.27	39.83	34.90	34.73	68.26	67.35	27.59	26.91	36.81	36.85	42.92	43.18	45.35
TiO_2	1.72	0.86	5.38	4.86	6.25	6.52	-	-	0.02	-	-	0.01	-	-	0.11
Al_2O_3	4.15	2.47	12.30	11.06	14.79	14.74	20.13	20.25	18.04	17.70	26.39	25.26	23.61	24.74	37.37
FeO	7.29	9.83	12.59	18.38	25.96	25.94	0.28	0.27	29.12	29.02	2.71	6.01	0.28	0.04	0.15
MnO	0.10	0.29	0.22	0.21	0.27	0.34	-	-	0.27	0.35	0.31	0.09	0.07	-	0.08
MgO	13.90	12.56	11.68	8.08	7.00	6.81	-	-	14.06	13.65	2.70	1.98	-	-	-
CaO	22.23	22.81	11.67	11.17	0.18	0.08	0.13	0.78	-	0.11	22.67	22.61	25.66	26.37	0.09
Na_2O	0.36	0.54	3.22	2.55	0.33	0.44	11.81	11.15	0.16	0.11	0.36	0.17	0.35	0.04	0.32
K_2O	-	-	0.92	1.46	8.78	9.03	0.02	0.06	-	-	0.06	-	-	0.11	10.56
Cr_2O_3	0.22	0.12	0.01	0.08	0.02	-	-	-		0.04	-	0.10	0.10	0.11	-
Formulae															
Si	1.855	1.921	5.986	6.124	5.337	5.315	2.969	2.954	2.909	2.892	5.928	5.951	5.508	5.444	6.073
Ti	0.048	0.024	0.601	0.563	0.719	0.751	-	-	0.001	-	-	-	-	-	0.011
Al	0.183	0.108	2.154	2.005	2.666	2.659	1.032	1.047	2.241	2.241	4.999	4.800	3.572	3.676	5.900
Fe	0.228	0.306	1.565	2.363	3.320	3.320	0.010	0.010	2.568	2.608	0.363	0.808	0.030	0.004	0.017
Mn	0.003	0.009	0.028	0.027	0.035	0.044	-	-	0.024	0.032	0.043	0.013	0.008	-	0.009
Mg	0.774	0.697	2.589	1.851	1.595	L555	-	-	2.210	2.186	0.646	0.475	-	-	-
Ca	0.890	0.910	1.859	1.840	0.029	0.013	0.006	0.037	-	0.013	3.910	3.912	3.529	3.563	0.013
Na	0.026	0.039	0.928	0.761	0.099	0.131	0.996	0.948	0.032	0.022	0.110	0.054	0.087	0.010	0.083
K	-	-	0.174	0.286	1.714	1.763	0.001	0.003	-	-	-	-	-	0.017	1.804
Cr	0.007	0.004	0.002	0.009	0.003	-	-	-	-	0.003	-	-	0.010	0.011	-
No. of oxygens or (cations)	6		23		22		8		14		-16		20		22

Muscovite
The white mica is almost pure muscovite with very little Fe and no Mg substituting for Al in the octahedral sites (Table 3). As muscovite is invariably associated with altered primary plagioclase, minor K within this phase is probably released on albitization and incorporated into locally developed white mica.

Plagioclase
All the plagioclase in the Padstow metadolerite has been completely altered during low-grade metamorphism and no relect primary magmatic compositions were found. The plagioclase is essentially pure albite (Table 3) with a maximum anorthite content of only An_5.

Discussion and conclusions

Petrogenesis
In terms of bulk chemistry the Padstow greenstone is a well-evolved, *incompatible* element enriched alkali dolerite, only differing from other Devonian alkali basic intrusives in containing brown amphibole.

The single characteristic feature of the chemistry of the primary mafic phases is their titaniferous nature and in conjunction with the salite composition and high non-quadrilateral component content of the clinopyroxene underlines the alkaline nature of the host basalt magma. Textural relationships and phase compositions indicate equilibrium crystallization under hydrous conditions at high, but falling temperatures with the progressive development of olivine, clinopyroxene, brown amphibole and finally biotite.

The mantling of kaersutite amphibole on early clinopyroxene indicates reaction between the melt and titaniferous pyroxene (cf. Donaldson, 1977, for the Quarsut sill), although the corroded titaniferous ore enclosed within the kaersutite suggests this phase may also be involved. A study by Lamoen (1980) of Ti-amphibole-bearing gabbros has also indicated that amphibole growth involved reaction between an extensive ore phase and early plagioclase. Experimental data on kaersutitic amphiboles (e.g. Helz, 1973; Ford, 1976) demonstrate that high Ti contents indicate crystallization at high temperatures and that they are stable up to about 1000-1100°C over a considerable pressure range, although kaersutite in association with clinopyroxene may coexist up to 1050° at relatively low pressures (Yagi et al., 1975). The actual upper stability limit of kaersutite however, is dependent on XH_2O and oxygen fugacity. The kaersutite studied here probably crystallized at very high temperatures and low fO2 conditions, although the proportions of water in the fluid phase is unknown.

The growth relationship and high Ti content of the biotite indicate that it is a primary phase (rather than metamorphic) and crystallized at a high temperature. Comparison with experimental data (Robert, 1976) shows that the Padstow biotite contains the maximum number of Ti atoms per unit formula (0.7) for crystallization at about 1000°C and 1kb pressure in an iron-free system.

Metamorphic grade

Recent metamorphic studies in south-west England have focussed on clay mineral assemblages in pelites (Brazier et al., 1979; Grainger and Witte, 1981) and analysis of secondary phases in meta-basic rocks (Floyd and Rowbotham, 1979; Barnes and Andrews, 1981; Robinson and Read, 1981) to elucidate metamorphic grade. The presence of prehnite and pumpellyite in the Padstow alkali dolerite, the paucity of epidote group minerals and the lack of actinolite indicates that it was metamorphosed in the prehnite-pumpellyite facies. Although there is some argument over the facies status of pumpellyite bearing rocks (e.g. Coombs et al., 1976; Schermerhorn 1975), the Padstow metadolerites probably represent a lower grade than the pumpellyite-actinolite metabasalts of the Roseland area, S. Cornwall, described by Barnes and Andrews (1981). It is generally assumed that the composition of pumpellyite reflects grade with aluminous types representing Pumpellyite-actinolite or glaucophane schist facies conditions (Coombs et al., 1976; Ernst et al., 1970) whereas iron rich types typify zeolite facies (Kawachi, 1975; Liou, 1979; Liou and Ernst, 1979). Certainly the general similarity in composition of the pumpellyites from south-West England rules out any effect of bulk composition occurring in both tholeiitic and alkaline basaltic rocks. However, the Padstow Al-pumpellyite is not associated with actinolite, as documented in other regional terrains, which suggests that its composition may not be wholly influenced by grade. Recently Offler et al. (1981) demonstrated that pumpellyites from low-grade terrains can be chemically very variable and possibly related to the degree of alteration of the primary phases, in particular Fe-Ti oxides. It was suggested that Al-pumpellyite, in the least altered rocks, forms from plagioclase, but as degradation proceeds Fe-pumpellyite develops obtaining Fe from ore and altered mafic minerals. This suggestion may have some bearing on the aluminous nature of the Padstow pumpellyite which is exclusively developed in plagioclase dominated areas and where most of the Fe ore is armoured against degradation within kaersutite.

Compared with chlorites from other low-grade metamorphic terrains the composition of the Padstow brunsvigites are typical of the prehnite-pumpellyite or greenschist facies (Liou, 1979; Liou & Ernst, 1979), whereas ripidolite chlorites have been described from the pumpellyite-actinolite facies (Coombs et al., 1976). Zeolite facies chlorites generally have higher Si/(Si + Al) values (Liou, 1979) and are represented by penninites and diabantites.

In conclusion the Padstow greenstone studied here was the product of hydrous, high temperature, equilibrium crystallization of alkaline basaltic magma. It was subsequently metamorphosed to the prehnite-pumpellyite facies during the Hercynian orogeny. Strictly speaking this particular group of greenstones are kaersutite-bearing alkali metadolerites and the term "proterobase" should be discarded.

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References

Arima, M. and Edgar, A.D. 1981. Substitution mechanisms and solubility of titanium in phlogopite from rocks of probably mantle origin. *Contrib. Mineral. Petrol., 77,* 288-295.

Barnes, R.P. and Andrews. J.R. 1981. Pumpellyite-actinolite grade regional metamorphism in S. Cornwall. *Proc. Ussher Soc., 5.* 139-146.

Bence. A.E., Papike, J.J. and Prewitt, C.E. 1970. Apollo 12 clinopyroxenes: chemical trends. *Earth Planet. Sci. Lett.. 8* 393-399.

Brazier, S.. Robinson, D. and Matthews, S.C. 1979. Studies of illite crystallinity in south-west England; some preliminary results and their geological setting. *N. Jb. Geol. Palaeont. Mb. 1L* 641-662.

Coombs, D.S., Nakamura, Y. and Vuagnat, M. 1976. Pumpellyite-actinolite facies schists of the Taveyanne Formation, near Loeche, Valais, Switzerland. *J. Petrol.. 17,* 440-471.

Cosgrove, M.E. 1972. The geochemistry of the potassium-rich Permian volcanic rocks of Devonshire, England. *Contrib. Mineral. Petrol.. 36.* 155-170.

Dewey, H. 1914. The geology of north Cornwall. *Proc. Geol. Assoc., 25,* 154-179.

Donaldson. C.M. 1977. Kaersutite overgrowths on highly aluminous titanaugite m the Quarsut sill. *Mineral. Mag., 41,* 297-300.

Ernst, W.G., Seki, Y., Onuki, H. and Gilbert, M.C. 1970. Comparative study of low-grade metamorphism in the California Coast Ranges and the metamorphic belt of Japan. *Geol. Soc. Am. Mem., 124.*

Floyd, P.A. and Winchester, J.A. 1975. Magma type and tectonic setting discrimination using immobile elements: *Earth Planet. Sci. Lett., 27,* 211-218.

Floyd, P.A. 1976. Geochemical variation in the greenstones of S.W. England. *J. Petrol., 17,* 522-545.

Floyd, P.A. and Rowbotham, G. 1979. Chemical composition of relict clinopyroxenes from the Mullion Island lavas, Cornwall. *Proc. Ussher Soc., 4,* 419-429.

Ford, C.E. 1976. Stability field of a natural kaersutite. *Prog. Expt. Petr. N.E.R.C., 3,* 285-288.

Giret, A., Bonin, B. and Leger, J.M. t980. Amphibole compositional trends in oversaturated and undersaturated alkaline plutonic ring complexes. *Can. Mineral., 18,* 481-495.

Grainger, P. and Witte, G. 1981. Clay mineral assemblages of Namurian shales in Devon & Cornwall. *Proc. Ussher Soc., 5,* 168-178.

Helz, R.T. 1973. Phase relations of basalts in their melting range at pH20 = 5 kb as a function of oxygen fugacity. *J. Petrol.; 14,* 249-302.

Hey, M.H. 1954. A new review of the chlorites. *Mineral. Mag., 30,* 277-287.

Juteau, T. and Rocci, G. 1974. Vers une meilleure connaissance du probleme des spilites a partir de donnees nouvelles sur le cortege spilite-keratophyrique hercynotype. *In:* Amstutz, G.C. (ed.) *Spilites and spilitic rocks* Springer-Verlag, Berlin. 253-329.

Kawachi, Y. 1975. Pumpellyite-actinolite and contiguous facies metamorphism in part of the upper Wakatipu District South, Island, New Zealand. *N.Z.J. Geol. Geophys., 18,* 401-441.

Kuniyoshi, S. and Liou, J.G. 1976. Burial metamorphism of the Karmutsen volcanic rocks, northeastern Vancouver Island, British Columbia. *Am. J. Sci., 276,* 1096-1119.

Lamoen, H. van., 1980. Ti zoning in corona hornblende of iron ore-bearing gabbros, Susimaki, Finland. *N. Jb. Min. Mh., 17,* 88-96.

Leake B.E. 1978. Nomenclature of amphiboles (for sub-committee on amphiboles, I.M.A.), *Mineral. Mag., 42,* 533-563.

Liou, J.G. 1979. Zeolite facies metamorphism 0f basaltic rocks from the East Taiwan ophiolite. *Am. Mineral., 64,* 1-14.

Liou, J.G. and Ernst, W.G. 1979. Oceanic ridge metamorphism of the East Taiwan ophiolite. *Contrib. Mineral. Petrol., 68,* 335-348.

Morton, R.D. and Smith, D.G.W. 1971. Differentiation and metasomatism within a Carboniferous spilite-keratophyre suite in S.W. England. *Mineral. Soc. Japan. Spec. Pap, 1,* 127-133.

Offler, R., Baker, C.K. and Gamble, J. 1981. Pumpellyites in two low-grade metamorphic terrains north of Newcastle, N.S.W., Australia. *Contrib. Mineral. Petrol., 76,* 171-176.

Passaglia, E. and Gottardi, G. 1973. Crystal chemistry and nomenclature of pumpellyites and julgoldites. *Can. Mineral.,* 12. 219-223.

Reid, C., Barrow, G. and Dewey, H. 1910. Geology of the country around Padstow and Camelford (sheets 335 and 336). *Mem. Geol. Surv. G.B.*

Reid, C., Barrow, G., Sherlock, R.L., Macalister, D.A. and Dewey, H. 1911. Geology of the country around Tavistock and Launceston (sheet 337). *Mem Geol. Surv. G.B.*

Robert, J.L. 1976. Ti solubility in synthetic phlogopite solid solutions: *Chem. Geol., 17,* 213-227.

Robinson, D. and Read, D. 1981. Metamorphism and mineral chemistry of greenschists from Trebarwith Strand, Cornwall. *Proc. Ussher Soc., 5,* 132-138.

Schermerhorn; L.J.G. 1975. Pumpellyite facies metamorphism in the Spanish Pyrite Belt. *Petrologie, 1,* 71-86.

Ussher, W,A.E- 1907 Geology of the country around Plymouth and Liskeard {sheet 348), *Mem. Geol. Surv. G.B.*

Yagi, Hariya, H., Onuma, K, and Tukushima, N. 1975. Stability relations of kaersutite. J. *Fac. Sci. Hokkaido Univ. (Series IV), 16,* 331-342.

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Hydothermal circulation and post-magmatic changes in granites of south-west England

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E.M. Durrance, A.V. Bromley, C.M. Bristow. M.J. Heath and J.M. Penman. 1982. Hydrothermal circulation and post-magmatic changes in granites of south-west England. *Proc. Ussher Soc., 5,* 304-320.

Prolonged hydrothermal convective circulation within the granites of south-west England is indicated by metalliferous mineralisation and kaolinisation processes which have acted since the time of granite emplacement. The requirements for hydrothermal circulation - a sufficient heat source and suitable permeability - are found to allow *modern* convective flow within the granites. Radiogenic heat maintains the granites at elevated temperatures, and the results of an electrical resistivity survey of the top few kilometres of the Dartmoor granite show that the *in situ* permeability is likely to be high. ^{222}Rn and U distributions in Dartmoor stream waters suggest that low values indicate sites of convective drawdown, with upwelling in adjacent areas giving high values. Residual compressive stress, acting mainly in an approximately NNW-SSE direction appears to control the high permeability pathways by opening fractures which trend in this direction. The present day heat flow pattern and distribution of thermal mine waters confirms the general character of the convective cells. The evolution of hydrothermal convective circulation since the emplacement of the granites suggests reactivation of convective cells by tectonic activity reopening fractures and the periodic input of enhanced mantle heat flow. Mapping of modern hydrothermal convection cells provides information which can lead to the prediction of hidden metalliferous mineralisation and china clay deposits, and has important implications for the efficient exploitation of geothermal energy.

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Introduction

Quantitative studies of the convective flow of groundwater through granite plutons have been made by Fehn *et al.* (1978) using the Conway granite, New Hampshire, as their model. They concluded that in plutons similar to the Conway granite, where the presence of radioelements results in a heat production of about 20 hgu (heat generation units or 10^{-13} cal cm^{-3}s^{-1}), active hydrothermal circulation could occur if the permeability of the granite was sufficiently great. Permeability was found to be the most important limiting factor in their models: where overall permeability was less than 0.05md (millidarcies) no convective groundwater flow was possible, and for high flow rates to become established permeability needed to be of the order of 0.5md or more.

Convective flow regimes are not necessarily confined to the pluton, but can impinge upon the envelope of host rocks. If the host has higher permeability than the pluton the net result may be an enhanced flow rate within the granite as well as in its envelope. Significantly, the loss of heat through the walls of the pluton can also be high, and topographic control is important in determining the geographic location of sites of drawdown (recharge) and upwell (discharge) within the convective system. The overall diameter of the convection cells was found by Fehn *et al.* (1978) to range between about 5km and 20km. However, the aspect ratio of convection cells can change with time, and reversal of flow is even possible (Elder, 1981).

Convective circulation of groundwater occurring within and around the south west England granites, which are similar to the Conway granite in many respects, is likely to be governed by the factors studied by Fehn *et al.* (1978). In this paper a review is made of the available evidence suggesting that hydrothermal convective circulation has occurred in the past and is still occurring today. This has shown that heat production, fracture permeability and groundwater character are all consistent with the hypothesis being tenable. The distribution and character of modern convection cells is studied in the Dartmoor granite using electrical resistivity techniques to investigate the fracture permeability of the granite in depth and surface geochemistry of ^{222}Rn and U used to identify sites of drawdown and upwell. Evidence from the thermal springs in some Cornish mines suggests the action of modern convection cells, and it is suggested that recognition of the distribution of these cells may be a major guide in mineral exploration.

The Granites of south-west England

Heat Production

The granites of south-west England are very similar to the Conway granite in their heat generation characteristics. Concentrations of radioelements are approximately the same in both areas, with an average of about 15ppm U occurring in the Conway granite and about 14ppm in south-west England, while Th at 57ppm and 20ppm and K at 4.0% and 4.3% respectively are also similar. Tammemagi and Smith (1975) indicated that a characteristic average heat production of about 11.2hgu was obtained from surface samples of south-west England granite and concluded that the Geevor sample quoted by Tammemagi and Wheildon (1974) as 15.6 hgu, could either be enriched in radioelements or be more representative of fresh rock than their surface samples. Wheildon *et al.* (1980) indicate that heat production values of up to 24hgu occur in south-west England. These values compare with that of about 20hgu for the Conway granite.

Geothermal gradients in the South West England granites are also similar to those in the Conway granite. Corrected values of up to 3.2hfu (heat flow units or 10^6 cal cm^{-2}s^{-1}) obtained in south-west England (Wheildon *et al.,* 1980) compare favourably with predicted values of 2.2hfu for non-convective models of the Conway granite and maxima of 4.5hfu and 4.0hfu, near the centre and edge respectively, for the pluton modelled with convective circulation.

Although radiogenic heat must be considered the main driving force for any localised convective circulation of groundwater in the granites of south-west England, magmatic heat could have maintained a vigorous convective circulation for a period of perhaps up to about 2 Ma after intrusion. Also, there is evidence in south-west England for the periodic input of additional heat, probably of mantle origin (Hawkes, 1982), That this is possible is shown by the post-granite volcanic and minor intrusive rocks of Stephanian and early Permian age; the Wolf Rock - Epson Shoal phonolite (dated at about 130 Ma) and the Lundy igneous complex (dated at about 54 Ma).

Permeability

Within the granites of south-west England *in situ* rock permeability may be related to fissures formed by either hydraulic fracturing or stress-relief fracturing, as well as by the presence of an intact-rock permeability.

The mechanism of hydraulic fracturing associated with hydrothermal activity has been studied by Phillips (1973), and was proposed by Jackson *et al.* (1977) as a method for creating the sheeted veins systems of Cligga Head and Hemerdon. A combination of hydraulic fracturing and explosive brecciation was also invoked by Allman-Ward *et al.* (1982) to explain the intrusion breccias which occur at Wheal Remfry and elsewhere in the St Austell granite. Indeed, Moore (1975) suggested that the entire lode system of south-west England may have been emplaced by hydraulic fracturing, however the big plutons are all composite (Exley and Stone, 1982) and it is difficult to envisage how they could each have accommodated a single internal hydrothermal cell at any stage during their construction. Instead, the protracted history of vein systems suggests that the main lodes occupy extensional fractures which developed in response to successive regional stress fields.

Laboratory measurements of intact-rock permeability in granites from the Carmenellis mass have yielded values in the range 10^{-8} -10^{-9}d (Brace, 1980; K. Sincock, pers. comm.). These values are several orders of magnitude too low to permit convective circulation, yet it is clear from studies on the northern part of the Carnmenellis granite (K. Sincock, pers. comm.) that much higher permeabilities existed in the past. Here quartz in the granite is invariably characterised by numerous closely-spaced planes of secondary fluid inclusions, approximately parallel to the major joint directions and regionally persistent. Although the granite has only about 30% modal quartz, it has a quartz-linked fabric (Fig. 1). Thus as Roedder (1971) has shown that planes of secondary inclusions are formed by annealing of microfractures containing films of hydrothermal fluids, when the quartz microfractures were open even the intact granite probably had a permeability several orders of magnitude higher than present day measurements.

Development of stress-relief fractures in the south-west England granites is likely to have occurred over a long time-scale. Although some fracturing undoubtedly occurred either at the time of emplacement or soon after, as the pluton cooled, the dominant major fracture system appears to have been associated with the intrusion of the early Permian (270 Ma) elvan dykes and the main phase of metalliferous mineralisation. These E-W to NE-SW trending fractures may have formed in response to post-orogenic relaxation, but it is more likely that they are associated with the onset of crustal rifting (Hawkes, 1982). Indeed, crustal rifting (with renewed volcanism) became the main feature of the tectonic environment of the areas surrounding south-west England during Mesozoic and Cenozoic times, although the effects of compressional tectonism are also witnessed throughout the Mesozoic (Hart, 1982).

Figure 1. Fabric of Carnmenellis granite, Carwynnen, near Troon. Quartz-black; Feldspars and micas-white; Length of sample = 100mm (Redrawn from image analyser photograph by K. Sincock).

In terms of the present day permeability, the Carnmenellis granite and its metamorphic envelope are characterised by two major sets of sub-vertical joints which trend at 070° and 160°. Average joint frequency varies over the granite outcrop between 1.5m and 2m. A system of sub-horizontal joints has similar frequency near the present land surface, though this appears to decrease rapidly with depth. Joint aperture is very variable and has not yet, received detailed study. Preliminary measurements of fracture-controlled permeability in the Carnmenellis granite have yielded values between an average of 10^{-4}d (Black, 1979)and 5 x 10^{-5} – 10^{-7}d (Batchelor, 1978; Brace, 1980). The upper limit of permeability is thus within the range of Fehn *et al.* (1978) suggested for large scale hydrothermal convective flow. However, joint controlled permeability is probably very variable in near-surface zones where it is affected by weathering and the deposition of clay minerals and iron oxides in the fractures.

The fracture permeability of the granites at the present day is largely controlled by the *in situ* stress characteristics. Recent determinations of *in situ* stress at the Camborne School of Mines Hot Dry Rock Project at Rosemanowas Quarry in the Carnmenellis granite and at South Crofty Mine (A.S. Batchelor pers. comm.) have revealed a large horizontal stress anisotropy. The maximum horizontal stress is about twice the magnitude of the minimum horizontal stress, reaching a value of approximately 75 MPa (megapascals) at a depth of 2000m. Preliminary indications are that the maximum horizontal stress is orientated approximately NNW-SSE. This may be significant in that discharges of thermal brines in deep mines around the Carnmenellis granite are almost always from NW-SE to NNW-SSE trending cross-courses. On a regional scale late mineralisation is largely confined to N-S to NNW-SSE trending fissure veins. It is thus likely that the existing stress anisotropy has regional significance and has persisted in south-west England for a rather long period of time - probably since the Early Kimmerian folding at about 200 Ma.

Groundwater

Water for convective circulation can be obtained from a variety of sources: magmatic, connate in the host rocks, dehydration or metamorphic water from the host rocks, meteoric water and the influx of sea-water. The granite magmas of south-west England are generally assumed to have had a low initial water content (Stone, 1975), but all other sources could have contributed to convective circulation at different times.

Meteoric water is now recognised as having contributed significantly to the processes of formation of the metalliferous mineral deposits (Sheppard, 1977) although its interaction with the granite is not simple. Fehn *et al.* (1978) have shown that the slope of the water table is a function of rock permeability and recharge rate, and for permeabilities of about 0.5md where rainfall exceeds 10cm year^{-1}, is likely to follow the topography closely.

Thus for similar permeabilities in the south-west England granites and a rainfall of up to about 2m year^{-1} the water table will be closely controlled by topography.

Water table slopes of only moderate value can induce water movements comparable in magnitude with those of a convective origin and, indeed, will influence the geographic distribution of the convection cells. However, if a surface layer of high permeability is present, then most of the Water flow is restricted to that layer. Beneath the growan, which overlies most of the granites of south-west England, a fairly dramatic decrease in permeability must take place. In these conditions run-off of meteoric water will mainly follow the topographic surface at no great depth, and although some meteoric water will penetrate the granite and become involved in convective circulation, it is doubtful that the magnitude of flow would be sufficient to affect the distribution of convection cells. Topographic amplitude over the granites of south-west England is also very small in comparison with systems which Fehn *et al.* (1978) suggested could control such distributions.

During Permian and Triassic times, when erosion exposed the granites of south-west England for the first time, rainfall over the Cornubian massif would have been very low, certainly less than a few centimetres per year and the water table very depressed (Durrance *et al.,* 1978). It is difficult to envisage that under such conditions the influx of meteoric water would have had any effect on convective circulation, and with a depressed water table convective circulation may not have been possible anyway. However, in Mesozoic and Cenozoic times the Cornubian Massif was for long periods a land area with a humid climate (Durrance and Grainger, 1977) and in the Liassic and Middle-Upper Chalk was subject to marine invasion. Surface water probably first invaded the granites and their host rocks, causing the water table to rise, in late Triassic or early Jurassic times, but such water - either meteoric or sea water - remained available until the present day.

The role of connate and dehydration/metamorphic water is more difficult to assess, but their main contribution to convective circulation must have occurred early in the history of the system. Connate water, especially, is likely to have been expelled before the emplacement of the granites, but dehydration/metamorphic waters could well have been abundant for a time after intrusion. Certainly the main phase of metalliferous mineralisation is likely to have involved convective circulation of dehydration/metamorphic waters, but the concept that the Mesozoic and Cenozoic phases of metalliferous mineralisation involved connate waters from the Carboniferous rocks is difficult to accept. Perhaps influx of Mesozoic sea water is a possible explanation, with tectonism aiding this by reactivation of fracture systems.

The re-establishment of convective circulation in late Triassic or early Jurassic times may well have been governed geographically by the topographic characteristics then present, although reactivation of the older systems might be expected. However, the general reduction in the topographic extremes of the Cornubian Massif that must have occurred throughout Mesozoic and Cenozoic times ,(even with complete marine submergence on occasion) would have ensured that the pattern of convective circulation established in the late Triassic could persist to the present day without significant modification.
Figure 2. Emanative Centres (Tin mineralisation) in south-west England (after Dines, 1956).

Carboniferous-Tertiary Hydrothermal Circulation

Metalliferous Mineralisation
Dewey's (1925) original view of concentric mineral zones, with a sequence of Sn-Cu-Zn-Pb-Fe minerals, developed around individual intrusions in south-west England, was modified by Dines (1956) who promulgated the concept of 'emanative centres' indicated by the occurrence of Sn mineralisation (Fig, 2). The emanative centres were considered to be exit paths by which hydrothermal solutions were expelled from the still molten interiors of the granite intrusions. As originally envisaged, the mineralisation resulted from the operation of a single pass hydrothermal fluid out of which a characteristic sequence of ore and gangue minerals were deposited along a falling temperature gradient. However, subsequent studies (Garnett, 1965; Moore and Jackson, 1977) have demonstrated excellent examples of telescoped mineralisation in the ore field whereby polyascendent hydrothermal fluids have deposited successively lower temperature assemblages within the same vein systems. Moore (1982) re-interpreted the emanative centres in terms of single pass hydrothermal convective cells analogous to those of modern geothermal systems, but operative at deeper crustal levels. He argued that individual convective cells remained active for only a part of a protracted hydrothermal history.

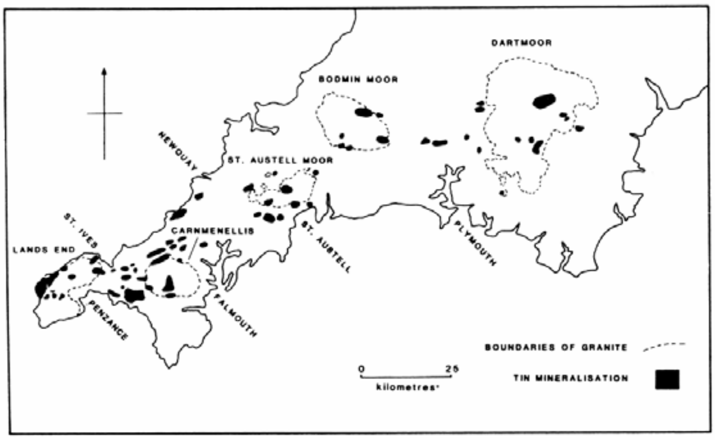

Figure 2. Emanative Centres (Tin mineralisation) in south-west England (after Dines, 1956).

Early Events
Recent work by Manning (1978, 1981) and Pichavant (1979) on the effect of F and B in depressing granite liquidus temperatures has indicated that the interval between crystallisation and the onset of greisening (about 450°C) and primary Sn-W mineralisation (380°C) may have been relatively small, thus suggesting continuity between magmatic and hydrothermal events. Indeed, because there is some indication (T.J. Shepherd, pers. comm.) that the granite porphyries of Hemerdon and Cligga Head are older than the main-stage south-west England granites, it is possible that the origin of the Sn-W sheeted vein systems which cut these porphyries lies in circulation set up by thermal energy from the later and more extensive main-stage granites.

Within the main-stage granites, however, the early events are mainly metasomatic. Apart from the widespread potash metasomatism, Hawkes and Dangerfield (1978) recognised areas where the place of biotite is taken by a Li-bearing mica (usually referred to as lithionite). Lithionite granite occurs principally in the western part of the St Austell pluton and in the Tregonning-Godolphin pluton.

Manning (1981) suggested that the Li-rich mica originated by a process whereby biotite was enriched in Li, and fluorite grains were formed along the mica cleavages. This was accompanied by a considerable reduction in the Fe content of the granite (Exley and Stone, 1964). Indeed, in terms of geochemical transfer, the removal of Fe probably involved more material than enrichment in Li. Lithionitisation and deferruginisation are both processes which may have operated at or about the same time as the potash metasomatism which Exley and Stone (1964) demonstrated to have taken place during the crystallisation of the primary minerals in the granites of south-west England, but further deferruginisation of the micas must also have taken place much later.

The formation of the metatourmalinite-hydrothermal breccia and Sn-Ti mineralisation described by Allman-Ward *et al.* (1982) at Wheal Remfry, and recognised at several other localities in the western part of the St Austell area, was also an early event. As noted above, it probably resulted from hydraulic fractures propagated during the emplacement and crystallisation of the main-stage St Austell granite. However, Wheal Remfry contrasts remarkably with the granite porphyry greisen-bordered sheeted veins systems (Table 1). The differences between the sheeted vein systems and the Wheal Remfrey breccia probably reflect the distinction between ore fluids partitioned from the early porphyries and those from the main-stage granites.

Main Mineralisation

The main lode systems occupy extensional fractures which trend approximately E-W in the Land's End -Godolphin area, ENE-WSW in the Gwinear-Camborne-Redruth-St Day-St Agnes-Perranporth region, and E-W in central and north Cornwall and in Devon.

Though locally influenced in frequency and direction by the proximity of the plutons, the main lode fractures clearly result from the action of regional stress fields. As such they provided focussed channelways for solutions which had derived their ore metals by leaching of dispersed precursor phases from both granite and host rocks. Edwards (1976) has pointed to the close spatial association of lode-type Cu deposits with basic volcanic and intrusive rocks throughout the region, and linked the occurrence of the Sb deposits of north Cornwall with spilites which carry anomalous concentrations of Sb.

Whether Sn and W might have been leached from a dispersed precursor phase is uncertain. However, there is some evidence that Sn and other high field strength elements are present in anomalous concentrations in biotite in certain of the south-west England granites, and that these are liberated during chloritisation and perhaps other alteration processes. In addition to high field strength elements the unaltered biotites are known to carry up to 1.5 wt.% F (Al Saleh *et al.,* 1977). Two types of chloritisation are recognisable in south-west England granites. In the first ("clean" chloritisation) biotite is pseudomorphed, wholly or in part by pale green chlorite alone. Relict pleochroic haloes remain but included zircon and uraninite have been removed. The chlorite is depleted, relative to fresh biotite, in high field strength elements and F. Elsewhere "dirty" chloritisation is characteristic, where the chlorite is accompanied by a wide range of fine-grained alteration products including futile, anatase, cassiterite, Ta-Nb oxides, W-bearing species, malacon after zircon and, ubiquitously, fluorite.

TOURMALINITE HYDROTHERMAL BRECCIA	GREISEN - EXOGREISEN
1. Associated with diatremic breccias which post-date the main-stage granite.	1. Developed in the apical portions of granite porphyry stocks which predate the main-stage granites.
2. Veinlet stockworks, mineralised breccias, replacement ore.	2. Sheeted vein complexes.
3. Haloes of tourmalinisation and ? disseminated TiO_2 polymorphs (rutile, anatase).	3. Haloes of tourmalinisation and phyllic alteration.
4. Simple ore mineralogy. Cassiterite, haematite, rutile.	4. Complex ore mineralogy. Cassiterite, wolframite, arsenopyrite, chalcopyrite, sphalerite, stannite, silver sulpho-salts.
5. Veins carry only tourmaline and quartz as gangue minerals.	5. Veins have strong borders of tourmaline and coarse muscovite (pre-ore) and carry quartz, fluorite and chlorite as post-ore gangue minerals.
6. Cassiterite has characteristic reddish-orange colour.	6. Cassiterite is brownish, fawn or honey-yellow in colour.
7. Tourmaline is typically very dark with very sharp zonal boundaries.	7. Tourmaline is typically pale in colour and is zoned from brown to bluish green with diffuse zone boundaries.
8. Late stage wood tin-haematite-quartz mineralisation.	8. Late stage chalcedony-siderite-marcasite mineralisation which cuts ore-bearing veins.
9. Quartz contains many single phase (vapour) inclusions suggesting boiling during mineralisation.	9. Fluid inclusions in quartz are mainly two phase (liquid/ vapour) or three phase (solid/liquid/vapour).
10. Low salinity inclusion fluids.	10. Low to moderate Salinity inclusion fluids.
11. Homogenisation temperatures 400-300°C.	11. Homogenisation temperatures 380-1ess than 250°C.

Table 1. Contrasts between the Wheal Remfrey breccia and sheeted vein systems.

In “clean" chloritisation the high field strength elements have been removed from the sites of liberation, with the simultaneous removal of F, suggesting an elegant mechanism for mobilising them into the pervading hydrothermal fluid. In "dirty" chloritisation, however, F is fixed as fluorite at the sites of liberation, and the high field strength elements remain as minute included phases within the secondary chlorite. A similar mechanism may operate during tourmalinisation of biotite, for secondary tourmaline is depleted in high field strength elements relative to the biotite it has replaced and it also carries inherited pleochroic haloes (though the inclusions responsible for such haloes have usually disappeared). In both processes the presence of relict pleochroic haloes indicates that a considerable period of time must have elapsed between crystallisation of the biotite and the onset of replacement.

Thus possible mechanism exists for leaching Sn, and perhaps other elements, from large volumes of crystallised granite by pervasive convective circulation. The complex mineral parageneses, established in many of the main lode systems, involving Cu, As, Pb and Zn sulphides which post-date Sn mineralisation, suggest that convecting hydrothermal fluids leaching large volumes of basic and pelitic country rocks may have been focussed into the same channelways. Isotopic data (Halliday and Mitchell, 1976), support a protracted, probably episodic hydrothermal evolution for the main lode systems. In the St Just mining district isotopic events occurred at 270 Ma, 210 Ma, 165 Ma and less than 100 Ma. Such protracted mineralisation could not have been sustained by magmatic or connate water alone; meteoric water must have replenished the convecting systems.

Cross-Course Mineralisation

Cross-course Pb-Zn-F mineralisation in the major mining areas and the N-S trending Pb-Zn-F zones of north-east Cornwall have been variously described as Mesozoic or Tertiary (Collins, 1912; Hill and MacAllister, 1906). Alderton (1975, 1978)indicated that the cross-course mineralisation resulted from the operation of high salinity ore fluids (25 eq wt% NaC1) at temperatures in the range 120°-160°C, in contrast to the low to moderate salinity fluids (0-13 eq wt% NaC1) with depositional temperatures between 170° and 350°C which characterised the early Pb-Zn mineralisation that occurs in veins parallel to the main lode system.

Alderton proposed that the late Pb-Zn^{-F} mineralisation had a separate origin from earlier, higher temperature events and suggested that the ore fluids may have originated as connate brines, with the ore minerals derived by leaching of dispersed sedimentary (biogenic) sulphides. However, as noted above, we consider that influx of Mesozoic sea water is a more likely source for convective circulation.

Kaolinisation

In contrast to Sheppard (1977) who considered that the kaolinites in the major china clay deposits of south-west England have a weathering origin, Bristow (1977) listed the most important arguments in favour of a hydrothermal origin as:

1. The funnel-shaped form of the deposits which have depth-extents greater than 250m.
2. The fact that unaltered granite overlies kaolinisation at depths of more than 250m.
3. The association of kaolinisation with greisen-bordered quartz-tourmaline veins.
4. Known instances of the crystallinity index of the kaolinite increasing towards a major quartz-tourmaline vein.

More recently Bray (1980) has described radiometric dating on the micas found in kaolinised potash feldspars in the Goonbarrow area of the St Austell granite. He obtained ages which are essentially restricted to the same period as the high temperature greisenisation, tourmalinisation and metalliferous mineralisation processes. Bray concluded that this indicated that the kaolinisation event took place at the same time, or shortly after the high temperature mineralisation. However, this view is unlikely to be correct because fluid inclusion work by Alderton and Rankin (in press) suggests that the areas of kaolinised granite are associated with a later generation of low temperature inclusions as well as the earlier high temperature ones. While the high temperature event alone cannot be the mechanism of kaolinisation, as often salinities were too high for kaolinisation to occur, exclusively low temperature alteration is also not possible. Kaolinisation involves the removal of something like 25% by weight of the granite and must require the flushing through the granite of a prodigious quantity of non-saline water. Unaltered granite, as noted above, has a very low permeability, so that enhancement of permeability by processes occurring early in the history of the granite is indicated as a necessary prelude to kaolinisation.

We consider therefore that at or about the same time as the high temperature mineralisation was taking place hydrothermal circulation caused large areas of granite to be partially altered to a permeable matrix capable of allowing reasonably free circulation of groundwater while later, low temperature fluids followed these zones of 'softened' granite to produce the kaolinite. Fluid inclusion evidence from the St Austell granite suggests that the high temperature process operated at a shallow depth, perhaps no more than 1km, thus implying a very steep geothermal gradient of several hundred celsius degrees per kilometre. This value is comparable to that found in areas of recent volcanicity and may well correlate with the Stephanian and early Permian thermal event.

In contrast to the relatively short-lived nature of the high temperature process, we envisage that the radiogenically driven convective circulation of groundwater within the granite which has given rise to the low temperature process, has operated more or less continuously since the

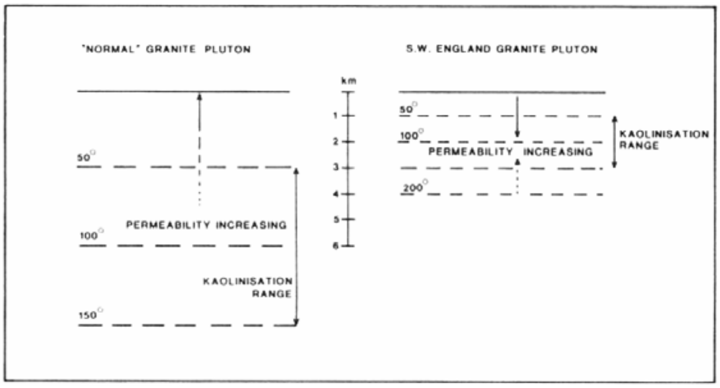

Figure 3. Kaolinisation conditions in granite plutons.

end of Triassic times. However, the vigour of the convective circulation is likely to have varied with the permeability of the granite, being affected by tectonic activity, and with the periodic input of enhanced mantle heat flow.

An interesting way of assessing this has come from the work of Fehn *et al.* (1978), who suggested that leaching of uranium from granites by descending limbs of convection cells leads to the formation of uranium deposits in zones of upwelling. In the vicinity of the kaolinised parts of the St Austell granite, uranium deposits occur around South Terras on the south-west side of the granite in N-S cross-courses, and in a series of localities on the north side of the granite in the St Columb area. Radiometric dating of the uranium in these deposits has given various ages up to the mid-Tertiary.

It is postulated that the exceptionally long life of this system, coupled with the existence of permeable zones formed by an earlier phase of high temperature alteration in the granite, has been responsible for the unusual extent of the kaolinisation in the St Austell granite. Further, the earlier metasomatic deferruginisation of the mica produced a low-iron parent granite which, when kaolinised, yielded low-iron white kaolins of great commercial value. All these processes were thus either directly, or indirectly, due to the high radioactive mineral content of the granite which provided the basic energy source to drive the circulation of water, but the depth at which the processes occur is also governed by the permeability of the granite. Permeability evidence, discussed elsewhere in this paper, together with the enhanced geothermal gradient of the granites, indicates a 'window' for the south-west England kaolinisation at a depth of about 2km, as shown in Figure 3.

Much of the metalliferous mineralisation in south-west England is in the form of sulphides, and it is likely that higher zones of metalliferous mineralisation, now removed by erosion, may have contained large concentrations of sulphides. Oxidation of sulphides, as for example alongside the Perran iron lode (Sabine, 1968) is known to cause kaolinisation, and there is evidence that pockets of kaolinised slate under Goss Moor in central Cornwall are underlain by sulphide-impregnated slate. Acid groundwater, arising from the oxidation by weathering of sulphides above the granite, may have been drawn down into the granite by convective circulation, and therefore have provided a reagent which accelerated kaolinisation. However, the total absence of alunite in the south-west England kaolins indicates that no great concentration of sulphate ions could have occurred. It is considered that there is no evidence that weathering has played other than a minor role in the formation of the major deposits of kaolin in south-west England.

Modern Hydrothermal Circulation

Electrical Resistivity Surveys

Fracture-controlled permeability in the Dartmoor granite to a depth of several kilometres has been investigated using an electrical resistivity dipole-dipole technique (Keller and Rapolla, 1974), with the source dipole 1km long. Three separate locations for the source dipole were used. (Fig. 4). The voltage distribution corresponding to the source signal was detected using two orthogonal 50m dipoles, which were aligned parallel and perpendicular to the source of axis at each recording site, for distances up to 9km from the source dipole.

The apparent resistivity values shown in Figure 4 were calculated assuming the granite to be an infinite homogenous half-space, the voltage step at the observation points being taken as the vector sum of the steps observed parallel and perpendicular to the dipole axis, irrespective of whether the resultant of the two vectors was in the direction corresponding to the physical assumptions. This procedure yielded an apparent resistivity less susceptible to local effects than the resistivities derived using either the parallel or the perpendicular component alone.

The most noticeable feature of these results is the very low values generally obtained for the apparent resistivity of the granite. Even taking into account the overall increase in resistivity that results when allowance is made for an overburden which may reach 20m thickness in the, conversion to true resistivity, the values are in the range 'wet to moist granite' given by Parasnis (1973).

In general, the resistivity values increase with the dipole separation, probably reflecting the greater depth of investigation at wide separations, and the closing of sub-horizontal ('pseudo-bedding') joints with depth. However, even at dipole separations of about 5km the resistivity values are still within the `moist granite' range of Parasnis.

The other striking feature of the results is the asymmetry of the resistivity values according to whether the surveys were conducted along approximately N-S or approximately E-W lines. This is shown by the values obtained from N-S lines generally displaying a fairly consistent pattern of uniform resistivity with only a slight moderate increase in resistivity at large dipole separations, while the E-W results are usually quite

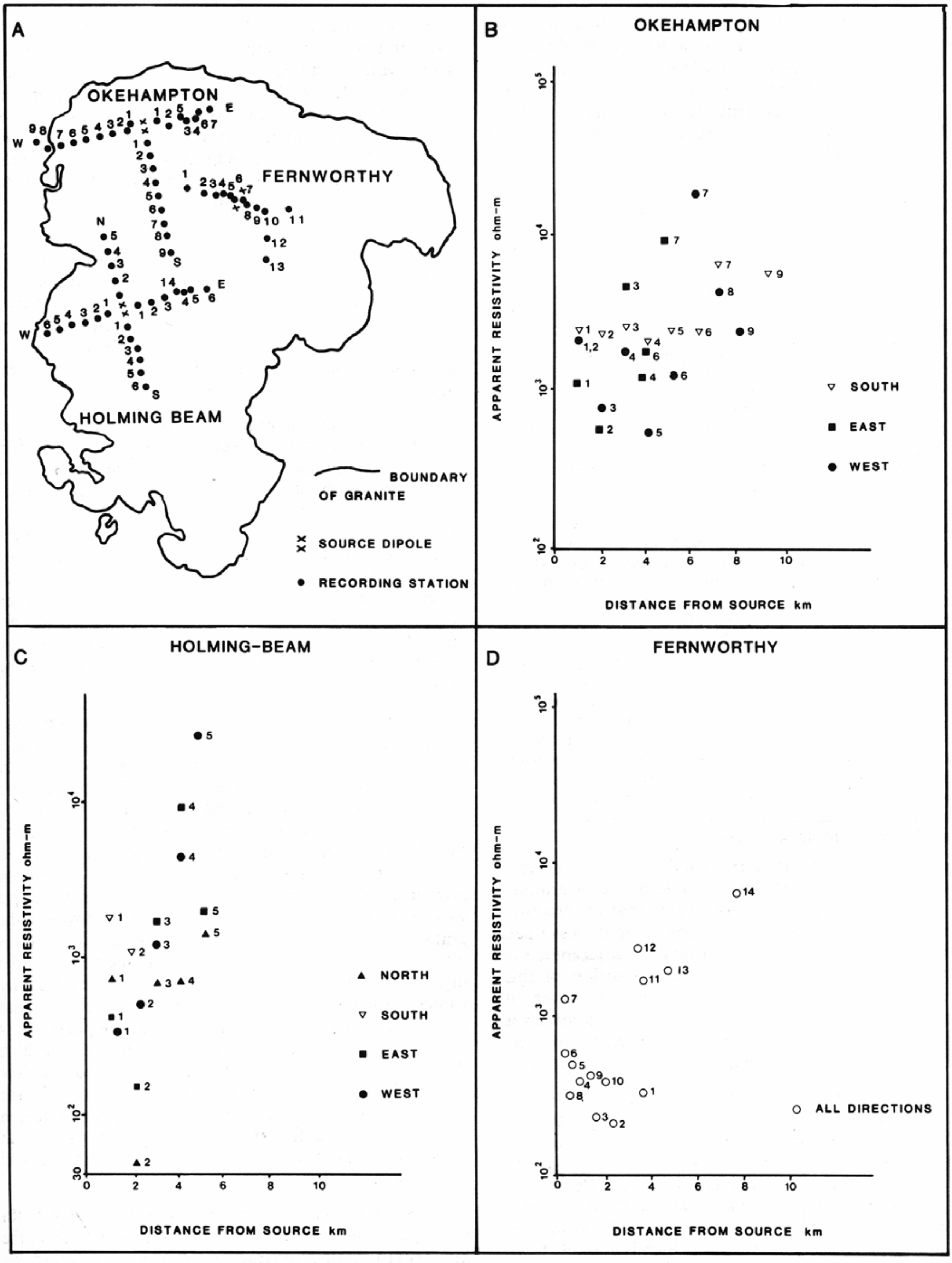

Figure 4. Electrical resistivity survey of Dartmoor. A. Positions of dipole-dipole sites; B. Results from the area south of Okehampton; C. Results from the area around Holming Beam; D. Results from the area around Fernworthy.

erratic with abnormally high and low values in close association. The origin of this asymmetry probably lies in the nature of the granite *in situ*. Open joints which trend approximately N-S probably provide good current pathways, but E-W current pathways vary in their character according to the degree of linkage of only irregularly open fractures.

Assessment of the porosity of the granite from resistivity data is possible using Archie's formula (Parasnis, 1979), which although generally applied to sedimentary formations may with caution be used for crystalline rocks when considered on a large enough scale:

$$P=Pof^{-m}s^{-n}$$

where

- p is the resistivity of a clay-free porous formation
- po is the resistivity of the water filling the pores
- f is the porosity fraction
- n is a parameter depending upon the proportion of water in the pores (usually about 2.0 if more than 30% of the pore space is occupied)
- m is a cementation factor, with a value of about 2.0 for well-cemented Palaeozoic sedimentary rocks.

For the Dartmoor granite in the Holming Beam and Okehampton areas, if a value of 5,000 ohm-m is taken for p, n taken as 2.0 (on the assumption of a high water table), m also as 2.0 (On the basis that it is unlikely for m to be less than 2.0 and a figure for the minimum porosity would be more useful than the maximum) and assuming a salinity for the groundwater to be similar to that of seawater (although greater salinities are possible, as shown by thermal mine waters), when a porosity of about 1% is then obtained. Factors which could invalidate this result are significant deviations in reality from the values used for the granite, extensive kaolinisation of the granite, or the presence of extensive veins of metalliferous minerals. However, different values of m and n are only likely to increase the porosity value, and it is unlikely that extensive alteration or mineralisation would not have been previously noticed in these areas (Hawkes, 1982; Beer and Scrivener, 1982). Lower values of fo would reduce the apparent porosity.

A porosity of 1% can be better visualised as a single lcm-wide open joint through every cubic metre of granite. Realistically, though, it is more likely that the fracture porosity would consist of a number of small, less open fractures and indeed any minor alteration adjacent to the fractures would also be seen as a proportion of this porosity. Even with these reservations, however, it follows that the granite to depths of a few kilometres is likely to possess an interconnected fracture porosity which is preferentially orientated approximately N-S.

In the Fernworthy area the resistivity values are so low, and with no obvious asymmetry to their geographic distributions, that fracturing must be particularly intense or groundwaters have a particularly high salinity. Using the same arguments as for the Holming Beam and Okehampton areas, a porosity of about 2% is obtained for Fernworthy. Unless kaolinisation of the granite in this area is extensively developed (which is unlikely from the geochemical evidence discussed below) or metalliferous mineralisation has a much greater development than suggested by Dines (1956), it follows that the permeability of the granite and/or the salinity of the groundwater in the Fernworthy area are likely to be very high indeed. It may be concluded that, apart from the closing of horizontal joints, the fracture permeability of the granite at a depth of a few kilometres is not dissimilar to that at the surface. Consequently this implies that the permeability imparted by vertically orientated fractures probably increases with depth.

Surface Geochemistry

Figure 5 shows the results of hydrogeochemical surveys of Dartmoor by Heath (1982) to determine the distribution of ^{222}Rn and U in stream waters. ^{222}Rn data and contours on Figure 5 have been obtained using the methods described by Durrance (1978). U was determined using a laser-exited fluorimetry system capable of resolution to 0.1 gl^{-1} U in water.

High ^{222}Rn values in Figure 5 show the main areas of concentration after the effects of random loss of ^{222}Rn have been eliminated. The source of the ^{222}Rn is the radioactive decay of 238U, and the presence of ^{222}Rn has been used as an indicator of its parent. The short half-life (3.825 days) of ^{222}Rn and its readiness to escape to the atmosphere mean that stream water ^{222}Rn anomalies cannot be far removed from their U source. However, in stream waters the ^{222}Rn levels are usually very low when compared with groundwater in the same area (by at least an order of magnitude) because of degassing to the atmosphere, so that high ^{222}Rn levels may also show the presence of groundwater influx into streams.

Although the presence of a spring near a sampling point can usually be easily detected by the development of a temperature anomaly and low pH values, and the ^{222}Rn results ignored (as in the construction of Figure 5), any general, more pervasive groundwater discharge is unlikely to be specifically recognised. Therefore, whereas the ^{222}Rn distribution pattern shown in Figure 5 could represent the spatial distribution of U in the Dartmoor area, it should more realistically be viewed as indicating a variation in the ease of ^{222}Rn transport through the granite - principally via interconnected fractures. In this context it is interesting to note the coincidence of the highest ^{222}Rn values and the exceptionally low resistivity values in the Fernworthy area. Again the inference is that fracture systems in the Fernworthy area are particularly intensively developed. Also, the possibility that a high degree of kaolinisation could be the cause of the low resistivities of the Fernworthy area is not borne out by the occurrence of high ^{222}Rn values. Generally the granite in ' areas of intense kaolinisation (such as Lee Moor in south Dartmoor) has been extremely depleted in U, and therefore is characterised by low ^{222}Rn values.

