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Edited by G.M Power

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# A comparison of the Andean Batholith in Peru with granites from the Southeast Asian Tin Belt.

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Granitoids from the Coastal Andean Batholith in Peru and from the Main Range and Eastern Provinces of the Southeast Asian Tin Belt are described and compared. The Andean granitoids are clearly related to oceanic-plate subduction and are of I-type, while the two granite provmces in Southeast Asia occur within distinct geological terrains which may have converged during the Permo-Triassic in a collage tectonic setting. The Main Range S-type tin granites are similar to granites elsewhere which are attributed to regimes of continental collision, whereas the Eastern Province I-type granitoids have many features in common with Andean granitoids. However. In some aspects of their geochemical and isotopic composition they show some affinity with Main Range Province granites. Although the granite provinces of Southeast Asia occupy distinct terrains. ages for their emplacement are similar. Their formation over the same time interval suggests that the underlying tectonic control was similar. It is inferred that composition of the source region may be a more important factor for determining the typology of some granites than is their tectonic setting.

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## Introduction

Granite studies in recent years have been dominated by the concept introduced by Chappell and White (1974) that granites reflect their source regions. This concept was subsequently expanded by Pitcher (1983) who suggested that the mobilization of granite magmas from different source regions was a result of the different tectonic settings prevailing within a plate tectonic scenario. Thus a scheme of origin was proposed which, beginning with the most primitive, mantle derived granites in oceanic island arcs, progressed through continental margin subduction related regimes (Andean) to post closure uplift and collisional regimes and ultimately to anorogenic alkaline granites.

It is generally considered that the I-type granitoids present in island arcs, Andean, and to some extent rift or uplift associated regions, are derived from an igneous source region, either in the mantle or lower crust; whereas S-type granitoids are associated with collisional margins and are derived from a sedimentary source region.

These two categories of granite are both geologically and compositionally different (Chappell and White 1974). The compositional differences in particular were considered by these authors to reflect their derivation from different source regions. It has been found in practice that many of the criteria advocated by Chappell and White as being effective discriminants in the Lachlan zone of Australia are not so effective elsewhere. Nevertheless, considering the geological and geochemical criteria in their totality, it has been found the scheme is useful in practical terms irrespective of the interpretation of the differences for magmagenesis.

In particular the scheme is effective for characterising regional granite populations, though there may well be difficulty in classifying the more fractionated plutons in any population (Cobbing *et al.* 1986). Moreover there are generally differences in the compositional features of both I and S-type granites from different populations. Thus the S-type granites from Peninsular Malaysia are rather different from those of the Lachlan zone of Australia (White and Chappell 1983, Cobbing *et al.* 1986). Similar differences from south Thailand were reported by Ishihara *et al.* (1980).

The objective of this review is to compare granite populations of different compositions and from different tectonic settings in order to assess the validity of the I-S scheme for the regions compared, and to evaluate the role that contrasting tectonic settings play in granite magmagenesis. The information available from the Andean Batholith in Peru (Pitcher *et al.* 1985), and on the granites of the Southeast Asian Tin Belt (Cobbing *et al.* 1986), is sufficient to allow the comparison of regional granite provinces from these contrasting orogenic belts (Table 1).

The tectonic setting for the Andes is one of continent-ocean plate convergence with the subduction of oceanic lithosphere, while that for Southeast Asia is of continental microplate convergence in which the granite provinces are linked to different geological terrains.

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In the Peruvian Andes there are two periods of plutonism; the .first, mainly Cretaceous, forms the Coastal Andean Batholith and the second of Tertiary age, is mostly present in the high Andes. In this discussion only the Cretaceous Andean Batholith will be considered (Figs. 1 and 2). In the Southeast Asian Tin Belt four granite provinces are present which may be wholly of S-type, wholly of I-type or of mixed S and I-type (Fig. 3). Two of these provinces will be considered, the Main Range S-type Province and the Eastern I-type Province (Fig. 3). These provinces are separated into two distinct geological terrains, but in the Indonesian Tin Islands they overlap to form a mixed granite population within one geological terrain (Fig. 3). The geochemical data presented is restricted to the occurrence of these provinces in Peninsular Malaysia.

## The Andean Batholith in Peru

The batholith (Fig. 1) forms a virtually continuous linear body about 65km in width and over 1500 kms in length made of probably more than 1,000 individual plutons; they are emplaced mainly into Cretaceous marine volcanics but also cut Cretacous sedimentary rocks and, in Southern Peru, Precambrian gneisses. These plutons have been distinguished by geological mapping and have been further investigated by geochemical and isotopic methods (Pitcher *et al* 1985). The broader structure of the batholith has also been established and it is now known to be divided into batholithic segments (Fig. 1) and that each segment is made up of an assemblage of Super-units wherein each Super-unit is confined to a particular segment, and, apart from some marginal overlap in some cases, does not stray into adjacent segments. Each Super-unit is present as a chain of plutons from 200-800 km in length which are mixed together with other Super-units to provide a complex plutonic terrain. Each super-unit is made up of a number of plutons with a similar range of lithologies and texture and with similar geochemical and isotopic signatures (Pitcher et *al.* 1985).

The normal range of lithologies for a Super-unit is from diorite to monzogranite and the most abundant lithology present is tonalite or granodiorite. Some of the later Super-units, more particularly those associated with the ring complexes in the Lima segment, are dominantly monzogranitic in composition. In the Arequipa segment some Super-units are more potassic and range from monzodiorite to monzogranite in composition.

The plutons which make up a Super-unit may be either simple or complex. Simple plutons are composed of one rock type only and are generally small and of circular shape. Complex plutons are generally zoned from a dioritic or tonalitic margin to a more acid central core of tonalite, granodiorite or monzogranite. Complex plutons vary in shape from circular to elliptical and some may be

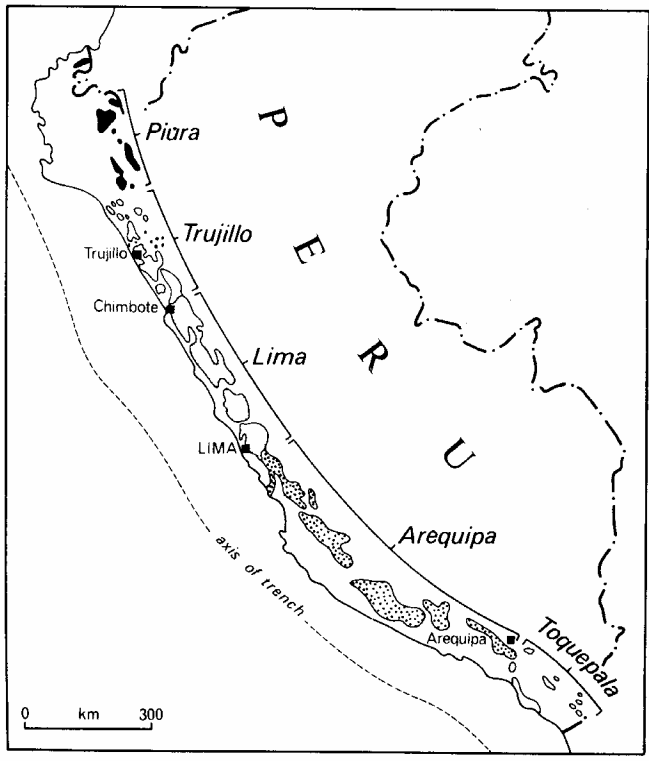


Figure 1. The major segments of the Andean Batholith of Peru.

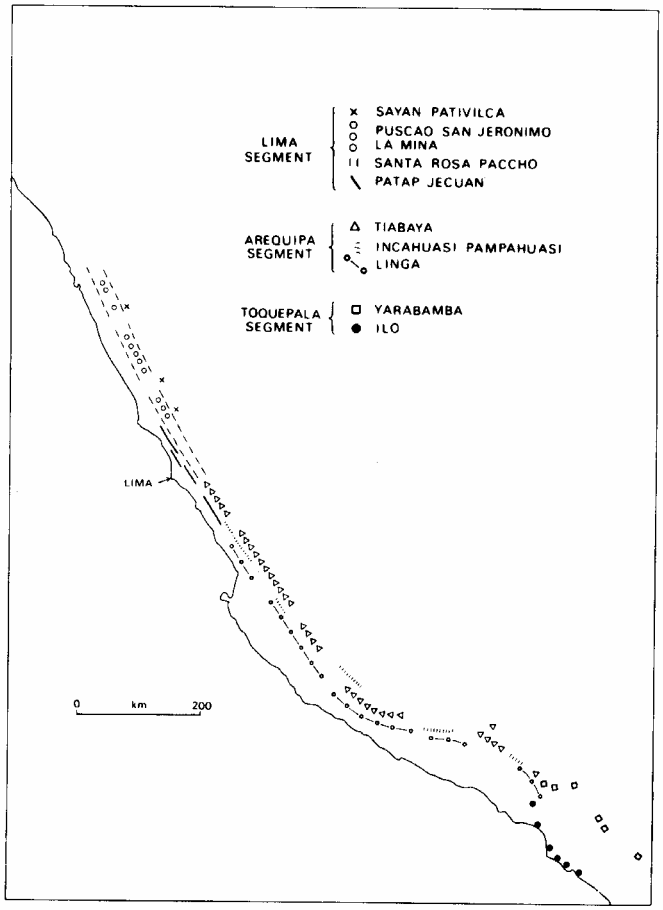


Figure 2. Distribution of the super-units within the Lima, Arequipa and Toquepala segments of the Andean Batholith.

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very large, up to 100 km in length and 35 km wide. Internal contacts within plutons are invariably sharp with no signs of chilling. Mafic enclaves are always present and are more abundant in tonalites and granodiorites than in monzogranites; although they are sometimes clearly derived from the volcanic envelope there are many cases where plutons emplaced into a non volcanic envelope have a similar density of mafic enclaves and there is consequently little doubt that the majority of them are cognate. The complex plutons most probably form as a result of multiple injection from a fraction-ating magma chamber.

Most plutons have steep sides and flat tops, and thermal aureoles are narrow. There is generally some evidence for a stoping mechanism of emplacement, and horizontal xenolith swarms resulting from the spalling of the roof are not uncommon.

Mafic dykes of andesitic composition, (Pitcher *et al.,* 1985) are present in all Super-units and, in some of the major tonalitic plutons, form substantial swarms. These dykes commonly have chilled margins against the granitoid host but in many cases the granite has subsequently invaded the dykes breaking them up into trails of mafic enclaves resembling xenolith swarms. Synplutonic dykes of this nature are of common occurrence in Andean terrains.

Most plutons are unfoliated but a few have foliated marginal zones and were probably emplaced as diapirs. Some plutons are strongly foliated on Andean trends and these are most abundant in southern Peru, being particularly notable in the Ilo Super-unit and the Torconta and Laderas plutons (Pitcher *et al.,* 1985). The foliations are confined to the plutons and are not present in the country rocks which suggests that the structures were developed as a result of emplacement.

The overall picture is one of passive emplacement by magmatic stoping at high levels in the crust, (Pitcher 1979), with little or no deformation and with very little thermal metamorphism. It will be seen later that similar features are present in Southeast Asian granites which are developed within a very different tectonic setting.

Mineralisation 'within the Andean Batholith is most notably of the porphyry copper type and it is clearly significant that all the major porphyry copper deposits in Southern Peru are hosted by the Yarabamba Super-Unit. Some local skarn mineralisation may be present in any region and gold vein mineralisation is well developed in southern Peru, but although there are hints of polymetallic vein mineralisation of similar type to that associated with the Tertiary plutonism, these are never developed on any scale and it may well be that the unroofing of the batholith has removed those deposits which may once have been developed.

The plutons were classified into categories which were eventually established as Super-units on the basis of their field characteristics and in particular of their granitic textures. It was found that the size, shape, crystal form and mineral association of the mafic minerals provided the most useful criteria, and were sufficient to establish a field classification which later geochemical and isotopic investigation has supported (Pitcher *et al.,* 1985). For the most part the granitoids are medium grained, grey, equigranular, biotite-hornblende-granodiorites and tonalites. The mafic minerals vary in their size and degree of crystallinity and range from perfectly euhedral separate crystals to shapeless aggregates of biotite and hornblende. Microscopically these granitoids exhibit a hypidiomorphic granular texture which is dominated by plagioclase laths, and with quartz and, in more acid rocks, orthoclase, occurring in interstices between the plagioclase. In the more acid monzogranites the textures are allotriomorphic and are dominated by quartz and K-feldspar. In these granites the K-feldspar is pink and megacrysts are commonly developed. Hornblende, however, is almost invariably present.

Secondary, or 2-phase textures as they have been designated (Cobbing *et al.,* 1986), are rare and tend to be confined to the more potassic Super-units such as Linga and Yarabamba. The general textural homogeneity probably reflects the lack of volatiles in the magmas.

## The Eastern Province in Peninsular Malaysia

The granitoids of this province (Fig. 3) are emplaced in a geological terrain of Carboniferous to Triassic shelf clastics with subordinate carbonates and locally abundant marine volcanics of intermediate to acid composition. The terrain as a whole, and the granitoids, appear to have some island arc affinities, (Mitchell 1977).

The granites occur as relatively small, elongate parallel batholiths of about 100 x 20 km arranged as clusters of batholiths and also as linear strings of isolated stocks. The size of the plutons which make up the batholiths ranges from 2-25 km with the smaller plutons having a circular outcrop, and the larger ones being elongate.

The range of lithologies within each batholith is mostly from diorite, to monzogranite, with monzogranite being the dominant lithology; gabbros, and even pyroxenites may occur in some bathotiths. The monzogranites are mainly coarse equigranular biotite granites which are commonly bordered by K-feldspar megacrystic hornblende-biotite granites. The megacrysts are usually grey or white in colour.

Super-units have not been recognised in the Eastern Province and each pluton seems to be individual and unique and is consequently distinguished as a granite unit. However, the plutons within each individual batholith seem to have a geochemical affinity which

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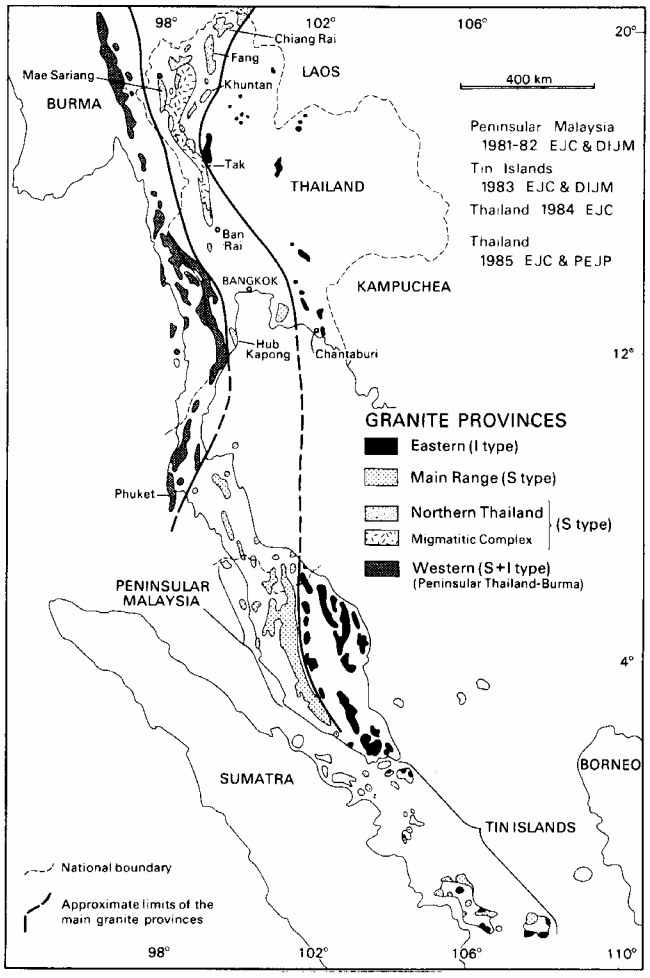


Figure 3. Distribution of granite provinces within the Southeast Asian Tin Belt.

distinguishes them from other batholiths (Cobbing *et al.* 1986). In this sense each batholith may be analogous to an Andean Super-unit but the precise equivalence of textures from different plutons is not present.

Plutons are mainly simple, being comprised of a single monzogranite unit but some are complex with margins of granodiorite or tonalite. Contacts are difficult to prove in jungle terrain but where seen they are invariably sharp. Mafic enclaves are abundant in tonalites and granodiorites but are uncommon in monzogranites. Mafic dykes are present in some plutons but are not common and some of them are post-plutonic. Synplutonic dykes, although developed locally, are uncommon.

The majority ofplutons are unfoliated although there are some which exhibit a patchy development of poorly oriented K-feldspar megacrysts. Exposures are generally not good enough in this terrain to establish the cause of the foliations present but many of them seem to be an alignment of primary texture minerals and were most probably developed as a result of pluton emplacement.

Cataclastic textures are also locally present and are clearly related to later fractures.

Most of the granites have a well developed primary texture with anhedral interlocking grain boundaries in an allotriomorphic granular texture. The textures of grano-diorites and tonalites are dominated by plagioclase in a hypidiomorphic granular texture with quartz and K-feldspar occurring in interstices in the plagioclase mesh. Microgranites, some megacrystic, are developed in some of the monzogranites. Such material, in anastamosing relationship with their hosts in marginal and apical zones gives rise to 2-phase rocks, but these are not extensive.

Mineralisation associated with the granites is usually of base metals in skarns, vein systems and breccia pipes. However some plutons are mineralised with tin which is present in chlorite bordered quartz veins but most typically as finely disseminated cassiterite in magnetite skarns at pluton boundaries.

Many of the geological features present are similar to those in Andean granitoids and like them there is every indication that the plutons were passively emplaced at high levels in the crust with little deformation and very little thermal metamorphism.

## The Main Range Province in Peninsular

Malaysia The granites of this province (Fig. 3) are emplaced into a terrain of mainly pelitic Clastics with subordinate limestones ranging from Ordovician to Devonian in age, and they produce restricted thermal aureoles in the country rocks. The granites occur mainly as large circular or elliptical plutons assembled in such close proximity as to form the great batholith which characterises much of the province. Isolated plutons and smaller batholiths continue northwards into Thailand and southward into Indonesia.

The compositional range is from granodiorite to monzogranite with very few examples being as basic as granodiorite. The granites are mainly coarse K-feldspar megacrystic biotite monzogranites with a primary texture characterised by interlocking grain boundaries giving a coarse allotriomorphic granular texture. The texture for each pluton is distinctive and each pluton is distinguished as a granite unit. The plutons which are coalesced into batholiths are distinguished in the field by the differences in their primary texture. Contacts between plutons, and with the country rocks are always sharp, and thermal aureoles narrow. Plutons are generally large, ranging from 15 to 50 km in maximum diameter with the larger plutons elongated along the regional strike. Each pluton normally consists of one granite unit and is therefore strictly speaking a simple pluton in spite of its size. However there is normally a great deal of variation

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| | Main Range Province | Eastern Province | Peru |
|---|---|---|---|
| **Age of Envelope** | Cambrian-Devonian | Carbon-iferous-Triassic | Cretaceous |
| **Lithology of Envelope** | Clastic sedi-mentary rocks with shelf carbonates | clastic sedi-mentary rocks with shelf carbonates and marine volcanics | Marine volcanics |
| **Granite Type** | S | I | I |
| **Range of Lithology** | granodiorite-monzogranite | gabbro-monzogranite | gabbro-monzogranite |
| **Distribution of Lithology** | unimodal contrasted | bimodal spectrum | continuous |
| **Predominant Lithology** | biotite monzogranite | biotite monzogranite | hornblende biotite tonalite. |
| **K-feldspar Megacrysts** | always present microcline perthite | present in some rocks orthoclase perthite | present in a few monzo-granites orthoclase perthite |
| **Hornblende** | absent | commonly present | always present |
| **Muscovite** | commonly present | very rare | absent |
| **Textures** | primary with abundant secondary | primary with some secondary | primary only |

| | Main Range Province | Eastern Province | Peru Province |
|---|---|---|---|
| **Cognate Enclaves** | sedimentary | mafic | mafic |
| **Mafic dykes** | absent | present | abundant |
| **Type of pluton** | simple with abundant secondary textural variants | simple and complex | complex and simple |
| **Type of Batholith** | one major batholith of large simple plutons | many minor batholiths of small simple and complex | one major bath-olith of large and small simple and complex |
| **Super-units** | absent | plutons absent | plutons present |
| **Granite age** | 200-230 Ma | 200-280 Ma | 60-100 Ma |
| **Initial ratio 87Sr/86Sr** | 0.711-0.719 | 0.708-0.712 | 0.704 |
| **Discordant Zircon age Ma** | 1500-1700 | 750-1350 | None |
| **T Nd/DM age** | 1300-1800 | 900-1400 | None |
| **Mineral-ization** | Sn W Ta greisen-bordered veins | Cu Pb Zn Mo Sn W, veins and skarns | Cu Mo por-phyry Cu W skarns Au/Ag veins. polymetallic veins. |

Table 1. Features of Granites from Peninsular Malaysia and the Peruvian Andes.

within plutons resulting from the development of secondary magmatic textures and the formation of a suite of derivatives which may be broadly classified as granite porphyries. Such 2-phase rocks range from host granite with small anastamosing veinlets or intergranular films of microgranite, through heterogeneous crowded porphyries with varying proportions of megacrysts derived from the primary texture host. These in turn are sharply cut by microgranite bodies of varying size which carry few megacrysts. The variants with secondary textures are usually more differentiated than the primary textured host and mineralisation is commonly associated with the microgranites and with the granitic porphyries.

Neither mafic enclaves nor mafic dykes are present in Main Range granites, metasedimentary enclaves may be present but these do not appear to resemble the rocks of the local envelope and are probably derived from lower crustal levels, perhaps even from the zone of magmagenesis.

Plutons in the Main Range are generally undeformed and any deformation present is clearly related to cataclastic degradation along faults and fractures.

Mineralisation present is dominated by tin, present mainly as cassiterite, in greisen-bordered vein swarms in the apical zones of some granites. The importance of tungsten increases towards the north and in some workings monazite and tantalum are significant byproducts.

The geological features of Main Range granites are consistent with their having been emplaced passively at high levels in the crust. However, they are geologically and chemically clearly of S-type (Table 1, Cobbing *et al.*

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1986) and in this respect they contrast with the granitoids of the Eastern Province and the Andes.

## Discussion

There is a clear geological affinity between the granites of the Eastern Province and those of the Andes in that they are both I-types in the terms of Chappell and White 1974 and have all the geological features characteristic of granitoids of this class. There are, however, certain important differences (Table 1). The Eastern Province is dominated by monzogranites many of which are biotite granites, whereas the Andean granitoids are dominated by tonalites and all rocks contain hornblende. The distribution of lithologies is bimodal in the Eastern Province and continuous in the Andes, and whereas the Andean Batholith is characterised by Super-units these are absent in the Eastern Province. Both are most probably derived from an igneous source region but whereas in the Andes this may have been of juvenile material or even of mantle origin (Cobbing & Pitcher 1983) that from the Eastern Province may have had a long residence time in the crust. Liew (1983), and Liew and McCulloch (1985), have shown by isotopic analyses of zircons and of Nd isotopes that the source region of Eastern Province granitoids is at least in part of mid-Proterozoic age and consequently the crustal provenance of these granites is now well established.

This conclusion is supported by the geochemical signature (Fig. 4) which shows that the Andean granites are more primitive in their trace element assemblage than those of the Eastern Province. In fact for a number of elements (Ta, Y and particularly Ce) the signature of the Eastern Province is closer to the S-type granites of the Main Range.

The Main Range granitoids are typically of S-type in their geological and geochemical affinities (Table 1 and Cobbing *et al.* 1986) and there is no difficulty in distinguishing them from Andean or Eastern Province granitoids. It is consequently surprising to find that on the multi-element plot (Fig. 4) the abundances for most elements are very close to those for the Eastern Province. It would appear to suggest that the source regions for Eastern and Main Range Provinces are compositionally more similar to one another than are the source regions of the Eastern Province and the Andes. This inference may be of value for interpreting the tectonic setting of the orogenic activity which produced the granites.

Pitcher (1983) has suggested that Andean I-type granites are associated with subduction of oceanic crust at continental margins but that granitoids with features similar to those of the Eastern Province, which he designates as 'Caledonian I,type', are associated with post closure uplift or extensional tectonics. S-type granites were considered as resulting from continental collision. This concept was extended by Pearce *et al.* 1984 who considered that the trace element composition of

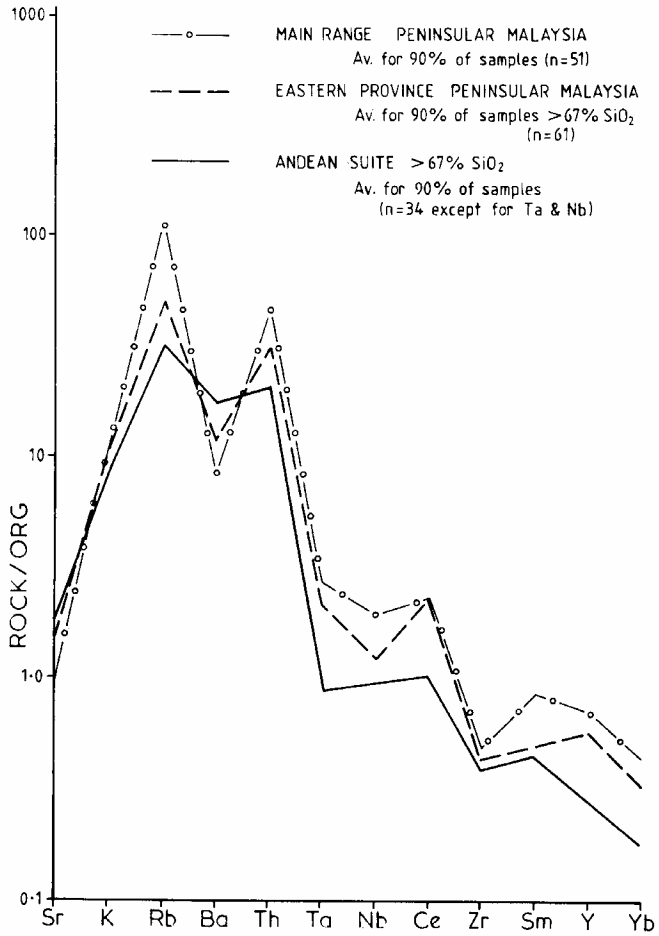


Figure 4. Hypothetical Ocean Ridge Granite (ORG) normalized geochemical patterns for the Main Range and Eastern Provinces of Peninsular Malaysia compared with the Andean Batholith in Peru. (Normalizing factors from Pearce *et al.* 1984).

granitic rocks was sufficiently characteristic to denote the tectonic setting of their formation, and on their Rb vs (Nb+Y) (Fig. 5) discriminant plot they distinguished three fields, syn collisional, volcanic arc and within plate which correspond to the S-type 1-type and A-type granites of White and Chappell (1983) and of Pitcher (1983) except that Pitcher's post collisional granites are not distinguished. The Main Range S-type granites plot mainly in the Syn Collisional field on the Rb vs (Nb+Y) (Fig. 5) diagram and overlap into the Volcanic Arc and Within Plate field, while the Eastern Province I-types plot mainly within the Volcanic Arc field but with substantial overlap into the Within Plate field (Cobbing *et al.* 1986) Andean granites plot well within the Volcanic Arc field and do not encroach upon the Within Plate field.

The multi-element plots and the Rb vs (Nb+Y) diagrams (Figs. 4 and 5) do satisfactorily distinguish the three granite populations under consideration on a compositional basis; whether they also define the tectonic setting for their formation may, however, be doubted. The compositional features could be equally well

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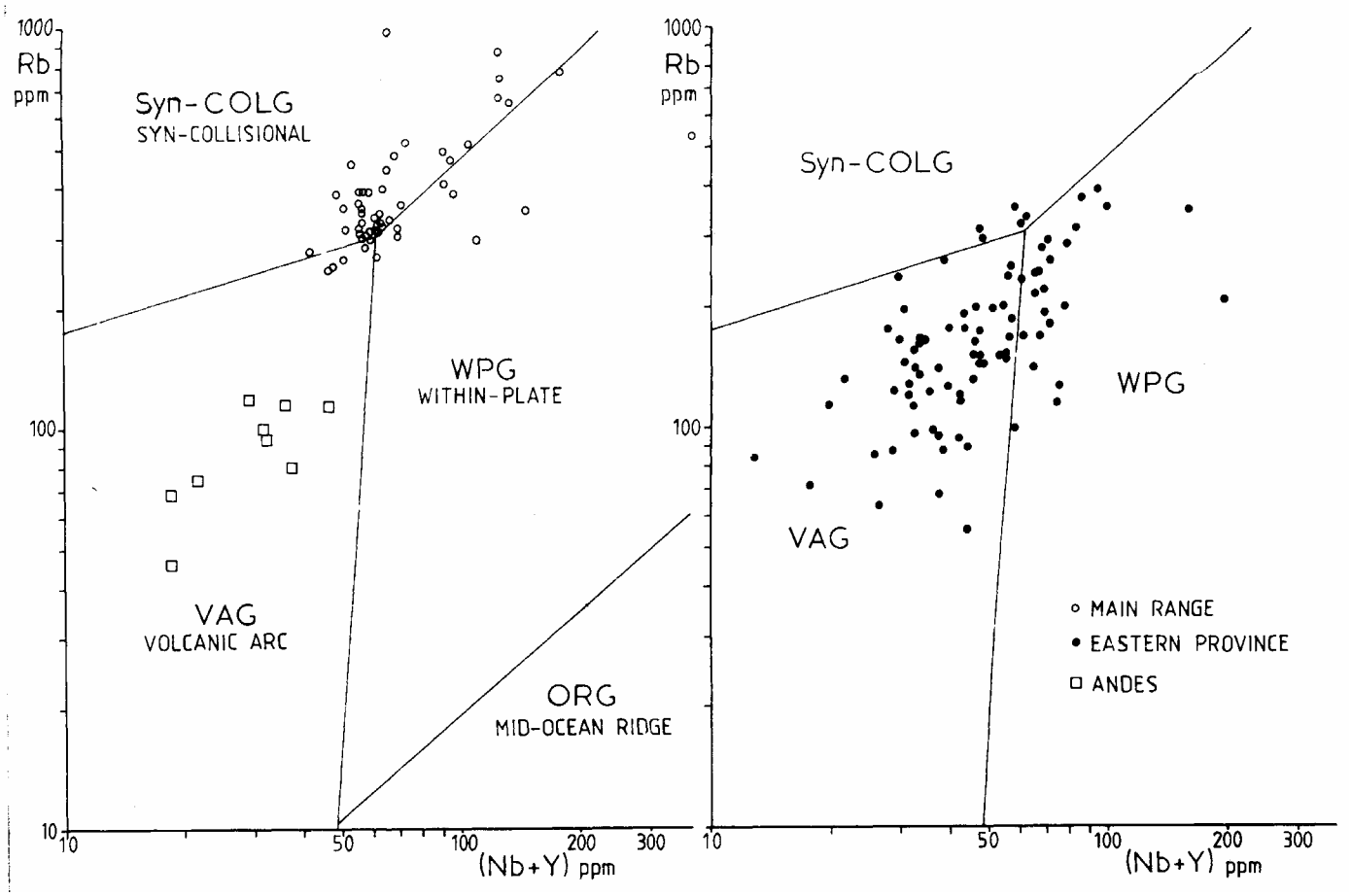


Figure 5. Rb vs (Nb+Y) discriminant plots for the granite provinces of Peninsular Malaysia and for the Andean Batholith showing the tectonic classification suggested by Pearce *et al.* (1984). Data points for the Andes, Tiabaya (Arequipa), Linga (Pisco), Senal Blanca (Trujillo). Pitcher *et al.* (1985).

explained by variations in the proportions of primitive to evolved crustal material in the source regions, a possibility supported by the available isotopic evidence (Table 1).

The tectonic setting of subduction of oceanic crust at a continental margin for the formation of the Andean granitoids is clear enough and the isotopic data (Table 1) supports a model of remelting of subducted juvenile crust or mantle. It is possible that the development of Super-units reflects wholesale, episodic batch melting in a uniform, primitive source region and is characteristic of this tectonic setting.

In Southeast Asia the granite provinces are clearly linked with different geological terrains which form separate parallel strips bounded by structural discontinuities at the western margin of the Sundaland craton except in the Tin Islands (Fig. 3), where the Main Range and Eastern Provinces Overlap. This geometry favours a collage interpretation, perhaps culminating with fusion of the disparate terrains and the production of granites at about 200 Ma. The currently favoured model (Stauffer 1983) is that elongate strips of crust were rifted off a passive continental margin, probably Gondwana and drifted northward across a Palaeozoic ocean, Palaeotethys, finally accreting against Eurasia with the formation of sutures marking the site of former oceanic domains.

The formation of a volcanic arc within one terrain and its absence in another is compatible with sucha model, but although granites seem to match their terrains, major plutonism in the two terrains coincided at from 230-200 Ma (Liew & Page 1985) and was presumably triggered by the approach and fusion of the terrains. The more extended history of plutonism in the Eastern Province back to 280 Ma (Hutchison 1977) suggests some pre closure plutonism in that Province which provided granites of similar character to the post-closure plutonism. This may mean that the tectonic setting for the two provinces is the same, i.e. collisional, but that p!utonism began earlier for reasons which are not currently understood.

Whereas it is difficult to suggest a satisfactory tectonic setting for granite generation in Southeast Asia on the basis of the information at present available, the geology and geochemistry of the granites themselves are distinctive enough to illuminate at least some of the problems. It is clear from the Rb vs (Nb+Y) (Fig. 5) and the multielement plots (Fig. 4) that both the Eastern Province and the Main Range granitoids are more

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enriched in LIL elements than are Andean granitoids. Moreover, the trace element profile of Eastern Province granitoids (Fig. 4), is closer to that of the Main Range granitoids than to the An&an granitoids. The 87Sr86Sr initial ratios (Table 1) indicate that both the Malaysian granite provinces have a crustal signature with that for the Main Range province being the stronger. Similarly the discordant zircon ages from the two provinces (Liew 1983; Liew & Page 1985) and the T Nd/DM data (Liew and McCulloch 1985) suggest that mid-Proterozoic crust was available in the source regions and contributed to the formation of both granite provinces. The close correspondence between the discordant zircon ages and T Nd/DM ages for the Main Range and Eastern Provinces respectively (Table 1) suggests that the crustal source regions for each of the two provinces were formed in two distinct mid-Proterozoic episodes. It may be speculated that these source regions were compositionally contrasted and that it is this which has controlled the contrasting granite geology of the two provinces irrespective of whatever tectonic process may have triggered melting in the source region.

## Conclusion

Whereas the tectonic settings of continent ocean convergence and continental collision may plausibly account for the generation of Andinotype I-type granitoids and Malaysian S-type granites, the information at present available suggests that Eastern Province I-type granitoids were generated at the same time and in the same tectonic setting as the Main Range Province S-types. Consequently the tectonic setting does not account for the observed difference in granite typology which is more likely to have been controlled by compositional differences in the source regions mobilized during magmagnesis. This suggests that the hypothesis of Pitcher (1983) and Pearce *et al.* (1984) that the geological features and trace element composition of granitic rocks denotes their tectonic setting should be treated with caution, at least with respect to Eastern Province granitoids and possibly also to Caledonian I-type granites elsewhere. In evaluating such problems it is essential that nO single data set be considered in isolation but rather in conjunction with all other criteria, particularly stratigraphical and palaeontological.

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## References

Chappell, B.W. and White, A.J.R. 1974. Two contrasting granite types *Pacific Geology, 8,* 173-4.

Cobbing, E.J. & Pitcher, W.S. 1983. Andean plutonism in Peru and its relationship to volcanism and metallogenesis at a segmented plate edge. J.A. Roddich (ed.), *Circum-Pacific Plutonic Terranes Geological Society of America, Memoir, 159,* 277-291.

Cobbing, E.J., Mallick, D.I.J., Pitfield, P.E.J. & Tech. L.H. 1986. The granites of the Southeast Asian Tin Belt. *Journal of the Geological Society of London, 143, 537-550.*

Hutchison, C.S. 1977. Granite emplacement and tectonic sub-division of Peninsular Malaysia. *Bulletin of the Geological Society of Malaysia 9,* Special Circum-Pacific volume, 18%207.

Ishihara, S., Sawato, H. & Shibata, K. 1980. Granites and Sn-W deposits of Peninsular Thailand, In: Ishihara, S., and Takenouchi, S., (eds.), *Granitic magamatism and related mineralization. Mining Geology Special Issue 8,* 223-241.

Liew, T.C. 1983. Petrogenesis of the Peninsular Malaysian granitoid batholiths. *Unpublished PhD thesis, Australian National University, Canberra.*

Liew, T.C. & Page, R.W. 1985. U-Pb zircon dating ofgranitoid plutons from the West Coast Province of Peninsular Malaysia. *Journal of the Geological Society of London, 142,* 516-526.

Liew, T.C. & McCulloch, M.T. 1985. Genesis of granitoid batholiths of Peninsular Malaysia and implications for models of crustal evolution: Evidence from a Nd-Sr isotopic and U-Pb zircon study. *Geochimica et Cosmochimica Acta 49,* 58%600.

Mitchell, A.H.G. 1977. Tectonic settings for emplacement of Southeast Asian tin granites. *Bulletin of the Geological Society of Malaysia 9, Special Circum-Pacific volume,* 123-140.

Mukasa, S.B. 1986. Zircon U-Pb ages of super-units in the Coastal batholith, Peru: Implications for magmatic and tectonic processes. *Geological Society of America Bulletin, 97,* 241-254.

Pearce, J.A., Harris, N.G.W. & Tindle, A.S. 1984. Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. *Journal of Petrology 25,* 956-983.

Pitcher, W.S. 1979. The nature, ascent and emplacement of granite magmas. *Journal Geological Society of London, 136,* 62%662.

Pitcher, W.S. 1983. Granite type and tectonic environment. In Hsu, K, (ed.), *Mountain Building Processes.* Academic Press, London, 19-40.

Pitcher, W.S., Atherton, M,P., Cobbing, E.J. & Beckinsale, R.D. 1985. *Magmatism at a plate edge - The Peruvian Andes.* Blackie, UK/Halsted Press, USA.

Stauffer, P.H. 1983. Unravelling the mosaic of Palaeozoic crustal blocks in Southeast Asia. *Geologische Rundschau, 72,* 1061 - 1080.

White, A.J.R. & Chappell, B.W. 1983. Granitoid types and their distribution in the Lachlan Fold Belt, southeastern Australia Geological Society of America, Memoir, 159, 21-34.

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*Read at the Annual Conference of the Ussher Society, January 1987*

# Chronology of magmatism in south-west England: the minor intrusions

D.P.F. DARBYSHIRE
T.J. SHEPHERD

Darbyshire, D.P.F. and Shepherd, T.J. 1987. Chronology ofmagmatism in south-west England: the minor intrusions. *Proceedings of the Ussher Society, 6,* 431-438.

Rb-Sr isochron data together with major, trace element and rare earth element geochemistry are presented for the Li-mica granite at Tregonning, Cornwall and for the minor Hercynian intrusions of south-west England -Carn Marth, Castle an Dinas St Austell, Kit Hill, Hingston Down and Hemerdon Ball. This work completes the Rb:Sr study of the Cornubian batholith and the age of 280 ±4 Ma for the Tregonning granite supports the earlier conclusion that the major plutons were emplaced c290 - 280 Ma. The geochemical and isotopic evidence for the minor intrusions implies that their relationship both temporal and genetic is not straightforward.

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## Introduction

A Rb-Sr study of Hercynian magmatism in south-west England (Darbyshire and Shepherd 1985) established that the major plutons were emplaced circa 290 - 280 Ma and that the inferred sequence of intrusion showed no geographic pattern. High initial $^{87}Sr/^{86}Sr$ (0.710 - 0.716) ratios are compatible with the S-type and peraluminous mineralogical characteristics of the granites. REE distributions are consistent with those for normal leucogranites, in that they have a high LREE/HREE ratio and negative europium anomaly. However, the REE profiles for Bodmin and Carnmenellis contrast markedly with those of Lands End and Dartmoor, implying differences both in the chemistry of the source region and in conditions of crystallisation.

This paper presents the results of the second phase of this study - the age, the Rb-Sr systematics and the geochemistry of the Li-mica granite at Tregonning and the minor granite intrusions: Cam Marth, Castle an Dinas St Austell, Kit Hill, Hingston Down and Hemerdon Ball. It is hoped that such information will contribute to a greater understanding of the area and provide the basis for constructive discussion.

## Sampling and sample preparation

The locations of sample sites, together with grid co-ordinates, are given in Appendix 1. The granite samples were jaw-crushed and split, and representative 100-200g subsamples finely ground to give -200 mesh powder for isotopic and geochemical analysis.

## Analytical techniques

Rb and Sr concentrations and Rb/Sr atomic ratios were determined by X-ray fluorescence spectrometry on 20g pellets pressed to 15 tonnes from -200 mesh powder. Each batch of samples included International reference standards, and appropriate corrections were made for instrumental dead time, background and line interferences (Pankhurst & O'Nions 1973). Several of the Tregonning granite samples have very high $^{87}Rb/^{86}Sr$ ratios (90-130) beyond the range covered by the XRF calibration standards. Therefore to minimise any systematic error the Rb and Sr concentrations and Rb/Sr ratios for all the Tregonning samples were determined by standard isotope dilution techniques using $^{84}Sr$ and $^{87}Rb$ isotopically-enriched spikes. After chemical separation involving ion exchange procedures, strontium was loaded on single tantalum filaments prepared with phosphoric acid. Similarly prepared filaments were used for the analysis of Rb in the Tregonning samples. Isotopic measurements were made on an automated VG Micromass 30cm radius, 90º magnetic field sector mass spectrometer operated at 7.2 Kv acceleration voltage.

Errors are quoted throughout as two standard deviations and the decay constant used in the age calculation is the value recommended by the IUGS Subcommission for Geochronology (Steiger and Jager 1977) 8?Rb = 1.42 x $10^{-11}a^{-1}$. Analytical uncertainties are estimated at 0.02% for $^{87}Sr/^{86}Sr$ and 1.0% for $^{87}Rb/^{86}Sr$. During the period of this study, the average $^{87}Sr/^{86}Sr$ determined for NBS 987 isotopic strontium standard was 0.71032 -+ 0.00002 (2 SEM, 16 analyses) and for Eimer and Amend SrCO3 was 0.70808 -+ 0.00002 (2 SEM, 21 analyses).

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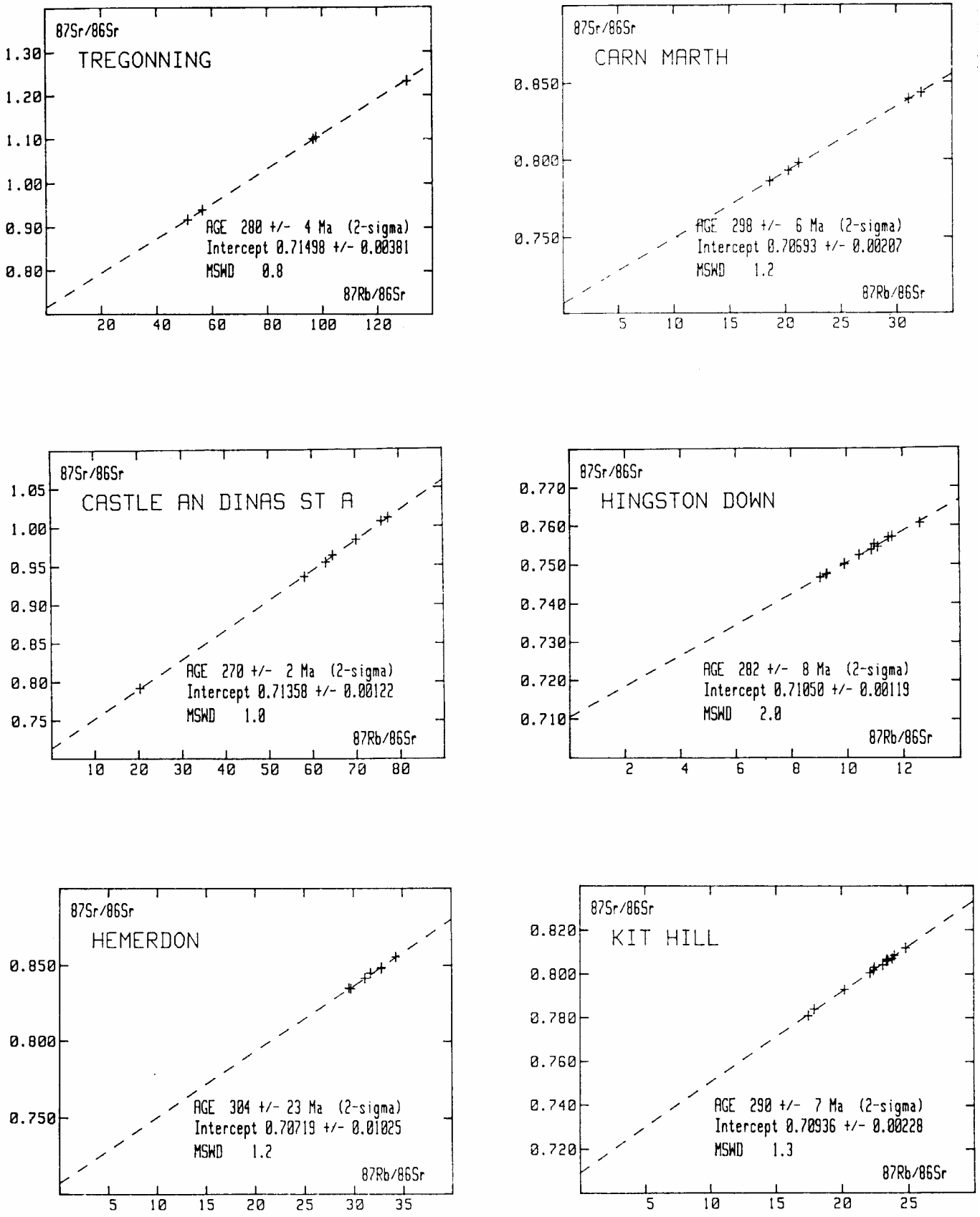


Figure 1. Whole rock isochrons for the minor intrusions.

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Regression lines are calculated using a least squares method based on York (1969). As a measure of the goodness of fit of the regression lines, the mean square of weighted deviates (MSWD) is employed (Brooks *et al.* 1972). Where the observed value exceeds a limiting or critical value (3.0) the scatter of data cannot be entirely accounted for by experimental and sampling errors. The data do not then satisfy the criteria for an isochron, and the values for age and initial ratio should be viewed with caution.

Whole rock geochemical analyses were carried out by X-ray fluorescence spectrometry (MESA, Nottingham) using fused beads for major and minor elements, and pressed powder pellets for trace elements. Analysis of the REE (La, Ce, Pr, Nd, Sm, Eu, Gd, Dy, Ho, Er, Yb, Lu) were obtained by inductively coupled plasma source emission spectrometry at Royal Holloway and Bedford New College, London (Walsh *et al.* 1981).

## Results and Discussion

*Tregonning granite* The Tregonning granite forms part of the Tregonning-Godolphin granite complex described by Stone (1975) and comprises a non-porphyritic lithium rich, topaz bearing granite. Seven samples were collected from the coastal exposure between Praa Sands and Legereath Zawn. However after thin section examination two were rejected as unsuitable for Rb-Sr analysis. The Rb-Sr data for the five analysed samples (Table 1) yield a well defined isochron giving an age of 280 $\pm$ 4 Ma with initial $^{87}Sr/^{86}Sr$ ratio 0.71498 $\pm$ 0.00381, MSWD 0.8 (Fig. 1).

The Tregonning samples are enriched in $P_20_5$, Nb, Rb, and Ta, are low in $TiO_2$ and Mg and are considerably impoverished in REE compared to the biotite granites. The chondrite-normalised REE pattern for T6B (Fig. 2a) shows a distinctive 'seagull' shape pattern in contrast to the steeply dipping profiles obtained for the other major plutons (Darbyshire and Shepherd 1985). Seagull shape REE profiles have been noted by other workers and appear characteristic of highly evolved leucogranites associated with Snow mineralisation. For example, Sn-W granites of Jurassic age in China (Le Bel *et al.* 1984) and Sn granites of Cretaceous age in Alaska (Hudson and Arth 1983) display all the same features.

Perhaps more relevant to this discussion are the Li-mica, topaz granites of the Mount Pleasant area of New Brunswick, Canada (Taylor *et al.* 1985). As in SW England they are genetically associated with larger masses of biotite - muscovite leucogranite. Though the two groups show few differences in major element chemistry, their trace element characteristics are quite distinctive. The Li-mica granites are appreciably enriched in Li, Rb and F and whilst the chondrite normalised REE values are markedly different the REE profiles are almost indistinguishable from those of Tregonning. The processes which lead to LREE and Eu

Table 1. Rb:Sr data for the Tregonning granite

| Sample No. | Rb ppm | Sr ppm | $^{87}Rb/^{86}Sr$ | $^{87}Sr/^{86}Sr$ |
|---|---|---|---|---|
| T1 | 1334 | 31.0 | 130.8 | 1.23262 |
| T3 | 1157 | 67.0 | 51.00 | 0.91730 |
| T4 | 970 | 51.0 | 56.28 | 0.93220 |
| T6A | 1113 | 34.6 | 96.61 | 1.10040 |
| T6B | 1161 | 35.6 | 97.60 | 1.10453 |

depletion coupled with HREE enrichmenrare somewhat uncertain and as yet there is no concensus of opinion. However it is recognised that extreme fractional crystallization, liquid-state diffusion and volatile transfer play a crucial role (Le Bel *pers comm.).* For Tregonning, the low ΣREE content (12.16ppm) would imply that the profile reflects the early crystallisation of accessory minerals.

*Carn Marth Granite*

The Carn Marth granite is separated from the main Carnmenellis pluton by a narrow trough of aureole rocks, however mine workings indicate that the granites are interconnected at relatively shallow depth. Five samples of coarse grained biotite granite yield a Rb-Sr whole rock isochron age of 298 ±6 Ma with an initial 878r/S6Sr ratio 0.70693 ±0.00207 and MSWD 1.2 (Fig. 1; data in Table 2). This age is statistically within error of that obtained for the mineral isochron from a sample of the Carnmenellis granite (C 1:290 ±2 Ma) interpreted by Darbyshire and Shepherd (1985) as giving a better estimate of the age of the Carnmenellis granite than the whole rock regression line (285 ±19 Ma) which indicated slight open system behaviour. However the initial ratio is significantly lower than that obtained for C 1 (0.7126 ±0.0003).

Geochemically the Cam Marth samples are richer in MgO, Cs, Nb and Rb than the Carnmenellis granite, while the REE profiles are extremely similar (Fig. 2b).

*Castle an Dinas, St Austell*

Seven samples from the Castle an Dinas granite, out-cropping to the north of the main St Austell granite mass, define an Rb-Sr isochron of age 270 ±2Ma with an initial 878r,/S6Sr ratio 0.71358 ±0.00122 and MSWD 1.0 (Fig. 1; data in Table 3). Manning and Exley (1984) have recognised two stages of magmatic activity in the St Austell area, the first represented by intrusion of several phases of biotite granite and the second by a later intrusion of non-megacrystic lithium mica granite, now

Table 2. Rb:Sr data for the Carn Marth granite

| Sample No. | Rb ppm | Sr ppm | $^{87}Rb/^{87}Sr$ | $^{87}Sr/^{86}Sr$ |
|---|---|---|---|---|
| CM2 | 569 | 78.3 | 21.24 | 0.7977 |
| CM3A | 605 | 55 | 32.21 | 0.84313 |
| CM3B | 603 | 56.8 | 31.08 | 0.83911 |
| CM4 | 560 | 80.3 | 20.32 | 0.79272 |
| CM5 | 525 | 82.2 | 18.62 | 0.78584 |

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designated topaz granite (see Hill and Manning 1987), which crystallized from a volatile-rich residual differentiate of the biotite granite magma. The Castle an Dinas biotite granite outcrop lies within the metasomatic aureole associated with the topaz granite, and moreover, altered non-megacrystic lithium mica granite is found in several levels of the Castle an Dines tungsten mine (Dines 1956).

The St Austell biotite granite yielded an isochron of age 285 ±4 Ma (Derbyshire and Shepherd 1985), The majority of the samples were collected from the Luxulyan Quarry well away from the postulated aureole of the topaz granite. However a sample from a borehole close to the limit of the aureole contained a lithium mica and has suffered incipient hydrothermal alteration, omitting this sample from the regression of St Austell biotite granite data makes little difference to the age: 288 -+ 6 Ma.

The Castle an Dines samples differ geochemically from the Luxulyan samples in having higher A 1203 and P205, and lower TiO2, MgO, and CaO. They are richer in Rb and Sn, poorer in Be, Ce, Nb, Ta, Th, Y and Zr. On plots of TiO2 vs Zr and Zr vs K/Rb they lie within the field of Li-mica granites. However on a plot of Y vs Nb they remain with the biotite granites. These contradictory characteristics are probably therefore a consequence of metasomatism due to overprinting by the adjacent topaz granite. While the REE profile for the Luxulyan biotite granite is comparable to those for Lands End and Dartmoor, the pattern obtained for the Castle an Dinas granite is almost indistinguishable from those for Bodmin and Carnmenellis (Figure 2c). This would imply a similar history of fractional crystallisation.

The 270 Ma age obtained for the Castle an Dinas samples could be interpreted as the resetting of the 285 Ma age by the later intrusion of topaz granite. Alternatively it may reflect a real interval of 15 - 20 Ma between separate phases of biotite granite. Lack of suitable material has hindered the determination of the age of the topaz granite and until this problem has been resolved the interpretation of the Castle an Dinas isochron remains equivocal.

Dines (1956) states that topaz rich elements of the Castle an Dines granite postdate a wolfram lode, cutting it off completely and in places granite veins cross the lode into country rock. The 270 Ma age of the granite thus gives a

Table 3. Rb:Sr data for Castle an Dinas St Austell

| Sample No. | Rb ppm | Sr ppm | $^{87}Rb/^{86}Sr$ | $^{87}Sr/^{86}Sr$ |
|---|---|---|---|---|
| E 34995 | 1050 | 150 | 20.38 | 0.79196 |
| E 34996 | 975 | 37.5 | 77.46 | 1.0113 |
| E 36069 | 964 | 44.2 | 64.71 | 0.96318 |
| E 36070 | 962 | 40.8 | 70.1 | 0.98337 |
| MR 30153 | 924 | 43.5 | 63.09 | 0.95438 |
| MR 30154 | 903 | 46 | 58.17 | 0.93593 |
| MR 30155 | 1002 | 39.4 | 75.88 | 1.0069 |

Table 4. Rb:Sr data for the Kit Hill granite

| Sample No. | Rb ppm | Sr ppm | $^{87}Rb/^{86}Sr$ | $^{87}Sr/^{86}Sr$ |
|---|---|---|---|---|
| KH1 | 469 | 78.2 | 17.48 | 0.78104 |
| KH2 | 526 | 61.9 | 24.84 | 0.81191 |
| KH3 | 530 | 66.1 | 23.41 | 0.8068 |
| KH4 | 468 | 76.2 | 17.92 | 0.78397 |
| KH5 | 564 | 68.8 | 23.98 | 0.8085 |
| KH6 | 502 | 72.4 | 20.22 | 0.79298 |
| KH7 | 531 | 66 | 23.5 | 0.80618 |
| KH8 | 565 | 74.5 | 22.15 | 0.8006 |
| KH9 | 544 | 70.7 | 22.47 | 0.80306 |
| KH10 | 551 | 67.8 | 23.83 | 0.80712 |
| KH11 | 551 | 71.7 | 22.41 | 0.8018 |
| KH12 | 554 | 70 | 23.11 | 0.80418 |
| E 38454 | 522 | 65.2 | 23.39 | 0.80592 |

minimum estimate of the age of tungsten mineralisation in the St Austeli area. This compares with the age of circa 270Ma obtained from fluid inclusion Rb-Sr isochrons for the main stage polymetallic mineralisation in the Camborne - Redruth and Lands End areas (Darbyshire and Shepherd 1985).

*Kit Hi//Granite*

Thirteen samples from this pluton yield an isochron of age 290 ±7 Ma with an initial S7Sr/86SR ratio 0.70936 ± 0.00228; MSWD 1.3 (Fig. 1; data in Table 4). While recognised as a separate outcrop, the Kit hill granite is considered to form part of a hidden granite ridge between the Dartmoor and Bodmin granites. The age statistically overlaps the preferred whole rock-mineral isochron age of 287 ±4 Ma determined for the Bodmin granite (Darbyshire and Shepherd 1985). The steep chondrite-normalised REE pattern for sample KH5 (Fig. 2d) with its small europium anomaly closely resembles the profiles obtained for the Carnmenellis and Bodmin grafiites (Darbyshire and Shepherd 1985'5. However the total rock geochemistry does not show a particular affinity to either Bodmin or Dartmoor

*Hingston Down Microgranite*

The Hingston Down microgranite lies 3 km to the east of the Kit Hill granite and has also been interpreted as an

Table 5. Rb:Sr data for Hingston Down microgranite

| Sample No. | Rb ppm | Sr ppm | $^{87}Rb/^{86}Sr$ | $^{87}Sr/^{86}Sr$ |
|---|---|---|---|---|
| HQ1 | 363 | 91 | 11.6 | 0.75712 |
| HQ5 | 360 | 101 | 10.42 | 0.75242 |
| HQ6 | 341 | 110 | 9.037 | 0.7467 |
| HQ7 | 374 | 98 | 11.09 | 0.7545 |
| HQ8 | 404 | 108 | 10.86 | 0.75373 |
| HQ9 | 413 | 110 | 10.96 | 0.75519 |
| HQ10 | 321 | 103 | 9.024 | 0.74677 |
| HQll | 353 | 111 | 9.243 | 0.74751 |
| HQ12 | 354 | 111 | 9.273 | 0.74765 |
| HQ13 | 419 | 106 | 11.48 | 0.75687 |
| E 38455 | 350 | 102 | 9.904 | 0.75021 |
| E 38456 | 351 | 103 | 9.905 | 0.75002 |
| E 38457 | 404 | 93.4 | 12.6 | 0.76058 |

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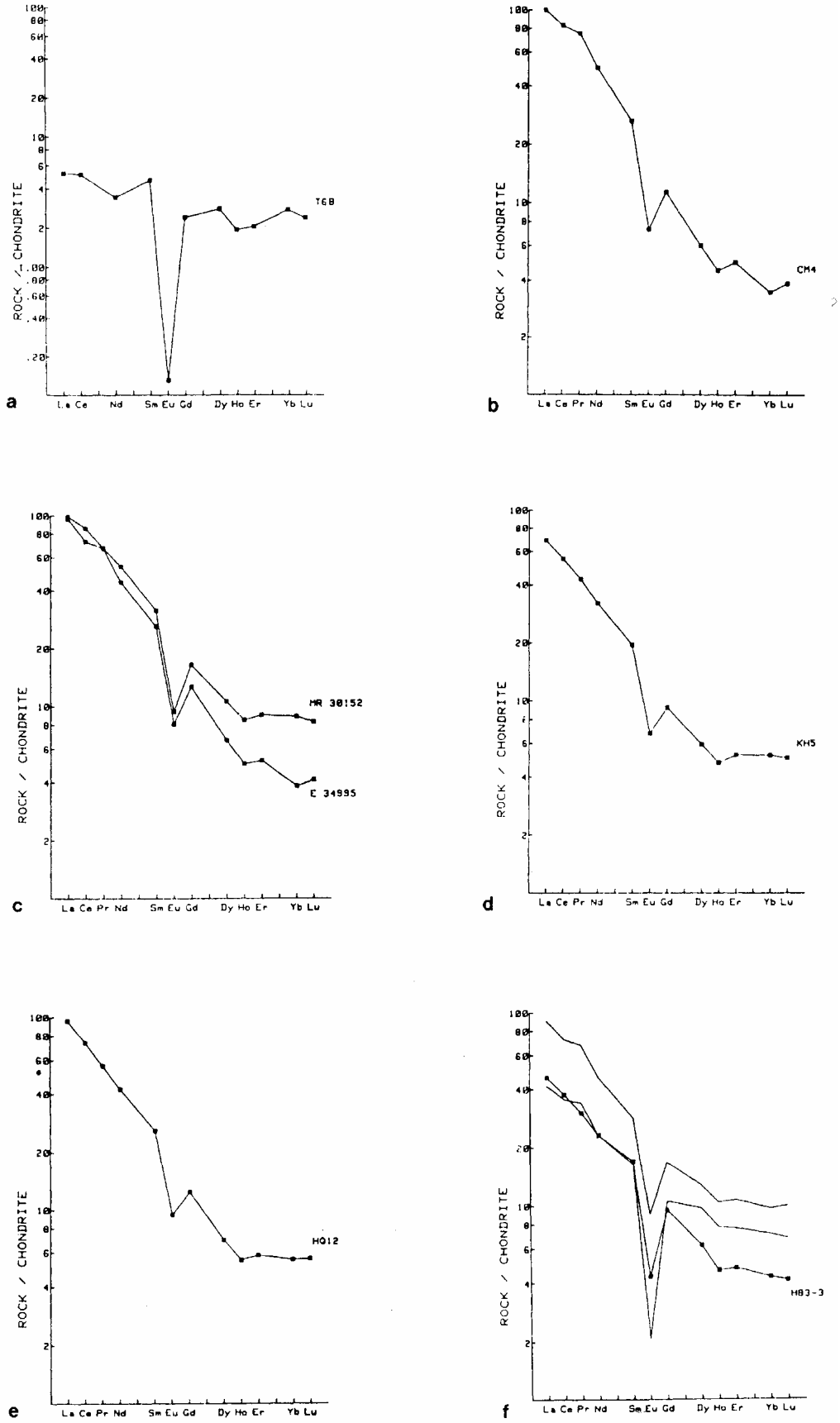


Figure 2. Rare earth element profiles. a) Tregonning granite; b) Carn Marth granite; c) Castle an Dinas, St Austell; d) Kit Hill granite; e) Hingston Down microgranite; f) Hemerdon Ball granite showing reference profiles for the Dartmoor granite (Darbyshire and Shepherd 1985).

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outcrop of the subsurface granite ridge between Dartmoor and' Bodmin. Thirteen samples define an isochron of age 282 ±8 Ma and initial $^{87}Sr/^{86}Sr$ ratio 0.71050 ±0.00119, MSWD *2.0* (Fig. 1; data in Table 5). This is indistinguishable within error from that obtained for Kit Hill.

A study of the normative compositions and trace element geochemistry of the microgranite together with those of the neighbouring Kit Hill and Gunnislake intrusions led Bull (1982) to suggest that the microgranite represented a less differentiated rock type. However allowing for the change in total REE content the profiles are not significantly different (Fig. 2d and 2e).

*Hemerdon Ball granite*

Hemerdon Ball granite lies to the southwest of the main Dartmoor pluton; it is heavily mineralised and characterised by a sheeted quartz vein complex. Seven borehole samples define an Rb-Sr isochron of age 304 ±23 Ma, with initial $^{87}Sr/^{86}Sr$ ratio 0.70719 ±0.01025 and MSWD 1.2 (Fig. 1); the large errors on the age and intercept reflect the limited spread of Rb/Sr ratios. This granite would appear to be considerably older than the neighbouring and much larger Dartmoor granite (280 ±1 Ma); however the ages do just overlap within statistical error.

Geochemically the samples resemble the poorly megacrystic variety of Dartmoor granite, although they have higher concentrations of $A1_2O_3$, As, Co, Ga and Sn

Table 6. Rb:Sr data for Hemerdon Ball granite

| **Sample No.** | **Rb ppm** | **Sr ppm** | **$^{87}Rb/^{86}Sr$** | **$^{87}Sr/^{S6}Sr$** |
|---|---|---|---|---|
| H83-1 | 466 | 45.9 | 29.74 | 0.83485 |
| H83-2 | 575 | 54.2 | 31.13 | 0.84179 |
| H83-3 | 498 | 42.6 | 34.31 | 0.85554 |
| H83-4a | 503 | 45 | 32.82 | 0.84813 |
| H83-4b | 508 | 45.4 | 32.84 | 0.84877 |
| H83-5 | 462 | 45.9 | 29.52 | 0.83532 |
| H76-1 | 538 | 49.8 | 31.17 | 0.84513 |

Table 7. Rare Earth Elements for selected whole rock samples

| | T6B | CM4 | E34995 | MR30152 | KH5 | HQ12 | H83-3 |
|---|---|---|---|---|---|---|---|
| La | 1.72 | 32.75 | 31.56 | 32.61 | 22.53 | 31.53 | 15.12 |
| Ce | 4.44 | 71.43 | 62.96 | 73.98 | 47.34 | 63.94 | 32.42 |
| Pr | - | 9.09 | 8.08 | 8.14 | 5.18 | 6.79 | 3.63 |
| Nd | 2.15 | 31.15 | 27.81 | 33.75 | 20.15 | 26.76 | 14.49 |
| Sm | 0.94 | 5.32 | 5.28 | 6.38 | 3.96 | 5.25 | 3.43 |
| Eu | 0.01 | 0.56 | 0.62 | 0.72 | 0.52 | 0.73 | 0.33 |
| Gd | 0.66 | 3.12 | 3.48 | 4.53 | 2.54 | 3.46 | 2.61 |
| Dy | 0.95 | 2.06 | 2.28 | 3.63 | 2.03 | 2.39 | 2.13 |
| Ho | 0.15 | 0.35 | 0.39 | 0.66 | 0.37 | 0.43 | 0.36 |
| Er | 0.46 | 1.11 | 1.17 | 2.02 | 1.17 | 1.31 | 1.07 |
| Yb | 0.6 | 0.76 | 0.84 | 1.94 | 1.14 | 1.22 | 0.94 |
| Lu | 0.08 | 0.13 | 0.14 | 0.28 | 0.17 | 0.19 | 0.14 |
| ZREE | 12.16 | 157.83 | 144.61 | 169.64 | 107.1 | 144 | 76.67 |

and are poorer in Nb, Th and Zn. The REE profile for Hemerdon (Fig. 2f) shows a depletion in heavy REE with respect to the Dartmoor granite. However recently completed Sm/Nd analysis (Darbyshire and Shepherd *in prep)* indicates that whereas both the megacrystic and poorly megacrystic Dartmoor granites have comparable 23 Nd values (-4.7), the data from two of the Hemerdon samples (-6.8 and -7.1) indicate a greater contribution of crustal material to the magma.

Since the Hemerdon Ball granite lies within the metamorphic aureole of the Dartmoor granite it is hard to conceive a mechanism which would allow it to retain an older age without showing evidence of subsequent isotopic disturbance, Unfortunately the limited range of Rb/Sr ratios of the Hemerdon samples and consequent high error on the age do not allow us to resolve this problem.

## Concluding Remarks

We believe that until there is more unequivocal evidence to show the consanguineity of the major and minor intrusives they should be viewed separately. The geochemical and isotopic evidence presented here implies that their relationship both temporal and genetic is not straightforward. Since the minor intrusives acted as foci for fluid circulation their varied trace element and isotope geochemistry may indicate a significant local country rock component.

Work on the Sm:Nd systematics of the major and minor intrusives together with their host rocks is almost

Appendix 1: Sample locations

| Sample No. | Description | Grid Reference |
|---|---|---|
| *Tregonning granite* | | |
| T1, T3 | Megiliggar | SW 607 267 |
| T4, T6A-B | Praa Sands | SW 586-274 |
| *Cam Marth* | | |
| CM2-5 | Quarry Carn Marth | SW 715 409 |
| *Castle an Dinas, St Austell* | | |
| E 34995 | Top of Castle an Dinas hill | SW 945 624 |
| E 34996; E 36069-70; MR 30153,5 | Dump near engine shaft of disused W mine | SW 946 622 |
| *St Austell granite* | | |
| MR 30152 | Luxulyan Quarry | SX 053 591 |
| *Kit Hill Granite* | | |
| E 38454; KHI-12 | Quarry N side Kit Hill | SW 374 717 |
| *Hingston Down Microgranite* | | |
| E 38455-7; HQI-13 | Hingston Quarry | SX 408 718 |
| *Hemerdon Ball Granite* | | |
| H76-1; H83-1 -H83-5 | Borehole DDH76 | SX 572 583 |

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## Appendix 2: XRF major and trace element data for selected samples

| Sample | $SiO_2$ | $TiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | MnO | MgO | CaO | $Na_2O$ | $K_2O$ | $P_2O_5$ | A/CNK |
|---|---|---|---|---|---|---|---|---|---|---|---|
| T1 | 70.55 | 0.05 | 16.4 | 1.11 | 0.05 | 0.04 | 0.5 | 4.34 | 4.33 | 0.49 | 1.29 |
| T3 | 68.6 | 0.05 | 16.67 | 2.29 | 0.08 | 0 | 1.02 | 2.15 | 5.92 | 0.37 | 1.41 |
| T4 | 71.13 | 0.04 | 16.21 | 1.56 | 0.07 | 0.05 | 0.78 | 3.36 | 4.81 | 0.43 | 1.33 |
| T6A | 71.01 | 0.06 | 16.76 | 1.43 | 0.06 | 0.04 | 0.41 | 4.4 | 3.89 | 0.47 | 1.37 |
| CM4 | 72.24 | 0.22 | 14.86 | 1.59 | 0.04 | 0.23 | 0.67 | 3.26 | 5.23 | 0.26 | 1.21 |
| CM5 | 72.5 | 0.22 | 14.89 | 1.64 | 0.05 | 0.23 | 0.7 | 3.41 | 5.08 | 0.26 | 1.2 |
| E 34995 | 73.42 | 0.05 | 15.38 | 1.09 | 0.04 | 0.03 | 0.34 | 3.51 | 4.74 | 0.41 | 1.33 |
| MR 30153 | 72.88 | 0.06 | 14.98 | 2.36 | 0.05 | 0.24 | 0.49 | 1.84 | 4.93 | 0.39 | 1.62 |
| MR 30155 | 72.48 | 0.07 | 15.19 | 2.3 | 0.06 | 0.19 | 0.48 | 2.13 | 4.84 | 0.37 | 1.58 |
| KH 1 | 72.33 | 0.21 | 15.05 | 1.72 | 0.05 | 0.36 | 0.61 | 3.03 | 5.38 | 0.21 | 1.26 |
| KH2 | 72.97 | 0.16 | 14.73 | 1.58 | 0.06 | 0.21 | 0.73 | 3.3 | 4.91 | 0.25 | 1.22 |
| KH3 | 72.51 | 0.19 | 14.68 | 1.66 | 0.05 | 0.28 | 0.72 | 3.35 | 4.98 | 0.23 | 1.2 |
| KH4 | 72.16 | 0.2 | 14.8 | 1.64 | 0.04 | 0.31 | 0.76 | 3.53 | 4.89 | 0.23 | 1.19 |
| HQ 1 | 72.71 | 0.16 | 14.3 | 1.54 | 0.05 | 0.27 | 0.73 | 2.94 | 5.65 | 0.19 | 1.16 |
| HQ5 | 72.88 | 0.18 | 14.44 | 1.66 | 0.6 | 0.25 | 0.76 | 3.06 | 5.55 | 0.17 | 1.16 |
| HQ6 | 73 | 0.18 | 14.38 | 1.63 | 0.02 | 0.19 | 0.77 | 3.05 | 5.66 | 0.18 | 1.15 |
| HQ7 | 72.63 | 0.17 | 14.34 | 1.71 | 0.04 | 0.24 | 0.69 | 2.83 | 5.87 | 0.19 | 1.17 |
| H83-2 | 72.5 | 0.17 | 14.83 | 1.47 | 0.02 | 0.16 | 0.85 | 2.69 | 5.44 | 0.24 | 1.25 |
| H83-3 | 73.84 | 0.17 | 14.54 | 1.23 | 0.03 | 0.21 | 0.64 | 3.38 | 5.01 | 0.25 | 1.2 |
| H83-4a | 74 | 0.16 | 14.44 | 1.23 | 0.04 | 0.15 | 0.67 | 3.08 | 5 | 0.23 | 1.23 |
| H83-5 | 72.68 | 0.17 | 14.6 | 1.42 | 0.04 | 0.21 | 0.6 | 3.22 | 5.12 | 0.21 | 1.22 |

| Sample | Ag | As | Ba | Bi | Cd | Ce | Co | Cs | Cu | Ga | La | Mo | Ni | Nb |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| T1 | 0 | 10 | 10 | 0 | 0 | 21 | 57 | 164 | 8 | 45 | 16 | 0 | 12 | 58 |
| T3 | 0 | 3523 | 31 | 11 | 0 | 36 | 71 | 63 | 8 | 42 | 6 | 0 | 8 | 54 |
| T4 | 0 | 114 | 32 | 0 | 0 | 0 | 93 | 50 | 12 | 38 | 7 | 0 | 4 | 57 |
| T6A | 0 | 14 | 26 | 0 | 1 | 10 | 83 | 69 | 4 | 39 | 7 | 0 | 7 | 84 |
| CM4 | 0 | 29 | 188 | 0 | 0 | 50 | 61 | 97 | 3 | 26 | 25 | 0 | 7 | 19 |
| CM5 | 0 | 23 | 199 | 0 | 0 | 61 | 51 | 71 | 5 | 26 | 27 | 0 | 4 | 18 |
| E 34995 | 1 | 7 | 22 | 4 | 1 | 15 | 22 | 112 | 17 | 29 | 9 | 0 | 11 | 35 |
| MR 30153 | 0 | 6 | 35 | 0 | 0 | 27 | 18 | 74 | 17 | 30 | 9 | 0 | 13 | 29 |
| MR 30155 | 0 | 6 | 42 | 0 | 1 | 28 | 24 | 73 | 24 | 33 | 7 | 0 | 11 | 31 |
| KH 1 | 0 | 16 | 253 | 0 | 0 | 55 | 76 | 25 | 5 | 24 | 25 | 1 | 9 | 18 |
| KH2 | 0 | 39 | 183 | 0 | 0 | 36 | 63 | 60 | 4 | 25 | 20 | 4 | 8 | 19 |
| KH3 | 0 | 48 | 198 | 0 | 1 | 43 | 79 | 49 | 3 | 25 | 22 | 3 | 11 | 19 |
| KH4 | 1 | 16 | 228 | 0 | 2 | 52 | 78 | 37 | 4 | 24 | 25 | 0 | 8 | 19 |
| HQ 1 | 0 | 25 | 340 | 0 | 0 | 68 | 94 | 27 | 7 | 20 | 33 | 0 | 7 | 14 |
| HQ5 | 0 | 12 | 365 | 0 | 1 | 57 | 95 | 19 | 7 | 19 | 35 | 1 | 3 | 14 |
| HQ6 | 0 | 19 | 413 | 0 | 2 | 64 | 54 | 16 | 8 | 19 | 26 | 0 | 2 | 13 |
| HQ7 | 0 | 101 | 418 | 0 | 1 | 69 | 73 | 27 | 19 | 20 | 31 | 23 | 6 | 15 |
| H83-2 | 1 | 95 | 52 | 0 | 1 | 41 | 72 | 44 | 7 | 28 | 13 | 0 | 10 | 15 |
| H83-3 | 0 | 165 | 47 | 0 | 0 | 28 | 77 | 26 | 7 | 28 | 15 | 7 | 4 | 15 |
| H83-4a | 0 | 141 | 53 | 1 | 1 | 46 | 67 | 28 | 6 | 29 | 15 | 3 | 5 | 17 |
| H83-5 | 1 | 83 | 54 | 0 | 1 | 47 | 71 | 27 | 4 | 26 | 18 | 0 | 7 | 15 |

| Sample | Pb | Rb | Sc | Sn | Sr | Ta | Te | Th | TI | U | V | Y | Zn | Zr |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| T1 | 11 | 1352 | 5 | 29 | 29 | 16 | 3 | 0 | 2 | 24 | 0 | 26 | 41 | 38 |
| T3 | 6 | 1148 | 6 | 20 | 65 | 18 | 2 | 4 | 0 | 15 | 0 | 20 | 42 | 34 |
| T4 | 7 | 970 | 4 | 33 | 51 | 17 | 0 | 1 | 0 | 14 | 0 | 26 | 35 | 35 |
| T6A | 9 | 1111 | 7 | 18 | 33 | 17 | 0 | 0 | 0 | 16 | 0 | 26 | 50 | 32 |
| CM4 | 27 | 554 | 2 | 16 | 83 | 4 | 0 | 21 | 0 | 15 | 15 | 19 | 38 | 123 |
| CM5 | 25 | 519 | 1 | 16 | 85 | 3 | 0 | 16 | 0 | 10 | 13 | 18 | 35 | 119 |
| E 34995 | 10 | 1047 | 2 | 55 | 154 | 6 | 0 | 1 | 6 | 0 | 0 | 22 | 16 | 31 |
| MR 30153 | 5 | 877 | 2 | 118 | 46 | 9 | 0 | 2 | 0 | 3 | 0 | 20 | 35 | 41 |
| MR 30155 | 8 | 1010 | 2 | 745 | 40 | 10 | 0 | 0 | 3 | 8 | 2 | 25 | 33 | 43 |
| KH 1 | 27 | 468 | 1 | 13 | 79 | 3 | 0 | 12 | 0 | 10 | 14 | 22 | 48 | 101 |
| KH2 | 20 | 532 | 2 | 36 | 62 | 0 | 0 | 13 | 0 | 11 | 7 | 21 | 48 | 84 |
| KH3 | 22 | 538 | 4 | 30 | 67 | 3 | 0 | 15 | 0 | 12 | 11 | 22 | 76 | 88 |
| KH4 | 30 | 468 | 4 | 13 | 79 | 2 | 0 | 16 | 0 | 11 | 18 | 23 | 35 | 98 |
| HQ 1 | 31 | 358 | 3 | 17 | 92 | 0 | 0 | 17 | 0 | 8 | 11 | 19 | 27 | 105 |
| HQ5 | 31 | 356 | 1 | 14 | 103 | 0 | 0 | 18 | 0 | 6 | 10 | 20 | 29 | 108 |
| HQ6 | 34 | 337 | 2 | 12 | 109 | 3 | 0 | 20 | 0 | 7 | 12 | 19 | 36 | 110 |
| HQ7 | 30 | 369 | 0 | 31 | 100 | 3 | 0 | 18 | 0 | 7 | 9 | 20 | 148 | 96 |
| H83-2 | 17 | 568 | 3 | 62 | 55 | 3 | 0 | 7 | 0 | 9 | 8 | 22 | 24 | 70 |
| H83-3 | 23 | 504 | 2 | 22 | 42 | 0 | 0 | 10 | 0 | 11 | 10 | 21 | 12 | 65 |
| H83-4a | 19 | 507 | 2 | 28 | 45 | 0 | 0 | 8 | 0 | 11 | 7 | 18 | 13 | 73 |
| H83-5 | 25 | 469 | 2 | 13 | 48 | 3 | 0 | 7 | 0 | 10 | 9 | 21 | 22 | 73 |

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Complete. Preliminary interpretation of the data suggests that this approach will provide a solution to some of the above problems.

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## References

Brookes, C., Hart, S.R. and Wendt, I. 1972. Realistic use of two error regression treatment as applied to rubidium-strontium data. *Reviews of Geophysics and Space Physics, 10,* 551-7.

Bull, B.W. 1982. Geology and mineralisation of an area around Tavistock south-west England. *Unpublished Ph.D. Thesis, University of Exeter.*

Darbyshire, D.P.F. and Shepherd, T.J. 1985. Chronology of granite magmatism and associated mineralization. *Journal of the Geological Society of London 142,* 1159-77.

Dines, H.G. 1956. The metalliferous mining region of south west England. *Memoirs Geological Survey of Great Britain 1 and 2.*

Hill, P. and Manning, D.A.C. 1987. Emplacement and hydro-thermal alteration of the St Austell granite. *Proceedings of the Ussher Society, 6, 000-000.*

Hudson, T. and Arth, J.G. 1983. Tin granites of Seward Peninsula, Alaska. *Geological Society of America Bulletin, 94,* 768-90.

Le Bel, L., Li, Y.D. and Sheng, J.F. 1984. Granite evolution of the Xihuashan-Dangping (Jiangxi, China) tungsten bearing
system. *Tschermaks Mineralogische und Petrographische Mitterlungen.*

Manning, D.A.C. and Exley, C.S. 1984. The origins of late stage rocks in the St Austell granite - a reinterpretation. *Journal of the Geological SoCiety of London, 141,* 581-91.

Pankhurst, R.J. and O'Nions, R.K. 1973. Determination of Rb/Sr and $^{87}Sr/^{86}Sr$ ratios of some standard rocks and evaluation of X-ray fluorescence spectrometry in Rb-Sr geochemistry. *Chemical Geology, 12,* 127-36.

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*Read at the Annual Conference of the Ussher Society, January 1987*

# Petrological features of the Land's End Granites.

B. BOOTH
C.S. EXLEY

Booth, B. and Exley, C.S. 1987. Petrological features of the Land's End Granites. *Proceedings of the Ussher Society 6,* 439-446.

The late- to post -kinematic Land's End granites, intruded into Mylor Formation metasediments and associated basic rocks, comprise five main facies: (t) coarse-grained, highly-megacrystic; (2)coarse-grained, moderately megacrystic; (3) coarse grained, non-megacrystic, 'basic'; (4) medium grained, poorly megacrystic; and (5) fine-grained, poorly megacrystic. There are also veins and dykes of various gramtic types. Jointing and flow structures accord with patterns in the other Cornubian granites.

Modal analyses demonstrate the mineral variations in the pluton and major element analyses show how these have evolved from a combination of contamination by country rock, differentiation and filter-pressing, and metasomatism. The original magma had a composition close to that of the ternary minimum in the 'granite system' and was derived by partial melting from deep-seated rock of broadly granodioritic character.

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The first substantial work on the Land's End granites was the Geological Survey Memoir by Reid and Flett (1907). Subsequently no investigation of the pluton as a whole was carried out until that of Booth (1966) on which the present paper is based. A remapping of the area was conducted by the Institute of Geological Sciences in the 1970s but the results of this are in report form (Hawkes and Dangerfield 1986) while the evolutionary sequence described by van Marcke de Lummen (1986) was based on evidence from a rather restricted area.

## Structure

Granite occupies about 194km2 of the Penwith peninsula, the remainder, in a discontinuous strip round the coast and between Lelant and Mousehole (SW469263), comprising contact metamorphosed and metasomatised mudstones and sandstones of the Devonian Mylor Formation and associated basaltic sills and lava flows. Contacts on the coast, e.g. SSW of Zennor, in Portheras Cove and south of Cape Cornwall (Fig. 1), demonstrate by veins and xenoliths that the granite was intrusive, and by the attitudes of bedding and cleavage that it tilted previously folded rocks and was thus late in the Variscan orogeny. Minor intrusions related to the main granite show that the emplacementprocess was prolonged (e.g. Booth *1966;* Stone and Exley 1984) and the pluton may be described as late-kinematic and much may be post kinematic. An Rb-Sr age of 268 -+ 2Ma was obtained by Darbyshire and Shepherd (1985) but this has been 're-set' and the true age is probably between 280 and 290Ma *(ibid.* and *pers. comm.).*

Exposure of the granites is variable; they form spectacular cliffs along parts of the coast (over 90m high near Zennor) but inland outcrops are restricted to quarries and to tors, most of which occur on the hills just inland from the north-west coast and have a mean height of some 213m O.D. The total natural vertical exposure is about 250m but this rises to over 580m if mines are included. Away from outcrops the rock underlies a gently south-easterly-sloping, undulating plateau with soil, rich in weathered granite fragments, reaching over 10m thickness in the valleys.

The form of the pluton is controlled by a combination of joints and flow structures, the former consisting of three main sets. Sub-horizontal floor joints, whose distance apart increases with depth, have resulted chiefly from relief of vertical stress but perhaps also from a preferred orientation in the fabric of the rock. Near contacts these joints dip outwards at between 20° and 30°, occasionally more or less steeply, but inland they undulate gently about the horizontal in approximate conformity with the surface topography. This is well demonstrated on Rosewall Hill, 3km WSW of St Ives, where stereographic projection of poles and detailed mapping show a slightly asymmetrical dome-like structure (Booth 1966). Secondly, there are three principal directions of sub-vertical joints, the poles to planes of 485 of which have been plotted stereographically (Booth *ibid.).* They consist of NW-SE-trending, smooth, closed 'longitudinal' ('L') joints and open, less regular 'cross' ('Q') joints striking ENE-WSW and E-by-N-W-by-S. All these are significant regional directions, differing only slightly from those in the other granite masses and fitting closely the pattern in

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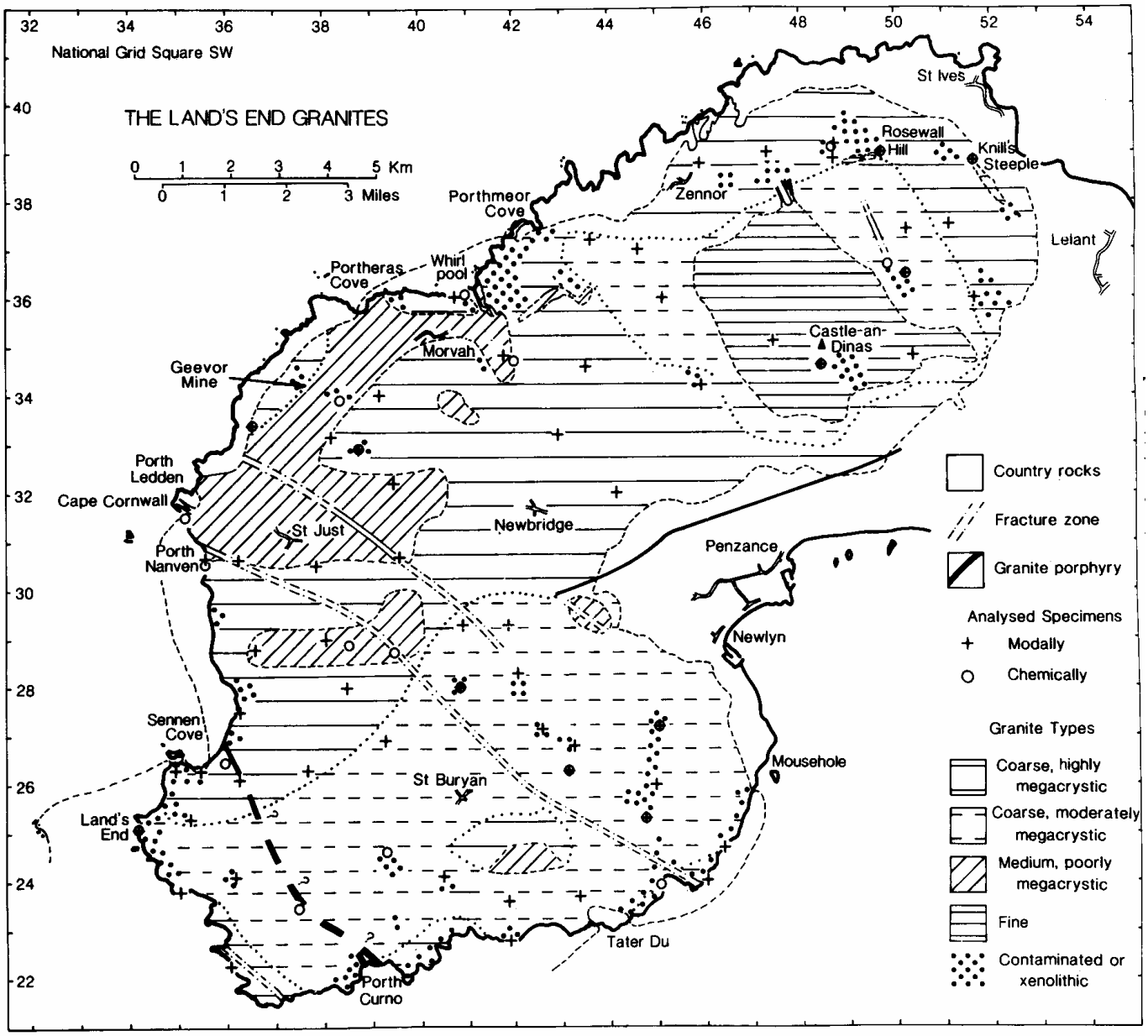


Figure 1. Map of the Land's End peninsula showing distribution of principal types of granite.

the Cornubian peninsula as a whole, as is shown by the tendency for major fractures to strike NW-SE (e.g. Dearman, 1963) and granite porphyry dykes and mineral veins to strike ENE-WSW. Locally, sub-vertical joints have determined the detailed shape of the coast. Thirdly, there is a group of joints striking approximately NE-SW and dipping at high angles to SE and NW. These have slickensides and veneers of tourmaline, chlorite or crushed granite and are dearly faults accommodating late movements in the pluton.

Flow structures are revealed by the orientation of potash feldspar megacrysts, the alignment of which is common and clearly seen close to contacts in Sennen Cove (SW353264), Porth Ledden (immediately north of Cape Cornwall) and at Tater-du (SW440230). This alignment follows the dip of the contact, while inland, as on Rosewall Hill, it follows the slopes of the hillsides. The alignment is not always regular, however, sometimes displaying 'swirls' and 'eddies', and since the megacrysts are believed mainly to be ofmetasomatic origin it follows that a flow fabric, involving primary feldspar crystals which acted as nuclei, must have been established in the solidifying magma.

## Granite Types

Using a combination of Coarseness Index (CI - Chayes 1956) and megacryst concentration, the granite mass has been subdivided into five chief varieties, of which the coarse- and medium-grained occupy slightly more than 90% of the outcrop. These are:

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(i) Coarse-grained, highly megacrystic - Cl mean 42, megacrysts average $400m^{-2}$, average length 6cm.
(ii) Coarse-grained, moderately megacrystic - CI mean 38, megacrysts average $100m^{-2}$, average length 4cm.
(iii) Medium-grained, poorly megacrystic - CI mean 50, megacrysts few or absent.
(iv) Fine-grained, poorly megacrystic - CI mean 111, megacrysts generally few but vary as between exposures at Castle-an-Dinas, Knill's Steeple (SW516386), Rosewall Hill (SW494389) and Morvah (SW411360). About 2cm long.
(v) Coarse-grained, poorly megacrystic and 'basic' - as inclusions and marginal rocks, often with much biotite and tourmaline.

The coarse- and medium-grained megacrystic varieties correspond with Type B of Exley and Stone (1982), the fine-grained variety with Type C and some of the basic variety with Type A.

Table 1 shows that the minerals composing these granites are those found in all the Cornubian masses and they exhibit the usual characteristics (Reid and Flett 1907; Stone 1979; Exley and Stone 1982). Details from Booth (1966) are summarized here but it should be emphasised that most minerals may show replacement relations with their neighbours. *Quartz* has an uneven distribution in the megacrystic granites and has a habit ranging from anhedral inclusions in K-feldspar and biotite, through interstitial and replacive, to rounded aggregates. There are varying degrees of strain and fracturing. *K-feldspar* is perthitic, twinned on. the Carlsbad law and occurs both in megacrysts and in the groundmass. Orthoclase only has been identified optically. Megacrysts may attain lengths up to 12.5cm in coarse granites and have curved or stepped crystal faces. There are inclusions of quartz, biotite and plagioclase, usually in one or two concentric zones. Groundmass K-feldspar is anhedral and interstitial. The presence of quartz, biotite and plagioclase together in a zone around a central core, the uneven nature of the crystal faces and the growth of K-feldspar across contacts between rocks of different textures and compositions, e.g. granite and xenolith, strongly suggest that the megacrysts have grown by potassium metasomatism, using early magmatic crystals as nuclei (Booth, 1967). Alteration is mainly to secondary white mica. *Plagioclase* varies from eu- to subhedral (in crystals up to 8mm long in coarse granites and 0.6mm long in fine granites) and to interstitial. Crystals, which are twinned on the Carlsbad, albite and pericline laws, are sometimes zoned, the usual composition being $An^{13}$-$An^{3}$. Cores of crystals included in K-feldspar may be as calcic as $An^{33}$ and in such crystals the zoning is attributed to changing magmatic conditions while the clear albite rim is the result of diffusion of albite from the host feldspar during unmixing to perthite. Alteration is to white mica and kaolinite. *Biotite* occurs in clusters of flakes 2-3mm across in the coarse granites, is sometimes intergrown with muscovite and altered to chlorite. Some flakes have a bronze colour and one such from a 'basic' granite had $Li_2O$ amounting to 1.6%, indicating a mica approaching zinnwaldite in composition. This is in a contaminated granite and is probably of late origin. Inclusions of ilmenite or rutile after alteration emphasise the titanium-rich nature of some biotite, and included zircon and monazite are common. *Muscovite* is in flakes 1-2mm across and seems to be present at the expense of biotite. It is most common in altered and mineralized rocks; indeed much is of secondary origin and some of this is after cordierite. *Tourmaline* occurs chiefly in irregular yellow-brown prisms up to 4mm long, with zones and patches of blue, and also in blue, radiating needles. It frequently has a replacive habit, particularly towards feldspar, and may be interstitial. *Cordierite,* always pseudomorphously replaced by pinitic white mica, occurs commonly in all the granites except the medium-grained and 'basic' varieties, especially in contaminated areas, and ranges from 2crn long in coarse to lcm long in frae rocks. *Adalusite* has pink cores and is often associated with biotite concentrations resulting from assimilation of pelitic material. *Accessory minerals* include apatite, zircon, monazite, ilmenite, rutile and iron ores. Apatite is surprisingly uncommon and topaz very rare.

## Distribution

The establishment of granite types and subsequently their distribution was accomplished by statistical collection and modal analysis of specimens. Because of irregular exposure it was impossible to sample on an exactly orthogonal basis and specimens were therefore collected from within 500 yards of orthogonally-spaced points at intervals of 1500 yards; this ensured a minimum spacing of 500 yards between specimens. Further, to reduce the unrepresentative nature of single specimens, several were taken from each exposure. Chayes (1956) has shown the requirements for achieving high confidence levels in modal analysis of rocks of varying coarseness; these were adopted and upwards of 4200 points usually counted (Barringer 1953) to give a reproducibility error of less than 1.41%. The significance of between-site variation was calculated initially using the quartz content. This proved to have a variance ratio (F) exceeding the tested critical values, indicating either a 99% or a 95% probability of a significant variation between sample sites. The arguments are discussed by Booth (1966).

Figure 1 shows the distribution of the main granite types with the exception of the 'basic' granite inclusions. Junctions between types are gradational, however, and may differ from those of Hawkes and Dangerfield (1978, 1986) because of the use of different criteria. Many details are not shown; in particular, megacrystic granite with a medium- to fine-grained matrix often occurs among the coarser varieties, especially near contacts with country rocks. Of the coarse-grained granite occupying most of the outcrop, the moderately megacrystic variety is found in areas south-west of St Ives and between Newlyn, Land's End and Porth Curno. The medium-grained variety is confined to a strip between Portheras Cove

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Table 1. Compositions of some Land's End rocks

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| **Mode** | N=47 | N=7 | N=3 | | | N=1 | N=1 | |
| Quartz | 32.61 | 37.18 | 35.53 | | | 25.59 | 30.87 | |
| K-spar | 32.29 | 29.9 | 29.2 | | | 6.55 | 8.13 | |
| Plag | 11.19 | 17.18 | 17.3 | | | 14.35 | 2.19 | |
| Biotite | 6.21 | 2.78 | 3.53 | | | 28.23 | 43.66 | |
| Musc | 2.92 | 2.81 | 4.63 | | | 2.23 | 6.07 | |
| Tour | 1.34 | 1.97 | 1.83 | | | 2.66 | - | |
| Andal | 0.27 | 0.11 | 0.14 | | Cord | 3.18 | - | |
| Zircon | 0.11 | 0.13 | 0.01 | | Rutile | 0.61 | - | |
| Ore | 0.15 | 0.09 | 0.09 | | - | | 1.42 | |
| 2y Mica in Ksp | 1.71 | 1.29 | 1.98 | | | 0.9 | 1.29 | |
| 2y Mica in Plag | 4.33 | 3.69 | 4.96 | | | 13.83 | 5.94 | |
| Clay | 6.67 | 2.67 | 0.72 | | Chlorite | 1.85 | 0.38 | |
| | 99.8 | 99.81 | 99.92 | | | 99.98 | 99.95 | |
| Points | 4268 | 4204 | 4462 | | | 2104 | 3774 | |
| CI | 40 | 50 | 112 | | | | - | |
| Col Ind | 7.48 | 4.84 | 5.46 | | | 31.5 | 45.08 | |
| Or/PI | 1.71 | 1.38 | 1.36 | | | 0.26 | 1.15 | |
| **Chemical analysis** | | | | | | | | |
| | N=22 | N--9 | N=3 | N=3 | N=1 | N=1 | N=5 | N=9 |
| $SiO_2$ | 71.79 | 72.8 | 73.04 | 74.61 | 69.6 | 59.97 | 62.48 | 56.51 |
| $TiO_2$ | 0.29 | 0.2 | 0.09 | 0.06 | 0.14 | 1.39 | 1.24 | 0.83 |
| $Al_2O_3$ | 14.9 | 14.39 | 14.53 | 15.1 | 15.05 | 17.16 | 16.68 | 21.78 |
| $Fe_2O_3$ | 0.88 | 0.74 | 0.64 | 0.42 | 1.57 | 3.34 | 1.52 | 1.91 |
| FeO | 1.5 | 0.98 | 0.65 | 0.33 | 0.86 | 6.66 | 6.71 | 5.48 |
| MnO | 0.03 | 0.05 | 0.02 | 0.02 | 0.02 | 0.11 | 0.13 | 0.08 |
| MgO | 0.84 | 0.49 | 0.48 | 0.29 | 0.32 | 2.03 | 1.68 | 3.21 |
| CaO | 0.89 | 0.77 | 0.65 | 0.69 | 0.55 | 0.91 | 1.84 | 2.51 |
| $Na_2O$ | 2.51 | 2.96 | 3.11 | 4.91 | 6.2 | 2 | 3.01 | 1.69 |
| $K_2O$ | 5.61 | 5.55 | 5.8 | 3.08 | 5.1 | 5 | 4.03 | 5.12 |
| $P_2O_5$ | 0.24 | 0.23 | 0.19 | 0.24 | 0.27 | 0.58 | 0.35 | 0.1 |
| HP+ | 0.52 | 0.57 | 0.52 | 0.26 | 0.36 | 0.74 | 0.54 | 1.06 |
| | 99.8 | 99.73 | 99.72 | 100.01 | 100.19 | 99.89 | 100.21 | 100.28 |
| **Catanorm** | | | | | | | | |
| Q | 29.7 | 29.44 | 27.94 | 30.31 | 12.28 | 20.63 | 18.5 | 13.04 |
| or | 32.62 | 32.33 | 33.67 | 1790 | 28.9 | 29.15 | 23.57 | 28.68 |
| ab | 22.15 | 26.00 | 27.42 | 43.27 | 50 | 17.9 | 26.66 | 14.48 |
| an | 2.71 | 2.31 | 2.5 | 1.45 | (2.80) | *0.95 | 6.22 | 9.53 |
| C | 3.95 | 2.89 | 2.39 | 3.58 | (0.4) | +8.72 | 5.49 | 10.39 |
| en | 2.26 | 1.29 | 1.33 | 0.76 | 0.82 | 5.56 | 4.58 | 8.47 |
| fs | 1.06 | 0.72 | 0.45 | 0.16 | 0.8 | 5.94 | 7.64 | 5.82 |
| mt | 0.76 | 0.73 | 0.67 | 0.45 | 0.52 | 3.45 | 1.6 | 1.89 |
| il | 0.38 | 0.28 | 0.11 | 0.06 | 0.18 | 1.96 | 1.75 | 1.09 |
| ap | 0.47 | 0.47 | 0.39 | 0.5 | 0.53 | 1.12 | 0.66 | 0.22 |

* acmite + wollastonite

1, coarse-grained granites; 2, medium-grained granites; 3, fine-grained granites; 4, aplites; 5, marginal granite (B36); 6, 'basic' granite (SC 1); 7, pelitic xenoliths; 8, pelitic homfelses. (Compiled from Booth 1966).

and Cape Cornwall, with extensions inland from both these places, and to isolated patches such as those south-west and south-east of Newbridge. The major fine-grained granite outcrop surrounds Castle-an-Dinas, with small areas to the north and north-east. It should be noted that coarse, highly megacrystic granite is found, in addition to the main northern and central area, near contacts (as, e.g. SSW of Portheras Cove and east of Porth Curno). The medium-grained and frae-grained granites occur beneath the coarser varieties and contacts can be seen, e.g., at the Whirlpool (SW411362) and near Porth Nanven (SW356306) in the case of medium and coarser varieties; and,at the Whirlpool and on Rosewall Hill (SW489392) in the case of fine and coarse varieties. In all these examples the relations can be interpreted as intrusive, as they originally were between 'Blue' and 'Giant' granites on Dartmoor (Brammall and Harwood, 1923) and between 'Normal' and 'Godaver' types on Bodmin Moor (Ghosh, 1927), but in the Land's End mass, whereas the fine-grained granites have developed a characteristic roof banding, the medium-grained granites have not.

For the study of more subtle variations in composition, the technique of trend surface analysis has been employed. This now well-known procedure and the calculations used here are discussed in detail by Booth (1964, 1966) and it suffices now to say that it seeks, by polynomial surface regression equations, to accommodate all three spatial co-ordinates with sample variations to separate purely local from areal changes over a number of sites and to calculate isopleths which then define a 'trend surface'. Two values may be plotted, viz. the trend surface itself, which is a 'best fit' for the areal or regional data, and the deviations or 'residual values' by which data locally depart from the surface. Both may be useful and are used to depict different information in Figure 2.

Figure 2(a) shows the trend surface for the *colour index* at a mean height of 350ft (107m) O.D. Values increase from south-east to north-west and to north-east and southwest of a central 'low'. The main component of colour index is biotite, a proportion of which is related to assimilation of stoped material. Reference to Figure 1 reveals that contaminated and xenolithic granite is most common round the periphery of the outcrop, as might be expected, but it is noticeable that those contaminated areas SSW of Newlyn appear not to have had much effect on the colour index. This is because biotite concentrations in these areas do not depart far from the mean of just over 6% for coarse-grained granites (Table 1). When the north-eastern part of the mass, which includes the main fine-grained granite is excluded, the colour index surface assumes a rather different shape (Fig. 2(b)) with a 'low' between Newbridge and Land's End surrounded by higher values. On the assumption that the outer parts of the intrusion would reveal more evidence of contamination than the inner parts, these two diagrams are interpreted as showing that the early magma stoped its way forward from SSE towards NNW (a direction compatible with suggested directions elsewhere, e.g. Dartmoor (Brammall and Harwood 1932); Cammenellis (Ghosh 1934); St Austell (Exley 1959)) and that there was a doming of the roof in the south-west.

The trend surface for *total feldspar* at 350ft (107m) O.D. (Fig. 2(c)) has an entirely different pattern, with sub-parallel isopleths striking roughly NW-SE and increasing in Value from north-east to south-west. There is clearly no

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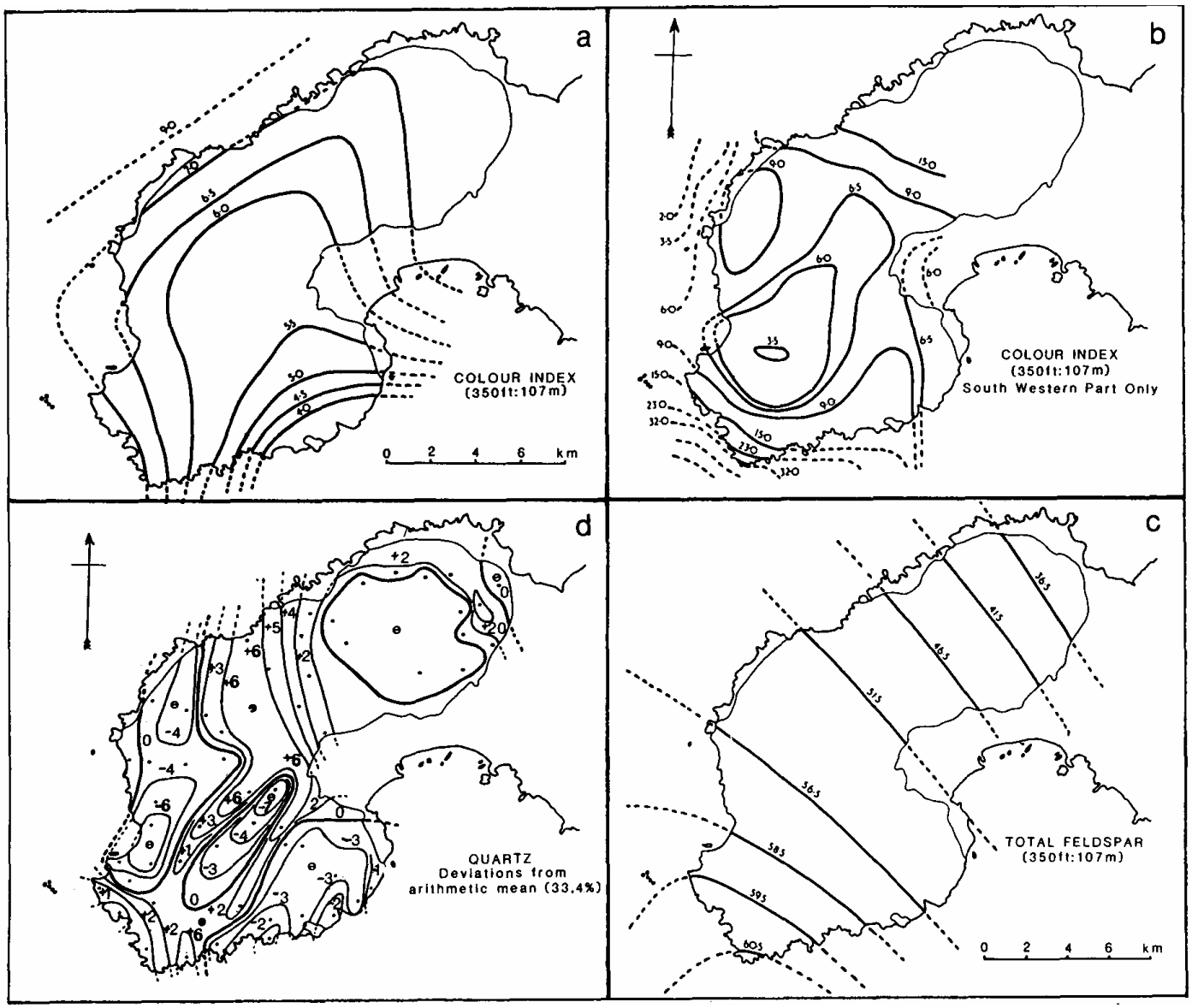


Figure 2. Isopleth maps of granite features. (a) Trend surface of *colour index* over whole granite outcrop. (b) Trend surface of *colour index* over south western part of granite outcrop. (c) Trend surface of *total feldspar* over whole granite outcrop. ((a), (b) and (c) computed for height of 350ft (107m) O.D.). (d) Deviations from arithmetic mean of modal *quartz* over whole granite outcrop.

direct relationship between these and the granite margin while the slope is markedly oblique, if not at right angles, to the assumed direction of magmatic flow. Bearing in mind that coarse, highly megacrystic granite, such as occurs round the southern coasts, and coarse, moderately megacrystic granite, such as occurs inland in the south, together give higher megacryst concentrations, while medium-and fine-grained granites, such as occur centrally and in the north, give lower megacryst concentrations (Fig. 1), there is a correlation between the total feldspar distribution and megacryst abundance. It is believed that this is a post-magmatic effect, superimposed on the original magmatic feldspar pattern by metasomatism.

The *quartz* distribution map (Fig. 2(d)) closely resembles that derived by computation of residual values from the trend surface although it actually shows deviations from the arithmetic mean of the quartz contents. Several conspicuously 'low' areas are shown, the most striking being that in the north which corresponds very closely with the fine-grained granite outcrop and its moderately megacrystic envelope (Fig. 1). Those south of Newbridge and south-west of Newlyn can be related to the moderately megacrystic granites while those in the west result from a few specimens with below-average quartz contents rather than particular rock types (Fig. 1 and Table 1).

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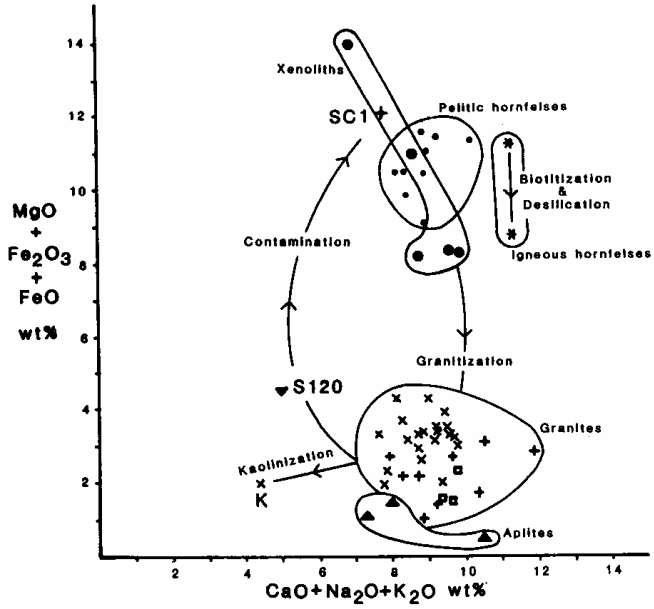


Figure 3. Plot of wt % MgO + $Fe_2O_3$ + FeO versus wt % CaO + $Na_2O$ + $K_2O$, showing fields of various rock types. × = coarse-grained granite; + = medium-grained granite; □ = fine-grained granite: ▲ = aplite; ▼ = 'intermediate' granite; K = kaolinized granite; ✧ = 'basic' granite; ● = xenolith; • = pelitic hornfels; * = igneous hornfels.

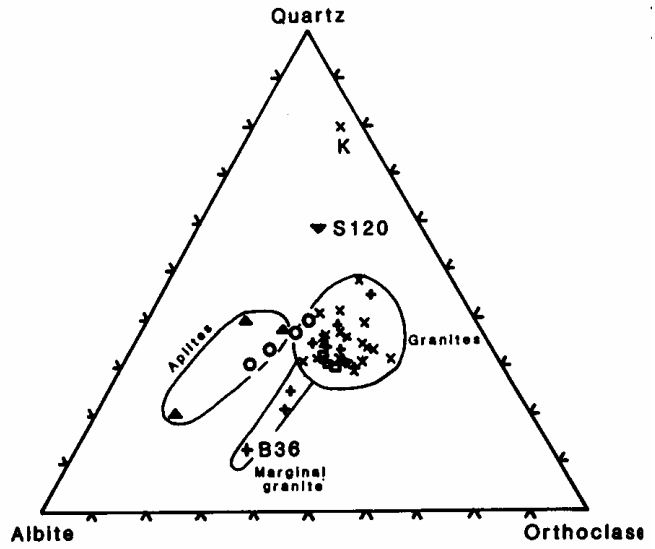


Figure 4. Plot of 'granite system', (normative quartz-orthoclase-albite system). Symbols as in Figure 3, plus 0 = isobaric minima at 0.5 (upper right), 1, 3, and 5 (lower left) kb ($PH_2O$).

Major Element Chemistry

Carried out before the advent of XRF methods, the analyses used in this study were performed by 'rapid wet' methods as described by Riley (1958). Details, with assessments of precision, accuracy and variation among specimens, are given by Booth (1966).

As the mean compositions in Table 1 (Columns 1-3) illustrate, the main granites vary rather little in their chemistry although there are considerable spreads in individual elements between specimens and these are the cause of the spread of points in the fields drawn in Figure 3 and 4 to define rock types.

In Figure 3 ($MgO+Fe_2O_3+FeO$ vs $CaO+Na_2O+K_2O$), all fields except that of the granites have a degree of elongation and depict trends by which xenoliths and hornfelses become granitized by loss of Fe and Mg and gain of Ca, Na and K, and granites become basified by the reverse process. Emphasised in this diagram are the compositions of a coarse 'basic' granite (SC1) and a transitional type ($Si_2O$) between this and the main granites. The latter include coarse, medium and fine types and while there is no clear separation it is seen that the medium and fine varieties, which are richer in Na20 than the coarse (Table 1), tend to be concentrated in the Fe-Mg-poor, Ca-Na-K-rich part of the field.

The Land's End granite analyses are plotted in the normative quartz-orthoclase-albite system in Figure 4, as are the ternary minima established by Tuttle and Bowen (1958). The aplites plot Clearly on the Ab-rich side of these and the granites on the Or-rich side. Most granites fall into a group in which the fine-grained varieties lie towards the Ab apex and the medium-grained tylfes, which have fairly constant Or contents, are spread linearly towards the Ab apex. Of the granites lyigg outside the main group, one (B36) is of a 'marginal' type and it and two medium-grained specimens which are unusually Ab-rich lie close to the thermal valley in the system. Another stray specimen has been severely kaolinized.

Table 2 lists analyses of granites and hornfelses taken at intervals on either side of a contact in the old 6W3 cross-cut in Geevor Mine (SW376342). $SiO_2$, $A1_2O_3$ and total Fe are relatively constant on each side but values change markedly as the junction is crossed, $SiO_2$ decreasing from granites to hornfels while the other two increase. Other elements behave less regularly and it is noticeable that

Table 2. Chemical analyses of rocks across contact, Geevor Mine

| | G36 | G24 | G12 | G1 | K1 | K12 | K24 | K36 |
|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 71.90 | 72.90 | 71.87 | 73.90 | 56.04 | 57.55 | 53.74 | 57.95 |
| $TiO_2$ | 0.26 | 0.16 | 0.23 | 0.05 | 0.76 | 0.88 | 0.95 | 0.83 |
| $Al_2O_3$ | 14.96 | 14.98 | 14.71 | 14.34 | 22.23 | 22.36 | 22.43 | 21.09 |
| $Fe_2O_3$ | 0.83 | 0.54 | 0.80 | 0.68 | 1.98 | 1.61 | 2.21 | 2.00 |
| FeO | 1.74 | 1.06 | 1.34 | 0.40 | 5.88 | 5.08 | 5.06 | 5.36 |
| MnO | 0.04 | 0.03 | 0.04 | 0.02 | 0.11 | 0.08 | 0.06 | 0.05 |
| MgO | 0.58 | 0.38 | 0.52 | 0.46 | 2.58 | 3.15 | 4.24 | 3.04 |
| CaO | 0.84 | 0.60 | 0.97 | 0.69 | 1.98 | 1.87 | 1.81 | 1.93 |
| $Na_2O$ | 1.90 | 2.08 | 2.76 | 3.18 | 2.66 | 1.28 | 1.44 | 1.60 |
| $K_2O$ | 5.75 | 6.77 | 5.99 | 5.57 | 4.37 | 5.35 | 5.71 | 4.85 |
| $P_2O_5$ | 0.25 | 0.17 | 0.25 | 0.21 | 0.29 | 0.08 | 0.04 | 0.08 |
| $H_2O+$ | 0.79 | 0.57 | 0.56 | 0.61 | 0.60 | 0.59 | 0.99 | 1.16 |
| | 99.84 | 100.24 | 100.04 | 100.11 | 99.48 | 99.88 | 99.68 | 99.94 |

G = granite; K = pelitic hornfels. Numbers indicate distance from contact in inches.

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there is a soda-rich zone close to the contact. In general, the coarse granite away from the contact is somewhat richer in total Fe and K20 than is usual (cfi Table 1).

## Discussion

Textures and modal and chemical analyses all provide evidence that the Land's End pluton has had a complex history and three chief evolutionary trends are discernible (Fig. 5).

*Contamination* is widespread and revealed by the presence of xenoliths in different stages of assimilation and by concentrations of biotite, andalusite and pinite after cordierite when xenoliths as such are no longer recognisable. Proximity to the roof is indicated by xenolithic material over most of the outcrop as well as round its perimeter, although there appear to be fewer in the central region around Newbridge (Fig. 1). The effects of contamination are seen in Figure 3 and Table 2 which show that the granite becomes less siliceous and more aluminous and femic; as a whole the granites are now peraluminous with corundum in the norm (Table 1). The 'marginal' and Geevor contact granites are more sodic than the main granites (Tables I and 2; Fig. 4) which suggests that the early magma itself might have been sodic. Microscope evidence supports this suggestion because the grain size and composition of minerals included in obviously later, metasomatically-formed crystals show the early rock to have been relatively fine-grained, leucocratic and plagioclase-rich. Brammall and Harwood (1932) argued similarly about Dartmoor granites.

*Differentiation.* The usual course of differentiation in granitic magmas produces an Fe- and Mg-poor, Na-rich residuum and Land's End rocks of this type occur as aplites which are not only intrusive into granites as well as country rocks but plot separately from other granites in Figures 3 and 4. The medium- and fine-grained granites also have these characteristics when compared with the coarse-grained granites but are not sufficiently distinct in this study to be regarded as differentiated fractions (Fig. 3) Van Marcke de Lummen (1986), however, using specimens from western and north-western parts of the mass and trace element analyses, believes this to be the case.

*Metasomatism.* The potassic nature of the main granites is a result of their high K-feldspar content, much of which

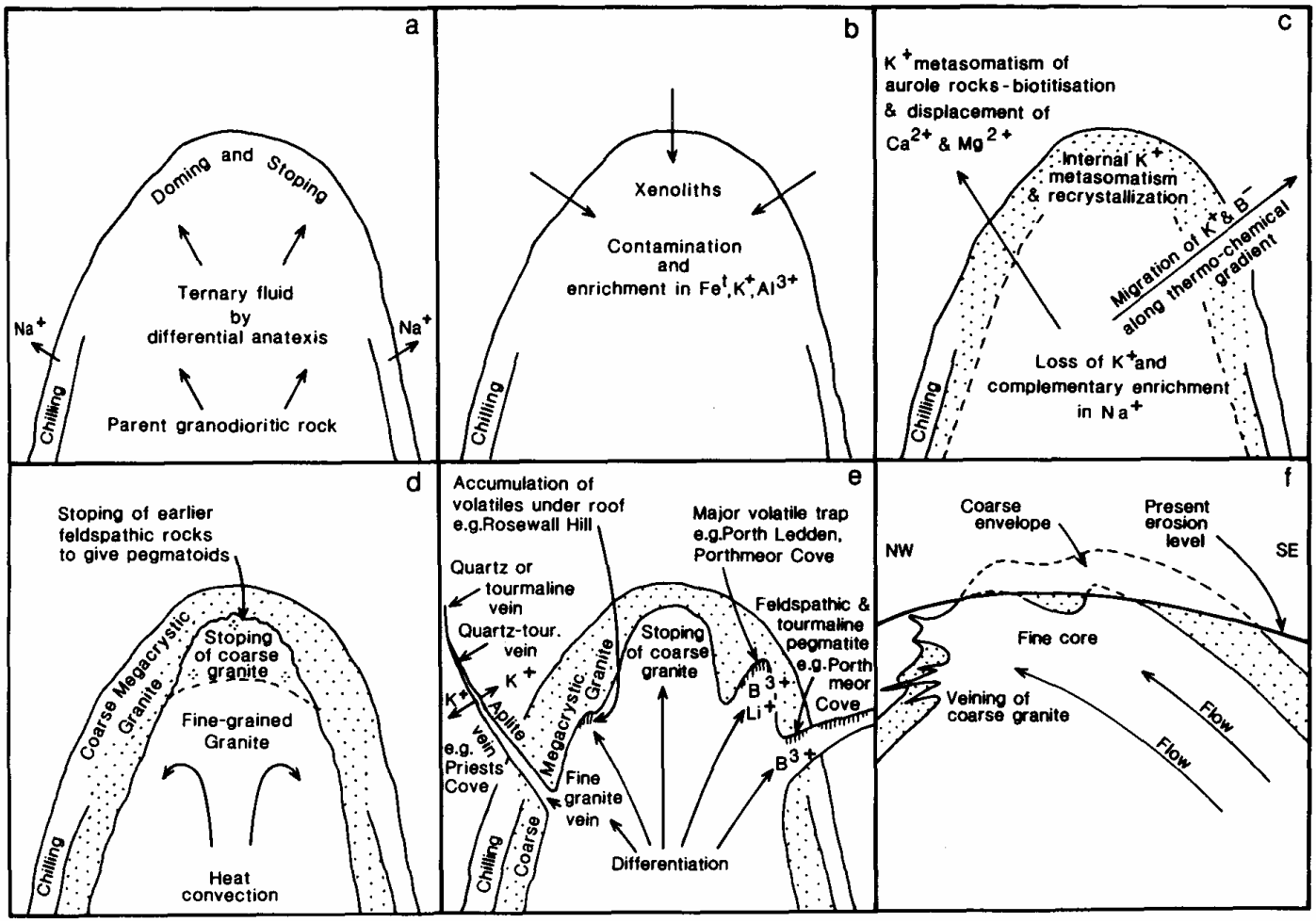


Figure 5. Diagrammatic evolutionary history of the Land's End granites. Not to scale.

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is in the form of megacrysts. Textural evidence has already been offered in argument that these were of late, metasomatic origin and Brammall and Harwood (1932) have demonstrated how the subtraction of hornfels components from present Dartmoor granites compositions leave a more sodic granite. By analogy it is believed that much of the potassium in the Land's End metasomatism originated from assimilated country rock and was disseminated at an early stage by a hydrous phase which encouraged recrystallization to a coarser texture. This process would be enhanced by the presence of boron which is now found everywhere in prismatic tourmaline crystals.

The history of the whole intrusion is interpreted as follows. An original magma, containing little anorthite and therefore having a composition approximating to that of the ternary minimum in the hydrous quartz-orthoclase-albite (i.e. 'granite') system, was intruded towards the end of the Variscan orogeny. There is no evidence of any major basic body from which this magma might have been derived by differentiation and it is therefore concluded that it was produced by differential anatexis ('partial melting') of the equivalent of granodiorite or granite gneiss. A composition between that of the aplites and specimen SC1 (Fig. 3 and Table 1) is envisaged. Rapid ascent and cooling produced a fine-grained crystal 'mush' lubricated by an interstitial aqueous phase and contaminated by assimilation of stoped country rock (Fig. 5a, b). The outward diffusion of the lubricating phase with its accompanying potassium both recrystallized and metasomatised the solid material and close to the relatively impermeable Mylor meta-sedimentary envelope prolonged soaking gave rise to a coarse-grained, highly megacrystic carapace with pegmatitic facies locally developed in traps (Fig. 5c). Within this, the majority of moderately megacrystic and medium- and fine-grained granites are found. The main frae-grained granite outcrops in the northern part of the mass are a consequence of continued or later mobilization of the innermost granite and its intrusion into the coarser cover (Fig. 5d). Concurrent differentiation and filter-pressing during these movements gave rise to the fine-grained granite and aplite veins. The similarities in texture and composition between the Castle-an-Dinas fine-grained granite and the Geevor fine-grained margin (Figs. 3 and 4; Tables I and 2) support this sequence of events, as do the occurrences of fine-grained areas within coarse granites. The significant feature appears to be imposition of metasomatism and coarsening upon fine-grained rock rather than the intrusion of finer into coarser types, except where there was a later remobilization stage. The evolutionary history in summarized in Figure 5e.

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## References

Barringer, A.R. 1953. The preparation of polished sections of ores and mill products using abrasives, and their quantitative study by point-counting methods. *Transactions of the Institution of Mining and Metallurgy, 63,* 21-41.

Booth, B. 1964. Progress report on the Land's end Granite. *Proceedings of the Ussher Society, 1,* 122-125. Booth, B. 1966. Petrogenesis of the Land's End granites. *Unpublished Ph. D. Thesis, University of Keele.*

Booth, B. 1967. Land's End granites and their relation to the granite system. *Nature, 213,* 896-897.

Booth, B. 1968. Petrogenetic significance of alkali feldspar megacrysts and their inclusions in Cornubian granites. *Nature, 217,* 1036-1038.

Brammall, A. and Harwood, H.F. 1923. The Dartmoor granite: its mineralogy, structure and petrology. *Mineralogical Magazine, 20,* 39-53.

Brammall, A. and Harwood, H.F. 1932. The Dartmoor granites: their genetic relationships. *Quarterly Journal of the Geological Society of London, 88,* 171-237.

Chayes, F. 1956. *Petrographic modal analysis.* J, Wiley and Sons, New York. Darbyshire, D.P.F. and Shepherd, T.J. 1985. Chronology of granite magmatism and associated mineralization, SW England. *Journal of the Geological Society of London, 142,* 1159-1177.

Dearman, W.R. 1963. Wrench-faulting in Cornwall and South Devon. *Proceedings of the Geologists' Association, 74,* 265-287. Exley, C.S. 1959. Magmatic differentiation and alteration in the St Austell granite. *Quarterly Journal of the Geological Society of London, 114,* 197-230.

Exley, C.S. and Stone, M. 1982, Hercynian intrusive rocks. *In:* Sutherland, D.S. (ed.) *Igneous rocks oftheBritishlsles.* J. Wiley & Sons, Chichester.

Ghosh, P.K. 1927. Petrology of the Bodmin Moor granite (eastern part), Cornwall. *MineralogicalMagazine, 2L 285-309.* Ghosh, P.K. 1934. The Carnmenellis granite: its petrology, metamorphism and tectonics. *Quarterly Journal of the Geological Society of London, 90,* 240-276.

Hawkes, J.R. and Dangerfield, J. 1978. The Variscan granites of south-west England: a progress report. *Proceedings of the Ussher Society, 4,* 158-171.

Hawkes, J.R. and Dangerfield, J. 1986. Petrological accounts of igneous rocks in the Land's End District: the Variscan granites. *British Geological Survey Mineralogy and Petrology Open File Report* 86/31, 34-82.

Reid, C. and Flett, J.S. 1907. The geology of the Land's End District. *Memoir, Geological Survey of Great Britain.* Riley, J.P. 1958. The rapid analysis of silicate rocks and minerals. *Analytica Chimica Acta, 19,* 413-425.

Stone, M. 1979. Textures of some Cornish granites. *Proceedings of the Ussher Society, 4,* 370-379. Stone, M. and Exley, C.S. 1984. Emplacement of the Porthmeor granite pluton, west Cornwall. *Proceedings of the Ussher Society, 6,* 42-45.

Tuttie, O.F. and Bowen, N.L. 1958. Origin of granite in the light of experimental studies in the system $NaA1Si_3O_8$.$KA1Si_30_8$-$SiO_2$-$H_20$. *Geological Society of America, Memoir 74.*

van Marcke de Lummen, G. 1986. Geochemical evolution of the Land's End granite (south-west England) in relation to tin potential in the light of data from western marginal areas. *Proceedings of the Ussher Society, 6,* 398-404.

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*Read at the Annual Conference of the Ussher Society, January 1987*

# Multiple intrusions and pervasive hydrothermal alteration in the St Austell Granite, Cornwall

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Hill, P.I. and Manning, D.A.C. 1987. Multiple intrusions and pervasive hydrothermal alteration in the St. Austell Granite, Cornwall. *Proceedings of the Ussher Society 6,* 447-453.

Recent detailed mapping of the St Austel[granite body has identified numerous granite types, which are divided on the basis of petrographic and chemical evidence into magmatic biotite granites, aphyric granites, tourmaline granites and topaz granites and other metasomatically altered granites. Contact relationships are complex. More than one phase of biotite granite emplacement was followed by extensive pervasive fluid circulation, which produced distinctive alteration facies including some early tungsten vein mineralisation. Later volatile-rich granites cut across this initial hydrothermal system. Subsequent hydrothermal activity was less extensive and involved further Sn-W mineralisation.

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## .Introduction

The St Austell Granite, Cornwall, has been mapped on a number of occasions over the years (Richardson 1923; Exley 1959). This early work distinguished a number of magmatic granite units, which were identified as biotite granites, lithionite granites and fluorite granites. The lithionite granite was divided into both non-porphyritic and porphyritic varieties, subsequently referred to as megacrystic and non-megacrystic lithium mica granites (Hawkes & Dangeffield 1978). This sequence of granites was believed to have been formed by magmatic different-iation with centripetal crystallisation (Exley, 1959). A recent review (Manning & Exley, 1984) has pointed towards a more complex history. These authors suggest that both the fluorite and megacrystic lithium mica granites were not of magmatic origin and were derived from magmatic topaz and biotite granites respectively, with metasomatic chemical exchange between the two.

In this paper we present evidence from detailed field mapping in china clay pits and laboratory geochemistry for a more diverse association of rock types, including granites very intensely affected by pervasive metasomatism. The excellent exposure afforded by the kaolin workings has permitted complex relationships to be observed, and our interpretation may be applicable to other areas of south-west England which are less well exposed. In additional to commercial kaolin deposits, the St Austell granite and its satellite plutons are hosts to tin and tungsten mineralisation. All three commodities are believed to be closely associated with the late magmatic and early hydrothermal processes which gave rise to the mapped granite varieties.

## Main granite units

The main granite types (Table 1) consist of a series of both magmatic and metasomatically altered granites which have been identified and mapped in the field. All are subject to varying degrees of kaolinisation which is considered to be a low temperature, possibly supergene, phenomenon (Sheppard, 1977). The alteration types allowing the metasomatic granites to be distinguished principally include tourmalinisation, with associated sericitic alteration and textural changes. Two dark micas have been distinguished and are subsequently referred to as biotite (with strong red brown-colourless pleochroism, subhedral shape and rich in inclusions of zircon, monazite etc.) or brown mica (with yellow brown-colourless pleochroism, anhedral shape and a less distinct cleavage). The granite varieties are described in order of emplacement, inferred from contact and geochemical data summarised later.

*Biotite granite* is typical of the biotite granites of the other S.W. England plutons and forms most of the east side of the St Austell stock, corresponding to Type B of Exley & Stone (1982). It is coarse, with K-feldspar megacrysts and primary biotite. A separate *equigranular biotite granite* can also be identified (eg Littlejohn pit SW983571). Although usually extensively kaolinised it is essentially non-megacrystic and has remnant biotite mica which is usually replaced by brown mica relatively free from inclusions. Small localised zones of alteration are usually centred on such areas of biotite replacement, with both tourmaline and topaz present.

In hand specimen *globular quartz granite,* as the name implies, is dominated by l-2cm rounded quartz glomerites. Viewed in thin section the rock can be divided into three textural components, namely a glomerite component, a remnant magmatic-groundmass component, and a replacive groundmass component. The glomerite component is dominated by 1-2cm sized

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Table 1. Summary of the contact relations between granite types in the St. Austell area

| Sequence | Biotite granite | Equigranular biotite granite | Globular quartz granite | Tourmaline granite | Aphryic granite | Topaz granite |
|---|---|---|---|---|---|---|
| **Biotite granite** | 1st | not observed | sharp. often marked by a curved crystal pegmatite. globular quartz granite tourmaline rich at contact. | exposure poor. gradational contact? | contact transitional. marginal tour-quartz spot rock within aphryic granite near to contact. | not observed |
| **Equigranular biotite granite** | | 2nd | contact variable often diffuse. sharp contacts with equigranular biotite cutting globular quartz granite sometimes present, pods of biotite granite within globular quartz granite at contact zone. | not observed | sharp. veins of Aphryic granite cut Equigranular biotite granite. curved crystal pegmatites sometimes lie within contd. | not observed |
| **Globular quartz granite** | | | 3rd | complex contact with development of globular quartz granite at contact between tourmaline and topaz granites. curved crystal pegmatite, crenulate and dendritic layers also present. | sharp. tour-qtz vugs within globular quartz, granite as contact is approached. | complicated zone CF. tourmaline-globular quartz granite contact. |
| **Tourmaline granite** | | | | 4th | not observed | sharp. with tour-quartz vugs in topaz granite as contact is approached. curved crystal pegmatites often lie within contact zone. |
| **Aphryic granite** | | | | | 5th | Not observed |
| **Topaz granite** | | | | | | 6th |

quartz aggregates showing crystal enlargement with the entrapment of the groundmass at the margins. Micro-perthite megacrysts are also present. The remnant groundmass texture consists of a number of minerals undergoing alteration and replacement. Microperthite is often subhedral and dotted by replacive groundmass minerals at the margins. Brown micas show low inter-ference colours and are embayed and corroded, undergoing replacement by quartz and topaz, and lack *zircon* inclusions. Plagioclase and quartz are also present. the fine (0.5mm) mosaic replacive groundmass consists of quartz, K-feldspar, plagioclase, brown-mica, topaz, tourmaline and accessory fluorite. Small xenolithic inclusions have also been identified. This rock type shows a range in textures extending to examples where the alteration leads to three megacrystic phases, quartz, microperthite and brown-mica, 'floating' within a fine mosaic replacive groundmass. It is also particularly rich in secondary tourmaline, present as acicular blue-*colourless* needles. The range of textures observed are not unlike those of two phase granites reported by Cobbing *et al.* (1986).

Fourth in the sequence is a *tourmaline granite,* which is non-megacrystic, 5-6mm in grain size, and characterised by fresh, euhedral, zoned, 1-2cms tourmaline needles with khaki brown-green colouration. It has both brown mica and muscovite present; the brown mica is pale in thin section, shows slight pleochroism, and shows various degrees of alteration. The most altered micas show extensive replacement and invasion by quartz, topaz and fluorite, which *occur* as inclusions. Albite dominates over K-feldspar but both are extremely clouded by secondary micas. Accessory topaz, apatite, fluorite and sulphides occur. The freshest tourmaline granite outcrops in Rocks pit (SX017582) where it is notably xenolith rich; xenoliths range in size from 2-50 cms, and are occasionally ringed by sulphides. A much more altered variety occurs in Gunheath pit (SX000565) where it is megacrystic and xenolith poor but still characterised by coarse tourmaline.

*The aphyric granite* is equigranular with a general variation in grain size from 2-5mm. In thin section the dominant feldspar is euhedral albite (approximately two thirds of the feldspar), while the microperthite is often embayed and invaded. Brown mica is altered and replaced by quartz, topaz, tourmaline and K-feldspar. Tourmaline, 1-2mm and commonly zoned (khaki brown-green), often displays secondary skeletal growth invading

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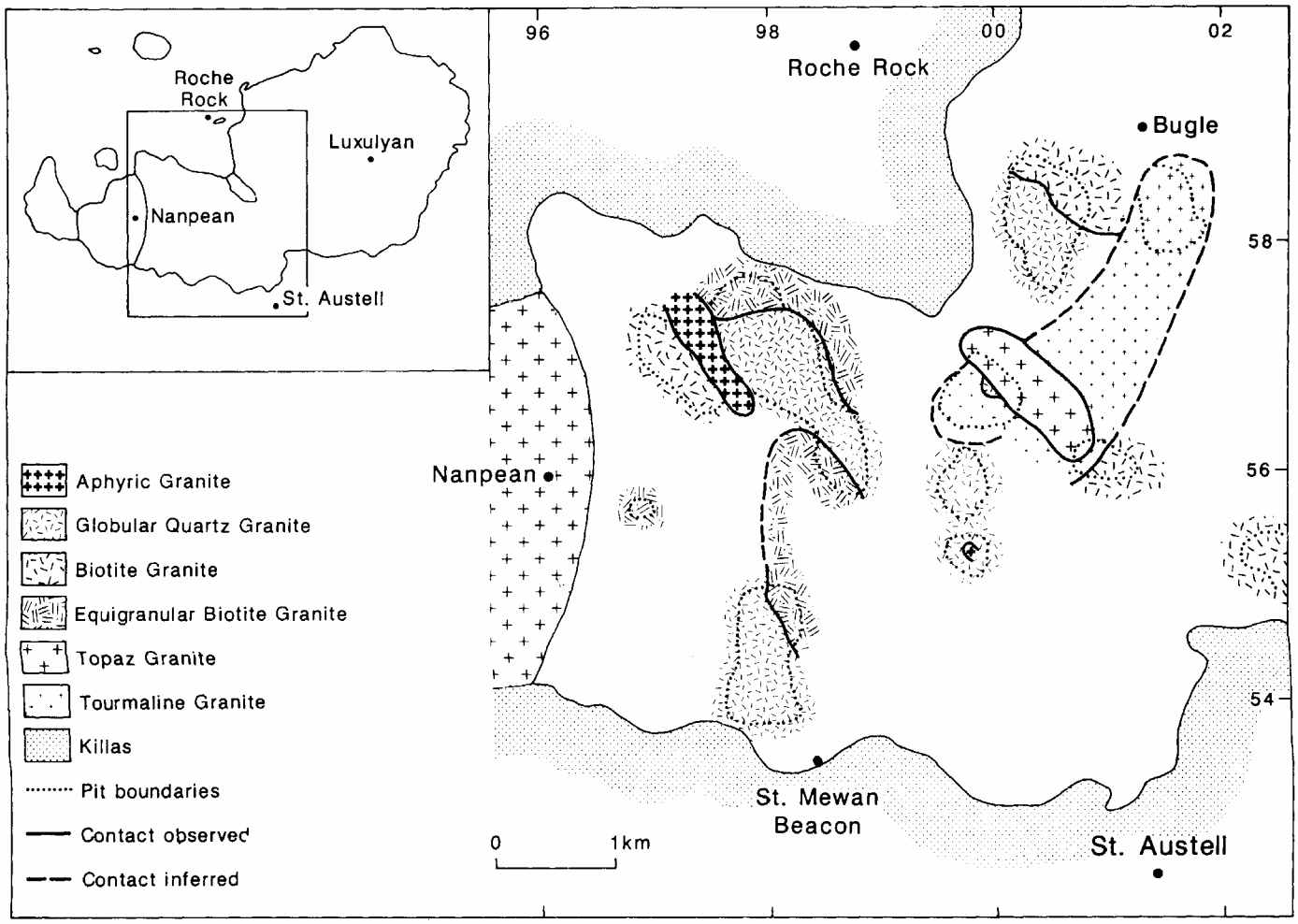


Figure 1. Distribution of Granite Types in the St Austell area.

into topaz and microperthite (in preference to plagioclase). Topaz occurs as small prismatic crystals sometimes intergrown with quartz. Accessory fluorite invades both K-feldspar and micas.

The tourmaline granite is cut by a *topaz granite* (Pichavant and Manning, 1984;) or, as termed by Exley (1959), a non-megacrystic lithium mica granite. It is medium-fine grained, and characterised by the essential presence of euhedral-subhedral topaz in addition to lithium mica, albite, orthoclase and quartz and is described more fully by Manning & Exley (1984).

Granite distribution and contact relationships The distribution of the six granite types within the central part of the St Austell granite (Fig. 1), along with contact relationships, summarised in Table 1, will now be discussed.

It should be noted that the eastern part of the body is made up of megacrystic biotite granite, with little field evidence for internal variation. In addition, the Western Lobe (Allman-Ward, 1982) is also homogeneous and composed of megacrystic biotite granite similar to that mapped in the central zone.

The area outlined in Figure 1 covers most of the region considered by Manning & Exley (1984) to be composed of a metasomatic textured granite resulting from the alteration of the biotite granite, and as can be seen is far more complex than was originally thought.

Biotite granite originally found as far west as Goonbarrow has been identified considerably further west at Dorothy pit (SW 975571), approximately lkm east of the main Nanpean topaz granite stock. Although here it consists of both megacrystic and non-megacrystic varieties it is chemically indistinct from other biotite granites sampled. Figure 1 shows in fact that much of the region between Goonbarrow and the Nanpean topaz granite stock is composed of equigranular biotite granite and globular quartz granite which appear to be intimately associated. Contacts between the two are variable. Purely transitional contacts are observed where the globular texture reverts to that of a truly coarse magmatic texture while sharp contacts are also observed.

In one location a wedge of equigranular biotite granite cuts sharply through the underlying globular quartz granite. Rounded blocks of the equigranular biotite granite are also identified within the globular quartz granite near

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contacts and their origin may be as xenoliths or unmetasomatised granite left behind a metasomatic front advancing into the biotite granite. Overall the contacts themselves appear to show both metasomatic (where transitional) or magmatic (where sharp) characteristics. Mapping completed by Bray (1980) in the Goonbarrow pit divided the granites present into the following types, a biotite-muscovite granite, a lithium mica-muscovite granite and a pale lithium mica-muscovite granite. He mapped a contact between the biotite and lithium bearing mica granites which is often marked by a curved crystal pegmatite. In the present study the lithium mica bearing types have been remapped as a globular quartz granite and although this type shows some internal variation it is not related to the distinctions made by Bray. The contact between the globular quartz granite and the biotite granite in Goonbarrow is complex and is usually denoted by a r6ck type with a darkened matrix of tourmaline and large K-feldspar megacrysts.

The aphyric granite is limited in extent to the Dorothy-Littlejohn pit divide and cuts sharply across the equigranular biotite granite and globular quartz granite, sending offshoots into the equigranular biotite granite. There is a marked development of quartz-tourmaline vugs within the globular quartz granite as the contact with the aphryic granite is reached. Contact with the biotite granite in Dorothy pit is largely transitional sometimes with marginal development of a rock enriched in small tourmaline spots, within the aphyric granite. As previously reported by Manning & Exley (1984) the contact zone between the tourmaline and topaz granite in the low levels of Gunheath pit is complex. An essentially sharp contact between the granite types to the west is complicated by the local development of the globular quartz granite facies at the contact. Elsewhere, the topaz granite contacts are marked by the occurrence of pegmatites, often with curved feldspar crystals. Xenoliths of globular quartz granite occur widely, but sparsely, within the topaz granite and are known locally as 'wains'.

Many of the curved crystal pegmatites reported previously (Bray, 1980, Badham & Stanworth, 1976) mark contacts, as at Goonbarrow and Gunheath pits. These show branching feldspar growth often referred to as unidirectional soldification textures (Shannon *et al* 1982;) and have been used to imply age relationships between neighbouring intrusions. In the Goonbarrowpit they branch towards the globular quartz granite, while in Gunheath pit two opposite directions of growth are observed and therefore caution must be taken in interpreting these to justify age relationships. Many more curved crystal pegmatites have been identified, mostly within the biotite granite (Penhale and Dorothy pits) but

Table 2. Representative Analyses

| | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| $SiO_2$ | 73.7 | 74.5 | 76.2 | 74.4 | 74.6 | 72.8 |
| $Al_2O_3$ | 14.9 | 14.6 | 13.3 | 14.6 | 13.6 | 13.1 |
| $Fe_2O_3$ | 1.72 | 1.48 | 1.21 | 1.29 | 1 | 1.02 |
| MgO | 0.32 | 0.26 | 0.2 | 0.12 | 0.13 | 0.06 |
| CaO | 0.8 | 0.6 | 0.63 | 0.53 | 0.61 | 0.56 |
| $Na_2O$ | 2.88 | 3.17 | 3.56 | 3.19 | 3.27 | 3.78 |
| $K_2O$ | 5.57 | 5.05 | 4.55 | 4.97 | 4.41 | 4.26 |
| $TiO_2$ | 0.24 | 0.13 | 0.08 | 0.12 | 0.07 | 0.04 |
| MnO | 0.03 | 0.03 | 0.03 | 0.05 | 0.02 | 0.1 |
| $P_2O_5$ | 0.26 | 0.32 | 0.42 | 0.28 | 0.37 | 0.46 |
| $B_2O_3$ | 0.16 | 0.18 | 0.3 | 0.31 | 0.23 | 0.1 |
| $Li_2O$ | 0.08 | 0.12 | 0.13 | 0.08 | 0.17 | 0.52 |
| F | d.l. | 0.55 | 0.71 | 0.26 | 0.73 | 1.1 |
| LOI | 0.65 | n.d. | n.d. | 0.54 | 0.73 | 1.24 |
| Total | 101.3 | 101 | 101.32 | 100.74 | 99.9 | 99.14 |
| O=F | - | 0.23 | 0.27 | 0.11 | 0.28 | 0.46 |
| Total | 101.3 | 101 | 101.05 | 100.63 | 99.7 | 98.68 |
| Zr | 98 | 73 | 47 | 61 | 40 | 19 |
| Y | 21 | 18 | 13 | 19 | 14 | 34 |
| Nb | 20 | 29 | 36 | 29 | 38 | 66 |
| Sr | 68 | 46 | 25 | 18 | 38 | 63 |
| Rb | 636 | 835 | 957 | 772 | 871 | 1969 |
| Ba | 232 | 95 | 60 | 23 | 134 | 50 |
| Ni | 6 | 7 | 9 | 13 | 10 | 16 |
| Pb | 24 | 16 | 12 | 16 | 9 | 2 |
| Cu | 4 | 5 | 20 | 16 | 8 | 8 |
| Zn | 50 | 27 | 36 | 51 | 24 | 95 |
| Li | 380 | 580 | 613 | 380 | 775 | 2400 |
| Ta | <5 | <5 | <5 | <5 | <5 | 32 |
| Cl | 160 | 230 | 220 | 100 | 300 | 150 |
| Nd | 27 | 25 | 20 | 17 | 16 | 23 |
| Ga | 29 | 31 | 31 | 33 | 28 | 56 |

n.d.: not determined. d. I.: at detection limit. 1. Biotite granite. 2. Equigranular biotite granite. 3. Globular quartz granite. 4. Tourmaline granite. 5. Aphyric granite. 6. Topaz granite.

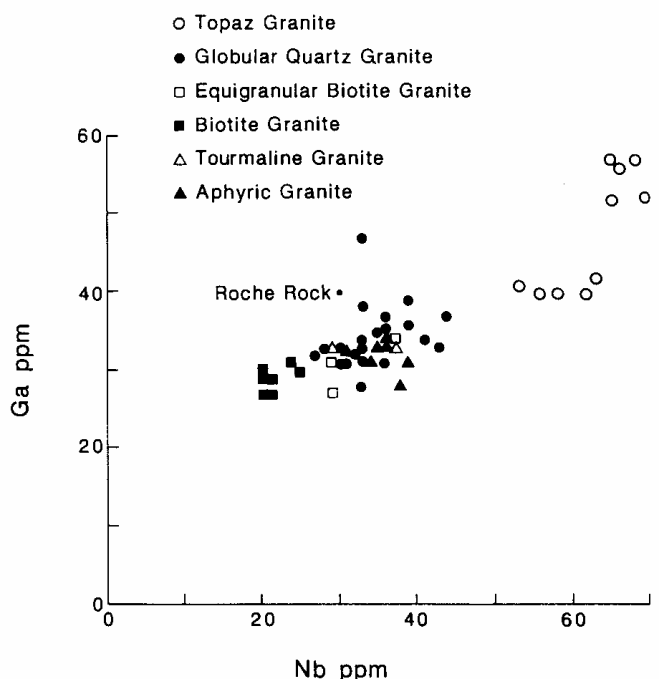


Figure 2. Ga - Nb variation diagram.

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also within the equigranular biotite and globular quartz granites. Their development appears to be late, following lines of weakness and major fracture pathways.

Finally it is worth noting that there is no evidence to support the faults inferred by Holder and Leveridge (1986) to cut this central zone of the St Austell stock.

## Geochemistry

Many of the contacts relating the various granite types identified above are complex and open to a number of interpretations. Geochemical data have been used to derive a possible sequence relating both intrusive and alteration events. Over one hundred samples have been analysed by A.A., X.R.F. and I.C.P. techniques for both major and trace elements. Representative analyses are given in Table 2.

It may be expected that through repeated hydrothermal events many elements will have been mobile, including most of the major and the low ionic potential elements such as Li and Rb, but some will have remained relatively immobile (mainly the high field strength elements). In order to deduce the magmatic sequence of these granites it has been necessary to identify suitable immobile elements, so that the alteration geochemistry characteristics are in effect removed. Most element pairs plotted in scatter plots show irregular variation, believed to be due principally to hydrothermal alteration. This is particularly true for the alkalis. On the other hand, Nb, Zr and Ga consistently show limited ranges in concentration and when plotted against each other relatively concentrated plots are obtained (Fig 2). None of these elements show any correlation with the alkalis (especially Rb or Li, which are sensitive alteration indicators) and so they are considered to have been immobile during hydrothermal alteration. The Ga vs Nb variation diagram (Fig 2) shows concentrated plots for the biotite, aphyric and topaz granites which suggests relative immobility of both these elements. The topaz granite defines two fields corresponding to the two separate intrusions forming the Nanpean and Hensbarrow stocks. A magmatic trend from low Ga and Nb values for the biotite granites to higher values of these elements for the late stage volatile enriched topaz granite is observed and is consistent with field evidence regarding their emplacement. The equigranular biotite can be seen to be more chemically evolved than the biotite granite. There is a general overlap for the other granite types but the globular quartz granite shows the largest variation in both these elements. It is important to note that this granite type plots within the region of the biotite granite, tourmaline granite and the aphyric granite or dilution lines from these granites rather than near the topaz granite.

A Nb-Zr variation diagram (Fig. 3) again shows a magmatic trend for the granites and concentrated plots for fields of granites suggesting again the relative immobility of Zr. The biotite granites with high Zr and low Nb define two concentrated plots. These two distinct groupings correspond to samples taken from Luxulyan (which are most Zr rich) and ones taken from the central area at Goonbarrow and Dorothy pits. There is a better chemical distinction between the equigranular biotite granites and the aphyric granite than observed in the Nb vs Ga plot. The globular quartz granite again shows variation in both these elements but is concentrated around the aphyric granite field, with a few points plotting towards the tourmaline and equigranular biotite

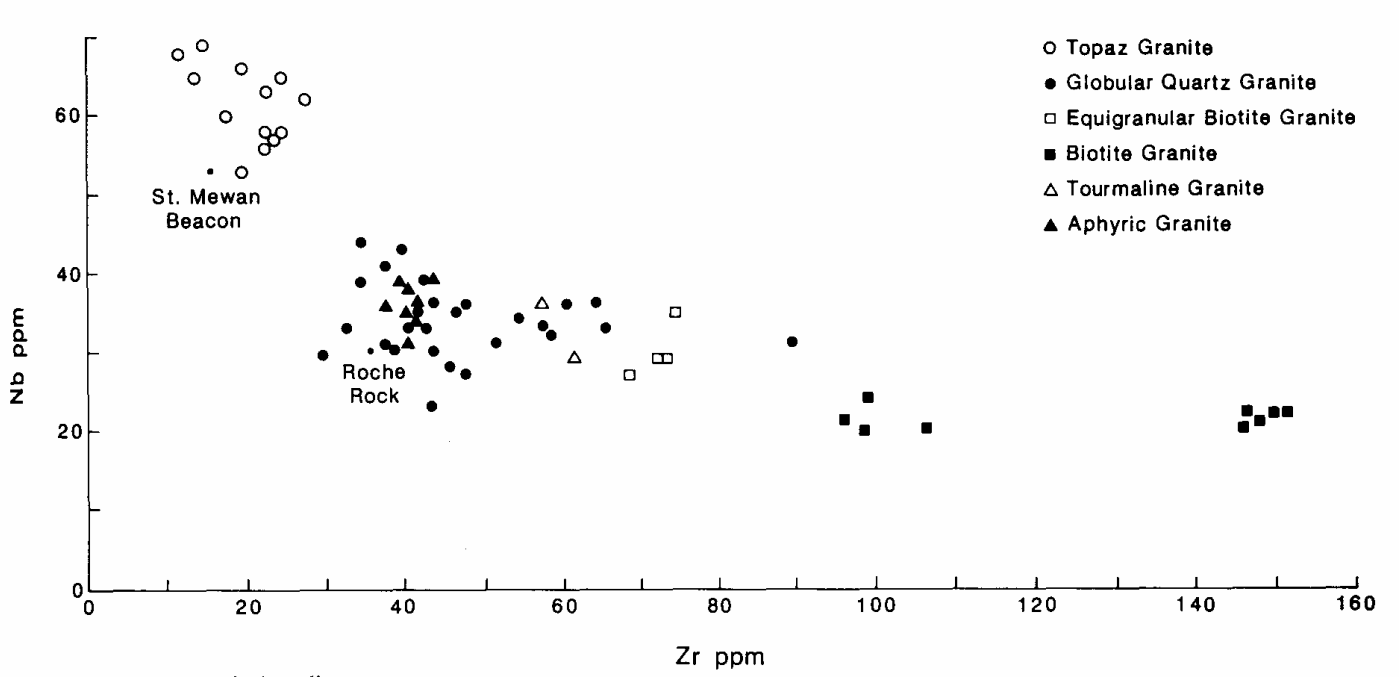


Figure 3. Nb - Zr variation diagram

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granite fields. Values for the unusual hydrothermal rock types of Roche Rock and St Mewan Beacon are also plotted for comparison, where available.

From Table 2 it can be observed that the granite types have high and variable concentrations of Li and Rb, with extreme enrichment in the late volatile-enriched topaz granites. Although both of these elements will have been mobile during alteration, plots against Nb show that both elements are enriched with increasing Nb. This is considered to be a magmatic trend although partly obscured by the effects of alteration. In addition the aphyric.granite shows notably high Cl contents (varying from 200 to 3000 ppm) possibly correlating with the chlorine content of the micas or with the abundance of fluid inclusions, which are the main sites that can be occupied by chlorine. Overall, there is extreme variability of certain elements within specific granite types, as demonstrated above.

Although not specifically considered in this paper the biotite granites of the Western lobe (Allman-Ward, 1982) plot within the fields of the two biotite granites considered here and generally show greater chemical similarities to the equigranular biotite granite.

## Discussion and conclusions

The granite varieties proposed here can be distinguished in the field and on both mineralogical and geochemical grounds. In detail there is a geochemical continuum, from megacrystic and coarse, non-megacrystic biotite granite types to aphyric granite and topaz granite, which have separate highly evolved compositions. The tourmaline granite is intermediate between these groups. On the Zr vs Nb variation diagram the globular quartz granite clusters near the aphyric granite. Texturally the globular quartz granite shows evidence of extensive metasomatic alteration. Because of the coarse globular quartz relics it is unlikely to have been derived from the aphyric granite which is much finer grained, and so a biotite or tourmaline granite precursor is preferred as these carry quartz of appropriate grain size. It has also been noted that the aphyric granite is observed to cut the equigranular biotite granite and the globular quartz granite and therefore represents a later intrusive event. The depletion in Zr shown by the globular quartz granite, compared with the biotite and tourmaline granites, implies that Zr has been mobile if the globular quartz granite was derived from either type. Alderton (1980)has shown the effects of various styles of alteration on element mobility and noted that Zr mobility is particularly important during tourmalinisation and kaolinisation. Tourmalinisation leads to a strong Zr depletion and he attributed this to the loss of zircon during replacement of biotite by tourmaline. This replacement has been identified in a number of the St Austell granite types, some tourmaline retaining a certain proportion of the inclusions that were once contained within the original mica, but its effects are certainly the greatest in the globular quartz granites. Here thc brown mica, believed to be derived from zircon-rich biotite, is relatively inclusion free, implying a loss of zircon. In addition to boron rich fluids, responsible for tourmalinisation and Zr mobility, F-bearing fluids also form part of the story as the brown mica shows replacement by topaz and quartz; F may have contributed to Zr transport. Kaolinisation may also affect the trace element concentrations due to associated density reductions, but this would lead to apparent increases in the Zr content and therefore cannot account for the loss in Zr observed in the globular quartz granite. It should be noted that Zr removed on such a scale involves very large fluid-rock ratios during hydrothermal alteration *(eg* Sciffman *et al* 1987), in view of its low solubility in hydrothermal fluids. The geochemical data, taken together with the petrographic evidence, thus support the postulate that the globular quartz granite represents highly altered granitic rock within the biotite granite- tourmaline granite trend.

Although the biotite granites show a geochemical continuum it is believed that the equigranular biotite (and possibly the Western Lobe biotite granite) represents a later separate magmatic event later than the megacrystic biotite granite of the Eastern part of the pluton, and the metasomatic effects have been restricted preferentially to this equigranular granite. Dire4:t evidence cannot support this since unaltered contacts between the biotite granite and equigranular biotite granite are not observed. Thus the contact between megacrystic biotite granite and globular quartz granite observed at Goonbarrow pit may represent an original truly magmatic contact, between the two biotite granite types, and the outcrops of biotite granites within the heavily altered region represent relics which have resisted pervasive metasomatic alteration, possibly due to local permeability variations.

It is possible to place constraints on the chronology of magmatic, mineralisation and metasomatic episodes by combining field observations of cross-cutting'relationships with radiometric age data. The earliest granite variety is the megacrystic biotite granite, which has been dated at 285 ± 4Ma (Darbyshire and Shepherd 1985). The youngest granite is the topaz granite, which cuts quartz wolframite veins at Castle-an-Dinas tungsten mine (Dines 1956). Altered rocks from Castle-an-Dinas which correspond to the globular quartz granite described in this paper have been dated by Darbyshire and Shepherd (1987) at 270 ±2Ma. This represents a maximum age for the topaz granite intruded into the globular quartz granite, but it may be that the alteration to give this facies is closely related to the emplacement of the topaz granite. The close spatial relationships between the two rock types and the tourmalinisation/alteration halos associated with the topaz granite (Manning 1985; Manning and Exley 1984), support this possibility. The topaz granite itself is host to Sn-W mineralisation, as minor quartz-cassiterite vein swarms in the Nanpean stock, and as vein and pegmatite mineralisation in the Hensbarrow stock (Manning 1983). Thus it can be seen that a complex sequence of events

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took place within an interval of the order of 15 Ma after the emplacement of the batholith, with overlap between both magmatic and hydrothermal processes.

Finally, it is worth noting that within the St Austell granite the highest quality kaolin is associated with highly altered rocks in which biotite has been replaced by tourmaline (such as the globular quartz and tourmaline granites), or in which the primary mica is lithium-rich (topaz and aphyric granites). In both cases iron is either absent or locked within silicate minerals resistant to the kaolinisation process. Detailed mapping of alteration granite types is therefore of economic interest with respect to identifying areas which are likely to be favourably kaolinised, and would consequently assist in pit design, clay extraction and quality control.

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## References

Alderton, D.H.M., Pearce, J.A. and Potts, P.J. 1980. Rare earth element mobility during granite alteration : evidence from South West England. *Earth and Planetary Science Letters, 49,* 149-165.

Allman-Ward, P. 1982. Hydrothermal phenomena in the Western Lobe of the St Austell granite, Cornwall. *Unpublished Ph.D. Thesis, University of London.*

Badham, J.P.N. and Stanworth, C.W. 1976. The curved crystal pegmatite, Goonbarrow. *Proceedings of the Ussher Society,* 3, 441-447.

Bray, C.J. 1980. Mineralisation, greisenisation and kaolinisation at Goonbarrow china clay pit, Cornwall, U.K. *Unpublished D. Phil thesis, University of Oxford*

Bray, C.J. and Spooner, E.T.C. 1983. Sheeted vein Sn-W mineralisation and greisenisation associated with economic kaolinisation, Goonbarrow china-clay pit, St Austell, Cornwall, England. Geologic relationships and chronology. *Economic Geology, 78,* 1064-1089.

Cobbing, E.J., Mallick, D.I.J., Pitfield, P.E.J. and Teoh, L.H. 1986. The granites of the Southeast Asian Tin Belt. *Journal of the Geological Society of London, 143, 537-550.*

Darbyshire, D.P.F. and Shepherd, T.J. 1985. Chronology of granite magmatism and associated mineralisation, SW England. *Journal of the Geological Society of London, 142,* 1159-1177.

Darbyshire, D.P.F. and Shepherd, T.J. 1987. Chronology of magmatism in south-west England: the minor intrusions. *Proceedings of the Ussher Society, 6, 000-000.*

Dines, H.G. 1956. The metalliferous mining region of south west England. *Memoir of the Geological Survey. G.B.*

Exley, C.S. 1959. Magmatic differentiation and alteration in the St Austell granite. *Quarterly Journal of the Geological Society of London, 114,* 197-230.

Exley, C.S. and Stone, M. 1982. Hercynian intrusive rocks. *In:* Sutherland, D.S. (ed) *Igneous rocks of the British Isles.* Wiley & Son, London.

Hawkes, J.R. and Dangerfield, J. 1978. TheVariscan granites of south-west England: a progress report. *Proceedings of the Ussher Society, 4,* 158-171.

Holder, M.T. and Leveridge, B,E. 1986. A model for the tectonic evolution of south Cornwall. *Journal of the Geological Society of London, 143,* 125-134.