However, the concept of simply associating high ^{222}Rn values and intense fracturing is also incorrect, as in the Sticklepath Fault Zone fracturing must be profound, Yet the ^{222}Rn levels are generally low. A possible explanation for this ambiguity may lie in the direction of groundwater

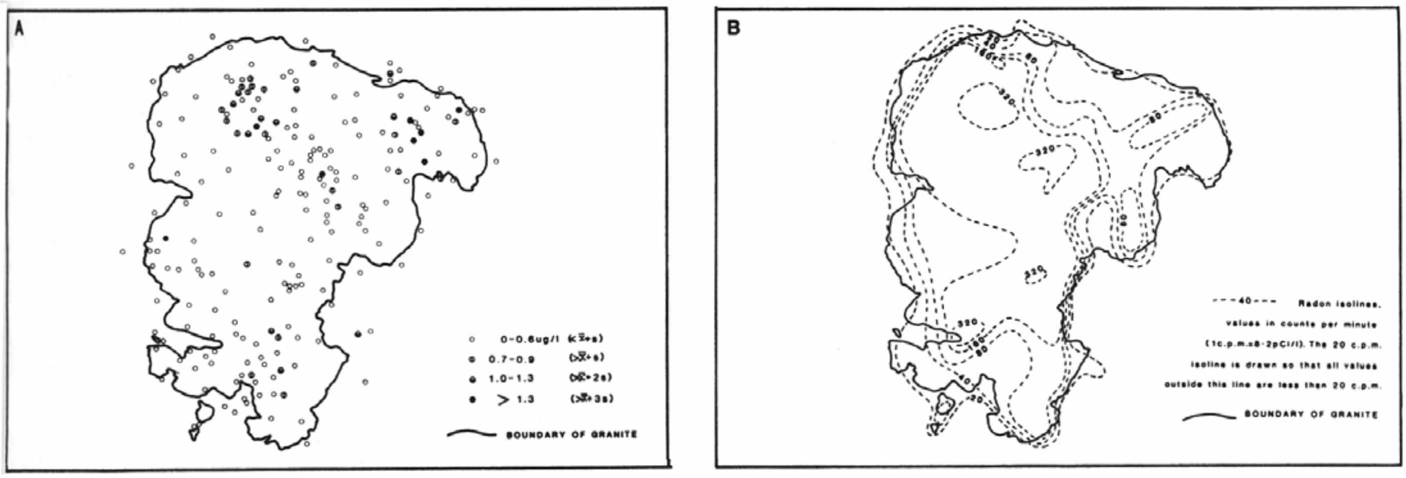

Figure 5. Stream water chemistry of Dartmoor. A. Uranium concentrations. B. Radon isolines

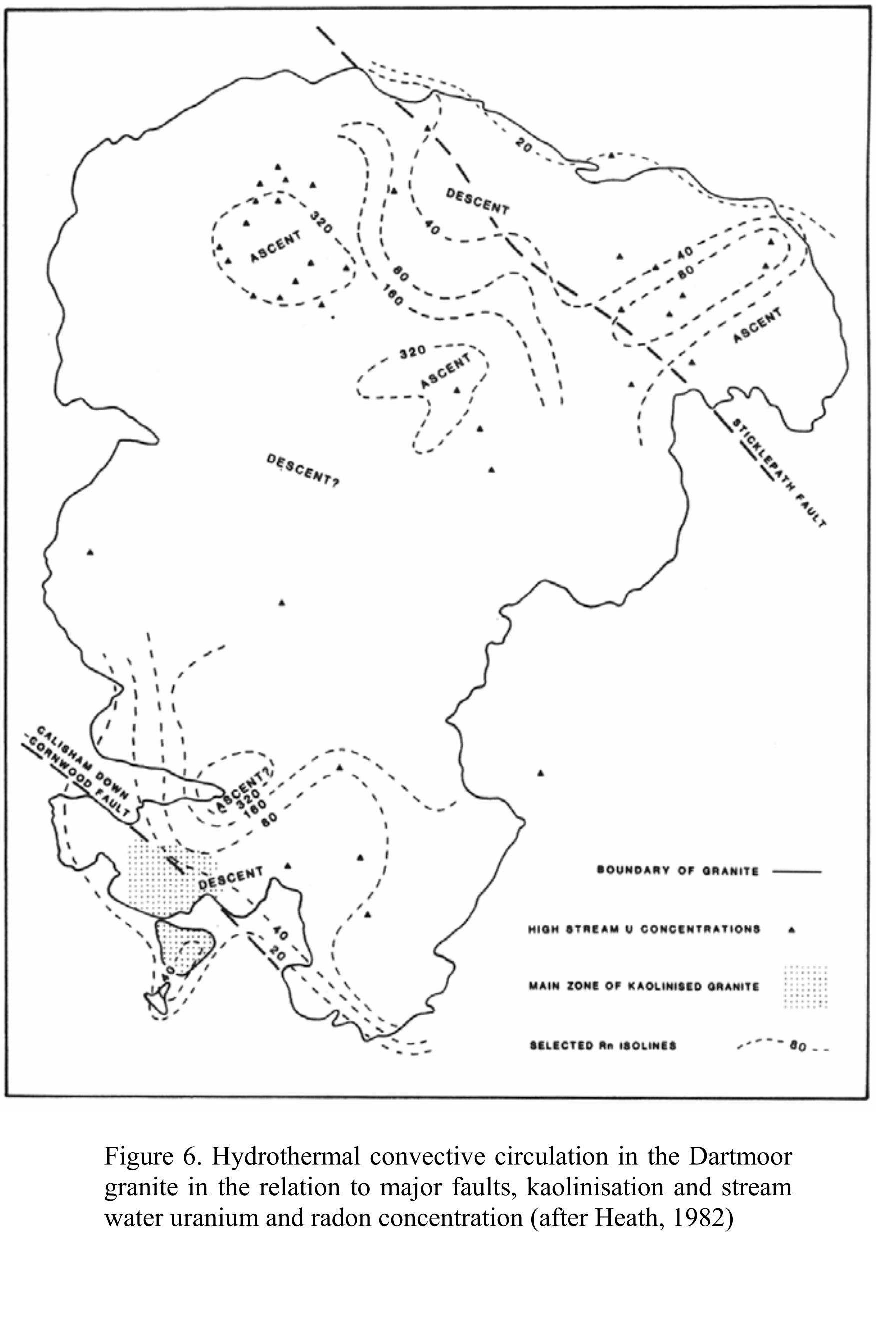

Figure 6. Hydrothermal convective circulation in the Dartmoor granite in the relation to major faults, kaolinisation and stream water uranium and radon concentration (after Heath, 1982)

movement - high ^{222}Rn values being associated with upward migration, low values with downward migration. Interestingly, high ^{222}Rn levels are found to occur on both sides of the Sticklepath Fault Zone.

The U data groups shown in Figure 5 represent the mean and standard deviation of the samples. Anomalous U concentrations are indicated by values where the mean is exceeded by more than three standard deviations (> x + 3s), while enriched (> x + 2s), enhanced (> x + s) and background (> x + s) classes are also used. The U distribution pattern in general follows that shown by the ^{222}Rn, with high values on either side of the Sticklepath Fault Zone, and marginal to the main areas of kaolinisation.

The extent to which the ^{222}Rn and the U distribution relate to the U being the parent of ^{222}Rn is, however, not clear - for both could relate to an underlying common factor. U because of its geochemical character, and ^{222}Rn because of its physical properties, are both highly mobile in the presence of circulating water. The association of low U values in areas of kaolinisation thus agrees with the model proposed above, that the areas of deeply kaolinised granite represent sites of drawdown of meteoric water. Following from this is the corollary that areas of high U values may represent the sites of upwelling (Fig. 6).

Heat Flow

Heat flow data from south-west England has been assembled by Wheildon *et al.* (1980), and values shown for both granite and host rock areas in Figure 7. The pattern of heat flow, in general, is quite straightforward, with high values - around 2.94 hfu - occurring over the granites, falling to a background of about 1.20 hfu in Exmoor and Somerset. An exceptionally high value is shown occurring at Sousson's Wood on Dartmoor (3.15 hfu), but other high values occur in the eastern part of the St Austell granite (3.01 hfu), at Wheal Jane (2.99 hfu) South Crofty (3.08 hfu), Troon (2.94 hfu) and Geevor (3.08 hfu). The high value at Sousson's Wood has, however, since been doubted by Francis (1980) and Wheildon (pers. comm.), who have pointed out that this figure is unreliable as the temperature gradient was not

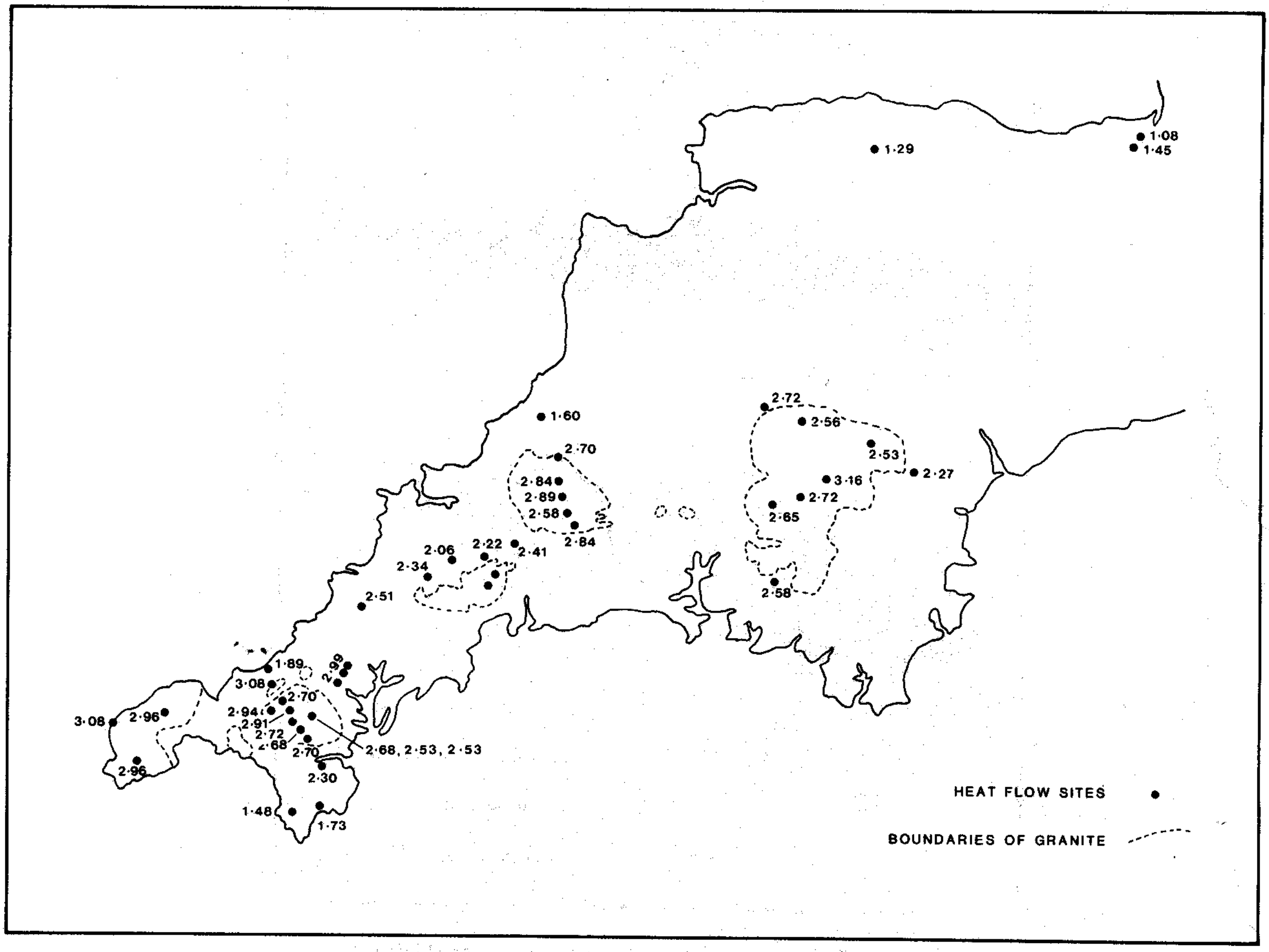

Figure 7. Heat flow values in south-west England (after Wheildon *et al.*, 1980).

well established in the measurement borehole - possibly due to water circulation taking place. Nevertheless, the coincidence of what appears to be highest heat flow value in south-west England with a position most distant from a granite margin (heat loss through the sides of the pluton is by no means negligible - Fehn *et al.* 1978), might be expected. The coincidence of high ^{222}Rn values with the high heat flow is also worth noting.

For the Carnmenellis granite, Wheildon *et al.* (1980) constructed a two-dimensional finite-element model to explain the heat flow along a NW-SE section, and showed that the modelled surface heat flows are in reasonable agreement with the measured values. This agreement was taken as indicating that contrasts of thermal conductivity and heat production between granite and host rocks, combined with the three-dimensional form of the pluton, were sufficient to account for the heat flow pattern without the need to introduce any enhancement of heat flow due to convective circulation.

For heat flow at Geevor and South Crofty, however Tammemagi and Wheildon (1974) had concluded that the measured values could not be explained simply by a combination of mantle and radiogenic heat. They considered that the high heat flow values are caused by the upwclling of thermal waters through deep fracture systems associated with zones of metalliferous mineralisation, and suggested that this might be related to young thermal events. This concept is similar to that proposed by Bott *et al.* (1972) for north-eastern England, and very much in line with the ideas developed herein, if divorced from only a direct association with zones of metalliferous mineralisation. In the light of the results obtained by Fehn *et al.* (1978), modern hydrothermal circulation would seem to be clearly in accord with the general pattern of heat flow in and around the Carnmenellis pluton.

Of the models considered by Fehn *et al.* (1978), the most appropriate to apply to Carnmenellis is that for a surface permeability of 5.Omd, decreasing by two orders of magnitude with depth (Fig. 8). In this model, three strong convection cells develop and give rise to zones of upwelling in the central area of the pluton and at its margins. The presence of a zone of enhanced heat flow marginal to the pluton is, therefore, clearly explained by a system of convective circulation. For the Carnmenellis pluton, high heat flows have been recorded at its margin, at South Crofty and Troon, as well as from the central part of the granite outcrop, and it would appear that it closely follows the system modelled by Fehn *et al.* High U values are also found in the streams along the south eastern margin of the Carnmenellis granite (Heath, 1982).

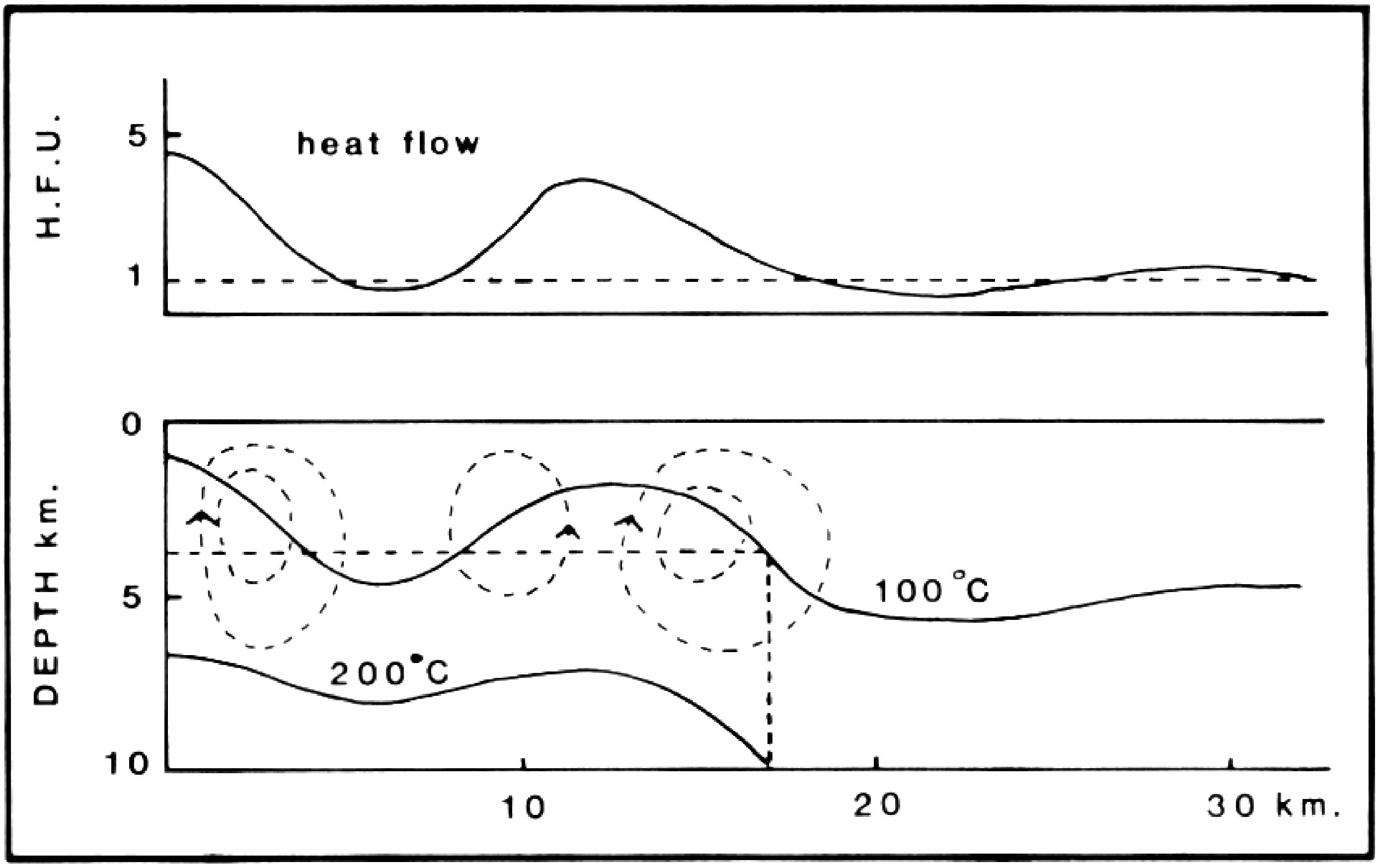

Figure 8. Model of convective circulation in granite pluton (after Fehn *et al.* 1978)

The main difference between the interpretation outlined above and that considered by Tammemagi and Wheildon (1974), is that whereas the hydrothermal convection was originally thought to be related just to the main belt of metalliferous mineralisation in south-west England (which the later work of Wheildon *et al.* (1980) has shown not be the case), the system of hydrothermal circulation taking place today consists of local convection cells distributed throughout the granites and around their margins. The presence of cells of hydrothermal convective circulation in areas of high permeability strata away from the granites is also possible in this context.

Thermal Mine Waters

Thermal brines have been recorded in deep mines from at least six localities in and adjacent to the Carnmenellis granite and at Botallack near the Land's End pluton. The brines generally discharge from N-S trending cross-courses or from boreholes which intersect such structures at depths of 100-700m below surface. Discharge temperatures vary between 15°C and more than 50°C (the higher temperatures are usually associated with the deeper discharge sites) and the brines may carry up to 20,000ppm total dissolved solids. Measured flow rates are as high as 40,000 Is^{-1} and the discharge rates, temperature and geochemistry of the South Crofty brines have remained essentially constant since the earliest reliable records were made in 1864.

Recent work on the thermal brines by Burgess *et al.* (in press) has suggested that they comprise a recent meteoric component (post - 1953) which has percolated downwards to at least 700m below surface and mixed with a stored groundwater component, also of meteoric origin. Various lines of evidence based on isotope abundances suggested that the stored component has had a residence time within the granite of at least 1Ma. Chemical geothermometers indicated that the likely equilibrium temperature for the South Crofty ground-waters is 54°C implying that with a geothermal gradient of 39°C km^{-1} (Tammemagi and Wheildon, 1974) they have circulated to a depth of l l00m. Recent evidence from deep boreholes at the Camborne School of Mines Hot Dry Rock site at Rosemanowas Quarry in the Carnmenellis granite indicates that surface-derived waters have penetrated to depths of at least 2000m.

The main chemical characteristics of the thermal brines are their strongly depleted $mNa^{+}/C1^{-}$ ratio and their enhanced mCa^{2+}/Na^{-} ratio. Li (up to 125ppm) and Sr (up to 40ppm) are significantly enriched compared with all other groundwater in the United Kingdom (Beer *et al.* 1978), Li is enriched with respect to seawater by three orders of magnitude. Similarly, F and B are present in significant amounts; B is five to ten times higher than in seawater.

Burgess *et al.* (in press) considered that the chemistry of the brines could be best explained by non-structural leaching and structural breakdown of biotite, and by plagioclase hydrolysis, On the basis of the chloride content of the South Crofty spring, they have suggested that over the last 100 years the volume of rock so affected must have been of the order of $0.2km^{3}$. However, the Li yield over the same period indicated an alteration volume of $0.01km^{3}$. Since the ratio of altered to fresh granite is, therefore, apparently rather low, it is clear that very much larger volumes of granite have been involved and reaction times have been considerably longer than 100 years.

The thermal brines indicate that at depth the Carnmenellis granite has significant fracture-controlled permeability, and that structural breakdown of biotite (which must release traces of ore metals) is still in progress. The solute levels achieved by water - granite reaction are claimed to be the highest recorded anywhere in the world, thus the thermal brines can only be regarded as a modern hydrothermal ore fluid.

Conclusions

Taken together, the evidence for convective hydrothermal circulation cells occurring within the granites of south-west England since the time of their emplacement, is overwhelming. However, it is clear that two main phases of Circulation have been present, temporally separated by a period during which the circulation became quiescent.

The main phase of metalliferous mineralisation in south-west England was associated with post-fracturing, post-elvan dyke emplacement processes which involved the presence of non-magmatic waters probably derived by dehydration of minerals in the host rocks. The time interval between the end of magmatic and the beginning of mineralisation events is uncertain at present. Some evidence suggests a continually evolving process, while other evidence indicates a break of perhaps as much as 20 Ma (Moore, 1982). However, the cooling history of a granite pluton with a heat production value of even 20 hgu would mean that temperatures in the order of 300-500°C could not be sustained for more than 1 Ma after intrusion. Therefore, if there is a significant time interval between granite emplacement and some metalliferous mineralisation a new input of heat is required - an input associated with the Stephanian and early Permian volcanicity of the area (Hawkes, 1982). Possibly a solution to the problem lies in a change from mainly metasomatic processes driven by magmatic heat, taking place soon after intrusion of the granites, to mainly mineralisation processes re-activated by the Stephanian-early Permian thermal event. It is over the period of this transition that the Sn-W and sulphide mineralisation of

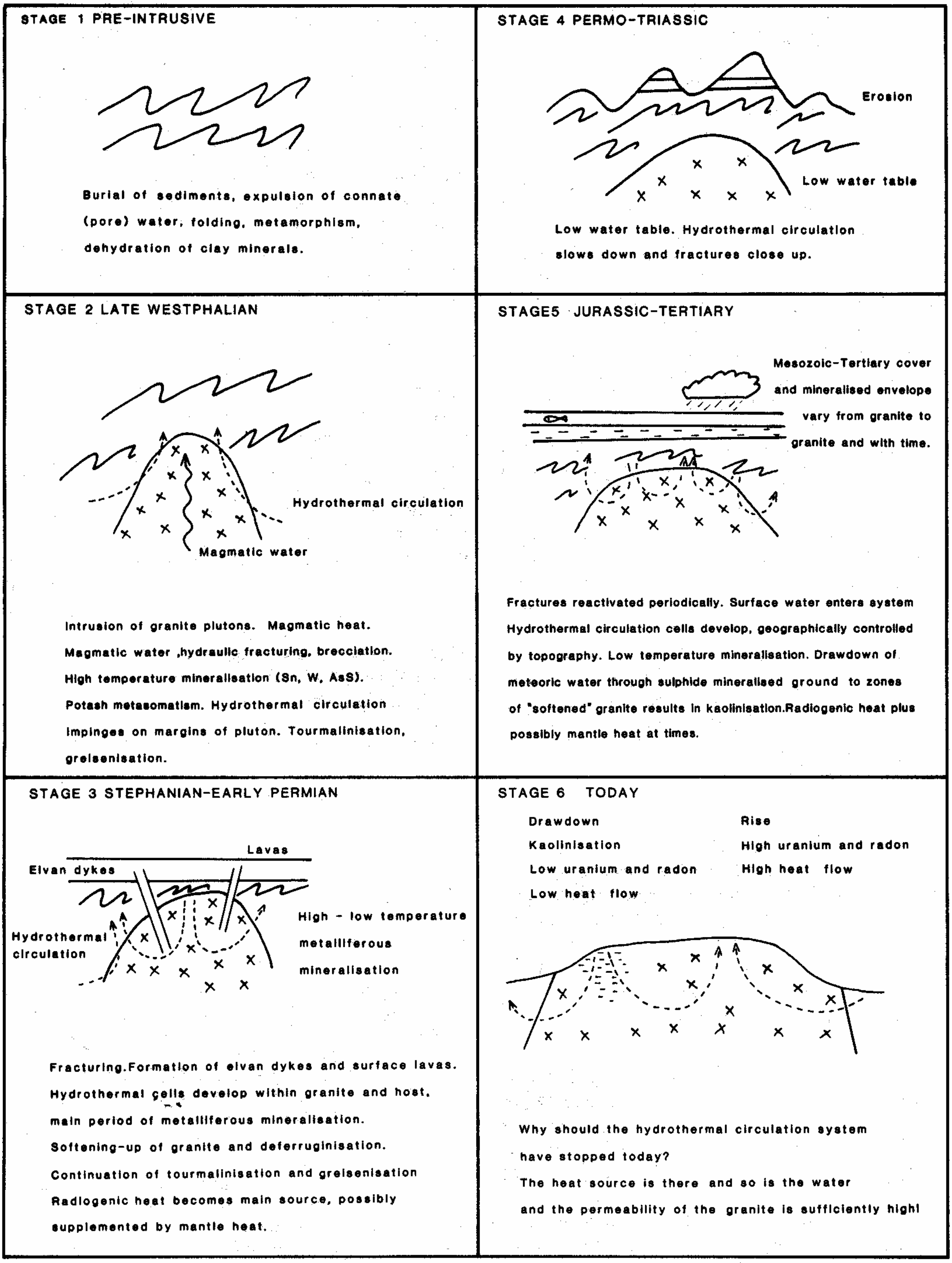

Figure 9. Model for the evolution of hydrothermal convective circulation in and around the granite plutons of south-west England.

zones over and around the granites and the high temperature softening and deferruginisation precursor phases to kaolinisation, occurred. Our model for the development of hydrothermal circulation through to this stage is shown in Figure 9, stages 1-3.

As the processes of mineralisation and alteration continued, it is probable that fractures became partially sealed, leading to the system dying through decreased permeability. This, together with the progressive decrease in the availability of water for circulation, experienced during Permian and Triassic times, led to the quiescent or stagnant phase - stage 4 in Figure 9. However, during this phase much of Devon and Cornwall was undergoing arid erosion, and a rugged, highland topography developed. This could have had a profound influence on the geographic distribution of convective circulation cells once the water table had risen, although reactivation of the older systems also seems to have occurred.

the end of the Triassic, sea level rose to cover much of southern England, but during the most of Mesozoic times Cornubia remained as an island: only occasionally did the sea cover the entire area. Humid conditions also became established in Mesozoic times. Thus meteoric water and/or saline surface water entered the Palaeozoic succession, aided by tectonic reactivation of fractures from time to time. The increased permeability that permitted this influx also allowed convective circulation to take place - driven by radiogenic heat from the granites and supplemented by the occasional input of enhanced mantle heat flow. The convection cells so established produced the low temperature mineralisation, particularly U-bearing deposits, and the sites of drawdown of meteoric water through zones of sulphide-mineralisated host rock gave conditions suitable for the second stage, low temperature processes of kaolinisation. Because the kaolinised areas are U - depleted, like Ball *et al.* (1978) we see the processes of kaolinisation and U mineralisation as being linked - drawdown giving the china clay, upwelling giving U-hearing and other mineral deposits.

It is this pattern of convective circulation (stage 5 in Fig. 9) that we see being maintained at the present day (stage 6 in Fig. 9). Circulation is thought to occur principally via open fractures which trend approximately N-S and be shown by the thermal springs which occur in some Cornish mines. As in the past, areas of modern drawdown may be identified by kaolinisation, low U and low ^{222}Rn, while upwelling areas are sites of mineral deposition and have high U and high ^{222}Rn levels. Heat flow values at drawdown sites should also be lower than those at upwelling - a pattern clearly illustrated by the distribution shown by Wheildon *et al.* (1980).

Apart from the very early mineralisation of the granite porphyries and main-stage granites, the distribution of the zones of main metalliferous mineralisation, late metalliferous mineralisation and kaolinisation in southwest England appears to follow the pattern of hydrothermal convective circulation seen today. Prediction of the occurrence of hidden metalliferous mineral deposits and china clay thus becomes possible if the character of the convection cells can be ascertained. The present work indicates that ^{222}Rn and U surface geochemistry can be employed successfully over granite areas for this purpose, but away from the granites the picture is unclear. It is hoped that He detection systems currently under development at the University of Exeter will eventually provide data that can be used to recognise the occurrence of convection cells away from the granite margins. Recognition of the presence of a modern hydr0thermal convective circulation system associated with the granites of south-west England also has important implications for exploration work connected with the efficient extraction of geothermal energy. The hot springs of South Crofty Mine could well indicate the presence of a large hydrothermal reservoir that could be easily tapped - a reservoir that is likely to contain a rich assemblage of dissolved elements, making the added attraction of solution mining a distinct possibility. ?

Finally, the authors are aware that much of the evidence brought together here comes from several separate granite plutons in south-west England. Much work remains to extend all aspects of study to even one pluton.

References

Alderton, D.H.M. 1975. Fluid inclusion studies in S.W. England. *Proc. Ussher Soc. 3,* 214-217.

Alderton, D.H.M. 1978. Fluid inclusion dates for lead-zinc ores from S.W. England. *Trans. Instn. Min. Metall. 87,* B132-B135.

Alderton, D.H.M. and Rankin, A.H. Fluid inclusions studies in the St Austell granite. (in press).

Allman-Ward, P., Halls, C., Rankin, A. and Bristow, C.M. 1982. An intrusive hydrothermal breccia body at Wheal Remfry in the western part of the St Austell granite pluton, Cornwall. *In:* Evans, A.M. (ed.) *Metallization associated with acid magmatism.* Wiley, Chichester, 1-28.

Al-Saleh, S., Fuge, R. and Rea, W.J. 1977. The geochemistry of some biotites from the Dartmoor Granite. *Proc. Ussher Soc. 4,* 37-48.

Ball, T.K., Basham, I.R. and Mickie, U, McL. 1979. Uraniferous vein occurrences of south-west England - Paragenesis and genesis. *Preprint, International Atomic Energy Agency Meeting on the Geology of Vein and Similar Type Uranium Deposits, Lisbon.*

Batchelor, A.S. 1978. The engineering properties of the South Western granites related to artificial geothermal exploitation. *Proc. Ussher Soc. 4,* 355-361.

Beer, K.E., Edmunds, W.M. and Hawkes, J.R. 1978. A preliminary look at lithium in the United Kingdom. *Energy 3,* 281-291.

Beer, K.E. and Scrivener, R.C. 1982. Metalliferous mineralisation. *In:* Durrance, E.M. and Laming, D.J.C. (eds.) The *Geology of Devon,* Exeter, 117-147.

Black, J.H. 1979. Results of multiple borehole pumping test in low permeability granite. *O.E. C.D. Meeting. Paris.*

Bott, M.H.P., Johnson, C.A.L., Mansfield, J. and Wheildon, J. 1972. Terrestrial heat flow in north-east England. *Geophys. J.R. Astr. Soc. 27,* 277-288.

Brace, W.F. 1980. Permeability of crystalline and argillaceous rocks. J. *Rock Mech. Min. Sci. Geomech. Abstr. 17,* 241-251.

Bray, C.J. 1980. Mineralisation, greisenisation and kaolinisation at Goonbarrow china clay pit, Cornwall, U.K. *Unpubl. Ph.D. Thesis, Univ. Oxford.*

Bristow, C.M. 1977. A review of the evidence for the origin of the kaolin deposits in S.W. England. *Proc. 8th International Kaolin Symposium and Meeting on Alunite, Madrid-Rome, September 7-16, 1977.*

Burgess, W.G., Edmunds, W.M., Andrews, J.N., Kay, R.L.F., and Lee, D.J. The original and circulation of groundwater in the Carnmenellis granite: The h ydrogeochemical evidence. (in press).

Collins, J.H. 1912. Observations on the west of England mining region. *Trans. R. Geol. Soc. Cornwall. 14,* 695p.

Dewey, H. 1925. The mineral zones of Cornwall. *Proc. Geol. Assoc. 36,* 107-135.

Dines, H.G. 1956. The metalliferous mining region of southwest England. *Men. Geol. Surv. G.B.*

Durrance, E.M. 1978. Radon in the stream waters of East Devon *Proc. Ussher Soc. 4,* 220-228.

Durrance, E.M. and Grainger, P. t977. The Cornubian island. *Proc. Ussher Soc. 3,* 82-85.

Durrance, E.M., Meads, R.E., Ballard, R.R.B. and Walsh, J.N. 1978. The oxidation state of iron in the Littleham Mudstone Formation of the New Red Sandstone Series (Permian-Triassic) of southeast Devon, England. *Bull. Geol. Soc. Am. 89,* 1231-1240.

Edwards, R.P. 1976. Aspects of trace metal and ore distribution in Cornwall. *Trans. Instn. Min. Metall. 85,* B83-B90. Elder, J. 1981. *Geothermal Systems.* Academic Press, London.

Exley, C.S. and Stone, M. 1964. The granite rocks of south west England *In:* Present views of some aspects of the geology of Cornwall and Devon. *150th Anniversary Volume. Roy. Geol. Soc. Cornwall.*

Exley, C.S. and Stone, M. 1982. Hercynian intrusive rocks. *In:* Sutherland, D.S. (ed). *Igneous Rocks of the British Isles,* Wiley, Chichester, 287-320.

Fehn, U., Cathles, L.M. and Holland, H.D. 1978. Hydrothermal convection and uranium deposits in abnormally radioactive plutons. *Econ. Geol. 73,* 1556-1566.

Francis, M.F. 1980. Investigation of the south-west England thermal anomaly zone. *Unpubl. Ph.D. Thesis, Univ. London.*

Garnett, R.H.T. *1965.* Local mineral zoning in Geevor tin mine, Cornwall. *In:* Symposium on problems of post magmatic ore deposition, Prague, 1963 *(Geological Survey of Czechoslovakia, 1965, I,* 91-96).

Halliday, A,N. and Mitchell, J.G. 1976. Preliminary isotopic age determinations for the St Just mining district. (Abstract) *Proc. Ussher Soc. 3,* 426.

Hart, M.B. 1982. The Marine Rocks of the Mesozoic. *In:* Durrance, E.M. and Laming, D.J.C, (eds.) The *Geology of Devon.* Exeter, 179-203.

Hawkes, J.R. 1982. The Dartmoor Granite and later volcanic rocks. *In:* Durrance, E.M. and Laming, D.J.C. (eds.) The *Geology of Devon.* Exeter. 85-116.

Hawkes, J.R. and Dangerfield, J. 1978. The Variscan granites of South West England: A progress report. *Proc. Ussher Soc. 4,* 158-171.

Heath, M.J. 1982. Uranium in the Dartmoor Granite: geochemical and radiogeological investigations in relation to the geothermal anomaly of south-west England. *Unpubl. Ph.D. Thesis, Univ. Exeter.*

Hill, J.B. and MacAllister, D.A. 1906. Geology of Falmouth and Truro and of the mining district of Camborne and Redruth. *Mem. Geol. Surv. G.B.*

Jackson, N.J., Moore, J.McM. and Rankin, A.H. 1977. Fluid inclusions and mineralisation at Cligga Head. J.. *Geol. Soc. Lond. 134,* 343-349.

Keller, C.V. and Rapolla, A. 1976. Electrical Prospecting Methods. *In:* Civetta, L., Gasprini, P., Luongo, R. and Rapolla, A. (eds). *Physical Volcanology.* Elsevier, Amsterdam.

Manning, D.A.C. 1978. Experimental problems encountered in the addition of fluorine to starting materials in the system Q-Ab-Or. *NERC Rpt. Progress in experimental petrology. 4,* 46--47.

Manning, D.A.C. 1981. The *effect* of fluorine on liquidus phase relationships in the system Q-Ab-Or with excess water at 1kb. *Contrib. Mineral. Petrol. 76,* 205-215.

Moore, J. McM. 1975. *A mechanical* interpretation of the vein and dyke systems of the S.W. England orefield. *Mineral. Deposita. 10.* 374-388.

Moore, J.McM. 1982. Mineral zonation near the granitic batholiths of south west and northern England, and some geothermal analogues. *In:* Evans, A.M. (ed.) *Metallisation associated with acid magmatism,* Wiley, Chichester, 229-241.

Moore, J.McM. and Jackson, N.J. 1977. Structure and mineralisation in the Cligga granite stock, S.W. England. *J. Geol. Soc. Lond. 133,* 467-480.

Parasnis, D.S. 1973. *Mining Geophysics.* Elsevier, Amsterdam. Parasnis, D.S. 1979. *Principles of Applied Geophysics.* Chapman and Hall, London.

Phillips, W.J. 1973. Mechanical effects of retrograde boiling and its probable importance in the formation of some porphyry ore deposits. *Inst. Mining Metall. Trans. 82B,* 90-98.

Pichavant, M. 1979. Etude experimentale a haute temperature et Ikban du rtle du bore dans quelques systemes silicates Interet petrologique et metallogenique. *These Docteur de Specialite. 3e cycle, C'Institut National Polytechnique de Lorraine.*

Roedder, E. 1971. Fluid inclusion studies on the porphyry-type ore deposits at Bingham Utah, Butte, Montana, and Climax, Colorado. *Econ. Geol. 66,* 98-120.

Sabine, P.A. 1968. Kaolinitic Wall-Rock Alteration of the Perran Iron Lode. *23rd Int. Geol. Cong. 14,* 45-53.

Sheppard, S.M.F. 1977. The Cornubian batholith, south west England: D/II and $^{18}O/^{16}O$ studies of kaolinite and other alteration minerals. J. *Geol. Soc. Lond. 133,* 573-591.

Stone, M. 1975. Structure and petrology of the Tregonning-Godolphin Granite, Cornwall, *Proc. Geol. Assoc. 86,* 155-170.

Tammemagi, H.Y. and Wlieildon, J. 1974. Terrestrial heat flow and heat generation in south west England. *Geophys. J.R. Astr. Soc. 38,* 83-94.

Tammemagi, H.Y. and Smith, N.L. 1975. Terrestrial heat flow and heat generation in south west England. J.. *Geol. Soc. Lond. 131* 415-427.

Wheildon, J., Francis, M.F., Ellis, J.R.L. and Thomas-Betts, A. 1980. Explanation and Interpretation of the S.W. England geothermal anomaly. *Preprint, Seminar on Geothermal Energy,* Strasbourg.

Read at the Annual Conference of the Ussher Society, January 1982

The argillite facies of the Middle Devonian succession in north Cornwall

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A.P. Beese, 1982, The argillite facies of the Middle Devonian succession in north Cornwall. *Proc. Ussher Soc. 5,* 321-332.

A nearly complete marine Middle Devonian succession comprising some 2000m of strongly deformed dark grey argillites is found along the coast of north Cornwall. Three lithostratigraphical units are defined, namely the Porthcothan Slate, Treyarnon Slate and Constantine Bay Slate Formations. This succession, here termed the Trevose Group, is characterised throughout by recurrent sedimentation of facies representing inner basin, outer (turbidite) fan and off-fan environments. A subsiding intracontinental basin with rapid fine-grained clastic sedimentation is interpreted. The central part of the succession is characterised by the highest incidence of turbidite muds and silts.

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Introduction

Dark grey argillites of the Middle Devonian are well exposed in the cliffs and rock platforms of the irregular coastline near Padstow (Fig. 1). Of particular value is the long dip section between Park Head and Trevose Head which provides a nearly complete sequence through east-west striking slates which have been folded into north facing recumbent folds (Fig. 2). To the south are the older Staddon Grits and Bedruthan Slates of supposed Lower and early Middle Devonian ages respectively, and to the north are the variable Upper Devonian argillite successions complexly folded into the St Minver Synclinorium (Fig. 1).

Fox (1901) was the first person to study properly the available palaeontological evidence between Newquay and Trevose Head, and concluded that the position of the Lower/Middle Devonian boundary is likely to be in the vicinity of Park Head (Fig. 1). The *Memoir* (Reid and others 1910) supplied new information on the stratigraphy and structure of the area but delineated a position for the Middle/Upper Devonian boundary which was too far south. House (1956) revised this boundary showing that the goniatites from Trevone were Givetian in age and not Upper Devonian. In his unpublished thesis, Ripley (1964) concentrated on the structural aspect of the beds in the Newquay to Trevose Head section. North of Park Head he determined a consistent northward younging of the slates (which he termed the Treyarnon Slates) showing that they had been defamed into north facing recumbent folds. He proposed subdivisions based on lithological criteria and attributed repetition of some of these along the coast to major normal faulting rather than to recurrent sedimentation as proposed here (see below). Gauss and House (1972) have described the youngest part of the Middle Devonian sequence between Constantine Bay (SW 85707505) and Dinas Head, west of Trevose Head (SW 85037613), designating this the type section for the Trevose Slates. They were further able to correlate these more southerly situated dark grey slates of the Trevone succession with similar beds to the north of Polzeath which belong to the Pentire succession (Fig. 1). More recently described are the preferred orientations of fossils in the Middle Devonian (Beese 1978).

While much recent work has been completed on the structure and stratigraphy of the Upper Devonian in north Cornwall (see Gauss and House 1972; Beese 1981; Beese *in preparation),* the more uniform lithologies of the Middle Devonian have attracted less interest. This paper assesses the stratigraphy of the dark grey argillites which is complicated by the repetition of lithologies on both the small and large scale, poor biostratigraphical control and strong deformation (Beese 1981), and then interprets the environmental evolution of the facies of the area during the Middle Devonian.

Structural Considerations

Detailed stratigraphical assessment of the dip sections between Park Head and Trevose Head and at Trevone (Fig. 1) was based on the appearance, palaeontological content and stratigraphical thickness of the lithologies present. The deformed nature of the argillites has complicated the stratigraphy and therefore attitudes of bedding, fold and fault structures and sedimentary way up structures were noted (see Beese 1981 and material stored in Hull University). In this way measured stratigraphical profiles were compiled for sequences of argillites without any visible significant faulting. By piecing these profiles together, and allowing wherever possible for the displacements of common steeply dipping normal faults, a probable overall stratigraphy was reconstructed. The general stratigraphy obtained should be fairly precise for such a large thickness of sediments (Fig. 3). Gaps in the succession are due to inaccessible cliff sections and occasional blown sand cover.

The Middle Devonian is deformed into a series of consistently north facing mesoscopic recumbent folds which are visible in cliff sections (Fig. 2). Therefore, the beds have either a normal northerly dip, or, an inverted southerly dip. In the south at Park Head the general (sheet) dip of the folded slates is to the north at a shallow angle. Moving northwards recumbent fold noses are often exposed, for example, at Treyarnon Bay. Finally, at Trevose Head and Trevone most of the succession dips south and is inverted. Therefore, moving from south to north the bedding becomes progressively overturned and the structure is interpreted as a major north facing recumbent fold with an axial plane which dips gently southwards (Fig. 2). Almost everywhere the associated slaty cleavage is close to horizontal and parallel to fold axial surfaces. Gauss (1973) suggested that the folds are of modified similar style. Therefore, to obtain a maximum estimate of stratigraphical thickness, the thickness of the beds parallel to the slaty cleavage rather than orthogonal bed thickness was measured, since the latter varies much more owing to thickening along fold hinges and thinning along fold limbs.

The amount of faulting present is crucial to the interpretation of the stratigraphy and the repeated pattern of facies within it (Fig. 3). However, the uniformity of the Middle Devonian lithologies is not

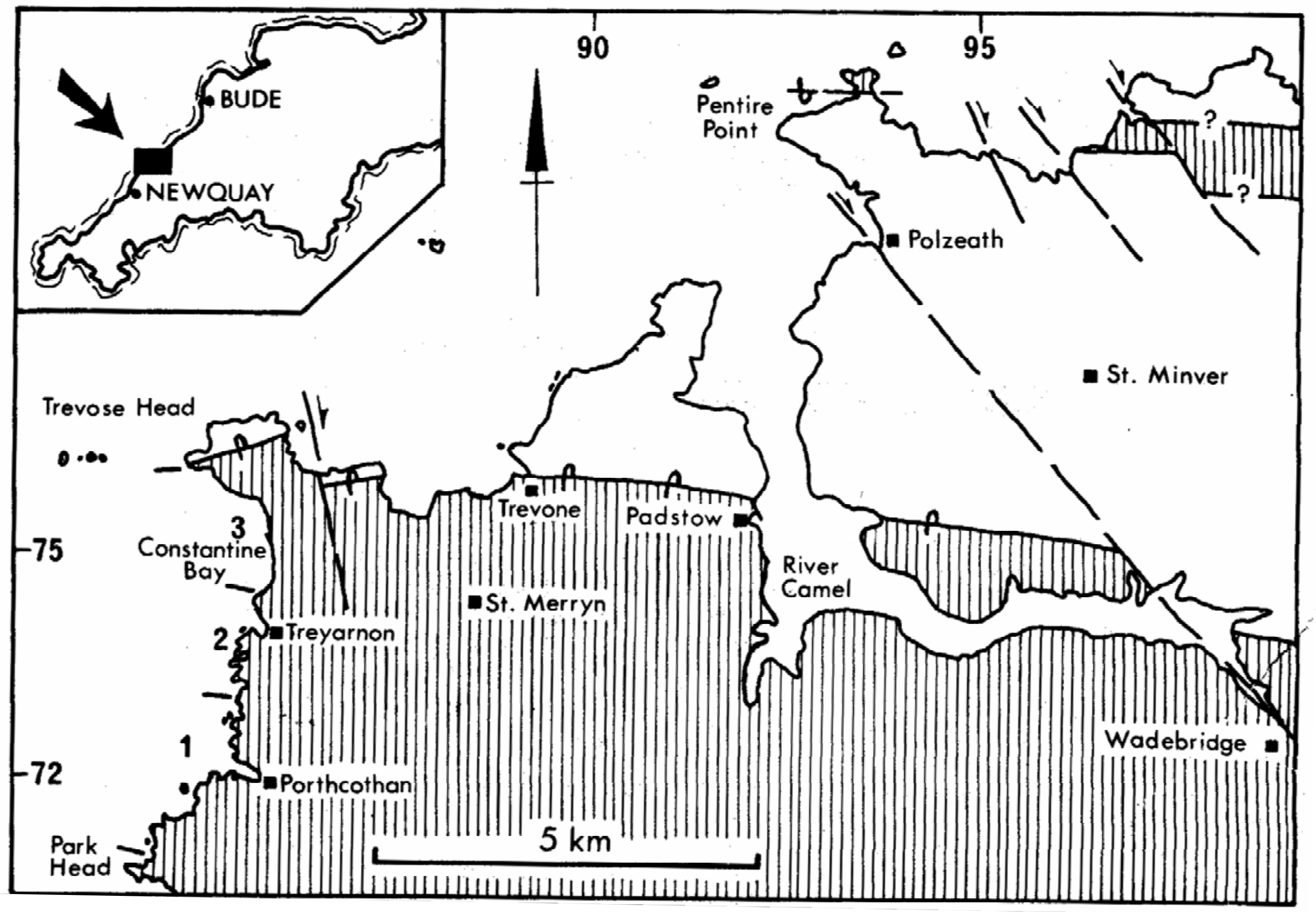

Figure 1. Sketch geological map of the St Minver Synclinorium showing the extent of the Middle Devonian (shaded) and Upper Devonian (blank), and the coastal exposures of the Porthcothan Slate (1), Treyarnon Slate (2) and Constantine Bay Slate (3) Formations (the sketch map is adapted from Roberts and Sanderson, 1971).

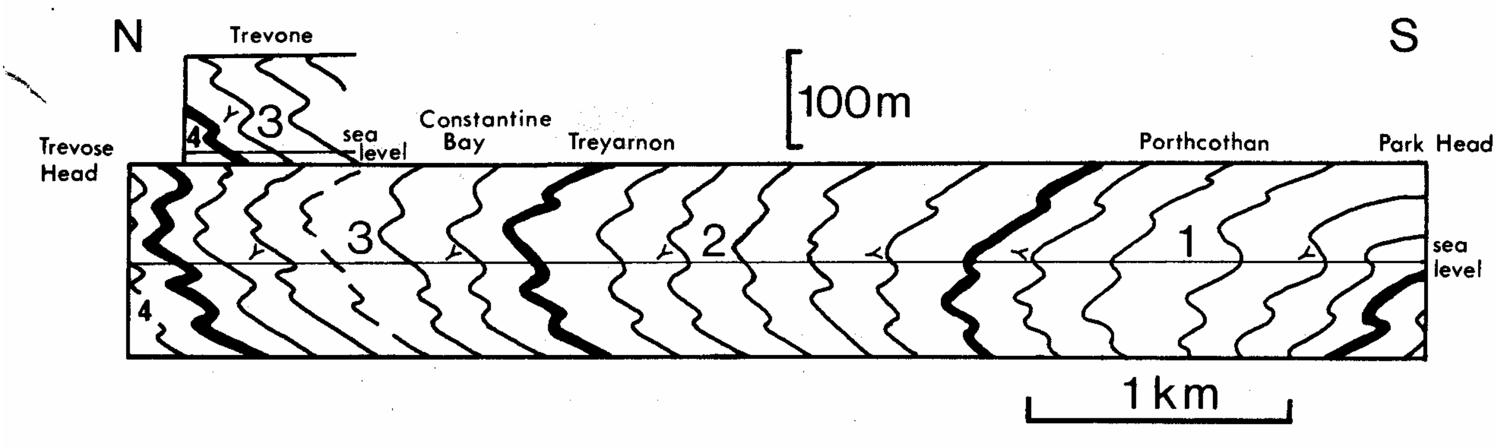

Figure 2. Schematic diagram showing the structure of the Porthcothan Slate (1), Treyarnon Slate (2) and Constantine Bay Slate (3) Formations, which are in turn overlain by the Marble Cliff Beds (4).

helpful to such analysis. As far as can be judged there is no major faulting because firstly, where marker bands are available maximum displacements along common steeply dipping normal faults and rare low-angle normal faults are between ten and twenty metres, and secondly, there are no sudden changes in argillite lithologies across bays and inlets Were unexposed faults might be expected. This evaluation runs counter to that of Ripley (1964) which suggested several major faults causing much more than just small-scale repetition of beds.

Stratigraphy

Three formal lithostratigraphical units, namely the Porthcothan Slate, Treyarnon Slate and Constantine Bay Slate Formations, are distinguished using the criterion of the essential argillite lithology, here termed the matrix argillite. In terms of thickness the matrix argillites form over 90% of the succession while individual beds are subordinate. Since all three formations represent a conformable sequence of dark grey argillites the formal group name, the Trevose Group, is chosen as a useful joint name for them. In his unpublished thesis, Ripley (1964) used the name Treyarnon Slates to cover the complete succession, and proposed three largely fault-bound subdivisions not accepted as valid here. Gauss and House (1972) introduced the term Trevose Slates for the youngest part of the Middle Devonian. The following discussion is confined to the descriptive aspects of the succession, while the interpretation of facies is left to the next section.

Porthcothan Slate Formation

This formation comprises 740m or more of homogeneous dark grey argillites. These are found in the type section which runs north and south of the inlet at Porthcothan (Fig. I). A 1m thick conformable greenstone band which may be volcanic occurs at Lower Butter Cove (SW 84377104) and is defined as the base of the formation.

The Memoir (Reid and others 1910) mentions other greenstone bands further to the south at Park Head (SW 840709) and Pentire Steps (SW 848704) in similarly low-lying slates; these may represent the same stratigraphical level. Some dark grey argillites exist below this band but the thickness of them is judged to be small because silty argillites with ferrugineous laminae, that is the Bedruthan Slates (Ripley 1964), occur immediately south of Pentire Steps. The upper limit of the formation is taken at the lithological transition occurring 200m southwest of Fox Cove (SW 85457318) where laminations in the argillites become consistently distinct.

The general homogeneity of the argillite matrix in the Porthcothan Slate Formation is its characteristic feature (Fig. 4a). Where occurring, pale grey laminae are well spaced. Thin lenticular black argillite bands are the commonest individual lithology (Figs. 4a and 4b), while thin pale grey argillite bands occur in zones at certain levels (Fig. 3). In the youngest 200m of the succession the matrix argillite is faintly laminated and slightly calcareous lithologies such as graded laminated silty beds (Fig. 4c) are more frequent (Fig. 3). Also abundant are diagenetic calcite and pyrite segregations. At Rowan Cove (SW 855726) a metre thick tuff band is exposed (Ripley 1964) and this may represent the coastal exposure of the tuff band noted in the *Memoir* (Reid and others 1910, p. 17) at localities south of St Merryn Church (SW 886737) and near Wadebridge (SW 983724).

Stratigraphically useful fossils are rare. According to Fox (1901), *Pteroconus mirus,* indicative of the lower part of the Middle Devonian, is found in the underlying Bedruthan Slates *(sensu* Ripley 1964) at Lower Butter Cove (SW 844711), that is near the base of this formation as defined here. Therefore, since the overlying Treyarnon Slate Formation is considered to be at least partly Eifelian in age (see above), this formation is also interpreted as Eifelian.