Manning, D.A.C. 1983, Disseminated tin sulphides in the St Austell granite. *Proceedings of the UssherSociety, 5,* 411-416.

Manning, D.A.C. and Exley, C.S. 1984. The origin of late-stage rocks in the St Austell granite - a reinterpretation. *Journalofthe Geological Society of London, 141,* 581-591.

Manning, D.A.C. 1985. Comparison of influence of magmatic water on form of granite-hosted Sn-W deposits and associated tourmalinisation from Thailand and south-west England; *In:* Hall, C. (ed.). *High Heat Production Granites, hydrothermal circulation and ore genesis.* The Institution of Mining and Metallurgy. 203-212.

Pichavant, M. and Manning D.A.C. 1984. Petrogenesis of tourmaline and topaz granites; the contribution of experimental data. *Physics of the Earth and Planetary Interiors, 35,* 31-50.

Richardson, W.A. 1923. A micrometric study of the St Austell granite. *Quarterly Journal of the Geological Society of London, 79,* 546-576.

Sciffman, P., Smith, B,M., Varga, R.J. and Moores, E.M. 1987. Geometry, conditions and timing of off-axis hydrothermal metamorphism and ore-deposits in the Solea Graben. *Nature, 325,* 124-126.

Shannon, J.R., Walker, B.M., Carten, R.B. and Geraghty, E.P. 1982. Unidirectional solidification textures and their significance in determining relative ages of intrusions at the Henderson Mine, Colorado. *Geology, 10,* 293-297.

Sheppard, S.M.F. 1977. The Cornubian batholith, S.W. Englanct: D/H and $^{18}O/^{16}O$ studies of kaolinite and other alteration minerals. *Journal of the Geological Society of London, 133,* 573-91.

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*Read at the Annual General Conference of the Ussher Society, January 1987*

# Geochemistry and origin of the Carnmenellis pluton, Cornwall: further considerations

MAURICE STONE

Stone, M. 1987. Geochemistry and origin of the Carnmenellis pluton, Cornwall: further considerations. *Proceedings of the Ussher Society 6*, 454-460.

The main components, namely, the Outer granite, the Inner granite and late microgranite dykes show simple variation in the progressive depletion of a femic suite of elements (Fe, Mg, Ca, Ti, Zr,Th, Sr and Ba) and total REE, together with a progressive lowering of the slope (Ce/Yb ratio) of the REE pattern. These features and a near constant $Zr/TiO_2$ ratio are consistent with simple biotite and accessory mineral fractionation. The higher trace alkalies, $SiO_2$ and F in part of the Outer granite and their overall lower correlations are attributed to late-stage redistribution.

It is suggested that partial melting of the deep crustal source rocks is associated with steep REE patterns in early-formed or restite biotite. Such patterns reflect incorporation of source monazite in both biotite and whole rock whilst some of the HREE were retained by garnet in the source rocks. The highly evolved nature of all these rocks precludes their direct crystallisation from a melt produced by the partial fusion of lower crustal pelitic source rocks.

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## Introduction

Ghosh (1934) referred to the coarse-grained granites of the Carnmenellis pluton as types I, II and III and believed that they had been emplaced in that order (Fig. 1). Subsequent investigation by A1-Turki and Stone (1978) indicated that types I and II are similar, but differ significantly from type III and these authors suggested that tYPes I and II constitute an Outer granite emplaced as a single magmatic pulse, followed by the Inner granite
(Ohosh type III) and then, perhaps, by the fine-grained granite.

Statistical analysis of new data for the three granite types of Ohosh (Table 1) indicates differences in a group of mostly related elements (and oxides), namely, $SiO_2$, Li, Mn, F, Ce, U, Cs and Sn between granite types I and II. These are considered to have undergone late- and post-magmatic mobility and redistribution. The relatively more stable elements (Fe, Ca, Sr and Ba, and particularly Ti, Zr and Th) indicate more fundamental similarities between types I and II and differences between these and type III.

These comparisons conf'u-m previous views that types i and II should be regarded as a single type, the Outer granite, whilst type III is distinct and forms a separate rock type, the Inner granite, although no clustering of any of the three types is revealed by Q-mode cluster analysis. However, the microgranite dykes (with which are included aplites) and granite porphyries ('elvans') each form distinct clusters. The fine-grained granites in the west and north-west part of the outcrop (Fig. 1) plot dearly with the granite porphyries as indicated earlier by Stone and Exley (1978). Average analyses of the five rock groups (Outer granite, Inner granite, fine-grained granite, microgranites, and 'elvans') are given in Table 2. Differences between these are most clearly displayed in the variation diagrams (Figs. 2 and 3).

## Chemical variation

The correlation matrix for the Carnmenellis data reveals two important features, namely, marked positive correlations within a group of elements and oxides comprising $TiO_2$, CaO, Zr, Sr, Ba, La, Ce and Th, associated with FeO and MgO and referred to here as the 'femic suite', and unusually low positive correlations within a group comprising Li, Rb, Cs, F, $SiO_2$ and commonly Sn, referred to here as the 'trace-alkali suite'. The former group is contained principally in biotite (and some in tourmaline) and the accessory mineral suite, whilst the latter dominate those elements referred to above that are believed to have undergone some late- and post-magmatic redistribution and show significant differences between Ghosh granite types I and II. An abridged correlation matrix shown in Table 3 illustrates the strong associations within the 'femic suite'.

Bivariate plots like that for $TiO_2$-FeO (Fig. 2a) also illustrate the close relationships between members of the 'femic suite'. They indicate that the Inner granite and the microgranites have been derived from the Outer granite composition by simple fractionation of the principal minerals containing this suite, namely, biotite and the accessory minerals. The broad trend of diminishing FeO

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Table 1. Comparison of Carnmenellis coarse-grained granites

| | I | II | III | M-W Test I-II | I-III | II-III |
|---|---|---|---|---|---|---|
| n | 22 | 11 | 11 | | | |
| $SiO_2$ | 71.74 | 73.08 | 72.84 | ** | * | NS |
| $TiO_2$ | 0.24 | 0.25 | 0.17 | NS | *** | *** |
| $A1_2O_3$ | 15.2 | 14.97 | 14.57 | NS | * | * |
| $Fe_2O_3$ | 0.47 | 0.42 | 0.5 | NS | NS | NS |
| FeO | 1.21 | 1.32 | 0.86 | NS | *** | *** |
| MgO | 0.43 | 0.41 | 0.38 | NS | NS | NS |
| CaO | 0.93 | 1.01 | 0.68 | NS | *** | *** |
| $Na_2O$ | 3 | 3.18 | 3.18 | NS | NS | NS |
| $K_2O$ | 5.19 | 4.9 | 4.91 | NS | NS | NS |
| $P_2O_5$ | 0.23 | 0.24 | 0.22 | NS | NS | NS |
| F | 0.4 | 0.29 | 0.24 | *** | *** | * |
| Nb | 12 | 12 | 14 | NS | NS | ** |
| Zr | 110 | 112 | 74 | NS | *** | *** |
| y | 17 | 15 | 14 | NS | NS | NS |
| Sr | 86 | 89 | 78 | NS | ** | ** |
| Rb | 505 | 465 | 469 | ** | * | NS |
| V | 16 | 15 | 11 | NS | *** | ** |
| Mn | 358 | 300 | 322 | ** | NS | NS |
| Ba | 257 | 262 | 223 | NS | * | * |
| La | 36 | 33 | 27 | NS | ** | NS |
| Ce | 78 | 63 | 59 | * | *** | * |
| U | 15 | 12 | 10 | * | ** | NS |
| Th | 14 | 13 | 8 | NS | *** | *** |
| Pb | 33 | 35 | 37 | NS | NS | NS |
| As | 15 | 11 | 48 | NS | NS | NS |
| Ga | 21 | 21 | 21 | NS | NS | NS |
| Zn | 40 | 45 | 57 | NS | *** | ** |
| Ni | 5 | 3 | 1 | NS | *** | ** |
| Cs | 56 | 39 | 58 | *** | NS | *** |
| Sn | 14 | 9 | 17 | * | ** | *** |
| Li | 434 | 400 | 412 | * | NS | NS |

I, II and III correspond with averages of the three granite types of Ghosh (1934). n = number of samples in each types.
M-W = Mann-Whitney U test.
The symbols ***, ** and * indicate rejection of $H_0$at the 0.001, 0.01 and 0.05 probability levels respectively: NS = not significant.

and MgO, illustrated in the FeO-MgO diagram (Fig. 23.3 of Exley and Stone 1982) itself suggests that biotite fractionation was a dominant process in the Sequence Outer granite, Inner granite and microgranites. Moreover, the high positive correlations between CaO and the rest of the 'femic suite' confirm the diminishing CaO content in plagioclase feldspar in this differentiation sequence.

The significant negative correlation (r= -0.909) between $Na_2O$ and $K_2O$ (Fig. 2b) is common to many, although, not all, granitic suites and reflects increases in one feldspar at the expense of the other at more or less constant quartz content. The trend shows an increasing sodium content in the main differentiation sequence, with the fine - grained granites plotting with the granite porphyries and displaying, marked potash enrichment.

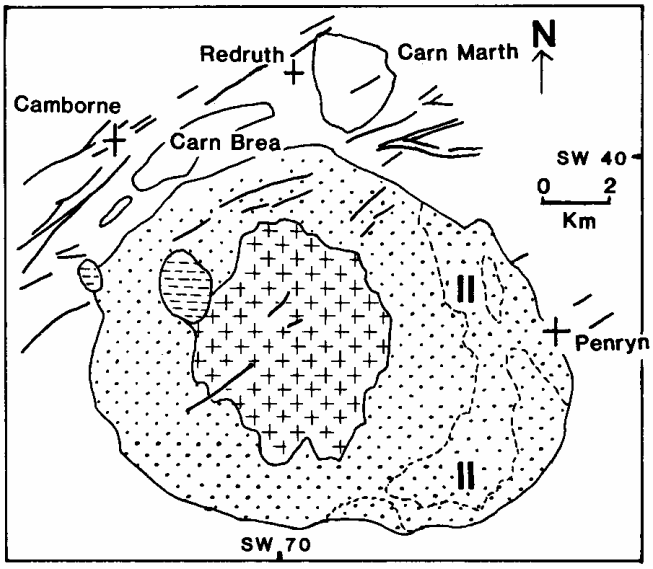


Figure 1. Sketch map of the Carnmenellis granite pluton (modified after that in Ghosh, 1934). Crosses = Inner granite; Dots = Outer granite - Ghosh type 11 granite indicated by 11 and dashed outline; Horizontal dashes = fine-grained granite; thicker lines show trend and position of some of the granite porphyry dykes. The coarse-grained megacrystic granite bodies of Carn Marth and Carn Brea to the north of the Carnmenellis granite are also indicated.

The trends shown by the bivariate plots are strongly reinforced by plots showing the mean and 95% confidence limits in terms of "Student's" t statistic for each of the Outer granite, Inner granite, microgranites and granite porphyries arranged in chronological order (Fig. 3). The marked and significant decrease in Th (Fig. 3a) is typical of the trend shown by members of the 'femic suite'. The pattern for K/Rb (Fig. 3b) shows little difference between the coarser rocks but demonstrates the evolved nature of the microgranites. Rb/Sr (not shown) increases and leads to the same conclusion. On the other hand, $Zr/TiO_2$ (Fig. 3c) illustrates that there is little change in the ratios within the 'femic suite', despite the fact that there is a decrease in both elements in the differentiation sequence. The marked differences between this ratio in the differentiation sequence and the granite porphyries indicate different petrogeneses. Neither the granite porphyries nor the frae-grained granites belong to the simple fractionation sequence of the type B granites and microgranites and will be considered more fully elsewhere.

*REE patterns*

Recently, Jefferies (1985a), Darbyshire and Shepherd (1985) and Charoy (1986) published new REE data and chondrite normalized plots for samples from the Carnmenellis pluton. Following Charoy (1986), all these data have been normalized (Fig. 4) using the chondrite values of Evensen *et al. (1978).* A new whole rock analysis (determined by neutron activation at Risley) is included

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Table 2. Analyses of Cammenellis granite types

| | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| $SiO_2$ | 72.18 | 72.84 | 73.66 | 75.71 | 73.91 |
| $TiO_2$ | 0.25 | 0.17 | 0.16 | 0.07 | 0.14 |
| $A1_2O_3$ | 15.13 | 14.57 | 14.98 | 14.43 | 14.37 |
| $Fe_2O_3$ | 0.45 | 0.5 | 0.96 | 0.56 | 0.75 |
| FeO | 1.25 | 0.86 | 0.4 | 0.48 | 0.64 |
| MgO | 0.43 | 0.38 | 0.11 | 0.13 | 0.25 |
| CaO | 0.96 | 0.68 | 0.36 | 0.57 | 0.45 |
| $Na_2O$ | 3.06 | 3.18 | 0.78 | 3.76 | 0.71 |
| $K_2O$ | 5.09 | 4.91 | 8.35 | 4.29 | 7.33 |
| $P_2O_5$ | 0.24 | 0.22 | 0.3 | 0.26 | 0.23 |
| F | 0.37 | 0.24 | 0.26 | 0.49 | 0.2 |
| Nb | 12 | 14 | 23 | 18 | 18 |
| Zr | 110 | 74 | 66 | 25 | 73 |
| Y | 16 | 14 | 4 | 5 | 10 |
| Sr | 87 | 78 | 30 | 27 | 60 |
| Rb | 492 | 469 | 642 | 604 | 767 |
| V | 16 | 11 | 11 | 4 | 10 |
| Mn | 339 | 322 | 188 | 259 | 378 |
| Ba | 259 | 223 | 202 | 111 | 219 |
| La | 35 | 27 | n.d. | 1 | 19 |
| Ce | 73 | 59 | n.d. | 19 | 42 |
| U | 14 | 10 | 11 | 12 | 13 |
| Th | 14 | 8 | 6 | 3 | 9 |
| Pb | 34 | 37 | 10 | 15 | 21 |
| Zn | 42 | 57 | 96 | 48 | 55 |
| Ni | 4 | 1 | 2 | tr | 3 |
| Cs | 50 | 58 | 45 | 46 | 59 |
| Srn | 12 | 17 | 18 | 15 | 44 |
| Li | 423 | 412 | 151 | 295 | 129 |
| K/Rb | 86.1 | 87.3 | 108.5 | 64.7 | 84.2 |
| Rb/Sr | 7 | 6 | 22.7 | 33.9 | 16.4 |
| Rb/Ba | 1.95 | 2.13 | 3.18 | 7.61 | 4.73 |
| Ba/Sr | 3.51 | 2.84 | 7.26 | 4.84 | 4.07 |
| $Zr/TiO_2$ | 452 | 429 | 409 | 420 | 678 |
| Nb/Y | 0.91 | 1.23 | 126 | 35.3 | 25.4 |
| No. of samples | 34 | 11 | 2 | 14 | 12 |

1* Outer granite; 2 = Inner granite; 3 = Fine-grained granite; 4 = microgranite and aplite; 5 = granite porphyry (elvan).
n.d. = not detected; tr = trace.

within the composition band of the Outer granite and a new biotite pattern (Fig. 5) is compared with one given by Charoy (op. cit.) together with the average of three monazites from Jefferies (1985). This average is almost identical to a single monazite analysis given by Charoy (1986). Jefferies (1985a) has shown that most of the whole rock REE patterns can be accounted for by the accessory mineral suite, in particular monazite, zircon, apatite and xenotime. It follows that any changes in these patterns largely reflect changes in the accessory mineral suite, except for the europium values which are dictated by both the accessory minerals and the feldspars.

A comparison between the slopes of the monazite and biotite REE patterns suggests that the LREE in the latter are determined by inclusions of the former. Also, the

Table 3. Pearson product moment correlation matrix: selected elements

| | $TiO_2$ | FeO | MgO | CaO | Zr | Y | Sr |
|---|---|---|---|---|---|---|---|
| FeO | 0.812 | | | | | | |
| MgO | 0.765 | 0.640 | | | | | |
| CaO | 0.816 | 0.806 | 0.672 | | | | |
| Zr | 0.945 | 0.784 | 0.766 | 0.844 | | | |
| Y | 0.598 | 0.363 | 0.724 | 0.558 | 0.607 | | |
| Sr | 0.820 | 0.721 | 0.784 | 0.779 | 0.867 | 0.589 | |
| Rb | -0.493 | -0.282 | -0.498 | -0.488 | -0.498 | -0.507 | -0.553 |
| V | 0.805 | 0.531 | 0.731 | 0.669 | 0.822 | 0.657 | 0.752 |
| Ba | 0.711 | 0.610 | 0.631 | 0.653 | 0.796 | 0.392 | 0.882 |
| La | 0.791 | 0.611 | 0.705 | 0.681 | 0.787 | 0.509 | 0.779 |
| Ce | 0.571 | 0.566 | 0.601 | 0.580 | 0.614 | 0.524 | 0.602 |
| Th | 0.911 | 0.761 | 0.737 | 0.848 | 0.952 | 0.602 | 0.803 |
| Cs | -0.047 | 0.111 | 0.007 | -0.062 | -0.047 | 0.003 | 0.011 |
| Sn | -0.360 | -0.267 | -0.168 | -0.438 | -0.339 | -0.257 | -0.314 |

| | Rb | V | Ba | La | Ce | Th | Cs |
|---|---|---|---|---|---|---|---|
| V | -0.424 | | | | | | |
| Ba | -0.517 | 0.679 | | | | | |
| La | -0.455 | 0.726 | 0.632 | | | | |
| Ce | -0.327 | 0.570 | 0.525 | 0.493 | | | |
| Th | -0.446 | 0.804 | 0.729 | 0.744 | 0.611 | | |
| Cs | 0.490 | 0.040 | 0.053 | 0.185 | 0.088 | -0.067 | |
| Sn | 0.404 | -0.217 | -0.154 | -0.259 | -0.128 | -0.366 | 0.533 |

similarities between the REE patterns of biotites and rocks, particularly for the LREE, suggest that biotites have included the LREE-rich accessory minerals in roughly the same proportions as their host rocks. Calculations based upon data of Jefferies (1984) and Charoy (1986) for monazite account almost completely for the Ce content of the Type B granites, whilst the overall flatter pattern of biotite compared with that of monazite is almost wholly due to HREE-rich accessory mineral inclusions, namely zircon and, in particular, tiny amounts of xenotime.

## Discussion and conclusions: origin of the the Carnmenellis granite

*Fractionation.* Simple fractionation in the main sequence of granitoids, namely, the Outer granite, Inner granite and microgranites, is revealed by variation diagrams that show a diminution in the highly positively correlated 'femic suite'. Such diagrams (Fig. 2a) are wholly consistent with biotite fractionation accompanied by the accessory mineral suite. Biotite shows relatively small changes in composition within this sequence. Fractionation of more calcic plagioclase feldspar has resulted in an increase in albite, but the trend of increase in Na is also helped by an overall plagioclase increase at the expense of K-feldspar (the negative correlation in Fig. 2b). Evidence for this behaviour is supported by the marked decrease in both Sr and Ba within the sequence. The product of this fractionation is the simple differentiation sequence Outer granite, Inner granite, micro-granites.

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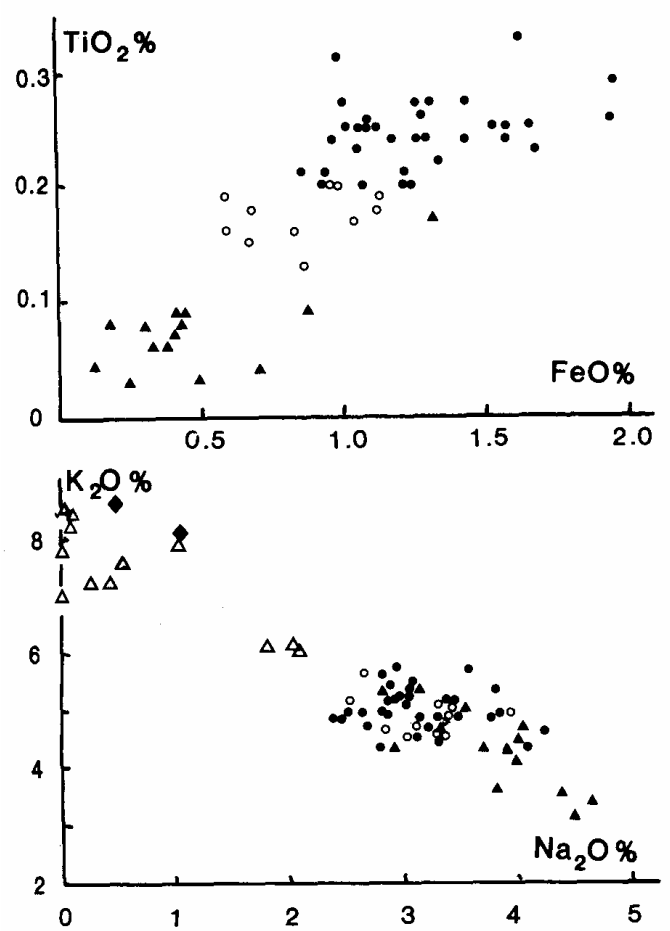


Figure 2. Bivariate data plots. (a) $TiO_2$(Wt%) - FeO (wt.%) plot showing typical 'femic element' association; (b) $K_2O$ (wt.%) - $Na_2O$ (wt.%) plot of all Carnmenellis data. Symbols: filled circles = Outer granite; open circles = Inner granite; filled triangles = microgranites; in addition, in Fig. 2b, open triangles = granite porphyries; filled diamonds = fine-grained (type C) granites.

*Late-stage redistribution.* Superimposed on this pattern in the largely unaltered Outer granite is a weak redistribution or metasomatism involving the 'trace-alkali suite'. This has resulted in low positive correlations between elements that commonly show stronger association. They are also those elements that distinguish between the two components (Ghosh granite types I and II) which form the Outer granite and reflect marginal increases of the 'trace-alkali suite' in the Ghosh type I granite. This, in turn, might suggest that the Ghosh type II granite occupies relict areas not affected by these late changes. Such changes are likely to occur in the last stages of crystallization or in the early post-magmatic period, when water released from the magma would be expected to aid recrystallization and modification of the magmatic fabric (Stone 1979, 1984).

*Source.* A crustal source for these rocks is indicated by the initial Sr isotope ratios (0.713; Darbyshire and Shepherd 1985), oxygen isotope data (indicating a politic

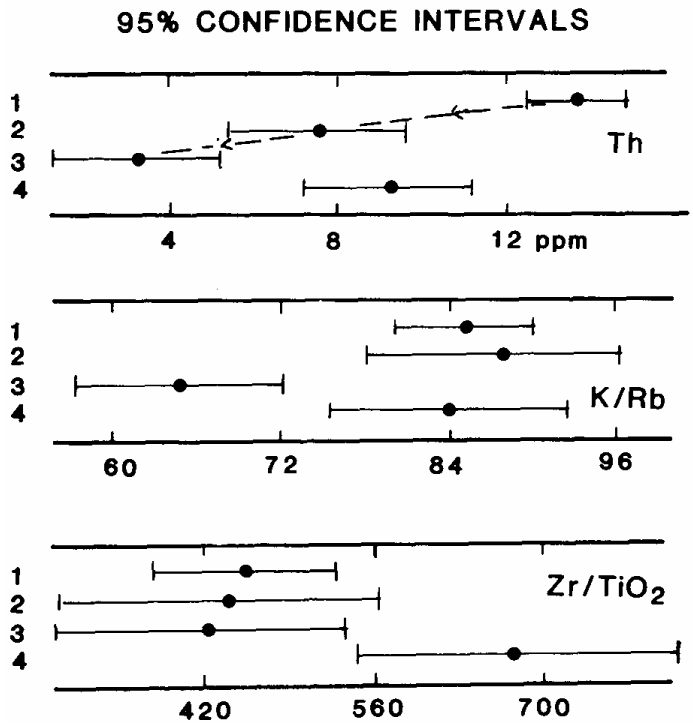


Figure 3. Copy of computer output showing means and 95% confidence intervals about the means (based upon pooled standard deviations). I = Outer granite; 2 = Inner granite; 3 = microgranites; 4 = granite porphyries.
(a) Th (ppm) (similar to other 'femic elements'); (b) K/Rb (wt ratio); (c) Zr (PPM)/$TiO_2$ (wt.%).

source; Sheppard 1977) and Sr and Pb isotope compositions from which a late Proterozoic source has been inferred (Hampton and Taylor, 1983). Further evidence for a pelitic source is the common occurrence of typically metamorphic minerals such as cordierite and especially andalusite in many specimens. Pelitic xenoliths with corundum, spinel and andalusite are considered by Jefferies (1985b) to be restite material derived from source rocks. Field and textural evidence indicates that the biotites are 'xenolithic' in origin (Stone 1979; Exley and Stone 1982; Charoy 1986) and were probably derived from the source rocks of their present host granites, although they are likely to have undergone chemical equilibration with their evolving host rocks. Such changes are indicated by the increasing A 1-content with differentiation (Charoy 1986), the differences between pelitic biotites and those in the present granites (Stone, Exley and George 1987, in press) and the small changes in biotite composition in the differentiation series Outer granite - Inner granite - microgranite referred to above.

*Rare-earth element patterns.* Charoy (1986) compared the RE E patterns of the type B granites of Carnmenellis with those of Brioverian pelites. He considered that the latter would provide a likely source owing to the age predictions of source material and its nature as discussed above. Modelling of REE led to the tentative suggestion that 30% partial melting off a Brioverian pelite source

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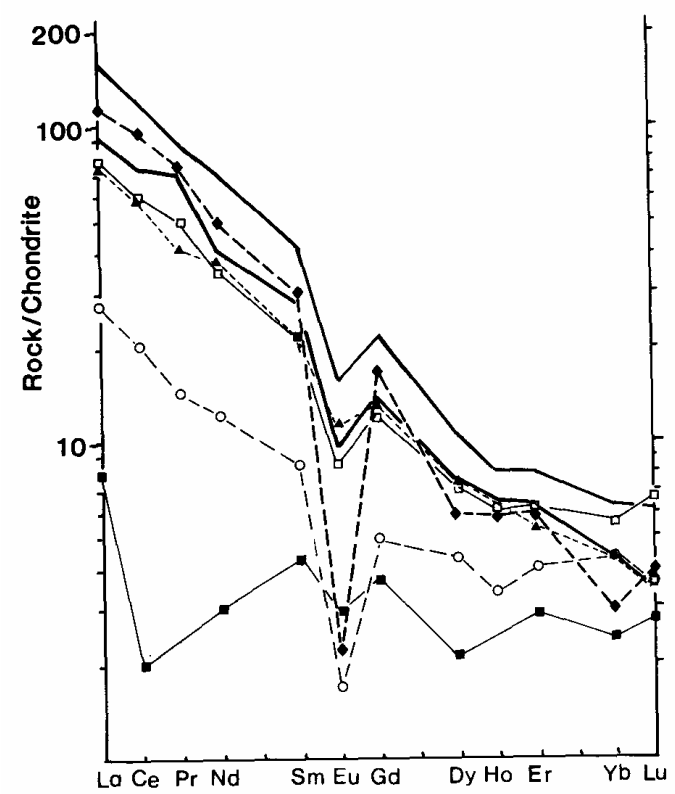


Figure 4. Chondrite-normalized REE patterns for rocks from the Cammenellis pluton. The Outer granite (13 analyses) falls within the two heavy lines. Two Inner granite samples are shown by open squares (Darbyshire and Shepherd, 1985, specimen C15) and filled triangles (Jefferies, 1985, specimen NJ4). Two microgranite dykes are shown by open circles (Jefferies, 1985, specimen NJ5) and filled squares (Charoy, 1986, specimen CARN5B). A new biotite analysis (MSO021B1) is shown by filled diamonds and heavy dashed line.

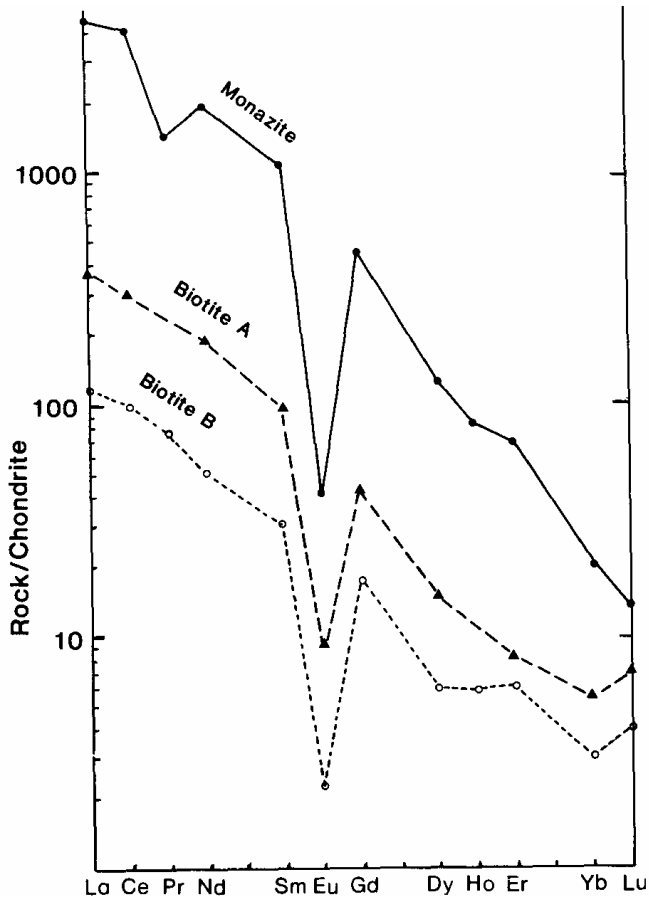


Figure 5. Chondrite-normalized REE pattern for average monazite (from Table II, Jefferies, 1985) divided by 100, and two biotites (A from Charoy, 1986; and B from Figure 4 of this paper).

would give a liquid having an REE composition close to that of the Carnmenellis Outer granite. However, useful modelling must constrain the nature of the partial melt. A considerable problem arises in assuming that the present granite could approximate the composition of liquid derived from the partial melting of a pelitic source rock. In addition to the melt phase, an upward moving magma would be expected to carry a large amount of restite source solids (White and Chappell, 1977) now represented by some or all of the biotite, some (and, perhaps quite a lot of) plagioclase feldspar and most of the accessory minerals in the present Outer granite.

The REE pattern for pelitic rocks is considerable flatter than that of the Carnmenellis granites. This is the case both for the Brioverian pelites quoted by Charoy (1986) and the pelites of the Mylor Formation (Mitropoulos, 1982). As indicated above, it seems likely that most of the REE will be held in the accessory minerals (Jefferies, 1985a), unless garnet or hornblende is present in considerable quantities (Hanson, 1978). The probable occurrence of garnet in the source rocks of the Cornubian granites is indicated by occurrences of garnet as an accessory mineral in the Dartmoor granite (Brammall and Harwood, 1932). At Chinkwell Tor, the garnet is a Mn-rich almandine (Brammall and Harwood, 1932)and recent microprobe analysis of garnet from the Sweltor Quarry on Dartmoor (Stone, unpublished data) confirms the almandine-rich (78%) composition. Such garnets, if abundant in a metamorphosed Brioverian or other pelitic source, will retain the HREE and thereby relatively enrich the LREE and enhance the LREE/HREE slope of an initial partial melt + solids. It is clear that such initial magmas will have steeper REE patterns than a proposed pelitic source rock, although as the extent of melting increases, the slope will, in the limit, approach that of the source.

A source origin for the biotites must also imply a source origin for the accessory mineral suite, at least, that part of it included in the biotites. This, in turn, indicates that the present REE pattern in the biotites is a reflection of that available from the source rocks. Whilst the biotites would be expected to undergo changes in their composition in response to re-equilibration with their new magmatic environment, their included refractory REE-bearing accessory minerals would not.

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*Petrogenetic interpretation of REE patterns.* As indicated above, it is considered that much of the LREE pattern of the Outer granite can be explained by the estimated amount of monazite present. The flattening of the HREE part of the pattern in the granite is due to the presence of zircon and, particularly, very small amounts ofxenotime, identified by Jefferies (1984). The biotite pattern of specimen MS0021BI (Figs. 4 and 5) lies within the range of the Outer granite patterns and the biotite pattern of Charoy (1986) is parallel to this, especially for the LREE. This implies that much of the REE pattern, especially the LREE, in both rock and biotite is due to accessory minerals. The overall steeper slope of the biotite REE pattern is considered to have resulted from the restite nature of this mineral or its early crystallization (Stone 1979; Charoy 1986). Therefore, the biotite REE pattern is interpreted as one "inherited" from the initial 'magma' (liquid + restite). Such biotite might be expected to "sample" the LREE-rich accessory minerals, perhaps in the same proportion as they occur in this initial magma or in the source rock in which it grew.

Subsequent flattening of the REE pattern, the result of LREE depletion, is a common feature of differentiation series in granitic rocks. It has been attributed to the separation of very small grains of LREE-rich accessory minerals such as monazite and/or allanite by Miller and Mittlefehldt (1982), but in the case of the Carnmenellis sequence this, together with a decrease in total REE and the 'femic suite', reflects both accessory mineral and biotite fractionation.

Thus, the early stage of melting of garnet-bearing source rock yields a steep REE pattern similar to that of monazite, especially for the LREE. This pattern is included in biotite which, along with the accessory minerals, undergoes crystal fractionation to give the flatter patterns of the later differentiates (Fig. 4). An important implication of this interpretation is that the overall flatter pattern of the earliest granite, i.e. the Outer granite, compared with the biotite pattern suggests that marked differentiation had already occurred either in a deeper reservoir or during transit from deeper in the crust, i.e. at the time of emplacement, the Outer granite was already highly differentiated with respect to the initial magma produced by crustal anatexis, as evidenced by other parameters like low K/Rb (Fig. 3b) and high Rb/Sr.

*Wider implications.* Darbyshire and Shepherd (1985) have shown that the REE patterns of the Bodmin and the Carnmenellis Type B granites are steeper than those of Land's End and Dartmoor. They suggest that the differences result from either different source rocks or a greater extent of melting for the flatter patterns of Dartmoor and Land's End. Certainly, this flatter REE pattern cannot result from greater differentiation in these instances since the type B granites of both the Land's End and Dartmoor plutons contain equal or larger amounts of the 'femic' suite, than those of the Cammenellis and Bodmin Moor plutons, but it could indicate either a greater extent of melting in which HREE participation was not inhibited or contamination by pelitic material. There is little evidence for contamination *in situ* in the granites of the Cornubian batholith, but contamination in transit is highly likely, particularly for the relatively dry, high temperature early magmas. Dilution of the biotites REE pattern (= initial magma) with the typical pelite pattern would lead to rocks with patterns similar to those of the early granites, but with higher total femic elements and associated trace elements like Zr and Th. These features are apparent in the coarser (type B) granites of the Land's End and Dartmoor plutons.

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## References

A1-Turki, K.I.S. and Stone, M., 1978. Petrographic and chemical distinction between the megacrystic members of the Carnmenellis granite, Cornwall. *Proceedings of the Ussher Society, 4,* 182-189.

Brammall, A. and Harwood, H.F., 1932. The Dartmoor granites: their genetic relationships. *Quarterly Journal of the Geological Society of London, 88,* 171-237.

Charoy, B., 1986. The genesis of the Cornubian batholith (South West England): the example of the Carnmenellis pluton. *Journal of Petrology, 27,* 571-604.

Darbyshire, D.P.F. and Shepherd, T.J., 1985. Chronology of granite magmatism and associated mineralization, SW England. *Journal of the Geological Society of London, 142,* 1159-1177.

Evensen, N.M., Hamilton, P.J. and O'Nions, R.K., 1978. Rare-earth abundances in chondritic meteorites. *Geochimica et Cosmochimica Acta, 42,* 1199-1212.

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

Ghosh, P.K., 1934. The Carnmenellis granite: its petrology, metamorphism and tectonics. *Quarterly Journal of the Geological Society of London, 90,* 240-276.

Hampton, C.M. and Taylor, P.N., 1983. The age and nature of the basement of Southern Britain: evidence from Sr and Pb isotopes in granites. *Journal of the Geological Society of London, 140,* 499-509.

Hanson, G.N., 1978. The application of trace elements to the petrogenesis of igneous rocks of granitic composition. *Earth and Planetary Science Letters, 38,* 26-43.

Jefferies, N.L., 1984. The radioactive accessory mineral assemblage of the Carnmenellis granite, Cornwall. *Proceedings of the Ussher Society, 6,* 35-41.

Jeff eries, N.L., 1985a. The distribution of the rare earth elements in the Carnmenellis pluton, Comwall. *MineralogicalMagazine, 49,* 495-504.

Jefferies, N.L., 1985b. The origin of sillimanite-bearing pelitic xenoliths within the Carnmenellis pluton, Cornwall. *Proceedings of the Ussher Society, 6,* 229-236.

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Miller, C.F. and Mittlefehldt, D.W., 1982. Depletion of light rare-earth elements in felsic magmas. *Geology, 10,* 129-133.

Mitropoulos, P., 1982. REE patterns of the metasedimentary rocks of the Land's End granite aureole (South west England). *Chemical Geology, 35,* 265-280.

Sheppard, S.M.F., 1977. The Cornubian batholith, south west England: D/H and $^{18}O/^{16}O$ studies of kaolinite and other alteration minerals. *Journal of the Geological Society of London,* 133, 573-591.

Stone, M., 1979. Textures of some Cornish granites. *Proceedings of the Ussher Society, 4,* 370-379. Stone, M., 1984. Textural evolution of lithium mica granites in the Cornubian batholith. *Proceedings of the Geologists' Association, 95,* 28-41.

Stone, M. and Exley, C.S., 1978. A cluster analysis of chemical data from the granites of SW England. *Proceedings of the Ussher Society, 4,* 172-181.

Stone, M., Exley, C.S. and George, M.C. in press. Compositions of trioctahedral micas in the Cornubian batholith. *Mineralogical Magazine.*

White, A.J.R. and Chappell, B.W., 1977. Ultrametamorphism and granitoid genesis. *Tectonophysics, 43,* 7-22.

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*Read at the Annual Conference of the Ussher Society, January 1987*

# Initial vitrinite reflectance results from the Carboniferous of north Devon and north Cornwall

CHRIS CORNFORD,
LEE YARNELL,
DUNCAN G. MURCHISON

Cornford, C. Yarnell, L. and Murchison, D.G. 1987. Initial vitrinite reflectance results from the Carboniferous of north Devon and north Cornwall. *Proceedings of the Ussher Society, 6,* 461-467.

Fifteen coastal and 100 inland samples from the Carboniferous (Culm) of north Devon and north Cornwall gave vitrinite reflectance values which can be interpreted in terms of Variscan burial and thrusting, and the emplacement of the Dartmoor granite. Lower vitrinite reflectance values (1.5 -2.67%R) in the Bideford area (Bideford and underlying Crackington Formations) suggest that it comprises a separate thrust slice (the Westward Ho! nappe). This nappe has had a shallower burial history compared with the contiguous Crackington and Bude Formation sediments from Hartland to Crackington Haven (4.41 - 5.67%R) to the south and the Lower Carboniferous Codden Hill Cherts to the north (5.0%R). Pre-thrusting burial of some 4.5 to 5.5 km is indicated for the Bideford area, in contrast to a depth of 5.8 to 7.0 km for the Hartland to CraCkington Haven strata. The structurally allochthonous nature of the Bideford area rocks could explain the unique nature of the cyclic fluvio-deltaic sediments of the Bideford Formation, and the unusual facies of the underlying Crackington Formation shales. Gas generation is still possible at these reflectance levels. North of Dartmoor the vitrinite reflectance values were plotted in the ranges < 2%R, 2.0 - 3.5%R, 3.5 - 5.0% R and > 5.0%R. While the samples from the metamorphic aureole fall in the > 5%R range (2 samples) or contain unmeasurable graphite grains, no clear decrease in reflectance is seen away from the granite contact. Explanations including a variable depth to top granite, the effects of dykes and hydrothermal fluids, a possible basal dislocation to the granite, and gravity sliding of heated thrust slices off the rising granite batholith are considered.

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## Introduction

The Carboniferous (Culm) sandstones and mudstones of North Devon and North Cornwall were laid down in a sedimentary trough south of the extensive shallow shelf and coastal plain on which the Carboniferous Limestone, Millstone Grit and Coal Measures were deposited. To the south lay the closing suture of the proto-Tethys, the compression giving rise to the Variscan tectonic event. Northward migration of the locus of deformation into the north Devon area produced the burial, folding, thrusting, intrusion and uplift that yields the characteristics of the Culm today. In this paper we report vitrinite reflectance values that can place limits on the extent of burial and thrusting, and the nature of the syn-orogenic intrusion event of the Dartmoor granite.

Vitrinite, organic matter usually of woody stem or bark origin, is commonly seen in microscope preparations of the shales and'silts of the Upper Carboniferous Culm of north and mid-Devon (Fig. 1). In extreme cases the remains occur in plant beds (as at Hartland Quay) or as poor quality coals (culm) as in the Bideford area. In general, however vitrinite occurs as dispersed coaly particlesin the 10 to 100 micron size range in the shales and silts of the Culm sequence. The other common type of organic particle, inertinite, derives from oxidized or burnt woody tissues (?fossil charcoal). It is important, but sometimes difficult, to distinguish the higher reflecting inertinite from vitrinite, in order to get an accurate vitrinite reflectance value.

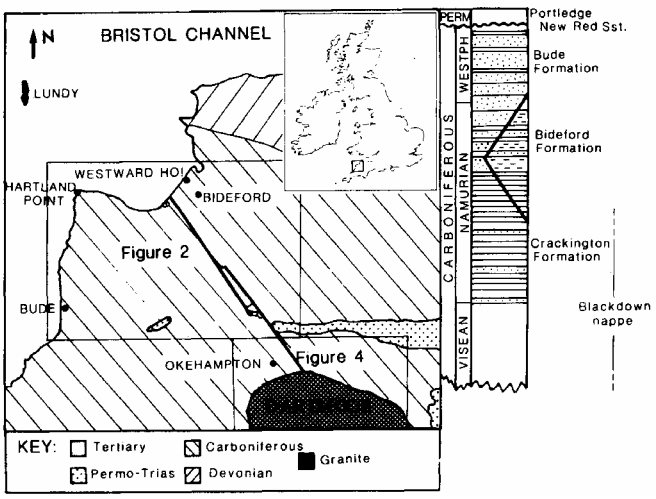


Figure 1. Location of the study area and summary stratigraph:

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## Methodology

Using a reflected light microscope to observe the highly polished surface of rock chips, the vitrinite particles can be seen and identified. For this study polished whole rock chips rather than isolated kerogen concentrates were mounted and polished. With a photometer attached, the reflectance was measured using oil immersion objectives and light of 546 nm wavelength. Polarized light was used but no stage rotation was attempted, resulting in the measurement of R-average rather than R-max. In any one sample up to 20 selected vitrinite particles were measured and their reflectance values, expressed as a percentage of the incident light, displayed as a histogram (Fig. 2, inset). An arithmetic mean and standard deviation is calculated for each sample (Table 1).

Accurately identifying the indigenous as opposed to the reworked or altered vitrinite is the crux of this method (Stach *et al.* 1982, Chapter 2). For this study vitrinite stringers, running parallel to the bedding were sought for measurement. Grains of vitrinite, especially if rounded, were avoided as they might be reworked.

While the authors are aware that inertinite can be distinguished from vitrinite by the degree of bire-flectance, and by the enhanced relief formed while polishing, the distinction is difficult to maintain when semi-fusinite is present. At the high maturities reached in many of the samples the distinction is essentially academic as vitrinite and inertinite reflectance levels will be similar.

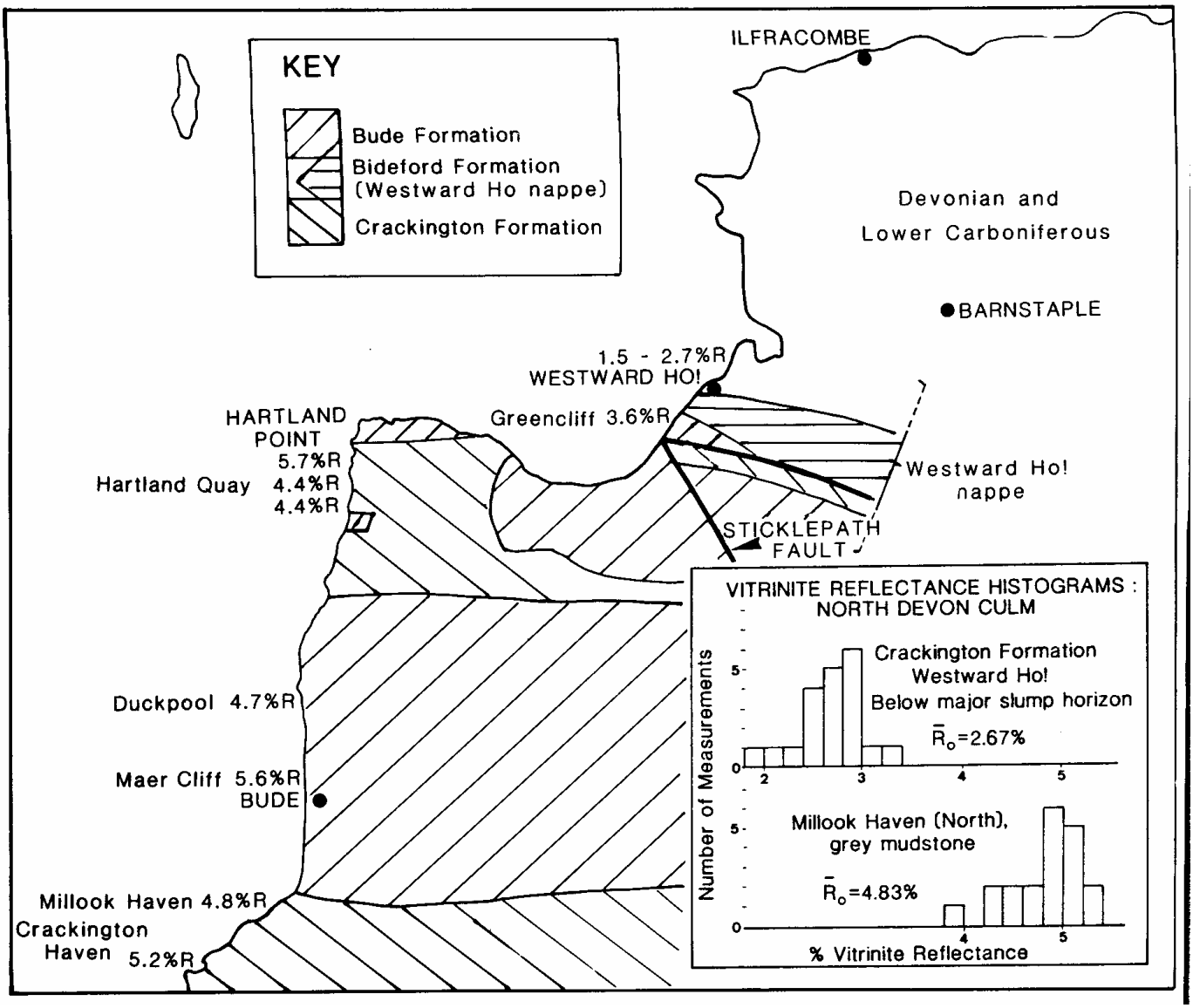


Figure 2. Simplified geology of the north Devon and north Cornwall coastal area showing the distribution of the reflectance values along the coastal section. Note the low values recorded at Westward Ho! The inset shows two contrasting reflectance populations for the Crackington Formation: upper shows low reflectance values at Westward Ho!; lower shows the high reflectance values measurements obtained at Millook Haven.

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Table 1. Vitrinite reflectance data from the Upper Carboniferous of the coast of North Devon and North Cornwall

| Location | Stratigraphy | *Mean | S.d. | n | Comments |
|---|---|---|---|---|---|
| Swimbridge | Codden Hill chert | 5 | 0.5 | - | Quarry sample |
| Westward Ho! | Crackington Fm. | 2.67 | 0.32 | 20 | Below slump horizon |
| Westward Ho! | Crackington Fm. | 2.46 | 0.53 | 14 | By Seafield |
| Comborough Cliff | Bideford Fm. | 2.5 | 0.2 | - | |
| Abbotsham Cliff | Bideford Fm. | 1.8 | 0.2 | - | |
| Abbotsham Cliff | Bideford Fm. | 1.5 | 0.2 | - | Coaly shale not 'in situ' |
| Abbotsham Cliff | Bideford Fm. | 1.6 | 0.1 | - | |
| Green Cliff | ? | 3.6 | 0.3 | - | Coaly debris |
| Titchbury Mouth | Crackington Fm. | 5.67 | 0.57 | 20 | Sheared coal lense |
| Hartland Quay | Crackington Fm. | 4.4 | 0.52 | 20 | Carbargillite |
| Hartland Quay | Crackington Fro. | 4.41 | 0.48 | 20 | Plant bed horizon |
| Duckpool | Bude Formation | 4.7 | 0.4 | - | Major shale |
| Maer Cliff | Bude Formation | 5.6 | 0.6 | - | |
| Millook Haven | Crackington Fm. | 4.83 | 0.36 | 20 | North side |
| Crackington Haven | Crackington Fm. | 5.18 | 0.74 | 20 | North side |

* Mean = arithmetic mean of n measurements with a standard deviation, (s.d.)

Vitrinite reflectance can be related to the temperature history of the rock sample (see reviews by Robert 1985; Waples 1984). Comparison with the reflectance-depth trends established elsewhere along the Variscan Front (Robert 1985, Chapter 15; Teichmüller and Teichmüller, 1979, 1986) allows limits to be placed on the maximum depth of burial of these samples.

In this paper vitrinite reflectance data are reported from outcrop samples from the north Devon and north Cornwall coast (15 analyses) and from the O kehampton area north of Dartmoor (100 samples).

## North Devon and north Cornwall coast samples

Examples of histograms from this area are shown in Figure 2 (inset) and the numerical data given in Table 1. The geographic distribution of values is shown in Figure 2. The overall range of reflectance values (1.5 to 5.7%R) is similar to that reported for the tectonically analogous sediments of the Eifel area of West Germany (Robert 1985, Chapter 15; Teichmiiller and Teichmuller 1979).

Geographically the data fall into two groups. From Hartland Quay and south to Millook and Crackington all vitrinite reflectance values are in excess of 4.41%R, while in the Westward Ho! - Abbotsham cliff section the values all fall below 2.67%R. An intermediate value of 3.6% was obtained from Greencliff at an intermediate location, while the stratigraphically older Codden Hill cherts at Swimbridge Quarry yielded a value of 5.0%.

The northern (Westward Ho! - Abbotsham) samples form a statistically separate group compared with the southern (Hartland Quay to Crackington) samples, although the sediments are believed to be, at least in part, stratigraphically equivalent (Edmonds *et al.* 1979).

## North Devon thrust slices - the Westward Ho! nappe

The above data suggest that the two areas have suffered different thermal histories, which on regional grounds means different burial histories during the end Carboniferous Variscan orogeny. These two areas must either now be in juxtaposition due to post-burial tectonic events (e.g. thrusting), or they are not stratigraphic equivalents, the Bideford Group being younger and hence less deeply buried than the Bude and Crackington Formations.

Published opinion indicates clearly that, based on goniatite bands, the Bideford Formation is at least in part a lateral equivalent of the Bude Formation (Edmonds *et al.* 1979). Goniatite identification is reported to be sometimes problematic; so this correlation should not be accepted without question.

Assuming a time equivalence, the Bideford Formation and the underlying 'Crackington' Formation (= Westward Ho! Formation of DeRaaf *et al.* 1965) were buried less deeply than the Bude and Crackington Formations to the south, and were brought together by thrusting. The conclusion is that the Westward Ho! -Bideford area belongs to a separate thrust slice from that comprising the remaining sampled area of north Devon and north Cornwall to the south. To determine the exact location of the boundaries of the Westward Ho! nappe will require additional sampling.

Limits can be placed on the burial of the samples by considering the reflectance values in the context of established depth/reflectance trends for Carboniferous samples along the strike of the Variscan Front (Fig. 3). The justification for citing these foreign reflectance trends is validated since the 1.2 km logged thickness of the Bideford and underlying 'Crackington' Formations gives (Fig. 3 inset) the same reflectance gradient as those observed in the North West Germany (Variscan maximum burial) and in the southern North Sea gas basin (Cretaceous maximum burial). A higher gradient was observed in Belgium.

From the Figure 3 plot it appears that the Bideford and underlying 'Crackington' Formations were buried between 4.5 and 5.5 km. The fact that maturity increases with stratigraphic sequence shows they were buried (and matured) and then uplifted and folded. Folding clearly post-dates maturation.

Estimates of the burial of the Bude and Crackington Formation further south all fall in the 5.8 - 7.0km zone.

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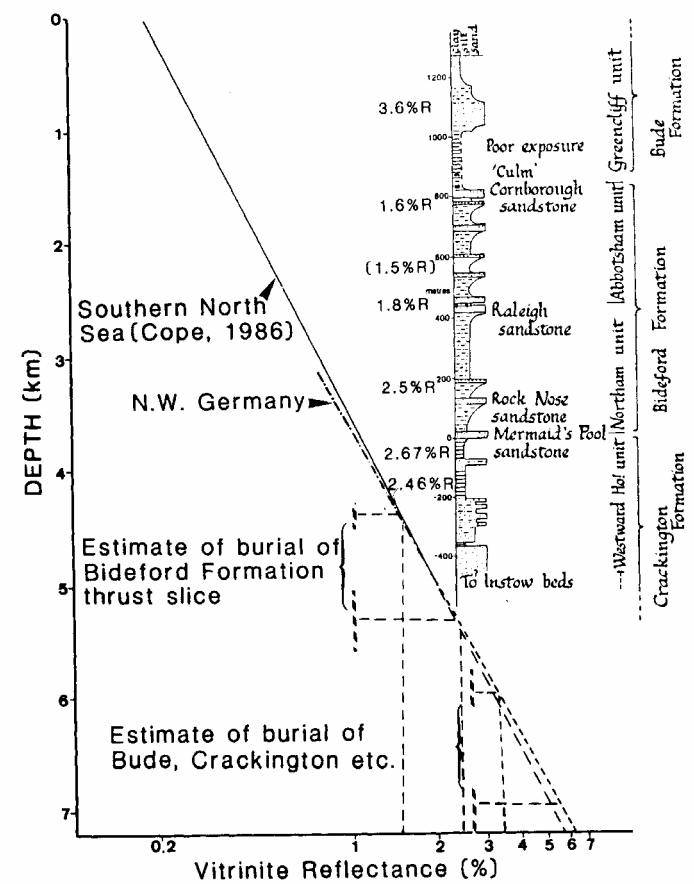


Figure 3. Vitrinite reflectance trends with depth for Upper Carboniferous strata of North West Europe, used to estimate the burial depths of the thrust units of the North Devon area. The north-west Germany trend is after Teichmuller and Teichmuller, 1986. Inset shows the detailed distribution of reflectance values relative to a composite section of the Westward Ho! nappe. In the field the beds are in a sequence of open folds, with dips in the 70-90° range.

One regional paradox that is eased by the recognition of the Bideford and underlying 'Crackington' Formations as being allochthonous is that of their atypical sedimentary facies (deRaaf et al 1965). There are numerous differences between the monotonous silty mudstones in the north (Westward Ho!) and the sandstones and shales of the south (Crackington Haven). If these are lateral equivalents, they clearly were deposited in different parts of the basin. Forcing both into the lithostratigraphically defined "Crackington Formation" seems even less justified once the tectonic nature of their juxtaposition is recognised.

More dramatically, the anomaly of the fluvial-deltaic Bideford Formation (Elliott 1976) associated with the otherwise deeper water (?lacustrine) Bude Formation (Higgs 1986), should not constrain paleogeography once the allochthonous nature of the former is recognised.

## North of Dartmoor

To the north of Dartmoor a larger number of samples were taken from sporadic outcrops, mainly in Upper Carboniferous shales and sandstones which are lateral equivalents to the rocks samples on the coast (Fig. 1). The Okehampton area falls within the Blackdown Nappe as defined by Turner (1986). Samples from stream bed and roadside outcrops predominate, forming the linear clusters of samples shown in Figure 4. Vitrinite reflectance values are presented in intervals of 0- 2%R, 2-3.5%R, 3.5 - 5.0%R, and > 5.0%R. Detailed values are reported in Yarnell (1984). Briefly considering the data the following conclusions can be drawn.

Reassuringly the two samples from the metamorphic aureole which yielded reflectance values fall, as expected, in the highest reflectance zone ( > 5%R). The majority of samples within the aureole contained small highly reflecting graphitic specules, which were too small to be measured.

Outside the metamorphic aureole, the granite appears to have had little effect on the reflectance values. Some concentric zonation might be expected, but if anything a discordant trend of reflectance with respect to the granite margin is observed. Low values in the 2 - 3.5%R range were recorded adjacent to the metamorphic aureole at three points in the area, while higher values (in the 3.5 - 5.0%R range) are observed furthest from the granite. Finally the Sticklepath Fault, believed to have last moved during the Tertiary, apparently has little effect on the data distribution.

All the data points are not equally valid. Sampling at inland outcrops presents problems, which are often insuperable, when trymg to obtain clean, unweathered rock samples. To investigate the effects of lithology and weathering, the samples were partitioned into:

* shales only, on the basis that silts and sands are more readily weathered (both now and in the Permo-Triassic);
* apparently unoxidised samples of different lithologies;
* those samples showing mesophase development - an indicator of contact metamorphism of vitrinite that had already achieved coking coal rank (1.0 - 1.8%R) prior to intrusion, although rapid heating and elevated pressures can produce the effect at lower reflectance levels (Goodarzi and Murchison 1978)

Plotting these various categories failed to alter significantly the regional pattern, other than to eliminate most of the 0- 2%R samples on the criteria of weathering or oxidation. In addition, two samples from the same locality can fall in different reflectance groups, but the differences are rarely significant given the range of reflectance values encountered.

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## Contact versus burial metamorphism

Thermal maturity adjacent to the granite could come from at least four sources:

1) contact metamorphism
2) radioactive generated heating effects
3) pre-intrusion burial
4) post-intrusion burial

Post-intrusion burial is not indicated since the Permian breccias which contain granite and associated volcanic clasts (e.g. at Teignmouth) show a level of induration inconsistent with these levels of vitrinite reflectance.

Pre-intrusion burial is possible, but the high level of variability suggests this cannot be the only factor affecting maturity unless each maturity "block" in Figure 4 is a separate tectonic unit with a separate maturation history. Pre-intrusion burial and nappe emplacement could have elevated all the rocks to a common background level of maturity. This level must be the lowest observed.

Although the 0 - 2.0%R range samples often show evidence of oxidation, the presence of mesophase confirms this level of maturity as the pre-contact metamorphism background level. This places limits on the maximum burial of the Upper Carboniferous rocks of 4 - 5km (Fig. 3) . This in turn places these limits on the maximum depth for intrusion of the granite at today's level of unroofing. In fact the heat flow over the granite is likely to be enhanced and consequently the maximum depth of burial likely to be substantially less (eg. 2.5- 4km if the geothermal gradient were to be doubled).

The background reflectance level of 0 - 2.0%R has been locally modified to levels of 2.0 - 3.5%R and 3.5 - 5.0%R (Fig. 4). The irregular pattern of the alteration may be related to the depth to the top of the granite, with high reflectance values occurring in areas of shallow sediment cover of the batholith. This would indicate a highly irregular granite surface.

A second possibility is that maturation is a function of hydrothermal alteration or contact metamorphism by dykes or along faults, though no evidence for either of these can be found. If either is the case then there may be some relationship between mineralization and reflectance level.

A third possibility is that there is a major structural detachment between the granite and the country rock on this margin of the batholith (Shackleton *et al.* 1982), and that the maturation in the country rock bears no relationship to the granite intrusion. It appears from Turner (1986) that granite intrusion post-dated nappe formation, and hence the sole thrust of the Blackdown

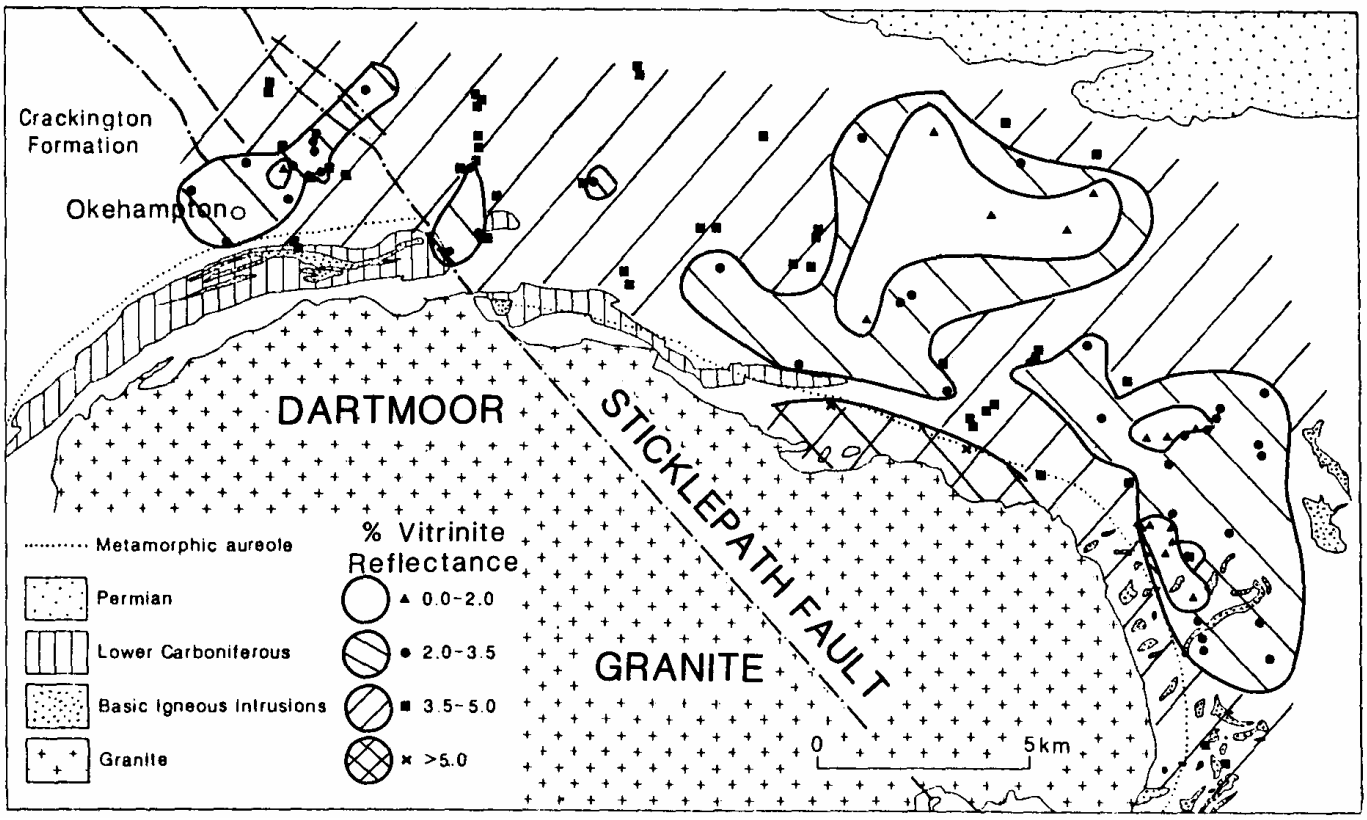


Figure 4. Distribution of vitrinite reflectance classes from all samples in the area to the north of Dartmoor. Note the absence of any concentric zonation round the intrusive body. The form of the contours is, however, not unique.

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nappe cannot detach the granite from the country rock. Again direct evidence for such a faulted or thrust contact is missing.

Finally it is possible that the sediments at this location represent gravity slides, slumping off the rising granite batholith. In this case the mélange would be expected to have a highly heterogeneous maturation history, and hence vitrinite reflectance profile.

## Regional View

The vitrinite data presented in this paper is in partial agreement with the regional maturation pattern derived from illite crystallinity measurements presented by Kelm (1986). In particular she identified an area of lower maturity ("diagenetic zone") in the Westward Ho! area. To the north of Dartmoor, however, the "?diagenetic zone" is shown in this paper to be much more complex. The north Dartmoor zone was questionably extended to the coast at Bude. The high reflectance values at Maer Cliff and Duckpool suggests a more complex pattern of maturation, though no samples were taken at Bude itself. Further sampling is clearly needed, as well as a good locally established correlation between iltite crystallinity and vitrinite reflectance.

Regionally it is interesting to note that the background (pre-intrusion) reflectance level surmised for the sediments north of Dartmoor *(ie* < 2%R) is about the same as the levels seen in the Westward Ho! nappe (1.5 - 2.67%R). It is also surprising that the exposed Dartmoor granite has no well defined reflectance aureole, considering the success of the German and Dutch workers in identifying hidden intrusions on the basis of surface reflectance trends (reviewed in Robert 1985, Chapter 16). Is it possible that some of the more mature thrust slices were heated while gravity sliding off (or over) the roof of the rising granite batholith of south-west England to their present positions?

## Time and Temperature

The depth versus vitrinite reflectance trend shown in Figure 3 results from the exposure of the samples to a given temperature, the temperature increasing with depth according to the geothermal gradient. The time of exposure to that temperature is also relevant, since the change of reflectance is kinetically controlled (Waples 1984).

The Variscan burial and uplift event occurred post-late Westphalian and pre-Permian, a period of about 15 million years. The cooling isotherm for the Dartmoor granite lies in the same period (271-309my). The time of the max'/mum burial event must have been very short *(e.g.* 5my.), and hence the temperatures of exposure of the Namurian and Westphalian very high, to reach the observed maturity levels.

Using the approach of Hood *et al.* (1975) and an effective heating time of 5my., the 5%R level is reached at 280°C and the 2%R level at 220°C. Taking these values together with the trend of Figure 3, and assuming a surface temperature of 20°C, gives a geothermal gradient of about 40°C/km as existing during the Variscan tectonic episode. Teichmuller and Teichmuller (1986) quote calculated palaeo-geothermal gradients in the range 69-88°C/km for the Ruhr and Upper Rhine Basins during the Upper Carboniferous maximum burial event. These gradients increase towards the line of the Variscan Front.

## Hydrocarbon Generation

Finally the recognition that some of the organic-rich Carboniferous shales south of the Variscan Front are of sufficiently low maturity to retain some gas-generating potential has economic significance. Major gas generation is believed to continue from vitrinitic kerogen up to vitrinite reflectance levels of 2.5 to 3.5%R (Cornford 1986).

The shales from north Devon analysed in this study range from 0.49 to 1.34% total organic carbon and contam a dominance of gas-prone kerogen. As discussed by Taylor (1986) hydrocarbon source potential and even reservoired hydrocarbons could have survived the Variscan heating episodes within specific thrust slices.

Based on the maturity data presented here, low maturity Carboniferous shales, as found in the Bideford Formation, could have generated gas on further post-Variscan burial. Such a situation could have occurred during the Permo-Trias, Jurassic or Lower Cretaceous in the Bristol Channel or Celtic Sea grabens to the west or in the Wessex Basin and English Channel to the east.

The possibility of Variscan generated gas surviving within these lower maturity thrust slices is possible on maturity grounds. However it is noted above that maximum burial predated folding. Thus the structures were not available to trap Variscan generated gas. In addition the Carboniferous lacks a good coherent seal for gas over the extended timespan required. Mesozoic structures, especially with a salt or evaporitic seal, could be highly prospective.

## References


Cope, M.J., 1986. An interpretation ofvitrinite reflectance data from the southern North Sea basin. In: Brooks. J. et al. (eds). *Habitat of Palaeozoic Gas in N. W. Europe, Geological Society Special Publication* No. 23. pp. 85-98.

Cornford. C.. 1986. Source rocks and hydrocarbons of the North Sea. In: Glennie, K.W. (ed), *Introduction to the Petroleum Geology of the North Sea. Blackwell Scientific Publications*, pp. 197-236.

deRaaf, J.F.M., Reading, H.G. and Walker, R.G., 1965. Cyclic sedimentation in the Lower Westphalian of North Devon, England. *Sedimentology*, 4, 1-52.

Edmonds, E.A., Williams, B.J. and Taylor, R.T., 1979. Geology of Bideford and Lundy Island. *Memoir of the Geological Survey of Great Britain, Sheet 292* et seq.


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Elliott, T., 1976. Upper Carboniferous sedimentary cycles produced by river-dominated, elongate deltas. *Journal of the Geological Society*, London, 132, 199-208.

Goodarzi, F. and Murchison, D.G., 1978. Influence of heating-rate variation on the anisotropy of carbonized vitrinites. *Fuel*, 57, 273-284.

Higgs, R., 1986. 'Lake Bude' (Early Westphalian, S.W. England): storm-dominated siliciclastic shelf sedimentation in an equatorial lake. *Proceedings of the Ussher Society*, 6, 417-418.

Hood, A., Gutjahr, C.C.M. and Heacock, R.L., 1975. Organic metamorphism and the generation of petroleum. *American Association of Petroleum Geologists Bulletin*, 59, 383-388.

Kelm, U., 1986. Mineralogy and illite crystallinity of the pelitic Devonian and Carboniferous strata of North Devon and West Somerset. *Proceedings of the Ussher Society*, 6, 338-343. Robert, P., 1985. Histoir Geothermique et Diagenese Organique. *Bulletin des Centres de Recherches Exploration-Production Elf-Aquitaine, Memoir* 8, Pau.

Shackleton, R.M., Ries, A.C. and Coward, M.P., 1982. An interpretation of the Variscan structures in South West England. *Journal of the Geological Society*, London, 139, 533-541.

Stach, E., Mackowsky, M-Th., Teichmuller, M., Taylor, G.H., Chandra, D. and Teichmuller, R., 1982. *Stach's Textbook of Coal Petrology (3rd Edition), Gebruder Borntraeger*, Berlin, Stuttgart.

Taylor, J.C.M., 1986. Gas prospects in the Variscan thrust province of Southern England. In: Brooks, J. et al. (eds). Habitat of Palaeozoic Gas in N. W. Europe, *Geological Society Special Publication No. 23*:. pp. 37-53.

Teichmuller, M. and Teichmuller R., 1979. Ein Inkohlungsprofil entlang der linkrheinischen Geotraverse yon Schleiden nach Aachen und die Inkohlung in der Nord-Sfid Zone der Eifel. *Fortschrite der Geologie der Rheinlands und Westphalen*, 27, 323-355.

Teichmuller, R. and Teichmuller M., 1986. Relation between coalification and palaeogeothermics in Variscan and Alpidic foredeeps of Western Europe. In: Buntebath, G. and Stegena, L. (eds*), Lecture Notes in Earth Science, vol 5, Paleogeothermics*, Springer-Verlag, Berlin, Heidelberg, pp. 53-78.

Turner, P.J., 1986. Stratigraphic and structural variations in central SW England: a critical appraisal. *Proceedings of the Geologists' Association*, 97, 331-345.

Waples, D.W., 1984. Thermal models for oil generation. In: Brooks, J. and Welte, D. (eds). *Advances in Petroleum Geochemistry, Volume 1*, Academic Press, Pp. 7-68.

Yarnell, L., 1984. Rank variation of the area bordering the northern margins of the Dartmoor granite. *Unpublished M. Sc. Thesis,* University of Newcastle-upon-Tyne, UK.

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*Read at the Annual Conference of the Ussher Society, January 1987*

# The Pre-Devonian geology of south-west England

JOHN C.W. COPE

Cope, John C.W. 1987. The Pre-Devonian geology of south-west England. *Proceedings of the Ussher Society, 7,* 468-473.

poorly known. From sediment supply into South Wales and from geophysical evidence it is possible to reconstruct a history of the area from. Precambrian times through to the Devonian. A significant area of metamorphic basement, Pretannia, forms the core of an area for which a conjectural palaeogeology is reconstructed.

*John* The Pre-Devonian geology of south-west England is very *C.W. Cope, Department of Geology, University College, Singleton Park, Swansea SA2 8PP*

## Introduction

In contrast to the Devonian and later history of southwest England little has been published on the pre-Devonian geology of the region. The only pre-Devonian rocks known at outcrop are the possible Precambrian areas of the Start and Eddystone (Doody and Brooks 1986) and the Ordovician quartzites of Gorran Haven and Veryan (Sadler 1973).

The earliest Devonian rocks are the Dartmouth Slates, described by Dineley (1966). These can be convincingly explained as a southern extension of the coastal plain Old Red Sandstone sediment which though unexposed can be assumed to extend northwards across Devon and the Bristol Channel into South Wales and the Welsh Borderland. The nature of the pre-Devonian surface is unknown and geophysical investigations (e.g. Brooks *et al.* 1984) have yielded little information on what may lie buried beneath the Devonian. Whatever the original nature of this pre-Devonian surface, much of it must have been subsumed by deep burial and intrusion of the Cornubian granites.

A recent study of the Palaeozoic history of the Bristol Channel area (Cope and Bassett 1987) has shown that the Bristol Channel landmass of earlier authors *(e.g.* Leeder 1982) was not merely a narrow east-west elongated strip of land as these authors had supposed (though the Devonian and later rocks show evidence of southerly derivation in south Wales and northerly derivation in north Devon). The Bristol Channel landmass was, these authors concluded, a posthumous exhumation of the northern faulted margin of an extensive land area which lay to the south in Precambrian and early Palaeozoic times to which the name Pretannia was given (Cope and Bassett *op. cit.).*

## The evidence for Pretannia

The Lower Palaeozoic rocks of south Wales show clear and continuing evidence of derivation from the south. Much of the southerly derived material could only have come from a metamorphic source of mica- or quartz-mica-schist. Mica abounds in the Upper Cambrian Merioneth Series of South-west Dyfed (formerly Pembrokeshire) (Crimes 1970) and in the Llangynog Inlier further to the east (Cope 1982) where individual beds are largely composed of the mineral. The overlying Tremadoc rocks of the Llangynog area contain highly micaceous units and mica is a constant constituent of the thick shale succession of the Tremadoc (Cope *et al.* 1978).

In the overlying Allt Cystanog Member of the Ogof I-Ien Formation (Fortey and Owens 1978) small clasts of mica schist occur (Cope 1980). The overlying Llanvim rocks too contain mica throughout a thick succession of deep water graptolitic mudstones.

Further up the succession southerly derived mica is an important component in the Long Quarry Beds of the Llandeilo-Llandovery area. These beds of Pridoli age again contain mica as the most conspicuous material at certain horizons and again the mica clearly calls for a metamorphic source area to the south (Potter and Price 1965).

Igneous rocks are also present as clasts in many conglomerates throughout the Lower Palaeozoic of South Wales. The basal Cambrian conglomerates in Pembrokeshire contain rhyolitic and intrusive rocks, which appear similar in composition to the local Pebidian volcanic and Dimetian granitic rocks. Similar Precambrian rhyolites occur in the Llangynog Inlier and Precambrian rhyolites are identifiable as clasts in conglomerates of early and mid Arenig age in the Llangynog Inlier (Cope 1980, Cope and Bassett 1987) and in both are associated with vein quartz, presumably derived from fault zones.

Vein quartz pebbles appear at other horizons too and Waimsley (1959) records vein quartz and jasper of southerly derivation in the Ludlow rocks of the Usk Inlier.

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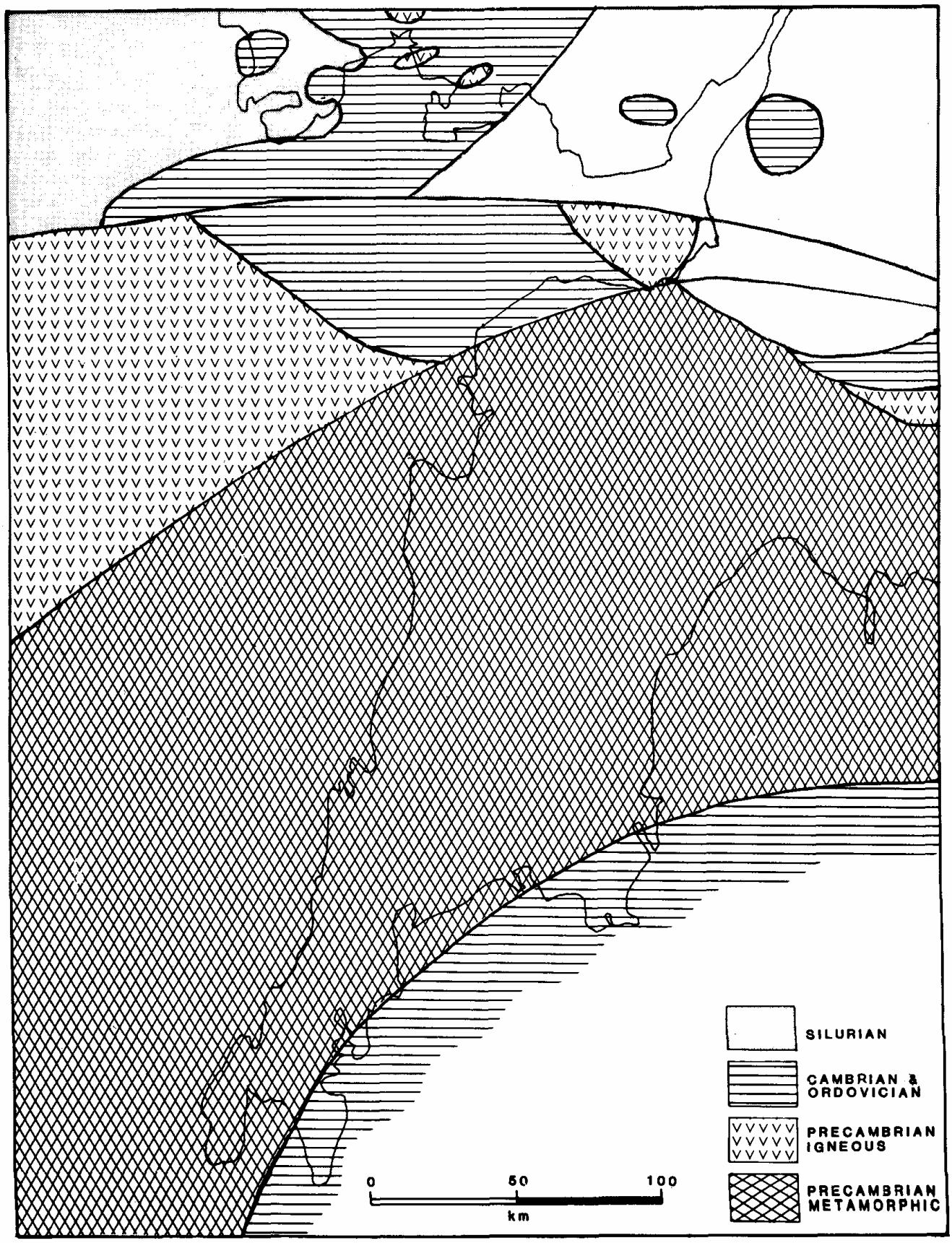


Figure 1. Conjectural pre-Devonian palaeogeological map of south-west England and adjacent regions. Areas to the north of the mid-line of the present Bristol Channel palinspastically increased by 50%, areas to the south of that line increased by 100%, to compensate for Variscan shortening. Outcrop pattern suggested for the Bristol Channel area based on geophysical evidence on basement depth and on clasts in various Devonian conglomerates.

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It is clear then that there is substantial evidence for a metamorphic source area to the south of South Wales in early Palaeozoic times. Associated with this metamorphic area and probably on its northern fringes and continuous with the known Precambrian rocks in South Wales was a succession of rhyolitic rocks of late Precambrian age. With these latter rocks were associated a range of intrusive rocks including porphyries, granophyric rocks, quartz keratophyres, etc. The abundant vein quartz pebbles suggest that the area of these rocks may have been substantially faulted. Pebbles from these rocks appear in several Devonian formations, including the Ridgeway Conglomerate (Williams 1964), the Llanishen Conglomerate (Allen 1975) both in south Wales, and in the Rawns Formation of north Devon (Tunbridge 1986).

The Precambrian basement of South Wales has been traced southwards across the Bristol Channel geophysically (Mechie and Brooks 1984). Their map of the Bristol Channel area (1984, fig. 20) shows the depth to Precambrian crystalline basement. Of particular interest is the contour in the Llangynog area (S. of Carmarthen) where the basement is shown to be at a depth of 3km. Now in that area, the rhyolites contain in their upper part sediments containing an Ediacara fauna (Cope 1977, 1983) suggesting that the rhyolites are of latest Precambrian age. The contour suggests that there is a thickness of 3km of these rhyolites before the basement is reached. To the south, this Precambrian surface dips southwards to a maximum depth of 7.5km off the north Devon coast (Mechie and Brooks fig. 20). Of this thickness some 3km can be explained as late Precambrian volcanic rocks and 2-2.5km as Lower Devonian/Old Red Sandstone, leaving some 2km to be explained by Lower Palaeozoic sediments; those now remaining are most likely to be of'Cambrian and Tremadoc age.

Early Cambrian quartzites are widespread across the Midlands Shelf beyond the margins of the Welsh Basin and it seems likely that similar quartzites could have existed over the Bristol Channel area. Lithic sandstones and quartzites with brachiopods recorded from the Ridgeway Conglomerate (Williams 1964) are most likely to be of Cambrian age (Cope and Bassett 1987) and if lying over the southern Bristol Channel could have contributed to the Ridgeway Conglomerate. Higher horizons present are likely to include some Upper Cambrian, and in the Ordovician a thick Tremadoc Series seems probable. Tremadoc rocks are widespread in southern Britain beyond the margins of the Welsh Basin. They are well known from Shropshire, the Malverns, the Tortworth Inlier, and more recently from the Llangynog Inlier (Cope *et al.* 1978, Owens *et al.* 1982). 2.5km of Tremadoc Shales was recorded in the Cooles Farm Borehole near Swindon (Wills 1978), and further to the south the Shrewton No. I Borehole, 15 km NW of Salisbury, proved some 1200m of Tremadoc without reaching the base (Whittaker 1980). Later Ordovician rocks over this area probably included originally Llanvirn, Llandeilo and Caradoc Series, but in view of the regression of Ashgill times the latter may not have been deposited there.

Some, if not all, of these later Ordovician rocks are likely to have been removed prior to the deposition of the Upper Llandovery and later Silurian sediments and volcanic rocks, known well to the east of the Bristol Channel area in the Tortworth Inlier and in the Mendips and suggested geophysically to the east by Chadwick *et al.* (1983).

There is thus no difficulty in explaining the 7.5km cover to the Precambrian crystalline rocks beneath the southern margin of the Bristol Channel. Further to the south from the depth of 7.5km Brooks *et al.* (1983) report that it appears that the crystalline basement rises suddenly to a depth of only 2.3kin. This was explained (Brooks *et al.* 1983, p. 194) to be possibly due to 'a shallow non-magnetic metamorphic basement (e.g. quartz-mica schist)'. This would be an entirely appropriate rock for the crystalline basement here and accords well with the mica of southerly derivation so common in the early Palaeozoic rocks of south Wales. This seems a more persuasive interpretation of the seismic data than the alternative of a massive quartzite or limestone within the Lower Palaeozoic or Lower Devonian rocks, restricted to the southernmost part of the Bristol Channel (Brooks *et al.* 1983, p. 194).

The signature of magnetic anomalies over north Devon as shown on the Geological Survey '10 mile' Aeromagnetic Map is one of low frequency and low amplitude, in contrast to the intense high frequency anomalies shown over S.W. Wales where the Precambrian basement shallows or is at outcrop. Apart from the modifications of this pattern by the linear Exmoor magnetic anomaly and the isolated anomaly due to the Lundy granite, the pattern is extremely similar to that under the Bristol Channel where the basement is at depths of up to 7.5km as noted above. Southwards over S.W. England the pronounced elliptical anomalies are clearly associated with the northern margin of the Cornubian batholith. Thus the magnetic anomaly pattern provides little direct evidence on the basement except that it allows one to conclude that it lies deeply buried under northernmost Devon.

Although gravity information is limited, the Bouguer anomaly maps indicate values of 20-25 mgals over north Devon in contrast to the extremely low values (-24 mgals) over Dartmoor and the Cornubian batholith (Bott and Scott 1964). In the Bristol Channel syncline values of only 4 mgals do not seem to be reflected in the magnetic anomaly path and presumably the gravity variations are reflecting the distribution of the less dense Mesozoic sediments.

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The south-west England Seismic Experiment of Brooks *et al.* (1984) shows that a deep reflector (R2) exists beneath the Cornubian batholith at a depth of c.12km and continues northwards for some 20kms at a depth of c. 10km. There is a velocity change across this boundary from c.5.75km/sec$^{-1}$ to c.6.2km/sec$^{-1}$ It is tempting to speculate that this may represent the top of the crystalline basement, although Brooks *et al.* interpreted it as a thrust on the grounds that they could trace a similar velocity change, although at a slightly different crustal level, beneath the granite.

It is unfortunate that the SWAT profiles (BIRPS and ECORS 1986) cannot contribute towards resolution of this problem, which now awaits further deep seismic work on land.

The presence of xenoliths of gneissic material has been reported recently in Upper Devonian lavas to the west of the Land's End granite (Goode and Merriman 1987). These authors conclude that these xenoliths, which show a fabric predating that of the Variscan fabric of the host rock, provide evidence of crystalline basement extending from west of the Land's End granite possibly as far as Haig Fras, and that similar gneisses could have been the source rock of the Cornubian batholith.

## The extent of Pretannia

To supply sediment for such a period of time, a substantial land area drained by a major river system would be required. To estimate the extent of this landmass it is necessary first of all to remove the effects of the Variscan deformation. Shackleton *et al. (1982)* have suggested that a minimum north/south shortening of 150km over S.W. England resulted from the Variscan movements. Removing the effects of this doubles the present N-S dimensions of the south-west peninsula to some 300km. The Precambrian rocks appear in the south of the area at Start Point and the Eddystone Rock (Doody and Brooks 1986). Resting on this Precambrian surface there is likely to have been a cover of Ordovician quartzites of Llandeilo age. These have been shown by Sadler (1973) to be a succession which has been transported no great distance and is not an allochthonous assemblage as had hitherto been supposed. The fauna of the quartzites was shown by Sadler to be entirely of Llandeilo age. Previous records of Silurian fossils from Cornwall (summarised by Cocks *et al.* 1971) can no longer be substantiated (Sadler 1973).

Cocks and Fortey (1982) considered the disposition of ArmoriCan quartzite facies in Arenig times. In their reconstruction (1982 fig. 2) there was a significant area

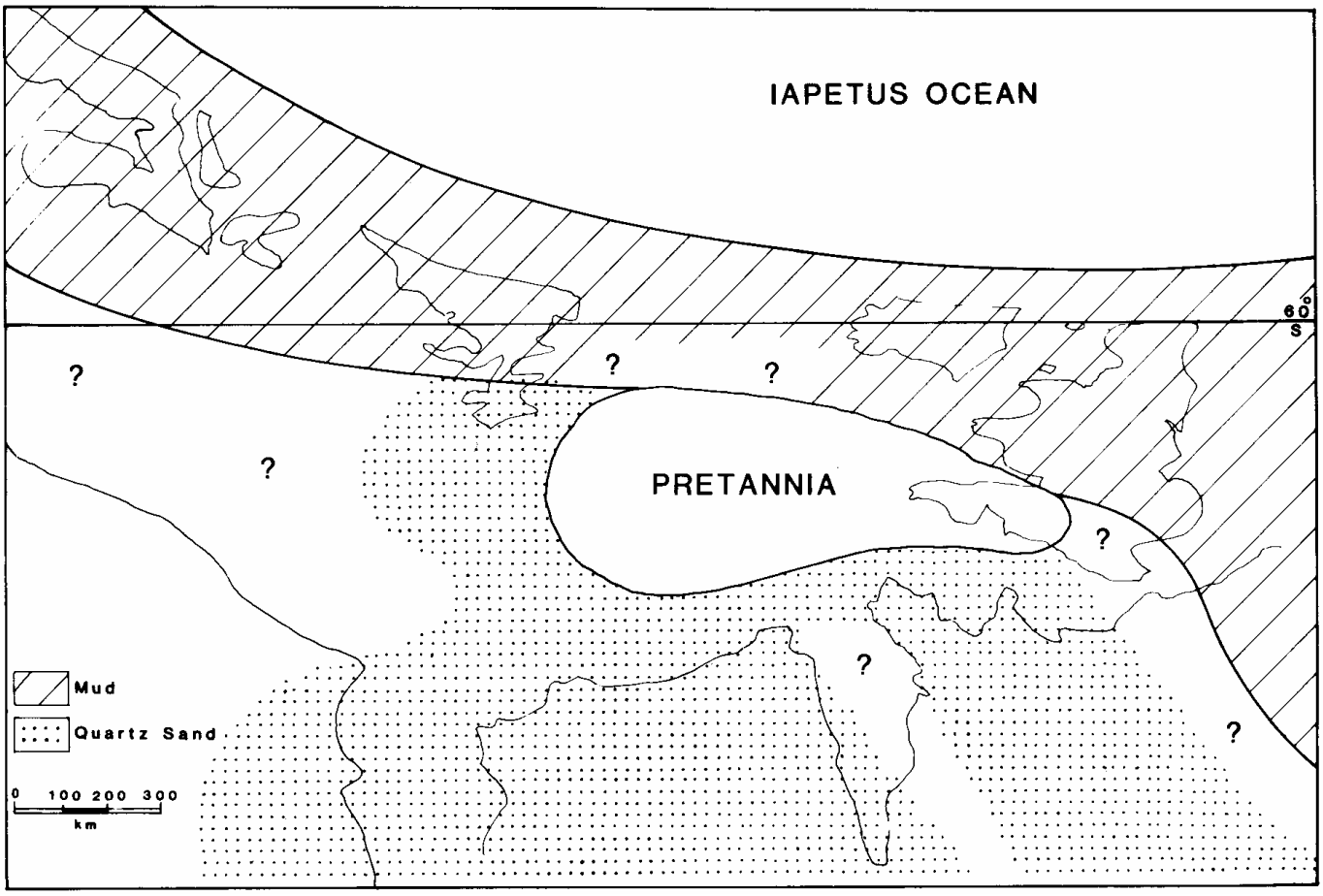


Figure 2. The site of Pretannia and its possible extent in early Ordovician (Arenig) times. Lithological information modified after Cocks and Fortey (1982). Note that no attempt at palinspastic reconstruction has been made.

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c. 1000km by 300km extending westwards from S.W. Britain for which they had no evidence. This area would provide the extensive site for Pretannia and the dimensions would be sufficient to provide the sedimentary source area. In Llandeilo times the quartzite facies was continuous from Normandy to Cornwall and the Veryan and Gorran quartzites are envisaged as the northern extremities of this facies, thinning out northwards onto the southern edge of the Pretannic continental mass. Later in Lower Palaeozoic times an oceanic area, the Rheic Ocean, separated southern England from Armorica (Cocks and Fortey 1982, fig. 5). Whether the whole of south-west England lay to the northern side of this ocean, or whether parts were to the south and later obducted onto the rest of Britain is uncertain, but in either case does not significantly alter the dimensions of the Pretannic block.

There are considerable similarities between the late Precambrian and Lower Palaeozoic sequences of Wales, and those of the Avalon Platform of Newfoundland. These have been discussed in some detail by Rast et al. (1976). The existence of a Precambrian block from southern Britain to Newfoundland with a suite of late Precambrian volcanic rocks on its north side could explain many of the similarities of the successions in the two areas. As in South Wales, the Precambrian crystalline basement is unknown at the surface in S.E. Newfoundland, but in the latter case can be seen further to the west in southern New Brunswick and Cape Breton Island. In the latter area the George River Group of metasediments is overlain by the Forchu Group consisting of acidic volcanics of late Precambrian age. There are clear parallels here with the succession which is presumed to have occurred in Pretannia.

## Conclusions

The geology of Pretannia must have consisted of a heartland of metasediments. In view of the derived mica, so abundant in South Wales, these metasediments are likely to have been quartz-mica-schists or mica-schists. To the south the Llandeilo quartzites would have lain unconformably over this basement. To the north a fault, across the north Devon area, separated the metamorphic basement to the south from an area to the north where rhyolitic volcanic rocks overlay that basement. The rhyolite outcrop included areas of intrusive rocks, including 'granitic and intermediate types. South of Pembrokeshire the rhyolites were overlain by a succession of Cambrian quartzites and lithic sandstones and, further to the west, Silurian volcanic and sedimentary rocks. Further to the east, a similar succession occurred with the Cambrian and Silurian resting unconformably on the northern side of the Precambrian block. Chadwick et al. (1983) have shown the basal Cambrian quartzite and Silurian volcanic rocks on a line of section southwards through Wiltshire. This can be interpreted as lying at the eastern end of the Pretannian block.

In early Devonian times the flush of molasse sediments from the north spread Old Red Sandstone sediments across the by now denuded highland of Pretannia, extending the swathe of sediment from the Welsh Borderland to south Devon. This was the final submergence of Pretannia; in the late Palaeozoic fault movement along the northern fringe exhumed the basement, but the heartland of the Pretannic block lay buried, to be largely subsumed beneath the new continent of Cornubia which was to rise in its place.

Acknowledgement. I would like to thank Dr. P. Styles for discussion of the geophysical evidence of basement depth under S.W. England.

## References

Allen, J.R.L. 1975. Source rocks of the Lower Old Red Sandstone: the Llanishen Conglomerate of the Cardiff area, South Wales. *Proceedings of the Geologists' Association*, 86, 63-76.

BIRPS and ECORS, 1986. Deep seismic profiling between England France and Ireland. *Journal of the Geological Society*, London, 143, 45-52.

Bott, M.H.P. and Scott, P. 1964. Recent geophysical studies in southwest England. In: Hosking, K.F.G. and Shrimpton, G.J. (eds.) *Present views of some aspects of the geology of Devon and Cornwall. Royal Geological Society of Cornwall*, 25-44.

Brooks, M., Doody, J.J. and al-Rawi, F.R.J. 1984. Major crustal reflectors beneath SW England. *Journal of the Geological Society*, London, 141, 94-103.

Brooks, M., Doody, J.J. and A1-Rawi, F.R.J. 1984. Major crustal investigations in the Variscides of southwest Britain. In: Hancock, P.L. (ed.). *The Variscan fold belt in the British Isles*. Adam Hilger, Bristol. 186-197.

Chadwick, R.A., Kenolty, N. and Whittaker, A. 1983. Crustal structure beneath southern England from deep seismic reflection profiles. *Journal of the Geological Society*, London, 140, 893-911.

Cocks, L.R.M. and Fortey, R.A. 1982. Faunal evidence for oceanic separations in the Palaeozoic of Britain. *Journal of the Geological Society*, London, 139, 467-480.

Cocks, L.R.M., Holland, C.H., Rickards, R.B. and Strachan, I. 1971. A correlation of Silurian rocks in the British Isles. *Journal of the Geological Society*, London, 127, 103-136. (Reprinted as Geological Society Special Report No. 1)

Cope, J.C.W. 1977. An Ediacara type fauna from South Wales.*Nature*, London, 268, 624.

Cope, J.C.W. 1980. The early history of the southern margin of the Twyi anticline, in the Carmarthen area, South Wales. In: Harris, A.L., Holland, C.H. and Leake, B.E. (eds.). *The Caledonides of the British Isles - reviewed. Special Publication of the Geological Society*, London, 8, 527-532.

Cope, J.C.W. 1982. The geology of the Llanstephan Peninsula. In: Bassett, M.G. (ed.). *Geological Excursions in Dyfed, South- West Wales*. National Museum of Wales, Cardiff, 259-270.

Cope, J.C.W. 1983. Precambrian fossils of the Carmarthen area, Dyfed. *Nature in Wales*, (n.s.) 2, 11-16.

Cope, J.C.W. and Bassett, M.G. in press. Sediment sources and Palaeozoic history of the Bristol Channel area. *Proceedings of the Geologists' Association*, 98.

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Cope, J.CW., Fortey, R.A. and Owens, R.M. 1978. Newly discovered Tremadoc rocks in the Carmarthen area, South Wales. *GeologicalMagazine*, 115, 195-198, pl. 1.

Crimes, T.P. 1970. A facies analysis of the Cambrian of Wales. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 7, 113-170.

Dineley, D.L. 1966. The Dartmouth Beds of Bigbury Bay, south Devon. *Quarterly Journal of the Geological Society*, London, 122, 187-217.

Doody, S.J. and Brooks, M. 1986. Seismic refraction investigation of the structural setting of the Lizard and Start Complexes, SW England. *Journal of the Geological Society*, London, 143, 135-140.

Fortey, R.A. and Owens, R.M. 1978. Early Ordovician (Arenig) stratigraphy and faunas of the Carmarthen district, southwest Wales. *Bulletin of the British Museum*, *Natural History* (Geology), 30, 225-294.

Geological Survey 1965. Aeromagnetic map of Great Britain. Sheet 2. Geological Survey, London. Goode, A.J.J., and Merriman, R.J. 1987. Evidence of crystalline basement west of the Land's End granite, Cornwall. *Proceedings of the Geologists' Association*, 98, 39-43.

Leeder, M.R. 1982. Upper Palaeozoic basins of the British Isles -Caledonide inheritance versus Hercynian plate margin processes. *Journal of the Geological Society*, London, 139, 479-491.

Mechie, J. and Brooks, M. 1985. A seismic study of deep geological structure in the British Channel area, SW Britain. *Geophysical Journal of the Royal Astronomical Society*, 78, 661-689.

Owens, R.M., Fortey, R.A., Cope, J.C.W., Rushton, A.W.A. and Bassett, M.G. 1982. Tremadoc faunas from the Carmarthen district, South Wales. *Geological Magazine*, 119, 1-38, pls. 1-8. Potter, J.F. and Pi'ice, J.H. 1965. Comparative sections through rocks of Ludlovian-Downtonian age in the Llandovery and Llandeilo districts. *Proceedings of the Geologists' Association*, 76, 379-402.

Rast, N., O'Brien, B.H. and Wardle, R.J. 1976. Relationships between Precambrian and Lower Palaeozoic rocks of the 'Avalon Platform' in New Brunswick, the northeast Appalachians and the British Isles. *Tectonophysics*, 30, 315-338. Sadler, P.M. 1973. An interpretation of new stratigraphic evidence from South Cornwall. *Proceedings of the Ussher Society*, 2, 535-550.

Shackleton, R.M., Ries, A.C. and Coward, M.P. 1982. An interpretation of the Variscan structures in SW England. *Journal of the Geological Society*, London, 139, 533-541.

Tunbridge, I.P. 1986. Mid-Devonian tectonics and sedimentation in the Bristol Channel area. *Journal of the Geological Society*, London, 143, 107-116.

Walmsley, V.G. 1959. The geology of the Usk Inlier (Monmouthshire). *Quarterly Journal of the Geological Society*, London, 114, 483-521, pl. 22.

Whittaker, A. 1980. Shrewton No. 1. Geological well completion report. *Report of the Deep Geology Unit*, Institute of Geological Sciences, No. 80/1.

Williams, B.P.J. 1964. The stratigraphy, petrology and sedimentation of the Ridgeway Conglomerate and associated formation in Pembrokeshire. *Unpublished Ph.D. thesis, University of Wales.*

Wills, L.J. 1978. A palaeogeological map of the Lower Palaeozoic floor below the cover of Upper Devonian, Carboniferous and later formations. *Memoir of the Geological Society*, London, 8, 1-36.

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*Read at the Annual Conference of the Ussher Society, January 1987*

# Sequence of coralline faunas and depositional environments in the Devonian carbonate succession of the Lemon Valley, near Newton Abbot, South Devon.

COLIN T. SCRUTTON
KEVIN B. GOODGER

Scrutton, C.T. and Goodger, K.B. 1987. Sequence of coralline faunas and depositional environments in the Devonian carbonate succession of the Lemon Valley, near Newton Abbot, South Devon. *Proceedings of the Ussher Society, 6,* 474-482.

The Middle and Upper Devonian Ugbrooke-East Ogwell Succession is best exposed in the Denbury and East Ogwell Units cropping out in the Lemon Valley and around East OgWell, near Newton Abbot. The lithologies and faunas of the Denbury Crinoidal Limestone, the Chercombe Bridge Limestone and the East Ogwell Limestone in ascending sequence, are outlined and their coralline associations are described and interpreted in terms of the evolution of the local depositional environment with time. The carbonate platform here was initiated on a thin crinoidal bank on which diverse coral and stromatoporoid faunas flourished in close to normal marine conditions. Occasional interdigitations of restricted facies foreshadowed a period of prolonged high-stress conditions characterised by distinctive stromatoporoids and the almost total absence of corals. The return to fully marine conditions was interrupted by a substantial volcanic episode, following which rich and diversified coral stromatoporoid faunas were re-established. Coral-bound mud mounds in which stromatoporoids are absent developed on the top of the carbonate platform as it subsided. The Lemon Valley sequence is considered to be of platform interior type but palaeogeographic reconstructions for mid and late Devonian times in the S Devon area are uncertain.

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## Introduction

The Middle and Upper Devonian carbonate platform of eastern South Devon is described as the Tor Bay Reef-Complex (Scrutton 1977 a, b). Coralline associations in the basal Daddyhole Limestone, representing the foundation of'the platform in the Torquay area, were described by Goodger *et al.* (1984). In this paper, we describe the coralline associations developed from base to top of the carbonate platform in the Lemon Valley sequences near Newton Abbot, in what is interpreted as a platform interior location (Fig. 1).

The outcrops along the densely wooded Lemon Valley and in the ground to the S around East Ogwell represent one of the best developed and understood sections inland (Fig. 2). Several sequences, originally located some distance apart, are brought together in thrust slices in this area (Selwood *et al.* 1984). However, transects a, b and c in the Chercombe Bridge-West Hill, Broadridge Wood and Foxley areas appear to represent a. more or less complete section of the carbonate sequence from its base, the late Eifelian Denbury Crinoidal Limestone, through the Chercombe Bridge Limestone, the Foxley Tuff and into Frasnian levels of the East Ogwell Limestone (Figs. 2, 3). This is the Denbury Unit of Selwood *etal.* (1984). Further observations On the East Ogwell Limestone in two transects, d and e, from two higher thrust sheets of the East Ogwell Unit, include details of the top of the

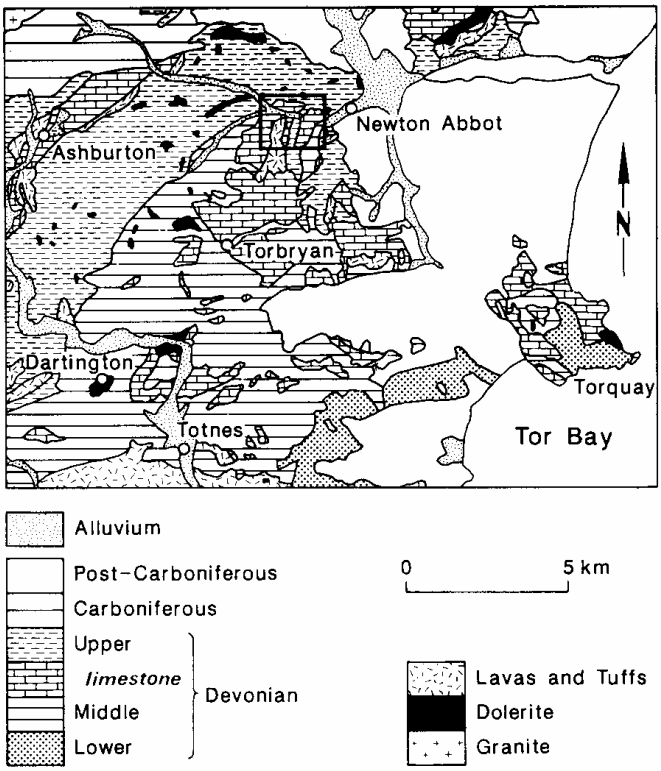


Figure 1. Geological map of part of eastern South Devon. The area enlarged in Figure 2 is indicated (after Scrutton 1978, Fig. 10b).

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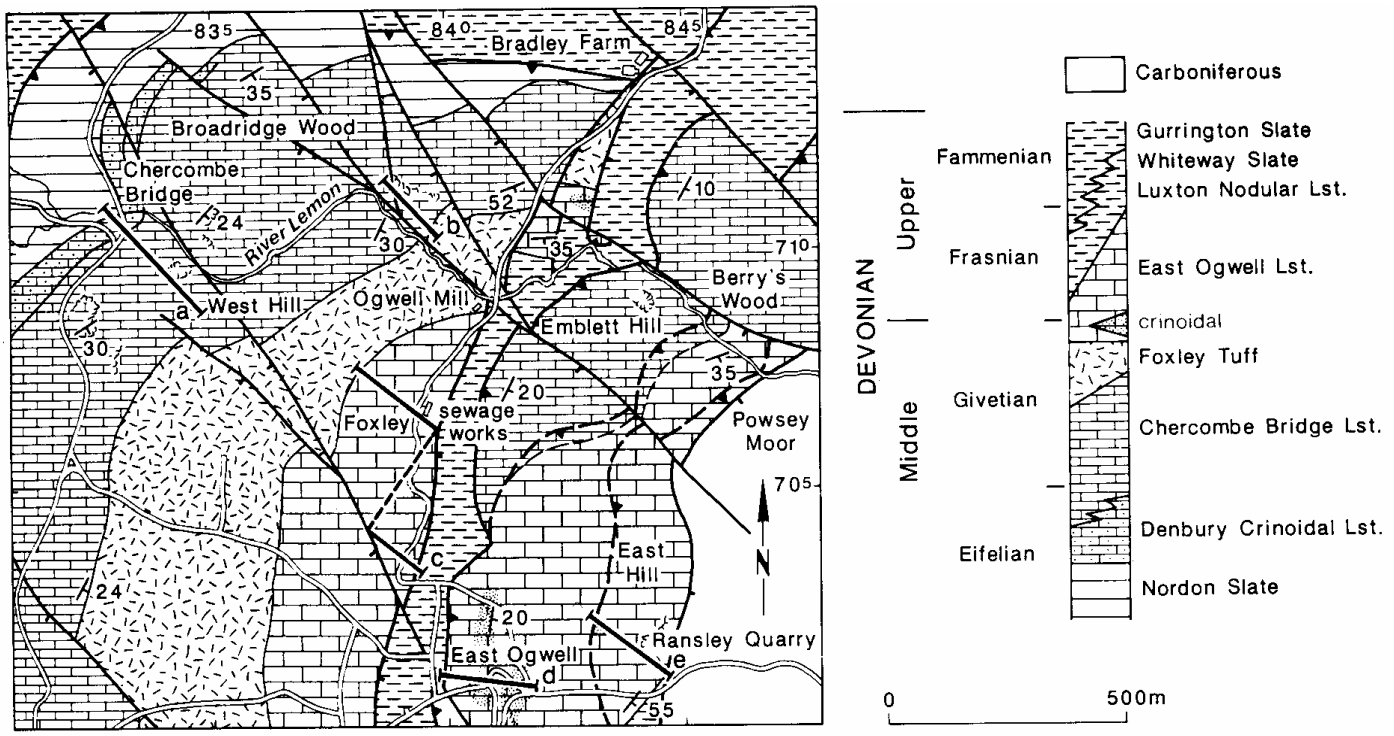


Figure 2. Geological map of the Lemon Valley and East Ogwell area, near Newton Abbot (after Scrutton 1977b, Fig. 4). Lines a-e represent the locations of the logged sections illustrated in Figure 3.

limestone succession locally. The sequences in both of these units belong to the Ugbrooke-East Ogwell Succession of Selwood *et al.* (1984).

The logs presented here (Fig. 3) are an order of magnitude less detailed than those in Goodger *et al.* (1984, Fig. 3), reflecting poorer and less persistent outcrop in this inland area. Otherwise data are presented in the same way. Grid references all refer to the SX 100 km x 100 km square of the National Grid.

## Stratigraphy

*Denbury Crinoidal Limestone*

Just W of Chercombe Bridge [8331 7108], reddish shales with thin, grey micritic limestone bands are transitional from the Nordon Slate to the Denbury Crinoidal Limestone. The unit is 24m thick hereabouts with 0.1 - 0.3m bedded crinoidal packstones passing up into 10m of massive recrystallised, variably crinoidal packstones. Fossils, apart from crinoid ossicles, are rare but include corals, bryozoa and brachiopods. The limestone is indirectly dated late Eifelian (Selwood *et al.* 1984).

*Chercombe Bridge Limestone*

The junction with the underlying Denbury Crinoidal Limestone is not exposed in the Lemon Valley but the lower part of the Chercombe Bridge Limestone is notably crinoidal. Conodonts from a disused quarry on the W slope of West Hill [8321 7089] suggest a possible late Eifelian age (Selwood *et al.,* 1984) whilst evidence from trilobites, brachiopods and.corals at slightly higher levels in Chercombe Bridge Quarry and on the N side of West Hill indicate the Eifelian - Givetian boundary approximately 50m above the base of the limestone (Selwood 1965; Scrutton 1977b).

The lower 25 - 30m of the Chercombe Bridge Limestone is poorly exposed: Immediately above the base, grey and pinkish-grey micritic wackestones and packstones contain *Squatneoalveolites, Cladopora* and *Planocoenites, Pterrorhiza* sp. and fragments of *Thamnophyllum* sp. with crinoid ossicles, scattered gastropods and brachiopods. At higher levels, approximately 30- 100m above the base, dark grey, well bedded micritic wackestones and packstones contain frequent biostromes rich in corals, stromatoporoids, and brachiopods, variably crinoidal, with calcareous algae and bryozoans, ostracods, less prominent gastropods and serpulids, and occasional trilobites. Beds vary from 50mm to lm thick, with some shaly interbeds. The wackestones-packstones are peloidal with calcispheres occasionally abundant, and much fine bioclastic debris. In many cases, the fossils have been gently winnowed but articulated brachiopods and unfragmented fasciculate colonies are preserved in less densely fossiliferous beds. Rugose corals include species of *Acanthophyllum, Ceratophyllum, Cystiphylloides, Dendrostella, Dohmophyllum, Grypophyllum* (3 species), *Heliophyllum* and *Stringophyllum* (3 species) with scattered *Thamnophyllum* branch fragments and rare *Amplexocarinia* (Scrutton 1977b). *Calceola* is present with *Cystiphylloides* at one level. Tabulate corals are *Alveolites* (3 species), *Caliapora, Favosites, Heliolite&*

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*Remesia, ?Scoliopora, Syringopora* and *Thamnopora. Ceratophyllum* sp. and *Dohmophyllumhelianthoides* (Goldfuss) are conspicuously confined to discrete horizoffs in which they have few associates. *Remesia,* with or without *Caliapora,* may also occur separately from other tabulates. Similarly, *Dendrostella trigemme* (Quenstedt) is most common as the dominant rugose coral in a baffiestone at the top of this part of the limestone. Stromatoporoids occur as laminar, tabular and small globular skeletons seldom exceeding 300mm in maximum dimension both in distinct bands and associated with other faunal elements. Some show inter-growth with *Syringopora. Stachyodes* is rather scattered but *Amphipora* is frequently present; both occur in mixed assemblages as welt as in monospecific bands, particularly the latter. Many rugose corals show thin encrustations of stromatoporoids, or less commonly fistuliporid bryozoans or *?lanocoenites,* acquired both in life and during post-mortem exposure on the sea floor. Uncoated coralla may show epithecal borings of presumed algal origin. Other prominent biostromes in the mid part of this sequence are crowded with dis-articulated shells of *Stringocephalus.*

About 100m above the base of the Chercombe Bridge Limestone, a striking faunal transition occurs. Corals, particularly Rugosa, become rare and biostromes of *Amphipora* become dominant, with occasional levels containing small, pyriform and globular stromato-poroids with some tabulate corals, separated by poorly or unfossiliferous wackestones.

This sequence is terminated by a fault on the NE side of West Hill but higher levels of the limestone, between about 120 and 150 m above the base, are well exposed in the disused Broadridge Quarry [8392 7110], the type section for the formation (Selwood *et al.* 1984). The 0.15 - Llm well bedded peloidal and bioclastic wackestones and packstones in the main face of the quarry are poorly fossiliferous except for thick baffiestones of *Amphipora* and rare horizons of pyriform stromatoporoids at higher levels. More scattered *Amphipora* and the tabulate corals *Remesia, Scoliopora* and *Thamnopora* occur at other levels, together with scattered brachiopods, bivalves and nests of gastropods. The packstones contain calcispheres, often abundantly, with ostracods, algae including *Renalcis* and *Girvanella* and rare foraminiferids. Fenestral fabrics are poorly developed at some horizons and algal laminites are rare. Quarry top ledges expose horizons rich in pyriform, globular *(Actinostroma)* and digitate *(Amphipora, Idiostroma* and *Stachyodes)* stromatoporoids, and more diverse tabulate corals including *Remesia, Scoliopora* and *Thamnopora* now joined by *Alveolites* and *Caliapora.* Throughout the quarry rugose corals are exceptionally rare, consisting of scattered *Temnophyllum, Stringophyllum isactis* (Frech), *Grypophyllum* and *Dendrostella.*

*The ca.* 25m of limestone between the highest quarry levels and the Foxley Tuff is very poorly exposed. It is partly dark grey poorly fossiliferous and well bedded, but some 10m below the tuff, an intercalation of more massive pale to medium grey rudstones and floatstones crop out on the S side of the valley, These are rich in *Hexagonaria* and *Alveolites,* associated with domal stromatoporoids, some with intergrown *Syringopora.*

*Foxley Tuff*

The carbonate succession is interrupted in the later Givetian by the 80m thick green, chloritic Foxley Tuff. Intercalated in the tuff are thin limestone bands containing scattered solitary corals including *Acanthophyllum.*

*East Ogwell Limestone*

Near the base of the East Ogwell Limestone at Foxley [838 705], trilobite fragments indicate a late Givetian age, whilst conodonts mid way up in the Foxley transect suggest the proximity of the Givetian - Frasnian boundary (Scrutton 1977b; Selwood *et al.* 1984). The limestones are poorly bedded to massive, pale, often pinky-grey, usually bioclastic packstones and grainstones but with beds and lenses of micrite.

The limestone is generally richly fossiliferous. Around Foxley, more micritic beds contain baffiestones of *Disphyllum* and *Thamnophyllum,* joined by *Peneckiella* in the Frasnian part of the sequence, with *Pterrorhiza, 'Thamnopora,* and some crinoidal material, brachiopods, ostracods and traces of echinoids. The matrix may be finely bioclastic, peloidal, with some algal material and locally a fine grainstone. Stromatopor0ids are rare, appearing either as thin laminae or as thin, in-life coatings of fasciculate coral branches. These bafflestones appear to alternate, although with unknown regularity, with more coarsely bioclastic wackestones, packstones, grainstones and richly fossiliferous rudstones. These contain *Acanthophyllum, Cyathophyllum (Cyathophyllum), Hexagonaria, Metriophyllum, Alveolites, Syringopora* and *Thamnopora* together with brachiopods, crinoid ossicles, bryozoa, the algae *Renalcis* and traces of *Rothpletzella,* the latter associated with *Wetheredella.* Tabular stromatoporoids are common, some with intergrown *Syringopora,* but *Stachyodes* is rare. Stromatoporoids, algae and auloporids overgrew coral material, largely post-mortem, whilst some solitary coralla are decorticated,

East Ogwell Limestone is poorly exposed in small quarries and in the road-side on East Ogwell village green [8412 7008]. Conodonts of *varcus* Zone age and the coral fauna suggest an earlier Givetian date here than for the base of the limestone at Foxley (Scrutton 1977b; Selwood *et al.* 1984). Lower levels, just above the thrust flooring the East Ogwell Unit, are coarse crinoidal packstones and grainstones. In mid sequence, white, crinoidal limestone: rich in bryozoan material, particularly fenestellids and fistuliporids, contain tabular stromatoporoids, some algal material, brachiopods and thin shelled bivalves, and locally *Sociophyllum* bafflestone. Associated corals include *Acanthophy. llum* with the tabulates *Alveolites,*

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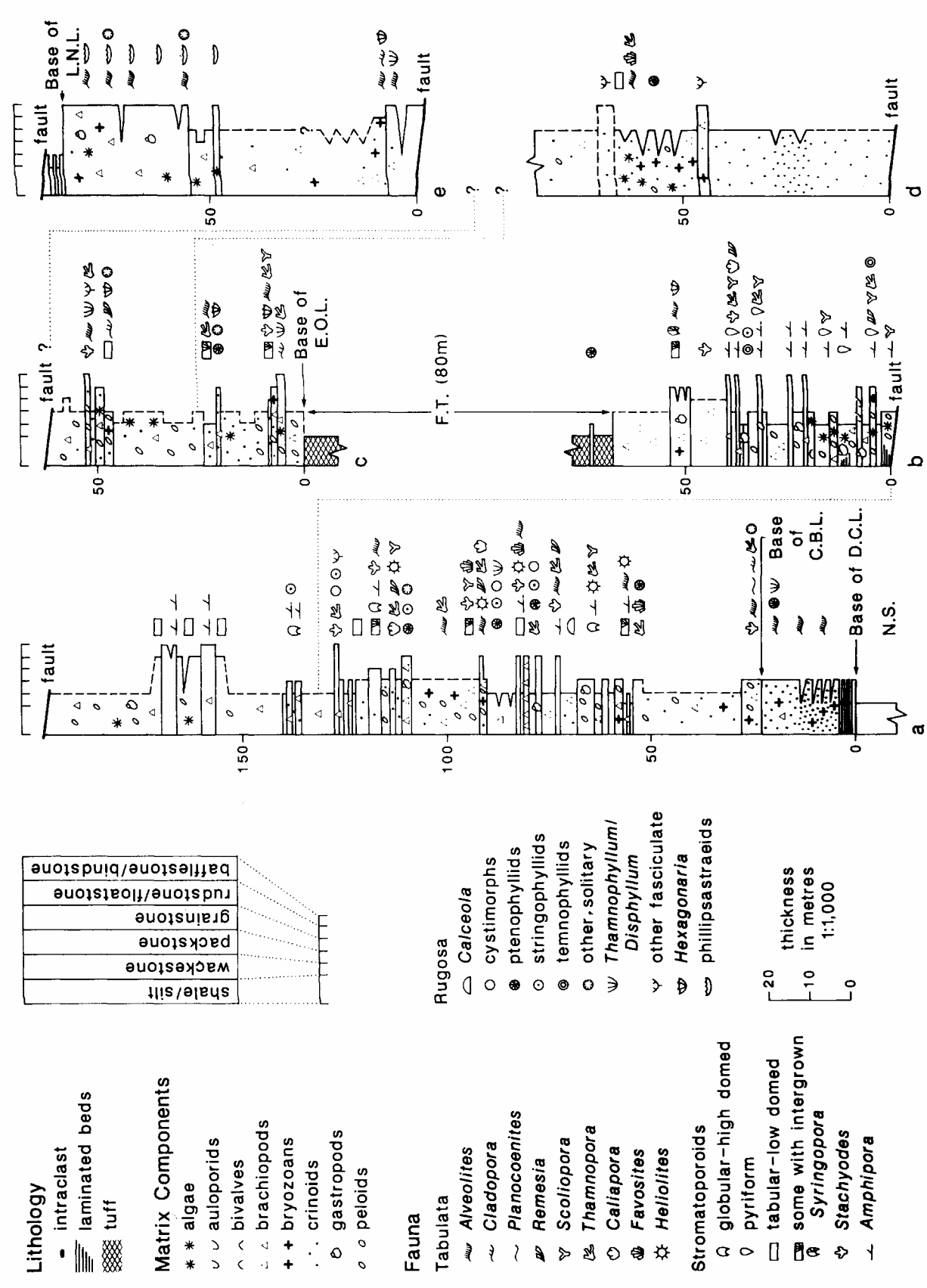


Figure 3. Stratigraphic logs of the carbonate succession in the transects indicated in Figure 2 and their proposed correlation: a. West Hill section; b. Broadridge Quarry; c. Foxley section; d. East Ogwell Green; e. Ransley section. Column lengths with a dashed margin represent sections unexposed or too poor to log. Abbreviations: N.S. Nordon Slate; D.C.L. Denbury Crinoidal Limestone; C.B.L. Chercombe Bridge Limestone; F.T. Foxley Tuff; E.O.L. East Ogwell Limestone; L.N.L. Luxton Nodular Limetone. Favosites and Thamnopora. The section ends with loss of outcrop at the E end of the green.

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Ransley Quarry [8443 7016], type locality for the formation (Selwood *et al* 1984), and the road cutting to the S expose the top of the East Ogwell Limestone in a small thrust slice within the East Ogwell Unit (Fig. 2), Conodonts of *triangularis* to *gigas* Zone age are recorded (Scrutton 1977b; Selwood *et al.* 1984). N of East Hill. lower levels in this thrust slice show alternations of *Thamnophyllum* baffiestone with rudstones containing *Hexagonaria,* similar to levels in the Foxley area but with less well differentiated faunas. Higher up in the road cutting [8437 7006], pale pinky grey packstones and grainstones are interbedded with bindstones of *Phillipsastrea* and *Frechastraea.* with associated *Haplothecia, Neaxon* and *Alveolites. The* matrix contains brachiopods, crinoids and some algae. These levels are transitional to mud mounds of salmon pink and pale grey, micritic limestones forming the top of the limestone, best exposed in Ransley Quarry itself They are dominantly *Frechastraea, Scrunonia* and *Alveolites* bindstones, with scattered crinoid ossicles, articulated brachiopods, gastropods, ostracods and some algal material *(?Epiphyton). The* large solitary coral *Hankaxis* is sparsely present. Spar filled shelter cavities are common beneath the sheet-like coral colonies. Stromatoporoids are entirely absent.

In the quarry, particularly S towards the road cutting, richly bioclastic pinky-grey thin bedded limestones with shale partings are considered transitional to the overlying Luxton Nodular Limestone. This unit crops out in the road cutting just W of a N - S normal fault which downthrows the Carboniferous to the E.

## Coralline faunas and faunal associations

Faunal associations are recurrent groupings of suites of genera and species. They represent elements of one or more communities that appear to have been related, either as sequentially or alternating colonisers of broadly discrete habitats in time and space (Goodger *et al.* 1984). They are thus broader in concept than assemblages, in the sense of Williams *et al.* (1981). The more common and distinctive constituent genera defining the coral associations are listed in Tables I (Tabulata) and 2 (Rugosa).

*Tabulate corals*

Although less diverse than the rugose corals, the tabulate corals (19 species in 11 genera) are the more important contributors of biomass throughout much of the succession. Most of the fauna has been recently systematically reviewed by Goodger (1986).

Of the associations described by Goodger *et al.* (1984), the *Planocoenites, Scoliopora, Alveolites and Thamnopora* associations are recognised in the Lemon Valley sequence. The *Planocoenites* association is only found in

Table 1. Composition of tabulate coral associations, in terms of their principal genera, as defined here and in Goodger *et at* (1984). Key: c - common; p - present; r - rare.

| | Association | | | | | |
|---|---|---|---|---|---|---|
| Genera | *Remesia* | *Scoliopora* | *Caliapora-Heliolites* | *Thamnopora* | *Alveolites* | *Planocoenites* |
| *Remesia* | c | p | r | | | |
| *Scoliopora* | r | p | r | | | |
| *Caliapora* | r | p | c | | | |
| *Thamnopora* | | p | p | c | r | |
| *Cladopora* | | r | r | p | p | c |
| *Favosites* | | | p | | ? | |
| *Alveolites* | | | p | p | c | r |
| *Heliolites* | | | c | | r | r |
| *Striatopora* | | | | r | | r |
| *Planocoenites* | | | | | p | c |
| *Squameoalveolites* | | | | | | r |

the basal few metres of the Chercombe Bridge Limestone but the outcrop is too poor to determine if any of the cyclic features described in Dyer's Quarry, Torquay are present (Goodger *et al.* 1984, p.22). The *Scoliopora* association is best developed in the sequence in Broadridge Quarry, interbedded with and succeeding *Amphipora* baffiestones. At the top of the quarry, the addition of *Alveofites* and *Caliapora* indicate transition to the *Caliapora-Heliolites* association. In the mid part of the Chercombe Bridge Limestone, below quarry level, the *Scoliopora* and possibly the *Remesia* associations can occasionally be identified interbedded with the strongly dominant *Caliapora-Heliolites* association. This latter is characteristically the most diverse tabulate coral association (Tab. 1), and is accompanied by rich faunas of rugose corals and stromatoporoids including *Stachyodes.* The presence of *Favosites* in the East Ogwell Limestone on East Ogwell Green may indicate the *Caliapora-Heliolites* association, although there is insufficient evidence to distinguish this fauna clearly from the *Alveolites* association. *Alveolites* is dominant in the East Ogwell Limestone, occurring with scattered *Thamnopora* and *$yringopora,* but not normally *Favosites,* as the *Alveolites* association. The extinction of *Favosites, Caliapora* and *Heliolites* in the late Givetian, however, blurs the distinction between these two associations. The *Thamnopora* association is only developed in some rugose coral baffiestones in the Foxley sequence of East Ogwell Limestone.

*Rugosa*

Rugose corals are common throughout much of the sequence in the Lemon Valley. 35 species belonging to 26 genera have been identified (Scrutton 1977b). Diversity is less than in comparable successions in northern Europe.

In the light of evidence from the Lemon Valley succession, the Ptenophyllid association is redefined here

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Table 2. Composition of rugose coral associations, in terms of their principal genera, as defined here and in Goodger *et al.* (1984). Key: c - common; p - present; r - rare.

| | Associations | | | | | | |
|---|---|---|---|---|---|---|---|
| Genera | *Temnophyllum* | Ptenophyllid | Cystimorph | *Thamnophyllum* | *Sociophyllum* | *Hexagonaria* | *Frechastraea* |
| *Temnophyllum* | r | | | | | | |
| *Dendrostella* | r | p | | | | | |
| *Grypophyllum* | r | c | p | | | | |
| *Stringophyllum* | r | c | p | | | | |
| *Ceratophyllum* | | p | | | | | |
| *Heliophyllum* | | r | | | | | |
| *Dohmophyllum* | | r | | | | | |
| *Cystiphylloides* | | c | p | | | | |
| *Calceola* | | | p | | | | |
| *Lekanophyllum* | | | c | | | | |
| *Digonophyllum* | | | p | | | | |
| *Mesophyllum* | | | c | | | | |
| *Thamnophyllum* | | r | r | c | | | |
| *Disphyllum* | | ? | | c | | | |
| *Acanthophyllum* | | c | r | | p | c | |
| *Peneckiella* | | | | p | | | |
| *Pterrorhiza* | | | | p | | p | |
| *Sociophyllum* | | | | | p | | |
| *Cyathophyllum* | | | | | | p | |
| *Hexagonaria* | | | | | | c | |
| *Tabulophyllum* | | | | | | p | |
| *Phillipsastrea* | | | | | | | c |
| *Haplothecia* | | | | | | | Ip |
| *Frechastraea* | | | | | | | c |
| *Hankaxis* | | | | | | | p |
| *Scruttonia* | | | | | | | p |

to exclude Lekanophyllum, Digonophyllum and Calceola, which are thus exclusive to the Cystimorph association. This latter association, common in Torquay, is only questionably represented here at one level low in the Chercombe Bridge Limestone where Calceola occurs. The Ptenophyllid association, poorly developed in Torquay (Goodger et al. 1984), is here a rich and diverse association of mainly solitary corals (Table 2), best developed in a series of rudstones and floatstones in the middle levels of the Chercombe Bridge Limestone. Fragments of Tharnnophyllum and ?Disphyllum may be derived from unexposed penecontemporaneous developments of the Thamnophyllum association.

Distinctive horizons monogeneric in Rugosa, but similar in other lithic and faunal respects to the Ptenophyllid association are considered subdivisions of it. One variant is dominated by Ceratophyllurn sp., accompanied by Caliapora, Remesia, and Stachyocles among others. The other is a Dendrostella bafflestone with rare Stringophyllurn, Grypophyllum plus Amphipora and large fragments of Stringocephalus. This latter grouping is transitional to levels in the Chercombe Bridge Limestone rich in Amphipora baffiestone. These higher levels have very rare, scattered Rugosa in interbedded wackestones, the Temnophyllum association.

The remaining associations are almost exclusive here to the East Ogwell Limestone. The Hexagonaria association is characterised by the nominate genus and several solitary Rugosa. In the lower to mid levels of the East Ogwell Limestone, this association is often interbedded with micritic bafflestone of the Thamnophyllum association, although the fasciculate colonies are less densely developed than in the Daddyhole Limestone in Torquay. In this latter association, solitary corals and stromatoporoids are rare. At the top of the East OgweU Limestone, the Frechastraea association is distinguished by a complete lack of stromatoporoids and is dominated by thin, platy colonies of massive frechastraeids.

The very sparse exposures yielding Sociophyllum and Acanthophyllum, together with fragments of stromato-• poroids, are probably representatives of an association not previously described but well developed in the Walls Hill Limestone Formation in Torquay (Scrutton 1977b). It is tentatively referred to here as the Sociophyllum association.

## Stromatoporoids

Stromatoporoids are prominent throughout much of the Lemon Valley carbonate succession but they are unstudied systematically. Apart from their widespread occurence as thin coatings on the epithecae ofrugosans, they fall into two broad groups.

Nodular, irregular to domical forms and laminar skeletons, up to 500mm diameter, are widely distributed with the Ptenophyllid and Hexagonaria associations. Some, usually nodular varities, may show symbiotic overgrowth of Syringopora and occasionally of other solitary corals. The dendroid Stachyodes is also commonly prominent with the Ptenophyllid association but rarer elsewhere. A formal association is not defined.

Amphipora, which occurs scattered with the Ptenophyllid and Caliapora-Heliolites associations, is the dominant element in dense micritic baffiestones. Interbedded biostromes contain disoriented pyriform skeletons of Actinostroma up to 400mm in height. Corals are absent or rarly represented by the Temnophyllum and Scoliopora associations. This distinctive Arnphipora association was formerly well seen in the wire cut faces of Ashburton Marble Quarry [7680 7107] (Scrutton 1977b). There, Actinostrorna - Amphipora cycles of 0.6 - lm thickness are developed, but similar cycles cannot be clearly demonstrated in the Lemon Valley.

## Environmental interpretation

The principles and methods involved in this analysis are those outlined inGoodger et al. (1984) and their results are drawn on here. However, the intermittent exposure in the Lemon Valley area allows a much less detailed inter-pretation to be attempted. Reviews of other Devonian

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reefs (Burchette 1981; Krebs 1974; Tsien 1971) and general summaries (Heckel 1974; House 1975) provide comparisons and background to the analysis.

As elsewhere in Devon (Scrutton 1977a, b), the carbonate platform was initiated on accumulations of crinoid debris. Derived material from nearby banks and the migration into the area of dense crinoid thickets occurred here in the later Eifelian. The sparse fauna represents patchy colonisation in normal marine conditions of a probably unstable substrate as bioclasts other than crinoid ossicles are uncommon. This phase was quickly succeeded by quiet, turbid conditions below wavebase with intermittent sediment input in which the rapid substrate coloniser Planocoenites was successful. Elsewhere in S Devon, however, crinoidal banks were initiated earlier and persisted later, accumulating to thicknesses in excess of 200 m (Scrutton 1977a,b; Selwood et al. 1984).

Conditions on the platform at higher levels alternated between marginally and moderately restricted conditions. The diverse Ptenophyllid and Caliapora-Heliolites associations, with their rich accompanying fauna, represent periods of near normal circulation. Generally recumbent solitary corals, bioclastic debris and disorientated massive skeletons suggest at least periodically higher water energy, whilst quite common overgrowth, some post-mortem, indicates low and/or intermittent sediment influx. However, horizons with particularly fasciculate corals in situ are probably the result of rapid burial by a thick sediment blanket. The generally small size of stromatoporoids and much fine sediment point to a slightly turbid environment. The dark colour of these limestones may reflect insufficient oxygen for, complete breakdown of organic matter and the formation of finely disseminated pyrite (Playford 1969; Scrutton 1977b).

The scattered Arnphipora debris in these horizons, the presence of calcispheres, and occasional interbedded Amphipora baffiestones clearly indicate the sporadic existence of more restricted conditions elsewhere which rarely encroached into the Lemon Valley area. These may represent periods of weakened circulation across the interior of a wide, shallow platform, leading to increased salinities or reduced oxygenation levels. The Ptenophyllid association is regarded as tolerant of marginally restricted environments (Goodger et al. 1984), although with reduced diversity, and the Caliapora-Heliolites association is concluded to be similarly tolerant. Higher in the Chercombe Bridge Limestone, the diverse coral associations disappear and there is evidence of more or less continuous high-stress conditions in the thick and repeated units of the Amphipora association. With lithic indicators of shallow, lagoonal or back-reef environments are sparse, low diversity coral faunas of the Temnophyllum and Scoliopora associations, both considered indicative of relatively high-stress conditions. Episodic sedimentation, with periods of winnowing, resulted in layers of prone Amphipora and disorientation of narrow-based pyriform stromatoporoids, supported by soft lime mud around their bases during life. Scrutton (1977b) speculated that this period of restricted conditions may have coincided with the principal period of reef construction on the platform margin in the Torquay - Brixham area. Although palaeogeographic reconstruction is most uncertain in view of the structural complexity of the area (Coward and McClay 1982; Selwood et al. 1984), such an explanation remains most likely in principle.

Horizons nearer the top of the limestone, with more diversified examples of the Scoliopora association, suggest a gradual amelioration of the conditions. Just prior to the volcanic episode represented by the Foxley Tuffs, paler limestones containing tabular and domal stromatoporoids with elements of the Hexagonaria and Alveolites associations, both more fully developed in the East Ogwell Limestone, herald the return locally of fully marine, shallow water, more agitated conditions: The outcrop, which cannot be traced laterally, may be part of a small bioherm.

During pauses in the eruption of the tuffs, thin limestones with elements of the Ptenophyllid association were deposited. Immediately afterwards, however, clearer, normal marine waters allowed colonisation of the substrate by diverse coralline faunas. In areas interpreted as quieter and perhaps slightly deeper, thickets of fasciculate Rugosa of the Thamnophyllum association flourished and were preserved (and probably killed) by thick episodic fine-sediment blankets. Elements of the Thamnopora association and a low density fauna are present in addition and overgrowth is restricted to some in-life encrustation of fasciculate coral branches by thin stromatoporoid veneers. In contrast, in adjacent horizons both vertically, and probably laterally although this cannot be demonstrated, stromatoporoids occur commonly with the Hexagonaria and Alveolites associations. These are preserved with a dense and diverse accompanying fauna m more coarsely bioclastic wackestones, packstones and grainstones interpreted as deposited in a shallower, higher energy, clear environment with low rates of sedimentation. There is significant evidence of post-mortem overgrowth of skeletal material. Relatively small stromatoporoid skeletons suggests a less than optimum environment for these calcareous sponges, which seem to have flourished best in higher energy conditions.

At the top of the East Ogwell Limestone, the highly distinctive corals of the Frechastraea association form a bindstone of pale grey to salmon pink micrite, aided by platy Alveolites. The sheet-like colonies must have rapidly colonised and stabilised the micrite substrate during pauses in sediment influx, the next blanket of which killed much of the live colony surfaces. This process built up bioherms on the top of the carbonate platform, probably in a deepening environment as they are succeeded by deeper water shales and nodular limestones of schwelle facies

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with, elsewhere, conodont, ostracod and goniatite faunas. Stromatoporoids are completely excluded, whether by competition with the frechastraeids or the depth of water is uncertain, although these bioherms clearly formed within the photic zone. Massive extinctions affected the stromatoporoids world wide at about this level.

Another distinct environment within the East Ogwell Limestone is represented by the tentatively identified Sociophyllum association. It's rich accompanying fauna and lithic characteristics are very similar to the reef facies exposed in Long Quarry Point at Torquay (Scrutton 1977a, b). This may represent a patch reef in the platform interior.

This analysis has concentrated on a single transect through the interior of the carbonate platform, albeit compiled from two structural units. Improving correlation suggests lateral facies changes across the platform but they have yet to be documented in detail. For example, sections elsewhere in the Newton Abbot area contain more Givetian patch reefs (Scrutton 1977b, Goodger 1986). Whether or not these are coeval, and whether they correspond to a reef-free period on the platform margin are possibilities that cannot be properly tested. On a broader scale, Selwood et al. (1984) consider the Chercombe Bridge Limestone of the Ugbrooke Unit to the N to be contemporaneous with the East Ogwell Limestone of the Lemon Valley area. However, the northern development is probably on a separate carbonate platform, cropping out now in the Chudleigh to Teign Valley area and separated from the Newton Abbot carbonate successions by a belt of continuous Nordon Slate deposition (Selwood and Thomas 1986). Furthermore, the structural complexity of this area makes any reassembly of the relationships between the coastal sequences around Tor Bay and those in land very uncertain.

## Conclusions

The carbonate sequences of the Denbury and East Ogwell Units in the Lemon Valley and East Ogwell area are described. The Denbury Crinoidal Limestone represents a crinoid bank facies which acted as the foundation for the carbonate platform in the late Eifelian. The lower to mid parts of the Chercombe Bridge Limestone contain generally well diversified coralline faunas representing shallow water, low energy, only slightly abnormal marine conditions. However, occasional interbedded horizons of Amphipora bafflestone and widespread fragments of Amphipora suggest periodic restricted circulation across the platform. In the higher parts of the limestone, diversified rugose and tabulate coral faunas disappear and a prolonged period of high-stress conditions, possibly back-reef in character, is indicated. Normal marine circulation was at least temporarily reestablished before the end of Chercombe Bridge Limestone deposition. Following a substantial local outpouring of tuffs, the paler grey to pink limestones of the East Ogwell Limestone contain rich and diversified coral stromatoporoid faunas indicative of shallow, well aerated, generally moderate energy environments in the later Givetian and Frasnian. The carbonate platform is locally capped by pink micritic bioherms containing a highly distinctive coral fauna and lacking stromatoporoids. These developed during subsidence and are succeeded by the schwelle facies of the Luxton Nodular Limestone. This sequence is considered characteristic of a platform interior situation.

Previously defined and new coralline associations are recognised as indicative of different environmental conditions. The Hexagonaria and Alveolites associations are characteristic of fully marine, clear, moderate energy, shallow water environments, whilst the Sociophyllurn association occurs in higher energy situations. The Alveolites association also appears to be tolerant of deeper water conditions with periodic heavy sediment imput, where it occurs with the Frechastraea association. The Planocoenites association occurs in quiet, less well oxygenated, more turbid marine conditions with intermittent sedimentation. In marine to marginally restricted, low energy, probably slightly turbid environments with generally low sediment imput, the Ptenophyllid and Caliapora-Heliolites associations are well developed. More restricted conditions contain low diversity coral faunas of the Scoliopora and the very sparse Temnophyllurn associations, whilst distinctive stromatoporoids of the Amphipora association characterise high stress conditions in which corals are virtually excluded.

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## References

Burchette, T.P. 1981. European Devonian reefs: a review of current concepts and models. In: Toomey, D.F. (ed) *European fossil reef models (S.E.P.M. Special Publication 30)*, 85-142. S.E.P.M., Tulsa.

Coward, M.P. and McClay, K.R. 1982. Thrust tectonics of S. Devon. *Journal of the Geological Society*, London, 140, 215-228.

Goodger, K.B. 1986. Taxonomy and palaeoecology of some English Devonian tabulate corals. *Unpublished Ph.D. Thesis, University of Newcastle upon Tyne.*

Goodger, K.B., Buglass, A. and Scrutton, C.T. 1984. Sequence of coralline faunas and depositional environments in the Middle Devonian Daddyhole Limestone Formation stratotype section, Torquay, Devon. *Proceedings of the Ussher Society*, 6, 13-24.

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Heckel, PH. I974. Carbonate buildups in the geologic record: a review. In: Laporte, L.F, (ed)*Reefs in time andspace (S.E.P.M. Special Publication 18)*, 90-154. S.E.P.M., Tulsa.

House, M.R. 1975. Faunas and time in the marine Devonian. Proceedings of the Yorkshire Geological Society, 40, 459-490. Krebs, W. 1974. Devonian carbonate complexes of Central Europe. In*: Laporte, L.F. (ed) Reefs in time and space (S.E.P.M. Special Publication 18*), 155-208. S.E.P.M., Tulsa.

Playford, P.E. 1969. Devonian carbonate complexes of Alberta and Western Australia: a comparative study. *Reports of the Geological Survey of Western Australia,* 1, 1-43.

Scrutton, C.T. 1977a. Reef facies in the Devonian limestones of eastern South Devon, England. *Mémoires, Bureau de Recherches Géologiques et Minières*, 89, 125-135.

Scrutton, C.T. 1977b. Facies variations in the Devonian limestones of eastern South Devon. *Geological Magazine*, 114, 165-193.

Scrutton, C.T. (ed) 1978. A field guide to selected areas of the Devonian of south-west England 72 pp. *The Palaeontological Association*, London.

Selwood, E.B. 1965. Dechenellid trilobites from the British Middle Devonian. *Bulletin of the British Museum* (Natural History), Geology, 10, 317-333.

Selwood, E.B., Edwards, R.A., Simpson, S., Chesher, J.A., Hamblin, R.J.O., Henson, M.R., Riddolls, B.W. and Waters, R,S. 1984. Geology of the country around Newton Abbot. *Memoirs of the British Geological Survey*. xiv + 213pp.

Selwood, E.B. and Thomas, J.M. 1986. Variscan facies and structure in central SW England, *Journal of the Geological Society of London,* 143, 199-207.

Tsien, H.H. 1971. The Middle and Upper Devonian reef-complexes of Belgium. *Petroleum Geology of Taiwan*, 8, 119-173.

Williams, A., Lockley, M.G. and Hurst, J.M. 1981. Benthic palaeocommunities represented in the Ffairfach Group and coeval Ordovician successions of Wales, *Palaeontology,* 24, 661-694.

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*Read at the Annual Conference of the Ussher Society, January 1987*

# Orbitally induced cycles in the Mesozoic sediments of S.W. England

M.B. HART

Hart, M.B. 1987. Orbitally induced cycles in the Mesozoic sediments of S.W. England. *Proceedings of the Ussher Society, 6.* 483-490.

The characteristic rhythmic bedding of the Upper Cretaceous carbonate successions of Southern England is thought to be the result of orbital variations. Both the 23,000 year and 41,500 year cycles appear to be present and can now be compared with the radiometric dating of late Cretaceous events, especially in the Cenomanian. Similar patterns are also demonstrated in the Chert Beds (of Albian? age) and the Blue Lias (of early Jurassic age).

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## Introduction

Recent work on Pleistocene successions has shown that climatic events and oxygen isotope abundances can be attributed to changes in orbital parameters (Imbrie 1985; papers in Berger et al. 1984). Cycles are known to occur at 19,000, 23,000, 41,500, 54,000, 100,000 and 413,000 year intervals and have been detected in Recent and sub-Recent sedimentary successions - especially those from pelagic environments. As many geological successions show cyclic sedimentation of one form or another it is interesting to speculate (House 1986) on the possible orbital control of such sequences. In many sedimentary successions however there are few, if any, viable radiometric dates (House 1985) available on which to base one's judgements and there are always additional problems (dissolution, diagenesis, etc.) which may hinder a valid statistical analysis.

## The Chalk Facies

The cyclicity in the chalk is readily apparent and it has been described and figured by several authors (Kennedy & Garrison 1975; Hancock 1976; Bromley & Ekdale 1986; Barron et al. 1985; Arthur et al. 1986; Robinson 1986a). The most typical, and best known, is that seen in the higher levels of the succession, where it is in the form of chalk-flint-chalk-flint cycles. In some cases individual flint layers can be traced for considerable distances (Mortimore ,1986; Robinson 1986b) and despite the probability that the flints were formed by diagenetic processes (Clayton 1986) their distribution must be a function of a basin-wide control. In the 'Lower Chalk' the cyclicity takes two forms. The cycles in the 'Chalk Marl' facies (of early to mid-Cenomanian age) are represented by the geologically-widespread limestone-marl-limestone rhythms. The limestones have distinct upper surfaces and the whole succession is intensely bioturbated (see Barron et al. 1985). In the 'Grey Chalk' facies (of mid- to late Cenomanian age) the cyclicity is picked out by the regularly spaced amastomosing wisps of clay within an otherwise pale cream chalk succession. These clay-rich horizons are probably dissolution features and are often associated with Chondrites burrow systems, the presence of which have been taken to indicate levels of local near-anoxia in the sediments (Bromley & Ekdale 1984). This sea floor anoxia is probably the result of the removal of oxygen by increased biodegradation at times of high productivity, especially in the surface waters.

In Recent or sub-Recent sediments the cyclicity attributed to orbital forcing has been demonstrated by statistical means and the application of techniques such as spectral analysis. In the 'geological' situation the data base is not so extensive and this approach may not always be possible. The detailed microfaunal analysis of limestone-marl-limestone rhythms has been attempted by the author but failed as it was impossible to process the various lithologies in a consistent way. Any variations in the results so obtained could therefore be invalid from the outset and involved data processing was rendered useless. In the chalk-with-flints facies of the Coniacian-Maastrichtian interval the difficulties are created by the diagenetic processes involved in the formation of the flints. It has been shown (Curry 1982; Hart et al. 1986) that some of the changes within, and adjacent to, the flints affect some taxa more than others and a detailed statistical treatment is again made suspect. In both cases, the intense bioturbation seen in the chalk facies might also render meaningless any results based on very closely spaced samples. Weedon (1986), in an attempt to gain more data points used the Walsh power spectra technique to interpret measured sections in the Blue Lias. This approach is possibly rendered invalid by the changes in sediment thickness generated by diagenesis and this would be particularly true if this method was applied to

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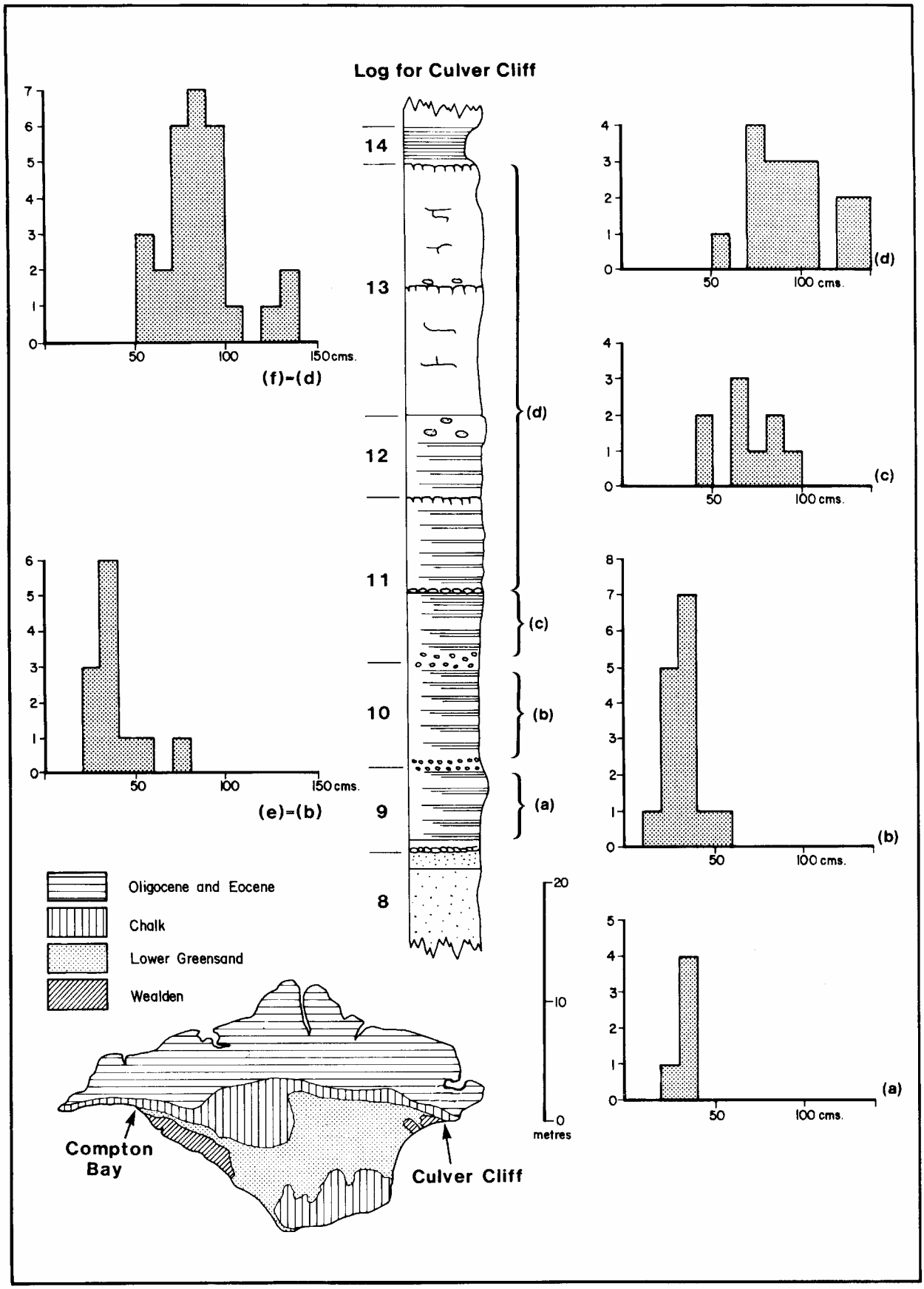


Figure 1. Analysis of the limestone/marl cycles present in the Lower Chalk succession, Culver Cliff, Isle of Wight. The succession has been divided into four units (a-d) and the measurements of cycle spacing plotted in separate histograms. Histograms (e) and (f) are based on the comparable succession at Compton Bay. The foraminiferal zones are based on the scheme of Carter & Hart (1977).

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the chalk-with-flints facies; the flints not being a part of the primary'depositional rhythmicity.

## Analysis of cycles in the Lower Chalk

The most complete succession of the Lower Chalk in the U.K. is that between Folkestone and Dover, but cliff falls have obscured some critical parts of the succession. The same is also true of the Beachy Head succession at Eastboume. At either end of the Isle of Wight however the sections at Compton Bay (west) and Culver Cliff (east) are presently well exposed. At Culver Cliff(Fig. 1) it is possible to measure the thicknesses of the cycles in four different 'groups' (Fig. 1 (a)-(d)). These are very obvious in the field (Hart & Swiecicki 1987, Fig 8.2), although both (a) and (b) would appear to have the same mean cycle spacings and can effectively be regarded as a single unit. In the rather thin succession represented by the lower half of foraminiferal zone 11 (Carter & Hart 1977) the main peak is at 65 cms while in unit (d) there are three rather vague peaks at 55 cms, 85-95 cms, and 135 cms. At Compton Bay (Fig. l(f)) there is a similar set of measurements to those shown in (d) but with more distinctive peaks at 55 cms, 85 cms and 135 cms. Of the astronomical cycles detected in modern sediments (Imbrie 1985) it is that for obliquity (tilt) that might have had the greatest effect on phytoplankton productivity. With this very bold assumption.one would predict that the main peak represents the 41,500 year frequency and this figure can then be used to calculate the duration of the various intervals shown in Figure I. Using the main cycle frequency for each interval (Fig. 1 (a+b), (c) and (d)) it is possible to arrive at an 'idealised' number of cycles for each given sequence of rock. This was calculated using the mean cycle frequency and the total known thickness of strata in each interval. As parts of the succession are unclear (covered by talus, faulted, covered in algae, etc) accurate measurements of every cycle could not be obtained and the number of cycles recorded in each histogram is not therefore the total number that must be present. The calculation of the 'idealised' number of cycles therefore also removes some of the inaccuracies inevitable in section measurement. The total number of 'idealised' cycles in each interval of rock was then used to calculate the total duration (Fig. 2) for each interval. The Culver Cliffsuccession (foraminiferal zones 8-13) can in this way be estimated as representing an interval of some 4,191,500 years, although clearly some allowance should also be made for non-sequences and known erosion surfaces. Harland *et al.* (1982) give the duration of the Cenomanian stage as 6,500,000 years, the Cenomanian/Turonian boundary being placed at 91.0Ma and the Albian/Cenomanian boundary at 97.5Ma. More recently Hallam *et al.* (1985) have given the duration of the Cenomanian (based on European data) at 4,500,000 years although they would appear to be in favour of using American data for the Albian/Cenomanian boundary which would increase that figure to 5,000,000 years. There appears to be general agreement over the date of 91.0Ma for the base of the Turonian while there is a range of values (95.5Ma, 96.0Ma and 97.5Ma) for the base of the Cenomanian. It is clear from the chronograms presented by Harland *et al.* (1982) that all of these estimates are based on individual dates with a precision of the order of+l million years. If one accepts Hallam *et al.* (1985) as giving the most recent value and uses the figure of 5,000,000 years as the duration of the Cenomanian stage this would appear to be well in excess of the predicted figure, based on the cyclicity, of 4,191,500 years. There are however good reasons for this difference of 808,500 years. The base of the Lower Chalk at Culver Cliff(Kennedy 1969; Carter & Hart 1977; Fig. 2) is much younger than that at Folkestone; Zone 7 and the greater part of Zone 8 being missing. The top of the Cenomanian (Rawson *et al.* 1978) is now drawn some metres above the *A.plenus* Marls and this, together with what is absent at the base of the Lower Chalk, could account for at least some of the difference. The major non-sequences also known from the succession should also account for a substantial period of time. However, as can be seen in Figure 2, Zone 8 at Folkestone is some 15 m. thick and on the basis of the mean cycle spacing seen in that interval would be expected to contain 42 cycles giving an additional 1,743,000 years. That figure, added to the 4,191,500 years obtained for the Culver Cliff succession, gives at total estimate for the Cenomanian of 5,934,000 years. This estimate reasonably placed between the Harland *et al.* figure of 6,500,000 years and the Haltam *et al.* figure of 5,000,000 years and would appear to confirm that the cycle data is providing some form of viable time scale. The dominance of the 41,500 year cycle is also confirmed by this as the 23,000 and 100,000 year cycles would give wildly inaccurate values for the duration of the Cenomanian if they were used in the calculations.

Robinson (1986a) has approached the same topic in a slightly different way, attempting to produce an estimate of the number of miCrorhythms per stage and reconciling this with the various estimates for the Duration of the Cenomanian stage. Using Harland *et al.'s* estimate he obtained a figure of 46,000 years for each microrhythm. Unfortunately Robinson does not appear to allow for non-sequences or for the variations of rhythm spacing shown in Figure 1, taking whole stages into a single calculation. Even so, had he used the Hallam *et al.* figure of 5,000,000 years he would have been close to a figure of 40,000 years for each rhythm.

## The Upper Greensand facies

In the Upper Greensand successions of S.E. Devonshire cyclicity is less obvious although it is present in both the Foxmould and the Chert Beds. This is best seen on the coast between Seaton and Branscombe (Fig. 3). If one performs the same analysis as that shown in Figure 1 for the chert-bearing strata in the upper part of the succession it shows a mean cycle thickness of 45 cms. There are some wider spacings visible (some over 1 metre

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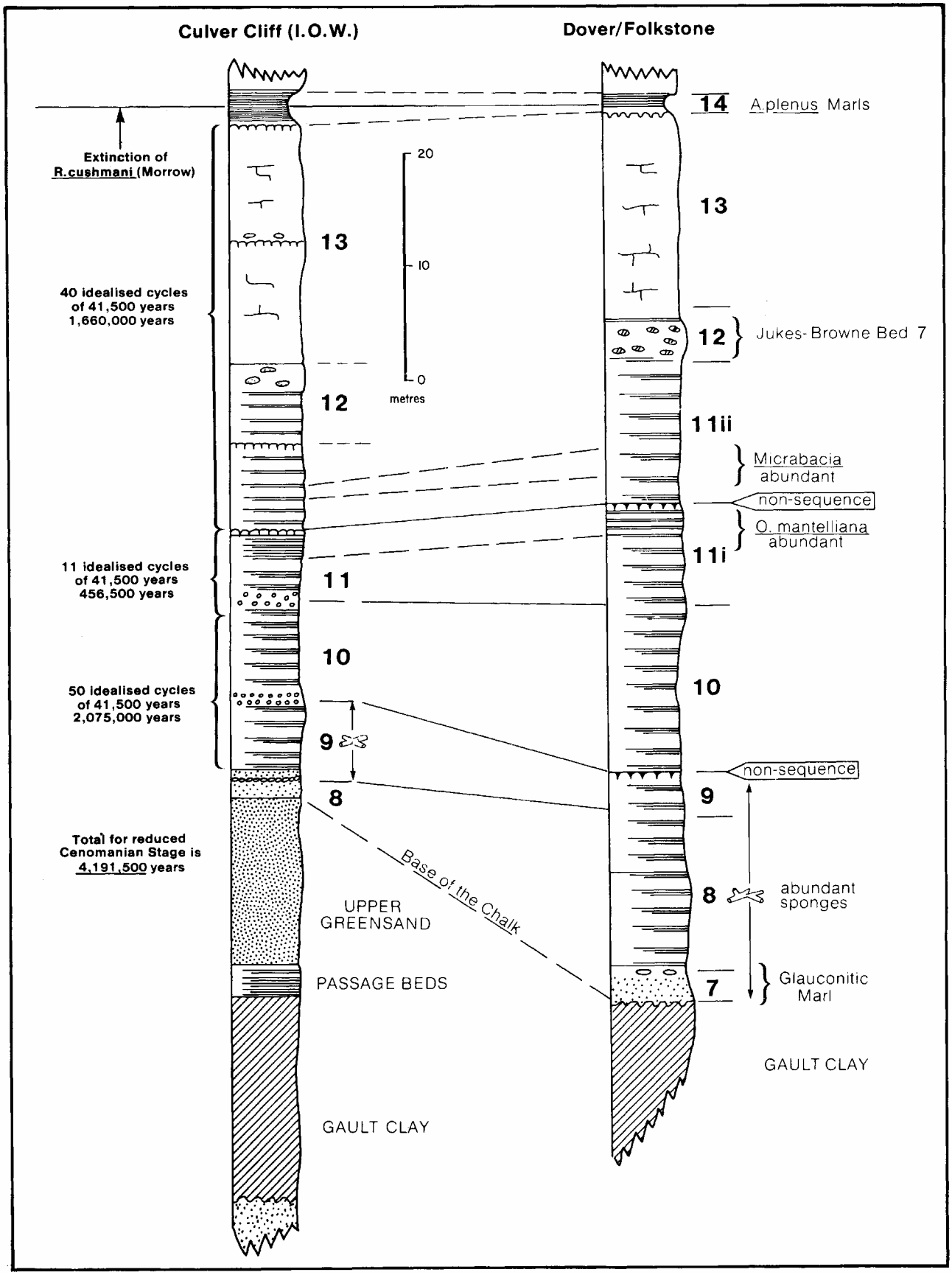


Figure 2. Comparison of the Lower Chalk successions at Culver Cliff and Folkestone/Dover. The number of idealised cycles in each unit was calculated from the mean cycles spacing and the total thickness of rock in each interval. The duration (4,191,500 years) of the abbreviated Culver Cliff succession can thus be compared directly to the most complete succession available in the U.K.

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in width) but these can be attributed to storm events on the basis of the sedimentologial evidence. The cyclicity in the Chert Beds is almost identical in spacing to that seen in the Chalk Marl (Fig. 1 (a), (b) and (c)). This is rather surprising as the Chert Beds are a ctastic succession and the cherts themselves are totally diagenetic (Williams 1986) in origin. The spacing of the cherts must either be the result of the presence of more porous strata (allowing the ingress of Si-bearing fluids) or represent initial concentrations of silica that have become emphasised by diagenesis. Cherts of Santonian age in Israel (Reiss, *pers. comm.)* are crowded with the frustules of diatoms although none have been seen in the Devon successions. If these cycles are related to variation in biogenic silica production then this may also be the case in the chalk-with-flints facies higher in the succession. Similar analyses of the whole of the Upper Cretaceous chalk succession have detected both the 23,000 and 41,500 year cycles (Hart, *in prep.)* as nearly as can be confirmed by the rather less convincing radiometric evidence available at that level.

Chert-bearing greensands of equivalent age are also seen along the Dorset coast where they gradually thin against the Mid-Dorset Swell. Cherts re-appear in the Upper Greensand succession at the southern end of the Isle of Wight (Rocken End), and there the average spacing is again between 40 and 45 cms.