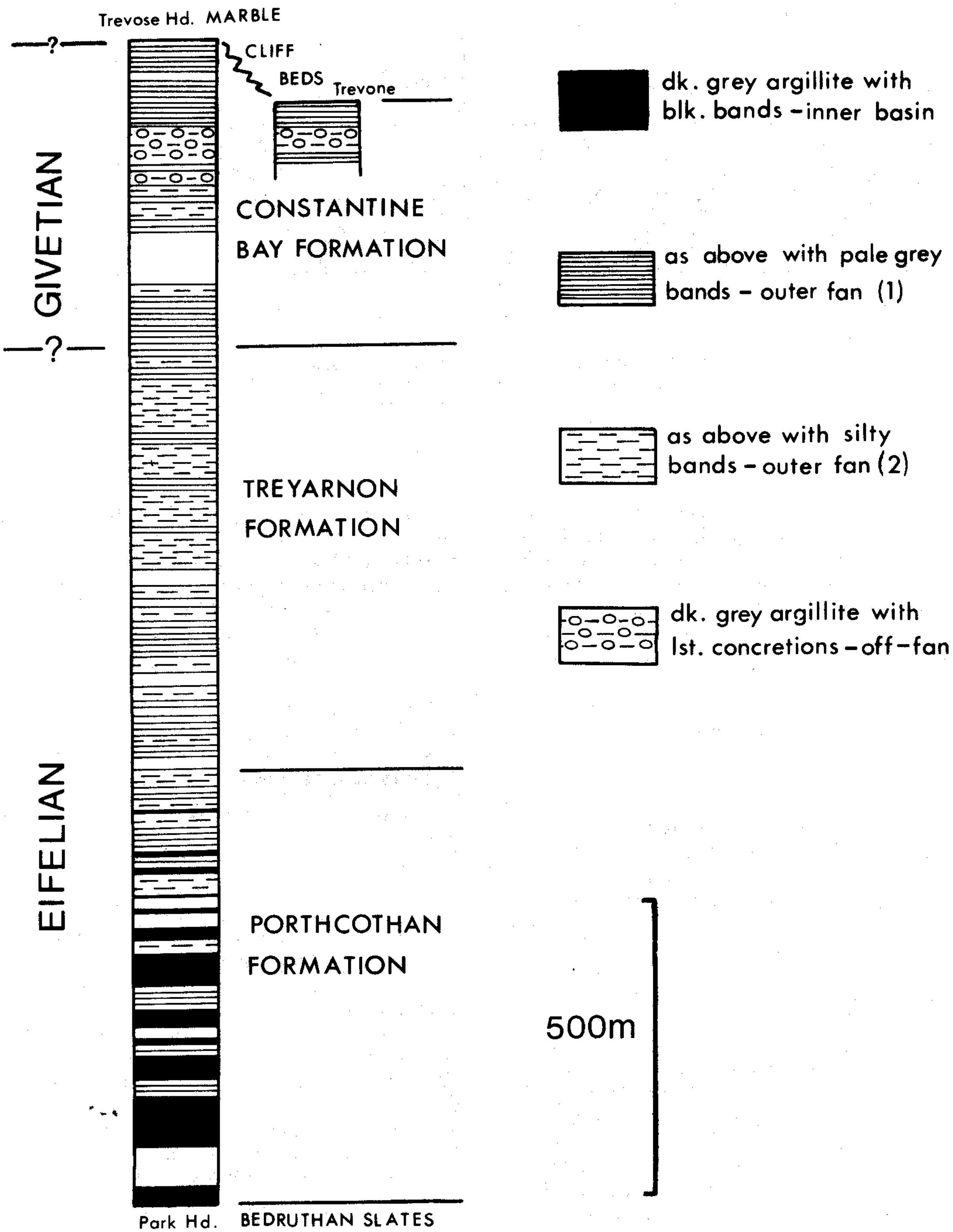

Figure 3. Summary diagram showing the distribution of the formations and facies with time. Blank portions Of the succession are unsurveyed owing to inaccessibility.

Easily the most abundant faunas are the minute dacryoconarids (nowakiids and styliolinids). According to Fox (1901) orthocones and conulariids are found at Trescore Island (SW 848720). Other impoverished faunas include crinoids, phacopid trilobites, solitary rugose corals and tabulate colonial corals (typically *Pleurodictyum).*

Treyarnon Slate Formation
This unit comprises an estimated 720m of distinctly laminated grey argillites (Fig. 3) which are exposed along the type section either side of the inlet at Treyarnon (Fig. I). The base of the unit above the Porthcothan Slate Formation is described above. The upper limit of the formation is found north of Chair Cove (SW 85777450). North of this point the argillites are consistently calcareous using the criterion of effervescence with dilute hydrochloric acid. This transition between non-calcareous and calcareous argillite is only about 20m thick.

The succession is characterised throughout by a matrix argillite with laminations alternately coloured dark and pale shades of grey (Figs. 5a and 5b), frequent rimmed black argillite bands (Fig. 5c), and commonly occurring zones of pale grey argillite bands (Fig. 5e) and laminated silty beds (Fig. 5f). Silty beds are typical of the formation. A few graded laminated silty beds exhibit cross-lamination (Fig. 40 and 'scour and fill' (Figs. 4e and 4f). Silty bands up to 40cra thick (Fig. 5d) are exposed at Fox Cove (SW 855733) and Treyarnon Bay (SW 857741); these are the coarsest lithologies found in the Trevose Group. Thin calcareous beds are sometimes found.

Only one stratigraphically useful fossil has been determined. Dr C.J. Burton (pers. comm.) has identified an unusually well preserved dacryoconarid from the lower part of the succession north of Fox Cove (SW 85457334) as *Nowakia sulcata* (Roemer). Palaeontologists have attached a number of age ranges to this species. Zagora (1964) designates an Upper Eifelian to Lower Givetian range, while Boucek (1964) notes its occurrence in the Upper Eifelian. A more recent reference to N. *sulcata* is by Lutke (1979) who confines the species to the Lower and Middle Eifelian, Therefore, the lower part of the formation is probably Eifelian and the whole unit may be older than Givetian. The rare calcareous bands present contain no conodonts (Dr N. Mouravieff, pers. comm)

Fauna is remarkably impoverished. The normally abundant dacryoconarids seem less abundant and rare crinoids are the only other fauna present.

Constantine Bay Slate Formation
An estimated 600m of dark grey calcareous argillites are exposed in the type section either side of Constantine Bay, where a large area of blown sand interrupts an estimated 100 to 150m of the succession. The section at Trevone Bay, 4.5km to the east, provides a second look at the top of the formation. The base of the unit above the Treyarnon Slate Formation is described above. The top of the formation is defined by the entry of an alternating limestone (turbidite) and dark grey argillite succession, which has been given the name Marble Cliff Beds by Kirchgasser (1970) and Gauss and House (1972). In the sections described here, this boundary occurs at the inlets of Mackerel Cove, south of Dinas Head (SW 85067616) and Trevone Bay (SW 89137597). Below this upper contact both sections contain remarkably similar dark grey argillite sequences with nodular and lenticular limestone beds and a collection of very diverse faunas, often pyritised. These have been tentatively correlated (Fig. 3) and therefore, explanations for the variable thickness of argillite above them are required. One is that the deposition of the limestone turbidite bands began much earlier in the succession to the east at Trevone Bay (Fig. 3), and a second is that the inlet there is the site of a large fault which has cut out some 50 to 100m of the succession. The first explanation is preferred here because there are a few thicker limestone turbidites developed within the Constantine Bay Slate Formation on the south side of the inlet very similar to those seen in the Marble Cliff Beds on the north side, and presumably therefore, not separated from them by 50 to 100m of argillites.

Laminations in the matrix argillites are variably developed. In the upper part of the succession, where groups of limestone nodules (septaria), lenticles and bands occur (Fig. 3), they are faint or absent. In the lower half of the succession they are distinct and associated with thin black, pale grey and silty argillite bands in the same way as in the underlying formation. However, unlike the preceding unit nearly all the lithologies are calcareous. The exception to this rule is the 50m of succession immediately south of Mackerel Cove (SW 850760). Pyrite and calcite segregations are common in the unit and framboidal pyrite occurring as octahedral microcrystallites has been detected using the Scanning Electron Microscope.

Goniatites from fossil horizons at Pentonwarra Point, Trevone Bay (SW 890760) are useful stratigraphical indicators. House (1956, 1963) has most recently assessed these faunas, clearly identifying a *terebratrurn* Zone assemblage which corresponds to the Upper Givetian. He tentatively suggests a possible Eifelian fauna including *Latarnarcestes noeggerathi* (von Buch) at Booby's Bay (SW 853758) and a Lower Givetian fauna with *Agoniatites kayseri* (Wedekind) at Constantine Bay (SW 857746). The Eifelian date may be incorrect because limestone concretions at Booby's Bay have now been correlated with those at Trevone Bay (Fig. 3). Confirmation of the Upper Givetian age for the youngest part of the unit was provided by Kirchgasser (1970) who isolated conodonts from the *varcus* Zone in the limestone turbidites at Trevone Bay (SW 890760), and established the position of the Lower/Middle Devonian boundary in the overlying Marble Cliff Beds (Fig. 3). Mouravieff (in House and others 1978) gives a more precise date of

Lower *varcus* Zone for the Trevone Bay limestones. Thin impure limestones from the older parts of the succession contain no conodonts (Dr N. Mouravieff, pers. comm.). Therefore, most if not all the Constantine Bay Slate Formation is probably Givetian m age.

Most of the diverse faunas in this formation are found at Booby's Bay (SW 853758) and Trevone Bay (SW 891760) in dark grey argillites associated with limestone concretions. Nearly all were discovered by Fox (1895, 1901) and were subsequently listed in the *Memoir* (Reid and others 1910). Drifted dacryoconarids are the most abundant faunas. Recently conodonts and ostracods have been found in the limestone turbidites from the south side of Trevone Bay (Dr N. Mouravieff, pers. comm.). In restricted horizons in the argillites other faunas include small gastropods, goniatites, bivalves *(Buchiola)* and brachiopods; a few large goniatites, occasional orthocones, conulariids, phacopid trilobites, bryzoans and solitary and colonial corals; a ganoid fish fragment reported from Trevone Bay (Fox 1895); and burrowing traces at Booby's Bay (SW 85307580) including *?Chondrites* (Beese 1981).

Facies Interpretation

The formations described above can be interpreted in terms of four facies (Fig. 3). The diagnostic features of these facies are the associations of the individual or minor lithologies which they contain. Many of these lithologies and hence facies are repeated throughout the succession whether the matrix argillite is homogeneous (Porthcothan Slate Formation), laminated (Treyarnon Slate Formation) or calcareous (Constantine Bay Slate Formation). It has already been argued that large scale repetition of any of the facies is unlikely to be due to the effect of faulting, since visible maximum displacements on faults are only in the order of a few tens of metres. In any case, identical individual bands within different matrix argillites are unlikely to represent the same stratigraphical level. However, the possibility cannot be ruled out that some of the small scale repetition illustrated in Figure 3 is the result of faulting.

The diagnosis, description, discussion and occurrence of each facies is dealt With in the same way as the definition of a fossil species. Genetic (environmental) rather than descriptive terminology is used for each facies. Although the latter system is more permanent if the interpretation of any facies is later changed, the large number of terms required make it cumbersome and inefficient. The properties of each facies are emphasised in this paper, while possible equivalent ancient and modern analogues are mentioned only briefly. The present author intends to publish a more complete discussion of both the Middle and Upper Devonian facies of north Cornwall at a later date.

All the facies are characterised by matrix argillite lithologies with a standard composition of micas and chlorite and subordinate amounts of quartz +/- calcite. Most of these minerals have been affected by diagenesis, but most of the quartz and calcite components probably represents detrital material.

Inner basin facies

This facies comprises dark grey argillites associated with only one minor lithological type - the thin black argillite bands(Figs. 3, 4a and 4b). The matrix argillite is nearly homogeneous with only well space pale grey laminations, 1 to 2mm in thickness. The black argillite bands, 1mm to 3cm thick, are usually lenticular but can be laterally continuous. Over relatively small stratigraphical intervals they are regularly spaced and in different exposures this spacing varies between one band to every 20cm to one every few metres of the matrix argillite. In thin section the bands are homogeneous and extremely fine-grained, although silt laminae are sometimes present. The bands contain virtually no silt-size quartz, and chlorite is abundant. There is no evidence to indicate that these black argillite bands are relatively rich in phosphate as suggested in the *Memoir* (Reid and others 1910, p.11) and by Gauss and House (1972, p. 156).

The faunas of the matrix argillites occur in restricted horizons and are probably current drifted. They comprise supposedly planktonic dacryoconarids, some large articulated crinoids which may be close to life position, and corals. In contrast the black argillite bands contain virtually no dacryoconarids, and, according to the *Memoir* (Reid and others 1910), rare conulariids whose adult mode of life is interpreted as unattached and similar to a free swimming medusoid (Moore and Harrington 1962).

Therefore, the generally structureless argillites are interpreted as the result of rapid clastic sedimentation in a marine basin influenced by weak current activity. The composition and faunal content of the black argillite bands possibly indicate deposition by a process which interrupted normal clastic and bioclastic input. Their origin may be linked to extreme distal turbidity current deposition because they are similar to the ungraded muds of Piper (1978), and in other facies form the youngest division of beds interpreted as fine-grained turbidites The lenticular nature of most of the bands which are relatively competent is considered to be secondary and may be the result of boudinage parallel to bedding during soft sediment deformation, as well as to later rotation during the formation of the slaty cleavage. The large thickness of sediments in this facies and its proximity to other facies with turbidite muds and silts necessitate its positioning within an inner (relatively proximal) rather than an outer (relatively distal) basin environment.

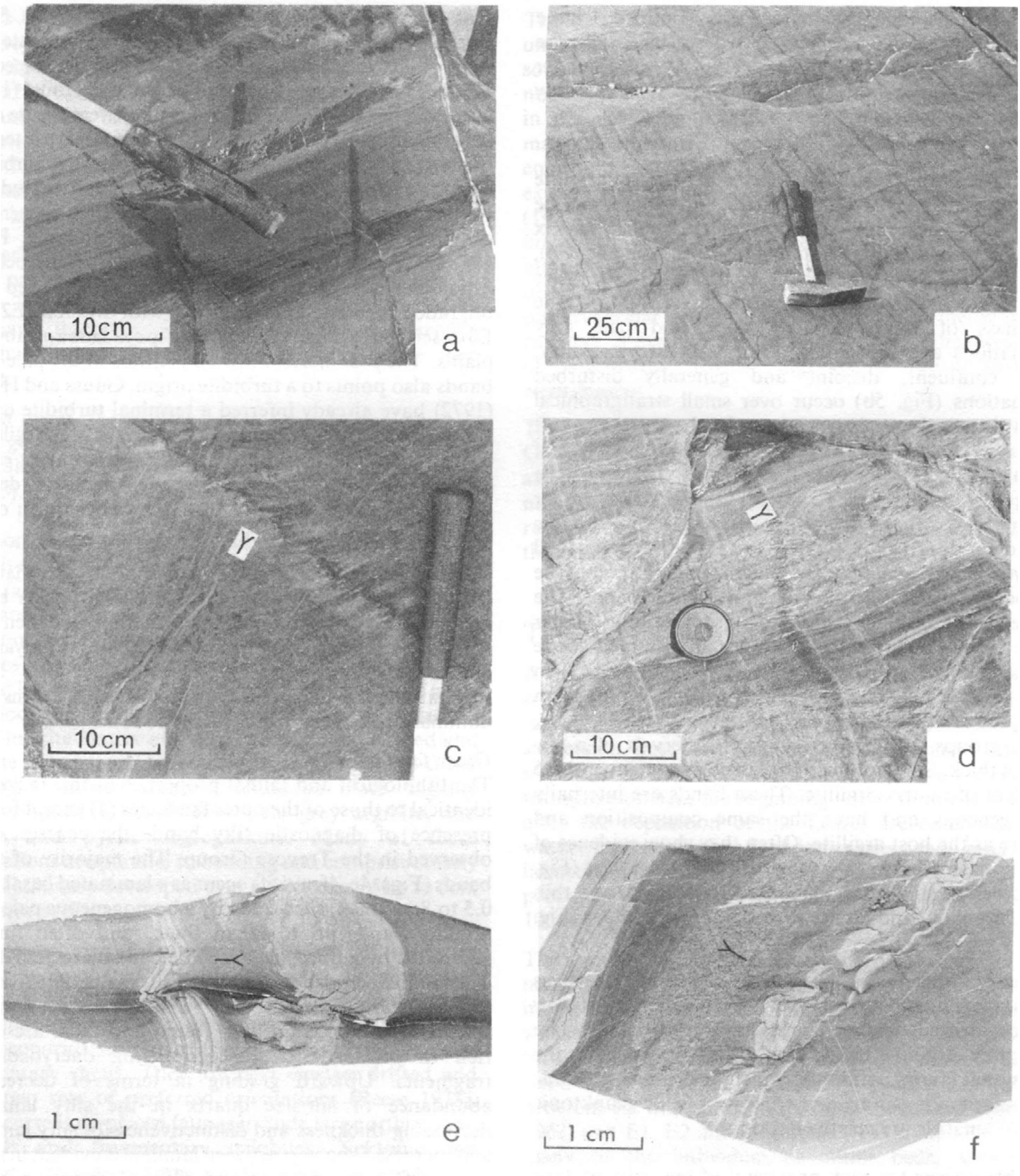

Figure 4. Photographs to illustrate argillite lithologies and facies.
(a) & (b) Lenticular black argillite bands in homogeneous dark grey argillite, inner basin facies.
(c) Pale grey argillite band with basal silty lamina, outer fan facies (1)
(d) Black argillite band with basal pale grey argillite seam, outer fan facies (1).
(e) & (f) Thin sections of laminated silty bands with 'scour and fill' and cross-laminated structures, outer fan facies (2)

The recurrent inner basin facies is confined to the Porthcothan Slate Formation where it forms the dominant thickness of sediments (Fig. 3). In the upper part of the formation it becomes increasingly insignificant and finally disappears.

Outer fan facies (1)
Dark grey argillites with thin black and pale grey argillite bands are diagnostic of this facies. Lithologies can be either non-calcareous or calcareous. Usually, matrix argillites are distinctly laminated (Figs. 5a and 5b), although this is not true for the occurrences of the facies in the Porthcothan Slate Formation (Fig. 3). The thickness of the alternately dark and pale grey laminations averages 2mm. Their structure is planar. Rare confluent, disjoint and generally disturbed laminatiobs (Fig. 5b) occur over small stratigraphical intervals of about lcm and probably represent soft sediment deformation. There is no evidence of bioturbation. No clear distinctions between the differently coloured laminae are found. The darker laminations appear to be relatively rich in organic carbon, detrital silt-size quartz and drifted dacryoconarid remains. The paler laminations may be thinner equivalents of the pale grey argillite bands. The properties of the black bands are the same as for the inner basin facies except that they are usually rimmed above and below by thin pale grey argillite bands up to 3cm thick (Fig. 5c). Pale grey argillite bands, 0.5cm to 10cm thick, are always present (Fig. 5e) and occur either singly, or, in groups within stratigraphical intervals of a few metres thick. Some occur as frequently as one to every 5 or 10cm of matrix argillite. These bands are internally homogeneous and have the same composition and texture as the the host argillite. Often they show evidence of grading; some having sharp bases and diffuse tops (Fig. 5e), others, a single basal lamina (Fig. 4c) and/or a thin black argillite band adjacent to the upper contact (Fig. 4d).

Faunas of this facies are scarce. The non-calcareous matrix argillites have relatively small numbers of *post mortem* drifted dacryoconarids preserved. The isolate pale grey argillite bands are distinctive because the occasional faunas within them include drifted benthonic forms: crinoids, corals and trilobites; while planktonic dacryoconarids are relatively rare.

Possible origins for each or several of the pairs of dark and pale grey laminations in the matrix argillite include input from a weak turbidity current, or, for each pair, seasonal input from biannual currents. A check on the likelihood of the latter can be made by considering the time taken to deposit the Treyarnon Slate Formation (720m thick) which forms roughly one third of the thickness of the Middle Devonian (2060+m) in north Cornwall. Using the average thickness of 2mm for each lamina observed above, one year's sedimentation would be 4mm thick. Assuming no major periods of non-deposition, this gives a time interval of only 0.2 million years for the sedimentation of the Treyarnon Slate Formation when 5 million years is a closer estimate to a third of the Middle Devonian according to the respective 12 and 17 million year figures of Friend and House (1964) and Boucot (1975). Using the 5 million year figure each pair of laminae would be deposited at minimum intervals of between 25 and 30 years. Therefore, the turbidity current hypothesis seems likely. Many authors studying Recent deep sea fan sediments have noted the occurrence of laminated muds within them (for example, Piper 1978), The pale grey argillite bands with their associated lithologies are clearly analogous to the graded and ungraded turbidite mud sequence with divisions E2 and E3 described by Piper (1978) for deep sea fans and abyssal plains. The *post mortem* drifted benthos in the pale grey bands also points to a turbidite origin. Gauss and House (1972) have already inferred a terminal turbidite origin for the 'light coloured banding' in the dark grey argillites. The rimmed black argillite bands may represent either cyclical turbidite muds, or, local alteration during diagenesis. The features of this facies suggest an outer (lower) fan environment.

This recurrent facies is represented in all three formations (Fig, 3). It is found in association with the inner basin facies in the Porthcothan Slate Formation, and then with the closely related outer fan facies (2) in the Treyarnon Slate Formation. In the Constantine Bay Slate Formation the facies is calcareous and forms the dominant thickness of the succession.

Outer fan facies (2)
The lithological and faunal properties of this facies are identical to those of the outer fan facies (1) except for the presence of diagnostic silty bands the coarsest bed observed in the Trevose Group. The majority of these bands (Figs. 4e, 4fand 50 occur as a laminated basal unit, 0.5 to 8em thick, succeeded by a homogeneous pale grey argillite band, up to 30cm thick, and often further succeeded by a thin black argillite band up to 3cm thick. The laminated portion comprises alternately silt-rich and argillite-rich units, each a few mm thick. Occasionally, calcareous versions are also found and these are often rich in bioclastic debris comprising dacryoconarid fragments. Upward grading in terms of decreasing abundance of silt-size quartz in the silty laminae, decreasing thickness and distinctiveness of silty laminae and increased spacing between laminae is evident in some cases. Often the thickest and siltiest lamination is not found at the base of the band (Fig. 5f). Irregular laminations are often present. In a few bands the lowest stratum is up to 2cra thick and comprises siltstone or silty argillite with cross-laminations (Fig. 4f), or convoluted and 'scour and fill' structures (Figs. 4e and 5f). These laminated silty lithologies are interpreted as the result of single turbidity currents with the D and E divisions described by Bouma (1962) or the turbidite silt and mud El, E2 and E3 divisions of Piper (1978). The coarsest representatives with cross-laminations or 'scour and fill' structures may be equivalent to Bouma's C division and

Piper's turbidite silts. Occasionally, generally massive pale grey Silty argillite or siltstone bands (Fig. 5d), up to 40cm thick, are found (for example, at Fox Cove, SW 85587328). Some of these bands are graded with diffuse tops and sharp bases and are tentatively interpreted as equivalent to the ungraded massive turbidite silts of Piper. The lithologies of this facies are similar to those of the outer fan facies (1), except that some of the individual bands interpreted as turbidites are coarser.
The earliest occurrence of this recurrent facies is in the upper part of the Porthcothan Slate Formation (Fig. 3). In the Treyarnon Slate Formation the facies forms the dominant thickness of beds, but in the overlying stratigraphic unit becomes less *important* and then absent.

Off-fan facies
Dark grey calcareous and poorly laminated argillites with calcareous concretions are diagnostic of this facies (Fig. 3). In the matrix argillite thin pale grey argillite bands occur at widely spaced intervals. Calcite is common as both a detrital and authigenic component, and silt-size quartz occurs in greater amounts than in the other facies. Wide pale grey argillite bands, up to 2m thick and full of crinoidal debris, are characteristic. The limestone lithologies include common small calcareous lenticles developed over stratigraphic intervals of a few metres; larger septaria, up to 12cm in diameter; and a few thin bioclastic bands. Pyritised crinoid ossicles preserved in the micrite matrix of the septaria are unflattened and indicate a preconsolidation origin for the nodules. Other lithologies include frequent lenticular black argillite bands rimmed by calcareous pale grey argillite, and calcite and pyrite segregations. Many of these segregations are parallel to bedding and comprise closely spaced laminase developed over a thickness of up to 5cm of matrix argillite.

At Booby's Bay and Trevone Bay the beds of this facies contain in restricted horizons the most abundant and diverse faunas of the Middle Devonian(see above). Most are supposedly pelagic and these' include numerous dacryoconarids which are found as both complete and fragmentary shells. They are *post mortem* drifted and show two sets of preferred orientations (Beese 1978). Other current displaced faunas include large orthocones, crinoids and fragmentary trilobites. Nektonic and benthonic faunas (except for the crinoids) are few in numbers. Some of the dwarfed goniatites, bivalves *(Buchiola),* gastropods and brachiopods are interpreted as having had a pseudoplanktonic mode of life (see review in House 1975). Evidence of activity by burrowing organisms is present only in this facies. There are several types of traces left by infaunal deposit feeders (Beese 1981). Horizontal burrows are current deflected and some of the vertical burrows attain a length of 15cm.

The orientated faunas and black bands which may be ungraded turbidite muds (see above) are evidence of some weak currents in this facies. Turbidite silts are notably absent. Calcite is significant suggesting a change in the clastic input into the basin. Organic activity is marked and may have resulted from encouraging environmental conditions. Increased organic matter may explain the relative abundance of pyrite and Raiswell (1971) has suggested that the origin of septaria may be linked to preferential deposition of carbonate with increased alkalinity near decaying organisms, The observed abundance of faunas may be due to a selective preservational effect since the fossilising mediums of calcite and pyrite are generally available. The incidence of burrowing forms suggests a more aerated environment.

The facies is limited to a relatively small thickness of the Constantine Bay Slate Formation (Fig. 3) where it is always adjacent to beds of the outer fan facies (1). The name 'off-fan facies' has been selected in order to represent an environment which is close to but not part of the outer fan.

The Middle Devonian Environment

A thick sequence of about 2060m of dark grey argillites representing uninterrupted sedimentation in a subsiding marine basin characterises the Middle Devonian succession west of Padstow., The development of this sequence is expected to have started with a major transgression near the beginning of the Middle Devonian after the deposition of the Lower Devonian shallow water facies of the Staddon Grits and after the immediately underlying Bedruthan Slates which are probably partly low Middle Devonian in age (Ripley 1964).

The amount and terrigenously derived nature of the matrix argillites and the fine grained turbidites often incorporated within them indicate a general environment whose position is closer to the distal or outer margins of a turbidite fan apron rather than the abyssal plain. Submarine volcanism is rare. The standard structural divisions for fine grained turbidites C, D and E (Bouma 1962) and El, E2 and E3 (Piper 1978) are recognised in many of the individual or minor beds. Stow and Shanmugam (1980) give a detailed sequence of up to nine divisions for fine grained beds deposited by a single turbidity current. Eight of these are distinguishable here, namely, silty laminae with scoured base and cross-laminations (T_0), convolute laminations (T_1), irregular laminations (T_0, regular laminations (T_3), indistinct and wispy laminations (T_4 and T_5), graded mud (T_6) and ungraded mud (T_7). The probable incidence of these divisions is as follows: beds with subdivisions T_0 to T_7 in the outer fan facies (2); with T_4 to T_7 in the outer fan facies (1); and with T_7 in the inner basin and off-fan facies. According to Stow and Shanmugam the lower divisions

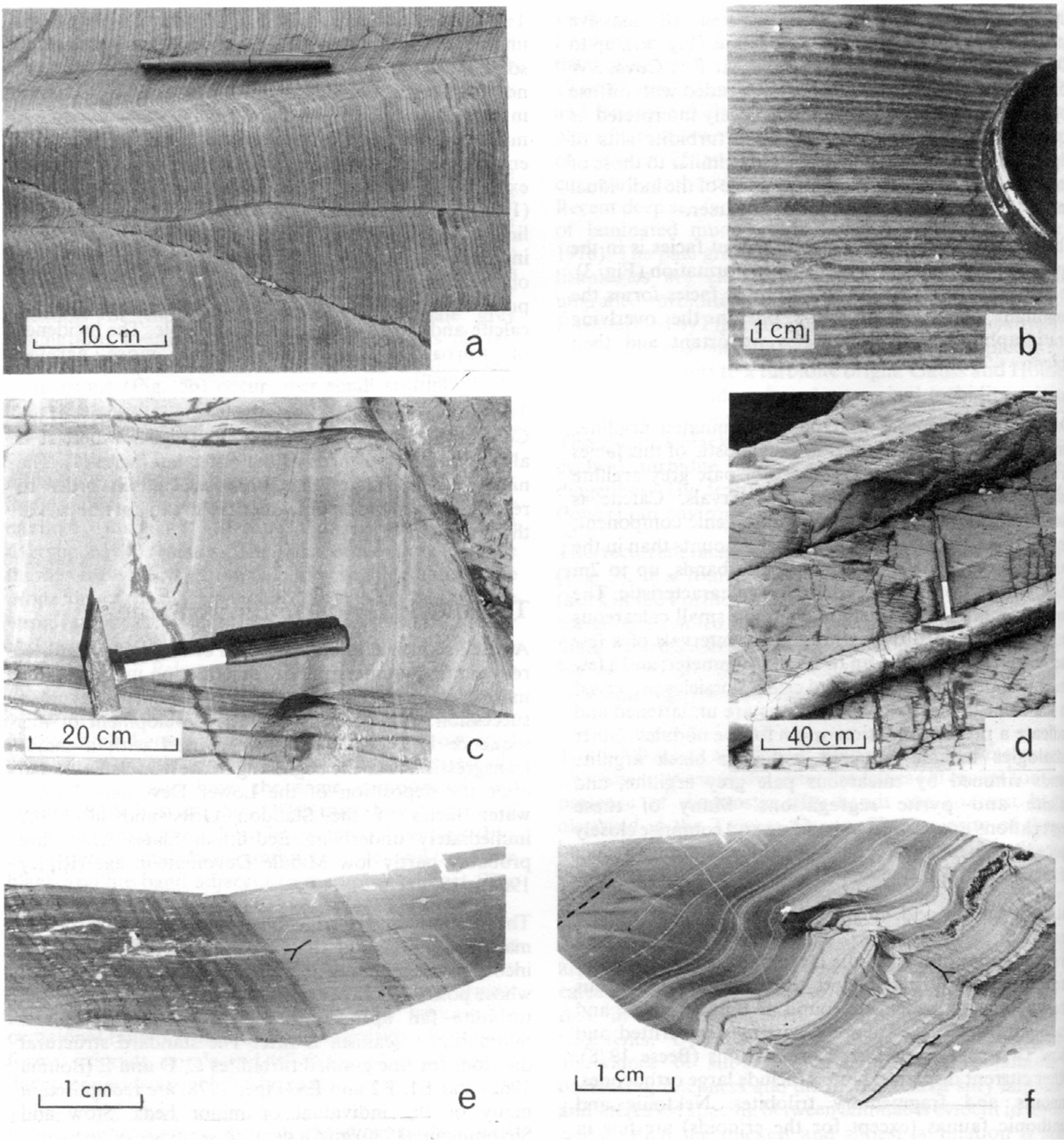

Figure 5. Photographs to illustrate argillite lithologies and facies.
(a) & (b) Argillite with alternately dark and pale grey argillite laminae, outer fan facies.
(c) Black argillite band rimmed by pale grey argillite bands, outer fan facies.
(d) Pale grey silty bands, outer fan facies (2).
(e) Thin section of graded pale grey argillite bands, outer fan facies.
(f) Thin section of laminated silty band with irregular laminae and probable 'scour and fill' structures, outer fan facies (2).

(T_0 to T_4) seem to characterise the 'high energy' near-channel fan areas, whereas the upper divisions (T_4 to T_8) are found in the 'low energy' outer fan and abyssal plain environments. Some of the thin bedded sediments interpreted as turbidites may be contourite muds. However, the characteristics of contourite muds such as silt laminae with no systematic distribution, biogenic debris and bioturbated structures (Piper 1978, Stow and Lovell 1979) are not obvious in the Trevose Group.

Therefore four facies pertinent to basinal or near-basinal conditions are interpreted. The depth of this basin is vague. The generally dominant *post mortem* transported pelagic faunas indicate bottom conditions with some current activity and a low oxygen content. The similarity in morphology and probable mode of life between the Recent pteropods and the Middle Devonian dacryoco-narids gives a guide to the likely maximum depth of deposition. Friedman (1965) has suggested that the aragonite shells of pteropods are commonest at depths of up to 2000m but suffer dissolution at depths exceeding 3000m. Therefore, deposition of the argillite facies is suggested as occurring at bathyal depths or shallower.

Two models can be used to explain the supposedly recurrent pattern of the facies (Fig. 3). Firstly, during deposition of the Porthcothan and Treyarnon Slate Formations (Eifelian) basinal sedimentation was increasingly interrupted by deposition of beds of the outer fan facies owing to a prograding turbidite fan. The incidence of the outer fan facies (2), which may be relatively proximal compared with the outer fan facies (1), also increases in the last part of this period indicating the probable maximum development of the fan. In the Constantine Bay Slate Formation of Eifelian (?) to Upper Givetian age carbonate input into the basin is increased and there is a return to dominance of the outer fan facies (1) followed by off-fan conditions. This last phase may represent a retreat of the fan apron or infilling of the basin. The end of the Middle Devonian is marked by a sudden change in sediment type with the arrival of the crinoidal limestone turbidites of the Marble Cliff Beds which probably originated on a local sea-floor rise (Tucker 1969). The second hypothesis is that of a static basin which Was affected by variable sedimentary input, For example, periodic instability at the basin margins may have been responsible for the deposition of the turbidite muds and silts. However, this explanation is less satisfactory than the first because as well as minor lithologies the matrix argillite is also variable with the opposite features of a homogeneous or laminated structure and/or calcareous or non-calcareous composition.

The regional context of the Middle Devonian is difficult to ascertain owing to the lack of exposure of equivalent facies in south-west England. Even as close as the Camel Estuary to the east (Fig. 1) shallower facies of dark grey argillites are indicated by an increase in benthonic faunas, particularly the trilobites and brachiopods (Gauss and House 1972). The source or sources of clastic material destined for the basin are not clear and may have existed both to the north and south. Webby (1966) describes fluviatile and deltaic sediments of Givetian age from north Devon and west Somerset, and suggests that their deposition was in a basin situated to the south of the area. Recent work on the Gramscatho Beds in south Cornwall suggests that they are proximally derived sandstone turbidites deposited *on* the *northern* margin of a fault-bound English massif (Hendriks 1970) and of roughly equivalent age to the Trevose Group (Wilson and Taylor 1976). In Wilson and Taylor's model the basinal facies would be in a northwesterly trending trough with the equivalent 'reef' limestone facies of south Devon situated on the more northerly shelf zone. These 'reef' facies may have contributed carbonate material to the Constantine Bay Slate Formation. Close comparison is possible between the Trevose Group and the Wissenbach Shale Facies of Germany. Krebs (1979) interprets deposition of the latter in an intracontinental basin situated between an 'external shelf' comprising continental shelves towards the north and an 'internal shelf comprising crystalline belts and/or volcanic arcs towards the south.

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References

Beese, A.P. 1978. Palaeocurrent studies in the Middle and Upper Devonian basinal facies of north Cornwall. *Proc. Ussher Soc. 4,* 135-144.

Beese, A.P. 1981. The marine argillite facies of the Middle and Upper Devonian, north Cornwall. *Unpubl. Ph.D. thesis Univ. Hull.*

Boucek, B. 1964. *The tentaculites of Bohemia: their morphology, taxonomy, ecology, phylogeny and biostratigraphy.* Czechoslovak Academy of Sciences, Prague, 215pp.

Boucot, A.J. 1975, *Evolution and extinction rate controls.* Elsevier, Amsterdam, 427pp.

Bouma, A.H. 1962. The *sedimentology of some flysch deposits.* Elsevier, Amsterdam, 168pp.

Fox, H. 1895. On some fossils from the coast sections in the parishes of Padstow and St Merryn. *Trans. R. Geol. Soc. Cornwall, 11,* 634-644.

Fox, H. 1901. On the distribution of fossils on the north coast of Cornwall, south of the Camel. *Trans. R. Geol. Soc. Cornwall, 12,* 535-545,

Friedman, G.M. 1965. Occurrence and stability relationships of aragonite, high-magnesium calcite and low-magnesium calcite under deep sea conditions. *Bull. Geol. Soc. Am.,* 76, 1191-1196.

Friend, P. F. and House, M.R. 1964. The Devonian Period. *In:* Harland, W.B. (ed.) The Phanerozoic Time-scale. *Q. J. Geol. Soc. Lond.,* 120S, 233-236.

Gauss, G.A. 1973. The structure of the Padstow area, North Cornwall. *Proc. Geol. Assoc., 84,* 283-313.

Gauss, G.A. and House, M.R. !972. The Devonian successions in the Padstow area, north Cornwall. J. *Geol. Soc. Lond., 128,* 151-172.

Hendriks, E.M.L. 1970. Facies variations in relation to tectonic evolution in Cornwall. *Trans. R. Geol. Soc. Cornwall, 20,* 114-151.

House, M.R. 1956. Devonian goniatites from north Cornwall. *Geol. Mag., 93,* 25%262.

House, M.R. 1963. Devonian ammonoid successions and facies in Devon and Cornwall. *Q. J. Geol. Soc. Lond., 119,* 1-27. House, M.R. 1975. Faunas and time in the marine Devonian. *Proc. Yorks. Geol. Soc., 40,* 459-490.

House, M.R., Mouravieff, N. and Beese, A.P. 1978. North Cornwall. *In:* Scrutton, C.T. (ed.) *Devonian of south-west England, Field guide,* Intern. Symp. Devonian System 1978. Palaeontological Association, pp. 57-58.

Kirchgasser, W.T. 1970. Conodonts from near the Middle/ Upper Devonian boundary in north Cornwall. *Palaeontology, 13,* 335-354.

Krebs, W. 1979. Devonian basinal facies. *In:* House, M.R., Scrutton, C.T. and Bassett, M.G. (eds.) The Devonian System. *Spec. Pap. Palaeont., 23,* 125-139.

Lutke, F. 1979. Biostratigraphical significance of the Devonian Dacryoconarida. *In:* House, M.R., Scrutton, C.T. and Bassett, M.G. (eds.) The Devonian System. *Spec. Pap: Palaeont, 23,* 281-289.

Moore, R.C. and Harrington, H.J. 1962. Conulata. *In:* Moore, R.C. (ed.) *Treatise on Invertebrate Palaeontology.* Geol. Soc. Am. and Kansas Press, vol. F, pp. 54-66.

Piper, D.J.W. 1978. Turbidite muds and silts on deepsea fans and abyssal plains. *In:* Stanley, D.J. and Kelling, G. (eds.) *Sedimentation in submarine canyons, fans and trenches.* Dowden, Hutchinson and Ross, Stroudsberg, Pennsylvania, pp. 167-176.

Raiswell, R. 1971. The growth of Cambrian and Liassic concretions. *Sedimentology, 17,* 147-171.

Reid, C., Barrow, G. and Dewey, H. 1910. The geology of the country around Padstow and Camelford. *Mem. Geol. Surv. Engl. & Wales.*

Ripley, M.J. 1964. The geology of the coastal area in the vicinity of Newquay, Cornwall. *Unpubl. Ph.D. thesis Univ. Birmingham*

Roberts, J.L. and Sanderson, D.J. 1971. Polyphase development of slaty cleavage and the confrontation of facing directions in the Devonian rocks of north Cornwall. *Nature: Physical Sci., 230,* 87-89.

Stow, D.A.V. and Lovell, J.P.B. Contourites: their recognition in modern and ancient sediments. *Earth Sci. Rev., 14,* 251-291.

Stow, D.A.V. and Shanmugam, G. 1980.Sequence of structures in fine-grained turbidites: comparison of recent deep-sea and ancient flysch sediments. *Sediment. Geol., 25,* 23-42.

Tucker, M.E. 1969. Crinoidal turbidites from the Devonian of Cornwall and their palaeogeographic significance. *Sedimentology, 13,* 281-290.

Webby, B.D. 1966. Middle-Upper Devonian palaeogeography of north Devon and west Somerset, England. *Palaeogeogr., Palaeoclimatol., Palaeoecol.,* 2, 2%46.

Wilson, A.C. and Taylor, R.T. 1976. Stratigraphy and sedimentation in west Cornwall. *Trans. R. Geol. Soc. Cornwall, 20,* 246-259.

Zagora, K. 1964. Tentaculiten aus dem thurengischen Devon, *Geologie, 13,* 1235-1273.

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Ventifacts from a deflation surface marking the top of the Budleigh Salterton Pebble Beds, east Devon

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A.J. Leonard, A.G. Moore and E.B. Selwood. Ventifacts from a deflation surface marking the top of the Budleigh Salterton Pebble Beds, east Devon; *Proc. Ussher Soc., 5,* 333-339.

An extensively developed ventifact horizon of Triassic age is described at the top of the Budleigh Salterton Pebble Beds, east Devon. Upper surface features of the ventifacts are attributed to wind action. They show a high grade of polish, and a variety of pits and flutes produced by submegascopic particles; these features are incised by striations marking the passage of saltating sand grains. Lower surfaces are irregular and were Produced by the dissolution of intergranular quartz of the quartzite pebbles. The determination of palaeowind direction by ventifacts is considered hazardous.
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Introduction

Wind faceted and polished pebbles or ventifacts are well known, from somewhat infrequent occurrences in the New Red Sandstone (Permo-Triassic) deposits of Great Britain. In Devon, Laming (1954) described small ventifacts from the Permian Dawlish Sands and Henson (1970) recorded a deflation surface yielding some well formed ventifacts at the top of the Pebble Beds at Budleigh Salterton. This horizon has now been identified extensively in inland exposures, where perfectly developed ventifacts are recognised; these show characters hitherto undescribed.

Distribution

The Budleigh Salterton Pebble Beds, a braided river deposit sourced from the south, consist largely of ellipsoidal quartzite pebbles with subordinate pebbles of vein quartz, schorl, sandstone and porphyry (Henson 1970). The pebbles have a maximum dimension of 45cm and all show a high degree of rounding. The formation dips c 5 degrees east and forms a prominent escarpment, characterised by moorland vegetation, extending from the coast at Budleigh Salterton towards Minehead in west Somerset. The dip slope marking the top of the formation is best examined on Woodbury Common (Fig. I). Here the ventifact layer previously identified on the coast takes the form of a tightly interlocking pavement of pebbles. It is most completely developed in the lower half of the dip slope but becomes increasingly dissected higher up slope. Deep stream sections cut into the Pebble Beds reveal no additional deflation layers, but show abraded ventifacts in Recent wash that clearly have been derived from the top of the formation.

Because of vegetation cover, the ventifact layer is indifferently exposed. Some of the most spectacular ventifacts described in this paper were discovered in deeply ploughed strips between Woodbury Castle and Uphams Plantation on Woodbury Common (Fig. lb). Individual exposures show distinct characters reflecting lithological variations at the top of the Pebble Beds. Since these result from deposition by a braided river system with its interlaced network of low sinuosity channels, rapid lateral changes in lithology resulting from deposition with varying velocities in channel and inter-channel sites are to be expected. Locally the pebbles show a high degree of sorting and a close packing which probably resulted from winnowing out of all finer grades transportable by wind, analogous to the serir surfaces in modern deserts. Only large (>5cm) pebbles attain a high degree of perfection of ventifact form; smaller pebbles were clearly less stable and many appear to have rolled for long periods in the wind producing highly polished but rounded forms.

Ventifact morphology

This paper is mainly concerned with the development of wind faceted forms. When found *in situ,* these show an upper surface which is characteristically faceted and polished and a flatter base which, with the exception of a marginal zone, extending from the upper surface for distances up to 2cm, generally shows no polishing.

(a) Upper Surface

The facets of the upper surface are slightly concave to strongly convex in form and variously inclined. Individual facets intersect to give forms ranging from

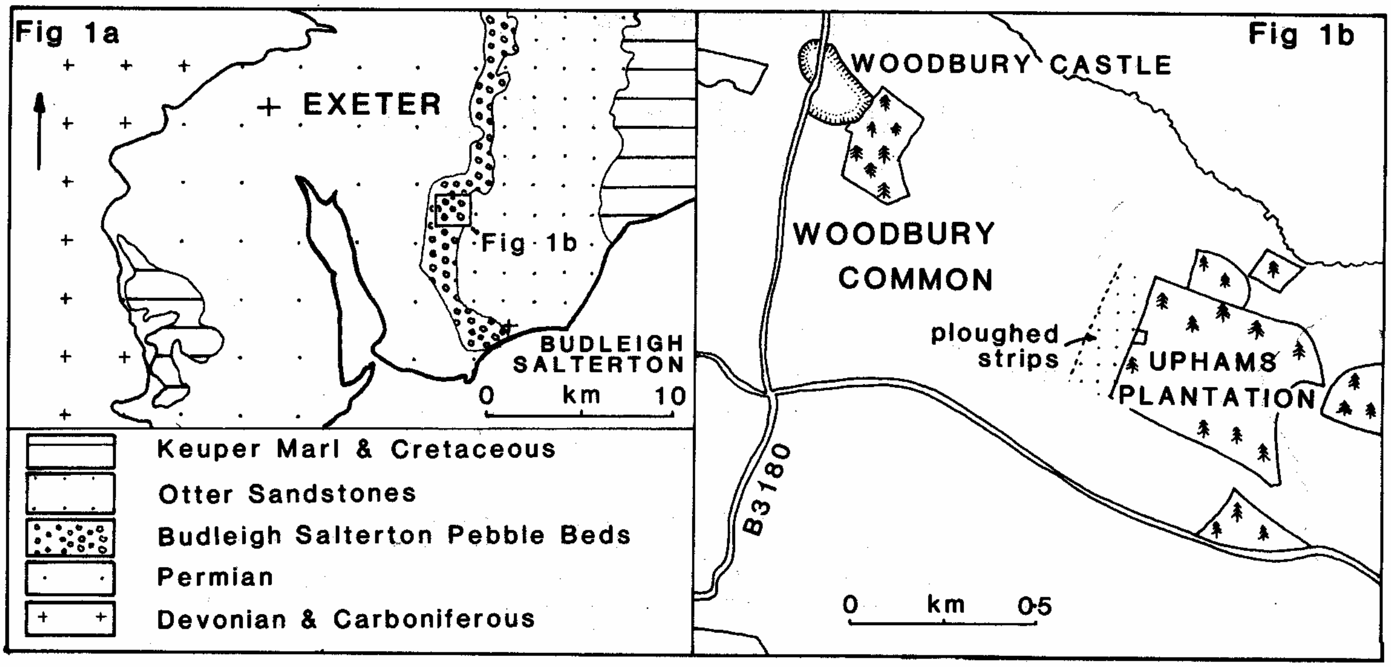

Figure 1. Locality Map.

zweikanter through dreikanter to various multifaceted forms that may develop into a smooth conical morphology (Fig. 2). In the majority of the cases the inclination of the facets decreases with increasing perfection of facet formation. Within limits there is a broad congruence of facet form on any one ventifact. Rarely however, a 'mature' ventifact may show anomalous, steeply inclined faces which may be less polished than those adjoining. These faces are usually defined by inhomogeneities such as quartz veins within the host pebble, (Fig. 3e) and clearly represent late fractures. Generally there is no relation between the *orientation* of ventifact faces and the fabric of the pebble.

The upper surface of all ventifacts which have not been reworked subsequent to formation, show medium to very high grades of polishing. The perfection of the polish varies directly with the composition of the pebble, thus homogeneous fine-grained and well cemented orthoquartzites produce the highest and most even polish. In such pebbles inhomogeneities, e.g. quartz veins, are evenly abraded. In coarser quartzites, primary sedimentary structures are differentially eroded and a less perfect polish results. Soft grains such as feldspar are preferentially removed to produce pitting; the resulting hollows frequently appear to have initiated the formation of large circular or elongate scour pits on low angle or horizontal surfaces. The circular pits, which have a maximum dimension of 2cm, are internally smooth, but may show a small upstanding central boss. Where these pits occur in large numbers on a surface, they mutually interfere to produce a polygonal pattern (Fig. 3f). The elongate pits may extend up to lengths of lcm and show a morphology reminiscent of flute casts. They are rounded to oval in form and apparently shallow down wind from the point of initiation of pit development (Fig. 3c, 3h).

At the microscopic level, individual facet faces are by no means planar; they show minutely terraced surfaces characterised by varying degrees of polish. Areas of highest polish, often showing mirror-like reflectivity, invariably occur as isolated topographic highs and can frequently be seen to represent a former, much more extensive surface which has been partially destroyed by a coarser abrasive. The development of this later abrasion is witnessed by large numbers of striations that can be traced continuously over surfaces for distances up to several centimetres in length. These striations, previously unrecorded on ventifact surfaces, occur in parallel, or sometimes as cross-cutting sets that are varyingly oriented with respect to ventifact morphology. Each set clearly indicates a separate erosive event. Striation sets may be straight, passing over the erosive pits described above without deviation, but downward or upward deflections frequently characterise the marginal areas of ventifact faces.

Under the scanning electron microscope the striations show average widths of 1001m and depths of up to 101am; they are internally smooth and parallel sided (Fig. 3a). The terminations are always gradational in one direction but the other is commonly sharply truncated (Fig. 3b). The striations represent the end member of a continuum of features initiated as a series of triangular shaped pits consistently oriented with their long axes parallel to the striations (Fig. 3c). Each pit is incised gradually to a

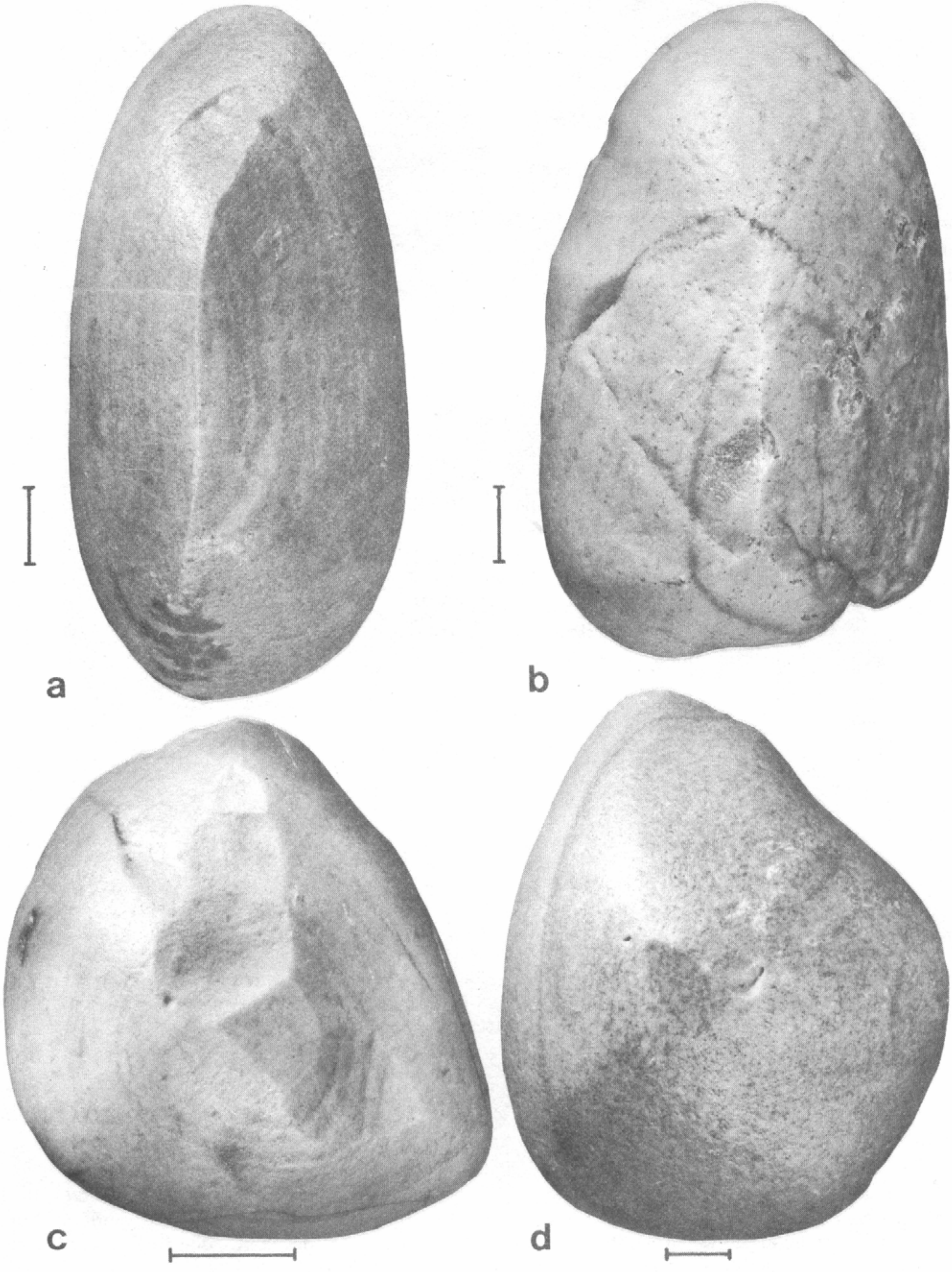

Figure 2. Various morphologies of ventifact upper surfaces showing well developed convex facets,
(a) zeikanter. (b) dreikanter. (c) multifaceted Ventifact. (d) smooth conical ventifact. Scale bar = 2cm.