In the lower part of the Upper Greensand succession there are bands of calcareous nodules ('cowstones') within what is normally termed the Foxmould. These nodules layers also have a distinct spacing, especially at Compton Bay on the Isle of Wight and on the Devon coast at Branscombe. The spacing between the nodule layers is much greater than 45 cms but this is probably the result of a much higher sedimentation rate in this more marginal environment.

The Blue Lias succession

Weedon (1985) has shown that the sedimentological features seen in the Blue Lias may be due to the 21,000 or 41,000 year astonomical cycles. As indicated above he used a form of Walsh power spectral analysis, even though the data came from a mixture of primary and diagenetic features. As was seen in the case of the Lower Chalk succession there are obvious groupings of cycle type and these have been treated separately in FigUre 4 (a)-(d). Unit (b) - *C.johnstoni* Zone to *A.laqueus* Zone inclusive - and unit (c) - *S. complanata* Zone to *A. bucklandi* Zone inclusive - produce similar mean cycle values and are therefore treated together. As indicated in Figure 4 the idealised cycle numbers when ascribed to the 41,400 year periodicity give a total duration for the Blue Lias of 5,082,090 years. Harland *et al.* (1982) give the Blue Lias a duration of 8,000,000 years (approximately) but the error bars shown in their figure 3.1 indicate a range of 20 million years for the Hettangian/Sinemurian boundary and only slightly less for the Rhaetian/Hettangian boundary. This degree of error indicates that the time to deposit the Blue Lias is quite within the range of figures being proposed by the cycle count. This was also the conclusion reached by House (1985, 1986) in a similar analysis of the cyclicity. It is interesting to note that as one ascends the Blue Lias succession (Fig. 4) and progresses into more open marine environments the mean cycle spacing increases. This is also true of the Cenomanian (Fig. 1) and must therefore indicate the effect of increasing sediment production by phytoplankton. This is also seen elsewhere in the Upper Cretaceous succession where, for example, the cycle spacing in ,the Coniacian is much less than in the Campanian.

## Conclusions

The recognition of an orbital control of the sedimentary cycles seen in parts of the Mesozoic succession is not proven. The data presented here are not rigorous enough and are not suitable for any real statistical testing. It is also impossible to predict how much time is represented by the various non-sequences known to exist in the Cenomanian succession (erosion surfaces, phosphate beds, hardgrounds, anoxic events, etc.). It is clear however that the figures obtained from this work are consistent with some of the known radiometric data and it is interesting to speculate on their validity; The features recorded in these successions are however far more prominent than the faint signal that would be anticipated from a study of modem sediments. This may perhaps be ascribed to a secondary concentration of carbonate and/or silica caused by diagenesis which has emphasised the original signal.

*Acknowledgements.* This work was funded by the research initiative of the National Advisory Body for P.S.H.E. (1985-8). Mr J. Abraham prepared the figures and Dr. C. Dodd (now with British Petroleum p.l.c.) assisted with some of the early fieldwork.

References

Arthur, M.A., Bottjer, D.J., Dean, W.E., Fischer, A.G., Hattin, D.E., Kauffman, E.G., Pratt, L.M. & Scholle, P.A. 1986. Rhythmic bedding in Upper Cretaceous pelagic carbonate sequences: Varying sedimentary response to climatic forcing. *Geology, 14,* 153-156.

Barron, E.J. Arthur, M.A. & Kauffman, E.G. 1985. Cretaceous rhythmic bedding sequences: a plausible link between orbital variations and climate. *Earth and Planetary Science Letters, 72,* 327-340.

Barger, A., Imbrie, J., Kukla, G. & Saltzman, B. (eds) 1984. *Milankovitch and Climate.* NATO ASI Series (2 vols), Dordrecht, Netherlands.

Bromley, R.G. & Ekdale, A.A. 1984. *Chondrites.* A trace fossil indicator of anoxia in sediments. *Science, 244,* 872-874. Bromley, R.G. & Ekdale, A.A. 1986. Flint and fabric in the European chalk. *In:* Steveking, G. de G. & Hart, M.B. (eds), *The scientific study of flint and chert.* Cambridge University Press, 70-82.

Carter, D.J. & Hart, M.B. 1977. Aspects of mid-Cretaceous stratigraphical -micropalaeontology. *Bulletin of the British Museum, Natural History, (Geology), London, 29,* 1-135.

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Clayton, C.J. 1986. The chemical environment of flint formation in Upper Cretaceous chalks. *In:* Steveking, G. de G. & Hart, M.B. (eds), *The scientific study of flint and chert.* Cambridge University Press, 43-54.

Curry, D. 1982. Differential preservation of foraminiferids in the English Upper Cretaceous - consequential observations. *In:* Banner, F.T. & Lord, A.R. (eds), *Aspects of Micropalaeontology,* George Allen & Unwin, London, 240-261.

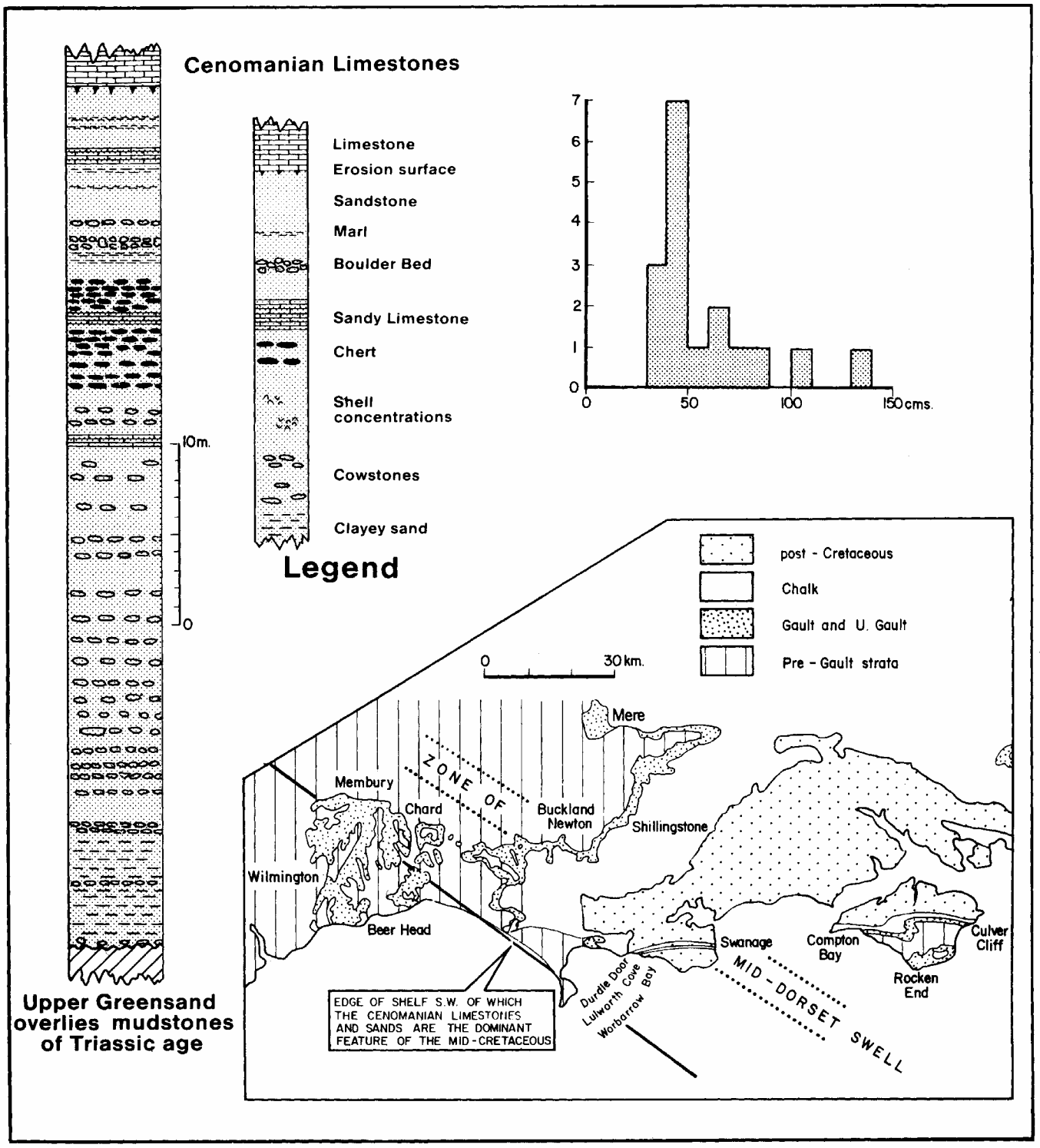


Figure 3. The Upper Greensand succession of the Branscombe-Beer Head section, S.E. Devon. The cherts are restricted to the middle of the succession and the histogram records the mid-chert to mid-chert spacing. The larger spacings (105 and 135 cms) are the result of storm events which must have dispersed the initial silica concentrations.

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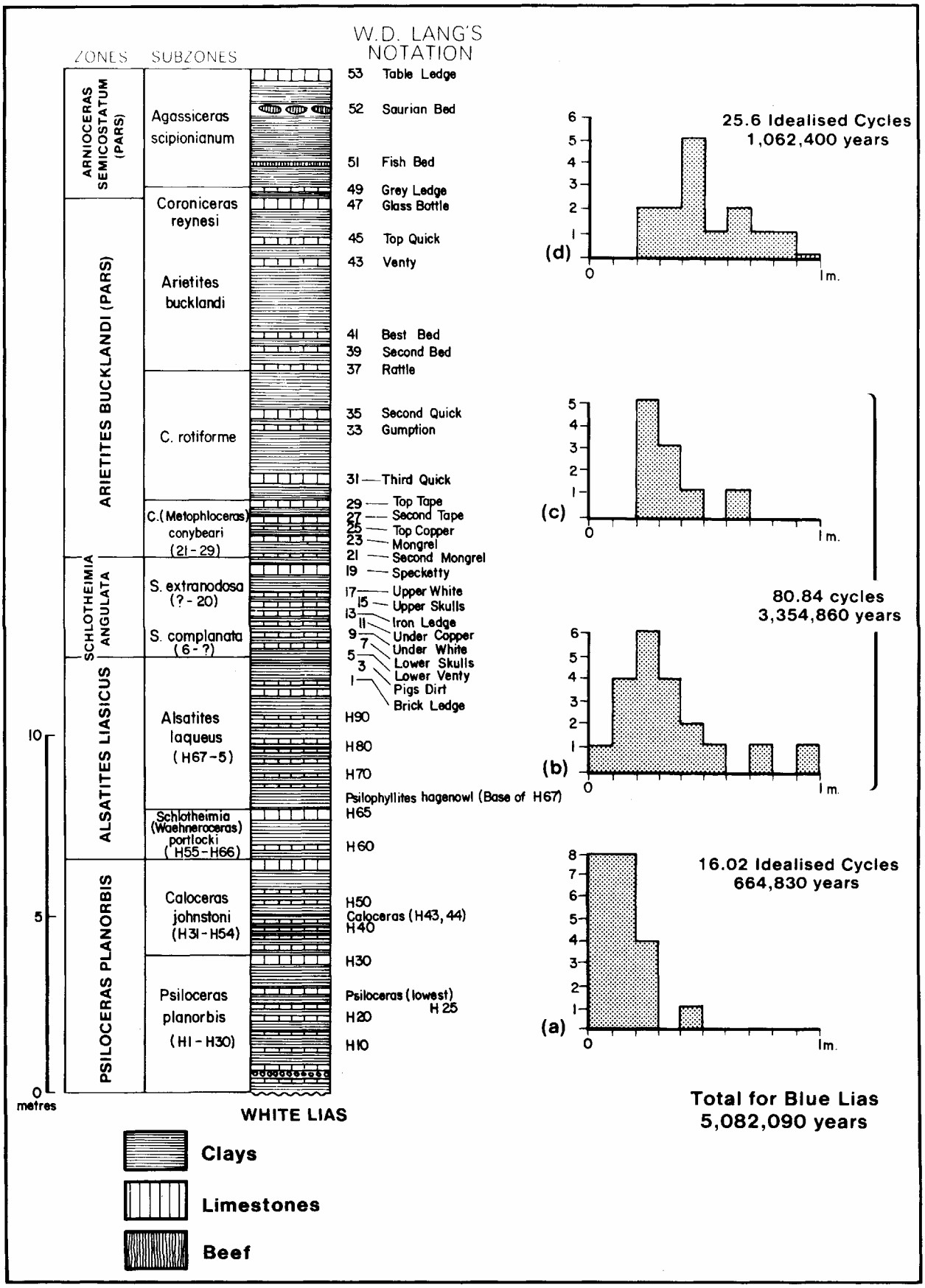


Figure 4. The Blue Lias succession on the Dorset coast west of the Cobb, Lyme Regis. Unit (a) embraces the *pre-planorbis* beds and the *P.planorbis* subzone, unit (b) the *C. johnstoni* to *A.laqueus* subzones, unit (c) the *S. angulata* zone and the lower two thirds of the *A.bucklandi* zone, while unit (d) represents the remainder of the succession. Hallam, A., Hancock, J.M., LaBrecque, J.L., Lowrie, W. & Channell, J.E.T.. 1985. Jurassic to Paleogene, Part 1. Jurassic and Cretaceous geochronology and Jurassic to Paleogene magnetostratigraphy. In: Snelling, N.J. (Ed.), The Chronology of the Geological Record Memoir 10, Geological Society of London, 118-140.

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Hancock, J.M. 1976. The petrology of the chalk. *Proceedings of the Geologists' Association, 86* (for 1975), 499-536.

Harland, W.B., Cox, A.V., Llewellyn, P.G., Pickton, C.A.G., Smith, A.G. & Walters, R. 1982. *A geologic time Scale,* Cambridge University Press, 13 lpp.

Hart, M.B., Bailey, H.W., Swiecicki, A. & Lakey, B.R. 1986. Upper Cretaceous flint meal faunas from Southern England. *In:* Sieveking, G. de G. & Hart, M.B. (eds), *The scientific study of flint and chert,* Cambridge University Press, 89-97.

Hart, M.B. & Swiecicki, A. 1987. Foraminifera of the chalk facies. *In:* Hart, M.B. (ed), The *Micropalaeontology of Carbonate Environments,* Horwood, Chichester, 121-137.

House, M.R. 1985. A new approach to an absolute timescale from measurements of orbital cycles and sedimentary micro-rhythms. *Nature, 315,* 721-725.

House, M.R. 1986. Are Jurassic sedimentary microrhythms due to orbital forcing? *Proceedings of the Ussher Society, 6,* 299-311.

Imbrie, J. 1985. A theoretical framework for the Pleistocene ice ages. *Journal of the Geological Society, 142,* 417-432. Kennedy, W.J. 1969. The correlation of the Lower Chalk of south-east England. *Proceedings of the Geologists' Association, 80,* 459-560,

Kennedy, W.J. &Garrison, R.E. 1975. Morphology and genesis of nodular chalks and hardgrounds in the Upper Cretaceous of southern England. *Sedimentology, 22,* 311-386.

Mortimore, R.N. 1986. Stratigraphy of the Upper Cretaceous White Chalk of Sussex. *Proceedings of the Geologists' Association,* 97 97-139.

Rawson, P.F., Curry, D., Dilley, F.C., Hancock, J.M., Kennedy, WJ., Neale, J.W. Wood, C.J. & Worssam, B.C. 1978. A correlation of Cretaceous rocks in the British Isles. *Special Report No. 9, Geological Society of London,* 70p.

Robinson, N.D. 1986a. Fining-upward microrhythms with basal scours in the Chalk of Kent and Surrey, England and their stratigraphic important. *Newsletters in Stratigraphy, 1Z* 21-28.

Robinson, N,D. 19861b. Lithostratigraphy of the Chalk Group of the North Downs, southeast England. *Proceedings of the Geologists' Association, 97* 141-170.

Weedon, G.P. 1985. Hemipelagic shelf sedimentation and climatic cycles: the basal Jurassic (Blue Lias) of South Britain. *Earth and Planetary Science Letters, 76,* 321-335.

Williams, C.L. 1986. The cherts of the Upper Greensand (Cretaceous) of south-east Devon. *In:* Sieveking, G. de G. & Hart, M.B. (eds), *The scientific study of flint and chert,* Cambridge University Press, 62-70.

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*Read at the Annual Conference of the Ussher Society, January 1987*

# Role of basinal brines in the genesis of polymetallic vein deposits, Kit Hill- Gunnislake area, SW England

T.J. SHEPHERD
R.C. SCRIVENER

Shepherd T.J., Scrivener R.C. 1987. Role of basinal brines in the genesis of polymetallic vein deposits, Kit Hill - Gunnislake area, SW England. *Proceedings of the Ussher Society,* 491-497.

A comparative fluid inclusion and REE study of the fluorite gangue from north-south trending Pb/Zn/Ag veins in the Tamar valley and east-west trending Cu/As/Sn veins in the Kit Hill-Gunnislake area reveals a remarkable chemical affinity between their respective mineralizing fluids. Salinity and temperature data for the former system demonstrate that the fluids are Na-Ca-C1 brines with a NaC 1 ?CaC 12 wt ratio of 1.2:1. Depositional conditions were more or less uniform throughout the Tamar valley and the fluids display a narrow compositional range (11-15 wt% NaC 1, 9-13 wt% CaC12) and an equally restricted temperature range (110-170°C). By comparison, fluorites from the east-west veins were deposited at much higher temperatures (215-305°C) from fluids showing a wide range in salinity (3-27 wt% NaC 1 equivs). Cryometric measurements show that the observed range is due to the mixing of a high salinity component containing 11 wt% NaC1 + 16 wt% CaC12 (NaC1/CaC12 wt ratio of 2:3) and a low salinity, less calcic component (4 wt% NaC1 equivs; NaC 1/CaC 12 wt ratio of 1:1) at more or less constant temperature. REE data show that the fluorites have similar REE abundances and define a common array when plotted according to their Tb/Ca and Tb/La atom ratios suggesting crystallization from the same parent solution. Fluorites from the higher temperature E-W veins are strongly depleted in Eu but are enriched in the heavier rare earths. By comparison, the lower temperature N-S vein fluorites show either weak negative or positive Eu anomalies implying Eu3+./Eu2+ redox changes or variation in the supply of Eu. All fluorites are depleted in the light rare earths. The cooler fluids are chemically similar to the North Pennine orefluids and post-Variscan fluorite/barite fluids of the Harz Mountains, which are considered to be highly evolved basinal brines. Thus the combined fluid inclusion/REE data support a hydrothermal model whereby the deposition of fluorite at temperatures in excess of 250° is a consequence of early, deep penetration of Na-Ca-C 1 brines into the E-W structures during the closing stages of mineral deposition, prior to the re-opening of pre-existing N-S structures. The fluorites record a hydrothermal continuum.

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## Introduction

For the SW England metallogenic province a general distinction is made between hydrothermal mineralization directly related to the emplacement of the Hercynian granites and hydrothermal mineralization of unknown age but unequivocal late post-magmatic origin. The former is represented by the swarms of quartz veins which follow the elongation of the underlying Cornubian batholith and display a close spatial relationship to the outcropping granites or inferred sub-surface ridges (Dines, 1956). These have an overall E-Wor NW-SE trend and carry significant quantities of Sn, W, Cu, Zn and As and are currently worked for Sn, Cu and W. In contrast. later hydrothermal events are characterised by Pb-Zn-Cu-F-Ba-U veins, known locally as 'cross courses', which trend N-S. Though less well developed the cross courses belong to an extensive system of cross faults and major fracture zones which are seen to cut, displace or terminate the E-W vein set in all areas of the province. Where the NS structures are mineralized, mineral deposition is clearly later than the E-W veins, Because of these apparent structural and mineralogical contrasts there is a tendency for them to be considered as separate events. Alderton (1978) drew attention to the marked differences in temperature and salinity of the ore fluids responsible for Pb-Sn ores associated with the two vein Sets and concluded that the cross course mineralization was of a different origin. However, as pointed out by Garnett (1966), prominent N-S structures existed during the formation of the NW-SE veins at the Geevor Mine, and exerted a strong control on the distribution and extent of cassiterite oreshoots. Pending reliable radiometric ages for the mineralization we seek to demonstrate here that fluids characteristic of the N-S veins were active during the middle to late stages of mineral deposition along E-W veins in the Kit Hill-Gunnislake area. This we interpret as evidence for a hydrothermal continuum and hence perhaps a greater genetic affinity. Preliminary REE patterns for the fluorite gangue are used to support this hypothesis.

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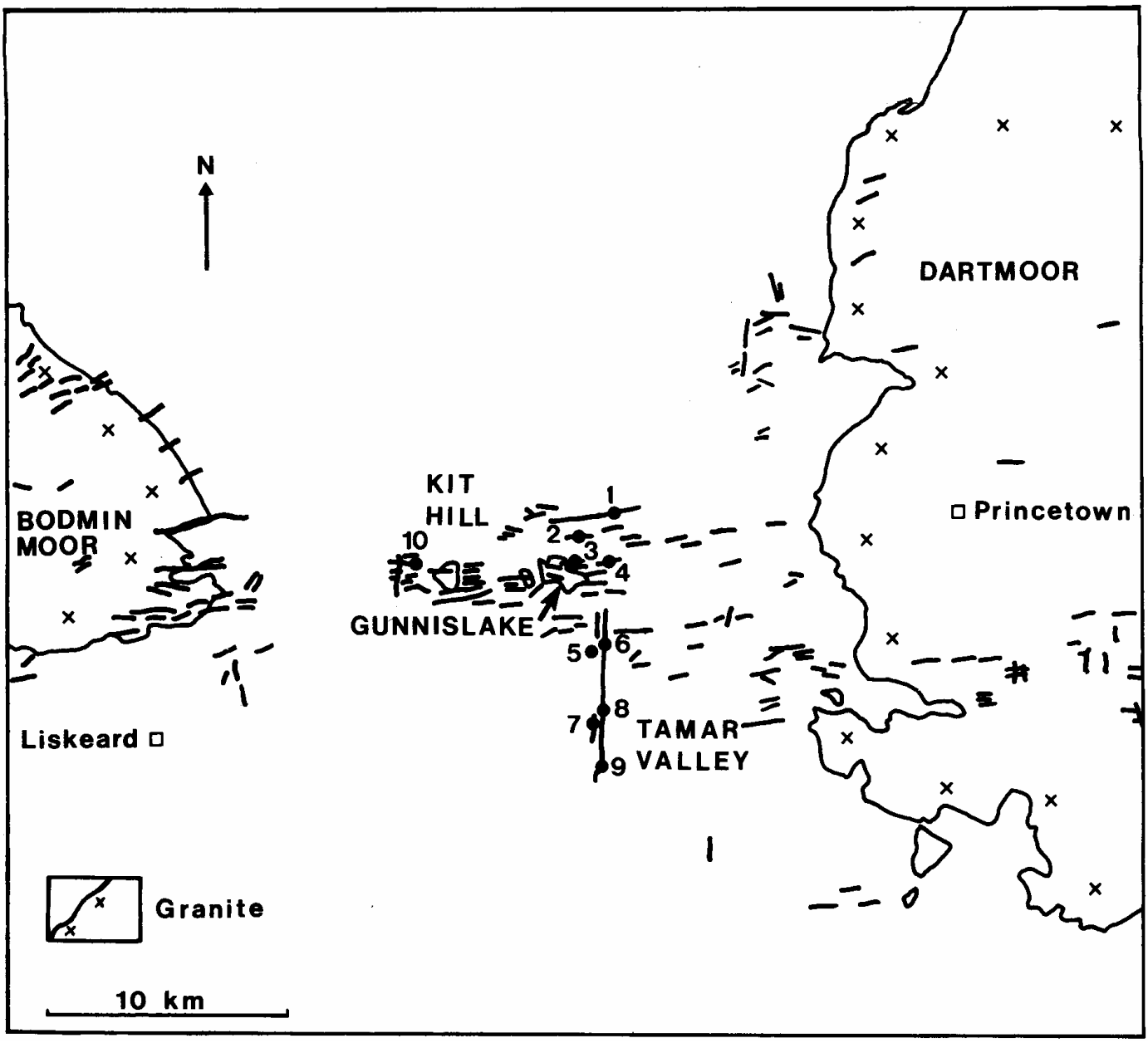


Figure 1. Outline geology of the Kit Hill-Gunnislake study area showing fluorite sample/mine locations. 1. Wheal Emma 2. Devon Great Consols 3. Old Gunnislake Mine 4. Wheal Crebor 5. Ward Mine 6. Buttspill Mine 7. North Hooe Mine 8. Lockridge Mine 9. South Tamar Mine.

## Geology and mineralization of the Kit Hill - Gunnislake area

The study area encloses the highly mineralized zone between the Dartmoor and Bodmin granites (Figure 1). Here the E-W vein systems are coincident with the small granite outcrops of Kit Hill, Gunnislake and Hingston Down which are interpreted as cupolas on a deeper E-W trending granite ridge (Edmonds and others, 1975). As well as granite, the host rocks comprise Middle to Upper Devonian slates, and locally limestones and mudstones with interbedded tuffs and lavas. Work by Bull (1982), supplemented by our own investigations, have shown that three major phases of ore deposition can be recognised, thought not necessarily in the same veins. Some of the complex parageneses reported arise from repeated opening and fracture infilling. After an early phase of wallrock tourmalinization adjacent to the fractures, the first major ore stage is quartz, chlo?ite, cassiterite, wolframite, arsenopyrite and pyrite. This is followed by the main polymetallic sulphide phase comprising quartz, fluorite, chlorite, pyrite, stannite, chalcopyrite, sphalerite, galena and minor arsenopyrite. The final phase is represented by an infilling of preexisting cavities and fractures by fluorite, siderite and minor Cu-Fe sulphides. Sequences involving an early oxide stage succeeded by one or more sulphide stages are typical of other mineralized areas in SW England (Moore and Jackson,

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1977; Jackson et al 1982) and many other Sn-W provinces (Rundquist, 1982). In the study area, chlorite-base metal sulphide assemblages predominate and there is only restricted development of tourmalini-zation with associated tin and iron oxides.

The N-S veins lie somewhat distant from the granite stocks and in the Kit Hill-Gunnislake area the best examples are in the Tamar Valley (Figure 1). Here two parallel veins, approximately 1.2 km apart, can be traced for a strike distance of 5 km. The main ore minerals are quartz, fluorite, calcite, sphalerite, pyrite and galena. East of the Dartmoor granite, barite replaces fluorite as the major spar mineral. To the north, the Tamar veins cut the Gunnislake Sn-W-Cu veins whilst to the south their extension is not known.

To permit a direct comparison between the two environments, fluorite was selected as the sampling medium because it is common to both vein sets, contains an abundance of fluid inclusions and carries a high concentration of REE. Where possible, in-situ sampling was adopted. Generally, lack of access to most mines meant that waste dumps provided the only available material. Samples analysed include, fluorite from Wheal Emma, Great Devon Consols, Crebor, Old Gunnislake, Holmbush, Buttspill, South Tamar, Lockridge, Ward and North Hooe mines.

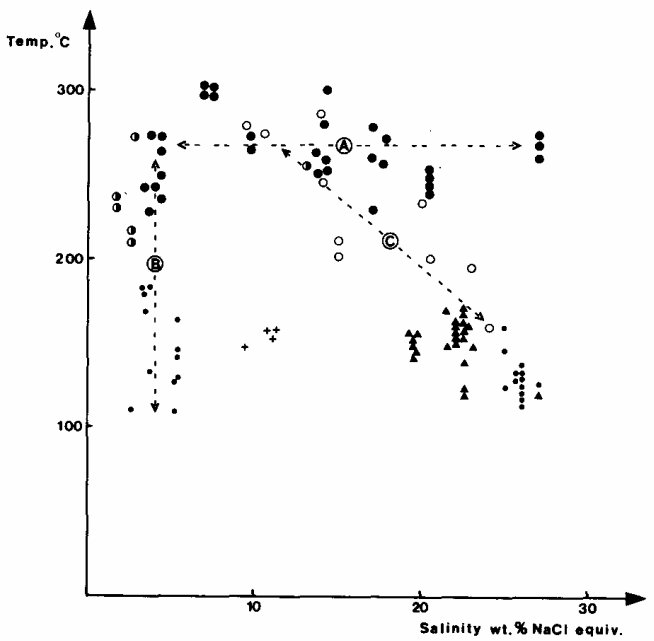


Figure 2. Variation in the temperature of homo-genization(TH) and salinity for inclusions in fluorite from the Kit Hill-Gunnislake area. Large filled circles = primary and psuedosecondary inclusions, E-W veins; small filled circles = secondary inclusions, E-W veins. Filled triangles = primary and psuedosecondary inclusions, N-S veins. Crosses = Holmbush fluorite. Large open circles = quartz-sulphide assemblages, E-W veins (data from Bull and Shepherd 1980). Large half-filled circles = quartz-spharelite assemblages, E-W veins (data from Alderton 1978). For trends A B C see text.

## Fluid inclusion studies

Without exception, the fluorites contain several generations of aqueous, two phase (liquid + vapour) inclusions. The most abundant inclusions occur along short, ell-healed, discontinuous fractures or in isolated groups. In the absence of obvious growth zoning, these are best described as pseudosecondary (PS); that is, intimately related to primary crystal growth but not necessarily confined to growth zones, Many contain a small opaque mineral or anisotropic daughter crystal. The second most abundant inclusions decorate well-defined, through-going fractures and are clearly secondary (S) in origin. These have significantly lower V/L ratios and do not contain daughter minerals. Thermometric results are shown in figures 2 and 3. Unless stated, salinities are reported as wt% NaC 1 equivalents, and temperatures as pressure uncorrected homogenisation temperatures (Th). All inclusions homogenise into the liquid state (L+V-)L.)

*(1) East-West veins*

For the E-W vein fluorites, two distinct fluids are present (Fig. 2); a high temperature fluid (215-305°C) with a wide and continuous range in salinity, and a lower temperature fluid (110-182°C) with marked salinity groupings at 4 and 26 wt% NaC1 equivalents. Since the low temperature fluid component is represented by secondary inclusions, it is realistic to assume that the fluorites were deposited under conditions given by the high temperature PS inclusions. Trend A shown in Figure 2 is interpreted as a mixing between a c. 4 wt% NaC 1 fluid and a c. 27 wt% NaC1 fluid at constant temperature (or thereabouts). In contrast, the constant composition trend (B) shown by the low salinity S inclusions is thought to represent a cooling of the low salinity end-member component with little or no mixing. Fluorite from the Holmbush Mine is an exception. This material is paragenetically later than the fluorite infill of other E-W veins (Bull and Shepherd 1980) and its mean salinity c. 10 wt% NaC 1 may be the result of localised mixing during the final stages of hydrothermal circulation within the E-W structures. Trend C is tentatively interpreted as the result of mixing between the two end-member components with time (i.e. it represents a time dependent cooling/mixing path).

First melting temperatures for the high salinity fluid are consistently less than *-55°C* and melting proceeds via ice and hydrohalite. Fluid compositions can therefore be modelled by the system $H_2O$-NaC1-$CaCl_2$ (eutectic temperature - 55°C). Occasionally, first melting is

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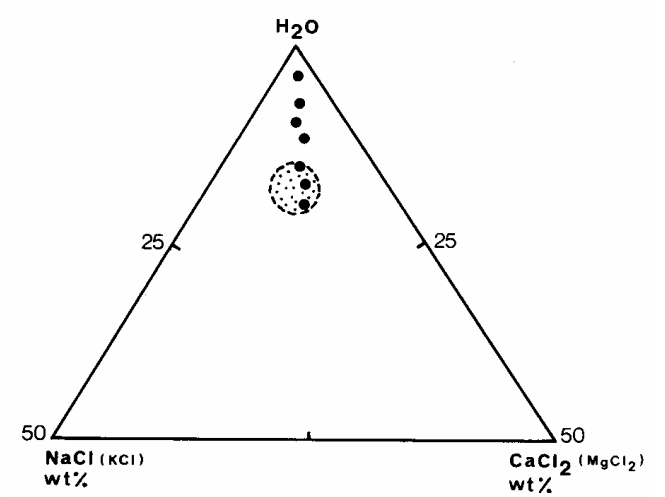


Figure 3. Ternary diagram $H_2O$-NaCl (+KC1)-$CaCl_2$ (+$MgCl_2$) showing the linear variation in fluid inclusion compositions for the E-W vein fluorites indicative of fluid mixing (see text). Also shown is the overall compositional field for inclusions in the N-S vein fluorites (stippled).

observed at -58°C. This suggests the presence of additional salts such as $MgCl_2$ and KCl, but their contribution to the total salt content cannot be estimated from the thermometric data alone. Hence we have adopted the expression 'NaCI+$CaCl_2$' equivalents where NaCl = NaCl+KCl and $CaC1_2$ = $CaCl_2$ + $MgCl_2$ since the melting characteristics are similar for each salt pair. When measuring low salinity inclusions, f'irst melting and hydrohalite melting are often difficult to recognise due to the small amount of liquid produced at the eutectic temperature. However, by using the melt-freeze-melt technique described by Shepherd, Rankin and Alderton (1985), reliable measurements were obtained for ttie larger, low salinity P and PS inclusions. Their melting characteristics demonstrate conclusively that these fluids likewise belong to the system $H_2O$-NaCl-$CaCl_2$. As seen in Figure 3, analyses for the E-W vein fluorites (filled circles) define a linear array towards the $H_2O$ apex, thus confirming the mixing trend A shown in Figure 3. Compositionally, the high salinity component contains the equivalent of 11 wt% NaC 1 + 16 wt% CaC12 (NaC1/$CaC1_2$ wt ratio of 2:3), whilst the low salinity component is less calcic (NaC1/$CaCl_2$ wt ratio of hi). The high salinity secondary inclusions are interpreted as an overprint of the later N-S fluids.

(ii) North-South veins

Fluids responsible for the deposition of fluorite in the N-S veins show no evidence of substantial fluid mixing and plot within a very restricted field on the Th-salinity diagram (110-170°C; 19-27 wt% NaC 1 equivs) (Figure 2). First melting temperatures are consistently less than -55ºC and melting proceeds via ice and hydrohalite. Both features signify the presence of $CaC1_2$. On average, the fluids contain the equivalent of 11-15 wt% NaC 1 and 9-13 wt% $CaC1_2$ (NaC1/$CaC1_2$ wt ratio of 1.1:1) See Figure 3, open circles). Though less calcic than for fluorite in the E-W veins, the difference is small. Moreover, the temperature range (110-170°(2) matches very closely that shown by secondary inclusions in the E-W veins, implying entrapment under similar thermal conditions or at the same time

## Rare earth element studies

REE data for the fluorites, obtained by ICP-emission spectroscopy (Walsh et al. 1981), are given in Table 1 and displayed as chondrite normalised plots in Figure 4. In chloride solutions, fluorite serves as an excellent linear amplifier of ore fluid REE patterns because the stability constants for the individual REE chloride complexes are more or less similar (Marchand et al. 1976). A detailed evaluation of REE variation is currently in progress but certain major features are already evident.

With the exception of those samples interpreted as remobilized (see below), fluorites from both vein sets show comparable ranges in total REE (50-200 ppm). This implies that REE transport was not controlled solely by the availability of chloride ligands (i.e. salinity). E-W vein fluorites display two patterns: those with significant negative Eu anomalies and mid-REE or HREE enrichment (Fig. 4a) and those with LREE enrichment and positive Eu anomalies (Fig. 4d). The N-S vein fluorite patterns are broadly similar, but differ in showing more pronounced mid-REE enrichment (Fig. 4b). However, Eu variation for the higher temperature E-W vein fluorites is unlikely to be due to changes in the Eu3+/Eu2+ ratio since at temperatures in excess of 250°C the more stable ion is Eu2+ (Sverjensky 1984). Compared to data for other British fluorites, the SW England samples have REE profiles with a strong sedimentary basin affinity. (Shepherd et al. 1982).

Using the Tb/Ca - Tb/La diagram defined by Moller and Parekh (1976) the fluorites plot well within the hydro-thermal field (Fig. 5). From this diagram it can also be seen that the N-S and E-W vein fluorites lie' along the same array; a vector ascribed by Moiler to primary crystallization from a parent solution. Samples which plot to the right of the main array (ie. T4, SW-82-1 and -2) are likewise ascribed to remobilization. This might explain their comparatively low REE contents and marked depletion in LREE (Fig. 4c).

The evidence provided by Figure 5 would suggest a common REE source, but no single fractionation mechanism or parent fluid can satisfactorily explain all the features illustrated, and pending further investigation a multiple REE source model is advocated.

## Discussion

Thermometric data for the N-S vein fluorites confirmthe temperatures and high salinities reported by Alderton (1978). The results differ in demonstrating that high

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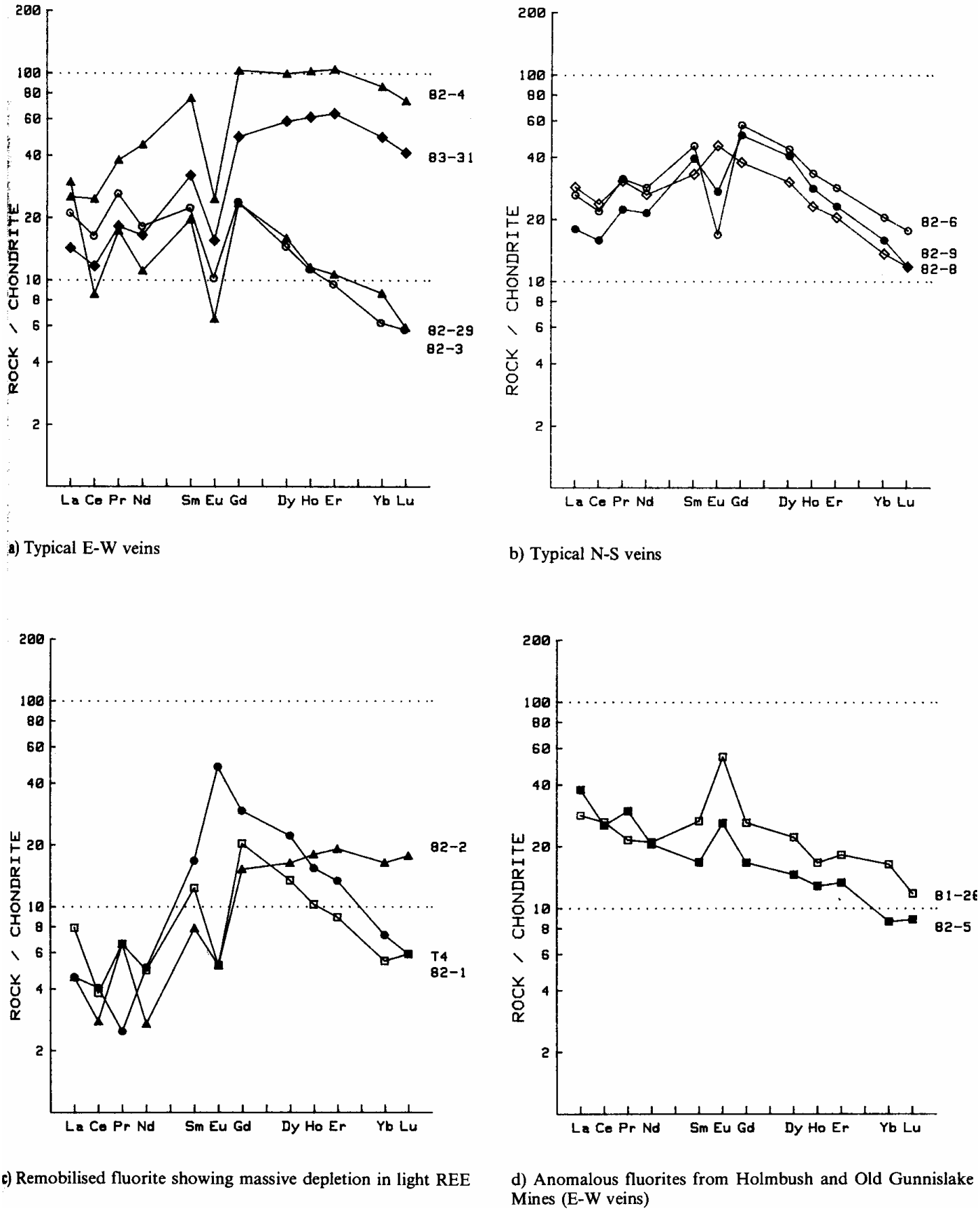


a) Typical E-W veins

b) Typical N-S veins

c) Remobilised fluorite showing massive depletion in light REE

d) Anomalous fluorites from Holmbush and Old Gunnislake Mines (E-W veins)

Figure 4. Chondrite normalised rare earth element patterns for the E-W and N-S vein fluorites.

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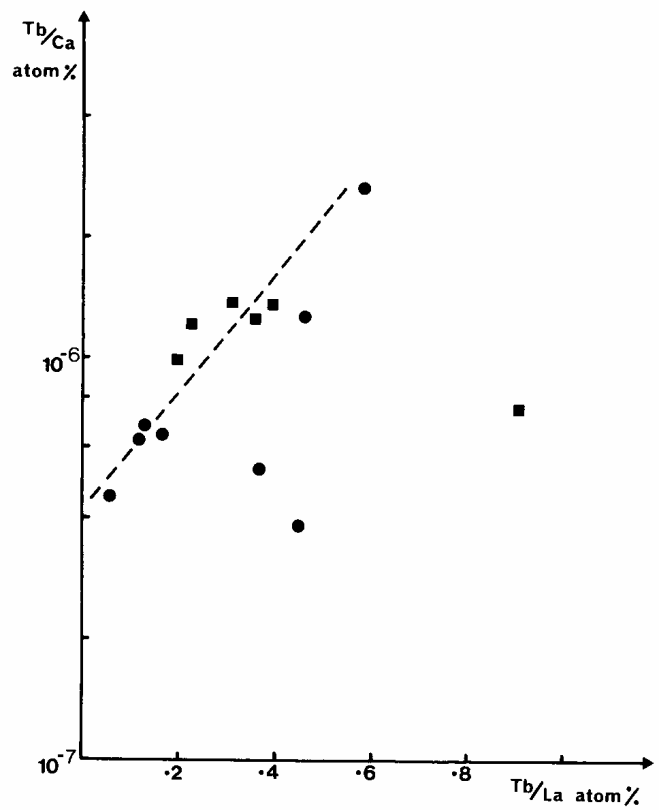


Figure 5. Tb/Ca-Tb/La covariance for the E-W and N-S vein fluorites (plot after Moller and Perekh 1976). Filled circles E-W veins, squares N-S veins.

salinity fluids were also present during the late to middle stages of mifieral deposition in the E-W veins. Furthermore, high homogenization temperatures for the E-W fluorites preclude any suggestion that the PS inclusions represent an overprint by later N-S vein fluids (i.e. secondary inclusions). The high salinity end-member component of the isothermal mixing trends shown in Figures 2 and 3 is compositionally distinctive and similar to those described by Jackson et al. (1982) for the quartz-cassiterite-sulphide-fluorite assemblages at Geevor Mine. However, the involvement of high salinity CaC 12 brines has probably been overlooked until now because at high dilution their detection is difficult. Close similarity in chemical composition between the E-W and N-S vein fluids, together with the apparent cooling/mixing trend (C) shown in Figure 2, suggests an early influx of Na-Ca-C 1 brines into the E-W structures during the second to third stages of mineral deposition. The N-S vein fluids show a strong chemical affinity with ore fluids associated with limestone-hosted fluorite deposits in the North Pennine orefield and post-Variscan fluorite/barite vein deposits of the Harz Mountains. The Pennine fluids are considered to be highly evolved formational brines (15 wt% NaC1 + 11 wt% CaC12; NaC1/CaC12 wt ratio of 1.3:1) expelled from adjacent Carboniferous and Permo-Triassic sedimentary basins during periods of rapid subsidence and extensional tectonics in the early Mesozoic (Shepherd et al. 1982, McKenzie 1978). In the Harz, the fluids are described as modified Na-Ca-C1 brines which penetrated the Variscan molasse from above and probably originated in Permian and Zechstein sediments (Behr and Gerler 1986 in press, Behr et al. 1984). The high NaCI content is presumed to have been derived by solution of Zechstein evaporites, whereas the high Ca content is thought to be the result of interaction with Permian feldspar-rich sediments. If the basinal origin is true for SW England, then the N-S fluorite fluids represent NaC 1-CaC 12 brines expelled from basins to the north and south of the structural 'high' formed by the Cornubian batholith. The more calcic character of the E-W vein fluids is more problematic. Possible explanations for the Ca-enrichment are firstly, cation exchange at elevated temperatures between basinal brines and plagioclase feldspars in the granites during deep fluid circulation and secondly, H+ ion metasomatism during wallrock alteration. The former mechanism is comparable to that proposed by Edmunds et al. (1984) to account for present-day saline groundwaters in the Carnmenellis Granite. Whereas the low temperature, high salinity S inclusions in fluorites from the E-W veins are probably an imprint of later 'cross course' mineralization, the corresponding low temperature, low salinity inclusions are thought to reflect a gradual waning of hydrothermal activity involving fluids of relatively shallow circulation.

Thus the timing of mineralization could be linked to a closure of the E-W fractures and a re-opening of preexisting N-S fractures following a change in the regional stress field at the end of the Carboniferous (Moore 1975). Having a N-S orientation, they would provide ideal channelways for fluids moving updip from adjacent basins. During the preceding period of Sn-W mineralisation, the dominant E-W fractures along the axis of the ridge would tend to tap higher level, low salinity, meteoric fluids. Accordingly, the deposition of fluorite in the E-W veins at temperatures in excess of 215°C is interpreted as a consequence of early, deep penetration of formational brines into the E-W fracture-controlled hydrothermal systems.

Recent geochronological studies (Halliday 1980, Darbyshire and Shepherd 1985) now cast doubt on the accepted close temporal relationship between the granites (as seen at outcrop) and mineralization. It would appear that main stage Sn-W mineralization could be 20 Ma younger than the associated host granite. This implies that both vein sets may be late post-magmatic with respect to their immediate granite hosts. [NB. the absolute age of N-S vein mineralization is still unknown.] Given the good agreement between fluid inclusion and REE data, there is now substantial evidence to suggest that the two systems without respect to fluorite constitute a hydrothermal continuum. Further support for the continuum hypothesis is provided by fluid inclusion studies of main stage sulphide ores in E-W veins of the Kit Hill-Gunnislake area (Shepherd et al. 1985). In the quartz gangue, a small

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proportion of PS inclusions have very low eutectics indicating an early involvement of CaC 12 brines. These are shown in Figure 3 and it is likely they would also plot along the mixing line shown in Figure 4.

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References

Alderton, D.H.M. 1978. Fluid inclusion data for lead-zinc ores from southwest England. *Transactions of the Institution of Mining and Metallurgy (Section B). 87,* B132-135.

Behr, H.J., Horn, E.E., Luders, V.. Reutel, Chr., 1984. Conclusions on the genesis of gangue mineralization of the Harz from the study of fluid inclusions. *Fortschrung Mineralogie, 62,* 18.

Behr, H.J. and Gerler, J., in press. Basinal brines as inclusions in post-Variscan mineralizations in the Federal Republic of Germany. *Chemical Geology.*

Bull, B.W. 1982. Geology and mineralization of an area around Tavistock south-west England. *Unpublished Ph.D. Thesis, University of Exeter.*

Bull, B.W. and Shepherd, T.J., 1980. Fluid inclusion study of mineralization in the Kit Hill-Gunnislake area, South West England. *Institute of Geological Sciences, Isotope Geology Unit Report Series 80/20.*

Darbyshire, D.P.F. and Shepherd, T.J. 1985. Chronology of granite magmatism and associated mineralization, S.W. England. *Journal of the Geological Society of London, 142,* 1159-1177.

Dines, H.G. 1956. The metalliferous mining region of southwest England. *Memoir of the Geological Survey of Great Britain.* H.M.S.O.

Edmonds, E.A., McKeown, M.C. and Williams, M. *1975. British Regional Geology, South West England* H.M.S.O. London.

Edmunds, W.M., Andrews, J.N., Burgress, W.G., Kay, R.L.F. and Lee, D.J. 1984. The evolution of saline and thermal waters in the Carnmenellis granite. *Mineralogical Magazine, 48, 407*-424.

Garnett, R.H.T., 1961. Structural control of mineralization in South-West England. *Mining Magazine, 105,* 329-337.

Halliday, A.N. t980. The timing of early and main stage ore mineralization in South West *Cornwall. Economic Geology, 75,* 752-759.

Jackson, N.J., Halliday, A.N., Sheppard, S.M.F. and Mitchell, J.G., 1982. Hydrothermal activity in the St. Just mining district, Cornwall. *In:* A.M. Evans (ed) *Metallization associated with acid magmatism.* Wiley, New York, 137-179.

Marchand, L., Joseph, D., Touray, J.C. and Treuil, M. 1976. Criteres d'analyse geochimique des gisements de fluorine bases sur retude de la distribution des lanthanides: application au gite du Maine (71-Cordesse, France). *MineraliaDeposita, 11,* 357-379.

McKenzie, D.. 1978. Some remarks on the development of sedimentary basins. *Earth and Planetary Science Letters, 40,* 25-32.

Moiler, P. and Parekh, P.P. 1976. Fractionation of the rare-earth elements as a geochemical indicator of fluorspar genesis. *International Symposium of Analytical Chemistry in Exploration, Mining and Processing of Materials (Symposium Proceedings Johannesburg 1976).* IUPAC, Johannesburg 1976, Extended Abstract, No. 107.

Moore, J.McM., 1975. A mechanical interpretation of the vein and dyke'systems of the SW England orefield. *Mineralium Deposita, 10,* 374-388.

Moore. J. McM. and Jackson, N.J., 1977. Structure and mineralization in the Cligga granite stock Cornwall. *Journal of Geological Society, London, 133,* 467-480.

Rundquist, D.V. 1982. Zoning of metallisation associated with acid magmatism. *In:* A.M. Evans (ed). *Metallization associated with acid magmatism.* Wiley, New York, 279-289.

Shepherd, T.J., Darbyshire, D.P.F., Moore, G.R. and Greenwood. D.A., 1982. Rare earth element and isotopic geochemistry of the North Pennine ore deposits. *Bulletin Bureau Recherche Geologique et Minieres, 4,* 371-377.

Shepherd, T.J., Miller, M.F., Scrivener, R.C., Darbyshire, D.P.F.. 1985. Hydrothermal fluid evolution in relation to mineralization in southwest England with special reference to the Dartmoor-Bodmin area. *In:* Halls, C. (ed). *High heat production (ttHP) granites, hydrothermal circulation and ore genesis.* Special conference issue, Institution of Mining and Metallurgy, St. Austell, England, 203-212.

Shepherd, T.J., Rankin, A.H and Alderton, D.H.M. 1985. A *practical guide to fiuM inclusion studies.* Blackie, Glasgow. Sverjensky, D.A. 1984. Europium redox equilibria in aqueous solution. *Earth and Planetary Science Letters, 67,* 70-78.

Walsh, J.N., Buckley, F. and Barker, J. 1981. The simultaneous determination of the rare-earth elements in rocks using inductively coupled plasma source spectrometry. *Chemical Geology, 33,* 141-153.

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*Read at the Annual Conference of the Ussher Society, January 1987*

# The evolution of the Northern Igneous Complex of Guernsey, Channel Islands - some isotopic evidence

R.S. D'LEMOS

D'Lemos, R.S. 1987. The evolution of the Northern Igneous Complex of Guernsey, Channel Islands - some isotopic evidence. *Proceedings of the Ussher Society 6,* 498-501.

The northern part of Guernsey comprises an igneous complex which has been interpreted as forming during the later part of the Cadomian Orogeny. Field relationships within the Northern Igneous Complex indicate that the Cobo Granite and the Bordeaux Diorite are contemporaneous and older than the L'Ancresse Granodiorite. A new Rb/Sr whole-rock isochron of 496 $\pm$13 Ma has been obtained for the Cobo Granite. The new data provides a younger age than previously supposed for a large part of the Cadomian igneous activity on Guernsey. Such a young age, when considered in conjunction with other recent isotopic studies, points to an important period of Cadomian magmatic activity within the North Armorican Massif after 550 Ma.

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## Introduction

Within the North Armorican Massif an Upper Proterozoic supracmstal volcanic-sedimentary sequence, the Brioverian, and the underlying crystalline basement, the Pentevrian, were deformed during the Cadomian Orogeny. A number of late- to post- tectonic igneous bodies were emplaced into the Brioverlan and Pentevrian units during the latter part of this orogeny. Until recently, regional syntheses *(eg* Roach 1977, Vidal *et al.* 1981) have envisaged Cadomian magmatism as being concentrated between 650 and 490 Ma. The coastline of Guernsey affords excellent exposure of a Cadomian igneous complex which is intrusive into Pentevrian basement (Roach 1966, Roach *et al. in* press). New Rb-Sr whole rock isochron evidence is presented here concerning one part of that complex, the Cobo Granite. Taken in conjunction with detailed field, petrographic and geochemical data for part of this complex, this evidence points to a younger age than previously supposed for the Cadomian magmatic activity on Guernsey and has implications for the overall understanding of the late Proterozoic to early Palaeozoic evolution of the North Armorican Massif.

## Geological and geochronological background

NOTE: Previously published age dates (given in brackets) have been recalculated from original data using a decay constant of $\lambda^{87}Rb = 1.42 \times 10^{-11}.a^{-1}$ (Steiger and Jager 1977). K/Ar ages recalculated from original data do not differ significantly from original dates quoted here.

The geology of Guerusey (Fig. 1) has been the subject of a number of investigations, prominent amongst which are the thesis works of Roach (1957) and Drysdall (1957) concerning the Southern Metamorphic Complex and Northern Igneous Complex respectively. Summaries of the geology of Guernsey are given by Roach (1966) and Roach *et al. (in* press). Adams (1967, 1976) provided the first Rb/Sr ages and geochronological framework for the evolution of parts of the North Armorican Massif which included data from Guernsey. Later, Calvez and Vidal (1978) reported U/Pb zircon ages of 2018 $\pm$ 15 Ma from basement (Icart) gneiss (Fig. 1). Although Adams considered the Perelle Gneiss (Fig. 1) to be broadly the same age as the Icart Gneiss, recent isotopic studies indicate a very much younger (approximately 700 Ma) age for the Perelle Gneiss (N. Wilson, personal communication). From a consideration of field relationships Roach (1977) argued that a four-point, combined mineral/whole-rock isochron (Adams 1967, 1976) of 598 (660 +- 25) Ma for the L'Eree Granite (Fig. 1) placed an older limit on Cadomian igneous activity in the north of the island. A five-point combined mineral/whole-rock isochron age of 535 (570 $\pm$15) Ma for the Cobo Granite was believed to Set a younger age limit to Cadomian igneous activity on the Island (Roach 1977).

## Analytical method and results

Following detailed field, petrographic and geochemical investigations, a subset of eight samplea (each weighing 3-5kg) was chosen for investigation by the Rb/Sr whole-rock isochron method in an attempt to gain an accurate age for the Cobo Granite. Age determinations were carried out at the British Geological Survey, London, using a combination of X-ray fluorescence spectrometry (Phillips PWI540) and mass spectrometry (Micromass

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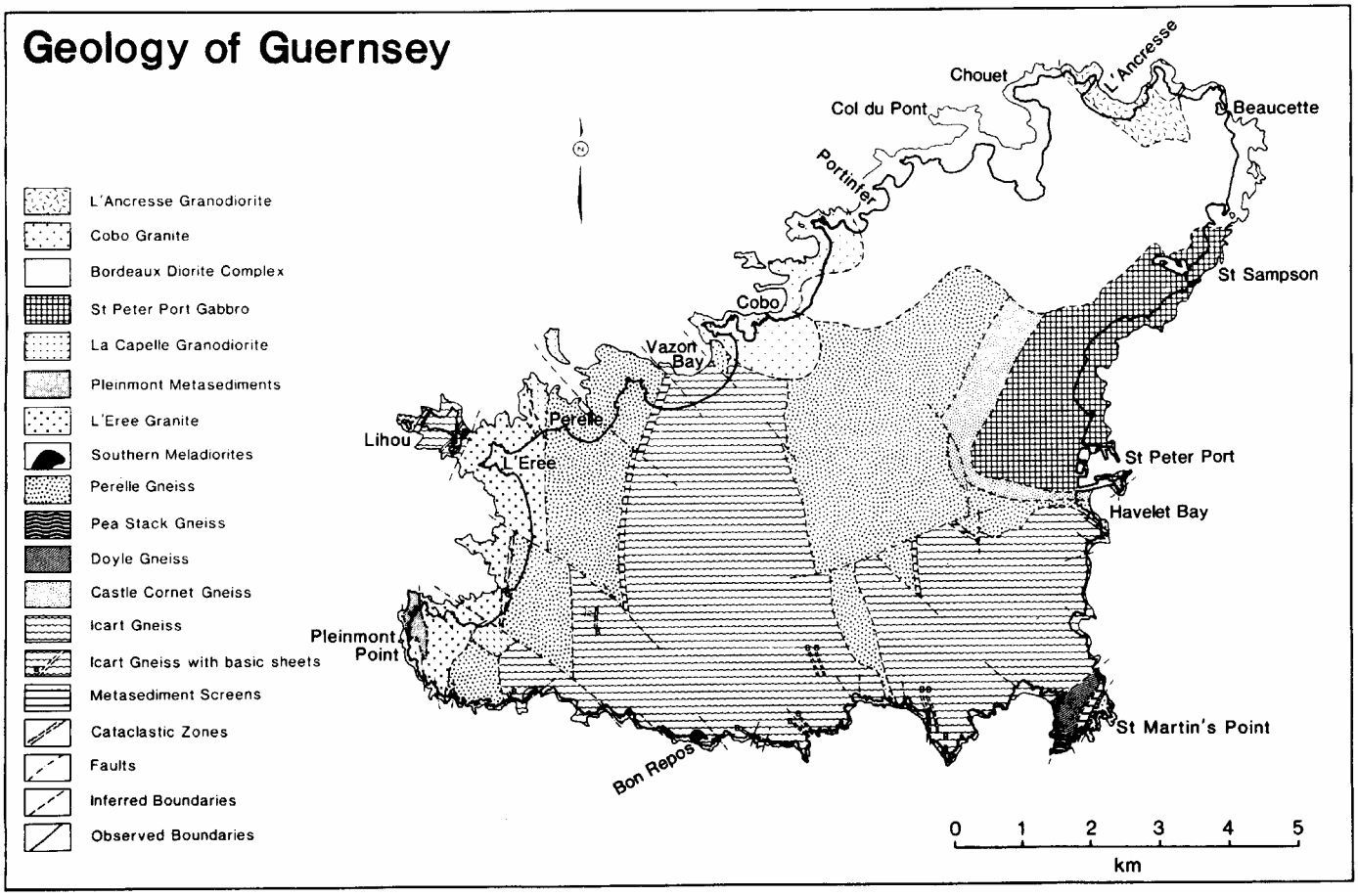


Figure 1. The geology of Guernsey (after Roach *et al.* in press).

30) utilising appropriate standards and instrumentcorrections (see Pankhurst and O'Nions 1973 and alsoDarbyshire and Sheppard 1985). Analytical uncertain-ties are estimated at 0.02% for $^{87}Sr/^{86}Sr$ and 1.0% for$^{87}Rb/^{86}Sr$. The decay constant used in the age calculationwas λ STRb = 1.42 x 10-11.a-1 (Steiger and Jager 1977).Regression lines were calculated from the data using theleast squares fit method of York (1969) and a measure ofthe fit of the data to the line calculated by the mean square of weighted deviates method of Brooks *et al.* (1972). An MSWD of 3.0 was taken as an upper limit for the acceptance of the line as an isochron.

Table 1 gives the abundances of rubidium and strontium and $^{87}Sr/^{86}Sr$ ratios. Figure 2 is an isochron plot of the data. The data defines an isochron (MSWD = 2.2) which gives an age of 496 ± 13 Ma with an initial strontium ratio of 0.7098 ± 0.00077.

## Interpretation of results

Field and petrographic evidence has established that the Cobo Granite has not undergone metamorphism. Geochemical investigation has shown that other than at its margins, the Cobo Granite apparently behaved as a closed system. Although an MSWD of less than 3 is not proof of the geological meaningfulness of an isochron (see for example Darbyshire and Sheppard 1985), it does,

| Sample No. | Rb ppm | Sr ppm | Rb/Sr At | $^{87}Sr/^{86}Sr$ |
|---|---|---|---|---|
| RDL 3 | 121.6 | 90.45 | 1.37832 | 0.7376 |
| RDL 4 | 122.77 | 67.39 | 1.86478 | 0.74691 |
| RDL 5 | 130.44 | 106.68 | 1.25344 | 0.73512 |
| RDL 7 | 131.88 | 88.5 | 1.52776 | 0.74032 |
| RDL 9 | 136.7 | 85.64 | 1.63466 | 0.7425 |
| RDL 14 | 134.36 | 105.33 | 1.30781 | 0.73584 |
| RDL 16 | 125.28 | 110.03 | 1.16728 | 0.7328 |
| RDL 40 | 132.24 | 80.62 | 1.68174 | 0.74338 |

Table 1. Rubidium and strontium concentrations and strontium isotope ratios for eight specimens of Cobo Granite.

nonetheless, point to the possibility of closed system behaviour, The difficulty in producing an isochron without error is attributed to a combination of instrument imprecision, the fairly limited range in Rb/Sr ratios in the Cobo Granite (a reflection on its homogeneity), and possibly to alteration of samples.

In the absence of strong evidence to the contrary and because of the likelihood of closed system behaviour, the isochron is interpreted as representing the emplacement age of the Cobo granite.

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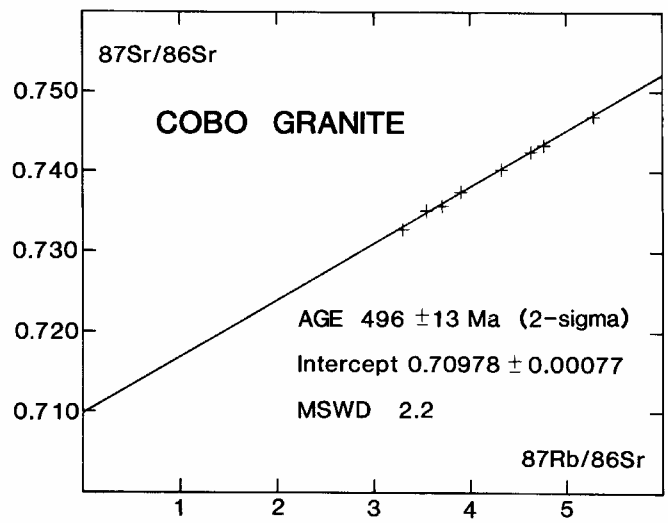

Figure 2. Rb/Sr whole rock isotope plot for the Cobo Granite.

## Implications of age

Field relationships exhibited at the margins of the Cobo Granite show that it was emplaced into the BOrdeaux Diorite Complex (Fig. 2) prior to the consolidation of the diorite magma (D'Lemos 1986). Supportive evidence for this hypothesis has been provided by detailed petrographical and geochemical studies (D'Lemos in prep). Such evidence includes the recognition of chill textures in mafic enclaves, and the occurrence of the Granite/Diorite Marginal Facies (D'Lemos 1986). This rock type, which is transitional between the Cobo Granite and the Bordeaux Diorite Complex, contains mafic xenocrysts in a granitic matrix, exhibits geochemical mixing trends, and is interpreted as forming during magma/magma interaction (D'Lemos in prep). This being the case, the emplacement age for the Cobo Granite also provides the age of the contemporaneous Bordeaux Diorite Complex which is itself composition-ally unfavourable for Rb/Sr isochron studies. The Bordeaux Diorite Complex in turn comprises a number of igneous rocks some of which exhibit evidence of contemporaneous localised mobility (Topley et al. 1982). The new age therefore dates a period of considerable magmatism in Northern Guernsey. Additionally, the age gives an older limit for the emplacement of the L'Ancresse Granodiorite (Fig. 1) since field relationships show that this body clearly post-dates the formation of the Bordeaux Diorite Complex (Roach et al. in press). Attempts to establish a precise age for the emplacement of the L'Ancresse Granodiorite by the Rb/Sr whole-rock isochron method have been unsuccessful (author's unpublished work). On the basis of field relationships it has been established that the St Peter Port Gabbro (Fig. 1) was the earliest of the post-deformational Cadomian intrusions on Guernsey (Roach et al. in press). The true age of this intrusion remains unresolved, the new evidence provides only a youngest possible age limit.

In summary the new age for the Cobo Granite dates an important period of magmatism in northem Guernsey at around 500 Ma.

## Comparison with previous work

The age of the Cobo Granite determined by Adams (1967, 1976) differs from that presented here. This is most probably explained by insufficient sampling on the part of Adams (the isochron is based upon only five data points and is strongly controlled by two mineral analyses) and analytical imprecision. Adams (1967) also provided a number of K/Ar mineral ages for dioritic members of the Bordeaux Diorite Complex. Three hornblende analyses give ages of 495 ± 14, 504 ± 14, and 510± 14Ma, which are broadly concordant with the Rb/Sr whole-rock age determined for the Cobo Granite by this study. A K/Ar biotite age of 545 ± 14 Ma from the Diorite must be questioned because of the low potassium content (1.25 wt%) of the sample. Two K/Ar mineral analyses for biotites from the L'Ancresse Granodiorite (Adams op cio of 542 ± 14 and 548 ± 14 Ma are difficult to reconcile with the new data. Biotite alteration, which is widespread within the L'Ancresse Granodiorite, might provide one possible explanation, whilst the difficulty in producing a Rb/Sr isochron for this rock-type (author's unpublished data) might reflect open system behaviour either during consolidation or at a later date, which might have upset the mineral ages.

## Implication for regional evolution

The present work shows that a major period of Cadomian magmatism on Guernsey occurred at around 500 Ma. On a regional scale, the Northern Igneous Complex can be broadly correlated with similar igneous complexes occurring on Jersey and at La Hague, France (Roach 1977). Recently, Bland (1985) provided whole-rock Rb/Sr isochron age dates for the various components of the South-West Granite Complex of Jersey of 550 + 12 Ma (porphyritic granite), 527 + 13 Ma (microgranite) and 483 + 13 Ma (coarse granite), and for the North-West Granite Complex of Jersey of 465 + 10 Ma (porphyritic granite), 438 + 17 Ma (coarse granite) and 426 + 14 Ma (red granite). Rb/Sr whole-rock investigations currently being undertaken for rocks from La Hague (author's unpublished data) also indicate ages for post-tectonic Cadomian magmatism younger than 550 Ma.

The ages of late- to post-tectonic Cadomian magmatism given above are in broad agreement with recently published data from the St Malo Migmatite Belt. Peucat (1986) has interpreted a Rb/Sr whole-rock age of 542 + 62 Ma and a U/Pb zircon age of 536 + 14 Ma from anatectic granites within the migmatite belt as recording a Cadomian metamorphic climax.

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## Conclusions

A whole-rock Rb/Sr isochron of 496 13 Ma provides an emplacement age not only for the Cobo Granite but also for the contemporaneous Bordeaux Diorite Complex and an older age limit for the L'Ancresse Granodiorite. This is a younger age than previously supposed for a large proportion of late Cadomian igneous activity on Guernsey. The age is in general agreement with recent geochronological investigations for similar late Cadomian igneous complexes on Jersey and at La Hague, and with an interpreted age of Cadomian metamorphism from the St Malo M igmatite Belt. In the light of emerging isotopic evidence, early geochronological frameworks (ie Adams 1967, 1976) for the evolution of the North Armorican Massif should be treated with some caution. A detailed evolutionary model for Cadomian events within the North Armorican Massif cannot be achieved until further accurate age data is forthcoming.

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## References

Adams, C.J.D. 1967. A geochronological and related isotopic study of rocks from north-western France and the Channel Islands (United Kingdom). *Unpublished PhD. thesis, University of Oxford.*

Adams, C.J.D. 1976. Geochronology of the Channel Islands and adjacent French mainland. *Journal of the Geological Society of London, 132,* 233-250.

Bland, A.M. 1985. The geology of the granites of western Jersey, with particular reference to the South-West Granite Complex. *Unpublished PhD thesis CNAA, (Oxford Polytechnic).*

Brooks, C., Hart, S.R. and Wendt, I. 1972. Realistic use of two error regression treatment as applied to rubidium - strontium data. *Review of Geophysics and Space Physics, 10.* 551-557.

Calvez, J.Y. and Vidal, P.H. 1987. Two Billion Years Old Relicts in the Hercynican Belt of Western Europe. *Contributions to Mineralogy and Petrology, 65,* 395-399.

Darbyshire, D.P.F. and Sheppard, T.J. 1985. Chronology of granite magmatism and associated mineralization, SW England. *Journal of the Geological Society of London, 142,* 1159-1177.

D'Lemos, R.S. 1986. Interaction between co-existing magmas: field evidence from the Cobo Granite and the Bordeaux Diorite Complex, north-west Guernsey, Channel Islands. *Proceedings of the Ussher Society, 6.* 323-329.

Pankhurst, R.J. and O'Nions, R.K. 1973. Determination of Rb/Sr and S*Sr/S6Sr ratios of some standard rocks and evaluation of X-ray Fluorescence Spectrometry in Rb-Sr Geochemistry. *Chemical Geology, 12,* 127-136.

Peucat, J.J. 1986. Behaviour of Rb-Sr whole-rock and U-Pb zircon systems during partial melting as shown in migmatite gneisses from the St Malo Massif, N.E. Brittany, France. *Journal of the Geological Society of London, 143.* 875-885.

Roach, R.A. 1966. Outline and guide to the geology of Guernsey. *Transactions of the Société Guernsiaise, l 7,* 751-776.

Roach, R.A. 1977. A review of the Precambrian rocks of the British Variscides and their relationships with the Precambrian of N.W. France. *In: La chain varisque ti'Europe moyenne et occidentale. Colloque International du Centre National de la Recherche Scientifique.* No 243, 61-79.

Roach. R.A., Topley, C.G.. Bland, A.M.. Brown, M. and D'Lemos, R.S. *in press.* An Outline and Guide to the Geology of Guernsey. Roedder Publications. London 2 vols.

Steiger, R.H. and Jager, E. 1977. Subcommision on geo-chronology; convention on the use of decay constants in geo- and cosmo-chronology. *Earth and Planetary Science Letters, 36.* 359-362.

Topley, C.G., Brown. M. and Power. G.M. 1982. Interpretation of field relationships of Diorites and associated rocks with particular reference to northwest Guernsey, C.I. *Geological Journal, 17,* 323-343.

Vidal, P., Auvray, B., Charlot, R. and Cogne, J. 1981. Pre-cadomian relicts in the Armorican Massif: their age and role in the evolution of the western and central European Cadomian -Hercynian belt. *Precambrian Research, 14.* 1-20.

York, D. 1969. Least squares fitting of a straight line with correlated errors. *Earth and Planetary Science Letters, 5.* 320-324.

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*Read at the Annual Conference of the Ussher Society, January 1987.*

# The Vazon Dyke Swarm, Guernsey, Channel Islands.

G.J. LEES
R.A. ROACH

Lees, G.J. and Roach, R.A. 1987. The Vazon Dyke Swarm, Guernsey, Channel Islands. *Proceedings of the Ussher Society, 6,* 502-509.

The Pentewian basement gneisses and schists of southern Guernsey are cut by a swarm of basic dykes which was emplaced prior to the main episode of late Precambrian Cadomian metamorphism and deformation. This suite of minor intrusions is termed the Vazon Dyke Swarm. As a result of the Cadomian event, the dolerites were metamorphosed within the low to middle greens chist facies and heterogeneously deformed. The swarm was emplaced prior to the development of the late Cadomian plutonic complex in northern Guernsey.

Chemically, the Vazon dykes are a series of well-evolved basalts and basaltic-andesites, generally subalkaline and tholeiitic in character. Moderate incompatible element enrichments are consistent with those of continental flood basalts.

The Vazon Dyke Swarm is tentatively correlated with the Hillion-Erquy Volcanic Formation - a suite of basaltic eruptives of early Brioverian age found in the region of the Bale de St Brienc, N. Brittany.

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## Introduction

Guernsey, is composed of metamorphic and plutonic igneous rocks ranging in age from early Proterozoic to early Palaeozoic. These rocks have been little affected by the Hercynian orogeny. The geology of the island can be divided into two parts; the Southern Metamorphic Complex and the Northern Igneous Complex (Roach 1966) (Fig. 1). The southern complex is composed largely of granitic and quartz-dioritic orthogneisses with minor metasediments (Roach 1957). These have been equated with the pre-Brioverian, Pentevrian basement complexes of north Brittany and Lower (western) Normandy (Graindor 1961; Adams, 1976; Roach 1977; Calvez and Vidal 1978) upon which the late Precambrian Brioverian supracrnstal sequence was deposited (Cogné, 1959, Roach *et al.* 1986). The southwest part of the metamorphic complex is formed by the weakly foliated L'Erée granite and the closely related Capelle grano-diorite, both of which may be either late components of the Pentevrian basement or early Cadomian plutons (Roach *et al.* in press). The northern part of the island is composed entirely of a late Cadomian celt-alkaline plutonic complex (Roach *et al. in* press) (Table 1).

The Southern Metamorphic Complex is cut by a large number of minor, generally dyke-like intrusions related to periods of magmatism both pre-dating and postdating the late Precambrian main deformation and greenschist facies metamorphic episode of the Cadomian orogeny (Roach 1977). In contrast, the Northern Igneous Complex, which post-dates the main Cadomian deformation and metamorphism, is cut by relatively few minor intrusions.

This paper is concerned with a major suite of dykes of basalt to basaltic-andesite composition, here termed the Vazon dykes, Which were emplaced into the Pentevrian basement complex of southern Guernsey prior to the main Cadomian deformation and metamorphism and therefore pre-date the formation of the Northern Igneous Complex (Table 1).

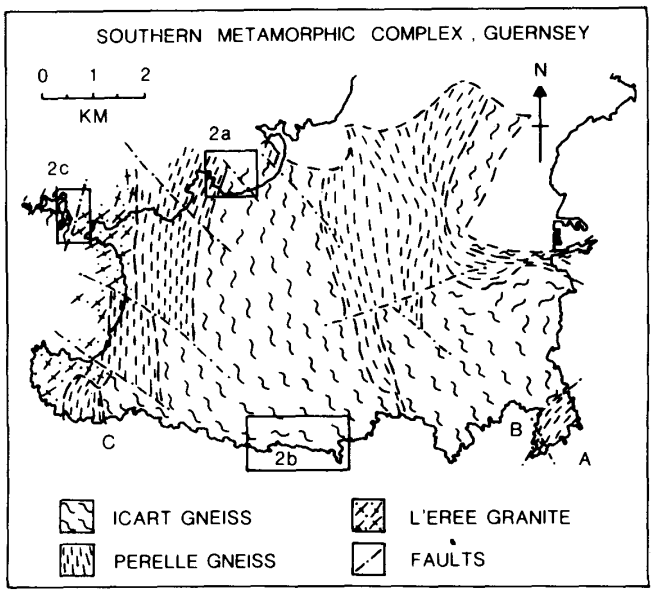


Figure 1. Simplified geological map of the Southern Metamorphic Complex, Guernsey, showing the distribution of units. Locations indicated are: A, Jerbourg Point; B, Moulin Huet Bay; C, Belle Elizabeth. Boxes marked 2a, 2b, 2c, are locations for the detailed maps of Fig. 2.

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**Dyke Chronology on Guernsey**

| Minor Intrusive Sequence | Age | Other Events |
|---|---|---|
| Lamprophyre dykes | Late Carboniferous -early Permian (?) | Faulting during the Hercynian orogeny |
| Albite dolerite dykes (Perelle-type). | Devonian-early Carboniferous (?) | |
| Microdiorite dykes and associated dolerites | End Precambrian -Cambrian | Emplacement of N. Igneous Complex and post-main phase Cadomian metamorphism and deformation |
| Cadomian | | |
| | Post-600 m.y. | Main Cadomian metamorphism and deformation |
| Metadolerite dyke swarm (Vazon-type) | Brioverian depositional cycle. Post-650 m.y. | Deposition of Pleinmont Sediment and emplacement of L'Erée Granite. Stratigraphical position of latter is unclear |
| Meladiorite intrusions (Bon Repos-type) | | |
| | Pentevrian Basement | |
| | | Formation of Perelle and Doyle quartz diorite gneisses |
| | 2,000-650 m.y. | |
| Amphibolite sheets | | Formation of Icart, Castle Cornet, and Pea Stack granitic gneisses |
| Concordant hornblende schist bands. Product of contemporaneous volcanism? | Pre-2,000 m.y. | Deposition of epiclastic sediments. |

Table 1 Dyke chronology in Guernsey, with respect to episodes of deformation and metamorphism.

Ansted and Latham (1862) first commented on the abundance of basic dykes in southern Guernsey. Further brief descriptions are given by Hill and Bonney (1884), Bonney and Hill (1912), Farquaharson (1924), Plymen (1933), and Roach (1957). Roach (1966) introduced the term Vazon-type dolerite dykes and showed them both to post-date the Bon Repos-type meladiorites and to predate emplacement of the Northern Igneous Complex (Table 1). Roach *(op. cit.)* distinguished these dykes from a suite of microgabbros cropping out along Moulin Huet Bay in southeast Guernsey. However, the latter are here regarded as simply a coarser variant of the common Vazon dykes.

## Field Occurrence

The Vazon Dyke Swarm is named after the occurrence of numerous, now metamorphosed, basic dykes, which crop out along the west side of Vazon Bay, west Guernsey, where they intrude the Perelle quartz diorite and the Icart granite orthogneisses (Fig. 2a). Representatives of this dyke swarm cut all the orthogneisses and schistose metasediments which form the Pentevrian basement complex, but their relationship to the L'Erée granite, the Capelle granodiorite, and the Pleinmont metasediment (which is contained within the L'Erée granite at the southwest tip of Guernsey) is uncertain (Roach *et al.* in press). The Vazon dykes commonly have a trend parallel to, or slightly to moderately oblique to, the foliation of the metamorphic rocks they invade. Thus their trend at different points around the island varies considerably,

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from NE-SW on Lihou in west Guernsey (Fig. 2c), to WNW-ESE along parts of the south coast (Fig. 2b), to NS or NNE-SSW in southeast Guernsey around Moulin Huet Bay and in the Jerbourg Peninsula. Their dip is variable, generally varying from moderate to steep, and may be either parallel or oblique to the foliation in the host rocks. Thickness variation in the dykes is considerable; adjacent dykes may vary from less than 0.5m to more than 10m. Several dykes locally exceed 15m. While the majority of dykes are broadly parallel-sided, in detail their margins may be irregular. Sudden changes in local direction of dyke margin, following major joints in the host rocks, are common. Rapid changes in thickness may also occur and adjacent dykes can be linked by offshoots.