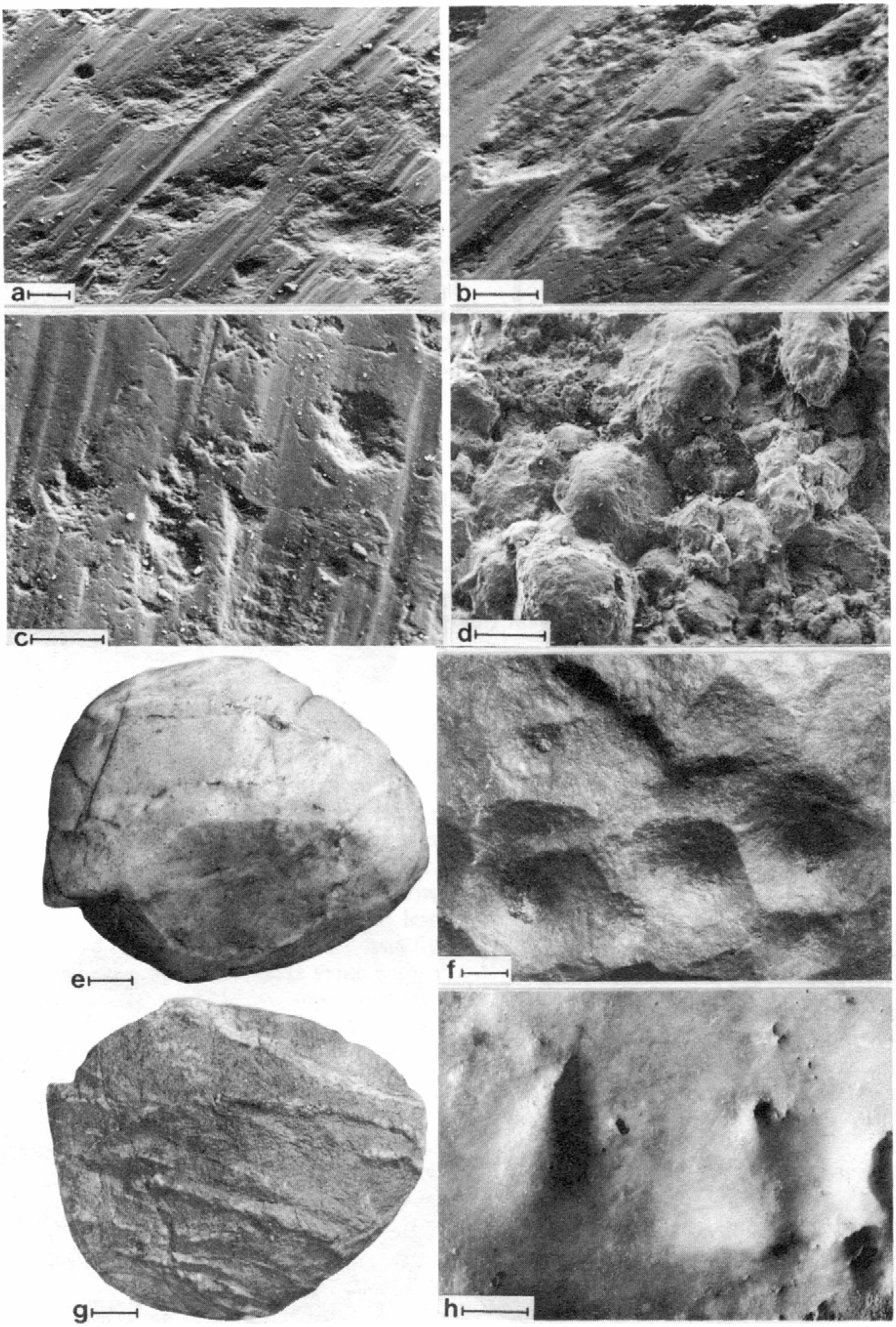

Figure 3. (a) Parallel striations developed on a highly polished quartzite surface. The large irregular pits are probably the result of softer mineral components. Scale bar = 100µm.
(b) Abrupt terminations of parallel sided striations.
Scale bar = 50 µm.
(c) Rounded micropits together with larger triangular pits, which have their long axes oriented parallel to the striations.
Scale bar = 100µm.
(d) Ventifact basal surface with upstanding detrital grains produced by the dissolution of intergranular cement.
Scale bar = 400µm.
(e) Upper surface of highly polished ventifact showing a small high angle facet developed due to fracturing controlled by a quartz vein. Scale bar = lcm.
(f) Rounded vortex pits, developed on a horizontal facet, interfering to produce a polygonal texture. Scale bar = 1.5cm.
(g) Basal surface of the ventifact whose upper surface is shown in Fig. 3e. The basal texture is extremely irregular with upstanding areas relating to texture inhomogeneities such as quartz veins. Scale bar = lcm.
(h) Detail of (c) showing the development of flute like vortex pits. Scale bar = 2mm.

sharp termination marking the base of the triangle. As the height of the triangle increases, the sides approach parallelism and passage into striations is effected.

High magnifications also reveal numerous micro-pits up to 50µm in diameter with no preferred orientation.

(b) Lower Surface
When found *in situ* or little moved from their position of formation, large ventifacts show basal surfaces strikingly different from the polished upper surfaces. Most are of a dull earthy appearance and are characterised by irregularities reflecting pre-existing textures within the host pebble (Fig. 3g). Thus quartz veins stand proud and sedimentary structures are etched into differential relief. A continuum of form has been observed, from an original convex pebble surface showing slight pitting through to an irregularly flattened or even concave surface. In many cases substantial loss of original pebble material has taken place.

Detailed examination of surfaces reveal that preferential removal of the intergranular siliceous cement (Fig 3d) has left the detrital grains protruding from the matrix. The cement is characterised by a series of irregular pits varying in size from 21µm to 30 µm (Fig. 4a).

In a minority of pebbles, progressive smoothing of the basal features described above may be observed; surface textures comparable to those of the upper surface are then developed.

Development of ventifact surfaces

(a) Upper Surface
The development of number, shape and orientation of facets on the upper surfaces of ventifacts has been the subject of much discussion. Broadly, two views have emerged; first, that wind erosion is dominant and second, that wind abrasion is subordinate to pebble fracturing. The latter view is strongly favoured by Sugden (1964) and Glennie (1970)who suggest that diurnal heating and cooling caused pebbles to fracture, and that the resulting surfaces were subsequently modified and polished by sandblasting. In the present study, infrequent but clear evidence of fracturing of pebbles during ventifact formation has been observed. However, the fractures always appear as late cross-cut modifications to well developed ventifacts. Such fractures are frequently related to inhomogeneities in the rock, and to quartz veins in particular. It is difficult to explain the development of smooth conical forms and the many delicately sculptured morphologies by fracturing.

Every ventifact examined during this investigation, supports the traditional view that wind erosion was the major agent active in their formation. Dietrich (1977) and Whitney and Dietrich (1973) have demonstrated both experimentally and in natural examples how effective submegascopic (4µ dust particles are in sculpturing and polishing surfaces. The process involves pit and flute formation in wind vortices; circular, embossed pits are

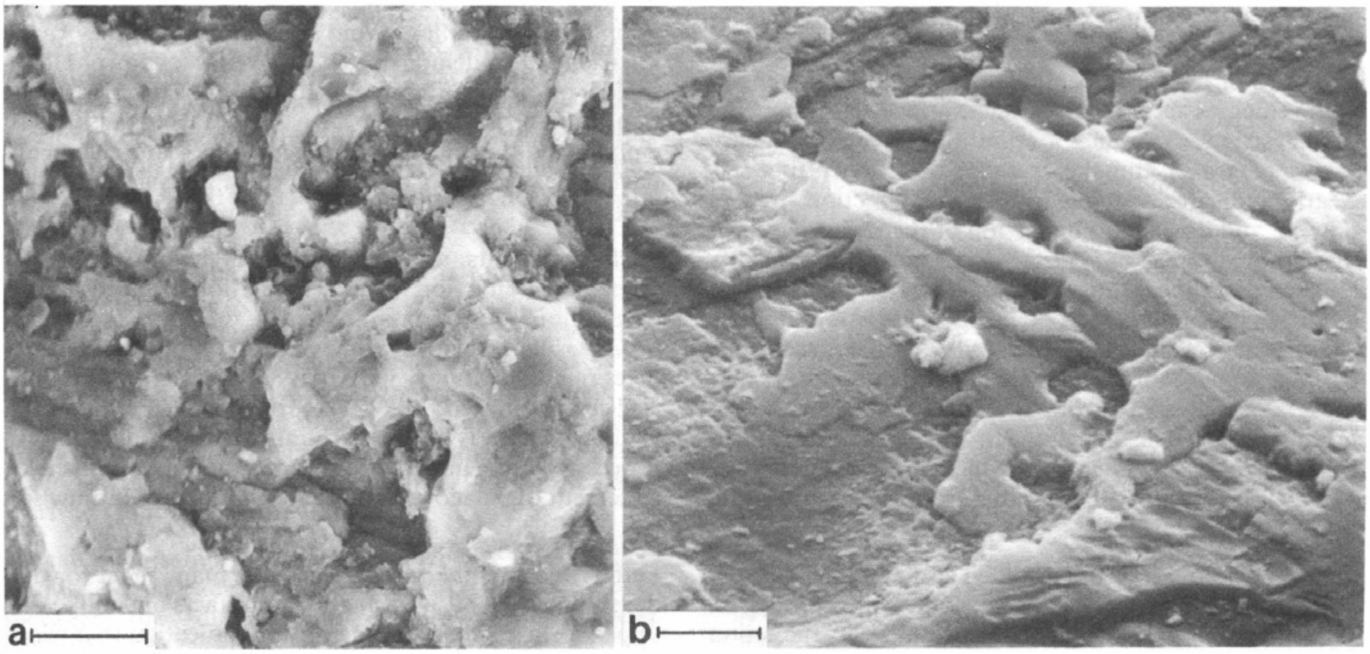

Figure 4. (a) High magnification of a basal surface showing the development of an irregular dissolution texture within the intergranular cement. Scale bar = 10 m.
(b) Thin deposit of secondary silica precipitated on a ventifact basal surface. Scale bar = 5 m.

developed by vortices oriented with their axes normal to pebble surfaces. The features they describe can be matched exactly on the Woodbury ventifacts.

The progress of ventifact formation can be traced fully in the pebbles of the Woodbury deflation surface; both the gross form of the pebble, and the detailed texture of the pebble surface are important. Large surface irregularities of pebble form considerably affected the development of polished surfaces, thus the initial polish was taken by local high areas while the lower areas remained rough and irregular in shape. Later, as the polished area extended, the overall relief was lowered and the depressions became ovoid in shape. These too later acquired a polish. Some of the large flutes observed may have originated this way.

On a smaller scale, the detailed texture of the pebble surface was similarly developed. These textures reflect grain size; thus fine grained quartzites show even, original water worn surfaces interrupted only by chattermarks and a shallow (1mm) irregular pitting which marks the sites of grains plucked during pebble formation. These were removed by wind abrasion without modification of their original form and a high polish was rapidly formed. Coarser grained rocks show a complex and extensive pitting of the surface, extending to several millimetres in depth but no chatter marks. At first abrasion caused subdivision of the large pits by the emergence of local highs, but as the polish developed, primary irregularities of the surface were elongated in the wind direction to give local small scale flutes forming part of the polished surface.

The sets of parallel sided striations and associated elongated triangular pits are believed to result from the sustained or bouncing contact of sand grains saltating at high velocities across the ventifact surface. Close packing of the striations argues for the movement of a dense carpet of grains and the presence of cross-cutting sets clearly indicates varying local wind direction. Where upward and downward deflection of the striation sets at the marginal areas of ventifact faces occurs, it probably resulted from local drag imposed upon the wind stream by the pebble surface. The blunted terminations characteristic of the triangular pits and most striations strongly suggest the down wind direction; it appears that the grains fell away from the surface to leave rough terminations when their impact velocity was dissipated by scouring. The micropits which are scattered over ventifact facets probably resulted from grains impacting normal to the surface.

The morphologies of the polished surfaces thus reveal a complex interplay between two contrasting processes. High grades of polish can only be produced by the action of dust particles acting over a long period of time. Conversely, the striations and associated features are produced by the episodic (sandstorm) action of saltating sand grains operating for short periods. The effect of the latter is to scour and, if sufficiently prolonged, eventually to destroy pre-existing highly polished surfaces, replacing them with a coarser polish consistent with the grade of the abrading sand. It follows that the striations feature only on highly polished surfaces. Considering the depth of striation produced by a single saltating sand grain, it appears likely that it is this action, rather than abrading dust particles which served as the principal erosive agent in the production of the Woodbury ventifacts. The authors have not observed comparable striations on any modern ventifact, this is thought to relate to the absence of a mirror-like polish. This polish appears to be especially well developed on the quartzite ventifacts of the Budleigh Salterton Pebble Beds.

Whitney (1978) has suggested that the maximum abrasive effect occurs in the lee of the pebble as a result of stagnation, counter flow and cushioning by interracial flow lines on the windward surface, and by negative flow to the leeward, bringing the sharp dust particles into contact with the downwind surfaces. Such surfaces tend to become flattened or concave. Although many of the Woodbury ventifacts attain near perfection of form, concave faces are extremely rare and provide no immediate support for this view. Pebbles with a single facet in the process of formation characteristically show both polish and striations. The latter can only have been produced by the direct action of the impinging wind; there is no evidence of a corresponding polishing of the pebble on the lee side.

Since the host quartzite pebbles are uniformly well rounded, the wide range of morphologies which the ventifacts now exhibit, must relate to their orientation in relation to local macro and micromorphological controls upon the prevailing wind direction. Whitney and Dietrich (1973) demonstrated how ventifact morphology varied between different positions in relation to sand dunes and depressions. On a smaller scale Higgins (1956) emphasized the effect that the ventifacts themselves may have over local wind directions, causing deviation by as much as 45°.

Such comments argue against the determination of palaeowind direction by an examination of facet or keel orientation. The striations, which the authors believe produce direct evidence of wind direction, cross facet faces in all directions. Variability of local wind direction is clearly indicated. The development and orientation of ventifact facets is almost certainly the result of complex processes acting under strictly local conditions. Any bold statement of palaeowind direction would appear unwise.

(b) Lower Surface
Differential weathering is Clearly the main agent for the development of basal surfaces of ventifacts but unlike the upper surfaces, there is generally no indication that wind abrasion has been involved in any way. All the evidence points to massive loss of pebble material by solution. The authors are unaware of solution on this scale having been described before in ventifacts.

The solubility of silica, especially quartz, is exceedingly low in normal surface water conditions; Morey *et al.,* (1962) report solubilities of 6ppm with pH<9, but above this pH the solubility of silica dramatically increases (Stumm and Morgan, 1970). Although surface waters in desert conditions are exceedingly rare, the precipitation of dew at night as a result of diurnal temperature changes is a well documented phenomenon. Since many surface rocks under desert conditions can be expected to bear a surface veneer of salts, either formed in place or introduced by wind transport from playa lakes, such dews could be highly saline. Many authors have thus involved desert dew formation as an important process in silica dissolution. Waugh (1970) features the process in his explanation of the development of the silica cement in the Penrith Sandstone of north-west England, and Folk (1978) emphasises the importance of desert dew in the development of quartz grain textures and the precipitation of "turtle skin coats" of silica in modern deserts. In these and most other published cases, the silica is derived from microscopic particles such as nannodust (Waugh, 1970) and opal phytoliths derived from spinifex (Folk, 1978). The Woodbury ventifacts demonstrate however, that *in situ* solution of siliceous rocks may also take place. Desert dew could collect beneath pebbles to generate microenvironments of exceedingly high pH. Such conditions could be maintained by nightly renewal. The scale of solution observed necessitates the persistence of this essentially surface phenomenon for long periods; this would be consistent with the perfection of development of the upper surfaces of the ventifacts.

A secondary but potentially important process developing the base of the pebbles could be the repeated precipitation and solution of salts in the minute solutional cavities between detrital grains. The mechanical disruptive force exerted by the growing crystals could be considerable. The importance of this phenomenon as an erosive agent has been demonstrated by Mottershead (1982) at sites just above high water mark on the coast of Devon at the present time.

The destiny of the dissolved silica is uncertain; some small areas on the ventifact bases show the development of scaley quartz deposits but this is quite insufficient to account for the volume of silica removed. Presumably the silica was carried down into the underlying sediment. No silica crusts have been observed, but detrital quartz grains throughout the Pebble Bed show scaley quartz overgrowths; small amounts of this may have been derived from the ventifact bases.

Local undermining of the ventifacts by wind action produces a characteristic rounded and polished junction between the roughened basal and polished upper surfaces. Occasionally, however, it appears that the undermining was on a sufficient scale to allow the ventifact to rotate and expose the basal surface. Irregularities of the basal surface can thus become smoothed and polished by wind action.

Conclusions

The ventifact surface textures reflect the importance of wind abrasion and dissolution processes in the development of their characteristic morphologies.

Wind abrasion by submegascopic particles resulted in highly polished and fluted upper surfaces, upon which sublinear striations were superimposed by the action of saltating sand grains. Facet development is complex but only reflects pebble fracturing to a limited extent. The relationship of facets to striation orientation suggests that the use of ventifacts as palaeowind indicators is hazardous. The basal surfaces were produced primarily as a result of dissolution of intergranular quartz, possibly aided by mechanical disintegration generated by growth of salt crystals. The dissolution was probably effected by evaporative concentration of desert dews producing fluids of high pH.

The extensive and clearly defined ventifact horizon at the top of the Budleigh Salterton Pebble Beds is the result of a prolonged period of deflation with little or no sand accumulation. This period of non deposition reflects a change in sedimentation from the coarse grained stream deposits of the Budleigh Salterton Pebble Beds to the finer grained sandstones and conglomerates of the Otter Sandstones.

References

Dietrich, R.V. 1977. Impact abrasion of harder by softer materials. *J. Geol., 85,* 242-46.

Folk, R.L. 1978. Angularity and silica coatings of Simpson Desert sand grains, N. Territory, Australia. J. *Sediment. Petrol. 48,* 611-24.

Glennie, K.W. 1970. Desert Sedimentary Environments, *Developments in Sedimentology 14,* Elsevier.

Henson, M.R. 1970. The Triassic rocks of south Devon. *Proc. Ussher Soc.,* 2, 172-77.

Higgins, C.G. 1956. Formation of small ventifacts. *J. Geol., 64,* 506-16.

Laming, D.J.C. 1954. Sedimentary processes in the formation of the New Red Sandstone of S. Devonshire. *Unpubl. Ph.D. Thesis, Imperial College, London.*

Morey, G.W., Foumier, R.D. and Rowe, J.J. 1962. The solubility of quartz in water in the temperature interval from 25° to 300°C. *Geochim. Cosmochim. Acta, 26,* 1029-43.

Mottershead, D.N. 1982. Rapid weathering of greenschist by coastal salt spray, east Prawle, south Devon: a preliminary report. *Proc. Ussher Soc., 5,* 347-353.

Stumm, W. and Morgan, J.J. 1970. *Aquatic Chemistry,* New York, Wiley Interscience.

Sugden, W. 1964. Origin of faceted pebbles in some Recent desert sediments of S. Iraq. *Sedimentology, 3,* 65-74.

Whitney, M.I. 1978. The role of vorticity in developing lineation by wind erosion. *Bull. Geol. Soc. Am. 89,* 1-18.

Whitney, M.I. and Deitrich, R.V. 1973. Ventifact sculpture by windblown dust. *Bull. Geol. Soc. Am. 84,* 2561-82.

Waugh, B. 1970. Petrology, provenance and silica diagenesis of the Penrith Sandstone (Lower Permian) of N.W. England. *J. Sediment. Petrol., 40,* 1226-40.

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The Mercia Mudstone Group (Triassic) in the western Wessex Basin

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G.K. Lott, R.A. Sobey, G. Warrington and A. Whittaker. 1982. The Mercia Mudstone Group (Triassic) in the western Wessex Basin. *Proc. Ussher Soc., 5,* 340-346.

The concealed Mercia Mudstone Group succession of the western Wessex Basin has been proved in deep boreholes drilled in Dorset and west Hampshire. The sequences in these boreholes are known principally from cuttings samples and petrophysical logs, on the basis of which six lithostratigraphic units are distinguished within the Mercia Mudstone Group. These units comprise largely mudstones and siltstones *but one* also incorporates substantial interbedded halite deposits locally and the succeeding unit has, at its base, a widely occurring and distinctive dolomitic/anhydritic member. *G.K. Lott and G. Warrington, Institute of Geological Sciences, Ring Road Halton, Leeds LSI5 8TQ. A. Whittaker, Institute of Geological Sciences, Keyworth, Nottingham NG12 5GG. R.A. Sobey, formerly Institute of Geological Sciences, Keyworth.*

Introduction

In the Wessex Basin (Kent 1949) the lithostratigraphy of the concealed Triassic succession is poorly known. Until relatively recently few boreholes had penetrated to the Triassic in this area (Falcon and Kent 1960; Terris and Bullerwell 1965) and before 1970 virtually none had proved the succession between the Jurassic and Palaeozoic rocks. A number of sections through that sequence have been drilled during the last ten years and those currently released from confidentiality by the Department of Energy (D.En.) provide a basis for an east-west traverse of some 105km from the Devon-Dorset border, close to the outcrops of Triassic rocks on the Devon coast, eastwards to Southampton Water.

The boreholes included in this account are Marshwood (Cangeo Warner; SY 3885 9880), Seaborough (Berkeley Petroleum; ST 4348 0620), Nettlecombe (Berkeley Petroleum; SY 5052 9544), Winterborne Kingston (Institute of Geological Sciences - D.En, SY 8470 9796), Cranborne (British Petroleum; SU 3408 9073) and Marchwood (IGS-D.En. SU 0341 0907) (Fig. 1). Reference is also made to the Triassic sequence drilled at the British Petroleum-Gas Council Wytch Farm Oilfield near Poole, Dorset (Fig, 1).

Very little information from these boreholes has previously been made available; summaries of the Wytch Farm and Winterborne Kingston successions are included in an account of the Wytch Farm Oilfield (Colter and Havard 1981) and brief references to the Marchwood succession have also appeared (Bloomer 1981; Scott and Senior 1981). The Winterborne Kingston Borehole succession was summarised by Warrington *et al.* (1980) and is the subject of a separate detailed account (Rhys, Lott and Calver (eds.), 1982). In the present account the lithostratigraphy of beds comprising the Mercia Mudstone Group, which are present between the Sherwood Sandstone and Penarth groups (Warrington *et al.* 1980) in the above boreholes, is reviewed. No biostratigraphical information is available from the Mercia Mudstone Group in these boreholes. However, at outcrop in south Devon, the Group rests upon sandstones containing middle Triassic (Anisian?) vertebrates (Walker 1969), and palynomorph assemblages of Carnian and Rhaetian age have been recovered from beds in the middle and highest parts of the Group respectively (Warrington 1971; Stevenson and Warrington 1971; Fisher 1972; Orbell 1973; Jeans 1978). The Mercia Mudstone Group in this region is therefore regarded as middle(?) to late Triassic (Ladinian(?) to Rhaetian) in age.

Lithostratigraphic units in the concealed Mercia Mudstone Group

The concealed Mercia Mudstone Group has rarely been cored in boreholes in western Wessex and subdivision of the succession encountered there is based principally upon analyses of petrophysical logs; particularly useful are the Gamma Ray and the Borehole Compensated Sonic (hereafter, BHCS or sonic velocity) logs (Fig. 2).

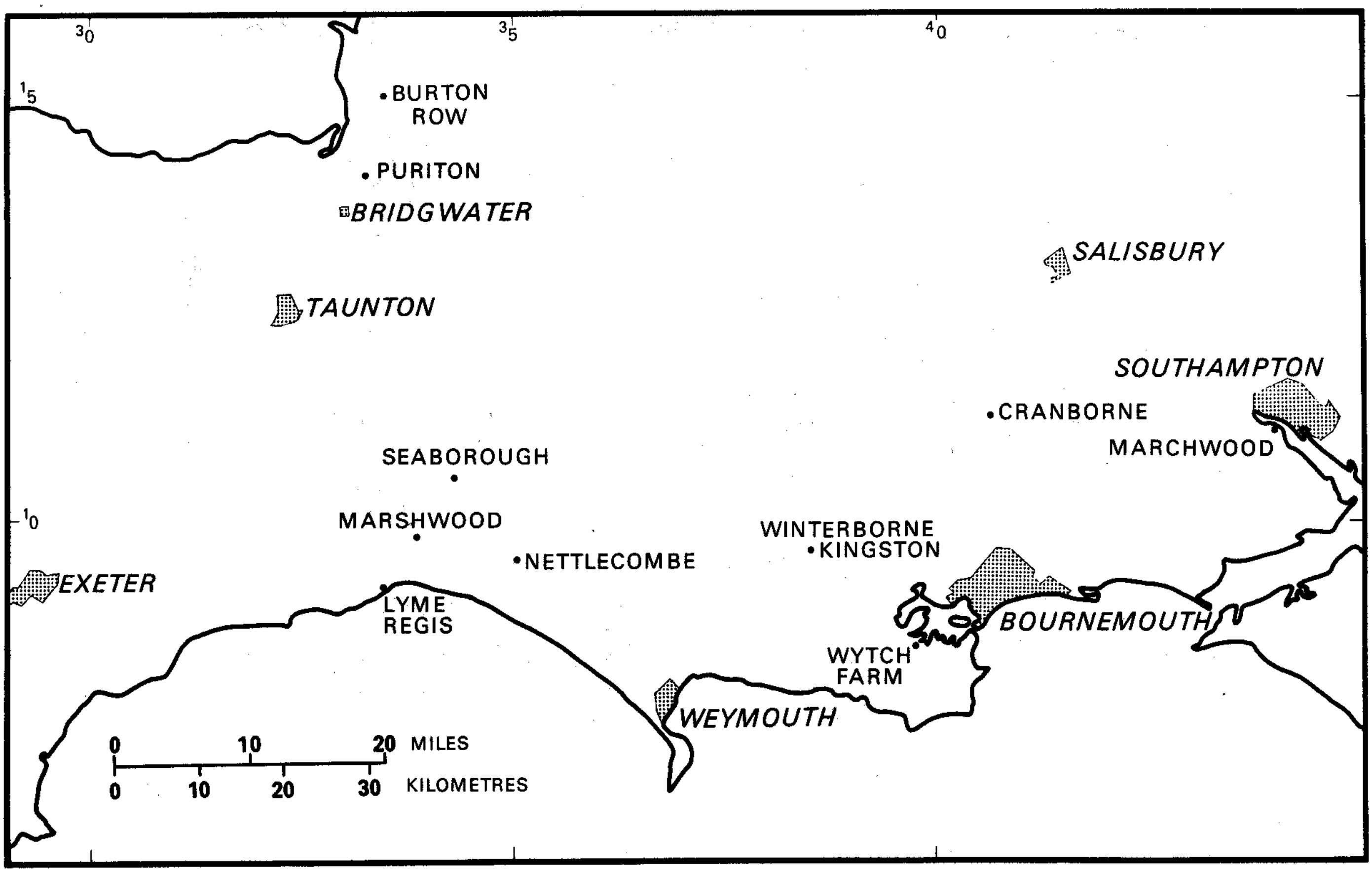


Figure 1. Location map.

The Gamma Ray log expresses, in API (American Petroleum Institute) units, the natural radioactivity of rock units; increases in the level of radioactivity cause the log trace to move towards the right. The BHCS log records the interval transit time (Δt) of sound through a formation; lower interval transit times, corresponding with higher sonic velocities, cause this log trace to move towards the right. Both Gamma Ray and BHCS logs afford useful information concerning the lithological characters of rock units and on the basis of such information, supplemented by evidence from other logs (where available) and from well cuttings, six major lithostratigraphic units are distinguished in the Mercia Mudstone Group. These units are designated A to F in ascending order (Fig. 2); their log characters are most clearly marked in records from the Nettlecombe Borehole and are described initially by reference to that section.

Unit A: base picked at an increase in gamma response relative to that obtained from underlying beds assigned to the Sherwood Sandstone Group. The gamma profile is generally higher in Unit A than in the immediately underlying beds and both gamma and sonic logs show less variable traces than in those beds.

The unit is interpreted as comprising predominantly red-brown, grey-green mottled, silty mudstones and siltstones with some harder, more calcareous or better-cemented beds producing peaks on the BHCS profile. Anhydrite or gypsum is present throughout in small amounts and traces of sandstone occur in the cuttings samples. Unit A is more homogeneous and predominantly finer-grained than the immediately underlying beds which yielded more variable petrophysical responses. The latter beds, assigned to the Sherwood Sandstone Group, are interpreted as comprising interbedded mudstones, siltstones and fine sandstones forming a transition between the largely arenaceous beds lower in that group and the predominantly argillaceous rocks of Unit A.

Unit B: base picked at a slight increase in the gamma and a decrease in the sonic velocity signatures. The distinctive gamma and low sonic profiles are extremely uniform throughout the unit and display only small-scale variations.

The unit is interpreted as comprising comparatively uniform soft red-brown mudstones.

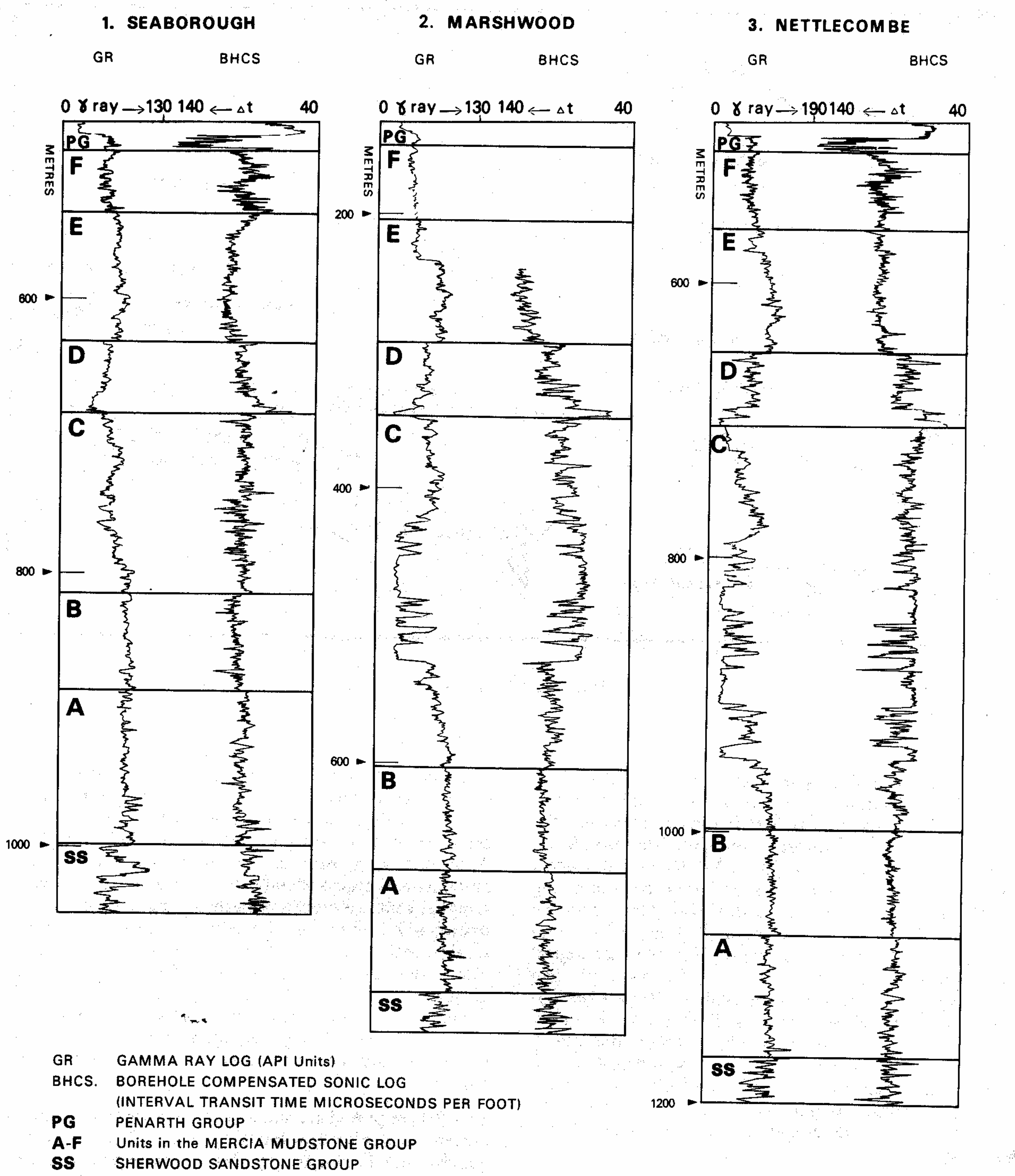
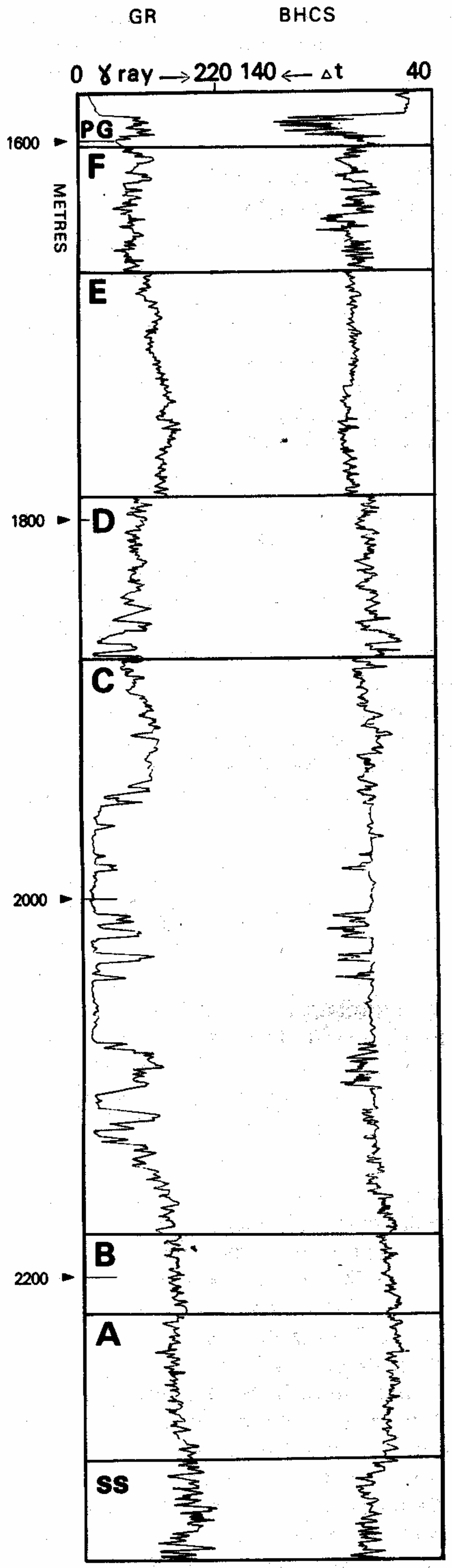
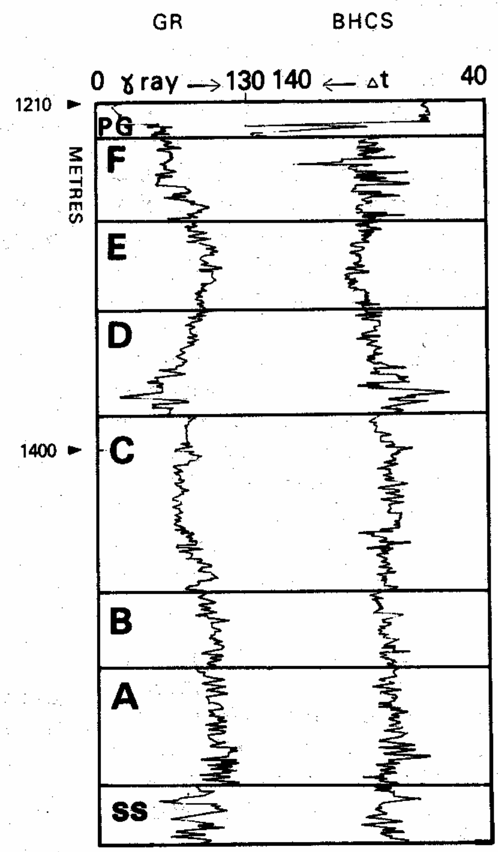


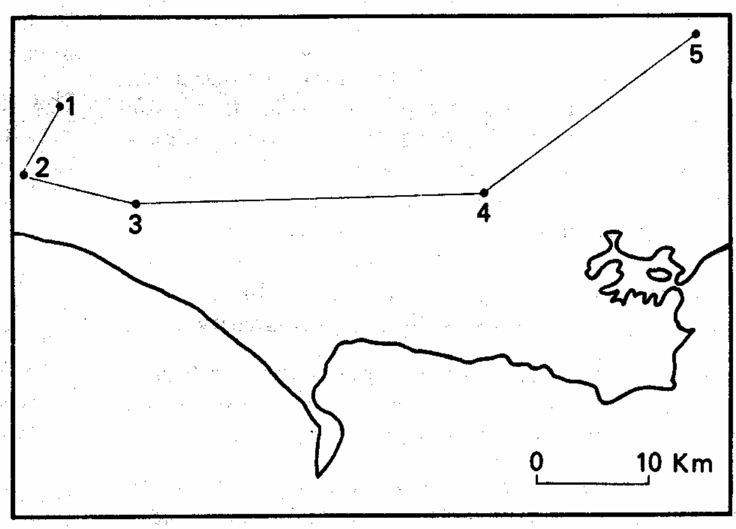
Figure 2. Lithostratigraphic correlation of Mercia Mudstone Group successions in selected sections from the Western Wessex Basin.

4. WINTERBORNE KINGSTON



5. CRANBORNE





Unit C base picked at a slight decrease in the gamma and increase in the sonic velocity responses.

Two contrasting gamma and sonic velocity signatures are apparent within this unit. In the first, which characterises the lowest and highest beds (Fig. 2), the gamma profile displays a progressive upward decline accompanied by increasing variation in the level of response. The sonic velocity responses increase slightly upwards and display wide variations in amplitude. Beds yielding these signatures are interpreted as comprising red-brown silty mudstones and siltstones with intercalated dolomitic units. In the Nettlecombe section the profiles representing these fine-grained clastic sediments are separated by an interval characterised by the low gamma and high sonic velocity returns which are indicative of the presence of substantial amounts of interbedded halite (Fig. 2). Fluctuations in the gamma and sonic velocity profiles within the halite-bearing middle part of Unit C are interpreted as representative only of mudstone interbeds; there are no instances of the very high gamma response indicative of the presence of potash salts.

Unit D: base picked at a minimum point on the gamma profile and at a strong increase in the sonic velocity response; the level of response is maintained in both profiles through the lowest 5 to 10m of the unit. Above this basal member progressively higher gamma and lower sonic velocity returns were recorded; both logs display wide fluctuations in amplitude.

The unit is interpreted as comprising predominantly hard dolomitic siltstones and mudstones with appreciable amounts of anhydrite or gypsum. The most prominent dolomitic/sulphate-rich development forms the basal member of the unit and gives rise to the sonic velocity peak which characterises that part of the sequence.

Unit E. base picked at the level of a marked increase in the gamma response and decrease in sonic velocity return. The gamma and sonic velocity profiles from this unit are more uniform and less variable than in Unit D; they display a 'waisted' form with a gamma maximum and sonic velocity minimum located in the lower half of the unit. The gamma profile declines progressively through the upper half of the unit and the sonic velocity trace, though less regular, displays a slight progressive increase.

The unit is interpreted as comprising predominantly red-brown silty mudstones with subordinate grey-green mudstones and traces of anhydrite or gypsum.

Unit F: base picked at a decrease in the gamma return and an increase in the sonic velocity response; this level marks the commencement of an interval characterised by relatively low and uniform gamma returns and a generally low but widely fluctuating sonic velocity profile. The top of this unit is picked at a level of slight increase in the gamma response and a marked decline in the sonic velocity return; this level marks the boundary-between the Mercia Mudstone and Penarth groups.

The unit is interpreted as comprising alternations of red-brown and grey-green silty mudstones and siltstones; the extremely irregular sonic velocity profile indicates the presence of alternating weakly and strongly cemented or dolomitic beds within this predominantly fine-grained succession.

Correlation of Mercia Mudstone Group sequences in western Wessex

The lithostratigraphic units distinguished in the Nettlecombe sequence are recognisable in the other concealed Mercia Mudstone Group sections discussed below (i.e. Seaborough, Marshwood, Winterborne Kingston, Cranborne and Marchwood) and correlations from Seaborough and Marshwood eastwards to Cranborne, based upon gamma ray and sonic velocity logs, are presented in Figure 2.

The sequences are thicker, with halite present in the middle part of Unit C, at sites situated in an east-west trending zone proved at Marshwood, Nettlecombe and Winterborne Kingston (Fig. 1). Flanking that area (e.g. to the north at Seaborough and to the south at Wytch Farm) and farther east (e.g. at Cranborne and Marchwood) the equivalent sequences are thinner and Unit C lacks halite. An association of occurrences of halite in the Mercia Mudstone Group with areas of intra-Triassic graben tectonics has been recognised (Warrington 1974, 1976; Whittaker 1980). The Central Somerset Basin is considered to have been an active graben structure during Triassic times (Whittaker 1973, 1975, 1980) and the existence of similar structures in the Wessex Basin has been postulated (Whittaker 1975, 1980). The saliferous beds present in Unit C between Marshwood and Winterborne Kingston may, therefore, occupy such a structure.

The succession (units A and B) below the saliferous unit (C) thickens westwards from 4lin at Marchwood and 91m at Cranborne to 167m at Marshwood and 186m at Seaborough. Within these beds the individual units A and B show an analogous westward thickening.

Thickness variations in Unit C are substantial and, in common with differences in the gamma and sonic velocity profiles from individual sections, result from the presence of halite in this unit at Marshwood, Nettlecombe, and Winterborne Kingston, and its absence at the other sites. The thickness of the saliferous (middle) part of Unit C increases eastwards from 103m at Marshwood to 190m at Winterborne Kingston and the .-thickness of individual beds of halite increases in the same direction, reaching a maximum of c. 33m in the latter section. The mudstones in: this unit beneath the saliferous beds increase in thickness westwards but no consistent 'variation is apparent in the thickness of the mudstones in this unit above the saliferous beds or in the total thickness of mudstone in Unit C as a whole.

The proportion of halite in the saliferous beds is estimated as up to 70%; much of the salt may occur in a mudstone matrix as haselgebirge (Whittaker 1980). The decrease in amplitude of fluctuations seen in the sonic velocity responses from these beds from Marshwood eastwards to Winterborne Kingston suggests that the evaporite in the latter section is purer, with fewer mudstone interbeds and less mudstone matrix in haselgebirge, than in the more westerly occurrences.

In the Seaborough, Cranborne and Marchwood sections, the presence of sulphates and dolomites in beds laterally equivalent to those with halite at Winterborne Kingston, etc., is indicated by intermittent narrow low gamma and high sonic velocity signatures on the petrophysical logs (Fig. 2). Substantial concentrations of those minerals commonly occur in beds laterally equivalent to occurrences of halite in the Mercia Mudstone Group (eg. in the Severn Basin: Warrington 1970, 1974; Wills 1970).

Unit D displays a relatively constant thickness of some 53 to 60m at Seaborough, Marshwood, Nettlecombe and Cranborne, but is appreciably thicker (84m) at Winterborne Kingston; a marked thinning to 17.5m occurs at Marchwood. The basal member of this unit is recognisable by its distinctive low gamma and high sonic velocity signatures in all the sections examined.

Beds comprising units E and F are thickest (186.5m) at Winterborne Kingston; farther west the thickness is some 142 to 151m, but to the east, at Cranborne (72m) and Marchwood (67m), it is appreciably thinner. The individual units E and F display analogous variations in thickness.

The most westerly of the sections of the concealed Mercia Mudstone Group considered here, at Marshwood, is only some 8km north-east of the site of the Lyme Regis Borehole (Jukes-Browne 1902; Warrington and Scrivener 1980), itself only c. 5km from the most easterly part of the Devon coast Mercia Mudstone Group outcrop at Charton Bay. The Group is exposed from Charton Bay westwards to Sidmouth, some 2 1km west of Lyme Regis.

The following correlation, is proposed between the succession known at outcrop and in the Lyme Regis Borehole, and the concealed succession, documented here, from the Marshwood Borehole and sections farther east. An important element in the correlation is the dolomitic/sulphate-rich member in the lower part of Unit D. These beds are regarded as representative of mudstones with arenaceous intercalations recorded 210-220m below the Penarth Group at Lyme Regis (Jukes-Browne 1902; Warrington and Scrivener 1980). The 210m of beds between those mudstones and the Penarth Group compare tolerably well in thickness with the proposed correlatives at Marshwood (193m) and at Nettlecombe (196m); the analogous succession at Seaborough is slightly thinner (188m) and at Winterborne Kingston is appreciably thicker (260m)(Fig. 2).

At outcrop the correlative of the basal member of Unit D is regarded as the interbedded mudstones and dolomitic siltstones and sandstones of the Weston Mouth Sandstone Member, which crops out in the Dunscombe and Weston cliffs between Branscombe and Sidmouth (Warrington *et al.* 1980; Warrington and Scrivener 1980). The correlatives of the higher part of Unit D and of units E and F are thus considered to comprise beds exposed above that member in the coast section from Weston Cliff eastwards to Branscombe and from Seaton eastwards to Culverhole.

Unit F of the concealed succession is considered, from the variations indicated in the gamma and sonic velocity profiles, to represent the lithologically heterogeneous Blue Anchor Formation and associated beds exposed at the top of the Mercia Mudstone Group east of Seaton.

The correlatives of units A to C of the concealed succession are regarded as occurring below the mudstones with arenaceous intercalations proved in the Lyme Regis Borehole (see above) and at outcrop are regarded as comprising the beds exposed between the Weston Mouth Sandstone Member in the Dunscombe cliffs and the base of the Mercia Mudstone Group farther west at Sidmouth. In the outcrop section, as also in the Lyme Regis Borehole, beds immediately below that correlated here with the dolomitic member at the base of Unit D are prominently colour-banded and include siltstones and dolomitic mudstones with, at outcrop, pseudomorphs after halite. It is considered likely that these beds are lateral equivalents of the saliferous part of Unit C of the concealed succession farther east.

Correlation with units in Mercia Mudstone Group successions of neighbouring areas

General comparisons can be made between the Mercia Mudstone Group succession documented here from western Wessex and those known to the north-west and north, in the Central Somerset and the Severn basins respectively.

The Weston Mouth Sandstone Member (Warrington *et al.* 1980) of the Devon coast section is here regarded as the representative, at outcrop, of the widespread and distinctive member noted at the base of Unit D in the concealed Wessex Basin succession (Fig. 2). The Weston Mouth Sandstone Member comprises predominantly grey dolomitic sandstones and siltstones with interbedded grey-green and red-brown mudstones. On lithological, sedimentological and palaeontological characters (Jeans 1978) this member constitutes a distinctive facies within the Mercia Mudstone Group. It may represent a temporary but widespread amelioration of the hypersaline sub-aqueous and arid terrestrial conditions under which the dolomitic red-brown mudstones and siltstones characteristic of the Group below the highest, Blue Anchor, formation were deposited (Warrington 1974). Distinctive members of analogous facies which occur at comparable levels in the

Group in the contiguous Central Somerset and Severn basins are regarded as correlatives of the Western Mouth Sandstone Member (Warrington *et al.* 1980) and hence also of the basal member of Unit D of the concealed Wessex Basin succession.

In the Central Somerset Basin this facies is represented by the buff to grey cross-bedded sandstones and interbedded bioturbated grey-green mudstones of the North Curry Sandstone Member (Warrington *et al.* 1980) and in the Severn Basin by the comparable Arden Sandstone Member. The latter is present in the southern Part of the Severn Basin in the Stowell Park Borehole (SP 084118) (Green and Melville 1956), where it occurs some 130m below the Penarth Group, and is also recognised in an outcrop which extends northwards through that basin and continues north-eastwards into Warwickshire.

Saliferous beds present in the Central Somerset Basin (Whittaker 1972, 1980) occur below the North Curry Sandstone Member (Warrington .et *al.* 1980). Those beds are therefore at a stratigraphic level comparable with the salt present locally in Unit C of the Wessex Basin succession and may be correlatives. The saliferous unit in the Central Somerset Basin was cored in the IGS Burton Row Borehole, (Fig. 1), Brent Knoll, (Whittaker 1972, 1980) and comprised largely haselgebirge-type admixtures of mudstone and halite concentrated in four main beds within a 49m section (Whittaker 1980); lesser amounts of halite occurred, principally in veins, through a thickness of some 154m of beds. The main saliferous section proved at Burton Row is, therefore, appreciably thinner than the possible correlatives recognised in sections at Marshwood (c. 103m), Nettlecombe (c. 142m) and Winterborne Kingston (c. 190m) in the Wessex Basin (Fig. 2). The saliferous sequence proved at Puriton (Fig. 1) in the Central Somerset Basin has yielded miospores of late Triassic (Carnian) age (Warrington 1980).

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References

Bloomer, J.R. 1981. Thermal conductivities of mudrocks in the United Kingdom. *Q. J. Eng. Geol. Lond., 14,* 357-362.

Colter, V.S. and Havard, D.J. 1981. The Wytch Farm Oil Field, Dorset. *In:* Illing, L.V. and Hobson, G.D. (eds.), *Petroleum Geology of the Continental Shelf of North-West Europe.* Institute of Petroleum, London, 494-503.

Falcon, N.L. and Kent, P.E. 1960. Geological results of Petroleum Exploration in Britain 1945-1957. *Mem. Geol. Soc. Lond.,* No. 2, 56pp.

Fisher, M.J. 1972. The Triassic palynoflora succession in England. *Geoscience and Man, 4,* I01-109.

Green, G.W. and Melville, R.V. 1956. The stratigraphy of the Stowell Park Borehole (1949-1951). *Bull. Geol. Surv. G.B.* No. 11, 1-66.

Jeans, C.V. 1978. The origin of the Triassic clay assemblages of Europe with special reference to the Keuper Marl and Rhaetic of parts of England. *Phil. Trans. R. Soc. A.289,* 549-639.

Jukes-Browne, A.J. 1902. On a Deep Boring at Lyme Regis. *Q. J. Geol. Soc. Lond., 58,* 279-289.

Kent, P.E. 1949. A structure contour map of the surface of the buried pre-Permian rocks of England and Wales. Proc. *Geol. Assoc., 60,* 87-104.

Orbell, G. 1973. Palynology of the British Rhaeto-Liassic. *Bull. Geol. Surv. G.B.,* No. 44, 1-44.

Rhys, G.H., Lott, G.K. and Calver, M.A. (eds.), 1982. The Winterborne Kingston Borehole, Dorset, England. *Rep Inst. Geol. Sci.,* 81/3, 196pp,

Scott, P.W. and Senior, J.R. 1981. Geothermal energy: report of a symposium. *Proc. Yorks. Geol. Soc., 43,* 347-356.

Stevenson, C.R. and Warrington, G. 1971. Jurassic and Cretaceous rocks of Wessex: Highest Keuper Deposits; discussion to Report of Field Meeting. *Proc. Geol. Assoc., 82,* 297-299.

Terris, A.P. and Bullerwell, W. 1965. Investigations into the underground structure of southern England. *Advmt. Sci, 22,* 232-252.

Walker, A.D. 1969. The reptile fauna of the "Lower Keuper" Sandstone· *Geol. Mag., 106,* 470-476.

Warrington, G. 1970. The stratigraphy and palaeontology of the 'Keuper' Series of the central Midlands of England. Q. J. *Geol. Soc. Lond., 126,* 183-223.

Warrington, G. 1971. Palynology of the New Red Sandstone sequence of the south Devon coast. *Proc. Ussher Soc., 2,* 307-314.

Warrington, G. 1974. Les évaporites du Trias britannique. *Bull. Soc. Geol. Fr.,* (7me ser.), XVI, 708-723.

Warrington, G. 1976. Triassic evaporites in south-West England (Abstract). *Proc. Ussher Soc., 3,* 354.

Warrington, G. 1980. Palynological studies of Triassic rocks in central Somerset (Abstract). *Proc. Ussher Soc., 5,* 90.

Warrington, G., Audley-Charles, M.G., Elliott, R.E., Evans, W.B., Ivimey-Cook, H.C. Kent, P.E. Robinson, P.L. Shotton, F.W. and Taylor, F.M. 1980. A correlation of Triassic rocks in the British Isles. *Spec. Rept. Geol. Soc. Lond.,* No. 13, 78pp.

Warrington, G. and Scrivener, R.C. 1980. The Lyme Regis (1901) Borehole succession and its relationship to the Triassic sequence of the east Devon coast. *Proc. Ussher Soc., 5,* 24-32.

Whittaker, A. 1972. The Somerset Saltfield. *Nature, Lond., 238,* 265-266.

Whittaker, A. 1973. The Central Somerset Basin. *Proc. Ussher Soc., 2,* 585-592.

Whittaker, A. 1975. A postulated post-Hercynian rift valley system in southern Britain. *Geol. Mag., 112,* 137-149.

Whittaker, A. 1980. Triassic Salt Deposits in Southern England. *Proc. 5th Int. Symposium on Salt; Northern Ohio Geol. Soc.,* 175-179.

Wills, L.J. 1970. The Triassic succession in the central Midlands. *Q. J. Geol. Soc. Lond., 126,* 225-285.

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Read at the Annual Conference of the Ussher Society, January 1982

Rapid weathering of greenschist by coastal salt spray, east Prawle, south Devon: a preliminary report.

D.N. MOTTERSHEAD

D.N. Mottershead 1982. Rapid weathering of greenschist by coastal salt spray, east Prawle, south Devon: a preliminary report. *Proc. Ussher Soc. 5,* 347-353.

The presence of a range of fresh microtopographic forms in the zone immediately above HWM is suggestive of rapid rock weathering, This is verified by direct measurement of rock surface lowering. Laboratory experiments indicate that the process responsible is most likely to be crystallisation of sodium chloride from seawater. Consideration of rock strength properties confirms that it is well within the capacity of this process.

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Introduction

The active operation of weathering processes in the study area is suggested by the existence of highly pitted and honeycombed rock, and rugose rock surfaces, which were noted by W.A.E. Ussher as long ago as 1904. Recently the presence of oil tapped pedestals of rock up to 11mm high has been described by the present author (Mottershead 1981, 1982). These clearly defined features are interpreted as indicating the protection of the subjacent rock by the patches of oil. Thus the pedestals are considered to emerge and increase in elevation as the surrounding rock surface is lowered by denudation, Direct measurement of surface lowering derived from 34 points indicates a mean denudation rate of 0.61mm at (Mottershead 1981, 1982). This is a high rate of denudation, and it implies rapid weathering and ready removal of the weathering products.