Three areas are shown in Figure 2 which illustrate the occurrence of the Vazon dykes. Along the west side of Vazon Bay (Fig. 2a) there are two main directions of dyke emplacement. One set, representatives of which exceed 10m in thickness, trends NNE-SSW approximately parallel to the foliation of the Perelle gneiss. This set is cut by thinner dykes, not usually over 3 m thick, which trend NNW-SSE (or NW-SE). The two sets of dykes, which produce a reticulated trellis-work pattern, are chemically similar. The Vazon dykes are cut by two hornblende microdiorite dykes of a suite postdating the main Cadomian deformation and metamorphism (Table 1). Along the south coast of Guernsey between Havre de Bon Repos and Pointe de la Moye, the Vazon dykes generally trend WNW-ESE (Fig. 2b). Here they generally dip in a northerly direction at a moderate angle. The dykes are mainly parallel and usually less than 5 m thick. In Havre de Bon Repos they cut the Bon Repos meladiorite, one of a suite of mafic (hornblendic) intrusions present along the south coast. The occurrence of the Vazon dolerites along the east side of Lihou Island, off the west coast of Guernsey opposite L'Erée Point, is shown on Figure 2c. Here they invade Icart gneiss and trend in a general NE-SW direction similar to that of the

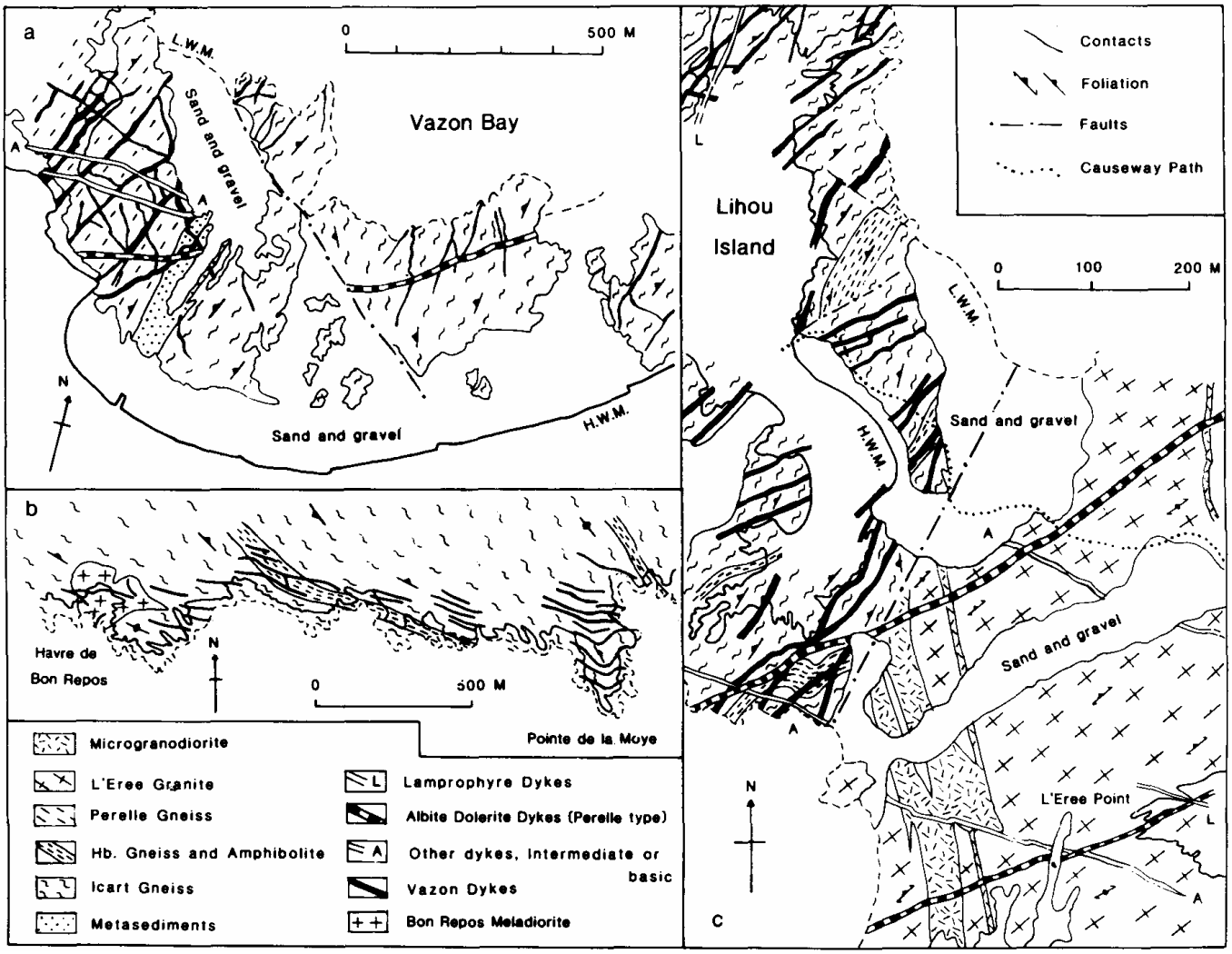


Figure 2. Geological maps of the three areas in the Southern Metamorphic Complex illustrating the occurrence of the Vazon dyke swarm: (a) W side of Vazon Bay; (b) S coast between Havre de Bon Repos and Pointe de la Moye; (c) E side of Lihou Island and L'Eree Point.

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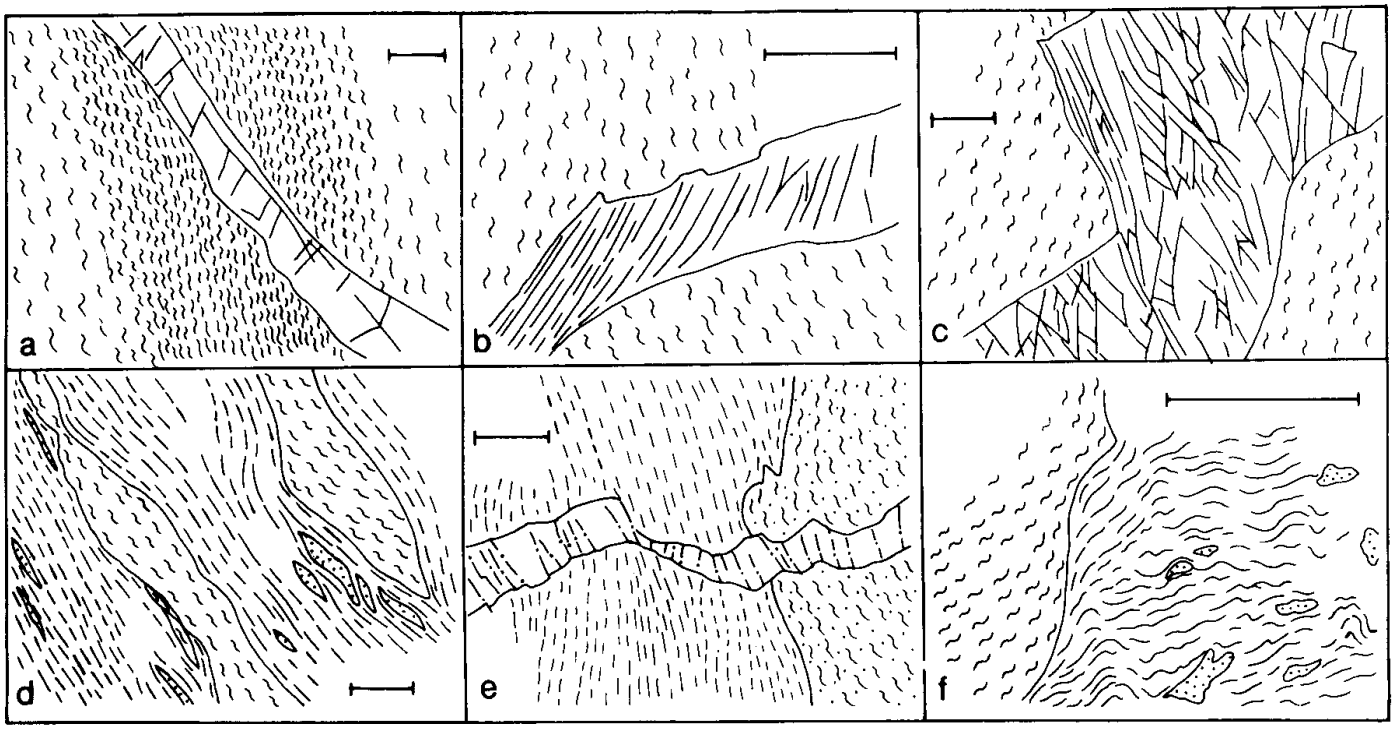
thicker, earlier set of Vazon dykes seen in Vazon Bay, with only minor cross-linking offshoots occurring. The most notable feature, seen on the map, is the absence of this swarm of dykes from the adjacent poorly foiiated L'Erée granite which forms the ground to the east, along the causeway and at L'Erée Point itselfi Although the L'Erée granite is in faulted contact with the Icart gneiss along the causeway and is separated along its eastern boundary from the Perelle gneiss by a zone of intense ductile shearing (Fig. 1), there is clear evidence that the granite post-dates the formation of the Pentevrian granitic and quartz dioritic gneisses. However, the relationship of this granite to the Vazon dykes is equivocal.

## Effects of Cadomian Deformation and Metamorphism

The regional greenschist facies metamorphic overprint which followed the emplacement of the Vazon dyke swarm has been assigned to the Cadomian orogeny (Roach 1977), during which both the principal metamorphism and the main deformation episode appear to have been broadly contemporaneous. A notable feature of the Vazon dyke swarm, which is particularly well seen along the south coast, is the variable extent to which dykes have been affected by deformation related to this orogeny (Roach *et al.* in press). A characteristic feature of the main deformation episode was the production of zones of moderate to high strain separating areas where, though the metamorphic overprint is clearly evident, the accompanying deformation features are of minor importance. Thus, in most of the ground covered by the areas depicted in Figure 2, the Vazon dykes are metamorphosed but generally undeformed, except possibly for minor shearing along their margins (Fig. 3a). In these low strain zones, the massive Vazon dykes retain a relict primary igneous fabric, commonly taking the form of prismatic to fibrous green amphibole aggregates after pyroxene, which sub-ophitically enclose variably altered plagio-ctase (An40.15). In other textural varieties, randomly orientated tabular plagioclase is set amongst anhedral amphibole aggregates. Rarely, primary clinopyroxene occurs as relict cores within the amphibole aggregates. Other minerals present, in addition to the above two principal phases, are greenish-brown biotite or chlorite, epidote, sphene, and ores. Quartz maybe present in small amounts.

In contrast to these areas of low Cadomian strain, there are others, for example on the west side of Belle Elizabeth in the southwest and in Moulin Huet Bay and on the Jerbourg Peninsula in the southeast, where Cadomian strain was higher and a variety of structures are seen in the Vazon dykes. The dykes may be crossed by a spaced




Field 3. Field sketches of Vazon Dykes illustrating the varying effects of Cadomian deformation. Scale bar in each example is 0.5m. (a) Undeformed dyke cutting variably foliated Icart gneiss. The dyke is crossed by several joints. Near boat platform, east side of Pointe de la Moye. (b) Dyke showing increasing development of fracture cleavage from left to right. Host rock is Icart gneiss. East side of Petit Bot. (c) Dyke crossed by numerous fractures, frequently in conjugate sets. Host rocks is Perelle gneiss. Telegraph Bay, east side of Jerbourg Point. (d) Foliated Vazon dyke, now a greenschist, La Jaonnet Bay, west side of Icart Point. The dotted areas are quartz-epidote pods. Host rock is Icart gneiss. (e) Hornblende microdiorite dyke cutting a Vazon dyke, previously converted to a greenschist. The microdiorite is crossed by a fracture cleavage. Host rock is Perelle gneiss. (f) Vazon dyke converted to a greenschist, showing microfolding of the schistosity. Host rock is Icart gneiss. Moulin Huet Bay.

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fracture cleavage (Fig. 3b) or a conjugate set of shear fractures (Fig. 3c)-(the slate-like basic dykes of Hill and Bonney, 1884). Here the dykes may also be sheared and foliated along their margins. In these dykes the original plagioclase has been recrystallized into aggregates of subgrains of sodic plagioclase which may still retain an overall tabular shape. Similarly the amphibole may occur as anhedral aggregates formed of small more euhedral subgrains. Some degree of mineral alignment may be present, notably along the more deformed dyke margins.

In zones of highest Cadomian strain a more pervasive schistose fabric is produced, generally aligned parallel to the margins of the deformed dyke (Fig. 3d). In such zones the dykes now appear as tectonic greenschists set within host rocks now converted to mylonite gneisses or mylonite schists. Because of ductility contrasts, the schistose Vazon dykes may occur as more irregular, sometimes even discontinuous, lenticular masses within these host rocks. The foliation in these greenschists is defined by elongated aggregates of green amphibole, which, together with biotite or chlorite, are moulded around oval to lenticular or more rarely prismatic sodic plagioclase. Chlorite may be more abundant than in the less deformed dykes and can be concentrated in lenses along with sphene. In all the dykes, the combined effect of Cadomian metamorphism and earth movements has been to produce a network of epidote-rich veins which vary Considerably in abundance.

At several localities along the south coast, hornblende microdiorite dykes are seen to cut across deformed Vazon dykes, which in some instances are now greenschists (Fig. 3c). These younger dykes have experienced only minor late Cadomian alteration and are generally little deformed except for a sporadic spaced cleavage related to late Cadomian movements.. Other evidence for such movements is seen in the generally small scale folding or crenulation of the schistosity present in the more highly deformed Vazon dykes (Fig. 30.

## Geochemistry

An examination involving a sample of 19 dykes of the Vazon swarm has been carried out in an attempt to delineate the ge0tectonic environment into which the magma was erupted. Geochemical analysis of major and trace elements was by X.R.F.S., of R,E.E. by I.C.P.S., and of low-level incompatible trace elements by I.N.A.A. As mentioned above, all the members of the dyke swarm have been subjected to low grade metamorphism, which can upset the original magmatic distribution of certain elements, making the magmatic signature less clear. To try to minimise the effects of element mobility, only those dykes showing the least effect of strain have been selected for analysis.

From their chemical compositions (Table 2, copies of the complete data are available from G.J. Lees), the Vazon

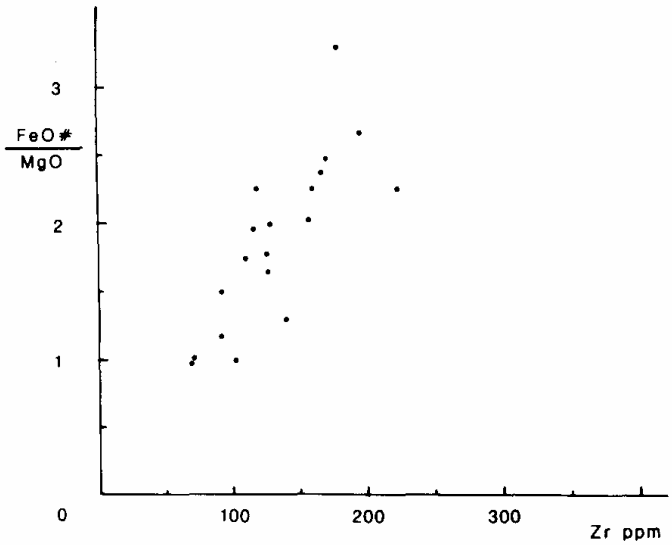


Figure 4. Geochemical plot of FeO*/MgO ratio against Zr in ppm as differentiation index illustrating the iron enrichment of the Vazon dyke suite.

Swarm is comprised dominantly of basalts and basaltic andesites. However, six dykes have an $Si0_2$ content above 55%, so are strictly andesites. The $Al_2O_3$ content is too low for high alumina basalts; the total iron content (Fe203*) is high; the MgO content is fairly low. Total alkali contents lie consistently below values expected for alkaline rocks in a total alkalies versus $SiO_2$ diagram. All these characters point to the eruption of a fairly evolved magma of subalkalic character. Correlations between $Si0_2$ and Zr (R = 0.84) and between MgO and Zr (R = 0.83) are fairly high, so Zr has been used as an index of differentiation in Figure 4. Here, the ratio $Fe_2O_3$*/MgO shows a reasonably good correlation with Zr (R = 0.80) indicating iron enrichment with fractionation. However, there are a few scattered points; this possibly indicates the presence of magma from more than one source within the Vazon dyke swarm. The relatively low concentrations of the three immobile incompatible HFS elements Y, Nb, and Zr, are consistent with a subalkalic character, while the reasonably good correlations of Y and Nb with Zr (R = 0.94 and 0.90 respectively) would indicate a tholeiitic magma.

The compatible trace elements Ni and Cr generally show concentrations below 65 ppm and 250 ppm respectively. However, one sample shows 207 ppm Ni and 544 ppm Cr, while three other samples show Ni contents between 77 and 84 ppm and Cr between 260 and 423 ppm. All these dykes have enhanced Mg0 contents. Thus, while most samples have MgO, Ni, and Cr contents which accord with well evolved basaltic magmas, some have concentrations which reflect their higher mafic contents and probably reflect greater amounts of clinopyroxene and perhaps olivine crystallising from the magma.

The chondrite-normalized R.E.E. patterns (Nakamura 1974) of six typical Vazon dykes (Fig. 5), all show

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| | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| $SiO_2$ | 48.39 | 52.63 | 52.54 | 52.85 | 3.12 | 52.48 |
| $TiO_2$ | 0.83 | 1.97 | 2.75 | 1.69 | 0.65 | 0.8 |
| $Al_2O_3$ | 13.39 | 12.23 | 12.04 | 13 | 0.45 | 15.48 |
| $Fe_2O_3$* | 11.17 | 14.6 | 16.5 | 13.16 | 1.7 | 10.39 |
| MnO | 0.13 | 0.19 | 0.26 | 0.17 | 0.03 | 0.17 |
| MgO | 9.93 | 5.88 | 4.54 | 6.85 | 1.84 | 7.05 |
| CaO | 12.39 | 5.68 | 6.55 | 7.56 | 2.17 | 8.7 |
| $Na_2O$ | 1.75 | 2.46 | 3.15 | 3.23 | 0.91 | 1.45 |
| $K_2O$ | 0.39 | 2.94 | 1.19 | 1.27 | 0.54 | 1.64 |
| $P_2O_5$ | 0.09 | 0.2 | 0.27 | 0.21 | 0.09 | 0.11 |
| LOI | 0.87 | 1.84 | 0.83 | 0.99 | 0.62 | 2.4 |
| Total | 100.45 | 100.62 | 99.73 | 100.98 | | 100.67 |
| **FeO*** | 0.97 | 2.23 | 3.27 | 1.87 | 0.62 | 1.33 |
| MgO | | | | | | |
| Zr | 70 | 161 | 180 | 137 | 43 | 61 |
| Y | 21 | 43 | 53 | 38 | 11 | 22 |
| Nb | 6 | 11 | 16 | 11 | 3 | 5 |
| Ni | 77 | 20 | 27 | 50 | 44 | 110 |
| Cr | 415 | 48 | 14 | 135 | 161 | 315 |
| La | 5.01 | 15.08 | 16.06 | 14.5 | 5 | 9.41 |
| Yb | 1.89 | 3.95 | 4.31 | 3.52 | 1.18 | 1.91 |
| La/YbN | 1.77 | 2.55 | 2.49 | 2.56 | 0.54 | 3.15 |
| Zr/Y | 3.6 | 3.7 | 3.4 | 3.6 | 0.6 | 2.8 |

Table 2. Chemical composition of selected members of the Vazon Dyke Swarm, with a typical Dahouet-type dyke of the H.E.V.F. for comparison. 1: VD-12 - 0.5m dyke in Perelle Gneiss from west side of Vazon; 2: VD-8 - lm dyke in Icart Gneiss from Petit Bot Bay; 3: VD-18 7.5m dyke in Icart Gneiss from west side of Lihou Island; 4 and 5: Mean and Standard Deviation of 19 Vazon dykes (La and Yb are of 8 dykes); 6: RAR80/98 Dahouet-type dyke from shore at Cesson, Cotes-du-Nord, N. Brittany.

L.R.E.E. enrichment with slightly upward concave profiles showing no obvious point of inflection between L.R.E.E and H.R.E.E. All samples show slight negative Eu anomalies which might indicate either the fractionation of plagioclase or alteration under the pervasive greenschist facies metamorphism ($Eu^{+2}$ being very similar in behaviOur to $Sr^{2+}$). All the patterns lie within and parallel to the envelope of the R.E.E. patterns of the Hillion Erquy Volcanic Formation of the Baie de St Brieuc, North Brittany (Fig. 5) (see below). La/YbN ratios for the dykes of the Vazon swarm range between 1.77 and 3.54, (X = 2.56±0.54), which compares with a range between 1.61 and 3.93 for the H.E.V.F. C= 2.72 0.55), and 2.31 and 3.31 for the two Dahouët-type dykes analysed for R.E.E.

The MORB - normalized 'spidergrams' (Pearce 1983) (Fig. 6) show consistent patterns of increasing concentration with incompatibility. The increased values of the coherent immobile element pair Nb and Ta compared with the pair Hf and Zr, and of the latter

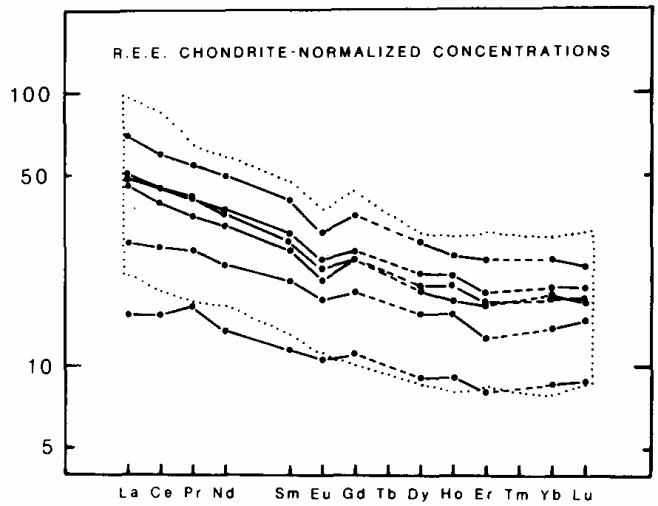


Figure 5. Chondrite-normalized R.E.E. diagram of six members of the Vazon dyke swarm (normalization scheme of Nakamura, 1974). The dotted lines indicate the R.E.E. envelope of the H.E.V.F.

compared with the pair Y and Yb is taken to indicate derivation from an enriched mantle source, probably the subcrustal lithosphere (Pearce 1983). Using the arguments advanced by Pearce (1983), any influence of subduction on the magma should be evident in an increased concentration of L.I.L. elements, Ba, Rb, K, Th, and Sr. The mobility of most of these elements during low grade metamorphism can obscure the original patterns. The marked negative Sr anomalies are almost certainly due to this cause. The L.I.L. element usually considered the most immobile is Th, for which only two determinations are available on the Vazon dyke swarm samples. The steady upward slope of the patterns between Yb and La (Fig. 6) makes it more difficult to estimate whether any anomalous increase in L.I.L. element concentration is present. Using Th, it does not appear that any such anomalously high L.I.L. content is present. However, Rb, Ba, and K, do show consistent anomalously high concentrations. The question of the presence of a subductlon zone component in the magma must thus remain unresolved. Crustal contamination of the magma cannot be satisfactorily evaluated without isotopic data. It may sometimes be indicated by the presence of a Nb-Ta depletion. Such a depletion is not seen in the Vazon dyke 'spidergrams'.

## Conclusions

Evidence has been presented above which establishes in southern Guernsey the presence of a dyke swarm of metadoleritic rocks whose eruption pre-dates the main Cadomian deformation and metamorphism. The geochemical character of the swarm is that of a well evolved tholeiitic suite, most of the dykes now being of basaltic-andesite composition, though some more Mg0 rich basalts and some still more evolved compositions - andesites - occur. The swarm intrudes several Pentevrian orthognetsses, the youngest of which has been tentatively

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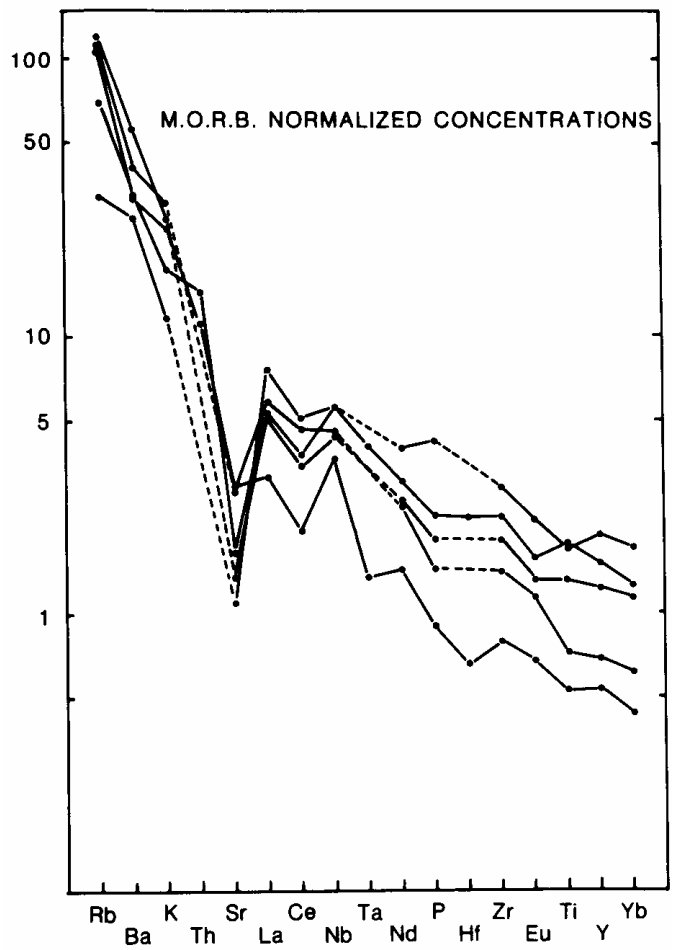


Figure 6. Incompatible element 'spidergram' offive members of the Vazon Dyke Swarm (normalization scheme of Pearce, 1983).

dated at c.700 Ma. (G.M. Power et al., in Coe, 1986). Thus, the Vazon dyke swarm appears to have been emplaced in the late Proterozoic prior to the onset of the Cadomian orogeny.

In the northern Armorican Massif, basic volcanics are intercalated with Brioverian sediments in several regions (Lees et al. 1987 and refs. therein). The stratigraphical position of the volcanic units is difficult to establish except in the case. of the 2km. thick sequence of basic submarine flows and associated intrusive sheets (H.E.V.F. of Lees et al. op. cit.) which form the lower part of the Brioverian sequence on the south side of the Bale de St Brieuc (Roach et al. 1986). Here the Brioverian rests with major unconformity on Pentevrian basement intruded by basic dykes (Dahouët-type dykes) postulated as feeders to the overlying basalts.

The H.E.V.F. comprises a series of evolved tholeiitic basalt to basaltic-andesite rocks showing virtually identical R.E.E. patterns and the same incompatible-element enriched spidergrams as the Vazon dykes (Lees et al., op. cit., and Fig. 5). Zr:Y ratios are slightly lower for the Vazon dykes (3.64 ± 0.43) than for the H.E.V.F. (3.83 ± 0.74) - (3.77 ± 0.63 for the Dahouët-type dykes) - indicating a slightly more enriched source for the H.E.V.F.

Rabu et al. (1983) and Cabanis et al. (1987) concluded that the tholeiitic basalts of the Bale de St Brieuc were erupted in a within-arc or back-arc environment lying above a southerly dipping subduction zone, with an active island arc situated to the north, along a WSW line from Cap de la Hague (Manche), through the Channel Islands, to the Tr6gor region of northern Brittany. However, Roach et al. (1986) and Lees et al. (1987) have interpreted the H.E.V.F. as basaltic rocks of continental tholeiite affinity, erupted through Pentevrian continental crust during a period of crustal extension and thinning, which led to the formation of an ensialic basin and the deposition of an epiclastic sequence - mainly turbiditic -above the H.E.V.F.

In view of the fact that (a) there is a close comparison between the geochemical character of the H.E.V.F. and the Vazon dykes, and (b) that both suites of rocks postdate the development of the Pentevrian basement but pre-date the main episode of Cadomian deformation and metamorphism, it is tentatively suggested that the Vazon dyke swarm may be a more northerly expression of the same magmatic cycle that produced the H.E.V.F.

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References

Adams, C.J.D. 1976. Geochronology of the Channel Islands and adjacent French Mainland. *Journal of the Geological Society*, London, 132, 233-250.

Ansted, D.T. and R.G. Latham, 1862. *The Channellslands, 3rd Edition*. Allen, London, 247-297.

Bonney, T.G. and E. Hill, 1912. Petrological notes on Guernsey, Herm, Sark, and Alderney. *Quarterly Journal of the'Geological Society*, London, 68, 31-57.

Cabanis, B., J. Chantraine and D. Rabu, 1987. Geochemical study of the Brioverian (Late Proterozoic)volcanic rocks in the northern Armorican Massif (France). - Implications for geodynamic evolution during the Cadomian. In: Pharoah, T.C., Beckinsale, R.D. and Rickard D.T. (eds.). *Geochemistry and Mineralogy of Proterozoic Volcanic Suites. Geological Society of London Special Publications.*

Calvez, J.Y. and P. Vidal, 1978. Two billion years old relicts in the Hercynian belt of Western Europe. *Contributions to Mineralogy and Petrology*, 65, 395-399.

Cogué, J. 1959. Donnees nouvelles sur l'Antecambrien dans l'Ouest de la France: Pentevrien et Bripverien en bale de Saint-Brieuc (Cotes-du-Nord). *Bulletin de la Société geologique de laFrance*, (7), L 112-118.

Coe, K. 1986. Geochemical aspects of granite and related rocks. *Journal of the Geological Society*, London, 143, 855-856. Farquaharson, D.S. 1924. The geology of Southern Guernsey. *Quarterly Journal of the Geological Society*, London, 80, 374-388.

Table of Contents

Graindor, M.J. 1961. Existence vraisemblable due Pentevrien dans les Iles Anglo-Normandes et de la Hague. *Bulletin de la Société Linnéenne de Normandie*, (10), 1, 44-46.

Hill, E. and T.G. Bonney, 1884. The Rocks of Guernsey. *Quarterly Journal of the Geological Society*, London, 40, 404-430.

Lees, G.J., R.A. Roach, M.M. Shuffiebotham and N.G. Griffiths, 1987. Upper Proterozoic Basaltic Volcanism in the Northern Massif Armoricain, France. In: Pharoah, T.C., Beckinsale, R.D., and Rickard, D.T. (eds.). *Geochemistry and Mineralogy of Proterozoic Volcanic Suites. Geological Society of London Special Publications.* 503-522.

Nakamura, N. 1974. Determination ofREE, Ba, Fe, Mg, Na and K in carbonaceous and ordinary chondrites. *Geochimica and Cosmochimica Acta*, 38, 757-775.

Pearce, J.A. 1983. Role of the Sub-continental Lithosphere in Magma Genesis at Active Continental Margins. In: Hawkesworth, C.J. and Norry, M.J. (eds.) *Continental Basalts and Mantle Xenoliths*, Shiva Publishing Ltd, Nantwich, 230-249.

Plymen, G.H., 1933. The Geology of Guernsey. *Transactions of the Société Guernesiaise*, 2, 301-318.

Rabu, D., J.J. Chauvel, and J. Chantraine. 1983. Nouvelles propositions pour la lithostratigraphie du Brioverien (Proterozoic supérieur) et pour l'evolution g6odynamique cadomienne en bale de Saint-Brieuc (Massif Armoricain). *Bulletin de la Société gdologique de la France*,(7), t.XXV, No. 243, pp. 61-79.

Roach, R.A., 1957. The Geology of the Metamorphic Complex of South and Central Guernsey. *Unpublished Ph.D. thesis, University of Nottingham.*

Roach, R.A., 1966. Outline and guide to the geology of Guernsey. *Transactions of the Société Guernesiaise*, 17, 751-776.

Roach, R.A., 1977. A review of the Precambrian rocks of the British Variscides and their relationship with the Precambrian of N.W. France. In: *La chaine varisque d'Europe moyenne et occidentale. Colloque Internationale du Centre National de la Recherche Scientific*, 243, 61-79.

Roach, R.A., Topley, C.G., Bland, A.M., Brown, M., and D'Lemos, R..S, in press, An outline and guide to the Geology of Guernsey, Channel Islands. *Roedder Publications,* London. 2 vols.

Roach, R.A., C.G. Topley, M. Brown, and M.M. Shuffiebotham, 1986. Brioverian volcanism and plutonism in the northern part of the Armorican Massif. Pre-conference excursion guide. *International Geological Correlation Programme Project 217, Proterozoic Geochemistry Conference,* British Geological Survey, Keyworth. 90p.

Saunders, A.D. and J. Tamey. 1984. Geochemical characteristics of basaltic volcanism within back-arc basins. In: Kokelaar, B.P. and Howells, M.F. *MarginalBasin Geology. Geological Society of London Special Publications, No. 16*, 59-76.

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*Read at the Annual Conference of the Ussher Society, January 1987*

# Some relationships within the igneous complex at Sorel Point, Jersey: metasomatism or magma-magma interaction?

S. SALMON

Salmon, S. 1987. Some relationships within the igneous complex at Sorel Point, Jersey: metasomatism or magma-magma interaction? *Proceedings of the Ussher Society 6,* 510-515.

At Sorel Point, Jersey, gabbros, diorites, granodiorites and granites occur in complex interrelationships. Granodiorite occurs in a narrow zone between aplogranite and diorite, and intrudes the diorite as veins, pipes and sheets, within which dioritic enclaves are common. The granodiorite also veins the aplogranite, but not so extensively. Contacts between the granodiorite and diorite are intimate, often lobate or crenulate. Diorites and dioritic enclaves often have fine grained margins.

It has been suggested that the diorites, and their complicated contact relationships, have been produced by metasomatic recrystallization and rheomorphism of solid gabbro by intruding granite. However, field observations suggest a different explanation, involving magma-magma interaction.

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## Introduction

An aspect of igneous petrology which has been the subject of much discussion over the years is the close spatial association of acidic and basic rocks, (e.g. Holmes 1931; Wager et al 1965; Bussell 1985). In some of these associations intermediate rock types are produced by magma-mixing (Anderson 1976; Kouchi and Sunagawa 1982; Vogel et al 1984), but frequently complete mixing does not occur and the contrasting rock types survive m often intimate relationships (Gamble 1979; Wiebe 1974) This incomplete mixing has been referred to as magma-mingling. Much field, petrographic and geochemical evidence has been produced which has led to general acceptance of these processes.

The field relationships characteristic of areas of magma-mingling are well documented (Blake et al 1965; Walker and Skelhorn 1966; Yoder 1973). Basic rocks often show a fine-grained margin, interpreted as being caused by chilling of the hotter basic magma against the cooler acid magma (Wager and Bailey 1953). Contacts are generally sharp, with lobate and/or crenulate outlines. Acid rock can be seen intruded into the basic rock as pipes (Elwell 1958; Elwell et al 1960) or net-veins (ElweU et al 1962). Common within the acid rock are enclaves of material similar to the basic rock, and the enclaves themselves can show crenulate outlines and chilled margins. Material from the surrounding acid rock can sometimes be seen ffiling straight sided cracks which cut across the fine-grained margin in rounded enclaves.

This paper is a contribution to the continuing discussion on magma-mingling and draws on field evidence from the classic exposures at Sorel Point in Jersey, Channel Islands (Fig. l).

The rocks at sorel Point have been described by Wells and Wooldridge (1931) and Bishop (1963). The area consists of a variety of plutonic igneous rocks - gabbros, diorites, granodiorites and granites. Bishop ascribed formation of the diorites to the metasomatism of solid gabbro by fluids from an invading granite. Both papers attribute the contact relationships between the diorite and granodiorite, with which this paper is chiefly concerned, to further modification of the diorite. It is suggested here, however, that there is sufficient good field evidence to show that magma-mingling occurred, i.e. that the two rock types once co-existed as magmas.

## Location and Geological Setting

Sorel Point lies on the north coast of Jersey, which, together with the other Channel Islands, lies within the

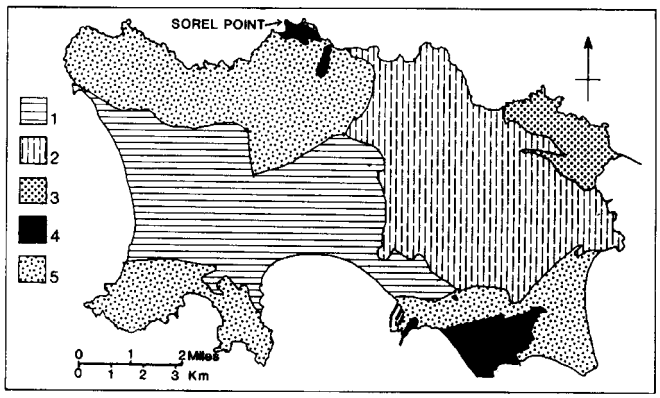


Figure 1. Simplified geological map of Jersey showing the major units: 1, Jersey Shale Formation; 2, Jersey Volcanics; 3, Rozel Conglomerate; 4, Basic Intrusives; 5, Granites.

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North Armorican Massif (Roach 1977). The island is made up largely of Brioverian sedimentary and volcanic rocks cut by three igneous bodies, known as the North-West, South-West and South-East Granites (Fig. 1). The South-West granite contains various lithologies all of which are granitic in composition (Bland 1984). The North,West and South-East bodies have a variety of basic and intermediate rocks associated with granites of variable composition. The North-West granite is an annular body (Bland 1985), comprising an outer coarse granite, a porphyritic granodiorite and an inner biotite microgranite. Around its eastern edge is a pink aplogranite which is in contact with the basic and intermediate rocks of Sorel Point and Ronez Quarry, which are the subject of this paper. Certain relationships around Sorel Point are described below. Many relationships similar to these can be seen within the South-East Granite complex (Bishop and Key, 1983).

## Geology of Sorel Point

It will be apparent from Figure 2, a simplified geological map of Sorel Point, that the bulk of the area is made up of gabbro. This gabbro is a hornblende bearing variety which is generally medium-grained and mesocratic, though variable in texture, colour-index and mineralogy. In the NW of the area it shows good modal layering, dipping 45 degrees to the south. Common within the gabbro are coarse appiniticpods (Wells and Bishop 1955; Key 1977) of plagioclase and amphiboles.

In the north and east of the area is a body of pink aplogranite. This is medium-grained, equigranular, leucocratic and miarolitic throughout.

On passing from the gabbro into the aplogranite two more lithologies are crossed. The gabbro gives way to diorite which is in turn in contact with granodiorite. This granodiorite lies between the diorite and aplogranite, forming a barrier which varies in thickness from a few centimetres up to around three metres. Only rarely do the diorite and aplogranite come into direct contact.

The diorite is generally fine to medium-grained, equigranular, consisting mostly of plagioclase and hornblende. Quartz ocelli, rimmed with sub- t° euhedral hornblende, are common throughout the diorite, though variable in abundance. In the field no control can be discerned on the abundance or distribution of the ocelli, for instance they do not appear to be controlled by close proximity to granodiorite veins or pipes.

The granodiorite intrudes the diorite extensively as sheets, which are variable in thickness from a few centimetres up to a metre or so, and veins and pipes. Thickness of veins and diameter of pipes both vary up to around 25 centimetres. Some veins of granodiorite also intrude the aplogranite. Although here termed grano-diorite the rock is variable in modal composition, from granite to granodiorite to quartz-monzodiorite. Feldspar megacrysts are common within the granodiorite, the megacrysts being variable in abundance and often showing good alignment sub-parallel to the margins of the intrusions. Both alkali-feldspar and plagioclase are present as megacrysts, with plagioclase being dominant, in a fine to medium-grained groundmass of quartz, plagioclase, alkali-feldspar, biotite and hornblende, hornblende being the dominant mafic mineral. This lithology is the same as that referred to by Wells and Wooldridge as "grey, porphyritic granite" (pp 194/5) and is presumably the granite described by Bishop (1963) aas the agent of metasomatism and rheomorphism (see "Conclusions" below).

All of these rock-types are cut by a coarse granite within which rapakivi-textured feldspars are common. This granite may be an offshoot of the outer coarse granite of the North-West granite, though the lack of inland exposure makes this uncertain.

## Relationships between Diorite and Granodiorite

Contacts between the diorite and granodiorite are generally sharp, often lobate and, on the small scale, undulose or crenulate (Fig. 3A). The grain size of the diorite becomes progressively finer as the contact is approached, suggestive of, and here interpreted as, a chilled margin. It is here suggested that this chilled margin was formed by the hotter dioritic magma being intruded by the cooler granodiorite magma. There is no grain size reduction in the granodiorite at the contacts. Relationships are often very irregular and intimate, suggesting considerable mobility on both sides.

Dioritic enclaves are common within the granodiorite, often in clusters or swarms (Fig. 3B). They range from centimetre-sized to metre-sized, having generally sharp contacts. The contacts are often crenulate, with typically fine-grained margins (Fig. 3C). Although generally rounded, enclaves can also be irregularly-shaped. They are sometimes cut by straight-sided cracks, cross-cutting the fine margin, occupied by material of the surrounding type (Fig. 3B). This suggests that as the enclaves crystallized and became brittle enough to fracture there was still some liquid present in the granodiorite.

Around Sorel Point there are many occurrences of granodiorite intruding the diorite as sub-cylindrical pipes. Most of the pipes appear to originate from the granodiorite sheet separating the diorite and the aplogranite. Pipes can also originate from other granodiorite sheets and can connect sheets on different structural levels. The pipes are roughly circular in cross-section, from 10 to 25 cm in diameter, and appear capable of penetrating the diorite for tens of metres. Near their base, where they widen out, the surrounding diorite has fine-grained margins. Along the pipes further away from the base the surrounding diorites do not show this fine grained margin at the contacts. Pipes appear to be

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straight only over distances of a few metres, more commonly showing some sinuosity and occasionally being anastomosing. Sometimes they connect to narrower veins. Pegmatitic pods are common within the pipes, occurring anywhere along the length and, in some cases, apparently forming the termination. There is often a distinct felsic aureole in the surrounding diorite, richer in quartz and alkali-feldspar, presumably originating from the pipe material in some way.

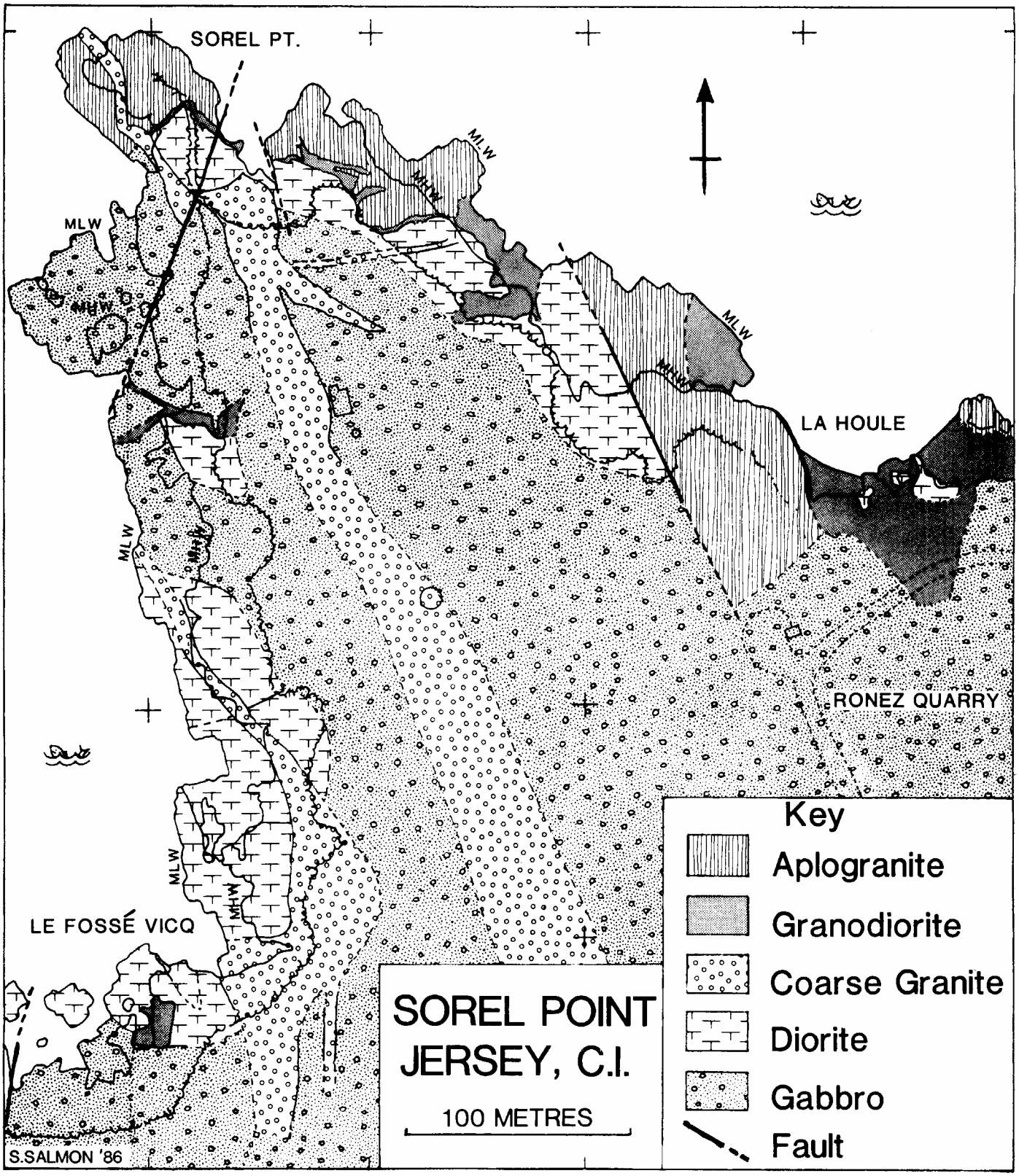


Figure 2. Simplified geological map of Sorel Point.

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On the west side of Sorel Point a small body of granodiorite separates layered gabbro to the north from diorite to the south. This body can be several metres wide, but at its narrowest is only around 50 centimetres. The contact of the granodiorite with the gabbro is fairly straight, sharp and angular. In one place the granodiorite can be seen cross-cutting an appinitic pod. Along this contact there is no apparent textural or mineralogical effect whatsoever on the gabbro, i.e. the gabbro adjacent to the contact looks the same as that a few metres away.

The contact between granodiorite and the diorite to the south is completely different. All the contact relationships previously described can be seen, including irregular, lobate and crenulate contacts with fine-grained margins in the diorite. The granodiorite intrudes the diorite to the south as a system of fine net veins which are irregular and against which the diorite shows fine-grained margins (Fig. 3D). Net-veining appears in other places around the area.

In summary, the following relationships occur at Sorel Point, each of which has been accepted elsewhere as evidence of co-existing acid and basic magmas (Blake *et al* 1965; Walker and Skelhorn 1966):

1. Progressive reduction of grain size in basic rocks approaching contacts - chilling?
2. No "chilling" in acid rocks at contacts.

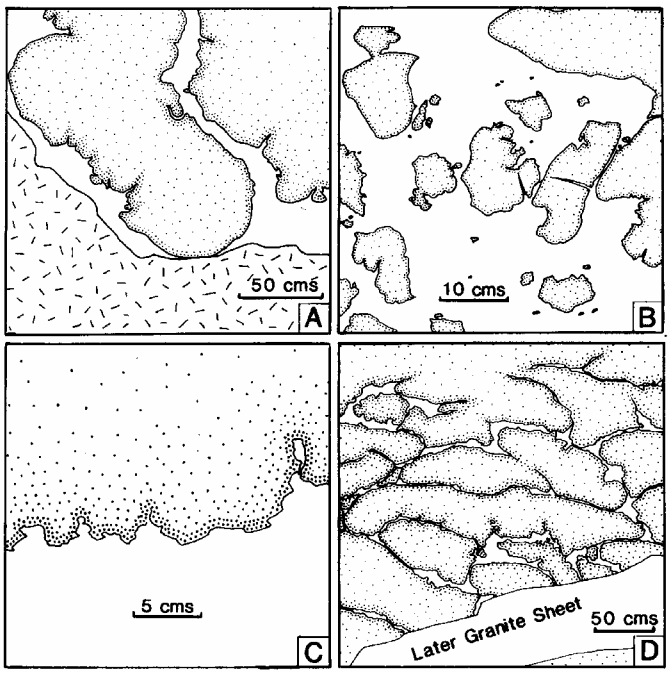


Figure 3. Sketches of field relationships, drawn from photographs. Ornament: dashed - aplogranite; clear - granodiorite; stippled - diorite (closer stippling indicates finer grain size). A: Typical lobate, crenulate contacts with fine grained margins between diorite and granodiorite. B: Cluster of dioritic enclaves within granodiorite. C: Edge of large dioritic enclave showing crenulte contact and fine grained margin against granodiorite. D: Granodiorite net-veins in diorite.

3. Lobate and/or crenulate contacts.
4. Enclaves of basic material common within the acid rock, commonly with crenulate contacts and fine-grained margins.
5. Basic enclaves often very irregularly shaped.
6. Enclaves often cut by straight-sided cracks whose material connects with the surrounding acid rock.
7. Piping of acid rock into basic rock.
8. Net-veining of basic rock by acid rock.

Discussion and Conclusions

In Bishop's (1963, p.293) model the gabbro, which was in a solid state, was metasomatized in response to the intrusion of a granitic magma. This metasomatism produced the diorite. Recrystallization associated with this metasomatism led to reduction of grain size, and this effect became stronger towards the granite contact. At the contact further migration of material to and from the granite further modified the diorite to the point that rheomorphism of the diorite occurred. Bishop states that the diorites "have at no time in their history been completely molten". A similar model was put forward by Bishop and Key (1983) to explain many of the relationships seen in the S.E. Jersey granite complex (but see also Topley and Brown, 1984, who interpreted these relationships as being of igneous rather than metasomatic origin). While it is accepted that Bishop's model may be viable under certain conditions it is here suggested that a simpler explanation at Sorel Point is that the two rock types were present as co-existing magmas, and that the relationships described above support this contention.

The lobate and crenulate nature of the contacts has been described in several of the references cited above as being typical of areas where two contrasting magmas have coexisted. The form of the crenulations (Fig. 3C) is consistent with the known effects of density contrast, i.e. that a less dense medium (e.g. acidic magma) will tend to rise into a more dense medium (e.g. basic magma). There are many geological analogies, e.g. salt diapirs, soft sediment deformation, where the main controlling factor is such a density contrast. These margins, which are normally accompanied by a marked progressive reduction in grain size, occur on both the surrounding diorite and dioritic enclaves.

The even grained nature of this fine grained margin is consistent with chilled margins seen in the plutonic environment, where a marked undercooling leads to formation of abundant crystal nuclei at the expense of growth rate. The absence of features such as skeletal, open-ended or variolitic textures does not preclude chilling, as it is now more generally accepted that such textures are associated with "quenching", i.e. very rapid crystallisation in response to high degrees of supercooling and supersaturation, such as in the outer skins of extrusive basalt pillows (Cox, Bell and Pankhurst 1979).

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If the intruding granodiorite had encountered a colcl, solid gabbro it. is likely that a chilled margin would have developed in the granodiorite. No evidence of such a chilled margin has been found in the area.

It is difficult to conceive of formation of pipes such as those described being possible if the surrounding rock were solid. On the other hand, it is likely that a granitic liquid would rise through a diorite rendered soft and rheomorphic by metasomatic action. At Sorel Point, however, such a model is problematical because one of the postulated effects of inducing rheomorphism in a previously solid rock by metasomatism, i.e. fine-grained margins in the diorite, is absent for most of the length of the pipes. If it is accepted that both rock types were present as co-existing magmas, as proposed here, than the problem is overcome, but it may then be asked why the diorite does not chill against the pipes. If the grano-diorite causes chilling of diorite along the main interface, then the energy of the crystallization will superheat the granodiorite to some extent, rendering it more mobile. As pipes of this magma break through the chilled margin the temperature contrast across the contact between it and a much larger volume of dioritic liquid, which is cooling down, may become so small that chilling of the dioritic magma would not occur. It is likely that there would also be some concentration of volatiles and hydrous fluids below the chilled interface, and that these would be carried into the pipes, allowing formation of pegmatitic pods.

Formation of the felsic aureoles preyiously described would be greatly facilitated by the presence of residual interstitial liquid in the diorite, allowing infiltration of material from the pipes; inducing small scale local metasomatism in contrast to the larger scale metasomatism envisaged in the model proposed by Bishop (1983).

The evidence described on the west side of Sorel Point, where a granodiorite body separates gabbro and diorite, appears to contradict the metasomatic theory. The granodiorite - gabbro contacts are typical of those seen where a magma intrudes a solid rock, while the contacts between granodiorite and diorite are typical of magma - magma relationships. Similar relationships can be seen in the SW of the area. If it were true that the intruding granodiorite (Bishop's granite, see above) was responsible for metasomatizing the gabbro to such an extent as to cause rheomorphism (with attendant fine-grained margins) it is surely likely that some effect would be apparent on the gabbro along this contact. No such effect can be seen anywhere along the contact. Similarly, Wells and Bishop (1955) and Key (1977) invoke metasomatism as being responsible for the formation of the appinitic pods, but the granodiorite can be clearly seen cross-cutting one of these pods.

Taken in isolation none of the relationships summarised in the previous section would be acceptable as proof that interaction between two co-existing magmas, of contrasting composition, had taken place. But when all of them occur in close proximity, within a relatively small area, then it is considered that they represent very good field evidence that these processes have occurred.

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## References

Anderson, A.T., 1976. Magma mixing: petrological process and volcanological tool. *Journal of Vulcanology and Geothermal Research*, 1, 3-33.

Bishop, A.C. 1963. Dark margins at igneous contacts: a critical study with special reference to those in Jersey. *Proceedings of the Geologists' Association*, 74, 289-300.

Bishop, A.C. and Key, C.H. 1983. Nature and origin of layering in the diorites of S.E. Jersey, C.L *Journal of the Geological Society of London*, 140, 921-937.

Blake, D.H., Elwell, R.W.D., Gibson, I.L., Skelhorn, R.R. and Walker, G.P.L. 1965. Some relationships resulting from the intimate association of acid and basic magmas. *Quarterly Journal of the Geological Society of London*, 12L 31-49.

Bland, A.M, 1984. Field relationships within the S.W. Jersey granite complex. Proceedings of the Ussher Society, 6, 54-59. Bland, A.M., 1985. The geology of the granites of western Jersey, with particular reference to the South-West granite complex. *Unpublished PhD thesis, Oxford Polytechnic.*

Bussell, M.A., 1985. The centred complex of Rio Huaura: a study of magma mixing and differentiation in high level magma chambers. In: Pitcher, W.S., Atherton, M.P., Cobbin, E.J. and Beckinsale, R.D. (eds.) *Magmatism At a Plate Edge. Blackie.*

Cox, K.G., Bell, J.D. and Pankhurst, R.J, 1979. The Interpretation of Igneous Rocks. George Allen and Unwin.

Elwell, R.W.D. 1958. Granophyre and hybrid pipes in a dolerite layer of Slieve Gullion. *Journal of Geology*, 66, 57-71.

Elwell, R.W.D., Skelhorn, R.R. and Drysdall, A.R. 1960. Inclined granitic pipes in the diorites of Guernsey. *Geological Magazine*, 97 88-106.

Elwell, R.W.D., Skelhom, R.R. and Drysdall, A.R. 1962. Net veining in the diorite of N.E. Guernsey, C.I. *Journal of Geology*, 70, 215-226.

Gamble, J.A. 1979. Some relationships between co-existing granitic and basaltic magmas and the genesis of hybrid rocks in the Tertiary central complex of Slieve Gullion, N.E. Ireland. *Journal of Vulcanology and Geothermal Research,*' 5, 297-316.

Holmes, A. 1931. The problem of the association of add and basic rocks in central complexes. *Geological Magazine*, 68, 241-255.

Key, C.H, 197T Origin of appinitic pockets in the diorites of Jersey, C.I. *Mineralogical Magazine*, 41, 183-192.

Kouchi, A. and Sunagawa, I., 1982. Experimental study of mixing of basaltic and dacitic magmas. ,*Science Reports of Tohoku University*, Japan, 15, 163-175.

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Roach, R.A. 1977. A review of the precambrian rocks of the British Variscides and their relationships with the precambrian of N.W. France. *In: La chaine varisque d'Europe moyenne et occidentale. Colloque international du Centre Nationale de la Recherche Scientifique, Rennes: Editions du CNRS*, 243, 61-79.

Topley, C.G. and Brown, M., 1984. Discussion on the nature and origin of layering in the diorites of S.E. Jersey, Channel Islands. *Journal of the Geological Society of London,* 141, 595-598.

Vogel, T.A., Younker, L.W., Wilband, J.T. and Kempmueller, J E., 1984. Magma - mixing: the Marsco suite, Isle of Skye, Scotland. *Contributions to Mineralogy and Petrology*, 87, 231-241.

Wager, L.R. and Bailey, E.B., 1953. Basic magma chilled against acid magma. *Nature*, 172, 68-70.

Wager, L.R., Vincent, E.A., Brown, G.M. and Bell, J.D. 1965. Marscoite and related rocks of the western Red Hills complex Isle of Skye. *Philosophical Transactions of the Royal Society of London*, 257A, 273-307.

Walker, G.P.L. and Skelhorn, R.R., 1966. Some associations of acid and basic igneous rocks. *Earth Science Reviews*, Z 93-109.

Wells, A.K. and Wooldridge, S.W., 1931. The rock groups of Jersey, with special reference to intrusive phenomena. *Proceedings of the Geologists' Association*, 1Z 178-215.

Wells, A.K. and Bishop, A.C., 1955. An appinitic facies associated with certain granites in Jersey, C.I. *Quarterly Journal of the Geological Society of London*, llL 143-166.

Wiebe, R.A., 1974. Coexisting intermediate and basic magmas, Ingonish, Cape Breton Island. Journal of Geology, 82, 74-87.

Yoder, H.S., 1973. Contemporaneous basaltic and rhyolitic magmas. *American Mineralogist*, 58, 153-171.

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*Read at the Annual Conference of the Ussher Society, January 1987*

# Cliff-top recession related to the development of coastal landsliding west of Budleigh Salterton, Devon

P. GRAINGER
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Grainger, P. and Kalaugher, P.G. 1987. Cliff-top recession related to the development of coastal landsliding west of Budleigh Salterton, Devon. *Proceedings of the Ussher Society,* 6 516-522.

Distinct lithological successions in the cliffs have produced a variety of landslide forms and processes along a 3 km length of coastline in East Devon, from Budleigh Salterton westwards to Littleham Cove. The cliffs are formed in Permo-Triassic red beds, dipping gently eastwards, with mudstone overlain by conglomerate and sandstone. Cliff-top recession over the last 100 years has been determined from Ordnance Survey maps and from aerial photographs. Very large landslide events occur rarely, but have a major influence on cliff-top recession, with tens of metres of retreat taking place. Other smaller events may become self-pcrpetuating landslide systems for several years or tens of years, accounting for recession rates of 1-2m per year locally. One such system, a short distance east of West Down Beacon, has been monitored in detail over the last seven years. A series of geomorphological maps is used to illustrate its earlier development as an example of the influence of landsliding on cliff-top recession.

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## Introduction

Distinct lithological successions in the cliffs have produced a variety of landslide forms and processes along a 3 km length of coastline in East Devon, from Budleigh Salterton westwards to Littleham Cove (;Fig. 1). This part of the coast is formed in Permo-Triassic strata which dip gently at about 5º eastwards (Fig. 2). From Littleham Cove, for the first 1.1 km along to the area known as The Floors, the cliff consists of slightly calcareous mudstone (the Littleham Mudstone Formation). At West Down Beacon and to the east the mudstone is overlain by about 20-25 m of weakly cemented sandy conglomerate (the Budleigh Salterton Pebble Beds). Further along the coast, towards Budleigh Salterton, the conglomerate is overlain by sandstone (the Otter Sandstone Formation). Kalaugher *et al.* (1986) divided this coastline into lengths (Units 1-5) based on the succession exposed in the cliffs (Fig. 2).

The coastal geomorphology varies with the response of the different exposed geological successions to marine erosion and to groundwater flow. Typical cliff profiles for the four main units are illustrated in Figure 3. A substantial storm beach of coarse pebbles and cobbles (mainly derived from the conglomerate) protects the base of the rock cliff from wave action, except in severe tidal · and weather conditions. The toes of large landslides where they protrude beyond the cliff also temporarily protect the base of the cliff from direct erosion.

In terms of hydrogeology, the conglomerate and sandstone formations, with relatively high hydraulic conductivity and porosity, form an unconfined aquifer floored by the mudstone with its much lower hydraulic conductivity. Their broad outcrop at the ground surface in this vicinity enables the aquifer to be recharged directly by infiltrating precipitation. On the cliff, seasonal seepage occurs from the low points of the slightly undulating erosion surface which forms the unconformable base of the conglomerate. Water movement within the Littleham Mudstone Formation takes Place largely by fissure flow, with a few bedding planes forming the dominant flow paths. The pattern of emergent seepage on the cliff indicates that some, but not all, of these bedding planes are in minor sandstone beds within the mudstone.

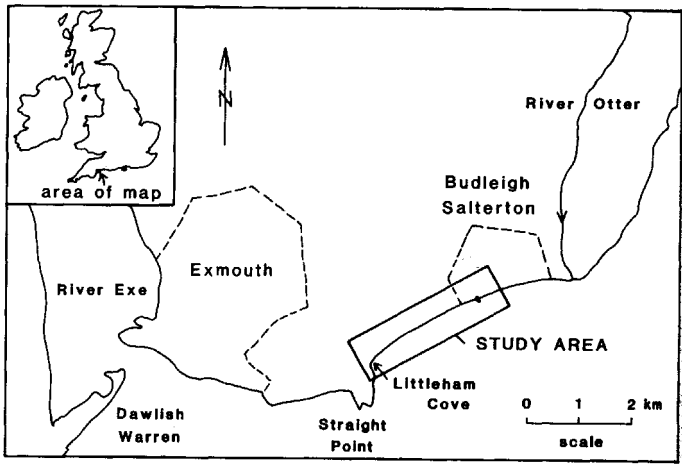


Figure 1. Location of the study area.

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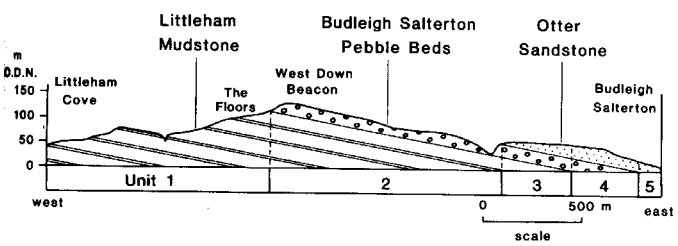


Figure 2. Geological section along the coast between Littleham Cove and Budleigh Salterton. The dividing lines for the units based on the succession in the cliffs are also shown. (vertical exaggeration: x 2.5).

The conglomerate and sandstone invariably form a steep cliff, whereas the underlying mudstone stands at a wide range of slope angles (30-70°). Weathering in response to natural changes of moisture content affects most of the mudstone: on exposure, cliff faces and detached blocks quickly develop a close fissure spacing and then soften. Some thin beds of mudstone and sandstone within the Littleham Mudstone Formation are slightly more resistant to weathering and erosion and hence are responsible for breaks of slope in the profile. Benches develop above these layers and landslide debris can accumulate there. A similar explanation is offered by Conway (1974) for the stepped cliff in Lower Lias mudrocks at the Black Ven landslide, Charmouth.

## History of landsliding

Kalaugher *et al.* (1986) have used maps and aerial and ground photographs to deduce the history of the geomorphological activity between Littleham Cove and Budleigh Salterton. Sufficient detail was extracted for the total coastal recession from 1888 to the present day to be plotted onto 1:10 000 maps (Fig. 4). Only the essential features of the history are repeated below.

Although at the present time in Unit 1 there are only small-scale processes operating which cause little cliff-top recession, there have m the past been massive failures: one of which caused cliff-top recession of about 75 m sometime between 1933 and 1937 at location 'a' (Fig. 4). Some debris from this major rock slide can still be seen on the wave-cut platform at low tide. The major retreat of the cliff base at the western end of the study area occurred between the 1934 and 1956 editions of the O.S. maps. Also during this period there were large changes in the cliff-top position (in two places) suggesting an overall relationship between the rate of marine erosion and the magnitude of mudstone landslides. There have been only minor changes in the position of both the cliff base and top in this area since 1956.

The Floors, a large area of vegetated cliff, appears to have been stable since before 1888. It must be assumed that this area had earlier suffered extremely large landslides and that it will eventually become unstable again.

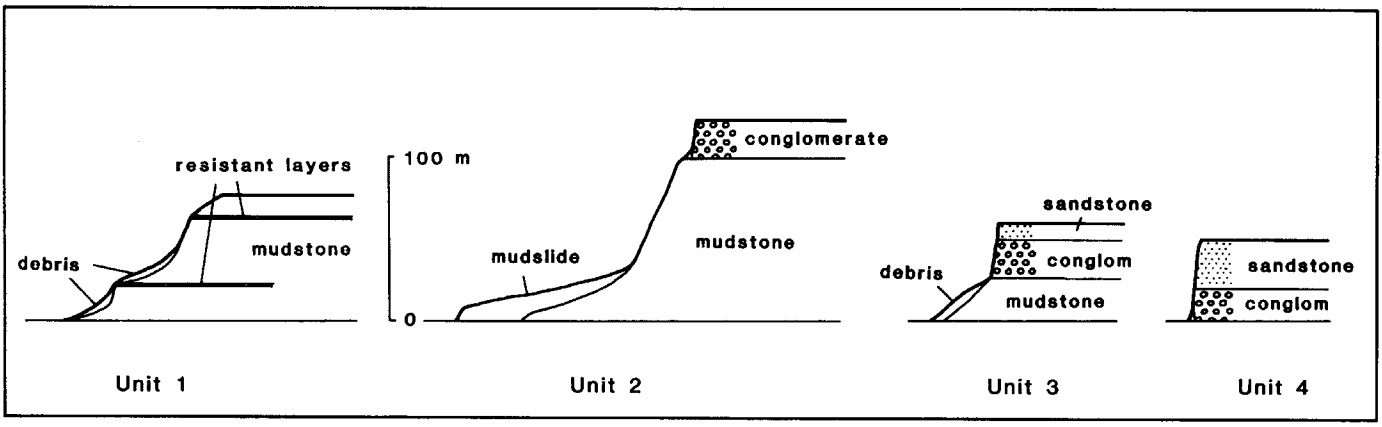


Figure 3. Typical cross sections to show cliff profiles in the main units.

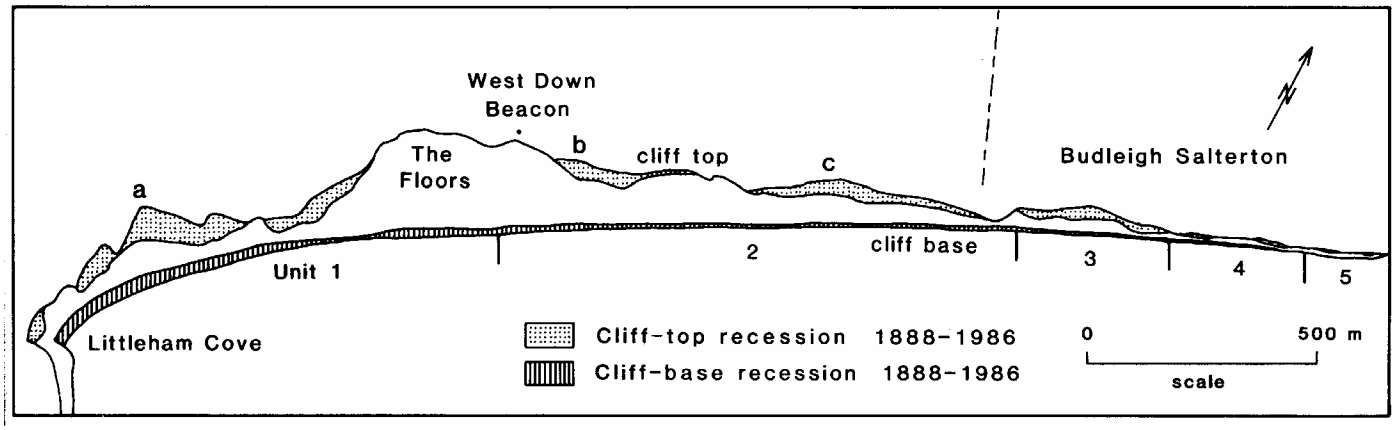


Figure 4. Cliff recession between 1888 and 1986.

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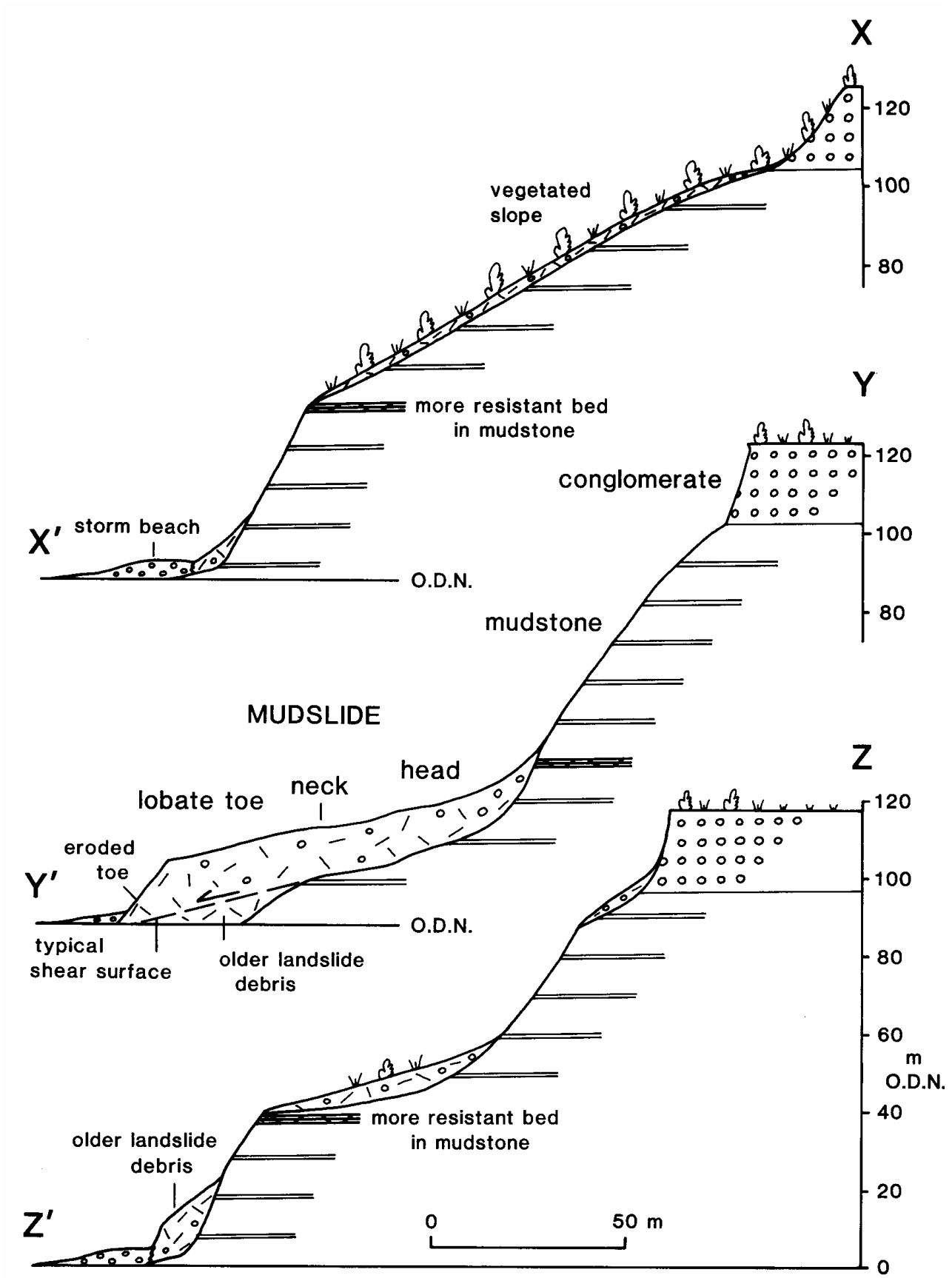


Figure 5. Sketch cross sections, through the West Down Beacon mudslide (YY') and through the cliffs either side (XX' and ZZ'). The lines of the sections are indicated in Figure 6. The mudslide has eroded through the more resistant bed in the Littleham Mudstone.

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| Date | Type | Reference | Source | Scale |
|---|---|---|---|---|
| 1888 | 1 | publ. 1889 | a | 1:2500 |
| 1903 | 1 | publ. 1905 | a | 1:2500 |
| 1928 | 2 | 23993 | b | |
| 1933 | 1 | publ. 1934 | a | 1:2500 |
| Aug 1937 | 2 | R3165 | b | |
| 13 Apr 1946 | 3 | RP 106G/UK/1412 | c | 1:9900 |
| 1955 | 1 | publ. 1956 | a | 1:2500 |
| 22 Apr 1960 | 3 | F2158/RAF/3510 | c | 1:10550 |
| 14 Jun 1961 | 3 | V OS/61/15 | c | 1:25000 |
| 25 Jun 1962 | 3 | V 58/RAF/5213 | c | 1:96500 |
| 26 Jul 1963 | 3 | 21722 543/ RAF/2332 | c | 1:13240 |
| 12 Jan 1969 | 3 | V2 58/RAF/9689 | c | 1:96500 |
| 6 Sep 1971 | 3 | V 39/RAF/3761 | c | 1:25000 |
| 6 Sep 1971 | 2 | P2 OBL39/RAF/ 3761 | c | |
| 9 Apr 1972 | 2 | A 223887-8 | b | |
| 1975 | 3 | 75 266 | a | 1:7670 |

Types: Lmap; 2:oblique aerial photo; 3: vertical aerial photo. Sources: a:Ordnance Survey; b:Aerofilms Ltd; c:Department of the Environment.
Table 1. Sources of data prior to 1979.

The landslide near West Down Beacon within Unit 2 (at location 'b' in Fig. 4), which is known from aerial photographs to have developed its present form in the 1960s, is described in detail in the tbllowing sections. The other presently active large landslide in this unit (at location 'c', Fig. 4) is also known to have developed at about this time.

Collapses of the cliffs in Units 3, 4 and 5 near Budleigh Salterton have made it necessary to re-route parts of the cliff-top path every twenty or thirty years. The most recent collapse was in the 1960s. Unit 3, in which mudstone is exposed in the lower cliff, has receded faster than Units 4 and 5.

## The landslide at West Down Beacon

The active landslide at West Down Beacon has been studied in detail since 1979 (Kalaugher and Grainger 1981) and well illustrates the relationship between landsliding and cliff-top recession in this area. In recent years the main activity has been concentrated in a mud-slide which has eroded an embayment into the lower cliff 200m east of West Down Beacon. The argillaceous matrix of the mudslide is derived from weathered and wetted mudstone and encloses clasts of unweathered mudstone blocks of all sizes, and cobbles from the conglomerate.

Behind the mudslide, the elevation of the clifftop is 123 m O.D.N. A cross section (YY' of Fig. 5) shows a concave slope, in contrast to the stepped cliff profiles on either side (sections XX' and ZZ'). The basal shear surface shown in Figure 5 is inferred from the survey measurements made before and after movements of the mudslide (Grainger and Kalaugher 1987) and from a seismic refraction survey at the toe. A geomorphological sketch map, Figure 6, shows the shape of the mudslide in plan view and the area supplying it with debris.

The following two sections describe the development of the landslide area before and after late 1979 respectively.

## Development of the landslide area before 1979

The development of landsliding at West Down Beacon, before direct field observations were started in 1979, has been investigated mainly by reference to aerial photographs and published maps. The sources of data are listed chronologically in Table 1.

The position of the top edge of the cliff (Figure 7) is recorded on the Ordnance Survey 1:2500 maps at different dates with sufficient accuracy to determine changes. The oblique aerial photographs, mainly taken looking'west from Budleigh Salterton, give an indication of the amount and position of landslide material on the beach at certain times. Two rather poor quality oblique photographs taken in 1928 and 1937 show no protruding mudslide toes at West Down Beacon. The cliff profile there at that time appears to have consisted of a sloping bench which separated lower and upper steep slopes in mudstone, rather like the present profile to the east of the active landslide (ZZ' on Fig. 5).

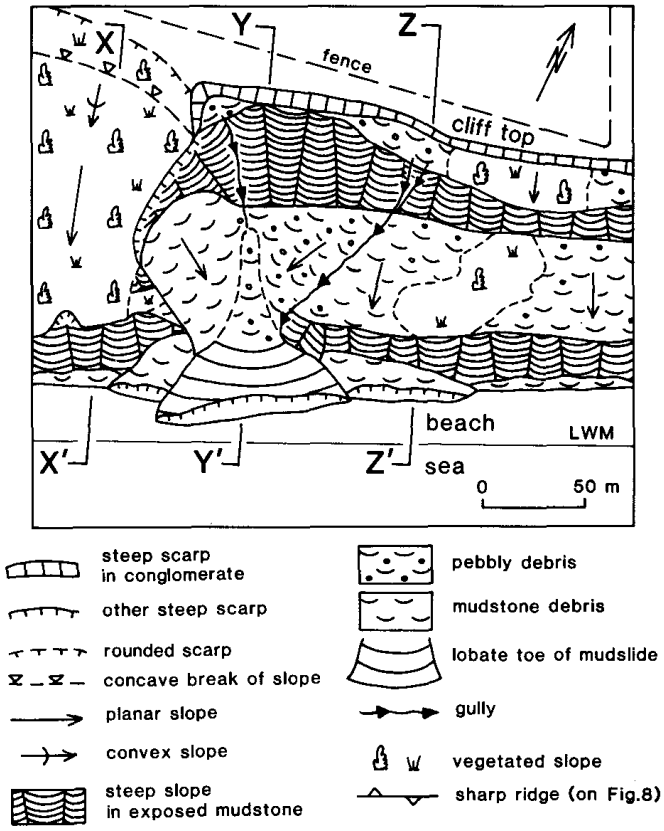


Figure 6. Geomorphological sketch map of the West Down Beacon landslide (August 1981). See Figure 5 for sections XX', YY' and ZZ'.

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Outline geomorphologieal maps have been constructed from six of the sets of vertical aerial photographs, those for 1946, 1960, 1963, 1969, 1971 and 1975 (Figure 8). The earliest vertical coverage (photographed in 1946) reveals that there had been considerable recession of the clifftop since the 1934 Ordnance Survey map. Recession extended almost as far back as the position shown'on the 1956 Ordnance Survey map. In 1946 (Figure 8a) there was a prominent sharp-crested ridge (A) in the mudstone bedrock of the landslide area. The cliffto the east of this ridge had the characteristic profile described in the previous section, with a very steep backscarp in the conglomerate at the top and a network of shallow gullies eroded into the mudstone by surface water. Immediately west of the ridge, a more pronounced gully (B) was developing, with a small debris accumulation at its lower end. West of this gully the cliff top curved inland slightly, as it does in 1986: the slope below, except for the small sea cliffat its base, had also by 1946 been stable long enough for vegetation to become established.

By April 1960 (Fig. 8b) further loss of cliff top had occurred to the east, leaving a distinct promontory (C) above the ridge (A), which still persisted as a feature. The eroded remnants of debris (D) piled against the sea cliff probably relate to the major falls from the cliff top. Comparison of the 1956 Ordnance Survey map with the 1960 aerial photograph indicates that the main falls took place between the time of the survey (in *1955* for the 1956 map) and 1960, and that the coastal footpath had to be re-routed. Only minor changes are apparent on further sets of vertical aerial photographs taken in t961 and 1962. On the next available coverage of July 1963 (Fig. 8c), very little alteration of the cliff top had occurred but a substantial amount of debris (E) had slid from the intermediate bench over the sea cliff, to the east of the ridge. The gully (B) west of the ridge had continued to deepen: arcuate forms (F) on its western flank are assumed to have been rotational landslide backscarps, created as the margin of the vegetated slope became undercut.

A very small-scale vertical photograph dated January 1969 supplies the next available information. Despite the lack of detail, an approximate map has been sketched because very large changes are evident (Fig. 8d). Two massive mudslide or debris slide lobes (G) extended across the beach at least 40 m beyond the foot of the sea cliff. The more easterly lobe appears to have originated near the cliff top, but neither were connected with significant falls of conglomerate. Only the tip of the promontory (C) had fallen. The ridge feature had disappeared, presumably having collapsed and disintegrated to form one of the lobes. The occurrence of a major landslide at about this time is corroborated by a local resident, Mr R.M. Cox of Budleigh Salterton *(pers. comm.).* The lack of photographs and map revisions between 1963 and 1969 does not allow accurate dating of this major event at West Down Beacon.

The mudstone ridge must have formed a supporting buttress and its loss evidently destabilised the top of the cliff: a major collapse of the conglomerate had taken place from the promontory before the next aerial photograph survey, in September 1971 (Figure 8e). The flow of conglomerate debris (H) reached over half way down the cliff onto the head of the main mudslide. The toe of this new mudslide (I) had again extended well across the beach and had possibly, as drawn in Figure 8e, overridden the remnants of the lobes visible in 1969. The oblique photograph taken at the same time shows the surface of the mudslide sloping at a steep angle towards the sea, indicating a relatively dry accumulation of debris. Six months later, when another oblique photograph was taken, the toe was still protruding.

By 1975 (Fig. 8f) a smaller mudslide (J) had become established, fed from the west by debris resulting from activity concentrated in the mudstone cliff (K) and from small falls of conglomerate. This pattern of landslide activity has persisted until 1986,

It should be noted that the maps of Figure 8, all drawn from vertical aerial photographs, have been adjusted to the same Scale, and any non-vertical distortion modified to correct the positions of permanent features recognised on the 1946 photographs.

## Observations of the landslide, 1979-86

The toe of the mudslide was surveyed after several of its movements between 1979 and 1985. Grainger and Kalaugher (1987) give details of these surveys (and of the

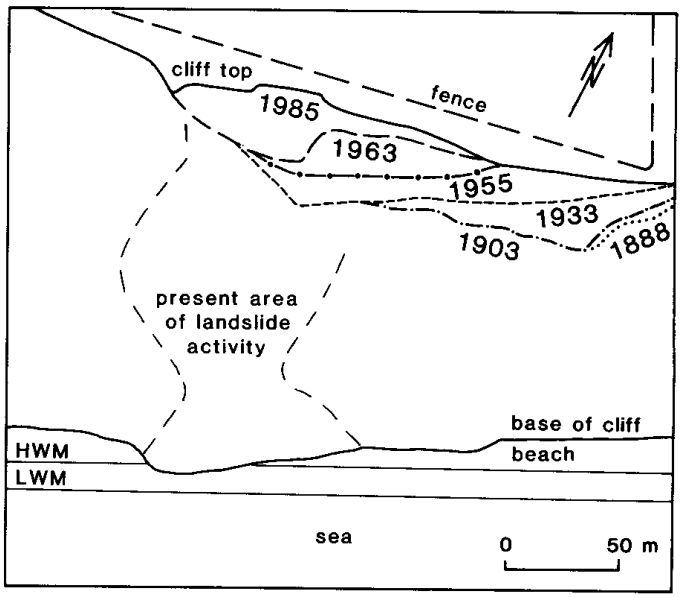


Figure 7. Retreat of the cliff top near West Down Beacon. The line for 1888 is derived from the Ordnance Survey 1:2500 map published in 1889; for 1903, 1933, and 1955 the lines are from the revisions published in 1905, 1934 and 1956 respectively. The line for 1963 is from an aerial photograph and that for 1985 from a field survey.

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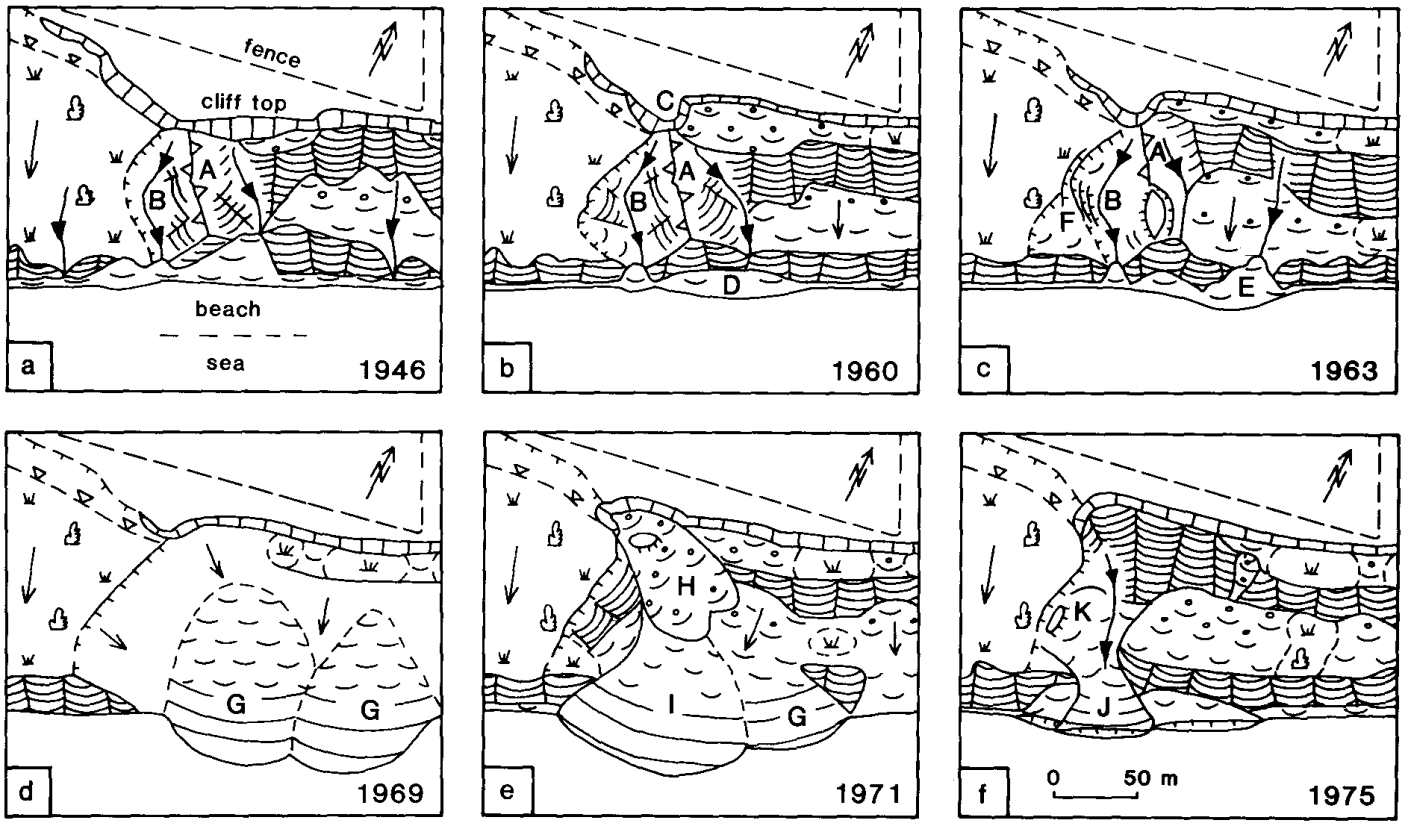


Figure 8. Geomorphological sketch maps showing the development of the landslide from 1946 to 1975, drawn from vertical aerial photographs. For the key to the symbols, see Figure 6. The mudstone bedrock symbol is largely omitted from 8d because of the uncertainty of interpretation resulting from the small scale of the 1969 photograph.

close monitoring of the one movement occurring during 1985). Within 5 years a total displacement of 100 m took place in a series of eleven separate surges with displacements of between 5 and 15 m. Some, but not all, of the surges were directly related to cliff-top recession in that they were initiated by large falls of conglomerate. At least one surge was initiated by a fall of mudstone which did not directly affect the cliff top.high-oblique black and white 35 mm aerial photography was started in September 1979 and, from 1981, has been flown soon after almost all of the mudslide movements. The resulting photographs have been examined stereoscopically so that geomorphological changes could be interpreted and field observations enhanced (Kalaugher *et al.* 1986). The dates of the photographs are given in Grainger and Kalaugher (1987) together with brief descriptions of the significant changes. An examination has also been made of the vertical and oblique aerial photographic coverage between 1979 and 1986 available from other sources.

## Conclusions

The cliff-top recession in the vicinity of West Down Beacon can be seen to be closely related to the landsliding. Since the development of the mudslide to its present form, when the central ridge collapsed just prior to 1969, there has been a marked increase in the rate of cliff-top recession (Fig. 7). Indeed the falls from the brittle conglomerate at the cliff top initiated some of the mudslide surges. The mudslide has removed debris which would otherwise have continued to bank up against the cliff.' the cliff top has remained exposed and liable to fall again, possibly initiating another surge of the mudslide.

The active landslides in Unit 2 are found where the low points of the undulations at the base of the conglomerate channel the discharge of groundwater. As the cliff-top recedes, the outcrops of the low points migrate laterally and so do the landslides. There is at the present time a threat developing for West Down Beacon itself as the neighbouring landslide is removing lateral support and leaving this highest point of the cliffs increasingly isolated.

Elsewhere between Littleham Cove and Budleigh Satterton the pattern of cliff-top recession varies with the type of landsliding which in turn is controlled by the lithology and groundwater conditions. Some very large landslides have occurred in Unit 1 where the cliff is formed entirely of Littleham Mudstone. Rather than being initiated by cliff-top recession, the landslides are here the immediate cause of the sometimes large and sudden recessions of the cliff top: such events may be followed by

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a period of many tens of years during which there is very little recession. The Floors area, for instance, has been stable for a very long time (more than 100 years) but must earlier have been the site of a massive landslide. Although there is an overall tendency for recession to even out irregularities in the line of the cliff top over a timescale of many hundreds of years, on the shorter timescale of tens of years indentations develop in the active landslide areas. By observing recent patterns of cliff-top recession it is possible to predict where further erosion will be concentrated.

*cknowledgements: The* authors would like to thank J. Saunders, J. Jones and Mrs Maureen Pugh for photographic work, R.L.P. Hodgson for continuing the field work, D.C. Baker and B.M. Evans for technical assistance, and R.M. Cox for help with the history of the site.

## References

Conway, B.W. 1974. The Black Ven landslip, Charmouth, Dorset. *The Institute of Geological Sciences,* Report No. 74/3. H.M.S.O., London.

Grainger, P. and Kalaugher, P.G. 1987. Intermittent surging movements of a coastal landslide. *Earth Surface Processes and Landform& 12(6),* 597-603.

Kalaugher, P.G. and Grainger, P. 1981. A coastal landslide at West Down Beacon, Budleigh Salterton, Devon. *Proceedings of the Ussher Society, 5,* 217-221.

Kalaugher, P.G., Grainger, P. and Hodgson, R.L.P. 1986. Cliff stability evaluation using geomorphological maps based on oblique aerial photographs. *Preprints of papers for the 22nd Annual Conference of the Engineering Group of the Geological Society held at Plymouth Polytechnic 8-12 September 1986,* 157-167.

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*Read at the Annual Conference of the Ussher Society, January 1987*

# Geochemistry of the Tintagel Volcanic Formation

D. ROBINSON
D. SEXTON

Robinson, D. and Sexton, D. 1987. Geochemistry of the Tintagel Volcanic Formation. *Proceedings of the Ussher Society, 6.* 523-528.

Geochemical data of 19 samples from the Tintagel Volcanic Formation have been analysed by factor analysis. This suggests that only 7% of the data variance still relates to the original magmatic character of the rocks. Despite this low figure it has still been possible to recognize the alkali basalt character of the sequence and demonstrate that the progressive eruption of less evolved material with time may be related to the tapping of a fractionated magma chamber.

*D. Robinson and D. Sexton. Department of Geology, University of Bristol. Bristol BS8 IRJ.*

## Introduction

The Tintagel Volcanic Formation (TVF) is an interbedded series of slates, volcaniclastics and lavas exposed on the north Cornish coast between Trebarwith Strand and Boscastle. The Formation. which attains a thickness of over 90 m, is of Lower Carboniferous age (Austin and Matthews 1967; Freshney *et al.* 1972: Selwood and Thomas 1986). Itte sequence has been subjected to several phases of deformation giving complex field relationships, the interpretation of which is the subject of some controversy (Sanderson 1979; Hobson and Sanderson 1983; Selwood and Thomas 1986).

The finer grained volcanic products in the TVF have a well developed penetrative foliation formed by abundant chlorite. The chlorite is the main phase formed during the Variscan metamorphism and is accompanied by albite, epidote, minor actinolite, muscovite and biotite (Phillips, 1928; Robinson and Read 1981; Primmer 1985a,b). Study of the pelitic units of the region (Brazier *et al.* 1979; Primmer 1985 a,b) has shown that the rocks in this area of southwest England record the highest grade of Variscan metamorphism, which reached greenschist facies with temperatures of 450-500°C (Primmer 1985 a,b). In an analysis of two samples from the TVF outcrop at Trebarwith Strand, Robinson and Read (1981) demonstrated also that a low greenschist facies metamorphism had developed. Porphyroblastic biotite, actinolite and albite, overgrowing the foliation in the rocks of this area, have been interpreted as equilibrium phases formed in a post-kinematic recrystallization event during regional stress relaxation (Robinson and Read 1981; Primmer 1985a, b).

Much work has been undertaken on the geochemical character of Variscan volcanic rocks m southwest England in order to identify the magma series and to aid in the interpretation of the plate tectonic setting in which they were erupted or emplaced (e.g. Floyd 1976, 1982, 1983). This work has concentrated on lavas and high level intrusives and little has been undertaken on the volcaniclastic components of the volcanism. The obvious reason being that such rocks are most susceptible to alteration and low grade metamorphism with the result that initial magmatic chemical characteristics are more likely to be obliterated. A review of the effects of these processes on basic lavas and intrusives in the region has been given by Floyd (1982, 1983). It has been shown that many elements were mobile and in order to establish primary magmatic features attention is best restricted to the immobile elements (e.g. Ti, P, Zr, Y, Nb, REE). The aim of this study has been to establish if any chemical signature of magmatic processes still remains in the TVF samples. The TVF belongs to the north Cornwall - north Devon belt of Variscan volcanism of which the lavas and intrusives show an alkali basalt character (Floyd, 1976, 1983).

## Samples and analytical methods

Nineteen samples were collected from outcrops of the TVF at Saddle Rocks, Bossiney Haven and Trebarwith Strand, with an attempt being made to place samples in a relative stratigraphic order. Only fine grained samples of tuffaceous-like material were chosen, with veins, vugs etc being avoided and a minimum of 2Kg per sample collected. Whole rock analysis was undertaken using an XRF technique for most major and all trace elements following the procedures of Harvey *et al,* (1973) and Robinson and Bennett (1981) for major and trace elements respectively. 'Wet' chemical methods were used for the determination of FeO, $CO_2$ and loss on ignition (LOI).

Because of the variability of the processes that have affected the TVF the data were processed using R-mode factor analysis. This multivariate technique has been

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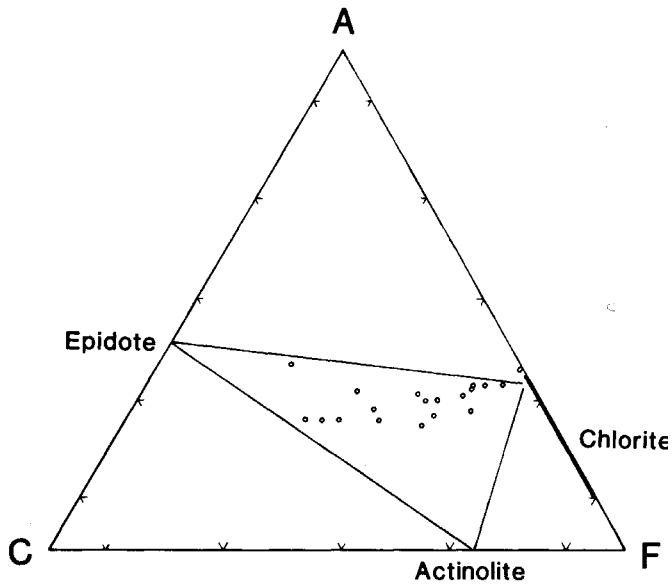

Figure 1. A-C-F diagram for Tintagel Volcanic Formation samples representative of lower greenschist levels for mafic rocks, + albite, + sphene, ± quartz, ± biotite, ± white mica, ± calcite.

used as an aid in the interpretation and in an attempt to quantify the processes giving rise to the geochemical diversification. The R-mode factor analysis which involves the examination of the large number of interrelationships between variables to produce a smaller number of factors which ideally account for much of the variance of the data. The application of.factor analysis to geological problems has been described by Spencer (1966) and there have been many uses of the technique such as in basaltic geochemistry (Shaw et al. 1974) and sedimentary geochemistry (Reeves and Saadi 1974). The reduction of the raw data set to the smaller number of factors is usually an aid in the interpretation, but it must be understood that the "factor" is used in the mathematical sense and it is the interpretation that assigns geological processes to these factors. The importance of each factor is denoted by the eigenvalue which indicates the proportion of the total data variance accounted for by each factor.

## Geochemistry

Major elements All samples are extensively altered and have high water (2-14%) and variable CO2 (0-4%) contents as well as variable oxidation ratios. All but one of the samples when plotted on an ACF diagram, representative of a low greenschist level, fall within the three-phase field of chlorite-albite-actinolite (Fig. 1). Although petrographic examination has not been undertaken it is to be expected from this data that the rocks have also the typical greenschist assemblages described from meta-volcanic rocks in this region (Robinson and Read 1981; Primmer 1985a, b).

| Factor | Percentage | | Cumulative percentage |
|---|---|---|---|
| 1 | 32.1 | | 32.1 |
| 2 | 20.1 | | 52.2 |
| 3 | 10.7 | | 62.9 |
| 4 | 10.4 | | 73.3 |
| 5 | 7.3 | | 80.6 |
| **Variable** | **Communality** | **Variable** | **Communality** |
| $SiO_2$ | 0.774 | Height | 0.567 |
| $Al_2O_3$ | 0.91 | Sr | 0.953 |
| $TiO_2$ | 0.841 | Rb | 0.762 |
| $Fe_2O_3$ | 0.875 | Y | 0.723 |
| FeO | 0.617 | Cr | 0.859 |
| CaO | 0.973 | Ni | 0.807 |
| MgO | 0.867 | Nd | 0.706 |
| $Na_2O$ | 0.856 | Sm | 0.692 |
| $K_2O$ | 0.919 | Ce | 0.884 |
| MnO | 0.678 | Ba | 0.609 |
| $P_2O_5$ | 0.748 | La | 0.836 |
| LOI | 0.866 | Nb | 0.927 |
| $CO_2$ | 0.782 | Zr | 0.908 |

Table 1. Percentage values for factors 1 to 5 and communality values of each of the 26 variables used in the statistical analysis

PROMAX FACTOR MATRIX

| Variable | Factor 1 | Factor 2 | Factor 3 | Factor 4 | Factor 5 |
|---|---|---|---|---|---|
| $SiO_2$ | 0.769 | | | 0.328 | |
| $Al_2O_3$ | 0.752 | | | | 0.263 |
| $TiO_2$ | | | | 0.692 | 0.473 |
| $Fe_2O_3$ | 0.433 | | -0.606 | | 0.259 |
| FeO | 0.718 | -0.325 | | | |
| CaO | -0.372 | | | -0.78 | |
| MgO | | 0.603 | | 0.541 | |
| $Na_2O$ | 0.401 | -0.718 | 0.486 | | |
| $K_2O$ | | | -0.881 | | |
| MnO | | | 0.534 | -0.493 | |
| $P_2O_5$ | -0.276 | | | 0.256 | 0.926 |
| LOI | -0.909 | | | | |
| $CO_2$ | -0.827 | | | | |
| Height | | -0.338 | | | -0.655 |
| Sr | 0.393 | | | -0.875 | |
| Rb | | | -0.823 | | |
| Y | | -0.258 | | | 0.73 |
| Cr | 0.302 | 0.835 | 0.302 | | |
| Ni | | 0.842 | | | |
| Nd | | -0.533 | 0.248 | | 0.491 |
| Sm | | 0.549 | 0.685 | | 0.351 |
| Ce | | | | | 0.834 |
| Ba | | | | | 0.776 |
| La | | | 0.252 | -0.259 | 0.823 |
| Nb | | | | | 0.907 |
| Zr | | | | | 0.817 |

Loadings less than 0.25 (6.25% variance) omitted

Table 2. Promax factor matrix showing factor loadings for each variable.

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A molecular norm recalculation (Irvine and Barager1971), but using anhydrous, normalized data and a $Fe_2O_3$/FeO ratio of 0.15, was undertaken. This shows a mixture between tholeiitic (6) and alkali basalt (13) magma series with a range from ankaramite to andesite rock types. This is a larger range in compositional type than reported from previous works which have shownthat volcanics in southwest England are of the bimodal basic-acid variety (Floyd 1983). The range seen in the normative analysis here is probably a response to the variable alteration between different samples, in terms ofoxidation, hydration, carbonation and element mobility during alteration and metamorphism.

## Factor analysis

Factor analysis of the data set has extracted 5 factors accounting for just over 80% of the data variance (Table 1). The analysis had reasonable success in accounting for the variance of many variables, ranging from 15 elements with high communalities of > 0.8, to 5 variables withvalues of < 0.7 showing that the treatment has not been successful in "explaining" their distribution.

The promax factor matrix (Table 2) gives the 5 factors and the affinity of each variable to the particular factors in terms of factor loadings. Factor 1, accounting for a data variance of over 30% is the most important in terms of the overall variation in the data set. High positive loadings are present for $SiO_2$, $A1_2O_3$ and FeO and high negative loading for LOI and $CO_2$ content (Table 2). Factor 1 appears to be an effect of dilution, as increasinghydration and carbonation results in lower values of the major chemical components and vice versa. It also highlights one of the disadvantages of factor analysis of geochemical data in that one major factor is usually related to the constant sum effect. Factors 2, 3 and 4each link variables that will have been mobile during alteration and metamorphic processes, namely $Na_2O$;$K_2O$ and Rb; CaO and Sr respectively, which suggests that these factors are related to non-magmatic processes. The association of high loadings in these factors (Table 2) for MgO, Cr and Ni; Sm; and $TiO_2$ suggests the abundances of these elements are also controlled to some degree by secondary features.

Factor 5, representing only some 7% of the variance of the data set, shows high loadings for elements such as $P_2O_5$, Y, Ce, La, Nb and Zr. These are regarded as the more immobile elements during processes of alteration and low grade metamorphism of basic rocks in southwest England (Floyd, 1976). This factor is interpreted therefore as representing the sole remnant in the geochemical data that is indicative of primary magmatic processes. This primary process will have produced some element variation and the relative "amount" of each sample related to this factor is given by its factor source. These sources are plotted against element abundances in Fig 2 a and b. Elements with high loadings for this factor show very limited scatter (e.g. Nb, Zr and Ce, Fig 2a and

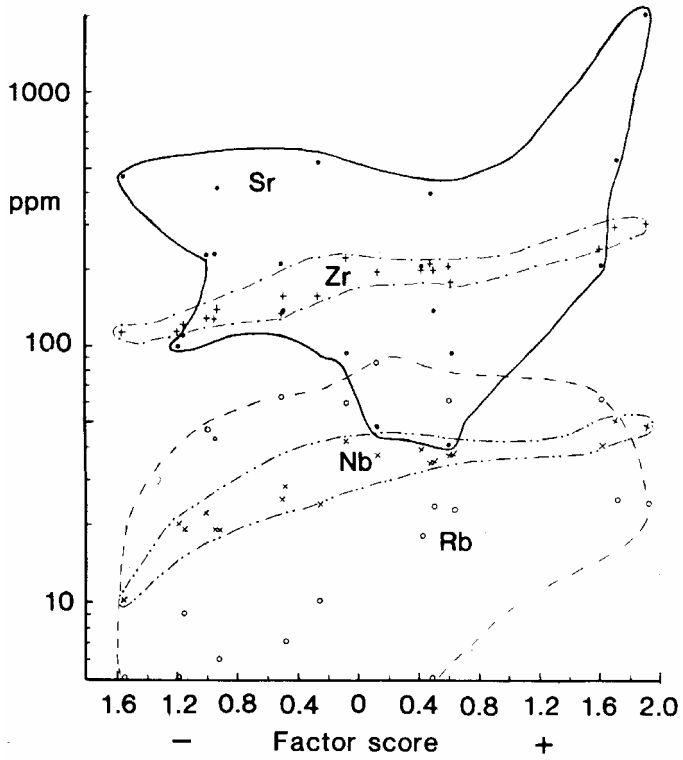
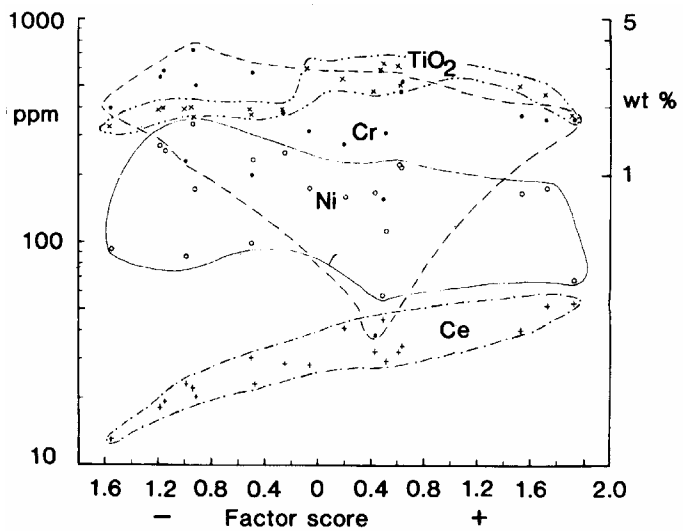



Figure 2. Plot of elemental abundances v factor scores for TVF samples. a) • = Sr; + = Zr; x = Nb; o = Rb; all values in ppm. b) x = $TiO_2$, values in wt. %; • = Cr; o = Ni; + = Ce; values in ppm.




b), but define a trend from low to higher concentrations with change from negative to positive factor scores respectively. In marked contrast, the mobile elements such as Sr and Rb show a great scatter and no relation ship to factor score. The elements Cr and Ni show no definitive relationship in these diagrams suggesting that they do not retain characteristics of the primary magmatic system; variation in Cr and Ni as a result of metamorphic segregation has also been documented by Floyd (1976). The ferromagnesian elements (FeO, MgO

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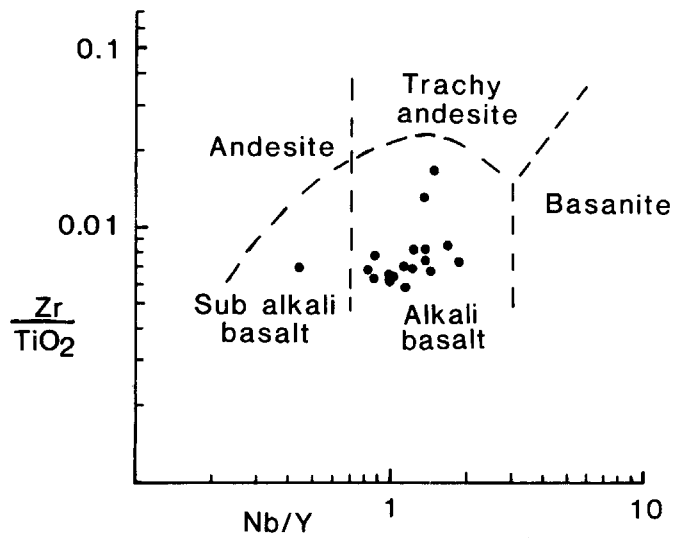


Figure 3. $Zr/TiO_2$ v Nb/Y discrimination diagram for magma type after Winchester and Floyd (1977).

Cr and Ni) however, have been used by Floyd (1983) to characterize fractionation processes in southwest England volcanic rocks. Certainly at the metamorphic grade attained by the TVF, the evidence from the factor analysis (Table 2, Fig 2 a and b) suggests that there is no magmatic fingerprint evident in the distribution of these elements. This is supported by Zr v Ni and Zr v Cr plots which, although defining crude negative relationships, show great scatter. Correlation coefficients for these pairs have low values of-0.351 and-0.363 respectively and do not appear significant.

Titanium is also regarded as one of the immobile elements but here, however, $TiO_2$ has a low loading for factor 5 (Table 2). Although it shows a low scatter in Fig. 2b there is no consistent variation in $TiO_2$ content with factor score as seen with Nb, Zr and Ce. This may suggest that $TiO_2$ has been mobile to some extent and this can occur in response to acidic fluids. Of some surprise also is the appearance of the LIL element Ba with a high loading for factor 5 (Table 2); it is an element not normally associated with other immobile elements and this may be a coincidence considering that the communality for Ba is low (Table 1).

## Magma type and fractionation processes

Magma type for the TVF has been defined using an association of elements that have the highest loadings for factor 5. Using a plot of $Zr/TiO_2$ v Nb/Y (Winchester and Floyd 1977) it is characterized as an alkali basalt, which is typical for the Upper Devonian and Lower Carboniferous volcanics of north Cornwall and Devon (Floyd 1976, 1983). The presence in southwest England of distinct comagmatic suites has been demonstrated by Floyd (1983), who has argued that constant incompatible element ratios for each volcanic centre defines one suite from another and the differences are related to variations in mantle source composition and/or variable amounts of melting. From Figure 4 it can be seen that the ratios

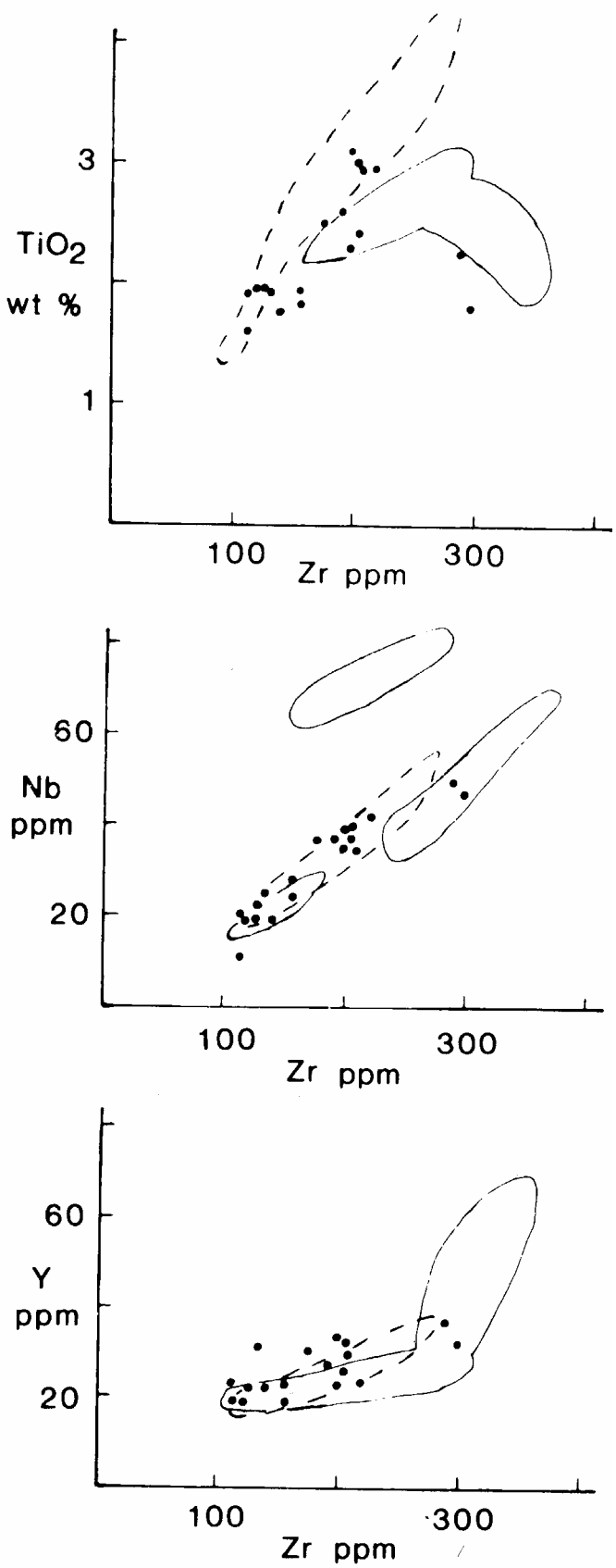


Figure 4. $TiO_2$ v Zr, Nb v Zr and Y v Zr plots showing TVF samples (•). Area enclosed by dashed and solid lines refer to southwest England alkali basalt extrusive and intrusive rocks respectively, after Floyd (1983).

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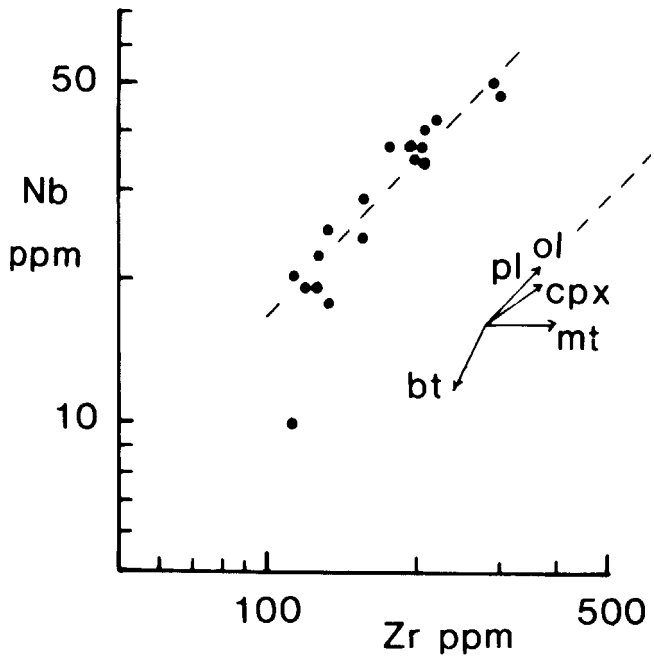


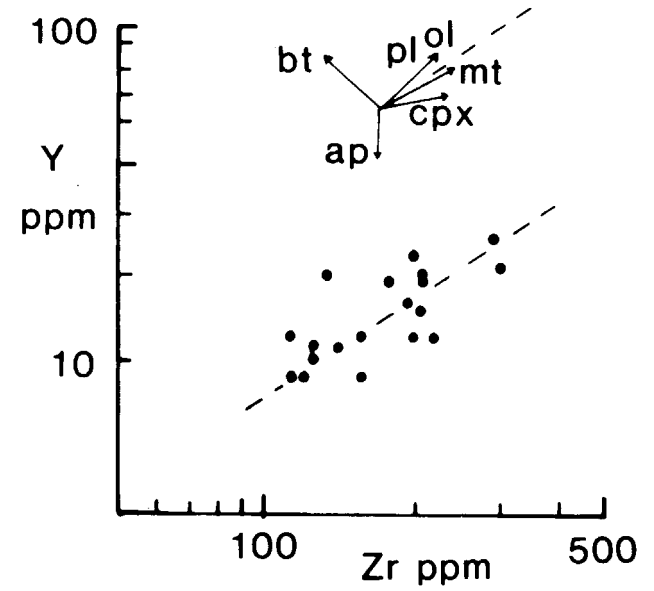


Figure 5. Nb v Zr and Y v Zr plots for TVF samples. Trends resulting from fractional crystallization of various phases shown by vector insets. pl = plagioclase, ol = olivine; cpx = clinopyroxene; mt = magnetite; bt = biotite; ap = apatite.

between Nb and Zr and Y and Zr are relatively constant, suggestive of a comagmatic suite. The data overlap most closely those from other alkali basalt types of Upper Devonian age and of extrusive character, rather than those from the intrusives of Devonian and Carboniferous age (Floyd 1982, 1983). This would suggest that the source of the TVF meta-volcanics is not related to fractionation of high level Carboniferous intrusives but has greater affinity to the melting source that gave rise to the Upper Devonian extrusives.

It is of interest to note that in Figure 4 there is most spread in the $TiO_2$ v Zr plot and this relates to the relatively low factor loading seen for $TiO_2$ relative to Factor 1 (Table 2).

In the comagmatic alkali basalts sequences of the region, low pressure fractionation of clinopyroxene, magnetite and olivine in the intrusives, and plagioclase in the extrusives has given rise to element variation patterns (Floyd, 1983). It is not possible to use the more diagnostic marie elements from the TVF rocks to deduce fractionation trends because of their mobility as discussed earlier. Nb and Y v Zr define trends that could be related to a fractionation process (Fig. 5), although mafic phases could be responsible in either case, it is plagioclase and olivine that show the most similar trends in the two diagrams. This accords well with the dominant plagioclase fractionation in Devonian alkali basalt extrusives (Floyd 1983) and the link shown earlier in relation to the present data and the Devonian extrusives shown in Figure 4.

## Chemical variation with stratigraphic position

In the promax factor matrix it is of note that the variable, of height within the sequence, shows a moderate negative loading for factor 5, which suggests some link between position and magmatic character. An attempt to semi-quantify this feature was undertaken by plotting factor score for each sample against relative position in the sequence (Fig. 6). As shown in the diagram there is a "zigzag" pattern to the sequence but overall there is a trend from positive factor scores at Iow levels to negative factor

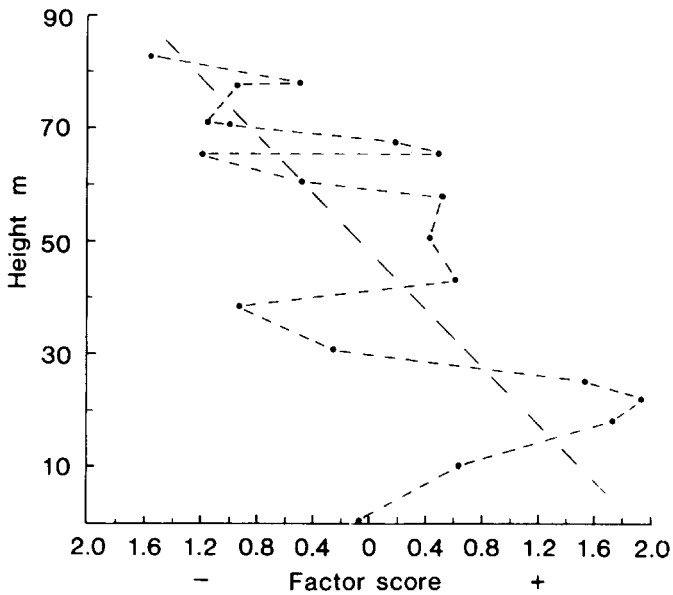


Figure 6. Plot of approximate position of TVF samples within the stratigraphic sequence against factor score. Dashed line represents regression line.

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scores at higher levels, as illustrated by the regression line. As shown in Figure 2a and b the change from positive to negative factor scores is linked to fraction-ation trends from higher to lower values of incompatible immobile trace elements. This suggests that the overall trend from the source giving rise to the TVF was for the most fractionated products to be erupted first followed by increasingly less fractionated material with time. The most probable cause of this was that the magma chamber giving rise to the volcanism was fractionated to some degree. This type of trend and cause has also been reported from other volcanic centres as documented by Fisher and Schmincke (1984). It is also interesting to speculate whether the zig-zag pattern shown in Fig. 6 may be related to fractionation of individual magma pulses within the overall evolution of the magma system. A much more detailed sampling survey would be required before such a proposal could be firmly supported.*Tectonic setting*

Designation of tectonic setting for basic rocks can be suggested from $TiO_2$x $10^{-2}$-Zr-Yx3 and Zr/Y v Zr plots. In the case of the TVF samples the data suggests a within-plate type of volcanism. This setting is typical for Upper Palaeozoic volcanics in southwest England irrespective of their character (Floyd 1982) and so the TVF samples, despite their alteration and metamorphism, concur with previous models of tectonic environment.

## Conclusions

The major and trace element geochemistry of 19 samples from the TVF shows most relation to the post magmatic alteration and metamorphic processes suffered by the sequence. Factor analysis of the data supports this inter-pretation and shows that factor 5 accounting for only 7% of the data variance links the elements $P_20_5$, Nb, Ce, La, Zr, Ba, and Y.

Analysis of the variation in these elements suggests that the TVF sequence is of an alkali basalt character erupted in a within-plate setting and as such accords with previous accounts of the volcanism in southwest England. The variation in these data also suggests that the TVF is more closely linked to the mantle melt sources of Upper Devonian extrusives with high-level fractionation of plagioclase and olivine. Variation between samples throughout the thickness of the formation suggests that eruption of less evolved material occurred progressively with time, and is interpreted as the tapping of a differentiated magma chamber.

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## References

Austin, R.L. and Matthews, S.C. 1967. *In: Annual report of the Institute of geological Science for 1966.*

Brazier, S., Robinson, D. and Matthews, S.C. 1979. Studies of illite crystallinity in southwest England. Some preliminary results and their geological setting. *Neues Jahrbuch Geologique Palaeontologie Montashe 11,* 641-662.

Fisher, R.V. and Schimincke, H.-U. 1984. *Pyroclastic Rocks,* Springer-Verlag, Berlin.

Floyd, P.A. 1976. Geochemical variation in the greenstones of SW England. *Journal of Petrology, 17,* 522-545.

Floyd, P.A. 1982. Chemical variation in Hercynian basalts relative to plate tectonics. *Journal of the Geological Society, 139,* 505-520.

Floyd, P.A. 1983. Composition and petrogenesis of the Lizard complex and pre-orogenic basaltic rocks in southwest England. *In:* Hancock, P.L. (ed.): *The Variscan Fold Belt in the British Isles,* 130-152; Hilger, Bristol.

Freshney, E.C. McKeown, M.C. and Williams, M. 1972. Geology of the coast between Tintagel and Bude. *Memoir of the Geological Survey of Great Britain.*

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 fluoresence spectrometry. *X-ray spectrometry,* Z 33-44.

Hobson, D.M. and Sanderson,D.J. 1983. Variscan deformation in southwest England. *In:* Hancock, P.L. (ed.): *The Variscan FoM Belt in the British Isles,* 108-129; Hilger, Bristol.

Irvine, T.N. and Barager, W.R.A. 1971. A guide to the chemical classification of the common igneous rocks. *Canadian Journal of Earth Sciences, 8,* 523-543.

Phillips, F.C. 1928. Metamorphism in the Upper Devonian of north Cornwall. *Geological Magazine, 65,* 541-556.

Primmer, T.J. 1985a A transition from diagenesis to green-schist facies within a major Variscan fold/thrust complex in south-west England. *Mineralogical Magazine, 49,* 365-374.

Primmer, T.J. 1985b, Low-grade Variscan regional meta-morphism in southwest England. *Unpublished PhD. Thesis, University of Bristol.*

Reeves, M.J. and Saadi, T.A.K. 1972. Factors controlling the deposition of some phosphate bearing strata from Jordan. *Economic Geology, 66,* 451-465.

Robinson, D. and Bennett, M.C. 1981. XRF determination of 19 trace elements in international geochemical reference standards. *Geostandards Newsletter, 5,* 175-181.

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

Sanderson, D.J. 1979. The transition from upright to recumbent folding in the Variscan fold:belt of southwest England: a model based on the kinematics of simple shear. *Journal of Structural Geology, 1,* 171-180.

Selwood, E.B. and Thomas, J.M. 1986. Upper Palaeozoic successions and nappe structures in north Cornwall. *Journal of the Geological Society, 143,* 75-82.

Shaw, D.M., Dupuy, C., Fratta, M. and Helsen, J. 1974. An application of factor analysis to basic volcanic rock geo-chemistry. *Bulletin Volcanologique, 38,* 1070-1089.

Spencer, D.W. 1966. Factor Analysis. *Publication number 66-39, Woods Hole Oceanographic lnstitute,* 25pp. Woods Hole, Massachusetts.

Winchester, J,A. and Floyd, P.A. 1977. Geochemical discrimination of different magma series and their different-iation products using immobile dements. *Chemical Geology, 20,* 325-343.

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*Read at the Annual Conference of the Ussher Society, January 1987*

# Heavy metals in Teign Valley sediments: ten years after

J.R. MEREFIELD

Merefieid, J.R. 1987. Heavy metals in Teign Valley sediments: ten years after. *Proceedings of the Ussher Society, 6,* 529-535.

A 1976 study of heavy metals in river and estuarine sediments (<2501n m fraction) of the Teign revealed anomalous accumulations of Ba, Pb and Zn. Highest concentrations were found in the middle Teign river adjacent to streams draining a former orefield. Anomalous values also occurred in the upper Teign estuary.

The present study after 10 years of sedimentation shows, by comparison, that concentrations of Ba in the Teign river have risen by 1.5 to 3.5 times. Concentrations ofPb, Zn and Mn have increased a little at 1.5 times 1976 levels, and Sn values by 2.4 times. Lead/Zinc ratios (above 0.75) prove useful in fingerprinting sediments with a geochemistry modified by anthropogenic factors. This zone extends 18 km from the middle Teign valley to the head of the Teign estuary. Concentrations of Ba, Pb, Zn and Mn show little change in the estuary. This is seen as further geochemical evidence of a net input of marine-derived detritus. This silty material mixes with river-derived sediments and mechanically dilutes the heavy metal chemistry.

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## Introduction

Geochemical drainage surveys in Devon by Horsnail (1968) and Nichol *et al.* (1967; 1971) revealed anomalous concentrations of trace elements in the Teign valley. A detailed follow-up in the middle Teign Valley demonstrated the contribution of heavy metals made to the river Teign by catchment streams draining a former orefield (Merefield 1974). Two sections of the Teign were found to contain accumulations of Ba, Pb and Zn (Merefield 1976a, b). The highest occurred in the middle Teign river adjacent to past mining sites and the secondary concentration was discovered at the head of the estuary. Teign sediments are now re-examined to assess the net results after ten years of sedimentation.

## Geology and Mineralisation

At a height of over 1700 feet (519m) the river Teign rises as the North Teign river on north-east Dartmoor. It flows over the granite north-east into the Chagford basin at 600 feet (183 m). Leaving the granite it flows east and then south over the band of Culm Measures (Lower Carboniferous) at 200 feet (61m) consisting of shales, mudstones, cherts and tuffs. Near Chudleigh Knighton the Teign reaches the plain of the Bovey deposits (Oligocene) comprised of clays, sands, gravels and lignites. At Newton Abbot the river turns sharply to the east and enters the site of the present-day estuary. Upper Devonian slates and mudstones occupy part of the north and south west sides, whilst Permian breccias surround the remainder.

Compared with other areas in Devon relatively little mining has taken place in the Teign valley (Hoskins 1960). However, exploitation of Dartmoor alluvial tin deposits worked in the Chagford area is known to have taken place as early as the 12th Century. Placer workings and the advent of "blowing houses" (Worth 1942) followed on, as well as the working of cassiterite bearing tin lodes. Tin lodes here are relatively poor, coursing generally east-west, filling vertical cracks and fissures in the granite. The most important working being the Great Week Consols Mine (Broughton 1967) which eventually closed in 1903.

Mineral deposits of the middle Teign valley occur in the much faulted and folded Culm Measures are comprised of three types (Dines 1956). They consist of north-south coursmg Ba-Pb-Zn lodes, east-west coursing Fe-quartz lodes and deposits of Mn (Fig. 1). Extensions of the N-S lode system have been discovered by Beer and Ball (1977). The history of mining here has been traced by Schmitz (1973). Exploitation reached a peak between 1840 and 1860 but some mines lingered on. The Bridford Baryte Mine was the last to close in 1958. Some reworking of mine dumps has occurred since 1982.

## Sample collection and preparation

For both 1976 and 1986 investigations, identical sampling sites and methods were used. Active sediments were taken at a mean density of one sample per 1.2 km of river travel (Fig. 1). Building construction has changed the site at one locality and this was not used in the new programme. Collection took place during the summer months when run-off was at its lowest, enabling ready access to the middle of the river channel, clear of any

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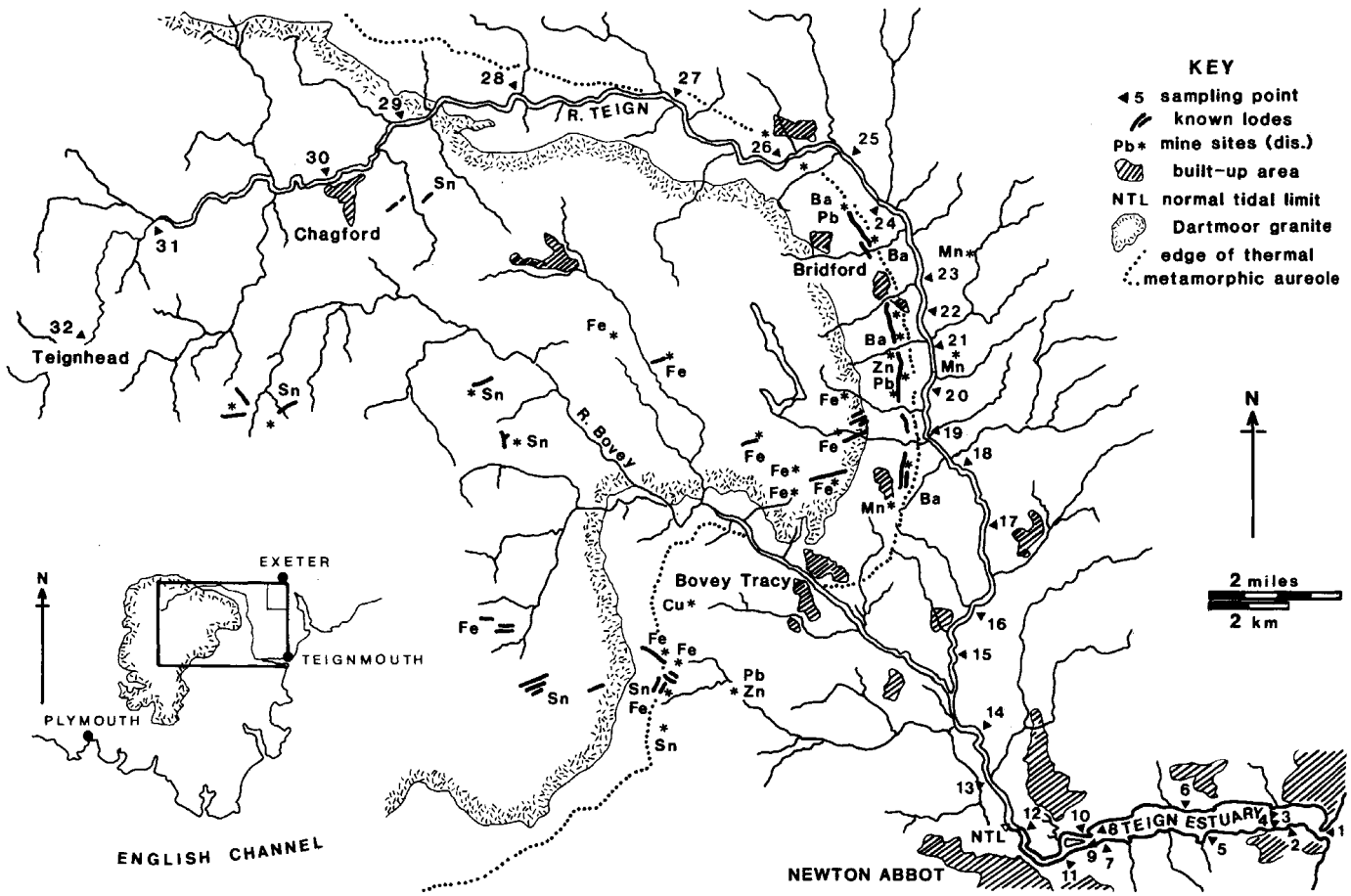


Figure 1. Location map and sampling points.

collapsed bank debris. Samples were air-dried and sieved. The fine sand, silt and clay fraction < 250µm was then ground and pelleted (Norrish and Hutton 1964).

## Analytical procedures

The pressed powder pellets were used in determinations of Ba, Pb, Zn, Mn and Sn by X-ray spectrometry (X.R.S.). Iron and Mn oxides were extracted from 5g of the powdered samples using a modified method of Le Riche and Weir (1963). The extractant used was a solution of ammonium oxalate in oxalic acid of pH 3.3. These treated samples were also pelleted and then analysed by X.R.S. X-ray diffraction was used to prove the presence of barytes and to examine mine waste for more soluble forms of Ba mineralisation.

## Results

Geochemical concentrations of heavy metals in the < 250 µm fraction are reported here contrasting results from the two investigations separated by 10 years of sedimentation.

*Barium*

A comparison of Ba values from 1976 with those of 1986 in the freshwater river section of the Teign shows a major increase (Merefield 1987). Downstream and adjacent to the Bridford Baryte Mine values have risen by 3.1 times to 7800 p.p.m. Ba. At Canonteign down-river from the Wheal Exmouth and Frank Mills mines the previously enriched zone has significantly increased in Ba concentrations to 12000 p.p.m.

Absolute values fall off downstream from there, as do relative 1986/1976 ratios from 3.6 to 1.5 times (Fig. 2). The anomalous zone has also extended downstream by 2km to Teign bridge where concentrations are presently 700 p.p.m. Ba. Values in the estuary remain little changed. The pattern is one of high values in the upper estuary (c.a. 2500 p.p.m. Ba) falling off down to the mouth (c.a. 250 p.p.m. Ba).

*Lead*

Concentrations of lead have risen little since 1976. The major anomaly in the middle Teign river (21,600 p.p.m. Pb) proves almost identical to that of the 1976 study (21,300 p.p.m. Pb). Values in .general suggest a downstream migration of the Pb-enriched zone (Fig. 3). Excluding one sample with a loss, 1986/1976 Pb ratios range from 1.0 to 6.4 with a mean of 1.8 in the freshwater section. In the estuary the established pattern is reaffirmed with little change. Relatively high values occur

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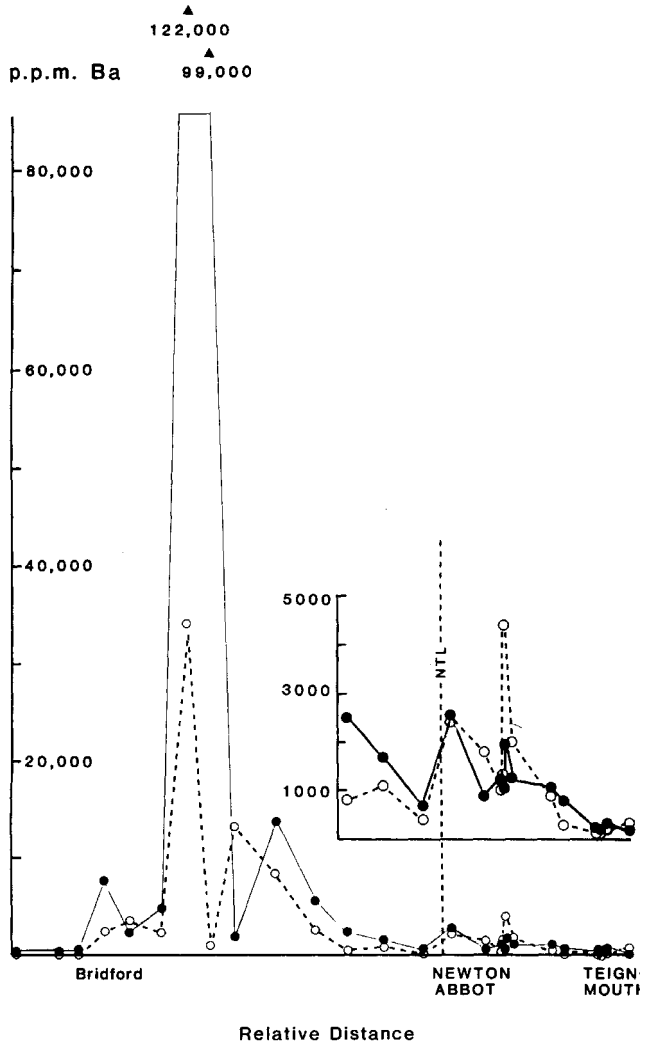


Figure 2. Distribution of Ba in < 250 μm sediments from the Teign. Open circles are 1976 values and black dots are 1986 concentrations. NTL is the normal tidal limit.

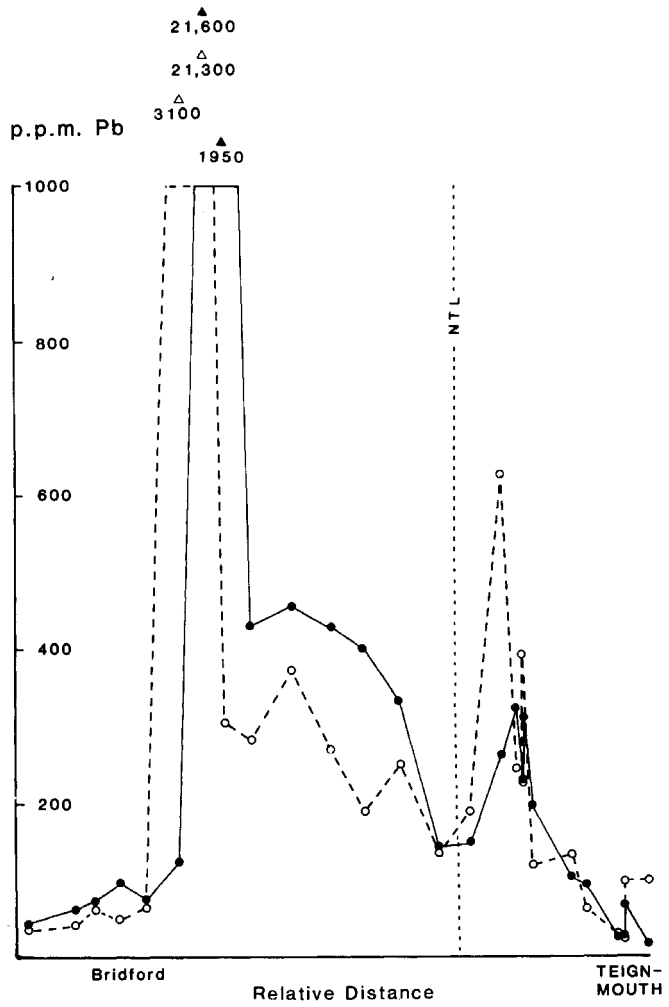


Figure 3. Distribution of Pb in < 250p m sediments from the Teign. Open circles are 1976 values and black dots are 1986 concentrations. NTL is the normal tidal limit.

in the upper estuary (c.a. 300 p.p.m. Pb) and concentrations then decrease towards Teignmouth (c.a. 40 p.p.m. Pb). Estuarine sediments give 1986/1976 Pb ratios from 0.2 to 2.3 with a mean of 1.0.

*Zinc*

Levels of zinc show slight increases in general compared to the first survey, but the peak values have reduced (Fig. 4). The highest concentration of 830 p.p.m. Zn for 1986 is now at sampling point 20 in the river section (Fig. 1) where formerly 1040 p.p.m. Zn was recorded. Overall in the freshwater section values now prove about 1.5 times those of 1976. In the estuary concentrations are highest around the Hackney marshes (c.a. 240 p.p.m. Zn) and fall off down to the mouth (c.a. 100 p.p.m. Zn). Values for 1986 are similar to those of 1976. The comparison ranges from 0.5to 1.1. times, with a mean of 0.9.

The range of Pb/Zn ratios from freshwater sediments in 1976 was 0.4 to 20.5 and is now little changed at 0.2 to 26.0. Ratios of Pb/Zn in the estuary were 0.27 to 2.23 and are now 0.23 to 1.42. Using Pb/Zn values from the Dartmoor granite, Lower Carboniferous shale, Upper Devonian slate and Permo-Triassic sandstone, mudstone and carbonate, a mean Pb/Zn threshold for local lithologies within the Teign catchment can be drawn (Fig. 5). It is suggested that ratios above the threshold may be deemed the result of anthropogenic activity. This would define such a zone from above Spara bridge in the freshwater section extending to below the Hackney marshes at the head of the estuary.

*Manganese*

Data for Mn from 1976 and 1986 investigations show similar patterns of high values in the middle Teign river falling off down-river and down-estuary (Fig. 6). Iron/manganese scavenging takes place in the Teign and

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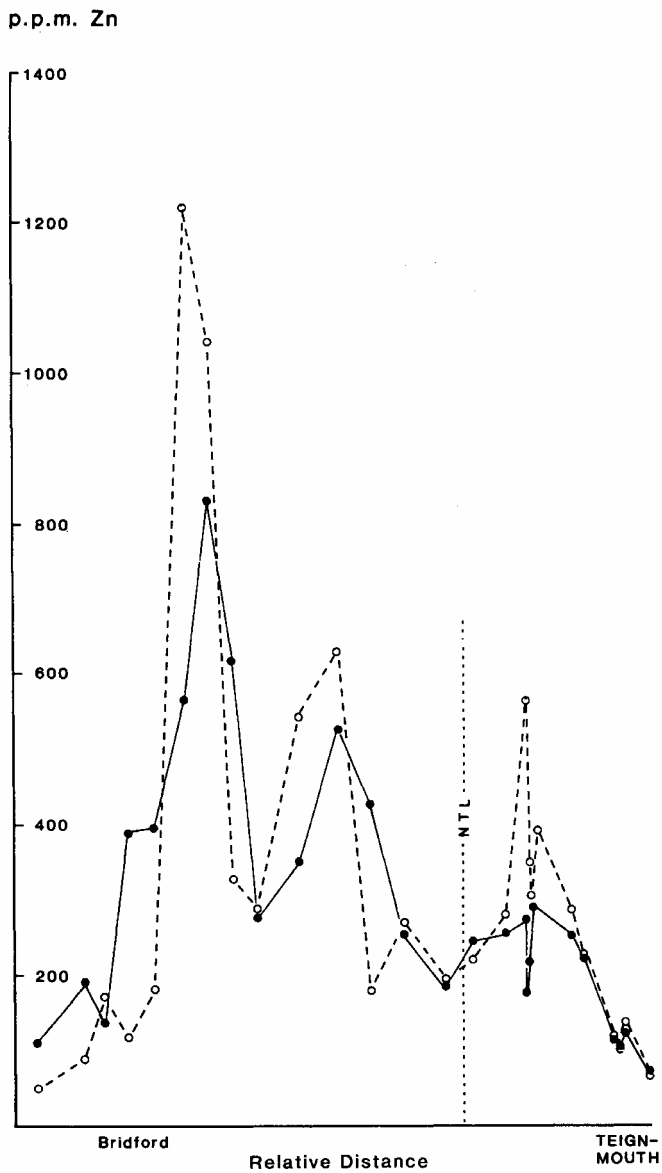


Figure 4. Distribution of Zn in < 250pm sediments from the Teign. Open circles are 1976 values and black dots are 1986 concentrations. NTL is the normal tidal limit.

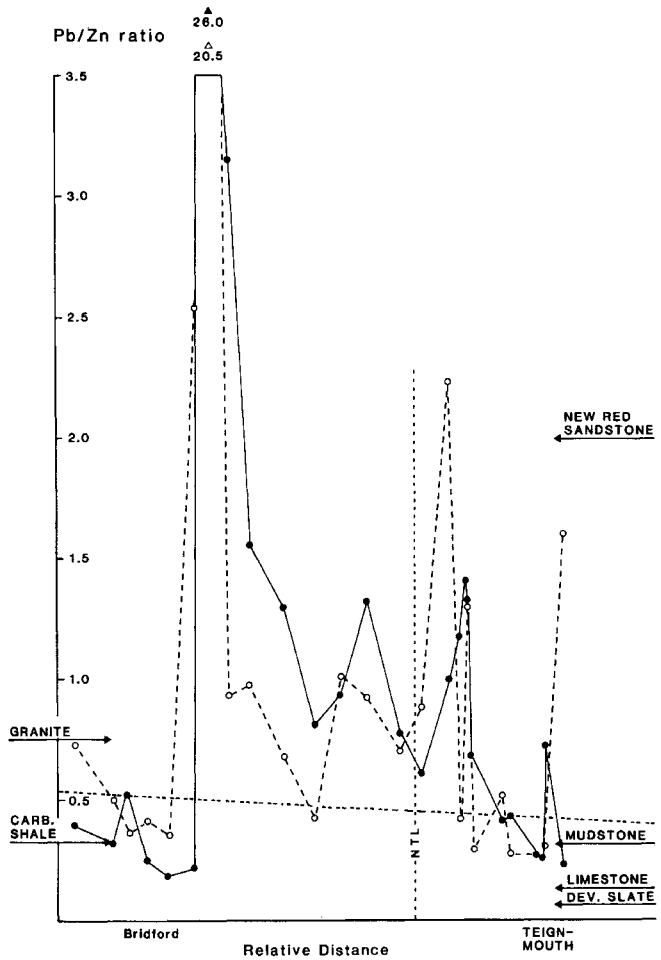


Figure 5. Comparison of Pb/Zn ratios from 1976 (open circles) and 1986 (black dots) sediments of the Teign. The broken line is based on Pb/Zn ratios of local lithologies. Values above this line are deemed to result from anthropogenic activities. The granite mean value is from Heath (1982), New Red Sandstone (Permo-Triassic) data from Cosgrove (1973), whilst, Carboniferous shale and Devonian slate values are from this study.

in its tributary streams (Nichol *et al.* 1967). Given favourable environmental conditions oxides of iron and manganese can precipitate onto the sediments, co-precipitating heavy metals. Experiments in the laboratory with ammonium oxalate in oxalic acid release the oxides/hydroxides. This leaching is accelerated under UV light, and the resultant losses of trace metals are used to estimate the status of Fe/Mn scavenging.

The results are given in Table 1 and show Pb and Zn to be especially affected by this mechanism. A change of pH and Eh to more acid reducing conditions releases the oxides from the bed of the river and with them the trapped heavy metals. This transient behaviour would explain the lack of direct correlation between the Mn and Pb/Zn patterns from Teign sediment data.

*Tin*

Additional samples were taken in 1976 to cover the section from the middle Teign valley up to the source of the river at Teignhead, and provide comprehensive Sn data. Drainage sediment work on north-east Dartmoor (Nichol *et al.* 1971) had previously identified streams likely to contribute Sn-rich granite detritus to the Teign. Whereas Ba-Pb-Zn enrichment is confined to the N-S lodes of the middle Teign valley, Sn is introduced at three localities. In the upper, values up to 1300 p.p.m. Sn have been recorded in Moortown Brook; at Beadon Brook in the middle Teign, concentrations are between 150 to 700 p.p.m. Sn; whilst levels in the River Bovey, which enters the lower Teign, reach > 700 p.p.m. Sn (Nichol *et al.* 1971). Tin values from 1976 confirm this, as concentrations increase sharply to 369 p.p.m. Sn

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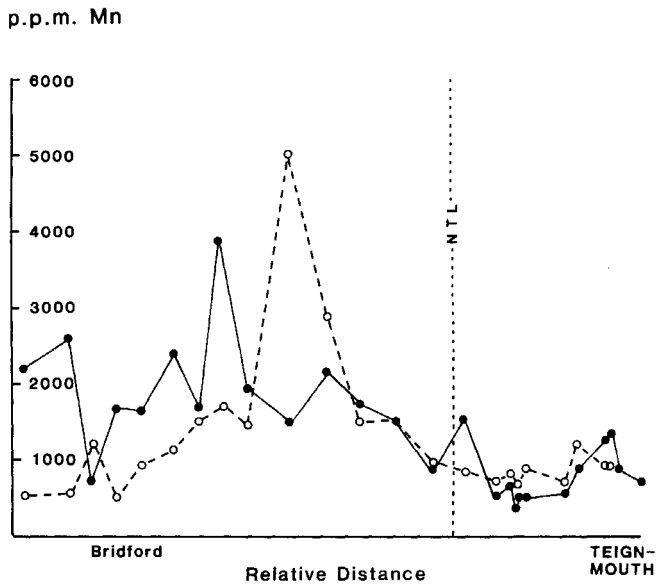


Figure 6. Distribution of Mn in <250$_1$4m sediments from the Teign. Open circles are 1976 values and black dots are 1986 concentrations. NTL is the normal tidal limit.

downstream from the confluence with Moortown Brook. Although somewhat erratic, these values then generally fall down-river away from the Dartmoor source (Fig. 7), but suggest additional predicted input in the middle and lower sections. Although not as complete, where 1986 data are available, they show some large increases in Sn concentrations. In the freshwater section these reach 6.4 times (mean 5 times) and in the estuary up to 5.2 times (mean 2 times).

## Discussion

*General*

Input of heavy metals to Teign drainage from disturbance of mine spoil heaps is likely. This could have resulted in the local increase of Ba and Pb, but does not explain the increase of Sn. Changes in land use (e.g. drainage, afforestation) could have raised the Sn budget. This ten year period has also seen the completion of the A380 bypass road and bridge at the head of the Teign estuary. Although exploitation of alluvial tin deposits in the catchment of the river Bovey ceased in 1975 (Beer and Scrivener 1982), cassiterite has been extracted from

Table 1. Percentage loss of metals with oxalate leach

| | **River** | | **Estuary** | |
|---|---|---|---|---|
| | **range %** | **mean %** | **range %** | **mean %** |
| | range % | | range % | |
| Barium | 22 - 86 | (53) | 13 - 56 | (37) |
| Tin | 17 - 93 | (65) | 23 - 70 | (44) |
| Lead | 18 - 99 | (70) | 20 - 92 | (64) |
| Manganese | 70 - 95 | (82) | 53 - 87 | (71) |
| Zinc | 49 - 99 | (83) | 70 - 89 | (82) |

Differences of values before and after leaching are divided by the original value to calculate the % loss.

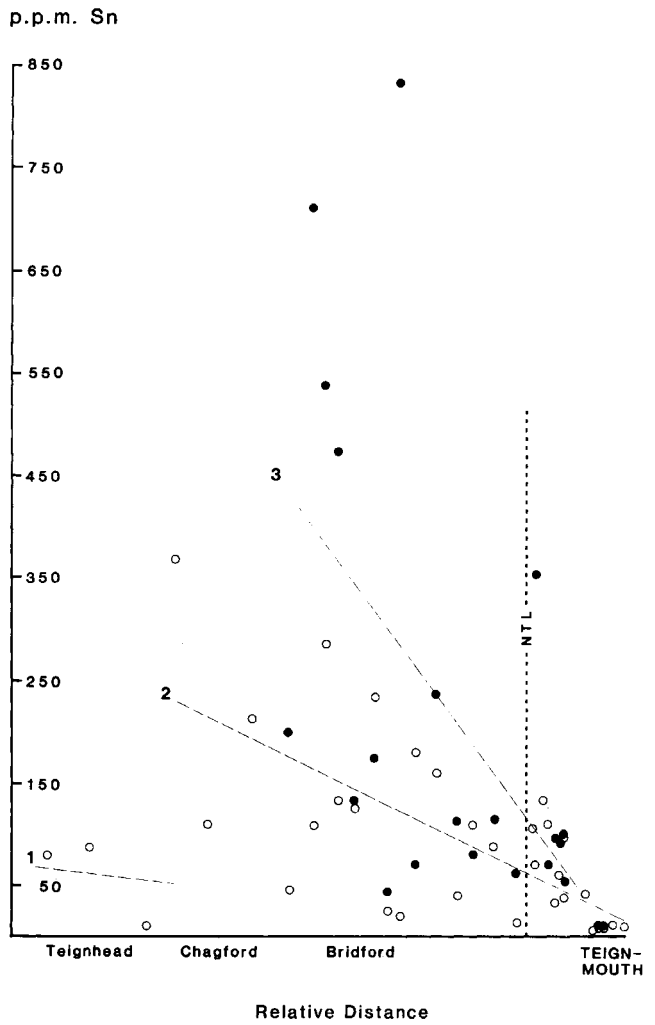


Figure 7. Distribution of Sn in sediments from Teignhead to Teignmouth from 1976 data (open circles). Concentrations from Steps Bridge to Teignmouth (black dots) are 1986 values. Regression line 1 is computed from Dartmoor granite sediments. Regression line 2 is from all 1976 data points below the influence of Moortown Brook. Regression line 3 is derived from all 1986 values.

alluvium overlying the Tertiary sediments of the Bovey Basin since 1976 (Selwood *et al.* 1984). Sands from the Aller Gravel (600-100pm; medium-fine sand) are known to contain Sn as cassiterite (Scrivener and Beer 1971), which is probably the tin-containing phase of the present-day Teign valley sediments.

*River (freshwater)*

The relatively high level of increase in Ba over Pb and Zn in the river contrasts their geochemical characteristics in the weathering environment. The relative insolublity of barytes (0.0002 at 15° C in water) together with its density (S.G. 4;2 - 4,4) would aid concentration in the bed load. Other resident grains, more resistant to erosion, would act as grinding agents (Merefield 1987), A more soluble form of Ba has not been detected by X-ray diffraction

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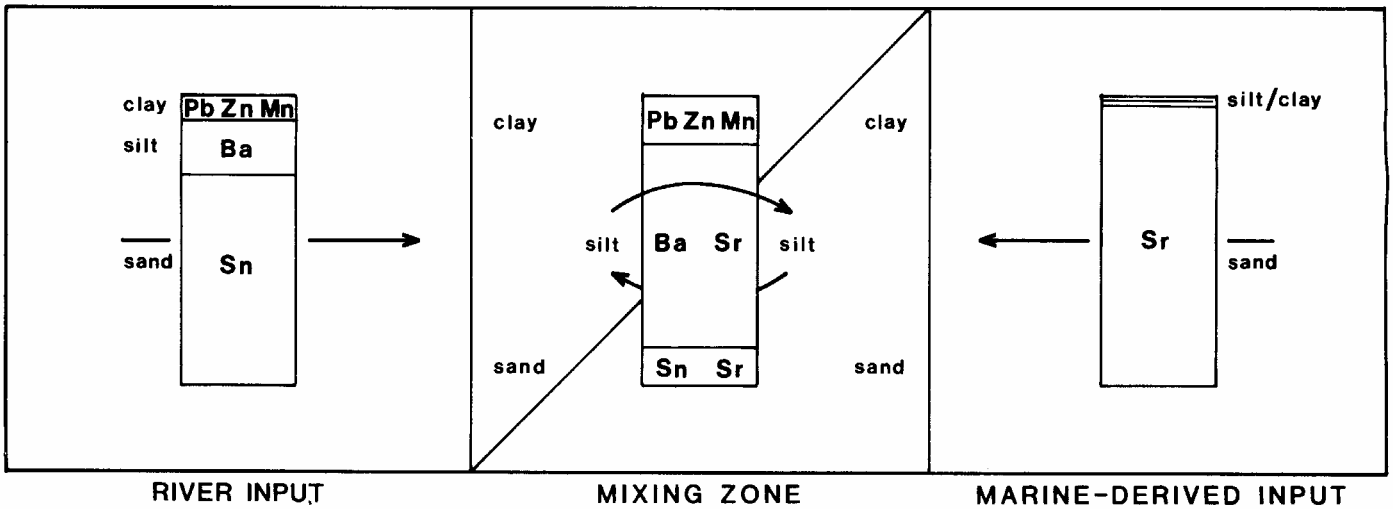


Figure 8. Schematic representation of sediment zones in the Teign estuary. Preferred particle sizes for heavy metals are shown. Carbonate Sr is also used as an indicator element for marine-derived input which mechanically dilutes river-derived material.

during this study. From hydrogeochemical work at a Zn-Pb mine at Gard (France) the relatively low concentration range for Ba in solution is reported as c.a. 2-807$\mu gl^{-1}$ (Bosch *et al.* 1986), and shows a barytes control. In contrast, Pb and Zn are geochemically susceptible to mobilisation according to local pH and Eh conditions. In the Teign valley, when acid and reducing conditions prevail they are mobilised. With higher runoff and oxidation the precipitation of Fe/Mn oxides causes co-precipitation of Pb, Zn and some Ba on gravels and sands. Transport then becomes mechanical and bound with the bed load until environmental conditions change. Distribution coefficients for trace elements in sediments from the Panama Basin show that an increase in the solid Mn content enhances the ability of particles to bind metals sfich as Zn, Pb and Ba (Balistrieri and Murray 1986). Mineralisation in the Teign valley provides a source of Mn for scavenging. It seems, however, that environmental conditions and mechanical dilution combine to keep Pb and Zn levels reasonably constant at present in river sediments of the Teign.

*Estuary*

A plot of wt.% silt against Ba concentration gives a positive correlation of 0.597, although significantly, some values from the estuary spoil this. The estuary is a trap for silt (Nunny 1980). Values recorded for samples from this study range from 23-73% silt in the upper estuary. However, there is little new evidence of either mechanical (Ba and possibly Sn) or geochemical (Pb and Zn) heavy metal enrichment in the Teign estuary.

Trace elements have been used to designate zones in the estuary on the basis of a river-derived (Ba), a marine derived (Sr) and a mixed section containing both types of geochemical indicators (Merefield 1981, 1982). In addition to geochemical evidence, exotic benthic foraminiferal tests are found in estuaries of south west England (Murray 1987). Less than 200Jnm in size, they are equivalent to quartz spheres of silt grade and indicate a net input of this material to the estuaries. A study of beach deposits from south-west England has demonstrated the high supply of Permo-Triassic detritus, as New Red Sandstone, to the south and east Devon coastal section (Merefield 1984). It appears, therefore, that up-estuary movement of marine-derived debris is causing the dilution of both mechanical input (Ba and possibly Sn) and geochemical input (Pb and Zn) heavy metals (Fig. 8).

## Conclusions

Concentrations of Ba in sediments (<250μm) of the middle Teign river have risen by 1.5 to 3.5 times during the last decade. Levels of Pb, Zn and Mn have risen a little at 1.5 times 1976 values. Although erratic, Sn concentrations show a general increase of 2.4 times those previously recorded (Table 2). The geochemical patterns suggest a general downstream migration of the heavy metal anomaly but further work is required for confirmation.

In the Teign estuary Ba, Pb, Zn and Mn values show little change. A net input of marine-derived sediments of silt-size mix with those of river input in the middle estuary to retain the *status quo.* Increases in Sn (1.5 times) may be due to its association with sand-size lithoclasts of Dartmoor granite introduced in the river channel.

Table 2. Mean 1986/1976 comparison of heavy metals in the Teign sediments

| | Ba | Pb | Zn | Mn | Sn |
|---|---|---|---|---|---|
| River | 1.9 | 1.6 | 1.5 | 1.5 | 2.4 |
| Estuary | 1.2 | 1.0 | 0.9 | 1.0 | 1.5 |

Values are means of 1986/1976 concentration ratios

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Lead/zinc ratios (above 0.75) prove useful in finger-printing sediments with a geochemistry modified by anthropogenic factors. This section extends 18 km from below Bridford in the middle Teign valley to below the Hackney marshes of the upper Teign estuary.

*Acknowledgements.* Thanks are due to Mrs. M.J. Knight for assistance with sample collection. Mr. M.C. George carried out X-ray diffraction work and Mrs. V. Ellis typed the manuscript.

## References

Balistrieri, L.S. and Murray, J.W. 1986. The surface chemistry of sediments from the Panama Basin: The influence of Mn oxides on metal adsorption. *Geochimica et CosmochimicaActa. 50,* 2235-2243.

Beer, K.E. and Ball, T.K. 1977. Barytes mineralization in the Teign Valley, Devon. *Transactions of the Institution of Mining and Metallurgy, 86,* B91-92.

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

Bosch, B., Leleu, M., Oustrière, P., Sarcia. C.. Sureau, J-F., Blommaert, W., Gijbels, R., Sadurski, A., Vandelannoote, R., Van Grieken, R. and Van 'T Dack, L. 1986. Hydrogeochemistry in the zinc-lead mining district of "Les Malines" (Gard, France). *Chemical Geology, 55.* 31-44.

Broughton, D.G. 1967. Tin working in the Eastern Disti-ict of the Parish of Chagford, Devon. *Proceedings of the Geologists' Association, 78,* 447-462.

Cosgrove, M.E. 1973. The geochemistry and mineralogy of the Permian Red Beds of southwest England. *Chemical Geology, 11,* 31-47.

Dines, H.G. 1956. The metalliferous miningregion of southwest England, 2. *Memoir o. f the Geological Survey of Great Britain.*

Heath, M.J. 1982. Uranium in the Dartmoor granite: geo-chemical and radiogeological investigations in relation to the southwest England geothermal anomaly. *Unpublished Ph.D thesis, University of Exeter.*

Horsnail, R.F. 1968. The significance of some regional geo-chemical patterns in North Wales and South-West England. *Unpublished Ph. D. thesis, University of London. Hoskins, W.G. 1960. Devon.* Collins, London, 600pp.

Le Riche, H.H. and Weir, A.H 1963. A method of studying trace elements in soil fractions. *Journal of Soil Science. 14,* 225-235.

Merefield, J.R. 1974. Major and trace element anomalies in stream sediments of the Teign Valley orefield. *Journal of Geochemical Exploration, 3.* 151-166.

Merefield, J.R. 1976a. Heavy element accumulations in the Teign Estuary. *Proceedings of the Ussher Society, 3.* 390.