This rapid rock weathering would appear to be limited to a zone above HWM, and not more than a few metres in width. Below this level rock surfaces tend to be smooth and mechanically sound where they are abraded directly by the sea. More than a few metres above HWM the coastal rock is covered by lichens which preclude direct weathering of the rock surface by mechanical agencies. It is in the intermediate zone where the weathering is shown to be most rapid.

This is a distinctive weathering environment. Various aspects of this weathering environment can be simulated in the laboratory in an attempt to identify the conditions, and therefore isolate the process responsible for the rapid breakdown of the greenschist.

The field area

The field area is located on the coast of south Devon some 4km west of Start Point, and close to the village of East Prawle (Fig. 1). The shore zone here consists of three dissected shore platforms, the lowest one washed by the present sea, and two raised platforms at elevations of approximately 4.5and 7.5m O.D. (Orme 1960), which are cut across the greenschist outcrop. This rock is mechanically sound in the unweathered state and strongly jointed, and presents a very craggy aspect to the sea.

This is an exposed coastline, and it falls within the macro tidal storm wave environment in the classification of J.L. Davies (1964). At high tide in storm conditions abundant spray is thrown up above HWM as waves break on the irregular rocky foreshore. In addition to this direct dowsing with spray, sea salt may also be brought ashore in aerosol form in sea mist or humid air. The bare rock surface is exposed directly to atmospheric gases, precipitation and solar radiation. Whilst there are no records of rock surface temperature, maximum and minimum air temperatures at Slapton, some 10km to the north ranged from -5.6 C to + 26.5 C during the period 1960-1973 (Ratsey 1975). Rock surface temperatures can be expected to show a wider range of extremes. The impermeable nature of the rock surface leads to rapid runoff of excess water and consequent drying. Under these conditions, therefore, the exposed coastal rocks are subject to frequent wetting and drying both by seawater and rainwater, and a considerable range of temperature, which combine to produce a distinctive weathering environment.

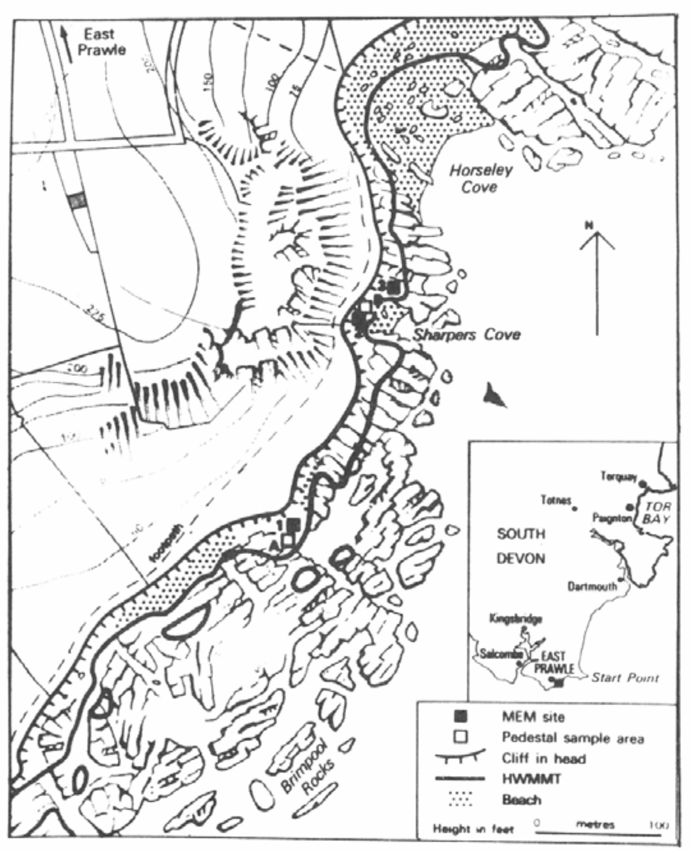

Figure 1. The field area showing erosion meter (MEM) sites and pedestal sample plots.

The greenschists have been described by both Ussher (1904) and Tilley (1923). Tilley identified two facies - chlorite-epidote-albite schist and hornblende-epidote-albite schist. The present study is concerned with the former. In the field it displays a grey-green colour with outstanding crystals of albite, a silky lustre and a marked schistose structure. Samples taken from the shore platform at Dutch End (SX 785356) were examined microscopically by G.M. Power. The estimated abundance of the mineral components is listed in Table 1.

Table 1. Estimated mineral abundance in greenschist.

	%
Albite	35-40
Actinolite	25-30
Chlorite	15-20
Epidote	10-20
Sphene	5
Muscovite	5
Quartz	2

The rock has a strongly foliated structure, in which bands of chlorite plates with intergrown fibres of amphibole oriented in parallel are separated by bands dominated by albite. Crystal size is commonly 20 x 300m, with albite forming larger crystals ranging up to 700-15001am. From the field observations outlined above, it is evident that these rocks have reacted to their present weathering environment vigorously, and are currently undergoing rapid weathering.

Field evidence of weathering process

Exposed rock in the zone where rapid weathering is occurring commonly exhibits a fresh appearance. It is clearly weakened in contrast to the abraded and hard rock surfaces below HWM. It can be easily scratched with a penknife, and the top 10mm is readily penetrated with a hand drill, whereby it disintegrates into granular fragments.

The products of natural weathering processes accumulate in depressions and on ledges on the rock surface in the form of rock meal. Table 2 shows the results of mechanical analysis of three samples of this material, in addition to a sample collected by scraping from a weathered rock surface. The dominant mode is sand, with a substantial proportion of silt grade material. There is little significant difference between the in situ material and the transported debris. It should be noted that there is a close relationship between the modal size of the weathering products and the crystal size of the parent rock.

Table 2. Mechanical analysis of weathering products, expressed as a percentage of different size grades.

			Transported material			In situ material
Granules	>	2000µm	1	8	1	5
Sand		60-2000µm	63	65	54	69
Silt		2-60µm	35	26	44	26
Clay	<	2µm	1	1	1	0

Microscopic analysis of these samples shows that they consist of crystal aggregates, individual crystals and crystal fragments. They are generally angular in shape, showing cleavage faces or crystal form apparently unmodified by solution pitting or any other identifiable chemical alteration. Examination of the weathering products leads to the conclusion that the mode of breakdown is fundamentally a mechanical process, leading to granular disintegration along pre-existing planes of weakness - intercrystalline bonds and cleavage planes. If chemical alteration has played a part in weakening bonds and facilitating breakdown, then its role appears to be strictly limited, for the weathering products show no direct evidence of chemical processes.

Laboratory simulation of weathering conditions

In order to identify the conditions responsible for the breakdown of these rocks in the field, a series of weathering experiments was carried out in the laboratory, in an attempt to isolate the various conditions of the weathering environment. Accordingly rock samples were subject to a diurnal cycle of wetting and drying under controlled conditions.

Four different regimes were employed. In each case the samples were immersed for one hour, then left to stand-for the remaining 23 hours of the diurnal cycle. It was not possible to control temperature, but maximum and minimum values were recorded for each 20 day cycle.

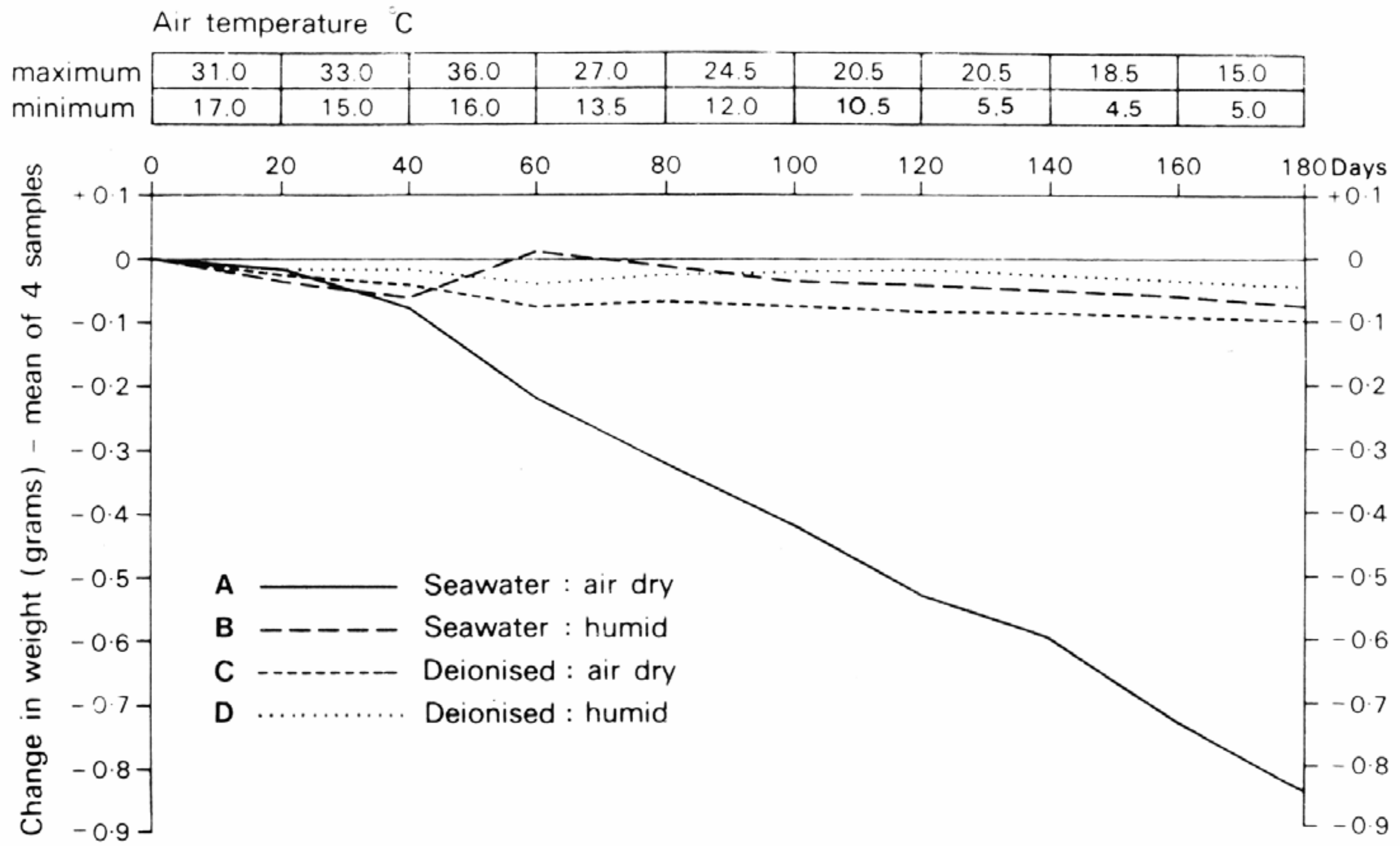

Figure 2. Simulation experiment of aspects of field weathering conditions.

Humidity conditions were controlled by allowing the samples to stand and air dry, or to remain in an enclosed humid atmosphere such that they remained continually moist. The four experimental treatments were as follows :-

A. Seawater with air drying
B. Seawater with humid atmosphere
C. Deionised water with air drying
D. Deionised water with humid atmosphere

Rock samples were taken from the weathering surface in the field. Cores were prepared, 32mm in diameter and ranging in weight from 24.4gm to 58.4gm. They displayed the weathering surface on top and were cut normal to the foliation of the rock. Four cores were submitted to each experimental treatment. After each 20 day cycle all samples were leached in boiling water to remove any accumulated salts or weathering products, and to detach by agitation any loosened particles. The samples were then dried and weighed, and the amount of weathering was determined in the form of weight loss. The experiment was run for 180 days, and the results are shown in Figure 2.

It is evident that treatments C, D and B had negligible effect, whilst treatment A, wetting and drying in seawater, caused a consistent loss of weight. In this treatment individual fragments and particles became visibly detached from the top surface (the surface formerly exposed to weathering in the field). At the termination of the experiment the rock fabric adjacent to this surface was found to be expanded and the rock was very friable. Particles detached during leaching were retrieved and proved to be predominantly of sand grade (95% by weight), and to show marked angularity of form. The amount of weight loss ranged from 0.475-1.103gm, with a mean of 0.832gm. If it is assumed that all the weathering took place from the top surface, then this represents a surface lowering rate of 0.44-1.02mm a^{-1} (mean 0.77mm a-l), which accords well with the measured field value of 0.61mm a^{-1}. It is possible, however, that some weathering took place (although not observed) on the sides and base of the cores, and it may therefore be more realistic to regard these as maximum values of surface lowering. The rate of weight loss is approximately constant, and is apparently independent of temperature, which varied considerably during the experiment with the seasonal march of temperature change. The experiment therefore appears to replicate to a very satisfactory degree both the mode of weathering, and the rate of weathering observed in the field.

A consideration of weathering processes

In the experiments described above, the weathering conditions were defined but individual weathering processes were not. With the experimental design adopted an individual weathering process is likely to be inhibited, permitted or accelerated under a given treatment. An assessment of weathering processes likely to be operating in each of the experimental treatments is shown in Table 3. Comparison of treatment C with other

Table 3. Postulated effectiveness of different weathering processes under the experimental regimes.

Treatment	Haloclasty	Oxidation	Hydrolysis	Other Ion exchange	Slaking
A	Nil	Permitted	Limited	Nil	Permitted
B	Nil	Nil	Permitted	Nil	Nil
C	Accelerated	Permitted	Limited	Permitted	Permitted
D	Nil	Nil	Permitted	Accelerated	Nil

treatments permits inferences to be made regarding the process likely to be responsible for rock breakdown. The only process uniquely associated with treatment A is haloclasty (salt weathering). Other processes likely to be operating in this treatment - oxidation, hydrolysis, other ion exchange processes and slaking - have negligible effect in the other treatments where they are inferred to be operating. By isolating the weathering conditions in this way, it is therefore concluded that haloclasty is the process most likely to be effecting the breakdown of the greenschist. This is an interesting contrast to the experiments of A.S. Goudie (1974) with seawater on other types of rock, which demonstrated only limited effects. The conclusion that haloclasty is the effective process is entirely consistent with the observational evidence of the experiment. The granular disintegration and the expanded rock fabric are both features which may be expected to result from such a mechanical process exerting tensile stresses within the rock.

Haloclasty has become increasingly recognised in recent years as a significant process in natural rock weathering. It is caused by the growth of salt crystals in pore spaces, exerting a tensile stress within the rock and tending to produce disintegration at the granular scale. It is therefore a mechanical effect produced by the growth of chemical substances. The effects of salts in promoting rock breakdown have long been appreciated in respect of building stone (Schaffer 1932, Winkler 1966). Only recently have they come to be recognised as an important process in geomorphology (Wellman and Wilson 1965, Cooke and Smalley 1968, Winkler and Singer 1972, Goudie 1977). The relevant literature is well reviewed by Evans (1970), whilst Goudie Cooke and Evans (1970) and Goudie (1974) have demonstrated experimentally the effects of saline solutions in causing the disintegration of rocks.

The process of salt weathering operates in three main ways. First, the evaporation of saline solutions in rock pores leads to the growth of salt crystals, which exert a *force of crystallisation* as they grow against the confining walls of the voids. Secondly, salts already emplaced within the pores by crystallisation may undergo hydration as a result of temperature and humidity changes. In consequence they undergo a volume increase, exerting a *hydration pressure as* they do so (Winkler and Wilhelm 1970). Thirdly, salts emplaced in pore spaces may expand due to heating. Since several common salts have a coefficient of expansion considerably higher than that of the confining rock, they will therefore exert pressure on the rock (Cooke and Smalley 1968). In all of these cases the growth of salt crystals exerts a tensile stress on the rock, creating a tendency to rupture at the granular scale.

In the present context the effect of temperature change is unlikely to be important, since the experiments show that the weathering rate is independent of temperature over the range of temperature likely to be prevalent in the field area. Attention therefore focuses on the possibility of crystallisation and hydration forces. Seawater contains a number of salts, of which sodium chloride (at a concentration of 27.2‰) is the most abundant. Several of the salts in seawater, although of low concentration, hyrate readily, and therefore provide the possibility of generating hydration pressures. These salts are magnesium chloride (3.8‰), calcium sulphate (1.3‰), magnesium sulphate (1.7‰) and magnesium bromide (0.08‰). Accordingly a second series of experiments was instigated, with a view to determining the effects of the single salts in isolation and with the assumption that the salts in seawater act individually.

Solutions were prepared of the individual salts, at the concentration of which each of the single salts is found in seawater. Rock samples, of the same form as employed in the previous experiment, were immersed in the saline solutions for one hour and allowed to air dry for the remainder of the diurnal cycle. Two samples were used in each solution and all solutions were maintained at constant concentration throughout. The experiments were run on the same lines as the previous one, with leaching, drying and weighing every 20 days for a period of 180 days.

The results of these experiments are shown in Figure 3. It is evident that sodium chloride is outstanding in its effect on the greenschist. It is therefore inferred that sodium chloride is the saline component of seawater which produces the most damaging effect, and by its force of crystallisation causing the rock to break down. The hydrating salts, in contrast, are shown to have a negligible effect at their low concentrations. It is perhaps not surprising that sodium chloride proves to be the most effective salt in seawater since, (with the exception of calcium sulphate which is present in only very low concentration) it will be the first to reach saturation and

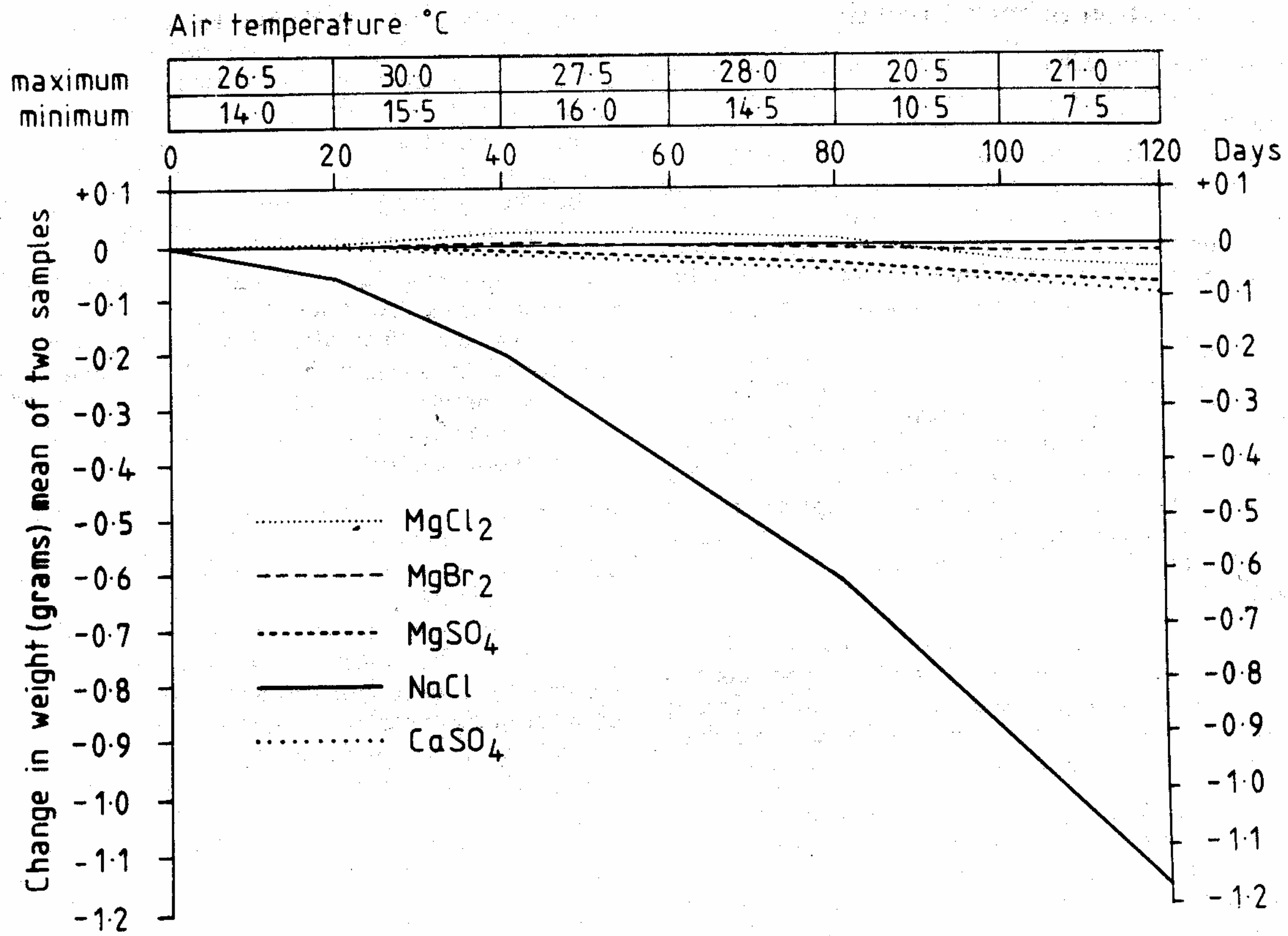

Figure 3. Weathering of greenschist by individual salt solution

therefore begin to crystallise during the evaporation of seawater. Furthermore, as Winkler and Singer (1972) show, it is the most powerful of a number of commonly occurring salts in terms of its force of crystallisation.

The pressure of salt crystal growth has been described by Correns (1949). He demonstrated, on theoretical grounds, that for crystal growth to occur against a confining medium, a film of supersaturated saline solution needs to be maintained at the interface of the crystal and the confining medium. For this to occur, the necessary conditions are defined in terms of the molar volume of the salt, the concentration of the solution, temperature and the pressure on the crystal, as follows:-

$$P = (RT/V).\ \log_n (C/Cs)$$

where
- P = pressure on the crystal
- R = universal gas constant
- T = absolute temperature
- V = molar volume of the crystalline salt
- Cs = concentration of the salt at saturation
- C = actual concentration of the saline solution during crystallisation

Correns demonstrated this relationship experimentally using crystals of alum, and showed good agreement between theory and experiment at C/Cs values up to 1.3, and decreasing agreement at higher values. Most of the terms in Correns equation can be readily evaluated in the present context, with the exception of C. Clearly the actual concentration of the saline solution during crystallisation will vary, and it will do so within the microscopic context of the pore spaces, rendering it extremely difficult to evaluate experimentally. Nevertheless, evaluation of the other terms of the equation permit its solution for a value of C/Cs, in order to determine whether this yields a realistic value.

The pressure which the growing crystal is required to generate in order to rupture the rock is, of course, equal to the tensile strength of the rock. This leads naturally to a consideration of the strength properties of the rock concerned.

A consideration of rock strength

The strength of a rock is comprised of the strength of the individual mineral components, and the intercrystalline bonds between them (Winkler 1975). A crude measure of mineral strength is provided by Moh's hardness value. Most of the minerals present in the greenschist have values in the range 5-7. Chlorite, however, one of the more abundant minerals, has a hardness value as low as 1.5-2.5 (Read 1948), which indicates that this mineral may contribute to an overall weakness in the rock.

A more precise estimate of rock strength, however, can be gained by direct testing of bulk rock samples. Since haloclasty produces tensile stresses, it is the tensile strength of the rock which is pertinent to the present case. This was assessed using the 'Brazilian' test, in which a circular disc of rock is subjected to a compressive stress across its diameter, thereby' including a tensile stress normal to the direction of the applied stress (Jaeger and Cook, 1979).

Youash (1969) has demonstrated that the strength of a rock varies according to the orientation of the applied stress in respect of layering within the rock. This is significant in relation to the highly foliated greenschist, which is markedly anisotropic in its mineral fabric.

Colback and Wiid (1965) have demonstrated that values of rock strength vary according to the moisture content of the rock, since the presence of water within the rock generates a pore water pressure which is opposed to the forces of intergranular bonding. Since haloclasty operates when the rock pores contain saline solutions, the saturated strength of the rock is more pertinent to the present problem than the more normally tested dry strength.

Tensile strength tests were carried out on 34 core samples 12.5mm in diameter taken from beneath the surface of the rock platform. Samples of both dry and saturated rock were tested. The former were oven-dried overnight, the latter were immersed in water for a similar period before testing. Tensile strength was determined both normal and parallel to the foliation. The results are set out in Table 4.

Table 4. Tensile strength determinations of the greenschist.

Condition	Orientation of tensile stress	n	Tensile strength MNm^{-2} Qt	σ
Dry	Parallel to foliation	10	10.35	2.47
Dry	Normal to foliation	8	3.19	0.47
Saturated	Parallel to foliation	8	6.27	0.64
Saturated	Normal to foliation	8	1.4	0.44

Within each set of samples tested there is a good measure of consistency, as indicated by the values of standard deviation. The rock is shown to be markedly anisotropic in respect of tensile strength, in both dry and saturated condition. Its resistance to rupture is shown to be much lower when the tensile stress is applied in the direction normal to the plane of foliation. Tensile strength values are reduced still further when the rock is in a saturated condition. The greenschist therefore possesses its lowest tensile strength in relation to stresses normal to the foliation, and when it is saturated. In this case its tensile strength is reduced by 90%, to one tenth of its maximum value - the dry strength measured parallel to the foliation, and has a mean value as low as 1.40 MNm^{-2}

These results may be compared with tensile strength values quoted by Bell (1980). A sample of 23 rocks yields a mean value of 10.48 MNm^{-2} very close to the tensile strength of dry greenschist parallel to the foliation. The tensile strength of this rock in the saturated condition normal to the foliation is, however, amongst the lowest values quoted by Bell.

Returning to the Correns equation, and substituting appropriate values for V and C in respect of sodium chloride, it is shown that at a temperature of 20°C a P value of 1.40 MNm^{-2} is generated when C/Cs is as low as 1.015. Thus a concentration of the saline solution only 1.5% above the normal saturation concentration is required to produce sufficient tensile stress at the surface of the growing crystal to disrupt the rock. Winkler (1975) states that C/Cs is likely to attain values as high as 100 during the later stages of evaporation of a saline solution. It would therefore appear that the low level of supersaturation required in the present case is readily achieved during evaporation and crystallisation.

Conclusion

The presence of oil-capped rock pedestals on the shore platform above HWM indicates that rapid weathering of greenschist is taking place in the spray zone. Laboratory experiments show that wetting and drying in seawater can produce sufficient mechanical weathering to account for both the mode of disintegration and the rate of lowering observed in the field. They also demonstrate that the crystallisation of sodium chloride is easily capable of disrupting the rock, and theoretical considerations show that the tensile strength of the greenschist can be overcome at only minimal levels of supersaturation of a solution of this salt during crystallisation. The power of sodium chloride weathering has long been recognised by civil engineers, and is confirmed by Winkler and Singer (1972).

The possibility of weathering of coastal rocks by sea salt was anticipated as long ago as 1936 by Bartrum, and attention was drawn to the neglect of this process by Wellman and Wilson (1965). Although most of their discussion focuses on arid environments, the latter authors point to the fact that the coastal environment immediately above HWM offers suitable conditions for the operation of salt weathering. The present study suggests that this can now be confirmed, and demonstrates the effectiveness of seawater in causing the breakdown of greenschist.

The present study ascribes the rapid weathering to the ! low mechanical strength of the saturated greenschist when stressed normal to the foliation. It is tempting to speculate that the relative abundance of the soft mineral chlorite may be the causative factor in the present 1 context, and some substance may be lent to this hypothesis by observations from other locations in south-west England. At Ayrmer Bay in south Devon, lenses of chloritic rock produce honeycombs similar to those observed at Prawle. At Godrevy Point in north Cornwall, incipient oil pedestals have been observed by the author on outcrops of greenstone. It may well be that close observation of other coastal outcrops of greenschists and greenstones in south-west England will yield further evidence of this kind of weathering.

Acknowledgements. Considerable thanks are due to a number of people who assisted in this study. A.I. Thomas of Slapton Ley Field Centre kindly provided much logistic support in the field. Dr G.M. Power carried out the mineralogical analyses. A.J. Poulsom provided the geotechnical data. The weathering experiments were carried out with the assistance of Dr B.E. Richards, Mrs J. Mottershead and Mrs J. Petrie. The Cartographic Unit of the Department of Geography, Portsmouth Polytechnic and Nell Hodgson drew up the diagrams.

References

Bartrum, J.A. 1936. Honeycomb weathering of rocks near the shore-line. *N.Z. J. Sci Tech. 18,* 593-600.

Cooke, R.U. and Smalley, I.J. 1968. Salt weathering in deserts. *Nature* 220 1226-7.

Bell, F.G. 1980. *Engineering geology and geotechnics.* Butterworth, London.

Colback, P.S.B. and Wiid, B.L. 1965. The influence of moisture content on the compressive strength of rock. *Proc. 3rd Canadian Rock Mech. Syrup. Toronto 1965,* 65-83.

Correns, C.W. 1949. Growth and dissolution of crystals under linear pressure. *In: Discussions of the Faraday Society 5, Crystal Growth,* Butterworth: London, 267,71.

Davies, J.L. 1964. *Geographical variation in coastal development.* Oliver & Boyd: Edinburgh.

Evans, I.S. 1970, Salt crystallisation and weathering: a review. *Revue de Geomorphologie Dynamique, 19,* 153-77.

Goudie, A.S. 1974. Further experimental investigation of rock weathering by salt and other mechanical processes. *Zeitschrift fur Geomorphologie Supp. Bd. 21,* 1-12.

Goudie, A.S. 1977. Sodium sulphate weathering and the disintegration of Mohenjo-Daro, Pakistan. *Earth Surface Processes, 2,* 75-86.

Goudie, A.S., Cooke, R.U. and Evans, I.S. 1970. Experimental investigation of rock weathering by salts. *Area 4,* 42-8.

Jaeger, J.C. and Cook, N.G.W. 1979. *Fundamentals of rock mechanics,* 3rd edition. Chapman & Hall: London.

Mottershead, D.N. 1981. The persistence of oil pollution on a rocky shore. *Applied Geography, L* 297-304.

Mottershead, D.N. 1982. Coastal spray weathering of bedrock in the supratidal zone at East Prawle, south Devon. *Field Studies,* (in press).

Orme, A.R. 1960. The raised beaches and strandlines of south Devon. *Field Studies 1,* 109-30.

Ratsey, S. 1975. The climate of Slapton Ley. *Field Studies, 4,*191-2062

Read, H.H. 1948. *Rutley's Elements of Mineralogy,* 24th edition. Geo. Allen & Unwin: London.

Schaffer, R.J. 1932. *The weathering of natural building stones.* H.M.S.O; London.

Tilley, C.E. 1925. The petrology of the metamorphosed rocks of the Start area (south Devon). *Q. J. Geol. Soc. Lond. 79,* 172-204.

Ussher, W.A.E., 1904. *The geology of the country around Kingsbridge and Salcombe. Mem. Geol. Surv. G.B.*

Wellman, H.W. and Wilson, A.T. 1965. Salt weathering, a neglected geological erosive agent in coastal and arid environments. *Nature, 205,* 1097-8.

Winkler, E.M. 1966. Important agents of weathering for building and monumental stone. *Eng. Geol. 15,* 381-400.

Winkler, E.M, 1973. *Stone: properties, durability in Man's environment.* Springer; Wien.

Winkler, E.M. and Singer, P.C. 1972. Crystallisation pressure of salts in stone and concrete. *Geol. Soc. Am. Bull. 83,* 3509-14.

Winkler, E.M. and Wilhelm, E.J. 1970. Salt burst by hydration pressures in architectural stone in urban atmosphere. *Geol. Soc. Am. Bull. 81,* 567-72.

Youash, Y. 1969. Tension tests on layered rocks. *Geol. Soc. Am. Bull. 80,* 303-6.

Discussion

M. Whiteley: By comparing the observed rates of erosion indicated by the micro-erosion meter with the mean height of the most mature oil-covered pedestals one can presumably obtain a measure of the longevity of the protective oil cover that allows the pedestal to develop. Are the results obtained consistent with the expected survival rates of small oil masses in a dynamic supra-tidal environment subject to the combined effects of physical and chemical weathering?

Author's reply: The age of the pedestals and the persistence of oil on the raised platform have been calculated in a previous publication (Mottershead 1981). The highest pedestals, and therefore the maximum duration of the oil are estimated at 17-18 years. Authorities who have visited the site in advance of the experimental work predicted that a range of 10-20 years would be the expected survival time of oil on this exposed rocky shore (A.L Bloom, M. Spooner, personal communication).

John Merefield: The recent natural evaporite deposits at Portland Bill, Dorset, examined by Saunders and West (1968) consisted almost entirely of halite crystals floating in a magnesium and sulphate-rich brine. Have you recognised similar surface deposits at East Prawle?
The Dorset deposits were ephermeral, could your erosion phenomenon be as weather dependant, and therefore erratic?

Author's reply: I have not observed at Prawle brine pools similar to those described, although there is on some occasions evidence of dried out brine pools in the form of salt crystals forming a rim around small depressions in the rock surface. No doubt if a visit to the site were made at the right time, then brine pools in a late stage of evaporation may well be seen.
The MEM data are beginning to suggest a distinct seasonal variation, with higher rates of surface lowering during the summer months, but a longer run of data is required before this can be demonstrated to an appropriate level of statistical confidence.
At times substantial deposits of rock meal can be found on the rock surface, Particularly in the summer. The accumulation of this material would appear to depend, however, not only on the rate of production by weathering, but also as a result of its not being removed by wind or surface wash by running water.

Read at the Annual Conference of the Ussher Society, January 1982

Aquifer characteristics of the Permian deposits in central Devonshire

J.C. DAVEY

Davey, J.C., 1982. Aquifer characteristics of the Permian deposits in central Devonshire. *Proc. Ussher Soc., 5,* 354-361.

The breccio-conglomerate and sandstone formations of the Permian strata in central Devonshire have been the subject of a major hydrogeological study. The layered nature of the deposits give rise to unconfined, confined and intermediate groundwater conditions which yield a wide range of aquifer characteristics. High water levels and steep hydraulic gradients are typical of the breccio-conglomerate formations in which nearly all groundwater movement is by way of fissure flow. Transmissivity values are dependent upon the penetration of fracture zones and their degree of interconnection. Varying from 1-100m^2/d, the highest values are attained only where extensive fracture systems or substantial thicknesses of sandstone are penetrated; The Clyst Sands exhibit slight hydraulic gradients and substantial intergranular flow, the latter suggested by laboratory work to account for up to 30% of all groundwater movement. Although transmissivities may be up to 300m^2/d, the highest values are usually recorded at Sites which experience substantial leakage. A water level map is presented and typical well hydrographs illustrated. Tables listing mean intergranular permeability for different lithologies and broad zones of transmissivity values for varying geological conditions are also given.

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Introduction

The Permian and Triassic strata in Devonshire and west Somerset form the major aquifers in south-west England. The Triassic deposits, particularly in east Devonshire, have been developed to provide large quantities of groundwater, but those of Permian age are relatively unexploited in respect of public supplies. A small number of isolated production wells have been commissioned to feed local service reservoirs or to augment surface water sources. However, until the present study (Davey, 198 la) little work had been undertaken on a regional scale to identify the characteristics controlling the groundwater regime operating within these deposits and assess the potential for future resource development.

The Permian strata cropping out in the Exbourne-Crediton-Bradninch area are contained within the west-east fault bounded Crediton trough. The outcrop width varies from 1km in the west to 7km in the east, and recent geophysical work (Davey, 1981b) has indicated a depth of up to 900m. A number of breccio-conglomerate and sandstone dominated formations have been variously identified and described during the last century by Ussher (1902), Hutchins (1954, 1963), Edmunds *et al.* (1968), Laming (1969) and Smith *et al.* (1974), Although no detailed map illustrating the outcrops of the individual formations has been published, the general occurrence of the breccias and sandstones is shown on One inch: One mile Geological Sheets nos. 324 (Okehampton) and 325 (Exeter). The few, generally localised, hydrogeological studies which have been undertaken were carried out by, or on behalf of, the statutory water undertaking. Following the Water Resources Act 1963, a hydrometric monitoring scheme was established and has provided some water level records from 1966 onwards. Additional monitoring commenced in 1969 and recently constructed wells have been incorporated into the scheme on their completion. The majority of groundwater data comes from the areas adjacent to the River Exe and River Culm. The first public supply well here was drilled and pump-tested in 1959, followed by others in 1966-67, 1970, 1973 and in 1976-78 during the present study. All but the foremost and latter were geologically logged by Professor A. Stuart. Although four production wells have been constructed, only two have been commissioned and just one, that drilled in 1959, is in regular use. Elsewhere in the study area, Devon River Authority undertook a full-scale pumping test at North Tawton in 1973 and, following the drought of 1975-76, the Central Water Planning Unit (now disbanded) outlined thirteen potential exploration sites of which three were subsequently drilled by the South West Water Authority. One production well south of Crediton feeds a nearby service reservoir.

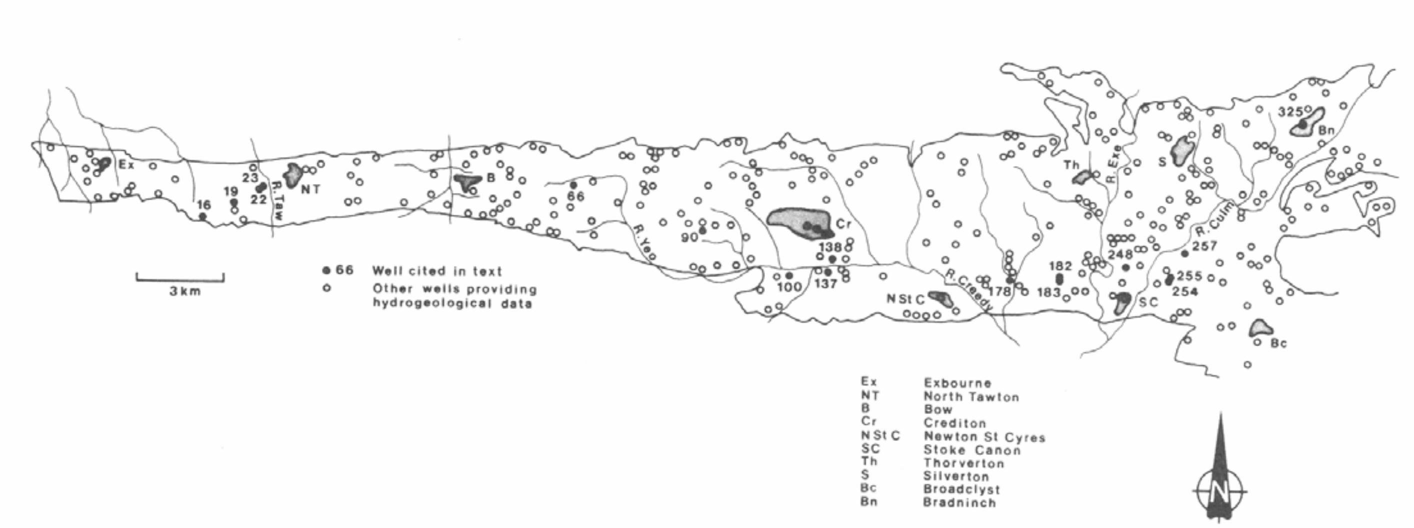

Figure 1. Location map showing the wells and springs used to provide hydrogeological information. (Only those Cited in the text are numbered. For full list see Davey 1981a).

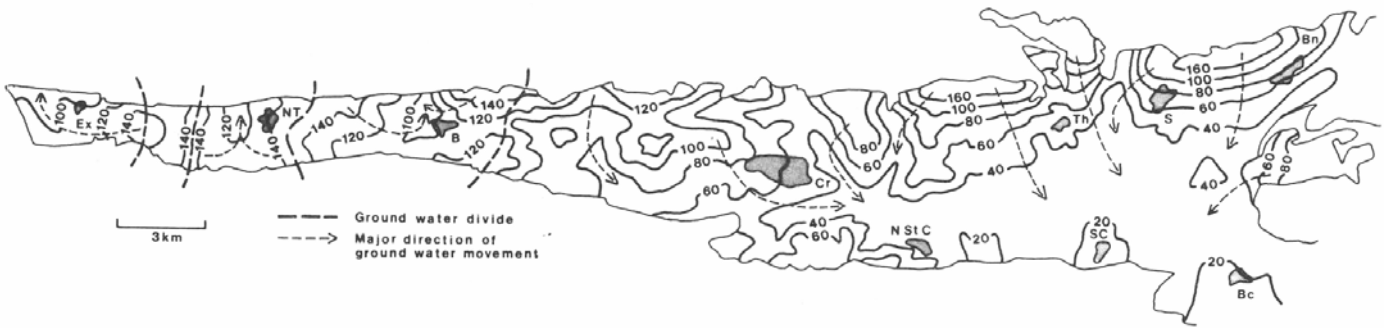

Figure 2. Water level configuration showing the major directions of groundwater movement within the Permian aquifers. (March 1977).

General Hydrogeology

The oldest formations, the Cadbury Breccias, Bow Conglomerates and Knowle Sandstones, occupy the western half of the outcrop. The lowermost Cadbury Breccias comprise a poorly defined series of loose, frequently clayey, basal gravels and are of little hydrogeological importance due to their relatively low permeability and transmissivity. In the generally well cemented Bow Conglomerates and Knowle Sandstones, groundwater movement is almost wholly controlled by the occurrence of fracture zones and the degree of connection between them. To the east, the Silverton Breccias probably represent some lateral extension of these formations and are of a similar hydrogeological nature.

The younger breccio-conglomerate formations, the Crediton Beds and St Cyres Beds (the Crediton Conglomerates of Edmonds *et al.* 1968) are frequently less well cemented and often rubbly in character with a clayey matrix. Although the degree of fracturing remains the major control upon groundwater movement, intergranular flow may not be insignificant.

Probably the youngest Permian strata in the area are the Clyst Sands which crop out to the east of Crediton. They comprise a series of often thinly bedded, moderately well cemented, fine-coarse grained sandstones interbedded with frequent siltstones, clays and occasional fine breccias. Of all the Permian formations this is the most valuable aquifer and is exploited by a number of relatively large sources. The uppermost units west of the Culm Valley are particularly fine-grained and comprise the major upper confining layer.

Groundwater Occurrence

The general principles controlling the occurrence and movement of groundwater in clastic aquifers are well documented. Although fissure flow dominates the hydrogeological regime in the study area there appears to be sufficient overall isotropy to permit consideration of groundwater occurrence on a regional scale. The wells and springs which provided hydrogeological data are shown in Figure 1. Full details of each site are given by Davey (1981a), whilst only those cited in the present text are numbered here.

Areal variation in groundwater levels

With water level data from long term monitoring wells and from many only measured during the period of study, it has been possible to prepare the rest water level map shown in Figure 2. In general, extremely localised conditions such as pumped levels or perched water tables have been disregarded. Despite the presence of numerous minor abstraction sites, cones of depression are limited in areal extent and do not show up on the regional map. Comparison of these levels with the topography suggests that the major groundwater divides and dominant flow paths broadly correspond with those of surface water catchments. Characteristically, water table contours are often a subdued reflection of the topography and this can be seen to be the case in this area. The majority of the outcrop, east of Bow, comprises a single catchment with overall groundwater movement south westwards, towards Newton St Cyres, Stoke Canon and Broadclyst. The western end of the outcrop appears to contain four minor groundwater catchments in which water moves northwards, corresponding approximately to the River Taw surface water system of its subcatchments.

There is considerable variation in hydraulic gradient. The steepest, slightly greater than 1 in 10, are encountered in the breccia uplands north of Thorverton and Silverton. The slightest gradients, as little as 1 in 200, occur in the low, flat area underlain by sandstone in the vicinity of Stoke Canon and Broadclyst. Gradients at other localities fall between these extremes, those in the undulating breccia hills around Bow and North Tawton approximating 1 in 30.

Variation in groundwater levels with time

Monitoring at several sites has been maintained for a number of years, a few providing continuous autographic records. Annual fluctuations in water levels are characterised by a relatively short period of recharge followed by much longer recession. Typical well hydrographs are shown in Figure 3. In most formations, recharge, which occurs for about four months of the year, is completed during January or February. Once recession commences, it generally continues until October or November. It is not uncommon in certain wet autumns for two recharge peaks to occur within the same calendar year; that expected in January-February with the following peak brought forward to November-December. Such a phenomenon is illustrated by the hydrograph from Columbjohn, Rewe (well no. 257 on Figures 1 and 3) for 1972.

The amplitude of annual fluctuations varies with aquifer type and geology: Wells such as Middle Trecott, Sampford Courtenay (no. 16) and Crofthayes, Bradninch (no. 325) in the better cemented breccio-conglomerates show the greatest variations, with ranges commonly up to 9m, although elsewhere 6-7m might be more usual. The St Cyres Beds, typified by the record from Middle Hollacombe, Crediton (well no. 90) appear to have a similar response, such large variations being due, in part at least, to the dominance of fissure flow. Records from the Clyst Sands show a much reduced range. Wells experiencing unconfined conditions, such as Burrow Farm, Rewe (no. 248) usually exhibit an annual range of approximately 5m whereas those tapping the confined aquifer units vary by little more than l-2m e.g. Columbjohn, Rewe (no. 257).

In confined conditions, the depth of the well may also be a significant control upon the water level, especially where there is a layered aquifer system due to variations in lithology. During the drilling of Jackmoor, Upton Pyne (well no. 178), the artesian overflow was closely monitored, with slightly less than $8m^3/d$ being produced when the confined aquifer was first encountered at approximately 19m depth. As drilling progressed, the piezometric head, and hence the overflow, increased, as shown in Figure 4, as each subordinate confining layer was penetrated. When the main aquifer unit was encountered below approximately 50m a flow rate of $76m^3/d$ was recorded.

During the 1976-76 drought, the driest fifteen month period in England and Wales since records began in 1727, groundwater sources from the Permian deposits were remarkably reliable. It has been calculated by the South West Water Authority that over the whole of the Permian outcrop in south west England, water levels fell on average, 0.3-0.5m below those normally expected by the end of the annual recession. Despite this reduction in resources, there was a noticeable lack of shortages amongst properties with private groundwater supplies. Although levels fell, few wells actually dried up.

Aquifer Properties

The assessment of aquifer properties must be one of the major contributions to any hydrogeological study. They indicate the ability of a given geological sequence to act as an "aquifer" in the strictest sense of the word, i.e. its ability not only to contain water, but to store and transmit it, and to yield it in an economical manner when pumped. The usual method of assessing such properties, predominantly Transmissivity, Permeability and Storage Coefficient is from pumping tests, the various techniques involved being well documented, notably by Kruiseman and De Ridder (1970).

Because these tests are extremely expensive in both equipment and manpower, full use must be made of the data collected. During this study, three-phase pumping tests were undertaken; an initial step drawdown phase during which discharge was increased in a number of short steps; a constant rate phase, where a given discharge was maintained for several hours, and a final recovery phase during which the rise in water level was monitored on cessation of pumping. The step drawdown phases have been analysed by a recent technique (Brereton, 1979) which permits the calculation of aquifer properties for individual steps. In addition to pumping tests, specific capacity and well response or "slug" test techniques were also used to estimate transmissivity and

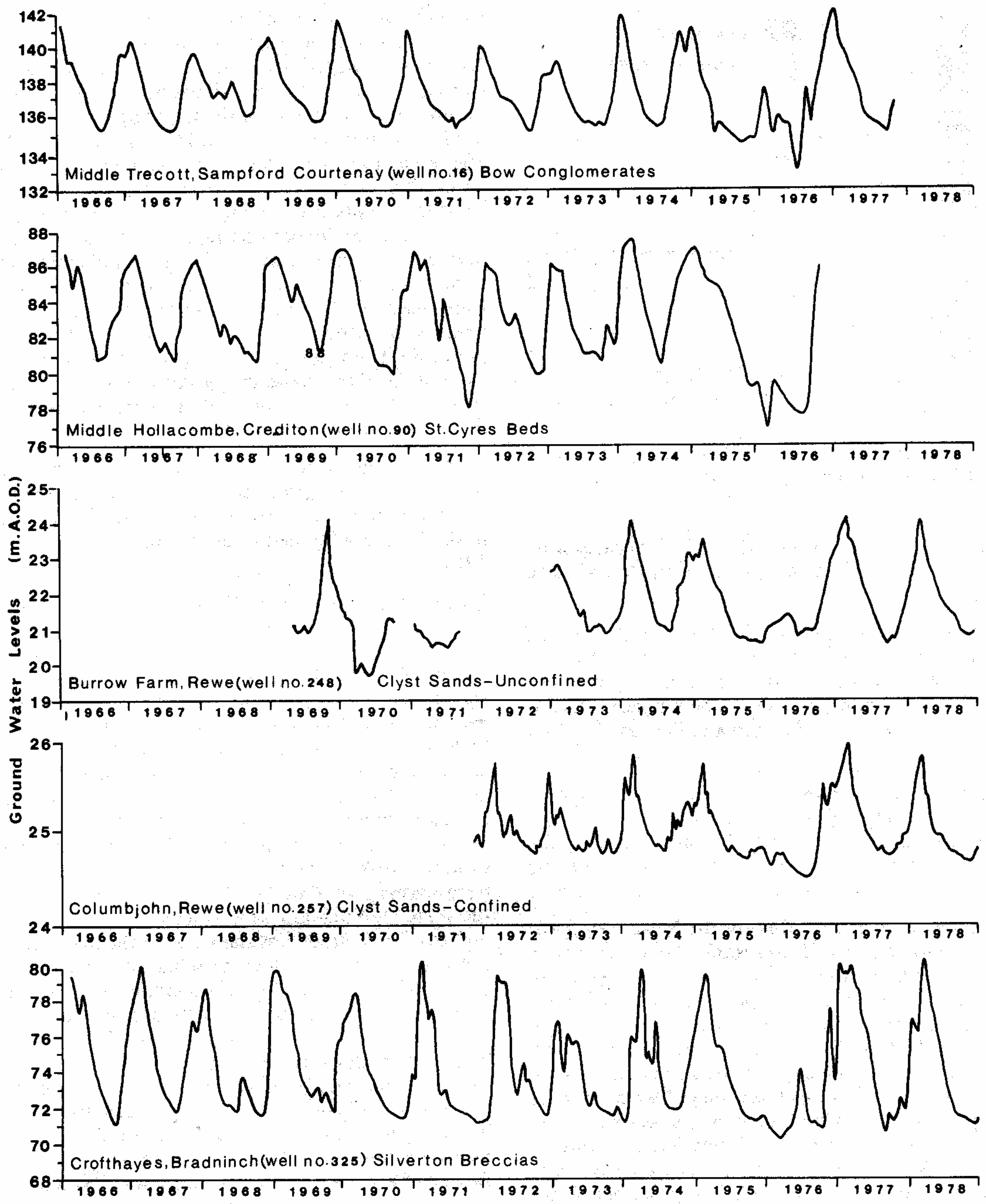

Figure 3. Well hydrographs showing groundwater level fluctuations typical of the Permian aquifers.

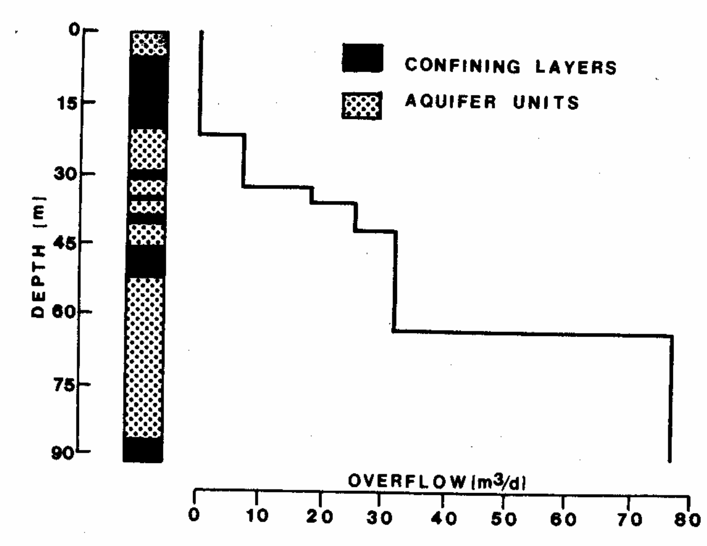

Figure 4. Increase in artesian overflow during drilling at Jackmoor Exploration Well, Upton Pyne.

storage, and determinations of intergranular permeability undertaken on surface samples and core material.

In addition to unconfined (water table) and confined (artesian) regimes, the presence within the Permian sequences of frequent variations in lithology produce intermediate conditions, both semi-unconfined and semi-confined as defined by Kruiseman and De Ridder (1970, p.18).

Although it is not necessary to consider every pumping test and each analysis of the data sets; it is useful to review a few results, particularly where they are affected by site specific characteristics, before proceeding to consider the overall aquifer characteristics.

The dominance of fissure flow in the better cemented breccio-conglomerates and the problems associated with failing to penetrate a well developed fracture system are illustrated by the well at Spires Cross, Sampford Courtenay (no. 19 on Figure 1). Despite passing through some 92m of the Bow Conglomerates the step drawdown measurements had to be curtailed at a discharge rate of $139m^3/d$ because the water level, then drawdown over 40m, approached the pump intake. All the water entering this well originates from a discrete fissure zone at approximately 70m depth and the average transmissivity obtained from the overflowing artesian regime here is just $3m^2/d$.

Just 1km to the east are two wells (nos. 22 and 23) which supply water to the large cheese factory at North Tawton. Despite the occurrence of a considerable thickness of sandy units, poor development of the first well and inadequate test data resulted in a transmissivity of only $16m^2/d$. The better organised test on the second gave just over $300m^2/d$, although some of the water may have been induced from the River Taw some 200m distant.

Colebrooke (well no. 66), at 181m the deepest in the area with a good geological record, penetrates both the Knowle Sandstones and the underlying Bow Conglomerates. The step drawdown phase showed a decline in transmissivity with increasing discharge rate in each of the 100 minute steps, from $72m^2/d$ at $382m^3/d$ to $30m^2/d$ at $1407m^3/d$, due to the dewatering of the more permeable upper sections in the Knowle Sandstones. Mudstone units are common throughout the sequence and during the longer constant rate phase at $917m^3/d$ delayed yield proved to be of considerable importance. Semi-unconfined conditions with an average transmissivity of some $60m^2/d$ appear to prevail at this site. Laboratory determinations of intergranular permeability on core material suggest that less than 2% of is this bulk field transmissivity is likely to be due to primary porosity, the majority of groundwater movement again being by way of fissure systems.

In the unconfined conditions experienced at Uton, south of Crediton, the production well (no. 100) gave an average transmissivity of $28m^2/d$ in 1978, little different to the $25m^2/d$ obtained when the well was completed in 1948.

There are a number of results from the Clyst Sands, the most significant coming from tests at Starved Oak Cross, Brampford Speke (well nos. 182 and 183), also carried out in 1978. With the pumping well and one observation well drilled to 93m and a number of shallow tube-wells, a wealth of data has been forthcoming from this site. The hydrogeological system here consists of a lower major aquifer confined by a less permeable upper aquifer, the latter, approximately 30m in thickness, containing many mudstone bands. This in turn is confined by near-surface, relatively impermeable horizons. The complete sequence exhibits leaky confined conditions with a mean transmissivity of $72m^2/d$. However, the permeability of the upper aquifer has been calculated to be some two orders of magnitude less than that of the major aquifer, 5.0 x 10-3m/d as opposed to 6.0 x 10'tm/d. Distance-drawdown solutions from the shallow wells within the upper aquifer indicate a difference in permeability between dip and strike directions, the former giving a value approximately 10% greater. Laboratory work suggests that intergranular permeability accounts for between 10 and 30% of the bulk field transmissivity. Also in the Clyst Sands but penetrating a less silty sequence, a mean transmissivity of $250m^2/d$ has been obtained from Bussells Farm, Stoke Canon (wells nos. 254 and 255).

The confining character of the upper units of the Clyst Sands appears across much of their outcrop. Although Ussher (1902) recognised a further stratigraphical division in this area comprising deposits similar to those of his "Lower Marls" found to the east (since renamed the Aylesbeare Group), such a division is not made on the published One inch: One mile Geological Sheet (no. 325). It is, however, shown on the first few hand-coloured copies produced and can also be identified on hydro-geological grounds. The soil characteristics in the area are consistent with the presence of such strata and in recent mapping (Dr D.C.J. Laming - pers. comm.) a sequence of fine deposits has apparently been recognised. During the present study, the isopachytes illustrated in Figure 5 have been tentatively constructed for this less permeable material and are shown in relation to the Clyst Sands outcrop as recorded on Sheet 325.

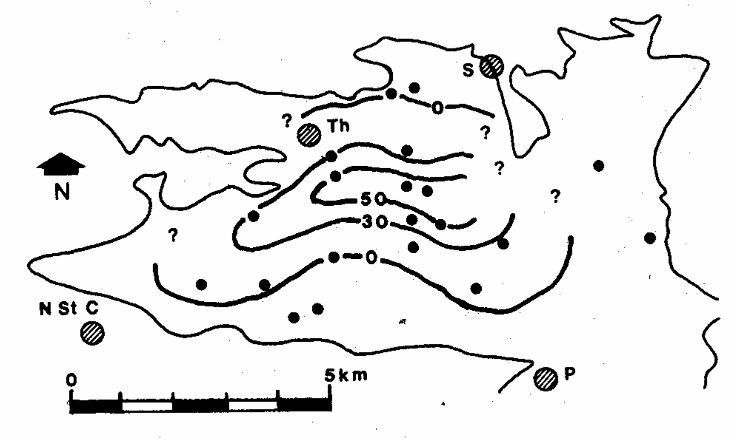

Figure 5. Isopachtyes (metres) for the less permeable sequence recognised within the Clyst Sands outcrop in the vicinity of Thorverton (Th), Silverton (S), Newton St Cyres (N.St.C) and Poltimore (P).

Little hydrogeological information is available from the Exeter Volcanic Series. Although these basaltic and potassic lavas are found as small scattered outcrops in the breccio-conglomerates and sandstone formations, few wells have been constructed in them; this fact itself being some indication of their poor aquifer potential. Despite the often vesicular nature of the lavas, their interconnected porosity, the "effective" porosity with regard to groundwater movement, is small and any flow will again be Via fracture zones. Sparse specific capacity data suggest values of transmissivity within the range of 1-20m^2/d.

Although there is considerable variation throughout the Permian deposits four major controls on their aquifer characteristics can be identified:
(i) the variation in lithology
(ii) the degree of cementation
(iii) the presence and interconnection of fissure zones
(iv) the availability of other bodies of water.

The effects of both variation in lithology and differing degrees of cementation may be seen from the mean values of intergranular permeability calculated for the major lithologies present within the Clyst Sands and listed in Table 1. Both the well cemented and moderately cemented groups of samples exhibit a decline in permeability with decreasing particle size. Although insufficient breccio-conglomerate samples were measured to give meaningful average values, there is also a decrease in permeability in the coarser material, as the percentage of each sample occupied by relatively impermeable pebbles increases.

Table 1: Mean intergranular permeability of the major lithologies present within the Clyst Sands.

Lithology	Mean Permeability (m/d)
Coarse-very coarse grained Sandstone	
well-cemented	0.38
Medium-coarse grained Sandstone	
well cemented	0.3
moderately cemented	1.3
Medium grained Sandstone	
well cemented	0.16
moderately cemented	0.8
Fine-medium grained Sandstone	
well cemented	0.01
moderately cemented	0.01
Fine grained Sandstone	
well cemented	0.009
Fine grained, silty, Sandstone	
well cemented	0.008
moderately cemented	0.003
Siltstone, well cemented	0.00005

Table 1 also shows an extremely significant increase in the intergranular permeability of a given lithotype when there is a slight reduction in cementation. In the medium-coarse, medium and fine, silty sandstones a four-fold increase is observed. Strangely, the mean permeability of the fine-medium sandstones is the same for both well cemented and moderately cemented samples.

Much of the aquifer test data illustrate the importance of fissure flow. The poor results obtained from a well penetrating a restricted fracture system have already been highlighted by reference to Spires Cross. Although fissures are, in effect, zones of the aquifer where porosity is 100%, the amount of water they contain may be of less significance than their ability to act as conduits, transporting water between adjacent but otherwise unconnected aquifer units or from surface water bodies. The difference between the transmissivity of 2m^2/d obtained from the Crediton Beds at Fordton House (well. no 137) and the 79m^2/d from Fordton Mill (no. 138) may reflect fissure development.

Several sites exhibit properties which are characteristic of significant quantities of water being derived from sources other than those geological units penetrated by the well, such as by leakage through an aquiclude or induced recharge from a nearby river. At Starved Oak Cross, pumping of the major aquifer derives substantial volumes of water by way of leakage from the less permeable upper aquifer. At Columbjohn, inflow equals discharge, with no further decline in the water level, after some 300 minutes when pumping at a rate of 456m^3/d. The River Culm just 73m distance appears to be the most likely source. At Bussells Farm, leakage has been calculated to originate approximately 350m from the well and although a source at this distance is not obvious, the River Culm some 700m away, is again the most likely, water possibly entering the zone of influence of the well via superficial alluvial deposits.

Table 2: Transmissivities of the Permian deposits in central Devonshire

0 - 10m^2/d	Well cemented breccio-conglomerates in which few major fissure zones are penetrated. Strata adjacent to the Culm Measures.
10 - 50m^2/d	Breccio-conglomerates containing some sandy units or in which considerable fissure zones are penetrated.
50 - 100m^2/d	Breccio-conglomerates containing appreciable thicknesses of sandstone units. The better cemented sandstones.
100 - 300m^2/d	Less well cemented sandstones in which both intergranular and fissure flow may be of equal importance. The higher values, however, are unlikely to be attained unless recharge is induced via leakage.
300 + m^2/d	Extremely permeable sequences into which flow can be induced from an adjacent surface water body.

From the data acquired it is possible to define broad ranges of aquifer transmissivities, shown in Table 2, for appropriate hydrogeological situations. Because the majority of tests were undertaken at sites at which there was the test well alone, it has only been possible to calculate storage coefficients for those few which have also yielded observation well data. Throughout the Permian deposits such values appear to be fairly uniform. Under confined groundwater conditions, the mean storage coefficient is approximately 0.0004, but is greater, as might be expected, in the more permeable sequences of the Clyst Sands where the average is about 0.008. No determinations of unconfined storage could be made due to the lack of suitable data.

Summary

The breccio-conglomerate and sandstone formations of the Permian deposits in central Devonshire have been the subject of a major hydrogeological study, Although experiencing only restricted resource development with regards to public water supply, the total abstraction from the many hundreds of private sources make these deposits one of the major aquifers in south west England.

Both unconfined and confined groundwater conditions are encountered and, on a regional scale, the piezometric surface generally falls within the water table contours presented in Figure 2. The highest levels, and the steepest hydraulic gradients, are characteristic of the breccio-conglomerates, particularly those in the vicinity of Thorverton and Silverton. Regional groundwater movement over much of the area is towards the south and southeast where the lowest hydraulic gradients are observed in the Clyst Sands. Well hydrographs are characterised by a short recharge period between November and February followed by a long recession. Fluctuations in water level vary from over 10m in the breccio-conglomerates to less than 2m in the confined units of the Clyst Sands.

Although site specific characteristics, particularly the localised development of fracture systems, are very important in determining aquifer properties, it has been possible to present broad ranges of transmissivity values which are likely to be obtained from these deposits. Whereas well cemented, poorly fractured breccio-conglomerates often give values less than 10m^3/d, values in excess of 100m^2/d may be obtained from the less well cemented sandstones. Higher values often result from leakage or induced recharge from surface water bodies. Laboratory measurements indicate that just slight increases in particle size or minor reductions in degree of cementation can produce significant increases in intergranular permeability and up to 30% of the ground water flow within the Clyst Sands may be attributed to inter-particulate movement.

The resource potential of the Permian aquifers in central Devonshire appears to be considerable. During the 1975-76 drought a few wells actually went dry despite a fall in the water level averaging 0.3-0.5m below that which might have been expected at the close of a more normal annual recession. Significant supplies from the older, better cemented formations are dependent upon the interception of major, interconnected fissure systems and only localised demand for groundwater is likely to be fully satisfied. Although greater quantities could be obtained from the less well cemented formations, very large scale abstraction for public supply will be limited to the Clyst Sands which already yield up to nearly 500m^3/d with little effect upon the regional hydrogeological regime and are capable of sustaining substantially increased abstraction provided careful resource development and management are undertaken.

Acknowledgements. This work could not have been undertaken without the full co-operation of the South West Water Authority whose Senior Hydrogeologist, Mr C.D.N. Tubb, and his staff, particularly Messrs T.R.N. Jones, G.J. Arter and I.C. Trew, never failed to give practical assistance and advice when requested. The author is also indebted to the many farmers, local businessmen and private householders who permitted access to their wells. Miss C. Heaphy meticulously prepared the diagrams.

References

Davey, J.C. 1981a. The hydrogeology of the Permian Aquifers in central and east Devonshire. *Unpubl. Ph.D. Thesis Univ. Bristol.*

Davey, J.C. 1981b. Recent geophysical studies across the Permian outcrop in central and east Devonshire. *Proc. Ussher Soc. 5,* 194-199.

Edmonds, E.A., Wright, J.E., Beer, K.E., Hawkes, J.R., Williams, M., Freshney, E.C. and Fenning, P.J. 1968. The geology of the country around Okehampton (Sheet 324). *Mem. Geol. Surv. G.B.*

Hutchins, P.F. 1954. The Lower New Red Sandstone of central Devon. *Unpubl. Ph.D. Thesis Univ. Cambridge.*

Hutchins, P.F. 1963. The Lower New Red Sandstone of the Crediton valley. *Geol. Mag., 100,* 107-128.

Kruiseman, G.P. and De Ridder, N.A. 1970. Analysis and evaluation of pumping test data. *Intern. Inst. Land Reclaim. Bull. 11,* Wageningen, 200pp.

Laming, D.J.C. 1969. New Red Sandstone stratigraphy in Devon and west Somerset *Proc. Ussher Soc., 2,* 23-25.

Smith, D.B., Brunsdon, R.G.W., Manning, P.I., Simpson, S. and Shotton, F.W. 1974. A correlation of Permian rocks in the British Isles. J. *Geol. Soc. Lond. 130,* 1-45.

Ussher, W.A.E. 1902. The Geology of the Country around Exeter. (Sheet 325). *Mem. Geol. Surv. G.B.*

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Read at the Annual Conference of the Ussher Society, January 1982

Exmoor channel patterns in relation to the flood of 1952

M.G. ANDERSON
A. CALVER

M.G. Anderson and A. Calver 1982. Exmoor channel patterns in relation to the flood of 1952. *Proc. Ussher Soc., 5,* 362-367.
The changes undergone by stream channel patterns on central Exmoor as a result of the passage of the August 1952 flood are detailed and comment is made on the longer term significance of these changes.
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Introduction

By their very nature large flood events are generally poorly documented in terms of their effect on river channel forms. However the flood which occurred on Exmoor on 15 August 1952, an event with a recurrence interval believed to be in the order of 1 in 150 years (Carson and Kirkby, 1972), is something of an exception. This flood is perhaps the best documented such event in Britain in terms of field notes and photographs taken shortly after the flood. Since the occurrence of this 1952 flood no runoff events approaching this magnitude have occurred.

In an earlier publication (Anderson and Calver, 1980) the authors detailed an example of changes in stream channel pattern in an Exmoor valley over a period which included the 1952 flood. Further investigations allow us to now present a comprehensive picture of 1952 channel pattern changes over a wide area of the central moor (Fig. l) and to comment on the longer term significance of these changes.

The geomorphological background of the central Exmoor area and information on a number of other aspects of the 1952 flood are to be found in the following papers:- Bleasdale and Douglas 1952, Dobbie and Wolf 1953, Gifford 1953, Green 1955, Kidson 1953, Marshall 1953, McClean 1953, Anderson and Calver 1977, 1980.

Techniques and data base

Three major data bases were used in this study. Air photograph coverage for the area is particularly good, being available for the following years: 1946 (1:9800), 1947 (1:8600), 1969 (1:32000), 1971 (l:12000), 1973 (1:7700), 1977 (l:13000). Secondly, detailed field photographs taken in September and October 1952 are available from the Institute of Geological Sciences. Thirdly, the authors were loaned field notes and photographs taken by Mr A. Bleasdale (then of the Meteorological Office) in September 1952 shortly after the passage of the flood.

The authors undertook a general field review with particular reference to the location of information available on 1952 conditions and a number of sites were selected for survey and detailed study. The general findings together with detailed 'type' examples are presented below.

Channel changes

Examination of the air photographs and 1952 field information shows that such channel changes as are apparent between 1946 and the present occurred at or shortly after the major 1952 flood. In the subsequent period 1953-1981 only relatively minor modifications to the channel plans have occurred. Figure 1 compiled from air photo study shows the reaches of channels which underwent marked change in plan as a result of the high runoff event of 1952. The nature of such channel plan change as occurred in 1952 is, in general, from a previously regularly or irregularly meandering channel to a less sinuous form.

A limited number of relevant oblique air photographs are available: Figure 2 shows a particularly informative panorama of the West Lyn valley on 22 August 1952, one week after the passage of the flood. On this photograph five zones (A-E) are identified as channel reaches representing 'type' responses of the region (Fig. 1) in general. These are discussed below together with the general controls which give rise to such responses.

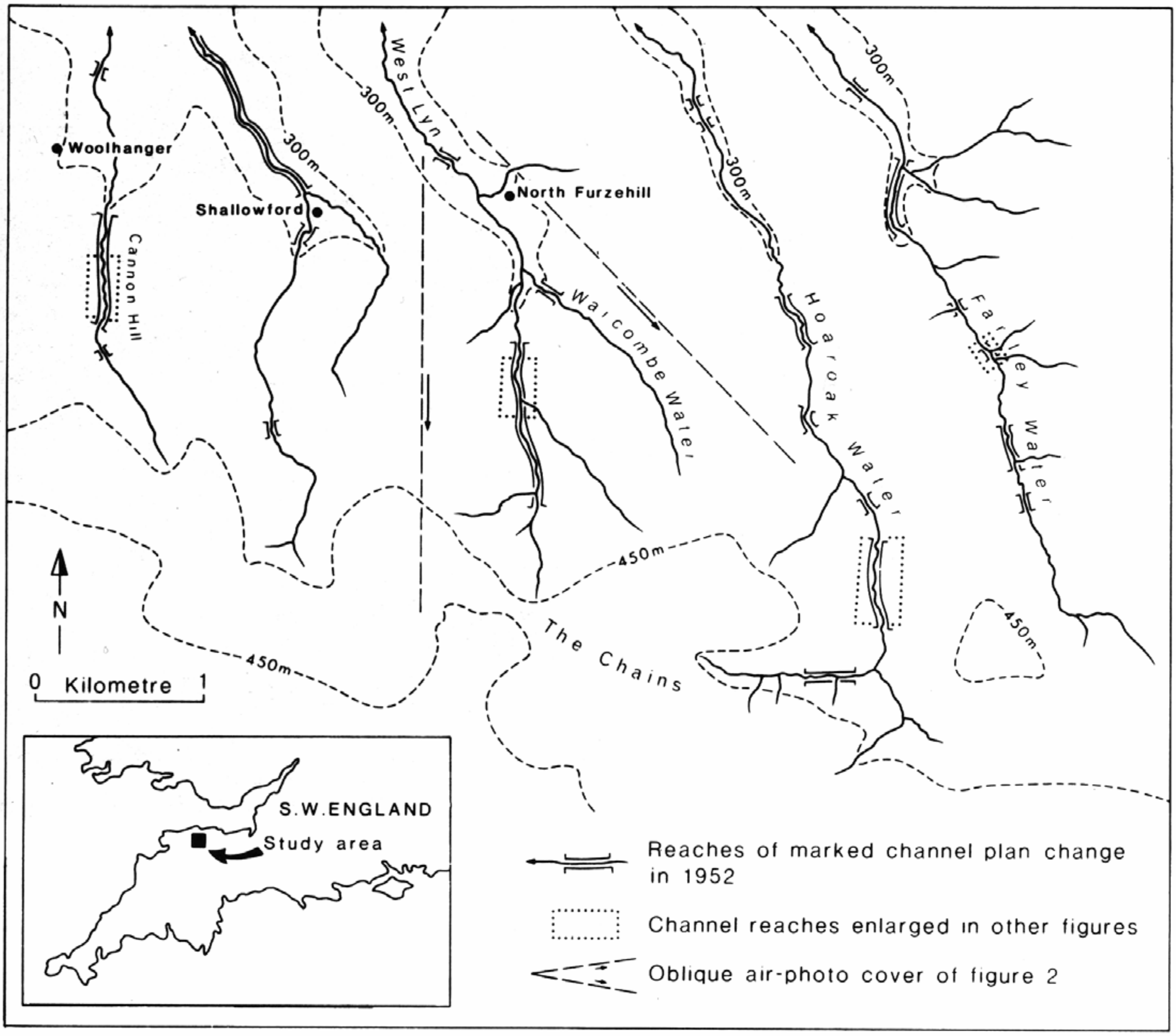


Figure 1. Map of field area showing reaches of marked channel plan change in 1952.

Channel reaches which experienced significant change in their plan form were those with sufficient drainage area to have generated high volumes of channel flow and, particularly, those where the high flow had been able upstream to entrain a substantial debris load whether from bedrock or, more readily, from partially weathered shattered hillslope and channel floor deposits. Debris played an important role in channel change by blocking or partially blocking existing routes. A further important criterion for he occurrence of flood-induced channel change is valley floor width: a wider floor presents, of course, more scope for a change of route, but over and above this is the fact that, given the drainage area and debris requirements noted above, zones of valley floor widening induced some attenuation of flow and the deposition of swaths of flood debris. This deposition obliterated to varying degrees the former channels and in a number of cases caused a period of braiding following the subsidence of flood waters before, commonly, a single stable channel was re-established. On narrow valley floors with high water and sediment loads, scouring and deepening of the existing channel tended to predominate.

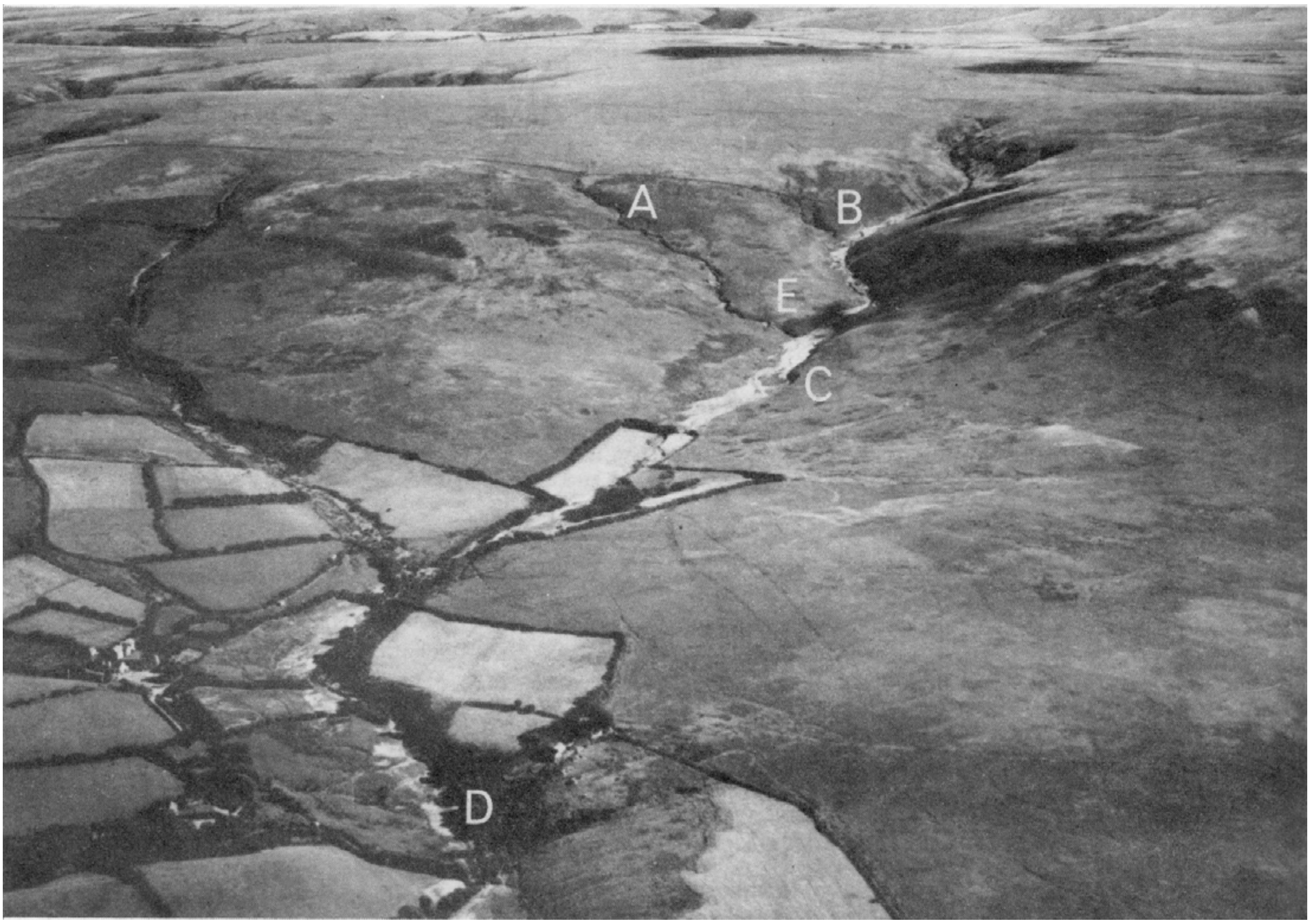


Figure 2. Oblique air photograph of West Lyn valley (for location see Figure 1).

These factors influencing channel behaviour in association with the flood mean that a number of valleys show some degree of systematic change in channel plan characteristics resulting from the flood (see for example Figure 2 of the West Lyn). Headwater areas of main streams and tributaries (A on Figure 2) are relatively little affected in terms of channel plan change; narrow upper stretches (B) (and other geologically determined valley constrictions) show incision and some minor channel plan change; the broadening of valley floors (C) is accompanied by deposition spreads and channel pattern change to a marked degree; while further downstream (D) within the area of Figure 1, as one approaches part of the moor where hedges and walls in many places restrict channel migration, plan change is often less marked despite overbank deposition. Superimposed on this pattern are changes at stream junctions (E) caused by abnormally high inflows of water and/or debris.

Figures 3-6 show the scale and nature of channel plan change and they detail abandoned channel segments which can be observed at present in the field. In addition to remnants of the channel existing immediately before the 1952 flood and those of intermediate phases in 1952 modifications, a number of earlier, pre-1946, channel segments are at present discernible in the field on the wider valley floors and particularly at valley floor edges. Valley floor deposits show evidence of both gradual and catastrophic channel plan change.

Three types of channel plan change associated with the 1952 flood can be identified. Firstly, Figure 3 (Farley Water) illustrates the complexity of change at stream junctions. Secondly, Figure 4 (Cannon Hill) shows the reduction in sinuosity found in upper reaches where plan changes were accompanied by downcutting due to the constricted nature of the reach. Thirdly, Figures 5 and 6 (West Lyn and Hoaroak Water) typify channel reaches where valley floors widen and the 1952 flood was responsible for widespread deposition followed by a degree of braiding and then the re-establishment of a single channel of generally reduced sinuosity in places substantially removed from its pre-flood course. Figures 7 and 8 similarly demonstrate this third category in the West Lyn valley.

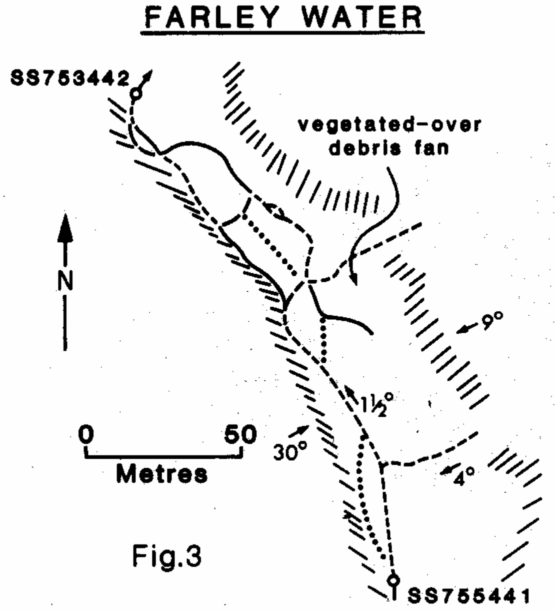


Figure 3. Mapped channel plan change in Farley Water.

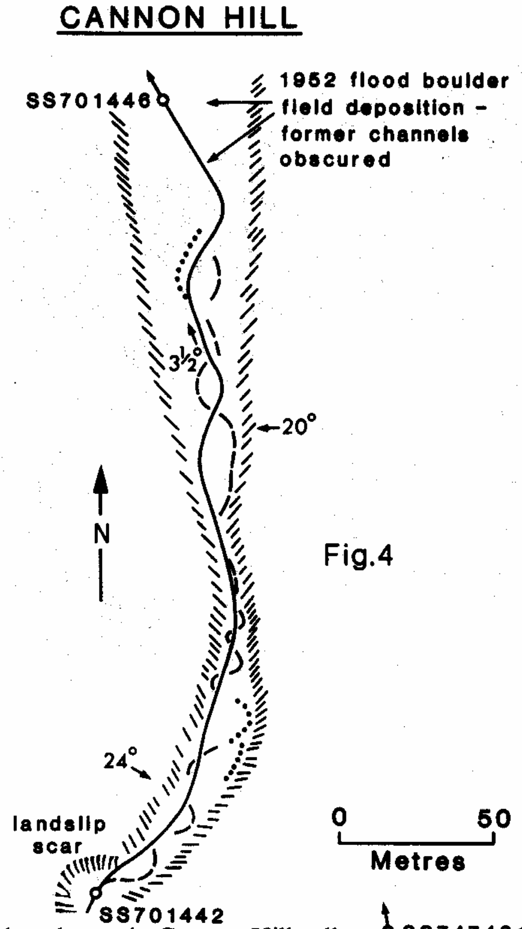


Figure 4.
Mapped channel plan change in Cannon Hill valley.

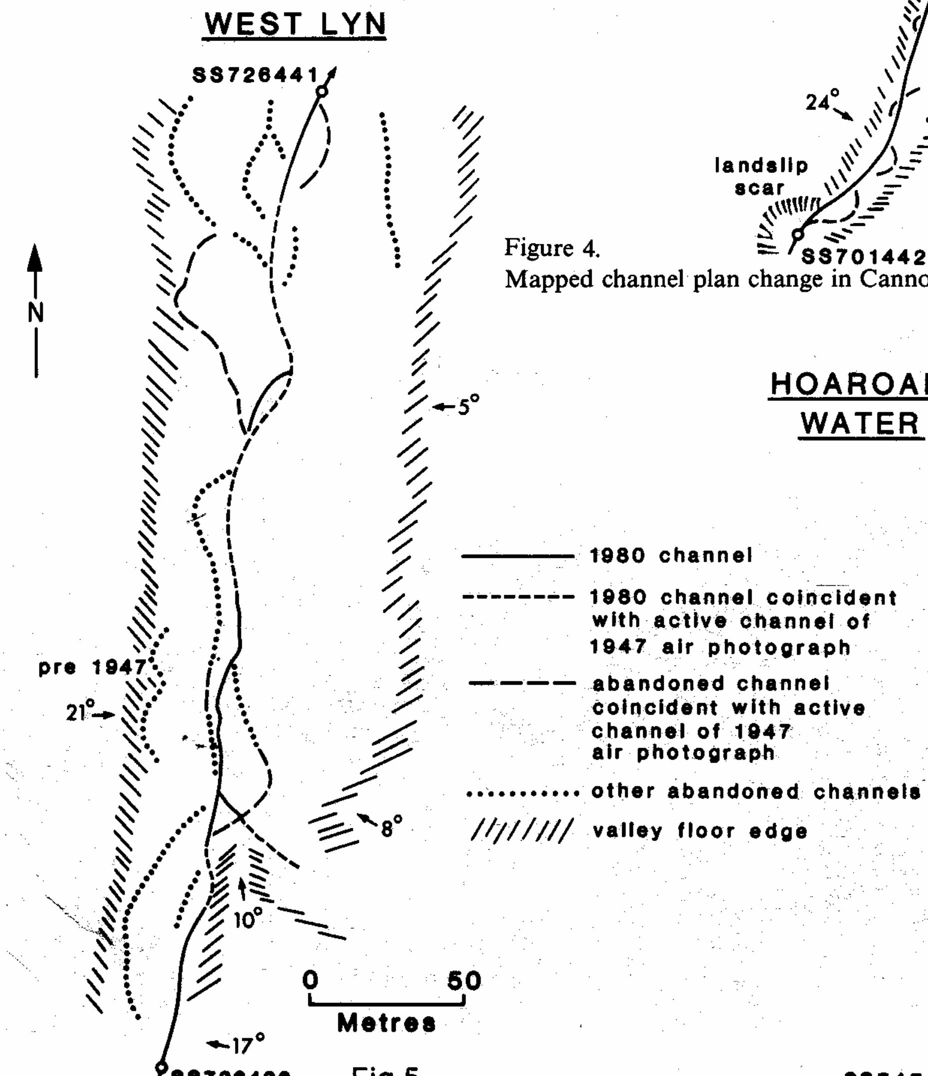
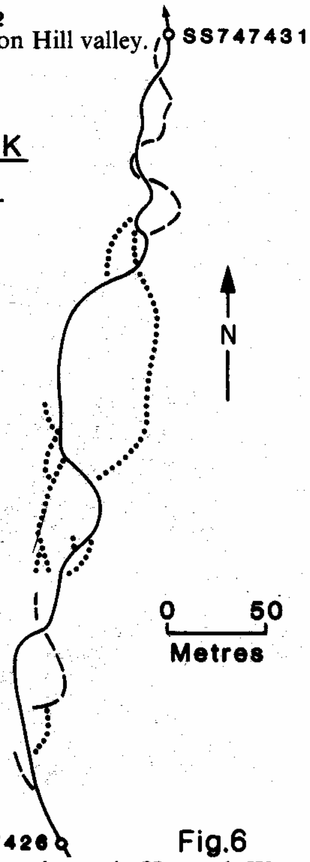


Figure 5. Mapped channel plan change in the West Lyn.



Mapped channel plan change in Hoaroak Water.

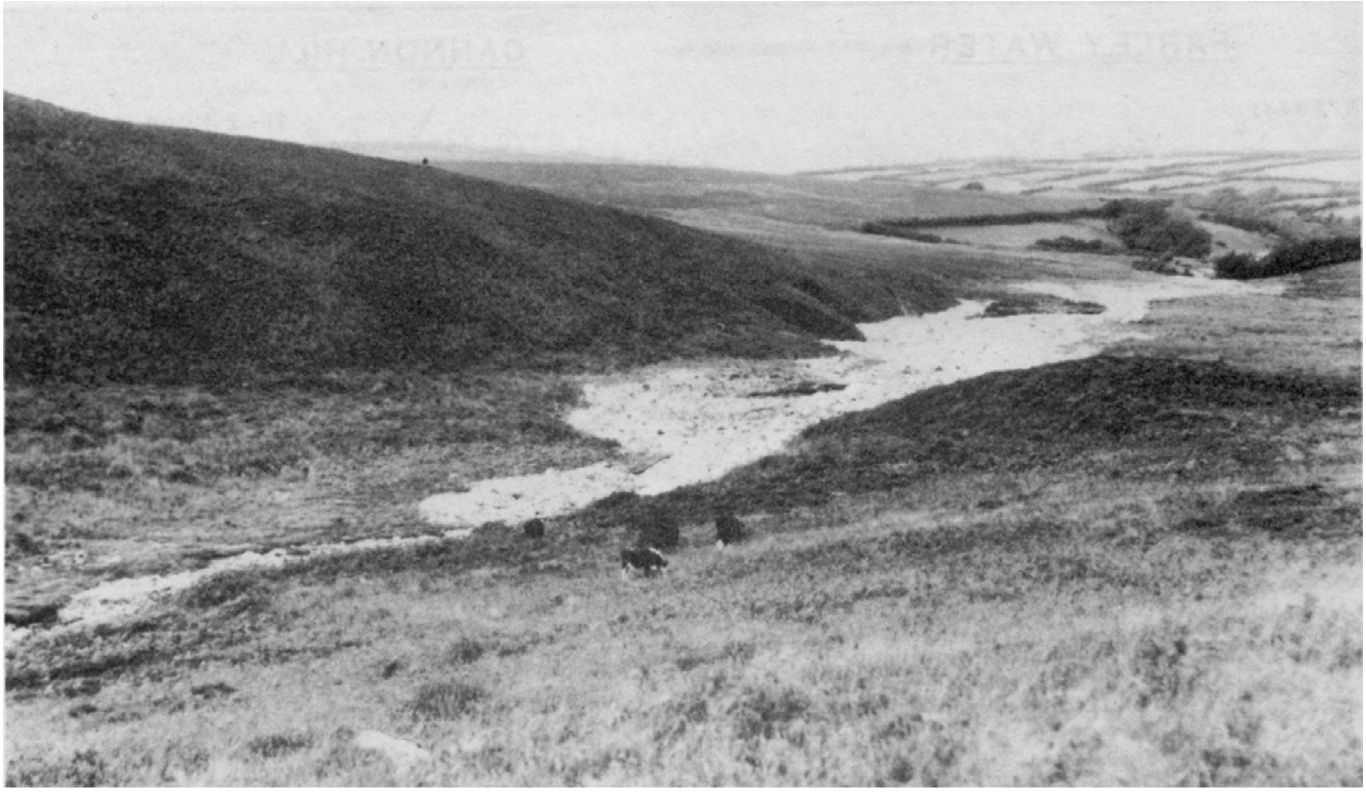


Figure 7. The west Lyn from approximately point E on Figure 2
looking down valley, 26 September, 1952.

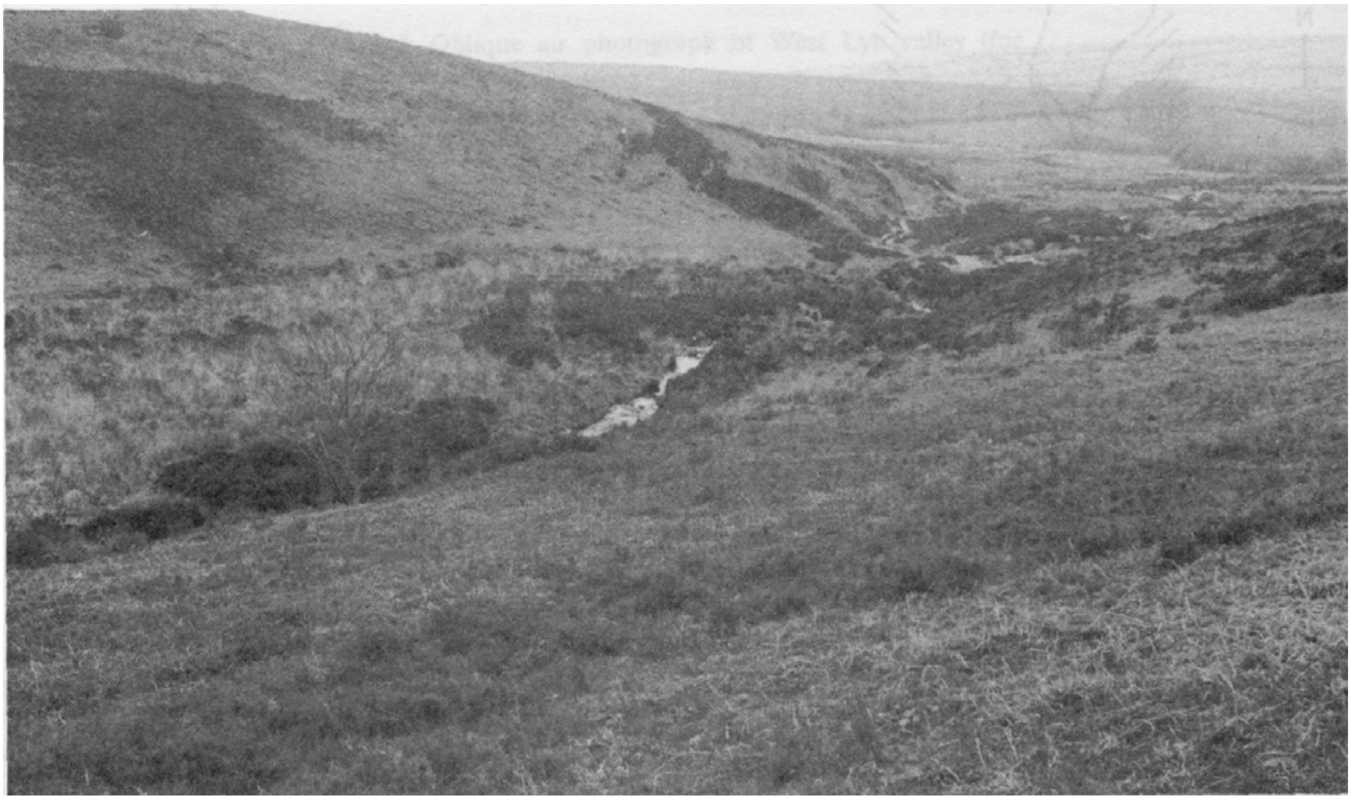


Figure 8. The West Lyn from the same viewpoint as Figure 7,
March 1980

Discussion

Channel plan changes in the period 1946-1981 are heavily dominated by those caused by the August 1952 flood, whether at the passage of the main flow or in the adjustment period shortly after. In the area of Figure 1 20% of the valley floor length underwent marked channel plan change in 1952. This is an overall value including tributaries: for the main streams alone the value is much higher. At the-same time almost the complete channel network saw some change in cross-section. That the flood debris deposited within the area of Figure 1 is greatly in excess of the material evacuated to the streams from slope base failures occurring at the time of the flood reflects the severity of headwater valley floor erosion, the more so if allowance is made for sediment transport downstream beyond the area of concern.

It is very apparent that aspects of the present day geomorphology of the area still reflect to a marked degree the extreme runoff event of 29 years ago: this relates not so much tot he overall form of hillslopes or valleys but to smaller scale aspects of the morphology, namely, in the types of areas we have defined above, the channel pattern and also, in varying degrees, channel cross-sections and, in places, slope-base form. In terms of channel and hillslope activity the post-flood period, from say 1953 onward, has not seen anything approaching the rate of 1952 flood - induced activity, nor indeed does total activity in the subsequent period approach that of 1952. Between 1953 and 1981 marked channel plan change has affected 1% of the valley floor length: these minor modifications to stream courses are apparent in terms of meander migration on a local scale.

On a longer time scale the significance of geomorphic activity like that of 1952 needs to be seen in the context of the whole of the recurrence interval of such an event and of the occurrence of other floods of greater and smaller magnitudes. Large floods bring about changes which may alter the otherwise expected effects of following floods: the deposition of subsequently easily-erodable debris in 1952, for example, meant increased transport rates in places in the relatively minor floods of 1979 compared with such an event before 1952. One factor influencing the occurrence of channel plan change, namely the availability of a supply of erodable debris, can thus vary over a much shorter time span than can factors such as valley floor width. The generally shorter channel courses and corresponding increases of gradient suggest some adaptation of the channel system to a form better able to cope with a large flood: the continuing, albeit to some extent spatially changed, availability of erodable debris and opportunities for flow blockage by sediment, rock debris or vegetation mean, though, that channel plan change on a marked scale is likely still to be a feature of a subsequent major flood. In this type of geomorphic environment, after the lapse of a fifth of the mean recurrence interval and with no intervening large runoff events, the effects of the 1 in 150 year flood are most significant in the explanation of existing channel plans and may for some time yet be expected to influence the detail of the behaviour of such high runoff events as may occur.

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References

Anderson, M.G. and Calver, A. 1977. On the persistence of landscape features formed by a large flood. *Transactions of the Institute of British Geographers, 2(2),* 243-254.

Anderson, M.G. and Calver, A. 1980. Channel plan changes following large floods. *In:* R.A. Cullingord, D.A. Davidson and J. Lewin (eds.) *Timescales in Geomorphology,* Wiley, 43-52.

Bleasdale, A. and Douglas, C.K.M. 1952. Storm over Exmoor on August 15, 1952. *Meteorological Magazine, 81,* 353-367.

Carson, M.A. and Kirkby, M.J. 1972. *Hillslope Form and Process,* Cambridge University Press.

Dobbie, C.H. and Wolf, P.O. 1953. The Lynmouth flood of August 1952. *Proceedings of the Institution of Civil Engineers,* Z 522-588.:

Gifford, J. 1953. Landslides on Exmoor caused by the storm of 15 August, 1952: *Geography, 38,* 9-17.

Green, G.W. 1955. North Exmoor floods, August 1952. *Bulletin of the Geological Survey of Great Britain,* 7, 68-84.

Kidson, C. 1953. The Exmoor storm and the Lynmouth floods. *Geography, 38,* 1-9.

Marshall, W.N. 1953. The Lynmouth floods *Weather,* 7, 338-342

McClean, W.N. 1953. The Lynmouth flood of 15th August 1952. *Journal of the Institution of Water Engineers,* 7, 157-159.

Read at the Annual Conference of the Ussher Society, January 1982

Loess in Cornwall

J.A. CATT
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J.A. Catt and S.J. Staines, 1982. Loess in Cornwall. *Proc. Ussher Soc., 5,* 368-375.

The distribution of Late Devensian loess in Cornwall and the Scilly Isles is described. Many Cornish soils are silty, but only some of them contain appreciable amounts of loess; others are derived mainly from slates, Detailed particle size analyses and the mineralogical composition of coarse silt fractions of the loess-containing horizons show that it differs from Late Devensian loess in east Devon and other parts of southern England, but probably contains only a little locally-derived aeolian sediment. Most of it was probably blown from glacial outwash deposits in the southern part of the Irish Sea basin.

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Introduction

During the last 2-3 decades soil mapping and research on soil parent materials has demonstrated that thin deposits of windblown silt (loess) are widespread in south and east England (Catt, 1978). In Cornwall they were originally recognised by Coombe *et al.* (1956) on the Lizard peninsula, where they give rise to stagnogley soils (Avery, 1980) characterised by "Short Heath" plant communities *(Agrostis setacea* heath). These contrast with the less acid "Tall Heath" *(Erica vagans - Schoenus* heath), "Rock Heath" *(Festuca ovina - Calluna* heath) and "Mixed Heath" *(Erica vagans Ulex europaeus* heath) communities on soils derived mainly from the serpentine. Further interest in these deposits has recently been aroused by Wintle (1981), who used thermoluminescence techniques to obtain Late Devensian dates for samples from the Lizard, the Scilly Isles and other sites in southern England.

Where loess is thick and in part unweathered, as in some areas of south-east England and many European and Asian countries, it is usually an unbedded pale yellowish brown calcareous silt, sometimes with terrestrial molluscs and carbonate nodules. The particle size distribution (10-15% clay, <10% sand, and a modal silt size in the 20-60μm range) is quite characteristic. However, in areas where the deposit is thin (<lm) and weathered throughout, it is often non-calcareous and more variable in colour and clay content. Thin layers are also prone to disturbance, erosion and reworking, so that mixing with other materials may further modify the colour and particle size distribution. The loess component in such mixed, weathered deposits, which are often equivalent to the topsoil and various subsoil horizons, is then identifiable only by the presence of a small mode in the 20-60μm range and a characteristic mineral assemblage in the same size range. In many parts of south and east England, loess deposited during the Late Devensian has a silt mineral suite related to glacial deposits of the same age in Yorkshire, Lincolnshire and Norfolk (Catt *et al.* 1974, Catt 1978), and beyond the ice limit this assemblage distinguishes the loessial silt from silt of other provenance.

Harrod *et al.* (1973) reported thin loess over various substrata (granite, Devonian limestone, Budleigh Salterton Pebble Beds, Clay-with-flints-and-cherts, and the Haldon Gravels) in east Devon, and equated the deposit with the Late Devensian loess further east. However, compared with the loess in eastern England and the Midlands, the Devon deposits are composed of finer silt that is rich in flaky minerals, a difference which Harrod *et al.* attributed to the winnowing effect of predominantly north-easterly periglacial winds responsible for deposition of the loess. This agreed with the suggest source in glacial outwash deposits in eastern England and on the floor of the North Sea, which would have been dry during the Late Devensian because of the eustatic fall of sea-level. However, it is unlikely that the North Sea basin could have provided all the loess of western Britain and northern France. From their mineralogical studies, Coombe *et al.* concluded that the Lizard loess was derived largely from nearby Hercynian granites, but it is also possible that Devensian outwash deposits in western Britain (e.g. in the Irish Sea basin) provided some of the loess in western areas.

Recent soil mapping in several parts of Cornwall and brief reconnaissance of the Scilly Isles has shown that silt-rich soils are quite widespread. They occur mainly on slates, schists, gneisses, gabbros and granites, and often seem to be derived from thin loess-containing head deposits overlying these solid rocks. However, it would be wrong to assume that all the silty soils contain loess, as physical disintegration *in situ* of many slates and schists could provide abundant silt-sized material. We therefore examined the detailed particle size distribution and silt mineralogy of some of the more silty soils to determine the distribution of Cornish loess more precisely, and also to compare it with the similarly analysed loess from other parts of southern England.

Location of samples

Silty horizons were examined from soils over various rock types on the Lizard peninsula (Ordnance Survey 1:25,000 sheets SW61, SW71, SW72, SW81 and SW82), and in the Hayle (SW53), Penryn (SW73), Falmouth (SW83), St Austell (SX05) and Camelford (SX18) areas, as follows:

1-3. Humic brown podzolic soil (variant of Moor Gate series) at 128m OD on granite at Godolphin Warren (SW 595310); Ah (8-29cm), Bs (29-49cm) and BC (49-85cm) horizons (Staines, 1979, pp.112-3).

4-6. Typical stagnogley soil (Croft Pascoe series) at 80m OD on serpentine of the Lizard plateau, under "Short Heath" vegetation (SW 686150); Ah (2-17cm), Bsg (17-26cm) and Btg (26-71cm) horizons.

7-9. Cambic gley soil (Traboe series) at 76m OD on serpentine of the Lizard plateau, under “Mixed Heath” vegetation (SW 690152); E (16-30cm), 2Bg2 (55-103cm) and 2BCgl (103-126cm) horizons.

10 and 11. Cambic gley soil (Eglos series) at 75m OD on granite-gneiss with serpentine on Lizard plateau (SW 708168); Ap (0-17cm) and Bg (17-29cm) horizons.

12-14. Stagnogleyic argillic brown earth (Gwavas series) at 67m OD on granite-gneiss with serpentine on spur of dissected Lizard plateau (SW 719155), Bw (25-53cm), Bt(g) (95-115cm) and 2BCg (132-150cra) horizons.

15-17: Argillic brown earth (variant of Trusham series) at 94m OD on gabbro, Goonhilly Downs (SW 753195); Eb (27-53cm), Bt(g) (72-124cm) and C (144-176cm) horizons.

18 and 19. Cambic gley soil (Traboe series) at 100m OD on serpentine in shallow valley on Lizard peninsula (SW 732204); Ah (5-13cm) and BCg (67-95cm) horizons.

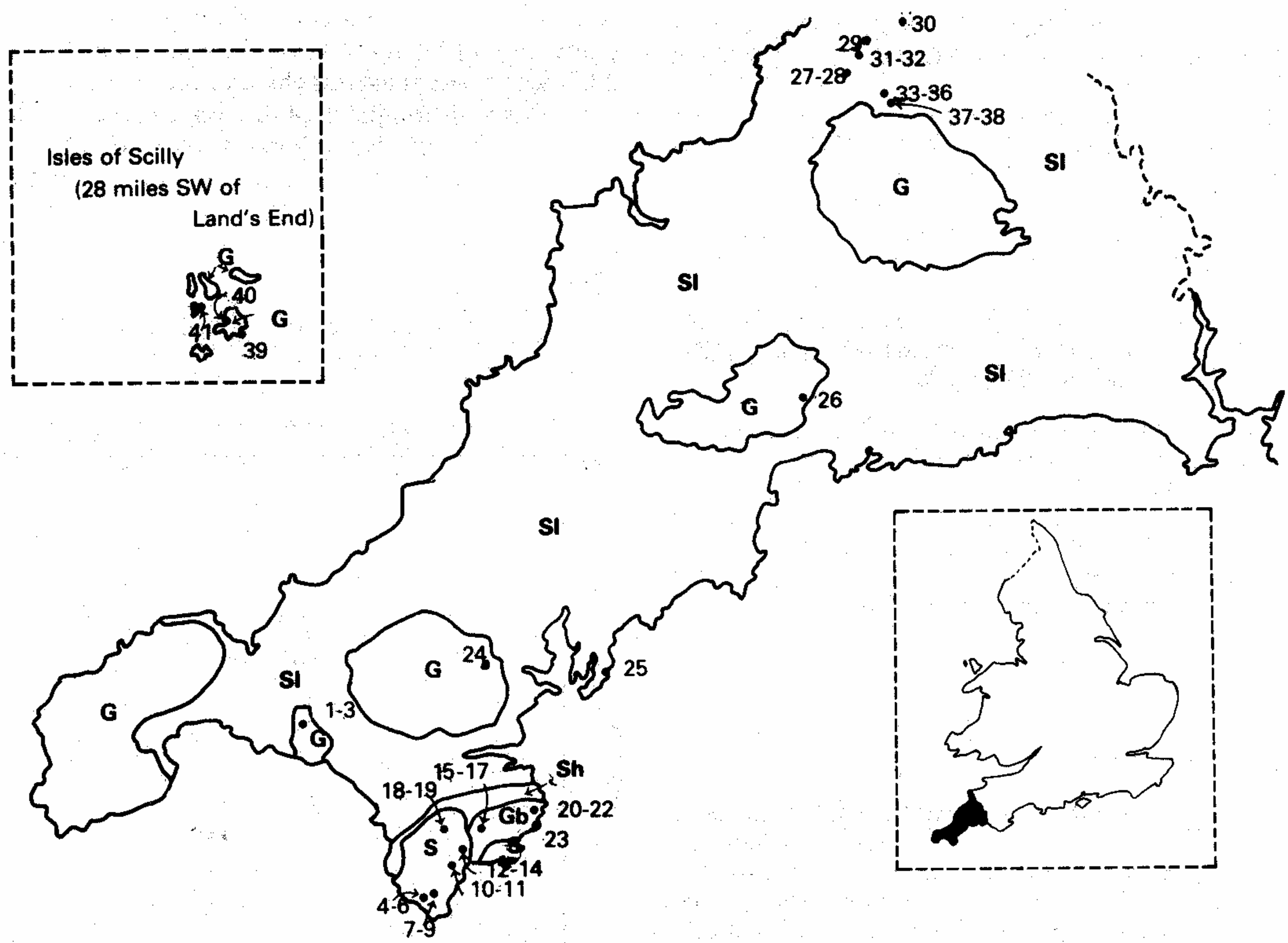

Figure 1. Distribution of loess in Cornwall and the Scilly Isles, and location of analysed samples numbered as in text. Sl = Slates with rare, random patches of thin loess mixed with weathered bedrock. Sh = Schists with rare, random patches of thin loess mixed with weathered bedrock. G = Granites with random patches of loess mixed with weathered bedrock, becoming more abundant westwards and covering approximately two-thirds of the Scilly Isles. Gb = Gabbro with random patches of loess mixed with weathered bedrock. S = Serpentine with thick, almost continuous cover of unmixed loess.

20-22. Typical brown earth (Lesneague series) at 64m OD on hornblende schist on upper valley side above Porthoustock Cove (SW 805220); Ap (0-12cra), Bw2 (32-76cm) and BC (76-120cm) horizons.
23. Typical brown earth (variant of Gwavas series) at 4m OD over raised beach gravels at Lowland Point (SW 803195), Lizard; C horizon (210-220cm). Flint flakes found in the surface horizon near this site were probably Mesolithic.
24. Typical brown podzolic soil (Moretonhampstead series) at 100m OD on granite head at Burnthouse, near Penryn (SW 766369); Bs horizon (40-60cm).
25. Stagnogleyic brown earth at 10m OD on slaty head at Towan Beach (SW 873332) on west side of Gerrans Bay; BC horizons (110-120cm) in frost wedge penetrating head.
26. Typical brown podzolic soil (Moretonhampstead series) at 120m OD on granite head at Great Prideaux, near Luxulyan (SX *057559);* Bs horizon (35-65cm).
27 and 28. Typical brown earth (Highweek series, deep phase) at 240m OD on Upper Devonian slates (SX 101858); Bwl (10-25cm) and BC 1 (45-57cm) horizons (Staines, 1976, pp.34-5).
29. Typical brown earth (Highweek series, deep phase) at 260m OD on Lower Carboniferous slates (SX 119887); Bw horizon (30-59cm) (Staines, 1976, pp.36-7).
30. Typical brown earth (Highweek series) at 230m OD on Lower Carboniferous slates (SX 199884); Bw horizon (12-30cra) (Staines, 1976, pp.35-6).
31 and 32. Gleyic brown earth (Ivybridge series) at 260m OD on Upper Carboniferous slates (SX I 11879); Bwl (10-29cra) and Bg (41-90cm) horizons (Staines, 1976, pp.40-1).
33-36. Ferric stagnopodzol (Hafren series) at 290m OD on Upper Devonian slates (SX 155850); Eg (8-15cm), Bsg (15-28cm), BC1 (28-44cm) and BC2 (44-80cm) horizons (Staines, 1976, pp.57-8).
37 and 38. Ironpan stagnopodzol (Hiraethog series) at 295m OD on Upper Devonian slates (SX 158838); Bsl (15-24cm)and Bs2 (24-39cm) horizons (Staines, 1976, pp.59-61.

The soil classes and horizon nomenclature used are from Avery (1980). In addition three samples from the Scilly Isles were studied: sample 39 was from Heliport Cliff, St Mary's (SV 918101), sample 40 from Porthloo, St Mary's (SV 907115), and sample 41 (kindly donated by Dr A.J. Sutcliffe of the British Museum, Natural History) from East Porth, Sampson (SV 878128). Figure 1 shows the location of all samples.

Analytical methods

Samples were air-dried and gently ground to pass a 2mm mesh, which retained stones >2mm. Particle size analysis at ø intervals (ø = -$\log_2$ grain size in mm) was determined by sieving and the pipette sampling technique after peroxidation to remove organic matter and dispersion by overnight shaking in a dilute solution of sodium hexametaphosphate. Coarse silt fractions (4-6 ø, 63-16 µm) were then separated from the same aqueous suspension by repeated settling under gravity. Each was divided into light and heavy minerals by centrifuging in bromoform (specific gravity 2.9 approximately), and analysed mineralogically with a polarising microscope. Other analytical techniques are those described by Avery and Bascomb (1974).

Results

Particle size distribution

The total silt (4-9 ø, 62-21µm) contents of the 41 samples analysed ranged from 37.7 to 87.4% by weight (oven-dry basis). Six samples, all from the Lizard area, contained >75% silt (samples 4, 5 and 6 from the Croft Pascoe series on serpentine under "Short Heath", sample 7 from the E horizon of the Traboe series on serpentine under "Mixed Heath", sample 13 from the Bt(g) horizon of the Gwavas series on granite-gneiss, and sample 23 from the variant of the Gwavas series on raised beach gravels at Lowland Point), and in each of these the modal size is the 4-5 ø range (usually about 40-44µm), and clay content greatly exceeds sand. In these respects the samples resemble loess from Kent, Belgium (Fig 2), and many other parts of the world.

Sixteen of the samples contained between 60 and 75% silt, and in all but one of these the amounts of clay were <25%, which is approximately the upper limit of clay content in soil horizons derived solely from loess. However, the percentages of sand in these samples ranged from 6.5 to 33.1, which often exceed the amounts normally found in loess. Also, although ten of the sixteen had a modal size in the 4-5 ø range, the others had considerably finer silt modes. It is therefore unlikely that any of these samples are purely loessial in origin; some may contain a little loess, but this is probably mixed with sand from other sources.

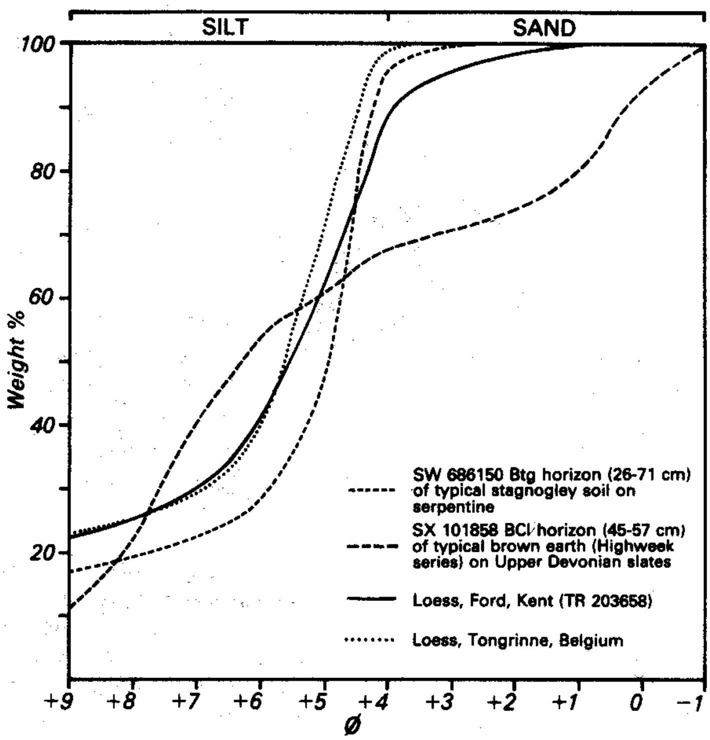

Figure 2. Particle size distribution (cumulative basis) of two silty soils from Cornwall, compared with typical loesses from Kent and Belgium.

The remaining nineteen samples, with silt contents 60%, contained even more sand (up to 50.4%), but no more clay (2.4-29.6%). Eight of these samples had modes in the 4-5 ø silt range, and may contain a little loess. However, in the other eleven the mode was finer (usually in the 7-8 ø, 8-4 m, range) and poorly defined, the silt being spread almost evenly over the five ø units (Fig. 2). These samples are unlikely to contain any loess; as many were from soils on slates, such as the Highweek (samples 27-30), Hafren (samples 35 and 36) and Hiraethog (sample 38) profiles, they are probably composed of weathered slate.

Coarse silt mineralogy

Table 1 gives the mineralogical composition of coarse silt fractions from six of the most silty samples from the Lizard area, all of which have strong modes in the 4-5 ø range, and also of three samples from the Scilly Isles. In the Lizard samples the amounts of quartz, alkali feldspar, flint, muscovite, glauconite, epidote and zoisite are fairly constant; muscovite and glauconite are less common in sample 4, but this is probably because of weathering, as the sample was taken very Close to the surface. In contrast, the other heavy minerals (principally zircon, tourmaline, chlorite, green hornblende, tremolite, yellow rutile and garnet) are more variable in amount. As Coombe *et al.* (1956) pointed out, some of the heavy minerals in the Lizard loess could be derived from local bedrock formations, so the range in amounts of some minerals may reflect local fluctuations in supply of silt from these sources. Coombe et al. recorded epidote in only one of the samples they analysed, but we identified it as a major constituent of the non-opaque heavy fraction of the 4-6 ø silt. They also reported apatite, topaz and bowlingite (fibrous saponite formed by alteration of olivine), which we failed to identify. These analytical inconsistencies may result partly from the different size limits of the fractions analysed (Coombe et al. found these minerals in the 20-200μm fraction, whereas we analysed the 16-63μm fraction only), but they may also indicate further local variation in the mineralogy of the loess.

Compared with the loess in east Devon described by Harrod *et al.* (1973), the Lizard samples generally have more silt-sized epidote, zoisite, zircon, green hornblende, tremolite, rutile, garnet and spinel, but less glauconite, chlorite and biotite (Table 1). The two assemblages are otherwise similar, but neither the westward increase in flaky minerals nor the westward decrease in modal particle size noticed in the loess of south-east England (Harrod *et al.* 1973; Catt, 1978) is continued into Cornwall. The incorporation of local silt minerals in the Cornish loess could have decreased the proportion of flaky minerals, but is unlikely to have changed the particle size distribution of the whole deposit sufficiently to move the mode from 26μm, a (the value for loess on Dartmoor and near Torquay) to 40-44μm. The Lizard loess has recently been dated as Late Devensian, the same age as that in east Kent (Wintle, 1981), so the mineralogical and textural differences cannot result from deposition at different times. Instead they suggest that the Cornish loess was mainly derived from a different source (and possibly a different direction) from the loess in east Devon and other parts of southern England.

Of the three samples from the Scilly Isles, two (40 and 4 I) are similar to the Lizard loess in both silt mineralogy (Table I) and particle size distribution. However, the third (sample 39) is much coarser, with a modal size of 60-65μm, and contains less alkali feldspar but more quartz in its 16-63μm fraction. This suggests that it contains only a small proportion (probably <50%) of loess, which has been mixed with a quartz-rich but feldspar-poor silty fine sand. This second component is unlikely to be derived from local granitic bedrock, which Would yield much feldspar, and is also unlike any of the head or glacial deposits on the islands described by Mitchell and Orme (1967). Its source is therefore unknown, but probably lies outside the islands; this implies that, like the loessial silt component, it was brought by the wind.

Despite some variation in the silt mineral assemblages and possible incorporation of material from Cornish bedrocks, most of the coarse silt cannot be derived from the rocks on which the deposit rests. As Coombe *et al.* (1956) noted, the abundance of quartz, alkali feldspar and some other minerals indicates that the loess of the Lizard is completely unrelated to the serpentine beneath. The mineralogical and particle size similarity of the silt in diverse physiographic situations as far apart as the Lizard and Scilly Isles can only be explained by long distance aeolian transportation. Although it is true that some of the characteristic minerals could have come from the Hercynian granites, there are many other possible sources for them, and the flint, glauconite and microcline (which is a common type of alkali feldspar in all the samples) are certainly from elsewhere. It is unlikely that physical weathering of granite, even by continued frost shattering in periglacial conditions, would produce much silt. As with loess in many other parts of the world, it is therefore more likely that most of the silt was derived from a more distant source than the local Hercynian granite outcrops, for example from glacial outwash on the floor of the Irish Sea.

Distribution of loess in Cornwall and Scilly Isles

All the analysed loess samples from the Lizard area contain approximately the same amounts of quartz and alkali feldspar in their 16-63μm fractions (Table I), and these are similar to the amounts in loess in Devon and other parts of southern England. Few other silty sediments in Cornwall contain even half as much feldspar as the loess, and those that do (some head and colluvial deposits) are probably derived partly from the loess. The only Other widespread pre-Devensian silty sediment in the county is slate, and all the samples of this we have examined contained <1% feldspar in their coarse silt fractions. It is therefore possible to use quartz: feldspar ratios to calculate the approximate amount of loessial coarse silt in mixed soil materials throughout the county.

Soil samples with a coarse silt quartz: feldspar ratio of 8:1 or less (as in the Lizard samples, Table 1) contain 100% loessial coarse silt, ones with a quartz: feldspar ratio of 16:1 contain approximately 50%, ones with a ratio of 32:1 contain only 25%, etc. The minimum percentage of 16-63µm silt in any of the pure loesses is about 50, so the maximum loess content of a mixed sample is no more than twice the amount of loessial coarse silt inferred from the quartz: feldspar ratio. Another reason why the loess percentages should be taken as maxima is that the calculation is based on the assumption that any coarse silt of non-loessial origin contributes quartz but no feldspar. This is never completely true, though we believe that the amounts of feldspar in slates and other Cornish pre-Devensian deposits are small enough to prevent us over-estimating loess contents by more than about 10%. Examination of the heavy silt mineral assemblages provided an additional check on the presence of loess in the samples, but as the slates or other non-loessial silts may have introduced no new heavy minerals, the heavy minerals could not be used alone to calculate loess contents.

Table 2 gives the amounts of loess calculated in this way for each of the 41 samples analysed. This shows that, with the exception of samples 23 and 25, the most loess-rich soils are confined to sites on granite, granite-gneiss and serpentine. At Towan Beach (sample 25) the loess-containing material is confined to a narrow frost-wedge penetrating the upper layers of a thick slaty head, which in turn overlies slates of the (?)Devonian Portscatho Series. Other soils on slates contain no more than 20% loess. The relatively thick loess at Lowland Point (sample 23) seems to be restricted to a small area occupied by the raised beach, which in turn rests on gabbro-troctolite. At the other site on gabbro (Goonhilly Downs), less than half the top 50cm only of the soil is composed of loess.

Among the samples with large or moderate (>35%) amounts of loess, all but two have modes in the 4-5 ø range (Table 2), whereas all but four of the samples with <30% loess have modes in size fractions other than 4-5 ø. Therefore, although particle size analysis at ø intervals is a fairly satisfactory means of identifying the loess, even when it is mixed with other material, some samples

	Sample 4 SW 686150 Ah (2 - 17 cm)	Sample 6 SW 686150 Btg (26 - 71 cm)	Sample 7 SW 690152 E (16 - 30 cm)	Sample 12 SW 719155 Bw (25 - 53 cm)	Sample 13 SW 719155 Bt(g) (95 - 115 cm)	Sample 23 SW 803195 C (210 - 220 cm)	Mean of six Lizard samples	Mean of eight loess samples, east Devon (Harrod *et al.* 1973)	Sample 39 Heliport Cliff St. Mary's, Scilly Isles	Sample 40 Porthloo St. Mary's, Scilly Isles	Sample 41 East Porth Sampson, Scilly Isles
% total silt 4-6 ø (by weight)	60.2	67.8	63.6	54.2	76.0	81.2	67.2	41.0	41.1	49.8	59.9
a) Light minerals											
Quartz %	79.4	81.0	83.0	84.6	83.5	82.7	82.4	81.8	87.3	81.4	78.8
Alkali Feldspar %	16.0	14.0	13.8	12.0	12.5	12.3	13.4	14.0	7.4	14.1	14.0
Flint %	1.1	1.0	0.8	0.3	0.6	1.1	0.8	1.0	0.6	0.8	1.1
Muscovite %	0.8	2.3	2.2	2.2	2.4	2.2	2.0	2.1	2.0	2.1	4.4
Glauconite %	-	1.3	0.1	0.3	0.6	1.7	0.8	1.1	1.1	1.6	1.4
Opal %	2.1	-	-	-	-	-	-	-	-	-	-
b) Non-opaque heavy minerals											
Total %	0.6	0.4	0.1	0.6	0.4	0.4	-	-	1.6	0.2	0.3
Epidote %	35.6	39.0	34.0	33.4	44.6	42.9	38.3	15.5	29.8	31.5	34.0
Zoisite %	2.0	3.4	2.2	1.7	1.9	4.4	2.6	1.1	2.9	2.0	2.8
Zircon %	22.1	16.0	18.7	12.4	15.4	9.5	15.6	7.3	16.1	4.7	8.2
Tourmaline %	11.1	4.2	5.1	3.4	3.3	7.0	5.7	4.7	5.0	2.1	4.2
Chlorite %	1.0	15.5	5.0	8.4	11.7	8.4	8.3	55.0	8.7	26.7	20.0
Biotite %	-	0.3	-	0.3	0.4	1.0	0.3	3.2	0.6	1.8	1.4
Green hornblende %	1.9	8.9	7.6	21.8	12.1	13.0	10.9	4.1	14.4	17.1	17.6
Brown hornblende %	0.1	0.1	0.2	1.1	0.1	1.4	0.5	0.4	0.6	0.4	0.5
Tremolite %	4.8	3.0	11.3	10.5	2.0	4.1	6.0	1.2	1.4	1.7	2.9
Yellow rutile %	7.8	3.5	4.4	2.4	2.7	2.7	3.9	2.3	5.6	4.0	2.7
Brown rutile %	2.6	0.8	1.1	1.4	1.7	0.9	1.4	0.7	1.9	0.8	0.8
Red rutile %	-	0.1	0.2	-	-	-	-	0.1	-	-	-
Anatase %	3.3	1.9	1.7	0.8	2.0	1.4	1.9	1.9	1.8	0.8	0.8
Brookite %	0.3	-	-	0.2	-	-	-	0.3	0.1	0.1	-
Staurolite %	1.5	0.8	0.4	0.1	0.7	0.6	0.7	0.5	0.6	0.6	0.7
Kyanite %	0.4	0.2	0.4	0.2	0.5	0.1	0.3	0.2	0.4	-	0.2
Andalusite %	0.2	-	-	-	-	-	-	-	-	-	-
Garnet %	2.1	2.2	5.0	1.9	0.9	1.8	2.3	1.5	8.8	4.0	4.5
Augite %	0.4	-	0.1	-	-	-	-	-	1.3	0.3	-
Brown spinel %	2.8	0.1	2.6	-	-	-	0.9	-	-	-	-
Sphene %	-	-	-	-	-	0.8	-	-	-	-	-
Monazite %	-	-	-	-	-	-	-	-	-	0.1	-

Table 1. Mineralogical composition of coarse silt (4-6 ~, 63-16 m) fractions from six loess samples from the Lizard area and three from the Scilly Isles, compared with the loess in east Devon. Light minerals are given as percentages of the coarse silt fraction, heavy minerals as percentages of the non-opaque heavy fraction, both based on counts of approximately 1000 grains.

Sample number	National Grid Reference	Sample depth (cm)	Nature of bedrock at site	Modal size range(ø)	% Coarse silt (6-4ø) (by weight)	Estimated maximum loess % in sample
1	SW 595310	8-29	granite	4-5	32	65
2	"	29-49	"	4-5	42	60
3	"	49-85	"	4-5	55	25
4	SW 686150	2-17	serpentine	4-5	60	100
5	"	17-26	"	4-5	58	80
6	"	26-71	"	4-5	68	100
7	SW 690152	16-30	"	4-5	64	100
8	"	55-103	"	5-6	33	40
9	"	103-126	"	5-6	24	15
10	SW 708168	0-17	granite-gneiss	4-5	35	35
11	"	17-29	"	4-5	32	30
12	SW 719155	29-53	"	4-5	54	100
13	"	95-115	"	4-5	76	100
14	"	132-150	"	3-4	24	0
15	SW 753195	27-53	gabbro	4-5	30	40
16	"	72-124	"	6-7	19	0
17	"	144-176	"	5-6	30	0
18	SW 732204	5-13	serpentine	4-5	44	80
19	"	67-95	"	6-7	14	0
20	SW 805220	0-12	hornblende schist	4-5	30	10
21	"	32-76	"	5-6	35	5
22	"	76-120	"	0-1	26	0
23	SW 803195	210-220	gabbro	4-5	81	100
24	SW 766369	40-60	granite	4-5	40	60
25	SW 873332	110-120	Devonian slates	4-5	41	60
26	SX 057559	35-65	granite	4-5	30	60
27	SX 101858	10-25	Upper Devonian slates	7-8	16	5
28	"	45-57	"	7-8	14	0
29	SX 119887	30-59	Lower Carboniferous slates	0-1	12	10
30	SX 199884	12-30	"	8-9	12	0
31	SX 111979	10-29	Upper Carboniferous slates	6-7	23	10
32	"	41-90	"	6-7	33	10
33	SX 155850	8-15	Upper Devonian slates	7-8	25	20
34	"	15-28	"	7-8	23	5
35	"	28-44	"	6-7	20	20
36	"	44-80	"	6-7	19	5
37	SX 158838	15-24	"	4-5	30	5
38	"	24-39	"	5-6	26	0
39	SV 918101	-	granite	3-4	41	35
40	SV 907115	-	"	4-5	50	100
41	SV 878128	-	"	4-5	60	100

Table 2. Loess contents of silty soils in Cornwall and the Isles of Scilly, based on amounts of coarse silt (4-6 ø, 63-16μm and the quartz/feldspar ratio in this fraction.

incorporating other silty or fine sandy components may contain as much as 40% loess without showing the characteristic coarse silt mode.

Combining the information in Table 2 with field observations made during the recent 1:250,000 soil survey of Cornwall and during 1:25,000 surveys of the Camelford, Hayle and Lizard districts (Staines, 1976, 1979, in press), it is possible to show the occurrence of loess throughout the county with some confidence (Fig. 1). Although many soils on the Devonian and Carboniferous slates are very silty, the results shown in Table 2suggest that only a little of this is loessial in origin. Most was probably derived from weathering of the slates. The only field evidence for loess on the slates is the occasional random occurrence of local stoneless silty subsoil layers, which mainly occur in south Cornwall, and the silt-filled wedge at Towan Beach. If a more continuous layer of loess originally covered these rocks, most of it has been removed by erosion. However, there is little evidence inland of reworked loess on footslopes or in valley and basin sites.

On the main Hercynian granite outcrops loess is much more widespread. Stoneless silt loam horizons composed largely of loess are common on the western granites of Lands End and the Scilly Isles (Table 3), but on granite further east its presence is indicated mainly by somewhat less silty soil horizons (mixtures of loess and granite head). Loess covers approximately two-thirds of the Scilly Isles granite outcrop, and 16-22% of the mainland granite outcrops. It is found mainly on flat sites, usually on the well-developed outcrops. It is found mainly on flat (?)marine planation surfaces. On Lands End most of the silty soils lie south and east of the higher ground (Fig. 3), suggesting it was derived from the north-west, as loess is often preferentially deposited on the lee side of obstacles. On the Scilly Isles the loess-rich silt loam horizons are confined to flat, relatively sheltered sites where there is little evidence of reworking. The deposit here generally overlies the main granite head, and shows only minor disturbance near the surface, where thin stony layers often occur. This suggests the loess was deposited here after the last main phase of gelifluction, and that is subsequently suffered little erosion.

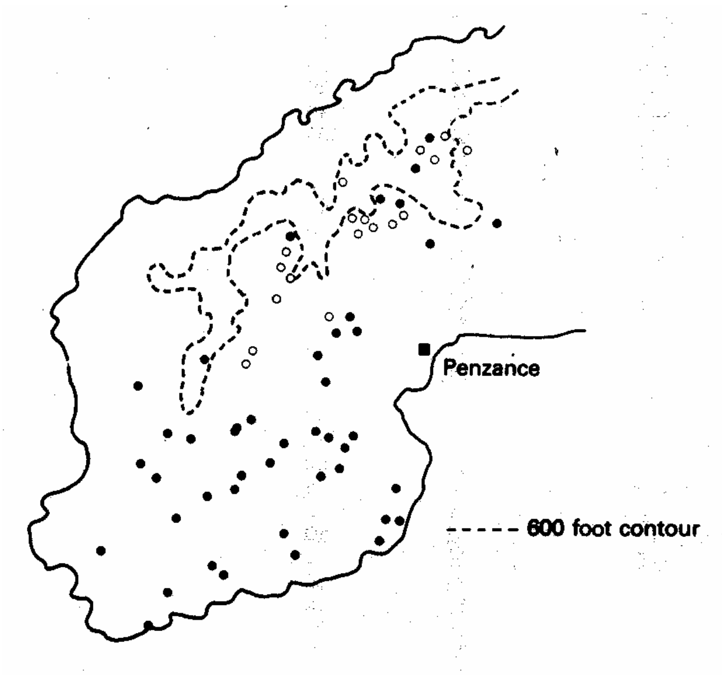

Figure 3. Sites on the Lands End peninsula where loess-rich loam horizons (closed circles) and less silty loessial horizons (open circles) were identified during soil mapping.

The most continuous loess deposits in Cornwall occur on the Lizard peninsula, where they are again mainly confined to the fiat planation surfaces. The thickest deposits (usually 0.5-1.5m, but locally up to 2.5m) are on the serpentine outcrop, where they form a nearly continuous mantle. There is little evidence of mixing with serpentine-derived material except on sloping sites near streams. Deposits on the gabbro and granite gneiss are generally thinner and less continuous.

Discussion and Conclusions

The different modal particle size and heavy silt minerals of the Late Devensian loess in Cornwall and the Scilly Isles compared with that elsewhere in southern England suggest the two are derived at least partly from different sources. As Coombe *et al.* (1956) noted, some of the silt minerals in the Cornish loess could come from local igneous rocks, such as the Hercynian granites, and the slight mineralogical variation of the loess from site to site could then be explained by irregular incorporation of locally derived aeolian material. However, it is unlikely

Table 3. Proportion of soils assessed to have loessial additions on the Cornish Hercynian Granites (observations made during 1:250,000 soil survey of Cornwall).

	%of soils with minor accumu-lations of silt	% soils with one or more stoneless silt loam horizons	Total No of obser-vations
Scilly Isles	3	61	72
Lands End Granite	10	12	339
Carnmenellis/Godolphin Granite	14	4	330
St Austell Granite	16	0	113

that more than a few per cent of the silt came from local rocks. As in eastern England (Cart 1978) and many other parts of the world, most of the loess in Cornwall and the Scilly Isles was probably derived from glacial outwash deposits. The most likely area of extensive Late Devensian outwash deposits that could have supplied loess to Cornwall was in the Irish Sea basin. The concentration of the loess in southern parts of Cornwall in the lee of higher ground, particularly on the Lands End peninsula, agrees with derivation from this direction (i.e. from N-NW), but mineralogical comparisons with Devensian glacial deposits in the Irish Sea area have yet to be made.

However, aeolian deposition in the lee of obstacles, such as the scarp-like hills of northern Penwith, does not account entirely for the observed distribution of loess in Cornwall. As in the Midlands and northern England (Catt, 1978), there is a definite correlation with bedrock type, the Cornish loess residing preferentially on serpentine and to a lesser extent on granites and gabbros, but hardly at all on schists and slates. Originally it must have been deposited more evenly than this, implying that the surfaces of some bedrock types were contemporaneously or subsequently subject to more intensive erosion than others. As the most continuous loess remnants occur on flat plateaux, and intervening slopes are often devoid of loess, the erosion must have been principally by mass movement on slopes.

Elsewhere in England much local downslope movement (colluviation) of loess resulted from Neolithic and later deforestation and agriculture, but the secondary loessial accumulations in valley, basin and footslope sites on the Cornish slates and schists are too small to account for much of the loess that would have fallen on the extensive outcrops of these rocks. Most was probably transported much further, and either Devensian gelifluction or late Flandrian surface run-off and streamflow could have transferred it into the sea. The present drainage density (stream length per unit area), estimated from large scale Ordnance Survey maps, is approximately 1.5 times greater in areas of slate bedrock than on serpentine and granite, so late Flandrian removal of material could have been slightly more rapid from the slate areas. However, most Neolithic and Bronze Age occupation sites in Cornwall occur on the granites, on the Lizard peninsula and in some coastal areas. It is only since the Iron Age that slate areas have been extensively settled, and even then the extent of cultivation was much less than in eastern England. This suggests *that* late *Flandrian* colluviation was less important than Devensian gelifluction in removing loess from the slate areas.

The ?Mesolithic flints in upper horizons of the loess profile at Lowland Point suggest that deposition here had ceased long before the late Flandrian. Patches of similar raised beach capped by loess and other aeolian sediments, often with an intervening head deposit, are common along the south Cornish coast (James, 1968, 1975) and on the Scilly Isles. However, most of the loess in such sites is either the original wind-deposited sediment or penecontemporaneously geliflucted material from nearby coastal slopes. It is not relevant to the problem of loess distribution inland, as loess eroded from the widespread slate outcrops should now occur mainly in marine and estuarine sediments well below present low tide level.

From the thickness and distribution of head deposits in Devon, Waters (1971) concluded that gelifluction removed material more efficiently from slate and sandstone outcrops than from the Dartmoor granite. This is probably because in periglacial areas ground ice accumulates more readily, and closer to the surface, in fine grained materials, including shales, than in much coarser sediments or massive bedrock (Zoltai and Pettapiece, 1973). As most of the loess on the Cornish granites and serpentine occurs on flat surfaces as a fairly distinct layer above the head deposits, there was less cryoturbation in such situations during or after loess deposition than on the shales, where any remaining loess is preserved in wedges or incorporated into patches of head. As in Devon, this implies less ground ice on massive bedrock like granite and serpentine, and consequently less gelifluction. The preferential removal of loess from Cornish slate areas thus probably dates mainly from the Late Devensian.

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References

Avery, B.W. 1980. Soil Classification for England and Wales (Higher Categories). *Soil Surv. Tech. Monograph 14,* 67pp.

Avery, B.W. and Bascomb, C.L. 1974. Soil Survey Laboratory Methods. *Soil Survey Technical Monograph 6,* 83pp.

Catt, J.A. 1978. The contribution of loess to soils in lowland Britain. pp. 12-20 *In:* J.G. Evans and S. Limbrey (eds.) *The Effect on the Landscape: the Lowland Zone.* Council for British Archaeology Research Report 21.

Catt, J.A., Weir, A.H. and Madgett, P.A. 1974. The loess of eastern Yorkshire and Lincolnshire. *Proc. Yorks. Geol. Soc. 40,* 23-39.

Coombe, D.E, Frost, L.C., Le Bas, M. and Watters, W. 1956. The nature and origin of the soils over the Cornish serpentine. *J. Ecol. 44,* 605-615.

Harrod, T.R., Catt, J.A. and Weir, A,H. 1973. Loess in Devon. *Proc. Ussher Soc. 2,* 554-564.

James, H.C.L. 1968. Aspects of the raised beaches of south Cornwall. *Proc. Ussher Soc. 2,* 55-56.

James, H.C.L. 1975. A Pleistocene section at Gunwalloe fishing cove, Lizard Peninsula. *Proc. Ussher Soc. 3,* 294-298.

Mitchell, G.F. and Orme, A.R. 1967. The Pleistocene deposits of the Isles of Scilly. *Quart. J. Geol. Soc. Lond. 123,* 59-92.

Staines, S.J. 1976. Soils in Cornwall I Sheet SX 18 (Camelford). *Soil Survey Record 34,* 148pp.

Staines, S.J. 1979. Soils in Cornwall II Sheet SW 53 (Hayle). *Soil Survey Record 57,* 198pp.

Waters, R.S. 1971. The significance of Quaternary events for the landform of south-west England. pp. 23-31 *In:* K.J. Gregory and W.L.D. Ravenhill (eds.) *Exeter Essays in Geography.* Univ. Exeter.

Wintle, A.G. 1981. Thermoluminescence dating of late Devensian loesses in southern England. *Nature, Lond. 289,* 479-480.

Zoltai, S.C. and Pettapiece, W.W. 1973. Terrain, vegetation and permafrost relationships, northern Mackenzie Valley and Yukon. *Environmental Social Committee Northern Pipelines. Task Force on Northern Oil Development Report* 73-4.

Aspects of the geochemistry of bismuth in south-west England

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Bi concentrations in south-west England granites are almost two orders of magnitude higher than those in world average estimates. The element is further concentrated during tourmalinisation but is unaffected by greisening and haematisation. Kaolinisation reduces the Bi content of the granites. In granitic cusps, very high levels of Bi occur associated with high tourmaline concentrations. A high degree of primary dispersion is observed around orebodies and, more importantly, many granite bodies are surrounded by such zones of metasomatic Bi enrichment. Soil Bi levels reflect the composition of the underlying rock, and soil geochemical surveys for Bi could be valuable in the search for lodes and granite cusps with which ore bodies are often associated.

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Introduction

Bismuth (atomic number 83, atomic mass 209) occupies a position in group Vb of the periodic table, which it shares with As, Sb and P. Crystallochemically it is closely related to As and Sb as well as to Pb (Bi^{3+} has an identical electronic structure to Pb^{2+}). Because of its generally low tenor in rocks and the difficulty of determining such low values by commonly used multi-element geochemical methods such as optical emission spectrometry and X-ray fluorescence spectrometry (XRFS), Bi determinations are seldom quoted in rock analyses. However, the rocks of south-west England, especially the granitic rocks, give values of Bi which are substantially above world averages and many values can thus be determined by XRFS, providing an unusual range of data from which reasonable deductions can be drawn about the general geochemistry of Bi.

Crystallochemical considerations
The main Bi minerals are as follows:-
(i) Metallic bismuth and rarer alloys with Ag and Au, mostly in massive form but occasionally as trigonal crystals.
(ii) Sulphides, selenides and tellurides of which bismuthinite (Bi_2S_3) is the most common.
(iii) Oxides, oxysalts etc, which generally occur as weathering products. The mineral russellite, with a composition close to Bi_2O_3, WO_3, is an isomorphous mixture of oxides, not a bismuth tungstate. Isomorphic replacement of As by Bi is unknown and of Sb by Bi is possible but rare. Occasionally there is coupled substitution of Pb and Cu for Bi giving rise to an isomorphous series such as bismuthinite-aikinite.

Bi shows distinctive chalcophilic tendency, mostly confirmed by its concentration in troilite phases of meteorites and its behaviour in ore mineral paragenetic studies. It can also exhibit a marked lithophilic tendency. Bi^{3+} is a relatively large cation (ionic radius i.r. = 1.16A) and in silicates a possible Bi^{3+} - Ca^{2+} (i.r. = 1.01A) substitution has been proposed. Brook and Ahrens (1961) found evidence of Bi concentration in early formed plagioclase-rich rocks and some concentration in apatites had been observed earlier by Goldschmidt (1954). Gurney and Ahrens (1969) confirmed high Bi in apatites but conceded the possibility that the Bi could have been contained in sulphide inclusions.

The possibility of diadochous replacement of rare earth elements (REE^{3+} i.r. = 0.9-1.01) by Bi^{3+} was suspected and investigated by Golschmidt (1954) and by Gurney and Ahrens (1969). Greenland, Gottfried and Campbell (1973) deduced that, according to the geochemical behaviour of Bi in three differentiated igneous rock suites, most of the Bi was contained in a minor mineral form (possibly sulphide) only trace amounts being in Ca minerals such as sphene and apatite.

Analytical Methods
X-ray fluorescence spectrometry was used throughout for the analysis of samples from south-west England. A rapid technique providing a detection limit of 4-7ppn. with a Siemens VRS spectrometer and an Mo tube was used mainly for the analysis of soils. For rock determinations a more sensitive procedure was employed, using a Philips 1450/10 AHP and Mo tube. In both cases, determinations were carried out on a minus

300 mesh material compressed into a disc with elvacite as a binder. Few rock reference standards are suitable for checking analysis at these concentration levels. Some indication of accuracy can be achieved by "spiking" methods and by comparison with other analytical procedures. In the range 10-180ppm product movement correlation coefficients of 0.958 and 0.956 were obtained in relation to atomic absorption and direct reading optical spectrometric determinations respectively. The detection limit of less than 2ppm is based on a signal above 3 x s.d. of background.

Bi Behaviour of Hydrothermal Systems

Bismuth sulphides are widely distributed in hydro-thermal systems, usually in pyro-metasomatic deposits associated with granite contacts with limestone and in hydrothermal veins. In the Cornubian province, Bi occurs chiefly as native metal and bismuthinite. Dines (1956) considered that the native bismuth was a weathering product of bismuthinite. Bi metal occurs mainly in the lower-temperature “cross-courses” but also in high-temperature early lodes of normal trend. In the latter case the mode of occurrence is often unknown since it is usually detected, as small particles only, in sand table and jig concentrates. The sulphide occurs in lodes, often lining vughs as at Fowey Console, St Austell, but more frequently in cross-courses associated with Co and Ni ores and often with Ag and U. Dines (1956) noted that only four mines recorded Bi output:-

(i) Wheal Owles in St Just district where Bi occurred in association with U and argentiferous galena in cross-courses to lodes trending SE-NW;
(ii) Dolcoath, Camborne district;
(iii) East Pool and Agar, Camborne district; both recording Bi production but with no record of provenance or association;
(iv) Dowgas, St Austell district, which produced bismuth and bismuthinite with an uncertain association. However, in this mine Ni ores were recorded as occurring in cross-courses and examination of mine dump material shows an association of Bi and Ni ores.

Other minor occurrences are noted at the Restormel Iron Lode where bismuth and bismuthinite occur in association with pyrolusite, goethite, barite and secondary uranium minerals. Further occurrences in low temperature lodes are at Rosewarne and Herland where Bi occurs with arsenopyrite, galena, cobaltite, smaltite, cerargyrite, pyrargyrite and silver in a cross-course. Also at Trenwith and the adjoining St Ives Consols where bismuth occurs in a complex Sn lode in which pitch-blende, molybdenite, galena and sphalerite are late arrivals. At Kingswood, Devon, bismuth and bismuthinite occur with pitchblende and Ni and Co minerals Traces of Bi minerals also occur in the South Terras uranium mine.

As at Wheal Trenwith Bi minerals were deposited late in the Fowey Consols Cu/Sn lode where bismuthinite crystals line vughs in the main lode. Three lodes in the Lanescot section carried bismuthinite in addition to copper ores, cassiterite, sphalerite, calamine, and silver ores.

In other Sn/W deposits bismuth carbonate has been recorded in the Cornubia tin mine at Roche while in the Castle an Dinas tungsten mine Bi metal, bismuthinite and russellite have all been detected (Hey, Bannister and Russell, 1938). Minor amounts of Bi in high temperature stockworks are recorded in the Cligga Head and Hemerdon Mines, in greisen-bordered veins and disseminations into wall rock close to the veins. Table concentrates at South Crofty and Geevor tin mines contained native bismuth (Darnley *et al.* 1965) while Hoskings (pers. comm.) has found bismuthinite in quartz enclosed vughs in the South Crofty lodes. Table 1 summarises the occurrences of Bi minerals.

In general, therefore, although small quantities frequently occur in high-temperature early lodes, Bi minerals form considerable concentrations in the much later and lower-temperature cross-courses. This behaviour largely mirrors that of uranium, with which Bi sometimes occurs.

There is a paucity of descriptive data concerning Bi minerals in high temperature lodes in south-west England. Very few mines are now accessible and consequently few modern mineralogical paragenetic studies have been possible. The records of occurrences arising from IGS work are the incidental result of studies of uranium ore mineral paragenesis, and since pitchblende deposits are located mainly in complex cross-courses, sampling is not comprehensive. Although Dines (1956) sometimes records very complete mineralogical data, it is clear that Bi occurs in concentrations which are too low to have been identified by his methods. For instance, in the Hemerdon orebody, Bi is present at a level of a few tens of ppm and consequently very difficult to recognise and assign to a mineral phase. At the Castle an Dinas mine, in spite of abundant bismuth, bismuthinite and russellite being recorded from the separating tables, a detailed examination of the stopes failed to record any Bi minerals in situ (Hey *et al.* 1938). It is therefore very probable that Bi is very much more widespread in the high-temperature lodes of Sn and W than previously suspected. No occurrences of Bi have been recorded in low temperature “cross courses” of simple mineralogy such as in the Menheniott and Bere Alston areas.

Mine or Locality	NGR	Mineral and Association	Source	
Botallack	SW 365 333	Bismuth, As, Co, Bi, U	MacAlister	1907
Buller	SW 700 395	Bismuthinite	MacAlister	1907
Castle an Dinas	SW 946 627	Bismuth, bismuthinite, russellite	Hey et al	1938
Cornubia	SW 994 595	Carbonate probably bismutite	Hey et al	1938
Dolcoath	SW 658 444	Bismuth, As, Co, Fluorite	Pearce	1978
East Pool & Agar	SW 672 416	Ni, Co	Dines	1956
Fowey Consols	SX 087 558	Bismuthinite, Cu, Fe	Dines	1956
Geevor	SW 372 348	Table concentrate, bismuth	Darnley et al	1965
Great Dowgas	SW 965 513	Bismuth, bismuthinite	Dines	1956
Kingswood	SX 705 665	Bismuth, galena, pitch-blende	Darnley et al	1965
Levant	SW 371 348	As	Stein	1952
Owles	SW 367 324	U ore	Dines	1956
Restormel	SX 101 609	Bismuth, bismuthinite, Fe, Ba, U	Dines	1956
Rosewarne & Herland	SW 595 370	Bismuth, As, Pb, Co, Sb, Ag	Dines	1956
St. Ives Consols	SW 514 400	Bismuth, U, Mo, Pb, Zn	Dines	1956
South Crofty	SW 672 414	Table concentrate,	Darnley et al	1965
South Terras	SW 935 499	Bismuth	Dines	1956
Speed	SW 523 387	Bismuth, Cu, Fe, U, pitch.	-	-
Tranack	SW 655 295			
Trenwith	SW 515 400	Bismuth, U, No, Pb, Zn	Dines	1956
Trugo	SW 895 607	Ni, Co	Hey et al	1938

Table 1. Bi occurrences south-west England

Bi in Granites

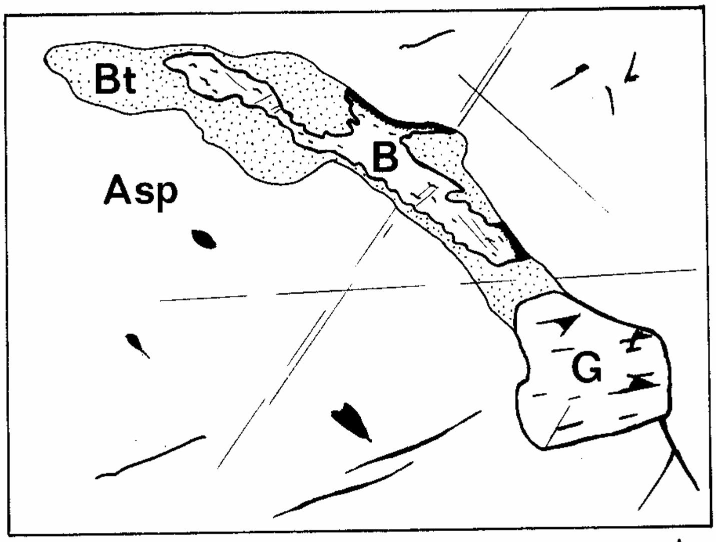
There is strong evidence that Bi, as well as being chalcophite, is concentrated in granitic magmas and their residual solutions and pegmatites, a result of difficulty in achieving diadochous replacement in the major constituent minerals (Goldschmidt, 1954). Greenland, Gottfried and Campbell (1973) showed that Bi was enriched in the later acid members of two batholithic differentiation series (Southern California and Idaho batholith). Although basic and acid rocks show a considerable overlap of values (Brooks and Ahrens, 1961) acid rocks are generally higher in Bi than average basic rocks (Marowsky and Wedepohl, 1971; Heinrich, Schulz-Dobrick and Wedepohl, 1980). Marowsky and Wedepohl (1971) analysed Hercynian granites from the Schwarzwald and Harz areas and obtained a mean of 0.065 ppm Bi. Heinrichs *et al.* (1980) obtained values ranging 0.03-0.68 ppm Bi with higher concentration in greisens (ca 5ppm).

In the Cornubian Bosworgey granite cusp Ball and Basham (in press) reported high values of Bi in the marginal zones of the cupola. They concluded that, although these higher values were in rocks which were commonly greisened, the high Bi occurred specifically in rocks which contained high concentrations of sulphides genetically independent of the greisening episode but possibly related to the introduction of tourmaline. An intergrowth of native bismuth and bismuthinite was recognised as the most important host for Bi, the two minerals being common as inclusions in arsenopyrite (Fig. 1).

Subsequent analyses have shown that high levels of Bi are also common in the main body granite rocks of the area. Concentrations are sufficiently high to provide a reasonable estimate of the Bi concentration in the granitic rocks despite many values being below the detection limit of the analytical method used.

Most of the sampling was conducted over the Land's End and Carnmenellis granites using unweathered specimens taken from mines, quarries and boreholes. Sampling from other plutons although more dispersed, generally attests to the validity of the conclusions.

Figure 2 shows a cumulative frequency-logarithmic probability plot for the analyses of samples from the Land's End and Carnmenellis plutons. The straight line indicates a large single population of values, lognormally distributed, with the possibility of another population with an inflection point at about 26ppm. There is some uncertainty about the exact position of the line but it would appear that the median can be located between 1 and 2ppm which is substantially higher by almost two orders of magnitude than other published values for granite.



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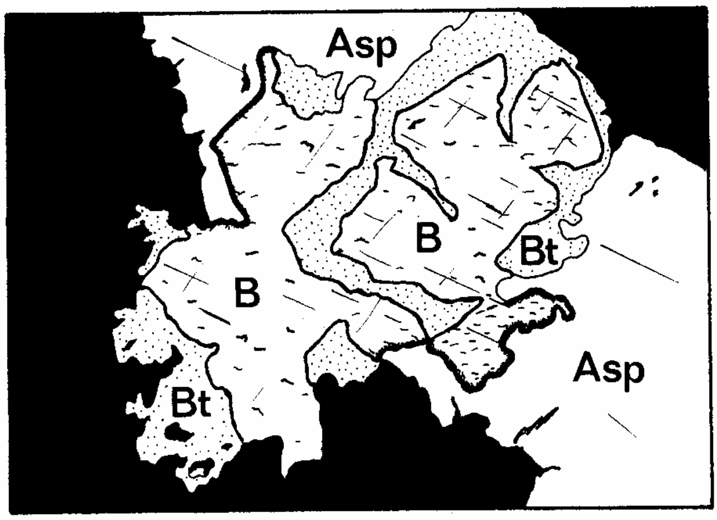

B

Figure 1. Drawings from photomicrographs, taken in reflected light, showing the textural relationships among native bismuth (B), bismuthinite (Bt), galena (G) and arsenopyrite (Asp) in granite from the Bosworgey Cusp. Black areas in 1B are quartz. The droplet or bleb-like form Of the native bismuth included in arsenopyrite is shown in 1A. Both figures show the partial replacement of bismuth by bismuthinite.
Scale of drawings 1A-field width = 0.3mm; 1B-field width = 1.0mm.

Granite Alteration

Several sequences of granite alteration have been studied and the Bi concentrations are given in Table 2. The types of alteration which have been studied are tourmalinisa-tion and greisenisation, which occur at high temperatures followed by haematitisation and kaolinisation which are lower temperature and oxidative phenomena (Hosking, 1969; Beer, 1978). Tourmalisation may predate greisenisation but often post dates it. Difficulties of interpreting the effects of different alteration processes arise from the existence in some areas of more than one style of alteration. The data are given for samples in which only one form of alteration is observed. The median for

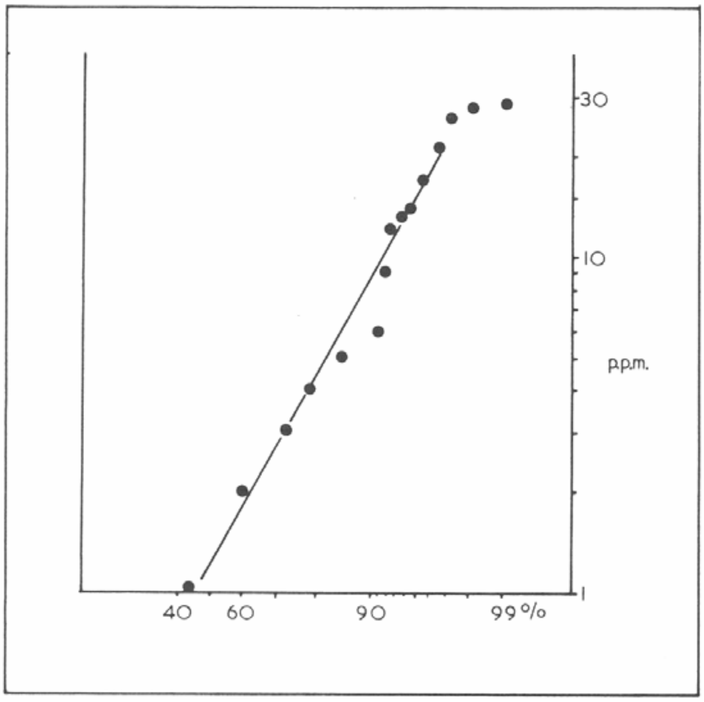

Figure 2. Logarithmic-cumulative frequency plot for Bi determinations in granite samples from the Carnmenellis and Lands End granites

normal granites emerges at 1.22ppm which is statistically indistinguishable from the 1.79ppm obtained for greisenised rock. The tourmalinised rocks were divided into two classes based. On the presence or absence of visible sulphides inhand specimens. Both classes contain high values of Bi (4.7 and 6ppm) and are statistically indistinguishable from the other. Haematitisation does not result in any detectable change in the concentration of Bi, a mean of 1.3ppm (s.d. 1.41) being obtained for 10 samples with a range from n-d to 4ppm.

A very limited study indicates that kaolinisation, at least of lithionite-bearing granite, can result in the mobilisation of Bi, probably as the result of oxidation of metal and sulphide. (Table 3).

	Number	Median	Standard Deviation
Fresh Granite	15	1.22	0.8
Greisened Granite	35	1.79	1.7
Tourmalinised Granite	8	6	9.1
Tourmalinised Granite with Sulphide	6	4.7	4.5
Haematitised Granite	10	1.3	1.4

Table 2 Bi concentrations in fresh and altered coarse granite

	Bi	Al_2O_3
1	n.d.	26.6
2	n.d.	23
3	n.d.	15.6
4	2	16.2
5	12	18.9

Table 3 Bi concentrations in samples from the Goonbarrow China Clay Pit showing the effects of kaolinisation upon the lithionite granite. The degree of visible kaolinisation decreases from 1-5.

Granitic Cusps

The smaller cusps which rise above the main batholith (Bott, Day, Masson Smith, 1959) carry considerable concentrations of both B, in the form of tourmaline, and Bi as bismuth/bismuthinite aggregates. In the Bosworgey cusp (NGR SW 581 337) nine samples of tourmalinised granite gave a mean value of 91ppm (s.d. 57.5, range 45-219) compared with 5 samples of the fresh granite where tourmaline was low but not absent, which gave a mean of 6.2 and range from not detectable to 31ppm. In the heavily mineralised section of the Hemerdon cusp, values of 138, 36, 33, 26ppm Bi were obtained, while one determination from the unmineralised part showed a concentration of only 2ppm.

Sedimentary and Metasedimentary Rocks

Sedimentary rocks usually contain higher concentrations of Bi than do igneous rocks. Values obtained for non-calcareous shales and greywackes are similar, at about 0.5ppm Bi (Marowsky and Wedepohl, 1971). These authors also concluded, from chemical considerations that Bi was generally higher in the clay fraction, but that organic material also tended to concentrate Bi to a great extent. Pelagic clay values were generally about 1ppm, which agrees with the present authors' values for the Mylor slate near Hayle, Cornwall.

Marowsky and Wedpohl (1971) presented the results of a study of Bi in one stratigraphical unit suffering progressive regional metamorphism, from a marly shale to a high amphibolite facies schist. The effect of the rising temperature was an enormous loss of Bi (along with Hg and Cd) from the original sedimentary rock by a factor of 5-6. Such high grade rocks are not typically found in south-west England but equivalent temperatures could be characteristic of the inner zones of the metamorphic aureoles surrounding the granites. However such rocks can be shown to be typically highly enriched in Bi. Thirteen samples of rocks within 0.5km of the Hemerdon granite cusp gave a mean of 35ppm Bi (s.d. 24.1, range 4-85ppm). Similar high values were obtained around the Bosworgey cusp but not close to the granite, where Bi was not detectable within 150m of the contact, The maximum values occur at about 200m from the contact (ranging 7-120ppm) thereafter slowly reducing to about 4ppm Bi at 500 to 600m and to values near the mean for shales at 1km.

In the Hemerdon aureole high Bi values are probably related in part to post emplacement mineralisation resulting in the small veins which carry wolframite. Such an association is not indicated for the Bosworgey Cusp however. The possibility that Bi could be leached from the external sedimentary pile and redeposited in the aureole is not supported by the admittedly sparse data from unaltered sediments and also by vapour chemical considerations. Whatever the ultimate source of the Bi, locally emanation of Bi from the granite is considered to be the cause of the distribution pattern and high values of Bi are suspected to be the norm around most granites (see observations on soils). The Castle an Dinas plug and the periphery of part of the Dartmoor granite, at least, show evidence for such Bi metasomatism.

The vaporisation of an element depends upon the vapour pressure of its compounds, on the nature of the gaseous phase and on temperature. Krauskopf (1957) calculated that, with the dissociation of Bi_2S_3 at 600°C and with 10^3atm. H_20 and $l0^{-6}$atm. S_2,in the gaseous phase, there could be an appreciable amount of Bi in the gaseous phase. Marowsky and Wedepohl (1971) concluded that the major proportion of Bi in sedimentary rocks occurred as the sulphide and our observations show that in granites the main minerals are bismuthinite and native bismuth. Under the pressure and temperature conditions of granite emplacement a high concentration of Bi in the vapour phase of granites and aureole is therefore predicted with a movement of Bi down a thermal and to a less extent concentration gradient. Higher concentrations of Bi in the aureole than in the granite are therefore suspected and are indeed observed. In the Bosworgey aureole the inner part is depleted in Bi as a result of the higher temperature found here, a zone of high Bi concentration being located at about 200m from the contact.

Aspects of the geochemical cycle

The Bi concentration in soils overlying rocks containing measurable concentrations of Bi reflects reasonably accurately the concentration in the underlying rocks. In the Hemerdon area soils (brown earths) overlying the mineralised granite (see above) gave a mean of 68ppm Bi within a range of 19-320ppm for 9 determinations. The slates from the inner part of the aureole within 300m of the contact have a mean of 35ppm, with a range of 4-85ppm, while soils overlying this zone averaged 29ppm, with range of 13-75ppm. At a distance of 1km, the concentration in soils was reduced to a mean of 15 in a range of 5-20ppm. Similar values were obtained in soils over the inner aureole of the Castle an Dinas granite (mean 32, range 18-65ppm 36 determinations) and even higher values were recorded in soils overlying the sub outcrop of the N-S trending W/As lode (typically 160ppm over the lode).

74 samples of soils (mainly brown earths) collected from various sites around the southwest quadrant of the Dartmoor granite, and over a distance extending from 0.5 to 2km from the mapped surface contact, gave a mean of 11ppm ranging n.d. - 22ppm.

Conclusions

The average concentration of Bi in south-west England granites (1-2ppm) is substantially greater than the world mean granite level (ca 0.05ppm). The Cornubian granites could thus be regarded equally as forming a Bi province as a Sn province, since Sn values have been enhanced by a factor of only ten (4-40ppm). Of the alterations of the granite that have been studied (tourmalinisation, greisenisation, haematitisation) only tourmalinisation is accompanied by an increase in the Bi content. This occurs chiefly where the association is with arsenopyrite included in late blue tourmaline, there being no such relationship with early formed subhedral brown tourmaline. The association of Bi with high temperature post-magmatic events is confirmed by its occurrence as a minor, or very minor, constituent of Sn and W lodes. Because of its rarity the paragenetic behaviour of Bi in such lodes is obscure. A considerable degree of primary dispersion of Bi into wall rock surrounding these high temperature lodes has been observed.

Mesothermal cross-course mineralisation of the complex type (Beer, 1978) commonly carries substantial quantities (sometimes mineable amounts) of Bi, usually in association with Ni, Co and U ores. The cross course mineralisation of simple type, such as occurs in the Bere Alston and Menheniott areas, has no reported bismuth minerals associated with it and limited soil geochemical surveys confirm the impression that Bi is not common in this lode type.

Granite cusps tend to exhibit high concentrations of Bi, along with B. The aureole of metamorphism surrounding the cusps is highly enriched in Bi, indicating substantial metasomatic introduction of Bi into slates. The enriched zone is either continuous with the granite, as Hemerdon, or separated from the granite by up to 200m of rock with Bi lower than detection limit, as at Bosworgey. This is regarded as reflecting the higher temperature of the inner metamorphic halo at Bosworgey. The results of soil geochemical studies at Castle an Dinas and around the south-western margin of the Dartmoor granite indicated that Bi metasomatism is a common accompaniment to granite intrusion in the area.

In the secondary environment, the Bi concentrations in soils reflects reasonably well the concentrations in the underlying rock types and appears to present few problems in interpretation owing to its relative immobility in hydromorphic transport mechanisms, at least in the residual soils in south-west England. By means of soil geochemical prospecting methods the positions of lodes and disseminated mineral deposits of Sn and W can be identified and zones of metasomatic enrichment around granites recognised.

Bi frequently occurs as the native element and at normal pressure pure bismuth has a melting point of 27 l°C. Since most lode and granite intrusion temperatures are considered to be substantially higher than this, and molten bismuth would have a considerable vapour pressure, there is a predisposition for primary dispersion to take place even when the overall concentrations are low. The high degree of primary dispersion, coupled with its poor secondary dispersion characteristics, makes Bi an important indicator element for both high temperature lodes and mesothermal cross course complex mineralisation, and indeed the element can indicate the presence of granites with which substantial ore bodies are frequently associated.

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References

Beer, K.E. 1978. Paragenesis in the Variscan metallogenic province of Cornwall and Devon, *In: Probleme der Paragenese,* 15-27. LAGOD, Freiberger Forschung.

Brooks, R.P. and Ahrens, L.H. 1961. Some observations on the distribution of thallium, cadmium, and bismuth in silicate rocks and the significance of covalency on their degree of association with other elements. *Geochim. Cosmochim. Acta, 23,* 100-115.

Bott, M.H.P., Day, A.A. and Masson-Smith, D.J. 1958. The geological interpretation of gravity and magnetic surveys in Devon and Cornwall. *Phil. Trans. Roy. Soc. (A) 25L* 161-191.

Darnley, A.G., English, T.N., Sprake, O., Preece, E.R. and Avery, D. 1965. Ages of uraninite and coffinite from south-west England. *Mineral. Mag. 34,* 159-176.

Dines H.G. 1956. The metalliferous mining region of southwest England, Vol. I and II. *Mem. Geol. Surv. G.B.*

Goldschmidt, V.M. 1954. *Geochemistry,* Clarendon Press.

Greenland, L.P., Gottfried, D. and Campbell, E.Y. 1973. Aspects of the magmatic geochemistry of bismuth, *Geochim. Cosmochim. Acta 37,* 283-295.

Gurney, J.J. and Ahrens, L.H. 1969. The bismuth contents of some rare-earth minerals, notably gadolinite. *Geochim. Cosmochim. Acta 33,* 417-420.

Heinrichs, H., Schulz-Dobrick, B. and Wedepohl, K.H. 1980. Terrestrial geochemistry of Cd, Bi, Ti, Pb, Zn and Rb. *Geochim. Cosmochim. Acta, 44,* 1519-1533.

Hey, M.H., Bannister, F.A. and Russell, A. 1938, Russellite, a new British Mineral. *Mineral. Mag., 15,* 41-54.

Hosking, K.F.G. 1969. The nature of the primary tin ores of the south-west of England. *In:* Fox, W. (ed.) *A second technical conference on Tin.* Bangkok Vol; 3, 1157-1244. London.

Krauskopf, K.B. 1957. The heavy metal content of magmatic vapour at 600°C. *Econ. Geol. 52,* 786-807.

Macalister, D.A. 1907. Mining notes. *In:* Geology of Land's End. *Mem. Geol. Surv. G.B.*

Marowsky, G. and Wedepohl, K.H. 1971. General trends in the behaviour of Cd, Hg, TI, Bi in some major rock forming processes. *Geochim. Cosmochim. Acta, 35,* 1255-1267.

Mintser, E.F. 1969. The geochemical properties of the behaviour of bismuth in hypogenic process. (Trans. from Russian). *In: Geochemistry of Bismuth, Benchmark Paper in Geology 49,* Dowden, Hutchinson and Ross Inc.

Pearce, R. 1878. Note on pitchblende in Cornwall. *Trans. Roy. Geol. Soc. Corn. 9.*

Pockley, R.P.C. 1964. Four new uranium-lead ages from Cornwall. *Mineral. Mag. 33,* 1081-1092.

Stein, P. 1952. A survey of uraniferous deposits in Cornwall. *Mining J. 238.*

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A revision of *"Orthis hipparionix"* (Brachiopoda) from the Lower Devonian of Devon and Cornwall

K.M EVANS

K.M. Evans, 1982. A revision of *"Orthis hipparionix"* (Brachiopoda) from the Lower Devonian of Devon and Cornwall. *Proc. Ussher Soc. 5,* 383-386.

Brachiopods described and figured by Davidson (1865) as *Orthis hipparionix* Vanuxem (?) are redetermined as specimens of *Proschizophoria personata* and *Athyris avirostris.* The taxonomic position of *Hipparionix hipponyx* (Schnur, 1851) is briefly discussed and material from North Devon which was previously assigned to this species is referred to *Schellwienella* sp.

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Introduction

In the second part of his work on British Devonian brachiopods, Davidson (1865) described and figured specimens from the "Lower Devonian slates and grits of Looe" under the name *Orthis hipparionix* Vanuxem (?). The illustrations of Davidson (1865, Pl. XVII; Figs. 8-12) are reproduced here in Figure 1 and photographs of the specimens are reproduced in Figure 2. The material comprises poorly preserved internal moulds in brown, friable sandstone and Davidson (1865, p.90) expressed doubt as to the accuracy of his determination because of the poor state of preservation. Following the publication of the Davidson Monograph, the name *Orthis hipparionix* appeared in several faunal lists from the Lower Devonian of south Devon and north Cornwall (Holl, 1868; Etheridge, 1882; Collins, 1893; Green, 1904).

Later authors, familiar with better preserved faunas from abroad, recognised that the material figured by Davidson included two or more species and the redeterminations of various authors are summarised in Table 1. In the course of a revision of the Lower Devonian brachiopod faunas of Britain, the present writer was able to examine Davidson's material and also collect comparative material from the Looe area. The marine Lower Devonian beds around Looe are referred to the Meadfoot Group and have yielded a brachiopod fauna indicative of a late Siegenian age (Evans, 1980; 1981).

	Schizophoria provulvaria	*Proschizo-phoria personata*	*Athyris avirostris*
Maurer, 1886	9, 12		
Drevermann, 1904	10?	8? 9, 12	
Asselberghs, 1921	10	8, 9, 12	11
Maillieux, 1931		8, 9, 10? 12	
Maillieux, 1936	10		
Pocock, 1966	9, 10?		
Boucot & others, 1966		8, 9, 12	
This work		8, 9, 10, 12	11

Table 1. Redeterminations of *Orthis hipparionix* according to various authors (numbers refer to Davidson, 1865, Pl. XVII).

Description and reassignment

A number of difficulties were encountered when an examination of Davidson's material was made. All the specimens are preserved in friable, brown sandstone in which the fine details of the moulds have been lost and the material is too friable to enable latex impressions to be made. The specimens have been distorted to various degrees (see below) and in all cases considerable flattening has occurred with the moulds preserved only in low relief. It is unfortunate that the original profiles have not been preserved as it has been shown that in the genus *Proschizophoria,* the profiles are a useful diagnostic character (Renouf, 1972). Descriptions of the figured specimens are summarised below.

Davidson (1865) Figure 11 (British Museum Natural History, specimen number B9073) is readily distinguished from the rest of the figured specimens by the strongly impressed muscle field which extends more than three-quarters the length of the valve. A more detailed examination of this specimen (Length 44mm, width 43mm) reveals the impressions of short, thick dental plates and there is evidence of thickening of the valve in the umbonal region. The sagittal length of the V-shaped muscle field is 22.5mm but the maximum extension of the diductor scars is 39mm. The figure is generally accurate and is laterally reversed. This specimen was redetermined as *Athyris avirostris* (Krantz, 1857) by Asselberghs (1921). Direct comparison with the type material (in the Institut fair Palaontologie der Rheinischen, Friedrich-Wilhelms-Universitat, Bonn) confirms this specimen to be a ventral valve of *Athyris avirostris.*

Davidson (1865) Figures 8, 9, 12 (BMNH numbers B9068, B9069 and B9072 respectively) have been assigned to *Proschizophoria personata* (Zeiler, 1857) by general agreement among several authors (Table 1). The type material of *P. personata* has been lost (Drevermann, 1904; Carls, 1974) but typical examples of this species from abroad compare closely with the figured specimens.

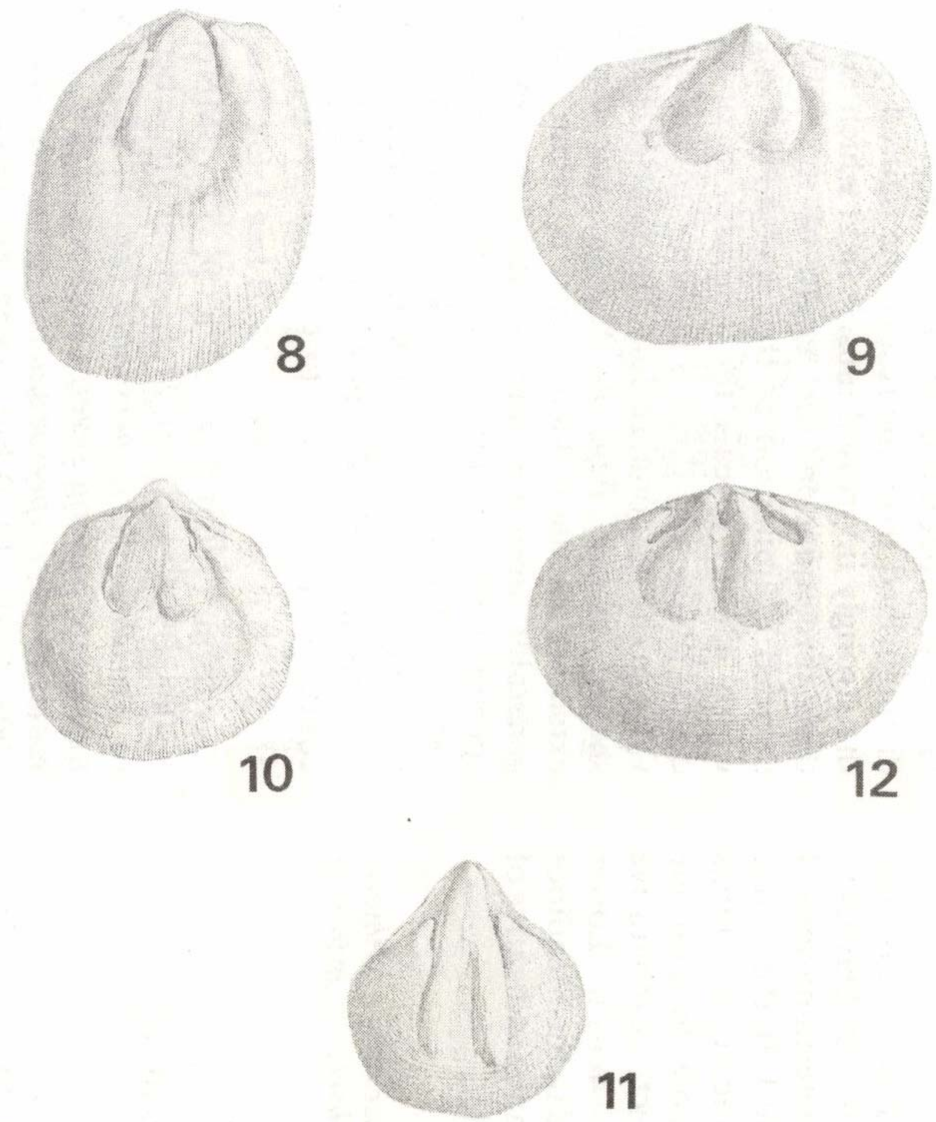

Figure 1. *Orthis hipparionix as* figured by Davidson, 1865, Pl. XVII, figures 8-12 and numbered here as in the original work. The specimen numbers are, for figures 8, 9, 11 and 12 respectively, B9068, B9069, B9073 and B9072 of the British Museum (Natural History) and for figure 10, number 6865 of the Geological Survey museum. The specimens are revised here as follows: figures 8, 9, 10 and 12-Proschizophoriapersonata, figure *11 - Athyris avirostris. The* scale bar represents lcm.

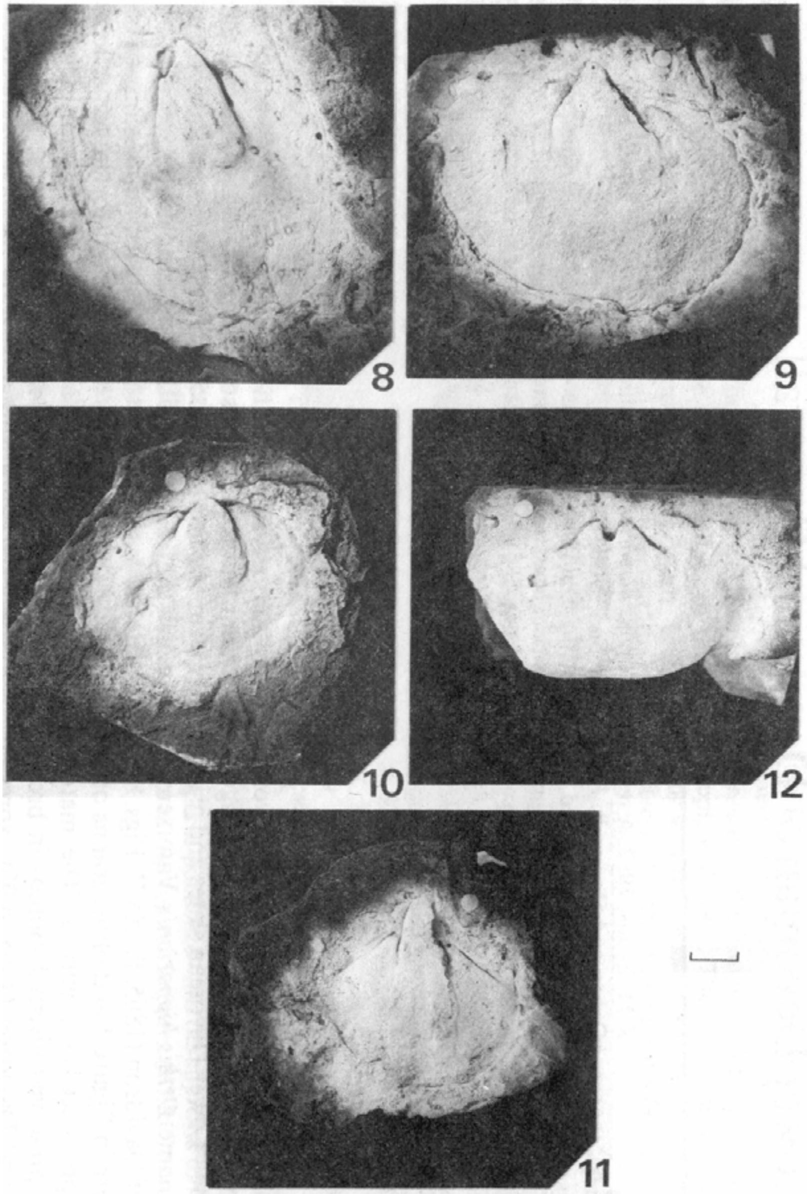

Figure 2. *Orthis hipparionix* of Davidson, 1865. Photographs of the specimens are illustrated here for the first time. For explanation of the numbers see figure 1. Scale bar represents lcm.

Figure 8 illustrates a large, subelliptical ventral valve with a strongly impressed, rounded triangular muscle field and well developed, pointed lateral apical cavities. The illustration shows that bilateral symmetry of the valve has been destroyed by distortion and comparison with the specimen reveals that the figure is laterally reversed. Closer examination of the specimen (L 65mm, W 56mm) reveals that the muscle field (L 28mm, W 19mm) has a weak anterior invagination which is not shown in Figure 8. The posterior part of the muscle field is missing, It is not clear whether the specimen has been damaged since it was figured by Davidson or whether the missing piece was "restored" for the plate, possibly using details from the muscle field of another, incomplete, specimen on the same slab.

Figure 9 is a good likeness to the Specimen but it, too, has been laterally reversed. Examination of the specimen (L 61mm, W 69mm) reveals a strongly impressed muscle field (L 28mm, W 26mm) with a well developed anterior invagination. Details of the specimen which were not figured comprise weak crenulations or striations around the rim of the valve which is very slightly recurved. Distortion has destroyed the bilateral symmetry of the specimen.

Figure 12 represents a dorsal valve which has undergone considerable distortion. The original domed profile has been almost completely flattened and the anterior portion has been bent under the rest of the valve giving an artificially shorter appearance. The figure of the specimen (L 32mm, W 62mm) has had the folding "restored" to some extent resulting in an overall elliptical shape. The muscle field (L 22mm, W 28mm) is strongly impressed and the rim of the valve is weakly recurved and bears faint crenulations or striations. The figure is not laterally reversed.

The specimens figures by Davidson (1865) as Figure 9 and 12 were designated the type specimens of the new species *Orthis provulvaria* which was erected by Maurer in 1886, however, this species was erected in a private publication without proper description or illustration and should, therefore, be considered a *nomen nudum.* Maurer fully described and figured O. *provulvaria* in 1893 from German material and this reference should be taken as the valid date of authorship of this species which is now referred to the genus *Schizophoria* King, 1850.

Davidson (1865) Figure 10 (Geological Survey Museum, specimen number 6865) has been referred to *Schizophoria provulvaria* by several authors (Table 1) but not, significantly, by Maurer who erected the species. Examination of this specimen (L 48mm, W54mm) reveals a poorly preserved ventral mould which displays a strongly impressed muscle field (L 18.5mm W 20mm) which is rounded triangular in outline and has an invagination in the anterior margin. Weak concentric growth increments can be seen in the anterior part of the valve. Traces of narrow, pointed lateral apical cavities are preserved but there is no trace of a median septum. In the illustration of Davidson, which is laterally reversed, the weak invagination has been exaggerated in Figure 10 to give the effect of a broad median septum dividing the muscle field and it was probably this feature which led some authors to assign it to *S. provulvaria.* Typical examples of *S. provulvaria* from abroad do not compare closely with this specimen and the dimensions of the ventral muscle field of specimen 6865 are not consistent with the range of *S. provulvaria* as plotted by Pocock (1966, p.390). To summarise, it is considered by the writer that all the details visible in specimen 6865 are consistent with *P. personata.*

Note on *Orthis hipparionix*

With the five specimens figures by Davidson (1865) referred to other genera and species, there remains the question of *"Orthis hipparionix"* itself and its record in the British Lower Devonian. The species which Davidson recorded from Looe has, itself, been the subject of confusion. In 1851, Schnur erected a new species *Orthis hipponyx* from European material but at a later date, Schnur (1853) considered this species to be synonymous with the American species *Hipparionix proximus* Vanuxem, 1842 and he erected a new specific name to include both the European and American material: *Orthis hipparionix* Schnur, 1853.

Davidson (1865) included Vanuxem, 1842 and Schnur, 1853 in his synonymy of O. *hipparionix* (sic) but, curiously, adopted the junior synonym which he credited, questionably, to Vanuxem. In the caption to Pl. XVII, and in his faunal lists of Devonian species, Davidson reverted to the original spelling of Schnur (1853); *Orthis hipparionix.*

The specimens described by Schnur (1851; 1853 are orthotetids which can be referred to the genus *Hipparionyx* Vanuxem, 1842, however, under the law of priority the senior synonym should be adopted. The orthotetids described by Schnur, which are common in the Lower Devonian beds of Germany, should therefore be assigned to *Hipparionyx hipponyx* (Schnur, 1851).

There is a record of *Orthotetes hipponyx* from the Lower Devonian Lynton Beds of North Devon in Hamling (1908) which was derived from an earlier paper, describing Hamling's material, by Whidborne (1901). The specimen figured by Whidborne is part of the Hamling Collection which is housed in the Museum of the Torquay Natural History Society. The figure of Whidborne (1901, Pl. CVII, Fig. 8) displays a poorly preserved ventral valve internal mould. There are several specimens of *"0. hipponyx"* in the Hamling Collection and the figured specimen has been tentatively identified by the writer as specimen number 1210. The specimen shows no trace of the strong, incurved muscle bounding ridges which are characteristic of the genus *Hipparionyx.* The writer has collected numerous similar examples from the Lynton Beds (Upper Emsian) but all are fragmentary remains and, in the absence of any better preserved material, has referred this taxon (Evans, 1980) to *Schellwienella* sp.

Conclusions

It is concluded that the records of *Orthis hipparionix* in Britain are largely based on the figures of Davidson (1865) which may be redetermined as follows:

Pl. XVII, Figs. 8, 9, 10, 12 *Proschizophoria personata* (Zeiler, 1857)

Pl. XVII, Fig. 11 *Athyris avirostris* (Kranz, 1857)

At the present time there is no confirmed record of the orthotetid *Hipparionyx hipponyx* from Britain, records from the Lynton Beds may be referred to *Schellwienella* sp.

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References

Asselberghs, E. 1921. Correlation between the Meadfoot Beds of Devonshire and the Siegenian of the Ardennes (Lower Devonian). *Geol. Mag., 58,* 165-169.

Boucot, A.J., Gauri, K.L. and Johnson, J.G. 1966. New Subfamily Proschizophoriinae of dalmanellid Brachiopods. *Palaont. Z., 40,* 155-172.

Carls, P. 1974. Die Proschizophoriinae (Brachiopoda; Silurium Devon) der Ostlichen Iberischen Ketten (Spanien). *Senck. Leth., 55,* 153-199.

Collins, J.H. 1893. A working list of the Palaeozoic fossils of Cornwall. *Trans. R. Geol. Soc. Cornwall, 11,* 421-479.

Davidson, T. 1865. A monograph of British fossil brachiopoda. *Palaeont. Soc. Monogr.,* Vol. 3, 6, Devonian II, 57-131.

Drevermann, F. 1904. 1 Die Fauna der Siegener Schichten Yon Seifen unweit Dierdorf (Westerwald). *Palaeontographica, 50,* 229-287.

Etheridge, R. 1882. Notes on some fossils from the Red Beds of the Lower Devonian, Torquay, South Devon. *Geol. Mag., 19,* 154-157.

Evans, K.M. 1980. Lower Devonian brachiopod faunas of Great Britain. *Unpubl, Ph.D. Thesis Univ. College Swansea.*

Evans, K.M. 1981. A marine fauna from the Dartmouth Beds (Lower Devonian) of Cornwall. *Geol. Mag., 118,* 517-523.

Green, U. 1904. Note on the Correlation of some Cornish Beds with the Gedinnian of Continental Europe. *Geol. Mag., 51,* 403-407.

Hamling, J. 1908. Recently discovered fossils from the Lower and Upper Devonian beds of North Devon. *Repts. Trans. Devonshire Assoc. Adv. Sci., 40,* 276-280.

Holl, H. 1868. On the older rocks of S. Devon and E. Cornwall. *Quart. J. Geol. Soc. Lond, 24,* 400-454.

King, W. 1850. A monograph of the Permian fossils of England. *Palaeont. Soc. Monogr., 3,* 1-258.

Kranz, A. 1857. Ueber ein neues bei Menzenberg aufgeschlossenes Petrefakten-Lager in den devonischen Schichten. *Verhandl. Naturhist. Vereins Preuss. Rheinl. Westf, 14,* 143-165.

Maillieux, E. 1931. La Faune des Gres et Schistes de Solieres (Siegen Moyen). *Mdm. Mus. Royl. Hist. Nat. Belg., 51* 1-90.

Maillieux, E. 1936. La faune et l'age des Quartzophyllades siegeniens de Longlier. *Mdm. Mus. roy. Hist. Nat. Belg., 73,* 1-140.

Maurer, F. 1886. Die Fauna des rechtsrheinischen Unterdevon aus meiner Sammlung zum Nachweis der Gliederung. *Tracts Miscellaneous, 10,* 1-32.

Maurer, F. 1893. Palaeontologisches Studien im Gebiet des rheinischen Devon. *Neus. Jahrb. f. Min. Geol. Palaont. 2,* 149-172.

Pocock, Y.P. 1966. Devonian schizophoriid brachiopods from Western Europe. *Palaeontology, 9,* 381-412.

Renouf, J.T. 1972. Brachiopods from the Grest *Orthis monnieri* Formation of Northwestern France and their significance in Gedinnian/Siegenian Stratigraphy of Europe. *Palaeontographica* Abt. A, *139,* 89-133.

Schnur, J. 1851. Die Brachiopoden aus dem Uebergangsgebirge der Eifel. Programm vereinigt, hohern Burger- und Provinzial-Gewerbeschule Trier (1850-1851), 2-16, Trier, Lintz.

Schnur, 1853. Zusammenstellung und Beschreibung sammtlicher im Uebergangsgebirge der Eifelverkommenden Brachiopoden. *Palaeontographica, 3,* 169-248.

Vanuxem, L. 1842. Geology of New York, comprising the survey of the Third Geological District, *Nat. Hist. New York, 4,* Geology pt. 3, 1-306.

Whidborne, C.F. 1901. Devonian fossils from Devonshire. *Geol. Mag., 8,* 529-540.

Zeiler, F. 1857. Versteinerungen der alteren rheinischen Grauwacke. *Verhandl. Naturhist. Vereins. Preuss. Rheinl. Westf., 14,* 45-51.

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The Iberian Pyrite Belt, south-west England and Hercynian geotectonics

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Introduction

The position of the Iberian Pyrite Belt in Hercynian geotectonics is as yet an unresolved question. Many workers have noticed the similarity in the disposition of structure, metamorphism and sedimentary facies in the Upper Palaeozoic basins of south-west England, the Rheno-Hercynian zones and its eastward extensions (Fig. 1). The similarity may be extended to encompass the Iberian Pyrite Belt and for that matter the extensional basins of the Montagne Noire and Pyrenees (Fig. 1). Links between these basins are subject to a great deal of debate (Franke and Engel, 1982). The latter two tie on the south side of a basement high which runs through central and north-western France swinging southwards and eventually south-eastwards through Iberia, the Armorican-Iberian Arc, Along with south-west England the Pyrite Belt lies on the opposite side of the Arc. Palaeomagnetic evidence suggests (Ries, et al, 1980) that the Arc represents a folded mountain belt, in which case the Pyrite Belt and south-west England occupy analogous positions on the northern margin. A comparison of their structural style and sequences affords one means of assessing the arguments for continuity. The structures in south-west England were reviewed by Sanderson & Dearman (1973) and a model suggesting north-north-westward overthrusting as the dominant sense of transport in south Cornwall recently presented (Rattey & Sanderson, in press). Some differences of opinion exist as to the transport directions in north Cornwall and south Devon. Local southward transport is inferred by Sanderson (1979) on the south side of the Culm basin whereas northwards transport of thrust sheets is proposed by workers revising the Tavistock (337) sheet egg Turner (1981). An outward directed sense of transport is well documented in the Pyrite Belt though because it lies 110° around the curvature of the Armorican-Iberian Arc - this is towards the west-south-west (Fig. 1).

Review of Pyrite Belt Structure

The earliest structures are pre-cleavage folds and .overthrusts. They occur both in Portugal (Schermerhorn & Stanton, 1969) and have recently been identified in Spain. Here they can be seen both in the west (eg near E1 Granado) and east (eg north of Rio Tinto). According to

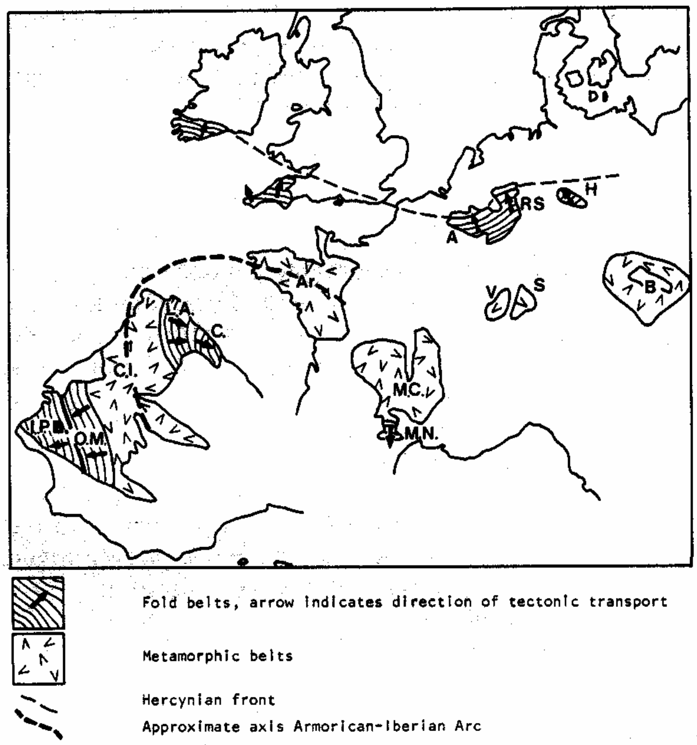

Figure 1. Hercynian areas of Europe after Barnes (1981).
A - Ardennes, Ar - Armorica, B - Bohemia, C - Cantabria,
CI - Central Iberia, H - Harz, IPB - Iberian Pyrite Belt,
L-A - Leon-West Asturian, MC - Massif Central, MN – Montagne Noire, OM - Ossa Morena, RS - Rheinisches Schiefergebirge,
S - Schwarzwald, V - Vosges.

Schermerhorn & Stanton (1969) the thrust sheets moved south-westwards and must be post Visean and they carry Devonian strata over "Culm" of Lower Visean age.

The main phase of deformation produced horizontal close to tight folds which are the major structures controlling the outcrop patterns. Interlimb angles generally decrease northwards producing near isoclinal structures in places. The folds tightly fold the early thrusts. They are accompanied by an axial planar cleavage which transects the earlier set of pre-cleavage folds and thrusts, usually at a very oblique angle. The cleavage is generally penetrative except in some of the massive volcanic units. The folds consistently verge and face south-westwards though the cleavage is usually fairly steeply inclined. Overturned limbs show a tendency to develop thrusts which become increasingly important towards the northeastern interior side of the Belt. Strain markers show that the majority of ductile deformation is associated with this main phase of folding. Preliminary investigation of the pattern of strain has revealed domains of both down-dip and horizontal extension. This suggests a combination of shortening normal to the Belt and strike-slip movement ie. a transpressive tectonic regime.

Several subsequent pulses of shortening have produced later folds and associated crenulation cleavages. At least three episodes can be distinguished in the Rio Tinto area, usually having a restricted occurrence in packets or strain bands.

Discussion

Because of the very considerable distance along strike between south-west England and the Pyrite Belt it would be unreasonable to expect any detailed structural correlations. Indeed it seems likely that there was a diachronous outwards migration of unstable flysch sedimentation and deformation in both areas. In southwest England the Mylor-Gramscatho Flysch Basin had developed by the Middle Devonian and subsequently in the early Carboniferous the Culm Basin formed to the North. There is no evidence that the two were ever linked but there is evidence that post-Namurian, pre-Westphalian uplift to the south was responsible for shedding debris into the higher levels of the Culm Basin (Selwood, 1966). Recent isotopic data (Styles & Rundle, in press; Davis, in press) strongly supports a Middle/Upper Devonian age for the generation of the Lizard Complex. Deformation in south Cornwall is attributed to the north-north-westwards obduction of the Lizard Complex (Rattey & Sanderson, in press). If, as seems usually to be the case with ophiolites, obduction swiftly followed generation then the deformation might have begun as early as the uppermost Devonian (Barnes & Andrews, in press). Further northwards in the Culm Basin deformation did not begin until at least late Westphalian (post Westphalian C, Freshney et al. 1979).

In the Pyrite Belt there was a south-westward migration of the "Culm" flysch basin as flysch deposits become progressively younger, the youngest in south-westernmost Portugal being of Westphalian A age (Schermerhorn, 1971). The age of deformation cannot be dated precisely but must be at least post Visean in the central part of the Pyrite Belt and post Westphalian A in the south. Post orogenic Westphalian D sediments occur in small basins flanking the northern and eastern margins of the Belt (Schermerhorn, 1971).

Development of ephemeral basins and diachronous deformational episodes are characteristic features of oblique slip mobile zones (Reading, 1980). The structure and stratigraphy of south-west England and the Iberian Pyrite Belt are consistent with an interpretation as representing the remnants of an oblique slip mobile zone subsequently deformed around the outside of the Armorican-Iberian Arc. Badham (in press) has argued that both areas were unconnected oblique-slip mobile zones bounding separate Hercynian microplates being translated westwards along the southern edge of Europe, until impaction and accretion at a major bend in the continental margin. Matte & Burg (1981) suggest an analogy with the collision of India and Asia whereby the Armorican-Iberian Arc is acquired after normal collision by progressive impingement of a southern continental promontory. These ideas form useful conceptual models and offer predictions which may be tested by field data. For example Badham's model predicts an overall dextral shear regime but Matte & Burg's model needs Opposing senses of shear on either side of the Armorican- Iberian Arc (dextral in Armorica) which is a primary impaction feature. There is considerable evidence of dextral shear in Armorica (Jegouzo, 1980). A model for the development of the Mylor-Gramscatho basin as a pull-apart floored by ocean crust in a dextral mobile zone is proposed by Barnes (1982). Data from Iberia is scanty. In the Pyrite Belt north-north-east trending dextral shears developed late in the main folding stage (Schermerhorn & Stanton, !969). Further data is being obtained to test these models.

Conclusions

Structures in the Iberian Pyrite Belt are consistent with the suggestion that both south-west England and the Iberian Pyrite Belt might have been formed in Hercynian oblique slip mobile zones. It is possible that they form the remnants of a once continuous dextral shear belt now deformed around the Armorican-Iberian Arc. Structural and stratigraphic evidence is unlikely to confirm this because by their very nature oblique-slip mobile zones lack continuity. Palaeomagnetic controls are likely to offer the best means of resolving the geotectonic arguments.

References

Badham, J.P.N. 1982. Strike-slip orogens - an explanation for the Hercynides, *J. Geol. Soc. Lond. 139,* 493-504.

Barnes, R.P. 1982. The geology of south Cornish melanges. *Unpubl. Ph.D. thesis Univ. Southampton.*

Barnes, R.P. and Andrews, J.R. (in press) Metamorphic evidence for the cold emplacement of the Lizard Complex. *J. Geol. Soc. Lond.*

Davies, G. (in press). Isotopic evolution of the Lizard Complex. *J. Geol. Soc. Lond.*

Franke, W. and Engel, W. 1982. Variscan sedimentary basins on the Continent and relations with south-west England. *Proc. Ussher Soc.,* 5,259-269.

Freshney, E.C, Edmonds, E:A., Taylor, R.T. and Williams, B.J. 1979. Geology of the country around Bude and Bradworthy. *Mem. Geol. Surv. G.B.* 66pp.

Jegouzo, P. 1980. The South Armorican shear zone. *J. Struct. Geol.* 2. 39-47.

Matte, Ph. and Burg, J.P. 1981. Sutures, thrusts and nappes in the Variscan Arc of w4stern Europe: plate tectonic implications. *Geol. Soc. Lond. Spec. Publ. 9,* 353-358.

Rattey, R.P. and Sanderson D.J. (in press). Structures in the Gramscatho and Mylor Beds and their bearing on emplacement of the Lizard. J. *Geol. Soc. Lond*

Reading, H.G. 1980. Characteristics and recognition of strike-slip fault systems. *Spec Publ. Int. Ass. Sediment, 4,* 7-26.

Ries, A.C., Richardson, A. and Shackleton, R.M. 1980. Rotation of the Iberian Arc: Palaeomagnetic results from North Spain. *Earth Plan. Sci. Letts., 50,* 301-310.

Sanderson, D.J. 1979. The transition from upright to recumbent folding in the Variscan fold belt of southwest England: a model based upon the kinematics of simple shear. *J. Struct. Geol. 1,* 171-180.

Sanderson, D.J. and Dearman, W.R. 1973. Structural zones of the Variscan fold belt in SW England, their location and development. *J. Geol. Soc. Lond. 129,* 527-536.

Schermerhorn, L.J.G. 1971. An outline stratigraphy of the Iberian Pyrite Belt. *Bol. Geol. y Min. 82,* 239-268.

Schermerhorn, L.J.G. and Stanton, W.I. 1969. Folded overthrusts at Aljustral (South Portugal). *Geol. Mag. 106,* 130-141.

Selwood, E:B., 1966. Derived fossil§ from Upper Culm Measures south of Launceston, Cornwall. *Proc. Ussher Soc. 1,* 234.

Styles, M.T. and Rundle, C.C. (in press). A whole rock Rb/Sr isochron for the Kennack gneiss. *J. Geol. Soc. Lond.*

Turner, P.J. 1981. Aspects of the structures of the Chillerton area, south-west Devonshire. *Proc. Ussher Soc. 5,* 153-162.

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Thrust and nappe tectonics in central south-west England (Abstract)

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Remapping of several IGS 1:50,000 Sheets in Devon and east Cornwall by the Geology Department at Exeter University under contract to NERC has led to a significant revision of our understanding of the stratigraphy and tectonics of the region. This work has been integrated with existing studies to produce a new interpretation for the evolution of the foldbelt. Important lateral variations in sedimentation and structure across the peninsula are noted and related to the influence of major deep fractures. Considerations of scale and timing of thrust and nappe development suggest that gravitational spreading, concomitant upon uplift in the south along pre-existing fractures, was an important element in the development of the structure, The current understanding of the geology is more consistent with this interpretation than one involving regional decollement and crustal shortening on the scale envisaged for many thrust and nappe terranes.

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The geology of the St Mellion outlier (Abstract)

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The St Mellion and Tamerton Foliot outliers, lying between Plymouth and Callington, form the most southerly outcrop of Carboniferous rocks in Britain. The outlier at St Mellion comprises some 60 sq. km. of mainly clastic sediments resting on a monotonous sequence of Upper Devonian slates. NW-SE trending high angle faults delimit the structure to the east and west. The outlier constitutes a series of allochthonous thrust slices emplaced over an autochthonous or parautochthonous 'basement' of Upper Devonian slates. In this sense the area may be defined as a klippe rather than an outlier.

Field mapping has resulted in the recognition of several formations within the area which range in age from upper Famennian to Namurian. Coarse clastic sediments containing comminuted plant debris are interpreted as the products of proximal turbidity flows and this style of sedimentation appears to control the majority of sedimentary successions known from the allochthon. An increasing component of igneous rocks is recognised within strata of Viséan age where tuffs, vesicular pillow lavas and dolerites occur in association with thin sandstones, cherts and black slates.

A southern, emergent land mass is considered to be the source of the sediment now preserved around St Mellion but its precise location and lithological nature is not known.

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The stratigraphy of south Cornish melanges (Abstract)

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'Crush breccias' exposed in south Cornwall are reinterpreted as a sedimentary melange sequence of about 1km thickness including up to 200m of interbedded rudites (Barnes 1982). This unit (called the 'Meneage Formation') occurs within the uppermost part of the Gramscatho Group of sediments (see Barnes and Andrews, 1982 for summary map of the geology). In Roseland it rests on the Eifelian Veryan Formation and includes limestone phacoids ranging from Gedinnian to Givetian in age; hence the Meneage Formation is Givetian or younger.

The melange includes a large proportion of slumped greywacke phacoids, which dominate towards the base of the sequence and also predominate locally higher up. Other parts of the sequence are composed of more varied melange including Ordovician quartzite phacoids (<200m long) and Devonian limestone phacoids (<10m long) often concentrated in separate distinct beds. The matrix is shale (now slate) throughout. Towards the top of the melange sequence bimodal volcanics occur in interbedded units and phacoids (<1km long). Greenstones (pillow lavas, breccias and tuffs) constitute a single ocean floor tholeiite suite. Minor gabbro, amphibolite and serpentinite are associated with one large greenstone phacoid (Nare Head in Roseland) and indicate derivation from some kind of ocean crust. Keratophyres (tuffs and lavas) were probably generated by partial melting of continental crust. Rudites occur interbedded in the centre of the sequence and stratigraphically higher as phacoids probably derived from the underlying member. The clast assemblage includes a wide range of lithologies indicative of a cratonic source. Certain parts of this debris suit are locally concentrated in monomict rudites comprising mica schist, amphibolite, deformed garnetiferous granite or deformed low grade meta-arenite clasts. A number of units which have always previously been mapped as 'greenstone' and 'amphibolite' are recognised as amphibolite rudites. A Lizard source cannot be attributed to any of the rudaceous debris.

Two coaxial phases of deformation have affected the whole sequence. Both phases generated northward verging folds which cause no major overturning of the strata. The first was the more important with a pervasive SE dipping slaty cleavage, a NW-SE extension lineation and associated regional pumpellyite-actinolite facies metamorphism.

The melange is interpreted as representing the early stages of deformation of the Gramscatho basin generated intracratonically in a strike slip zone.

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References

Barnes, R.P. 1982. The geology of south Cornish melanges. *Unpubl. Ph.D. Thesis, Univ. Southampton.*

Barnes, R.P. and Andrews, J.R. 1982. Pumpellyite-actinolite grade regional metamorphism in south Cornwall. *Proc. Ussher Soc., 5,* 139-146.

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Megacrysts in volcanic rocks from Pitts Cleave Quarry, near Tavistock (Abstract)

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This note reports the discovery, over the period 1952-54, of megacrysts and sporadic rock inclusions in the Carboniferous volcanic rocks exposed in Pitts Cleave Quarry (SX 501762) near Tavistock. During this time, the material was collected loose in one place only, on the then upper 125 metres (400 foot) level of the working quarry (Dearman and Butcher 1959 Fig 4a), having been brought down, it was thought, from a Position about two-thirds up the near vertical upper face. Because the megacrysts and associated inclusions could not be located in place at that time, no account of them was included in the general description of the volcanic rocks in this area (Dearman and Butcher 1959 p.64).

Visiting this now disused quarry briefly in May 1980, similar material was located at the northern end (SX 50257617) of the higher 150 metres level which had been cut in the later years of the quarry's active life. Preliminary examination of this new material confirms the presence of the same assemblage as previously collected loose.

The assemblage is characterised by an abundance of dark clinopyroxene megacrysts with occasional black amphibole megacrysts showing well-developed cleavage faces. The largest of the latter so far found reaches nearly 5cm across. Feldspar megacrysts present a ghost appearance in the host rock which consists of the typical fine-grained greenish dolerite. Chlorite ocelli, typically elliptical and a few millimetres in size, commonly crowd the host rock. The sporadic rock inclusions are mostly flakes of sediments in which the bedding can be clearly seen, but a few coarse-grained igneous rock fragments have been identified. In, preliminary thin section analysis, the clinopyroxene and amphibole megacrysts are largely unaltered, the latter being a brown hornblende. The feldspars, on the other hand, are almost completely altered to secondary minerals. The megacrysts appear to be cognate with the host rock.

In view of the importance which such megacrysts and other inclusions in volcanic rocks now have as geochemical indicators as to the nature of both crust and mantle in a plate tectonic setting, it seems worth recording that this is the only locality so far known for such an assemblage in the Hercynian trough volcanism of south-west Britain, recently reviewed by Floyd (1982).

Acknowledgements. Thanks are due to E.C.C. Quarries Ltd. for permission to visit this quarry and collect material, and to my colleagues John Holbrook and Ian Chaplin for assistance in collecting further material.

References

Dearman, W.R. and Butcher, N.E. 1959. The Geology of the Devonian and Carboniferous rocks of the north-west border of the Dartmoor granite, Devonshire. Proc. *Geol. Assoc., 70,* 51-92.

Floyd, P.A. 1982. *In:* Sutherland, D.S. (ed.). *Igneous rocks of the British Isles.* Chapter 16. The Hercynian trough: Devonian and Carboniferous volcanism in south-western Britain. John Wiley & Sons Ltd.

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Gold-bearing carbonate veins in the Middle Devonian Limestone of Hope's Nose, Torquay (Abstract)

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The occurrence of gold in carbonate veins cutting the Middle Devonian Limestone in the vicinity of the sewage outfall at the eastern extremity of Hope's Nose, was first reported by Gordon (1922). A later and fuller account was given by Russell (1929). This work is based on the study of specimens held by Torquay Natural History Museum and also upon observations made in the field. The opportunity has been taken to make a detailed mineralogical and petrological examination of the auriferous veins involving optical and SEM microscopy, X-ray diffraction analysis, chemical analysis and the microthermometric analysis oF fluid inclusions.

The individual veins are developed as narrow irregular pods and lenses along vertical or subvertical fractures. which strike roughly east-west. The enclosing limestone beds demonstrate normal and reverse movements of the fractures up to a maximum of 0.75m. Fourteen gold-bearing structures have been identified: these form a swarm in which the components are separated by up to 20m or so of apparently barren limestone.

At least three stages of deposition can be recognised in the veins. The earliest is coarse, euhedral, purple and yellowish-cream, ferroan calcite which commonly includes angular breccia clasts of the host limestone. This early calcite yields rather abundant fine red hematite on dissolution in acetic acid. The second stage, with which the gold is intergrown, is of biscuit-coloured, fine-grained, anhedral calcite and dolomite of saccharoidal texture, or, less commonly, coarser cream-coloured anhedral calcite. Both varieties contain cavities filled with yellow-brown hydroxides of iron. Dissolution of the second stage carbonate in acetic acid yields the native gold and also small, up to 3mm, water-clear, bipyramidal quartz crystals which may include small hematite flakes or, more rarely, filaments of native gold. The later and barren carbonate stages may be of carious, buff-coloured calcite or massive, white aragonite; the latter is sometimes associated with chalcedonic quartz.

Native gold occurs as branching filaments, which may be sparsely distributed throughout the host, or which may form dense and complex dendritic aggregates up to 20mm across. Growth of the dendrites is apparently controlled by micro-fractures in the host and also by rhombohedral crystalline cleavage traces in the carbonate gangue. Most of the gold is of a rich yellow colour, but there are local variations from deep brownish yellow to pale silvery yellow. XRD analysis, together with SEM-EDA analysis has revealed that much of the gold is of high purity but that the silver- and deep-coloured varieties may contain up to 16% of palladium. In certain specimens, the palladium-bearing gold bears euhedral microcrystals of a low-arsenic variety of the rare mineral mertieite, $Pd_5\{Sb,As)_2$. Traces of silver were present in some of the gold specimens at the extreme limit detectable by EDA analysis (□1%). Traces of pyrite and marcasite together with a little goethite were the only other species found in the gold concentrates.

Fluid inclusions were examined in the calcite gangue and also in the associated bipyramidal quartz crystals. In many cases these were monophase (liquid only) at room temperature, while others contained liquid and vapour. The latter, on heating, homogenised into the liquid phase over the temperature range 65°C to 120°C. Freezing measurements demonstrated consistently low first melting temperatures around -55°C. At -30°C there was about 50% ice and 50% liquid; hydrohalite was not observed. Final ice melting occurred at □20°C. The freezing data suggests that the fluids are rich in $CaCl_2$ with total gross salinities in the range 20 to 23 equiv wt % NaCl. Based on the ice/liquid ratio at -30°C the $CaCl_2$/ NaCl ratio probably has a minimum value of 3.

References

Gordon, W.T. 1922. Native gold at Torquay, Devonshire. *Nature, 109,* 583.

Russell, A. 1929. On the occurrence of native gold at Hope's Nose, Torquay, Devonshire. *Mineral Mag. 126,* 159-162.

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British Triassic palaeontology: supplement 6

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Since the submission of the writer's previous supplement *(Proc. Ussher Soc., 5,* 242; 1981) to his paper on British Triassic palaeontology, the following works dealing with or including aspects of that subject have appeared:

Benton, M.J. and Walker, A.D. 1981. The use of flexible synthetic rubbers for casts of complex fossils from natural moulds. *Geol. Mag., 118, (5),* 551-556.

Copestake, P. 1981. Chapter 5: Triassic. Pp. 78-80 *In:* Jenkins, D.G. and Murray, J.W. (eds.), *Stratigraphical Atlas of Fossil Foraminifera.* Horwood, Chichester, 310pp.

Evans, C.D.R., Lott, G.K. and Warrington, G. (Compilers). 1981. The *Zephyr* (1977) wells, South-Western Approaches and western English Channel.. *Rep. Inst. Geol. Sci.,* 81/8, iv + 44pp.

Fisher, M.J. and Dunay, R.E. 1981. Palynology and the Triassic/Jurassic boundary. *Rev. Palaeobot. Palynol., 34. (1),* 129-135.

Fraser, N. 1981. Reptiles from Triassic fissure deposits. *Palaeontological Association Annual Conference (Exeter); Abstracts.* pp. 4-5.

Kent, P.E. 1980. Eastern England from the Tees to the Wash, (2nd edn.). *Brit. Reg. Geol..* viii + 155pp.

Lovell, J.P.B., Pollard. J.E. and Steel, R.J. 1981. Correspondence: Intertidal sediments in the Auchenhew Beds (Triassic) of Arran. *Scott J. Geol.~ 17. (3),* 223-226.

Marshall, J.E.A. and Whiteside, D.I. 1981. Depositional history of palynomorphs from a Triassic cave filling, (Abstract). P. 435 *In:* Brooks, J. (ed.), *Organic Maturation Studies and Fossil Fuel Exploration.* Academic Press, London, xiii + 441pp

Marshall, J.E.A. and Whiteside, D.I. 1981. The palynological dating of a Triassic cave filling. *Palaeontological Association Annual Conference (Exeter); Abstracts,* p.9,

Mayall, M.J. 1981. The Late Triassic Blue Anchor Formation and the initial Rhaetian marine transgression in south-west Britain. *Geol. Mag., 118. (4),* 377-384.

Mayall, M.J. and Wright, V.P. 1981. Algal tuft structures in stromatolites from the upper Triassic of south-west England. *Palaeontology, 24, (3),* 655-660.

Pollard, J.E. 1981. A comparison between the Triassic trace fossils of Cheshire and south Germany. *Palaeontology, 24, (3),* 555-588.

Robinson, K.W., Shannon, P.M. and Young, D.G.G. 1981. The Fastnet Basin: An Integrated Analysis. Chapter 41, pp.444-454 *In:* Illing, L.V. and Hobson, G.D. (ed), *Petroleum Geology of the Continental Shelf of North-west Europe.* Heyden & Son, London, and Institute of Petroleum, London, xviii + 521pp.

Visscher, H. and van der Zwan, C.J. 1981 Palynology of the Circum-Mediterranean Triassic: phytogeographical and palaeoclimatological implications. *Geol. Rundschau. 70. (2),* 625-636.

Warrington, G. 1981. The indigenous micropalaeontology of British Triassic shelf sea deposits. Pp. 61-70 *In:* Neale, J.W. and Brasier, M.D. (eds.), *Microfossils from Recent and fossil shelf seas.* Horwood, Chichester. 380pp.

Whiteside, D.I. 1981. New faunal and floral discoveries from fissures. *Palaeontological Association Annual Conference (Exeter); Abstracts.* p. 14.

Wilson, H.E. 1981. Permian and Mesozoic. Chapter 12, pp.201-212 *In* Holland, C.F. (ed.), *A Geology of Ireland.* Scottish Academic Press. Edinburgh, x + 335pp.

Wright, V.P. and Mayall. M. 1981. Organism - Sediment Interactions in Stromatolites: an Example from the Upper Triassic of South West Britain. Pp. 74-84 *In:* Monty, C. (ed.), *Phanerozoic Stromatolites: Case Histories.* Springer-Verlag, Berlin, x + 249pp.

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