Merefield, J.R. 1976b. Barium build-up in the Teign Estuary. *Marine Pollution Bulletin,* 7, 214-216.

Merefield, J.R. 1981. Caesium in the up-estuary transport of sediments. *Marine Geology, 39.* M45-M55.

Merefield, J.R. 1982. Modern carbonate marine-sands in estuaries of southwest England. *Geological Magazine. 119,* 567-580.

Merefield, J.R. 1984. Modern cool-water beach sands of southwest England. *Journal of Sedimentary Petrology, 54,* 413-424.

Merefield, J.R. 1987. Ten Years of barium build-up in the Teign. *Marine Pollution Bulletin, l&* 220-222.

Murray, J.W. 1987. Biogenic indicators of suspended sediment transport in marginal marine environments: quantitative examples from SW Britain. *Journal of the Geological Society of London, 144,* 127-133.

Nichol, I., Horsnail, R.F. and Webb, J.S. 1967. Geochemical patterns related to precipitation of manganese oxides. *Transactions of the Institution of Mining and Metallurgy, 76,* Bl13-115.

Nichol, I., Thornton, I., Webb, J.S., Fletcher, W.K., Horsnail, R.F., and Khaleelee, J. 1971. Regional geochemical reconnaissance of part of Devon and north

Cornwall. *Report Institute of Geological Sciences, 71.*

Norrish, K. and Hutton. J.T. 1964. Preparation of samples for analysis of X-ray fluorescent spectrography. *Commonwealth Scientific and lndustrial Research Organization Division of soils, Adelaide, Report 3/64, lOpp.*

Nunny, R.S. 1980. A study of sediment dynamics in a shallow estuary River Teign, Devonshire. *Unpublished Ph.D thesis. University of Exeter.*

Selwood. E.B.. Edwards. R.A.. Simpson, S., Chesher. J.A.. Hamblin. R.J.O.. Henson. M.R.. Riddolls, B.W. and Waters, R.A. 1984. Geology of the country around Newton Abbot. *Memoir of the British Geological Survey of England and Wales.*

Schmitz. C.J. 1973. Teign Valley lead mines. *Sheffield: Northern Cavern and Mine Research Society Occasional Publication. 6.* 125pp.

Scrivener. R.C. and Beer. K.E. 1971. Cassiterite in the Aller Gravels near Newton Abbot. *Proceedings of the Ussher Society,* g 326-329,

Worth. R.H. 1942. The Dartmoor blowing house. *Proceedings of the Devonshire Association. 72.* 201-250.

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*Read at the Annual Conference of the Ussher Society, January 1987*

# Trace elements in soils around the Hemerdon tungsten deposit, Devon; implications for exploration

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Andrews, M.J., Ball, T.K., Fuge, R., Nicholson, R.A. and Peachey, D. 1987. Trace elements in soils around the Hemerdon tungsten deposit, Devon; implications for exploration. *Proceedings of the Ussher Society, 6,* 536-541.

Surface and B-horizon soil samples collected from four traverses over the Hemerdon tungsten deposit have been analysed for W, Sn, Pb, Zn, Cu, As, Sb, Bi, Se, Te, Fe, Y, La, Ce, Ti, Zr, Nb, Mn, Ni, Rb, Ca, Sr, Ba, Br, U, Mo and Th by XRF, and F, C 1 and I by automated colorimetric methods. This survey has been undertaken to establish concentration levels and evaluate potential pathfinder dements for this type of mineralisation. All samples analysed contained anomalous concentrations of W, Sn, As, Sb, Bi and F, therefore these elements have potential for delineating mineralised areas on a regional scale. A number of the elements investigated also displayed localised enrichments, possibly related to underlying geology and mineralisation, and identification of coinciding anomalies for various elements could aid detailed exploration.

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## Introduction

Investigations of trace element soil geochemistry have been undertaken in the vicinity of the Hemerdon tungsten deposit, situated 11 km northeast of Plymouth, Devon. The aims of this work were to investigate the concentrations of selected trace elements in soils in the vicinity of this type of deposit, and to identify potential pathfinder or indicator elements applicable to geochemical prospecting for bulk tonnage W mineralisation in southwest England.

The geology of the Hemerdon deposit has been described by Cameron (1951) and Dines (1956). An extensive drilling programme carried out at the Hemerdon mine by AMAX in the late 1970's identified a zone of W-Sn mineralisation 650m long by 120-150m with and established reserves published as 45 million tonnes of ore grading at 0.17% W and 0.025% Sn (Mining Magazine, October, 1979). The mineralisation is associated with a dyke-like body of altered granite which extends northeastwards from the Hemerdon Ball granite (Fig. 1) which is a small cupola cropping out immediately to the south of the Crownhill granite stock and intruded into metamorphosed slates and fine sandstones of Upper Devonian age known locally as the killas. The Hemerdon Ball granite is generally unaltered, but the granite within the near vertical dyke-like protuberance is intensely kaolinised and is crosscut by numerous quartz, quartz-feldspar and greisen bordered quartz veins which contain

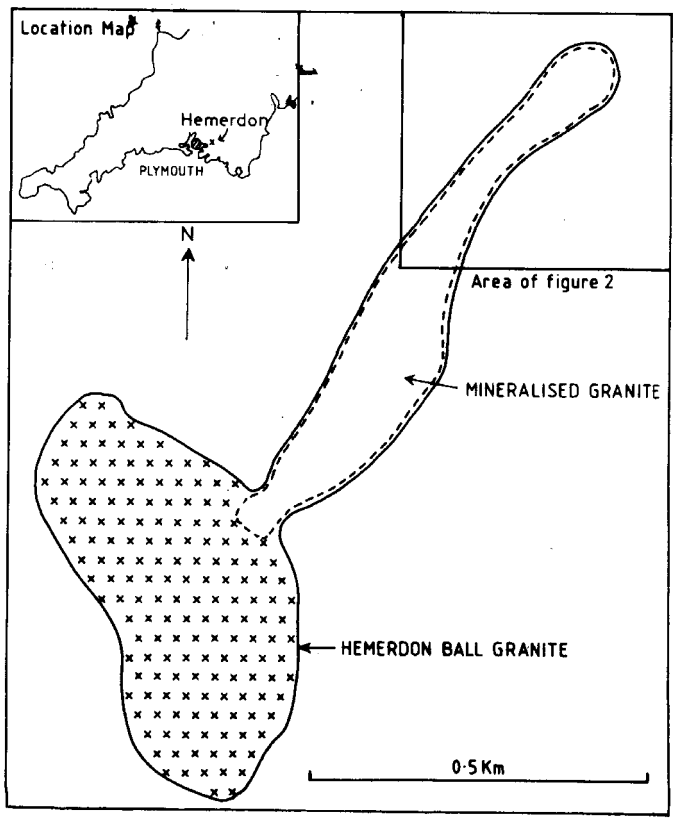


Figure 1. Location map and outcrop of the Hemerdon Ball granite.

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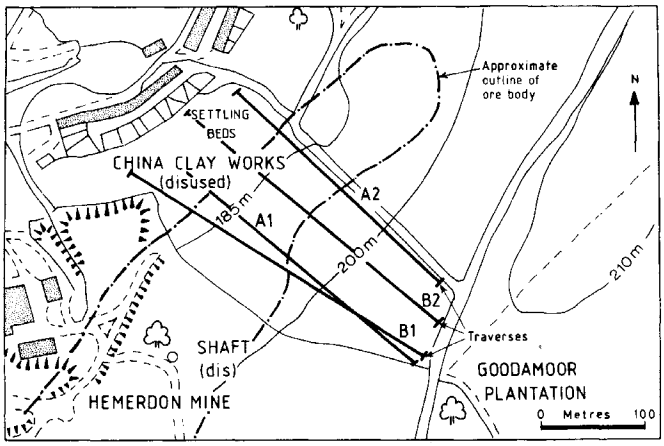

Figure 2. The area north-east of the Hemerdon tungsten mine showing the location of the soil geochemistry traverses.

wolframite and cassiterite. These veins constitute an extensive sheeted vein stockwork. Near the surface hematite and scorodite also occur (Cameron 1951), however below a depth of 40m kaolinisation of the granite decreases and arsenopyrite is locally common. The mineralisation also extends into the sedimentary rocks marginal to the intrusion

The area selected for this study lies in the agricultural pastures immediately to the north east of the Hemerdon mine buildings. Figure 2 shows the location of the sample traverses and the position of the underlying unexposed ore body. At this locality the soils are freely drained brown earths developed on a parent material of head and regolith. Apart from modification of the upper 20cm of the soil profile by ploughing the area is undisturbed. The survey area lies at approximately 200m OD and slopes gently northwest towards the disused china clay works in the Smallhanger Brook valley.

The results of a soil gas geochemistry study at this locality have been reported by Ball *et al.* (1985), who demonstrated that high CO2 values and low 02 values in soil gases outlined the position of the ore body, whereas high values of evolved sulphur gases (pS) were detected peripheral to the deposit. The location of the pS anomalies are interpreted as reflecting the higher near-surface occurrence of sulphides in the inner part of the metamorphic aureole. The sample sites on Traverse A-1and Traverse A-2 correspond with two of the lines for the soil gas study.

Methodology

28 surface soil samples (0-15cm depth) were collected at 25m intervals for soil gas evolution studies alongTraverses A-1 and A-2 (by TKB, RAN and DP).Subsequently, 54 B-horizon soils were sampled from 20-35cm depth at 12.5m intervals on Traverses B-I and B-2(by MJA and RF), using a screw auger. Samples wereoven dried at 80°C prior to mechanical disaggregauonwith mortar and pestle followed by sieving. From Traverses A-1 and A-2 the -60 mesh fractions were analysed for Fe, Y, La, Ce, Ti, Zr, Nb, Mo, Rb, Ca, Sr, Ba, U, Th, Mn, Ni, As, Sb, Bi, Pb, Zn, Cu, Sn and W using XRF (at BGS, Grays Inn road). From lines B-1 and B-2 the -80 mesh fractions were analysed for W, Sn, Br, Pb, Zn, Cu, As, Sb, Bi, Se and Te by XRF at the Department of Geology, Nottingham University. The halogens F, C1 and I were determined by automated colorimetric methods at the Department of Geology, U.C.W., Aberystwyth, F using the Zr-xylenol orange complex technique (Fuge, 1976; Fuge and Andrews, 1985), C1 using the ferric thiocyanate method (Fuge, 1976) and I using the catalytic/photometric method of Fuge *et al.* (1978).

Table 1. Summary statistics for analyses of Hemerdon soil samples. (All values are given in ppm except for Fe and Ti which are percentages).

a) Surface soils (0-15cm depth)

| Element | Range | Mean | sd |
|---|---|---|---|
| Fe% | 4.8 - 11.6 | 6.7 | 1.39 |
| Y | 14 - 28 | 21 | 3.3 |
| La | 35 - 62 | 46 | 7.5 |
| Ce | 29 - 77 | 54 | 11.2 |
| Ti% | 0.61- 1.38 | 0.94 | 0.19 |
| Zr | 16 - 25 | 21 | 2.2 |
| Nb | 18 - 30 | 23 | 3.1 |
| Mo | nd - 6 | 2.5 | 1.4 |
| Rb | 235 - 470 | 361 | 48 |
| Ca | 700 - 5350 | 2360 | 932 |
| As | 62 - 116 | 84 | 12 |
| Ba | 95 - 540 | 290 | 79 |
| U | 1- 10 | 4.9 | 1.8 |
| Th | 13 - 30 | 22 | 19 |
| Mn | 180 - 460 | 292 | 71 |
| Ni | 14 - 35 | 20 | 4.1 |
| As | 210 - 1220 | 494 | 213 |
| Sb | 2 - 35 | 11 | 5.5 |
| Bi | 13 - 320 | 40 | 56 |
| Pb | 17 - 137 | 62 | 28 |
| Zn | 59 - 142 | 85 | 17 |
| Cu | 22 - 130 | 55 | 24 |
| Sn | 109 - 295 | 185 | 49 |
| W | 211- 1480 | 486 | 267 |

b) B-horizon soils (20-35cm depth)

| Element | Range | Mean | sd |
|---|---|---|---|
| As | 290 - 838 | 479 | 126 |
| Sb | 5 - 22 | 10 | 3.4 |
| Bi | 17 - 107 | 52 | 20 |
| Se | 1-5 | 3.6 | 0.9 |
| Te | 1 | - | - |
| F | 1335 - 5250 | 2412 | 700 |
| Cl | 42 - 323 | 138 | 67 |
| Br | 39 - 161 | 98 | 31 |
| I | 7.4 - 48 | 15 | 10 |
| Pb | 13 - 29 | 18 | 3 |
| Zn | 39 - 108 | 59 | 14 |
| Cu | 47 - 143 | 86 | 21 |
| Sn | 89 - 290 | 138 | 33 |
| W | 285 - 1148 | 560 | 173 |

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## Results

Summary statistics for trace element concentrations in all the samples analysed are presented in Table 1. Traverse plots of surface soil data, from Traverses A-1 and A-2, are shown in Figure 3, and data for the B-horizon samples, from Traverses B-1 and B-2, are shown in Figure 4.

One surface sample on Traverse A-l, directly overlying the southeast contact of the mineralised granite, contained highly anomalous concentrations of U, As, Sb, Bi, Cu, Fe, Sn and W. Although a number of the elements, including Sb, Bi, Cu and W, are also enriched in B- horizon samples collected nearby, on Traverse B-l, others are not. Therefore while this sample may be reflecting the underlying mineralisation, the possibility of contamination by windblown fine tailings from the nearby mineral dressing plant cannot be discounted.

Brooks (1972) suggests that the average concentration of Sn and W in soils is 10 ppm and I ppm respectively. Clearly, in all the samples analysed, Sn and W show very marked enrichment over these general background levels. Along Traverse A-1 these elements are high over the margins of the mineralised granite, and displacement of the anomalies to the northwest by down-slope processes is evident. These elements do not clearly reflect the underlying geology on Traverse A-2 or either of the B-horizon sample lines. However on both B-1 and B-2 high W values were detected in the vicinity of the marked break of slope shown in Figure 4.

The Group V chalcophile elements, As, Sb and Bi, have been suggested as possible pathfinders for this style of mineralisation (Boyle 1974), and the levels detected in this study are very much greater than typical concentrations in soils reported by Brooks (1972) (5 ppm As, 0.5 ppm Sb, 0.5 ppm Bi). Bi has the clearest surface soil response to the underlying mineralisation. On Traverse A-1 Bi increases to a peak of 320 ppm over the southeast granite contact with less pronounced enrichment over the northwest contact and also down-slope of the deposit. Traverse A-2 clearly shows enrichment of Bi from a background of 17 ppm to values of 35-40 ppm over and downslope from the northwest contact. Bi in subsurface soils displays enrichment directly over the break of slope indicated on Traverses B-1 and B-2. The As concentrations show a general decrease from southeast to northwest in both surface and subsurface soils from all the traverses.

The Pb, Zn and Cu concentrations in the surface soils show little systematic variation along Traverses A-1 and A-2. These elements also appear to be poor indicators of the underlying mineralisation in the B- horizon samples. High Cu is apparent in the vicinity of the break of slope

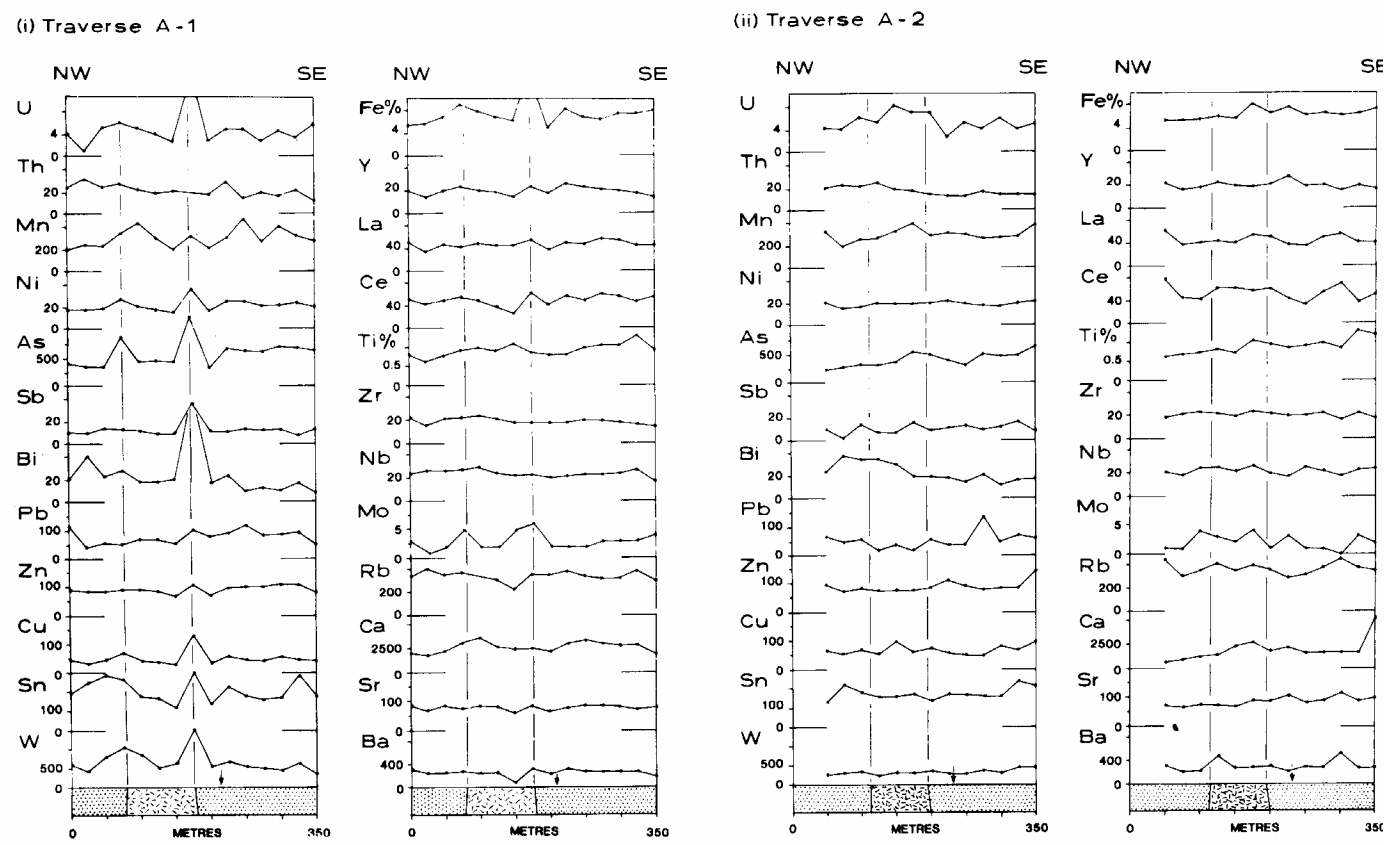


Figure 3. Surface soil geochemistry for (i) Traverse A-1 and (ii) traverse A-2. Sample depth 0-15cm. Values are in ppm except Fe and Ti given in percent. (Black arrow - position of break of slope, Stipple shading - underlying mineralised granite, Dot - killas).

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on both Traverses B-I and B-2. While high Pb values do occur over the mineralised granite on Traverse B- 1, this is not seen in B-2 and, in fact, Traverse A-2 indicates lower levels of Pb over the granite.

U enrichment in surface soils overlying the granite is evident in the samples from both Traverses A-1 and A-2, while there appears to be no relative enrichment in Th.

Although Mo was generally detected at only very low concentrations in the surface soils, the data plotted on both Traverse A-1 and A-2 show enrichment up to 6 ppm over the granite from the normal background values of 2 ppm.

The B-horizon samples from Hemerdon contain very high concentrations of F compared to both the general levels in soils elsewhere in Britain (R. Fuge, unpublished data; Andrews et al. 1984) and the median value of 300 ppm F reported by Connor and Shackelette (1975) for soils in the United States. The highly anomalous samples occur in the vicinity of the break of slope on both traverses and F enrichment is evident in soils above the granite on Traverse B-1. CI shows a more complex distribution with the highest value on Traverse B-1

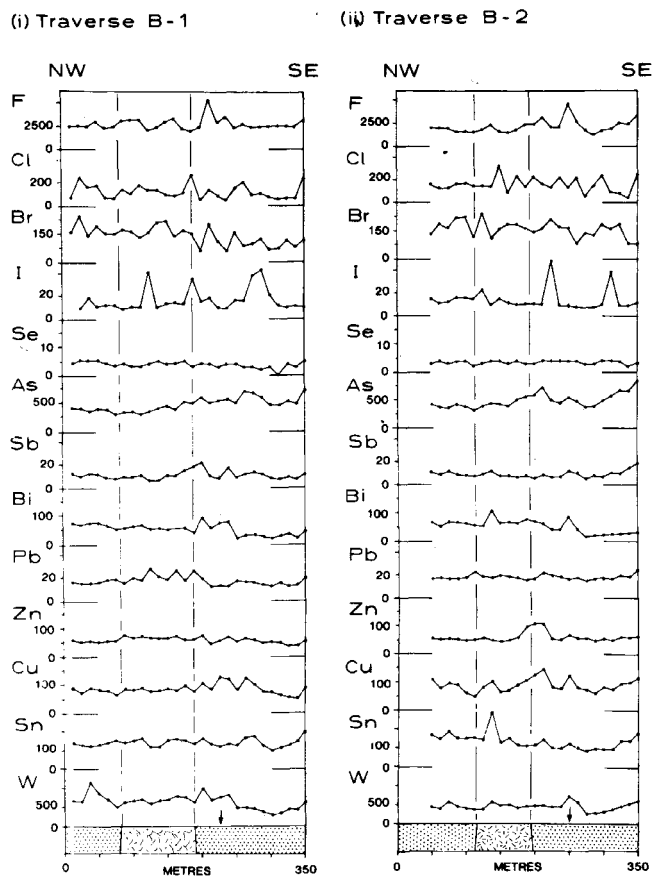


Figure 4. B-horizon soil geochemistry for (i) Traverse B-1 and (ii) Traverse B-2. Sample depth 20-35cm. Values are in ppm. (Symbols as for Figure 3.)

occurring over the southeast margin of the orebody. Along B-2 the highest concentrations of C 1 are observed in a zone of variable C 1 occurring over the granite and extending southeastward beyond the break of slope. Br concentrations show great variation, having no systematic pattern of distribution along either traverse. Except for a number of isolated anomalous samples, seen over, and to the southeast of the granite, the I concentrations detected are consistent with the background levels for soils determined in other areas of similar proximity to the sea (Johnson, 1980, Fuge and Johnson, 1986).

Overall the concentration of Se was consistently low and Te was below the limit of detection (1 ppm) in all the samples analysed.

## Discussion

The elements Mo and Bi are usually greatly enriched within granite hosted W-Sn stockworks associated with greisenisation. A large number of other elements may often be concentrated also, these include Li, Rb, Cs, Be, B, F, U, Sc, REEs, Re, Mn, Fe, Cu, Ag, Au, Zn, Cd, Ga, In, TI, Ge, Pb, As and S (Boyle, 1974). Watson *et al.* (1984) state that the Cornubian granites are enriched in Rb, Th, U, Ta, Be and Li and depleted in Ba, Sr and Ti relative to "normal" calc-alkaline granites. Ball and Basham (1984) add B, Fe, P, Zn, Ga, Nb, Cs and Pb to this list of enriched elements and Zr to the elements depleted relative to typical granites.

Geochemical data for selected non-mineralised, kaolinised samples of the Hemerdon granite are given by Beer and Ball (1987). This particular granite can be classified as a rather primitive type "B" granite (after Stone and Exley 1986). Compared with average type "B" granites the Hemerdon rocks contain higher concentrations of Ti, Fe, As, REEs, Cu, Rb, Sn and W and lower concentrations of Na, K, Ba, Nb, Th, U, and Zr.

It is possible that the enrichment in As, Cu, Sn and W detected by Ball and Beer (1987) could be the result of widespread dispersion around the individual mineral veins. Unpublished data on the geochemistry of the killas shows no significant or systematic contrast with the granite for Th, Ce, Y, Zr, Nb, Sr, and Ba. This is reflected by the composition of soils but peculiarly Ca and Ti, which show contrasting lower levels in the granite, show no evidence of such depletion in the soils.

Beer and Ball (1986) have described the wide primary dispersion of W and Sn in killas adjacent to the Hemerdon granite, demonstrating that values above background for these elements extend beyond 1200m from the margins of the mineralised granite. The secondary dispersion of W and Sn around Hemerdon is also extensive and it is apparent that the sample traverses have not extended into background.

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The almost ubiquitous relationship of Bi with greisen associated W mineralisation is readily apparent at Hemerdon, where a concentration of 2 ppm has been reported for the unmineralised granite and analyses of the mineralised granite range from 26 ppm to 138 ppm (Ball *et al.* 1982). These workers have also shown that Bi is enriched significantly in the killas within 500m of the granite contact at Hemerdon. This broad primary dispersion of Bi would account for the extensive overall enrichment detected in this study. Bi displays a close relationship with underlying mineralisation on both the surface and B-horizon traverses.

The use of I and C 1 as pathfinders for various types of mineralisation has been discussed by Andrews *et al.* (1984) and Fuge *et al.* (1986), and it has been suggested that I behaves as a chalcopbile element, showing a tendency to be enriched in sulphide minerals (Fuge and Johnson, 1984). In this study ! was found to occur generally at levels near to a mean value of 15 ppm, however a number of isolated highs were detected. As a number of these I highs coincide with As peaks there is a possibility these may indicate sulphide mineralisation. Although greisenisation and kaolinisation have been shown to deplete C1 in granites (Fuge and Power, 1969) the C1- ion plays a major role in the transport of metals in hydrothermal solutions and has been found to be the major anion in many fluid inclusions and hydrothermal waters. All the samples analysed contained similar levels of C1 to soils from other areas in the British Isles (AndreWs *et al.* 1984; Fuge *et al.* 1986).

The association of F with the processes of Sn and W mineralisation has long been recognised (Daubree 1841; Hosking 1972) and the possibility of its use as a pathfinder for greisen W-Sn mineralisation has recently been advanced (Rose *et al.* 1979). Fuge and Power (1969) demonstrated the enrichment of the Cornubian granites in C1 and F, and in particular they highlighted the extreme F enrichment associated with the southwest England greisens. The F concentrations for all the soils analysed exceeds general background values by an order of magnitude. The highest F values detected on Traverse B-I and B-2, coincide with high W, Cu and Bi over the break of slope and possibly indicates the location of either a mineralised vein or other structure affecting the migration of ions in the killas marginal to the intrusion.

## Conclusions

From the results of this study, the following conclusions can be drawn regarding the use of soil geochemistry for exploration for bulk tonnage tungsten deposits of this type:

(1) None of the traverses sampled extended into background for W, Sn, As, Sb, Bi and F, therefore all these elements develop broad secondary dispersion patterns in soils and are of potential use in geochemical prospecting to identify the general location of mineralised areas.

(2) At a more local scale, W, Sn, Bi, U and Mo enrichment in surface soils appears to relate spatially to the occurrence of underlying granite-hosted mineralisation.

(3) Coinciding high concentrations of W, F, Cu and Bi were detected in B-horizon samples and possibly relate to the location of mineralised structures. In addition C1, I, As, Sb, Pb and Zn in B-horizon samples may also be of use in delineating metalliferous targets.

(4) Although no single element unambiguously indicates the location of the underlying mineralisation, coinciding soil anomalies of element associations commonly related to this type of mineralisation do, eg. W, Sn, Bi, U, Mo and F. Therefore multi-element surveys involving the determination of these elements and others such as Pb, Zn, I, C1, and Sb would have useful application in locating W mineralisation. The automated photometric and XRF methods used in this study are readily applicable to this approach.

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## References

Andrews, M.J., Bibby, J.M, Fuge, R. and Johnson, C.C. 1984. The distribution of iodine and chlorine in soils over lead-zinc mineralisation, east of Glogfawr, Mid-Wales. *Journal of Geochemical Exploration*, 20, 19-32.

Anon, 1979. Hemerdon - Britain's Largest tungsten deposit.*Mining Magazine, 141,* 342-351.

Ball, T.K. and Basham, I.R. 1984. Petrogenesis of the Bosworgey granitic cusp in the SW England tin province and its implications for ore mineral genesis. *Mineralium Deposita,19,* 70-77.

Ball, T.K., Basham, I.R., Bland, D., and Smith, T.K. 1982. Aspects of the geochemistry of Bismuth in south-west England. *proceedings of the Ussher Society, 5,* 376-382.

Ball, T.K., Nicholson, R.A., and Peachey, D. 1985. Gas geochemistry as an aid to detection of buried mineral deposits. *Transactions of the Institution of Mining and Metallurgy, (Section B: Applied Earth Science), 94,* B181-B188.

Beer, K.E. and Ball, T.K. 1986. Tin and tungsten in pelitic rocks from S.W. England and their behaviour in contact zones of granites in mineralised areas. *Proceedings of the Ussher Society, 6,* 330-338.

Beer, K.E. and Ball, T.K. 1987. Tungsten mineralisation and magmatism in S.W. England. *In:* "Gisements de tungstene: Metallogenie, exploration, mineralogie et exploitation". BRGM. (In press).

Brooks, R.R. 1972. Geobotany and biogeochemistry in mineral exploration. Harper and Row, New York, 290pp.

Boyle, R.W. 1974. Elemental associations in mineral deposits and indicator elements of interest in geochemical

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prospecting (revised). *Geological Survey of Canada, Paper 74-45*. 40pp.
Cameron, J. 195 I. The Geology of the Hemerdon wolfram mine, Devon. *Transactions of the Institution of Mining andMetallurgy*, 6L 1-14.
Connor, J.J. and Shacklette, H.T. 1975. Background geochemistry of some soils, plants, and vegetables in the conterminous United States. *U.S. Geological Survey Professional Paper* 574-F, 164pp.
Daubree, A. 1841. Mémoire sur le gisement, la construction et l'origine des amas de minéral détain. *Annales des Mines, 3e Serie, tome xx*, 65-112.
Dines, H.G. 1956. The metalliferous mining region of Southwest England. *Memoirs of the Geological Survey of Great Britain*, 2 volumes, 795pp.
Fuge, R. 1976. The automated colorimetric determination of fluorine and chlorine in geological samples. *Chemical Geology*, 17, 37-43.
Fuge, R. and Andrews, M.J. 1985. The automated photometric determination of total fluorine in mineral exploration. *Journal of Geochemical Exploration*, 23, 293-297.
Fuge, R., Andrews, M.J. and Johnson, C.C. 1986. Chlorine and iodine, potential pathfinder elements in exploration geochemistry. *Applied Geochemistry*, 1, 111-116.
Fuge, R. and Johnson, C.C. 1984. Evidence for the chalcophile nature of iodine. *Chemical Geology*, 43, 347-352.
Fuge, R., Johnson, C.C., and Phillips, W.J. 1978. An automated method for the determination of iodine in geochemical samples. *Chemical Geology*, 23, 255-265.
Fuge, R. and Power, G.M. 1969. Chlorine and fluorine in granitic rocks from S.W. England. *Geochimica et Cosmochimica Acta*, 33, 888-893.
Hosking, K.F.G. 1972. The truth concerning Daubree's work on the genesis of cassiterite. *Geological Society of Malaysia Newsletter*, 36, 6-7.
Johnson, C.C. 1980. The geochemistry of iodine and a preliminary investigation into it's potential use as a pathfinder element in geochemical exploration. *UnpublishedPh. D. Thesis, University College of Wales, Aberystwyth*, 323pp.
Stone, M. and Exley, C.S. 1986. High heat production granites of south west England and their associated mineralization a review. *Transactions of the Institution of Mining andMetallurgy*, (Section B: Applied Earth Science), 95, B25-B36.
Rose, A.W., Hawkes, H.E. and Webb, J.S. 1979. Geochemistry in mineral exploration. *Academic Press*, London, 2nd edition, 657pp.
Watson, J., Fowler, M.B., Plant, J.A. and Simpson, P.R. 1984. Variscan-Caledonian comparisons: late orogenic granites. *Proceedings of the Ussher Society*, 6, 2-12.

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*Read at the Annual Conference of the Ussher Society, January 1987*

# The Otterton Trough: implications of groundwater helium data

R.G. GREGORY
E·M. DURRANCE

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A total of 12 South West Water Authority abstraction wells situated in the Otter Valley, East Devon, were sampled for $^{4}$He analysis in June 1983 and February 1984. The wells are all located on the Otter sandstones (Triassic) and penetrate the Budleigh Salterton pebble beds. They occur around Harpford and near Colaton Raleigh. Samples from the Harpford area on both occasions showed significantly elevated levels of 4He compared with the atmospheric equilibrium concentration. In contrast, nile abundances from the wells near Colaton Raleigh were all consistently lower and showed seasonal variation. The nile probably has a shallow source in U-bearing mineralisation within the Permian - Triassic succession, as well as a deep source in the Devonian - Carboniferous basement· Taken together with the pattern of U-series disequilibrium values and the Bouguer anomalies in the area, the distribution of nile anomalies appears to be related to an approximately E-W trending feature which is coincident with the Sidmouth Gap. This feature is interpreted as the northern margin of a pre-Triassic rift: the Otterton Trough.

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## Introduction

In East Devon a pattern of groundwater flow controlled by major E-W trending faults has been identified by Durrance and Heath (1985). Because of the scale on which zones of ascending and descending groundwater are found along these faults and the absence of any relationship which could indicate that a topographic head is responsible, a thermal driving force has been suggested as the cause of the groundwater circulation. The model of' thermal waters rising up deep-seated fractures leading to the hydrothermal charging of aquifers cut by the fractures, has been used by Durrance (1984) to explain the occurrence of sedimentary-hosted metalliferous mineralisation in East Devon. To examine whether exchange of groundwaters between deep-seated fractures and aquifers is taking place today, 12 samples of groundwater from the East Devon aquifer were taken from boreholes in the Otter Valley and analysed for their nile content during the summer of 1983 and the winter of 1984. Analyses of $^{222}$Rn were also made on 2 samples from different parts of the aquifer.

Both $^{4}$He and turn are radiogenic gases. $^{4}$He forms from the radioactive decay of ruth and $^{238}$U to Pb, each alpha-particle emitted in these series acquiring extra-nuclear electrons, but $^{222}$Rn is only a product of the radioactive decay of $^{238}$U. Also, while $^{4}$He is stable, turn has a half-life of 3.825 days. After their formation both these gases tend to migrate towards the surface of the Earth, although rapid transfer is only possible through groundwater flow within fractures. Even then the rate of movement may be too slow for $^{222}$Rn originating at depth to survive to reach the surface. Where a fracture carrying $^{4}$He and $^{222}$Rn intersects an aquifer, the gases will migrate with the groundwater from the fracture into the aquifer provided the aquifer is at least partially free-draining. Changes in the concentration of nile and $^{222}$Rn with position in an aquifer, and any seasonal variation in these abundances caused by meteorological conditions, can then indicate the relative importance of deep and shallow groundwaters in the aquifer and the distance over which groundwater from a fracture has a recognisable influence.

## Fractures in East Devon

Although the structure of the New Red Sandstone of East Devon appears on outcrop to be a simple succession of strata gently dipping eastwards (Fig. 1), the subsurface picture could be more complex. To the west of the Exe Estuary, important Variscan thrusts occur in the Devonian and Carboniferous basement (Selwood *et al.* 1984). Just as in the Crediton and Tiverton areas, it is possible that deposition of the Stephanian and Lower Permian rocks beneath East Devon could have been controlled by a rift valley developed during tensile reactivation of these thrusts (Durrance 1985).

Evidence for this rift valley has become available from U-series disequilibrium studies indicating groundwater movement along important E-W faults, even though these faults have little effect on the outcrop pattern in the area (Durrance and Heath 1985). Nevertheless, one of these faults passing close to Harpford appears to have

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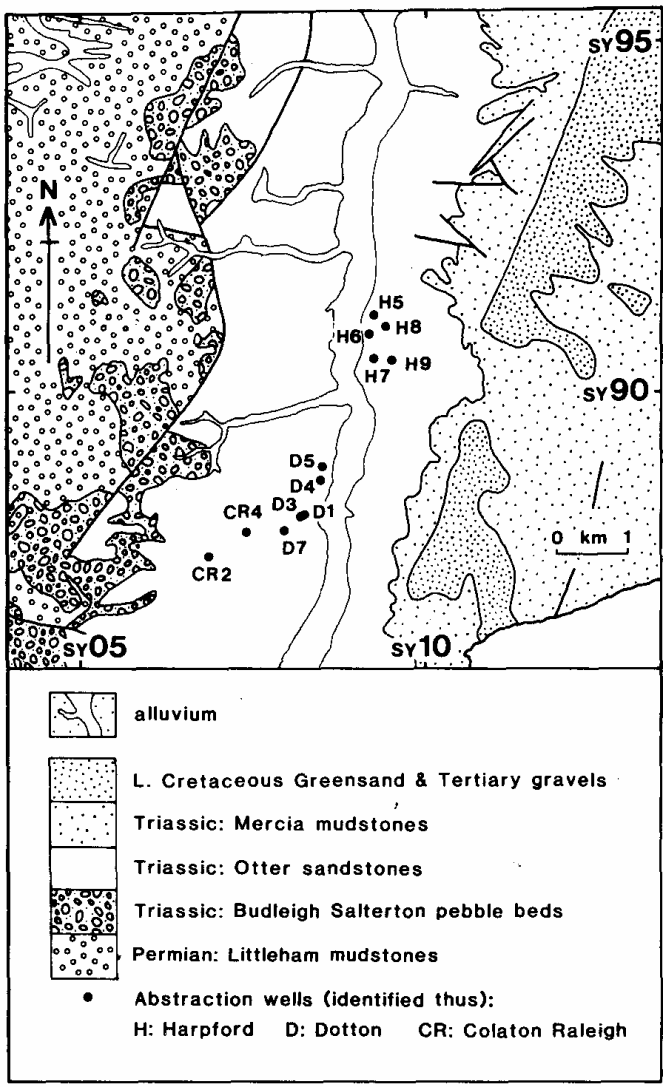


Figure 1. The geology of the Harpford - Colaton Raleigh area of East Devon, with the positions of the sample sites indicated.

propagated fractures through the higher parts of the New Red Sandstone succession and the Cretaceous-Tertiary strata to give a line of weakness which enabled erosion Of the Sidmouth Gap. The distribution of Bouguer anomalies in East Devon also suggests the presence of a hidden trough of New Red Sandstone rocks in the area south of Harpford (Fig. 2). Because the anomalies appear to be centred on an E-W line through Otterton, this feature was termed the Otterton Trough by Durrance (1983).

To the east of Exeter it is apparent that the E-W fault which lies along the southern margin of the Crediton Trough and separates the New Red Sandstone breccias from the basement rocks, has propagated fractures through Upper Permian strata although it did not exert any control over the sedimentation of these younger beds (Bristow and Scrivener 1984). The presence of these fractures was also indicated in the results of the U-series disequilibrium survey given by Durrance and Heath (1985). In addition, the U-series disequilibrium results showed that the fractures even propagated through the Triassic, Cretaceous and Tertiary successions. The easterly extension of the Crediton Trough thus provides a model for interpreting the hidden structure south of Harp ford.

If the gravity anomaly due to the Otterton Trough of about 3mgals is caused by a density contrast of 110kgm$^{-3}$ between the Devonian - Carboniferous basement and the overlying Stephanian and Lower Permian succession, as identified by Davey (1981) in the Crediton Trough, then a buried rift valley containing approximately 300m of New Red Sandstone strata is indicated (Durrance 1983). This is comparable with the thickness of sediment found in the western part of the Crediton Trough. The form of the faulted margins of the Otterton Trough may therefore be similar to those of the Crediton Trough (Durrance 1985). The northern edge of the Otterton Trough trends E-W near the line of the Sidmouth Gap, while the southern boundary appears to lie parallel with the coast at Budleigh Salterton. The closure of the isogals to the west of Otterton indicates that the trough terminates before reaching the Exe Estuary. Similar westerly terminations of the Crediton and Tiverton Troughs also occur.

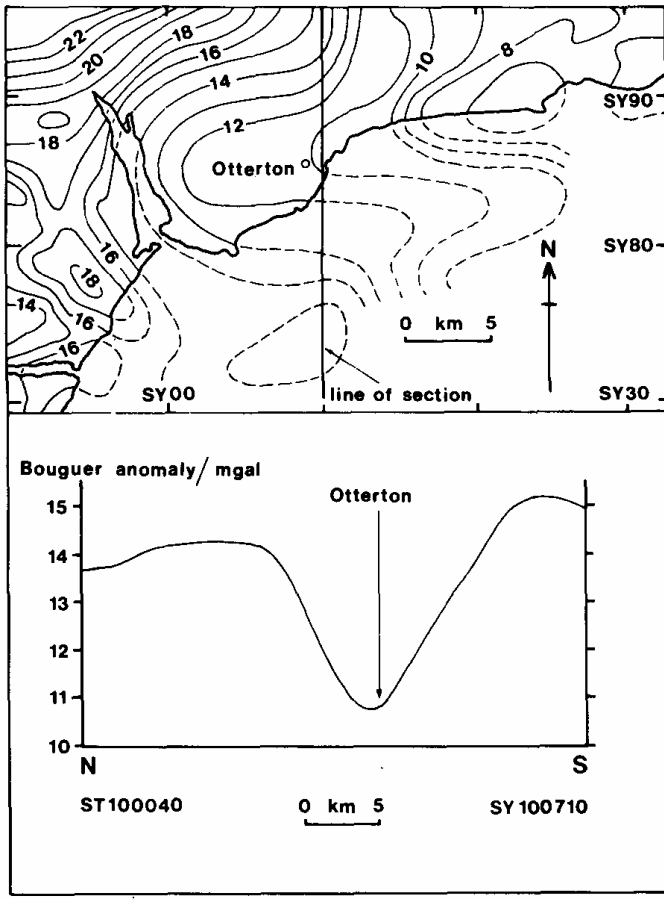


Figure 2. Bouguer anomaly map and N-S section of the Otterton Trough. The line of section continues to the north of the area covered by the map. All values, given in milligals. After the 1:25000 map of the British Geological Survey.

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## Generation of $^{4}He$ and $^{222}Rn$ within the New Red Sandstone

Studies of the Upper Permian rocks in East Devon by Carter (1931) and Perutz (1939) showed the presence of various types of U-rich nodules. These nodules possibly represent a significant source of $^{4}He$ and $^{222}Rn$, but the extent to which these gases will be released is controlled by the mineralogy of the nodules. Perutz (1939) proposed that the radioactive material is amorphous, colloidal calciocarnotite, but Wyley (1961) identified the presence of metatyuyamunite, while Harrison (1975) suggested that the U-bearing material is coffinite. Durrance and George (1976) also observed metatyuyamunite, and alpha-cristobalite. The metatyuyamunite was believed to be derived from the spontaneous dehydration of tyuyamunite, while the presence of alpha-cristobalite suggested that the original U-bearing material was coffinite together with thucolite. The ease of alteration of the U-bearing minerals and their low density indicate that release of $^{4}He$ and $^{222}Rn$ from the nodules will probably take place without difficulty.

Although the main occurrence of nodules is in the Littleham mudstones, nodules have also been found in the lower part of the Mercia Mudstone Formation. The results of a streamwater U survey of East Devon confirmed this distribution (Durrance 1984). Apart from indicating that the nodules provide a fairly uniform source of $^{4}He$ and $^{222}Rn$ across the Otterton Trough, their distribution suggests that lateral movement of the mineralising solutions within the pebble beds/sandstones aquifer was more easily accomplished than vertical ascent. Free-draining conditions must therefore have been present in the aquifer at the time of mineralisation.

## Dissolved gas measurements from ground-waters in the Otter Valley

The sample collection sites used for this survey were the South West Water Authority abstraction wells situated in the Otter Valley (Fig. 1). Of these wells, 5 occur in the vicinity of Harpford, 5 near Dotton, and a further 2 at Colaton Raleigh. These 12 sample sites lie on a NNE-SSW line approximately parallel to the regional strike of the Permian and Triassic strata. The wells are all sunk in the outcrop of the Otter sandstones and extend into the underlying Budleigh Salterton pebble beds.

Samples were collected for $^{4}He$ analysis in plastic bottles fitted with plastic caps which were sealed with an O-ring and incorporated a rubber septum. The bottles were filled to a pre-set level giving a known headspace and water volume. The bottles were shaken for two minutes and allowed to stand for a further two minutes to permit equilibration of the gas phase with the water phase. Samples of the gas phase within the container were then collected in $10cm^{3}$ plastic disposable syringes for subsequent analysis. The 2 samples which were collected for $^{222}Rn$ analysis were stored in glass bottles with no

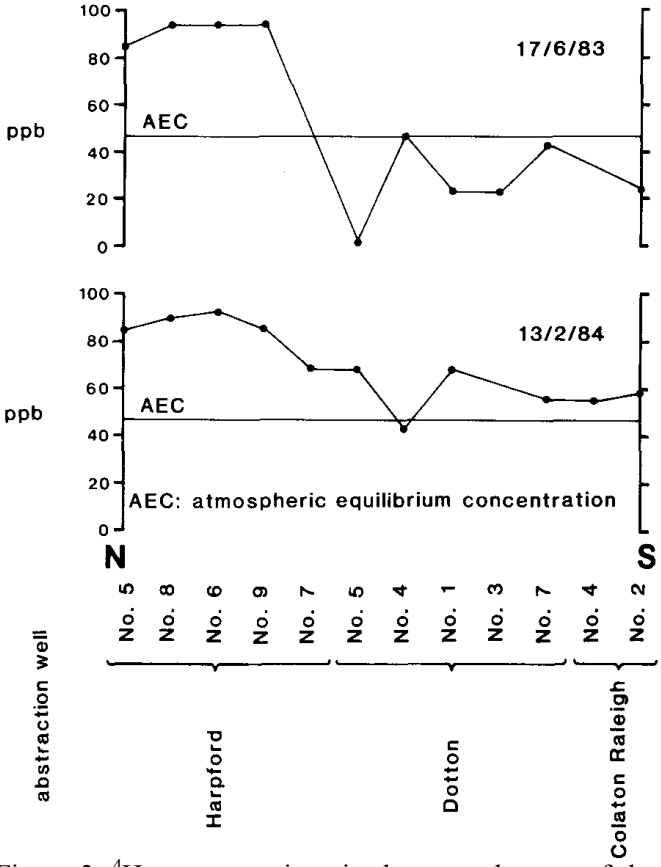


Figure 3. $^{4}He$ concentrations in the groundwaters of the Otter Valley.

headspace gas, so that degassing of the samples and $^{222}Rn$ activity measurements could be carried out in the laboratory. As all samples were obtained from specimen taps at the top of each borehole, degassing of the ground-water during sample collection was considered negligible. Analyses were carried out using the equipment and methods described by Gregory and Durrance (1987). $^{4}He$ concentrations were determined by mass spectrometry and $^{222}Rn$ activities by alpha particle scintillometry.

The concentrations of $^{4}He$ observed in the water samples collected on 17/6/83 showed a very clear pattern of high values from the wells sampled in the Harpford area (85-95ppb $^{4}He$), while the wells in the Dotton and Colaton Raleigh areas, on the other hand, showed concentrations of $^{4}He$ which were less than or equal to the atmospheric equilibrmm concentration of 47ppb $^{4}He$ and 10°C (Table 1, Fig. 3). These low concentrations range down to only 2ppb $^{4}He$, which indicates almost complete degassing of $^{4}He$ from the water.

The samples which were collected on 13/2/84, however, showed a somewhat different pattern (Table 1, Fig. 3). The concentrations of $^{4}He$ in the groundwaters from the Harpford area were similar to those found in the earlier survey, but those from Dotton and Colaton Raleigh were mostly higher than in the results from the previous survey. Only one mmor exception occurs, as Dotton No. 4 well

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remained effectively constant (43ppb compared with 47ppb from the earlier survey). In addition, while all the samples obtained from Harpford remained above the atmospheric equilibrium concentration of $^{4}He$, with the exception of Dotton No. 4 well, those from Dotton and Colaton Raleigh changed from below the atmospheric equilibrium level in June 1983 to concentrations above this level in February 1984. This indicates that the factors which determine the groundwater concentration of 4He in the Harpford area are somewhat different from those controlling groundwater $^{4}He$ concentrations in the Dotton and Colaton Raleigh areas.

Although the range of $^{4}He$ concentrations obtained during February 1984 is only half that found in June 1983, the relative behaviour of $^{4}He$ in both surveys is comparable, with a Pearson correlation of 0.710 for the two sets of data (Table 1). This suggests that while the consistently high values seen in the Harpford area appear to be unaffected by whatever produces the variation in the concentrations at Dotton and Colaton Raleigh, the changes observed at Dotton and Colaton Raleigh are all of a comparable magnitude and probably reflect a common response to a single cause. The 2 samples collected for $^{222}Rn$ analysis (Table 1) showed that $^{222}Rn$ activities in the groundwaters are higher than in the surface waters which overlie these sedimentary rocks. The surface waters typically have $^{222}Rn$ activities less than $3Bql^{-1}$ (Durrance, 1978). Although only two measurements were made it is difficult to recognise any significant difference between the two areas.

## Interpretation of results

There is no evidence of U-mineralisation in either the Budleigh Salterton pebble beds or the Otter sandstones which could be a source of the large 4He concentrations found in the groundwaters of the Otter Valley. It seems likely, therefore, that both the $^{222}Rn$ and the $^{4}He$ have been mainly derived from the U-bearing mineralised horizons at the top of the Littleham mudstones, although some contribution from the mineralisation near the base of the Mercia mudstone is possible. However, the fact that the $^{4}He$ concentrations display a marked variation in character between Harpford and Dotton/Colaton Raleigh suggests that some structural control is being exercised over the movement of $^{4}He$ into the groundwater, and that a deeper source of $^{4}He$ is also present.

The model of groundwater movement along deep-seated faults proposed by Durrance (1984) shows that recharge of aquifers in the Permian and Triassic strata from the underlying Devonian - Carboniferous basement may have taken place during the formation of the metalliferous mineralisation in East Devon. Indeed, the Otter sandstones - Budleigh Salterton pebble beds aquifer, the most important in the area, lies between the uraniferous nodule horizons in the Littleham and Mercia mudstones. While this model was proposed for a fossil hydrothermal system, it is quite possible that the same structural control of groundwater movement is still acting today. It is not difficult to envisage, therefore, a system of recharge taking place in this aquifer where a component of deep groundwater, derived from the Devonian Carboniferous basement, accompanies groundwater from a shallower source. The presence of the high $^{4}He$ concentrations observed from the wells in the Harpford area compares well with the position of the northern faulted margin of the Otterton Trough. This suggests that the small seasonal variation shown by $^{4}He$ at these sites, and their consistently high $^{4}He$ concentrations, may be explained by the $^{4}He$ being derived from the basement along a deep fracture.

In contrast, $^{4}He$ concentrations in the samples from Dotton and Colaton Raleigh, which lie nearer the centre of the Otterton Trough, are generally lower than those found at Harpford and show a marked seasonal variation. There is evidence that $^{4}He$ concentrations in unconfined or semi-confined aquifers could be expected to be in dynamic equilibrium with the atmosphere through degassing in the aquifers (Butt and Gole, 1986). This proess may take place laterally and vertically throughout an aquifer, or via fractures which cut the aquifer cap rocks. The transport mechanisms which may modify the gas concentrations are of two major types: earth-mechanical (Gingrich and Fisher 1976), and fluid-convectional (Fleischer and Mogro-Campero 1978). Diffusion acts on a lesser scale and cannot alone account for the patterns observed. Butt and Gole (1986) have recognised that it is particularly difficult to establish any single mechanism which may control the variation in $^{4}He$ concentrations in a hydrological system of this type.

| Well | Grid Reference | He/ppb 17/6/1983 | He/ppb 13/2/1984 | $Rn/Bql^{-1}$ 13/2/1984 |
|---|---|---|---|---|
| Harpford No.5 | 93910 | 85 | 85 | nd |
| Harpford No.6 | 91907 | 94 | 92 | nd |
| Harpford No.7 | 93904 | nd | 69 | nd |
| Harpford No.8 | 94908 | 94 | 89 | nd |
| Harpford No.9 | 95904 | 94 | 86 | 10 |
| Dotton No.1 | 83883 | 24 | 68 | nd |
| Dotton No.3 | 83883 | *24* | nd | nd |
| Dotton No.4 | 85887 | 47 | 43 | nd |
| Dotton No.5 | 85889 | 2 | 69 | nd |
| Dotton No.7 | 80881 | 43 | 56 | nd |
| Colaton Raleigh No.2 | 70887 | 24 | 58 | 14 |
| Colaton Raleigh No.4 | 75880 | nd | 55 | nd |
| Mean | | 53 | 70 | 12 |
| Median | | 45 | 69 | |
| Minimum | | 2 | 43 | 10 |
| Maximum | | 94 | 92 | 14 |
| Standard deviation | | 35 | 16 | |

Pearson correlation for He data: 0.710

Table 1. Helium, radon and summary statistics from the Otter Valley abstraction wells, East Devon.
nd: not determined.

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However, they have observed twofold variations in concentrations over lateral distances of 100m or so, and $^4$He concentrations may drop to equilibrium levels within 220m from a zone of anomalous concentration (Butt and Gole 1986; Gole *et al.* 1986). These variations have been attributed to (1) the presence of a $^4$He source (either structural or radiogenic) independent of'the age and residence time of the groundwater in an aquifer, (2) influx of groundwater with a low $^4$He content, indicating a shallow source nearer to equilibrium, and (3) the presence of structural traps. Butt and Gole (1986) also showed that dilutional effects occur where there is mixing of groundwaters from more than one aquifer. This may well be the case in East Devon where minor aquifers both overlie and underlie the main Otter sandstones- Budleigh Salterton pebble beds aquifer, and all are unconfined to some degree although not as free-draining as must have been the case during the passage of the mineralising solutions.

It is thus reasonable to suggest that the low concentrations of $^4$He observed in the Dotton and Colaton Raleigh wells have a component which, at least in part, is derived from the lateral dispersion of $^4$He rising up deep-seated fractures from the basement. Nevertheless, the fact that only limited amounts of $^4$He have travelled the 2km from Harpford indicates that groundwater flowing into the aquifer from these fractures is far less important today than during the formation of the metalliferous mineralisation. The change in character could be due to a number of reasons. For example, lateral dispersion may vary temporally due to physical (earth-mechanical) effects such as atmospheric pressure changes, temperature gradients controlling subsurface fluid movement, and the relative contribution of sweep gases from depth (Durrance and Gregory 1987).

If the main sotirce of $^4$He at Dotton and Colaton Raleigh is the U-mineralisation in the Littleham and Mercia mudstones, local migration pathways must be present. Because the uraniferous nodule horizons lie immediately adjacent to the pebble beds - sandstones aquifer, movement of released $^4$He is not needed over a large distance. In all probability, the release of $^4$He into the aquifer depends only upon the presence of micro-fractures in the mudstones. Movement of $^{222}$Rn would be similarly controlled. The occurrence of high $^{222}$Rn activities in the aquifer waters from the Harpford area, over the fracture zone, and also from Dotton/Colaton Raleigh, where only background concentrations of $^4$He are observed, supports this hypothesis.

Conclusions

The presence of a pre-Triassic rift valley trending E-W beneath Otterton in East Devon is indicated by the distribution of Bouguer anomalies in the area. To maintain a consistent terminology with similar structures elsewhere in Devon, the rift valley is known as the Otterton Trough. U-series disequilibrium studies suggest that the northern margin of the Otterton Trough passes through Harpford, in a position coincident with the Sidmouth Gap. This northern margin of the trough is interpreted as an important pre-Triassic fault, the trough having formed by tensile reactivation of a Variscan thrust in the Devonian - Carboniferous basement. Propagation of fractures through the Triassic - Tertiary strata above the fault produced the line of weakness which was exploited in the erosion of the Sidmouth Gap.

$^4$He concentrations in the groundwaters of the Otter Sandstones - Budleigh Salterton pebble beds aquifer are high near the faulted northern margin of the trough and show little seasonal fluctuation. This is interpreted as indicating a deep-seated source for the $^4$He, with migration taking place along the fault and into the aquifer. As the $^4$He will be transported mainly by flowing groundwater, this is consistent with models which indicate the hydrothermal charging of aquifers by solutions rising from depth along major fractures.

In contrast, nearer the centre of the Otterton Trough, at Dotton and Colaton Raleigh, the $^4$He concentrations are lower and show marked seasonal change. This is consistent with a shallow source for most of the $^4$He, and atmospheric pumping effects. U-bearing mineralisation in the Littleham and Mercia mudstones which are adjacent to the Otter sandstones - Budleigh Salterton pebble beds aquifer, is considered to be the source of most of the $^4$He present in this part of the aquifer. Lateral movement through the aquifer of groundwaters rising up deep-seated fractures thus today appears to be limited to less than 2km. This contrasts with the model of extensive hydrothermal charging of the aquifer from deep-seated fractures used to explan the occurrence of the metalliferous mineralisation in the New Red Sandstone of East Devon.

Although $^{222}$Rn activities in the streams of the Otter Valley are low, higher activities in the groundwaters support the view that the U-mineralisation in the Littleham and Merica mudstones is a source of radiogenic gas in the aquifer. However, the presence of the northern margin fault near Harpford does not appear to have acted to increase the rate of transfer of $^{222}$Rn from the mudstones to the aquifer. The transfer of background levels of the radiogenic gases is therefore taking place uniformly across the boundaries of the aquifer throughout the area underlain by the Otterton Trough. This suggests that numerous microfractures are present within the mudstones which contain the uraniferous nodules.

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## References


Bristow, C.R and Scrivener, R.C, 1984. The stratigraphy and structure of the Lower New Red sandstone of the Exeter district. *Proceedings of the Ussher Society, 6,* 68-74.

Butt, C.R.M. and Gole, M.J., 1986. Groundwater helium surveys in mineral exploration in Australia. *Journal of Geochemical Exploration, 25,* 309-344.

Carter, G.E.L., 1931. An occurrence of vanadiferous nodules in the Permian beds of South Devon. *Mineralogical Magazine, 22,* 609-613.

Davey, J.C., 1981. Geophysical studies across the Permian outcrop in central and east Devon. *Proceedings of the Ussher Society, 5,* 194-199.

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

Durrance, E.M., 1983. Radiological indications of hydrothermal circulation in South East Devon. *Unpublished Ph.D. thesis, University of Exeter.*

Durrance, E.M., 1984. Uranium in the New Red Sandstone of south-east Devon. *Proceedings of the Ussher Society. 6,* 108-115.

Durrance, E.M., 1985. A possible major Variscan thrust along the southern margin of the Bude Formation, south-west England. *Proceedings of the Ussher Society, 6,* 173-179.

Durrance, E.M. and George, M.C., 1976. Metatyuyamunite from the uraniferous-vanadiferous nodules in the Permian marls and sandstones of Budleigh Salterton, Devon. *Proceedings of the Ussher Society, 3,* 435-440.

Durrance, E.M. and Gregory, R.G., 1987. Helium and radon transport mechanisms, heat flow and hydrothermal circulation in southwest England. *Proceedings of the Ussher Society, 6, 555-556.*

Durrance, E.M. and Heath, M.J., 1985. Thermal groundwater movement and radionuclide transport in SW England. *Mineralogical Magazine, 49,* 289-299.

Fleischer, R.L. and Mogro-Campero, A., 1978. Mapping of integrated radon emanation for detection of long distance migration of gases within the Earth: Techniques and principles. *Journal of Geophysical Research, 83,* 3539-3549.

Gingrich, J.E. and Fisher, J.C. 1976. Uranium exploration using the Track-Etch method. *Exploration of Uranium Ore Deposits Symposium.* Vienna, International Atomic Energy Agency, 213-227.

Gole, M.J., Butt, C.R.M. and Snelling, A.A., 1986. A groundwater helium survey of the Koongarra uranium deposit, Pine Creek Geosyncline, Northern Territory. *Uranium, 2, 343-360.*

Gregory, R.G. and Durrance, E.M., 1987. Helium, radon and hydrothermal circulation in the Carnmenellis radiothermal granite in southwest England. *Journal of GeophysicalResearch, in press.*

Harrison, R.K. 1975. Concretionary concentrations of the rarer elements in Permo-Triassic red beds of south-west England. *Bulletin of the Geological Survey (UK), 52,* 1-26.

Perutz, M., 1939. Radioactive nodules from Devonshire, England. *Mineralogische unt Petrographische Mitteilungen, 5 L* 141-161.

Selwood, E.B., Edwards, R.A., Simpson, S., Chesher, J.A., Hamblin, R.J.O., Riddolls, B.W. and Waters, R.A., 1984. Geology of the country around Newton Abbot. *Memoir of the British Geological Survey Sheet 339.* H.M.S.O., London.

Wyley, J.F., 1961. Metatyuyamunite from the Permian, Budleigh Salterton, Devon. *Notes of the Mineralogical Society llZ*


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*Read at the Annual Conference of the Ussher Society, January 1987*

# A mechanistic approach to the paragenetic interpretation of mineral lodes in Cornwall

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The paragenetic and structural diversity of the mineral lodes in Cornwall and Devon is well known (ag. MacAlister 1906, 1908; Dines 1956 and Hosking 1964). Isotopic dating supported by studies of the temperature and composition of fluids trapped in inclusions of different generations have shown that mineralization occurred over a geologically protracted period (Jackson *et' al.* 1982; Darbyshire and Shepherd 1985) and that hydrothermal fluids were supplied from different sources at different times (Alderton 1975; Shepherd *et al.* 1985; Scrivener *et al.* 1986). Whereas the general assertion that mineralization is both polyascendent and polygenetic is beyond doubt, it is still necessary to establish criteria by which the mechanisms responsible for the introduction of fluids and the precipitation of minerals during each stage of hydrothermal evolution can be identified.

Fracture geometry and textural variations in the ore minerals and gangue provide a basis for a mechanical and kinetic interpretation of paragenetic development which leads, intuitively, to constraints on the types of fluid flow and the sources tapped during each stage. Such an approach can help to limit the dichotomy of interpretation persisting in the literature, in which the dynamic processes inferred by Hunt (1884) and MacAlister (1906) are set against the passive mode of genesis favoured by Collins (1912) who wrote:

> "there is no reason to believe that any of these lode-fissures have been formed by anything like explosive forces. On the contrary, it would seem that the "vera causa" in most, if not all cases has been gravitational force operating during periods of contraction or relaxation of pressure".

This bold assertion is not compatible with much of the structural and textural evidence which leads to the conclusion that greisen veins, sheeted vein stackworks and the initial stages of propagation of the great composite lodes took place by a mechanism of **autogenous hydraulic pulsation** within a regime of variable confining tectonic stress. The basis for the operation of this mechanism has been described by Allman-Ward *et al.* (1982), providing a dynamic refinement of the mechanical interpretation of vein systems in Southwest England as given by Moore (1985) in which the concept of "fluid pressure cells" was invoked. The idealized growth

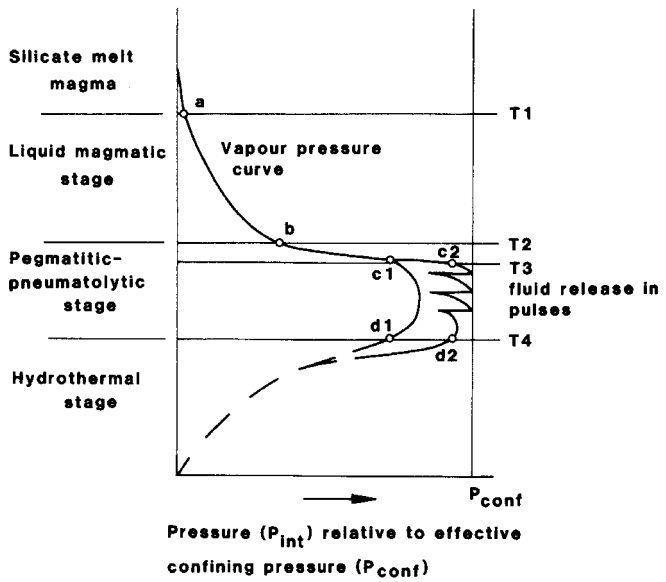


Figure 1. Diagram, based on the concepts of Niggli (1920, 1929), showing the evolution of vapour pressure relative to confining pressure and declining temperature in a crystallising volatile-rich granite magma. The path b-$c_1$-d, is that followed by a plutonic body in which the confining pressure remains greater than the evolved vapour pressure. Deuteric alteration will occur but the volatiles will ultimately be dissipated by diffusion into the surrounding rocks. The path b-$c_2$-$d_2$ is that taken when the granite body is emplaced at a hypabyssal level and the fluids are released in pulses to form veins of pneumatolytic type, eg greisen lodes with tin and tungsten minerals.

of a lode by a sequence of pulses originating from a magmatic focus is illustrated in Figura 1. This diagram can be related to the generalized curve for the evolution and subsequent diffusion of vapour pressure in a volatile-rich granite magma crystallizing under confinement which was illustrated originally by Niggli (1929) and has been adapted for the purpose of the present discussion in Figure 2.

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This mode of fracture propagation-in which the hydrothermal column is effectively confined between successive pulses provides an explanation of the bridging and interlocked texture of the quartz gangue and the sporadic nucleation of cassiterite and wolframite which gives rise to the coarse bunchy aggregates which characterise the growth of these minerals in greisen veins. This textural feature also has economic consequences which were discussed by Reid and Scrivenor (1906) with specific reference to the greisen veins at Cligga Head. Selvedge alteration, which is often significantly wider than the dilation on the lode structure, can be viewed not only in terms of the chemical disequilibrium between the greisening fluid and the minerals of the wallrock but also in terms of the hydraulic disequilibrium between the vein fluids and the pore fluids in the wallrocks. Because the fluids generated at this stage of hydrothermal development are, by inference, formed at magmatic temperatures and confined at lithostatic pressures they are able to produce gross metasomatic changes in the wallrocks, leading to pervasive textural and mineralogical reconstitution. The various types of pervasive alteration which are particularly characteristic of the mineral lodes associated with Variscan granites have been given local names, such as **greisen** (Saxon German),

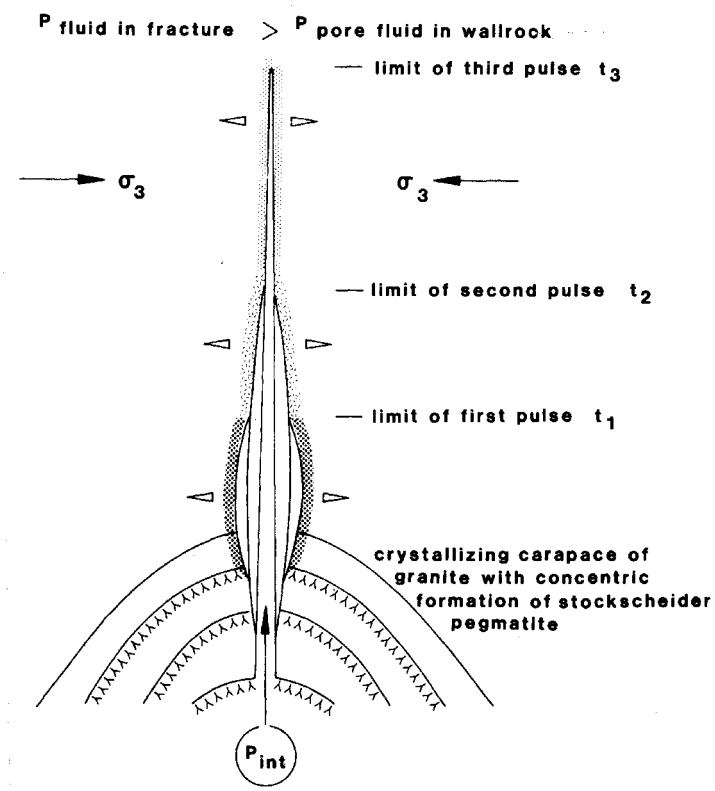


Figure 2. Illustration of the concept of autogenous magmato-hydrothermal pulsation. A pulse can occur when:

$$P_{int} = \sigma + T$$

$\sigma_3$- least principal confining stress, T - the tensile strength of the rock. Changes in fluid composition may occur from pulse to pulse so that the mineralogy of the vein filling and the wallrock alteration varies systematically.

**capel** and **peach** (Cornish). They, together with other deuteric and metasomatic transformations within the granites, fall explicitly in the domain of the pneumatolytic stage of hydrothermal evolution as defined by Niggli *(op. cit.)*

The intrinsic paragenetic association of cassiterite with silicate alteration of pneumatolytic facies was recognised by Daubree (1841), and the economic importance of this relationship in determining the nature of the mineralized structures in the mining districts of Southwest England was emphasised by Clement le Neve Foster in 1855, who wrote:

> "many of the principal and most productive tin lodes in Cornwall are simply tabular masses of altered granite adjacent to fissures."

Autogenous pulsation provides one alternative for the mechanistic interpretation of **Pulsation Zoning** as conceived by Smimow (1937). The polyascendent characteristics of greisen and quartz-tourmaline lodes formed simply by extensional dilation in fractures overlying hydrothermal foci associated with cupolas of the Cornubian batholith, as for instance in the case of the Great Beam Mine at Goonbarrow, at Cligga Headand St Michael's Mount, can be explained by this process. In the evolution of the great composite lodes, which are the main expression of Variscan mineralization in the orefield of Southwest England, the interplay of hydraulic pressures and tectonically directed shear stresses is more complicated so that autogenous magmato-hydro-thermal pulses can take place with tectonic assistance.

It is inferred that the energy driving autogenous pulsation is provided physico-chemically by crystallisation of the

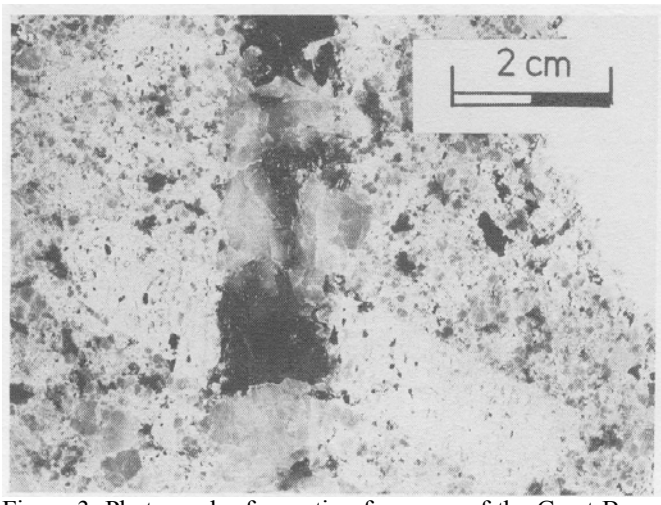


Figure 3. Photograph of a section from one of the Great Beam greisen lodes exposed in the Goonbarrow Pit. The vein has opened simply by dilation. There is no differential displacement of the part of the feldspar megacryst cut by the vein. There is evidently no bilateral symmetry in the quartz gangue and the wolframite crystals from a typical 'bunch' bridging the fracture.

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magma; therefore intermittent dilation of the lode system may be expectpd to give rise to textural changes at the magmatic source:.: Episodic crystaltisation in stoekscheider pegmatites and other types of unidirectional crystallisation texture at the internal contacts marking sub-stages in the magmatic evolution of the composite plutons are believed to identify the foci from which these magmato-hydrotbermal pulses originated. Hydraulic ·advance during fracture propagation can be correlated with momentary reductions of vapour pressure which then lead to adiabatic crystallization at the magmatic focus (Tuttle and Bowen 1958). This process could account for the formation of the distinctive texture in which an aplitic matrix cements coarse dendrites of feldspar, tourmaline and mica produced during the preceding stage of votatile accumulation ina confined pegmatitic phase.

The German word Stockscheider means "sheath of the stock" and originates in the Erzgebirge of Saxony where

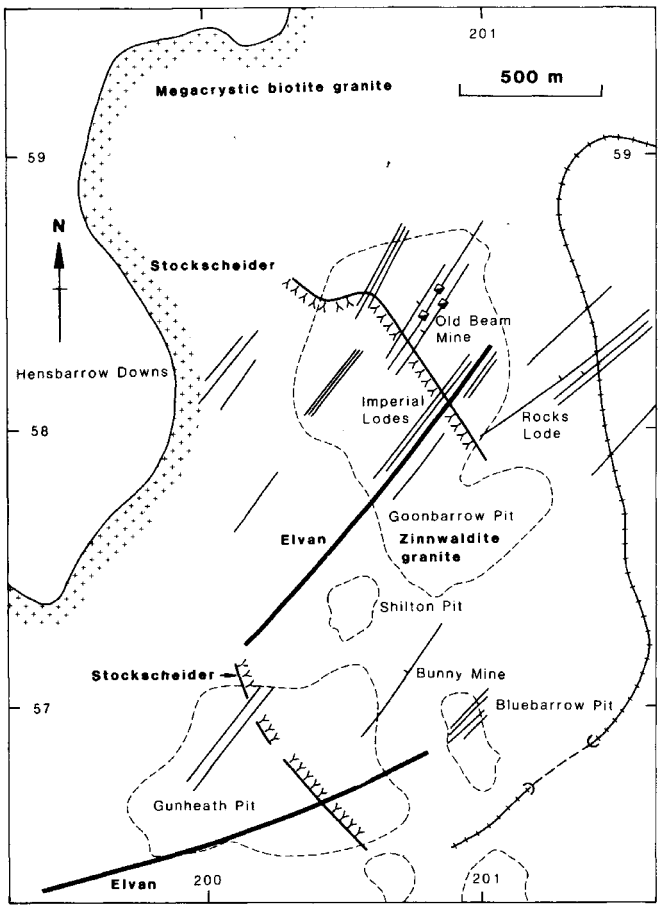


Figure 4. Sketch map showing the geology of a part of the St. Austell pluton in the vicinity of Goonbarrow and Gunheath Pits. A stockscheider pegmatite marks the contact of the later cupola of zinnwaldite granite, emplaced within the megacrystic biotite granite. A number of tourmaliniferous greisen lodes are rooted within, or below this cupola. The latest igneous event was the emplacement of the yellow gilbertitic elvan dykes which cut both granites and lodes.

these unidirectional pegmatic growths have long been known to occur on the contacts of lithium-rich cupolas at mineralized centres in the Variscan plutons. Description of those at Altenberg and Sadisdorf are given by Baumann and Schlegel (1967) and by Baumann (1970). The relationship between a stockscheider pegmatite complex, systems of sheeted greisen veins, and a later generation of elvan dykes is well-exposed in the central part of the St. Austell ptuton where the Hensbarrow cupola ofzinnwaldite granite is emplaced inthe earlier megacrystic biotite granite. Figure 4 is a reconnaissance map showing the critical features of the geology of this area. Comparable relationships can also be observed in other mineralized cupolas in Southwest Engiand, notably at St. Michael's Mount and Cligga Head. The common association of stockscheider pegmatites with Sn-W mineralization in greisen vein structures and related zones of pneumatolytic alteration in the Variscan granites thus appears to be a relationship of genetic significance, providing evidence of the link between the pegmatitic and pneumatolytic aspects of hydrothermal evolution in accordance with the concepts of Niggli.

The textural features diagnostic ofautogenous Pulsation are in marked contrast to those which are produced when gross decompression of the fit/ids in the propagating fractures takes place. This phenomenon is particularly prevalent in boron-rich systems of magmatic departure which have given rise to both tourmaline-cemented intrusive hydrothermal breccias originating from higher levels within the plutons, and to the breccia-lodes of the main stage of mineralization rooted deep within the batholith at foci formed significantly later during the Variscan cycle of magmatic and hydrothermal evolution in Cornwall. In both types of structure the pattern of spalling and brecciation is distinctive. The breccia body at Wheal Remfry shows textural features in common with those noted in similar tourmaline breccias formed at hypabyssal levels in mineralized calc-alkaline eruptives in the Andes, the Mexican Sierras and the Southwestern United States (Allman-Ward *et al.* 1982), a review of which has been given recently by Sillitoe (t985). A variety of processes have been invoked to explain the explosive exfoliation and disintegration of the wallrocks and fragments in these breccias. The textural relationships observed are compatible with their formation as a result of the hydraulic shock produced by the instantaneous reversal of fluid pressfire in the wallrocks relative to that in the adjacent fractures when decompression of the hydrothermal column took place, a phenomenon for which the term "**hydraulic decrepitation**" has been suggested (Halls and Allman-Ward 1986). The meaning of decrepitation has been established by usage to describe the process of crackling and disintegration ora material arising from internal pressures caused by heating (O.E.D.) With appropriate qualification the word can also serve effectively to describe the disruptive crackling produced by reversals in hydraulic pressure when these re of the same order as the tensile strength of the rocks concerned.

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The evidence that decompressive events of the type under discussion were geologically instantaneous is shown by the cementation of angular rock and mineral fragments in supporting microcrystalline hydrothermal matrices consisting of quartz, tourmaline, chlorite, rutile and, locally, cassiterite. The microscopic grain size of these matrices is interpreted as a kinetic effect due to the rapid nucleation which occured when adiabatic decompression of the hydrothermal column took place. The separation of volatile-rich fractions from a condensed residue would also be expected to occur as fluid phase relations responded to the change in confining pressure.

The textures of the early tourmaline breccia bodies such as that exposed at Wheal Remfry are amenable to interpretation because of the explicit contrast between clasts and matrix, locally enhanced by the effects of later kaolinization (Allman-Ward *et al.* 1982). Of greater economic interest are the generations of hydrothermal brecciation forming the major part of the exploitable "tin stone" in the great composite lodes which constitute the main stage of Variscan mineralization in the Camborne mining district and adjacent areas. MacAlister (1908) identified this category of lode rocks as the most important of all. He noted that, in some important mines, the width of the brecciated zones ranged "from a few feet to many fathoms" and that, in a number of cases, very little differential movement of the lode walls has occurred. The mechanism of decrepitative fragmentation, triggered by the hydraulic shock which accompanied decompression of the hydrothermal column, can also be used to explain the textural features observed in the brecciated facies of these composite lodes. At the macroscopic scale, the details of the brecciation in the capel and peach forming the relevant parts of the lodes are largely obscured in uniformly dark aggregates of quartz, tourmaline and chlorite which tbrm the bulk of their altered and brecciated selvedges. The petrographic details of the textures of brecciation and cementation in these stanniferous veinstones have, however, been described in some detail by Flett (1903), and comparable rocks from a major part of the ore reserves which determine the continued economic viability of lode working at the South Crofty Mine.

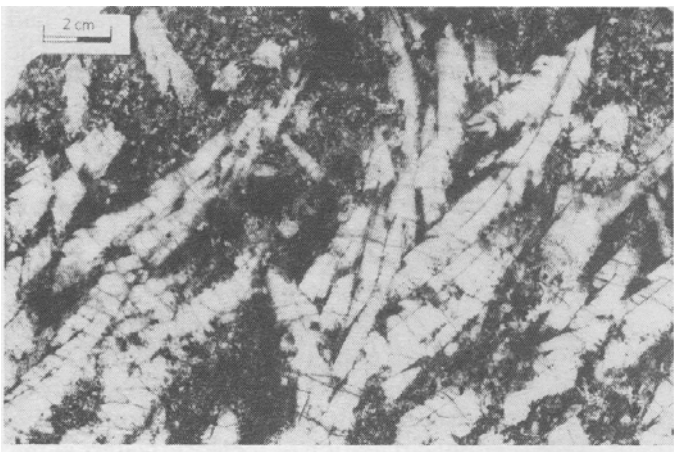


Figure 5. Photograph of a section of the Goonbarrow stockscheider showing the distinctive curved plumose dendrites of potash feldspar together with radiating groups of tourmaline crystals set in a finer aplitic matrix.

The balance of evidence suggests that the duration of magmatically-linked hydrothermal events involving hydraulic decompression and decrepitative brecciation was very limited and that massive adiabatic crystallisation at the focus formed a barrier to recharge of the hydrothermal column. This behaviour is probably different from that of phreatomagmatic and phreatic breccia-forming systems at subvolcanic levels where recharge of the column could be maintained from external sources and fluidisation would be sustained by episodic boiling through natural throttles so that attritive rounding of clasts would be more commonplace.

The paragenetic relationships characteristic of the later stages of development of the great composite lodes and of the cross-courses indicate that repeated episodes

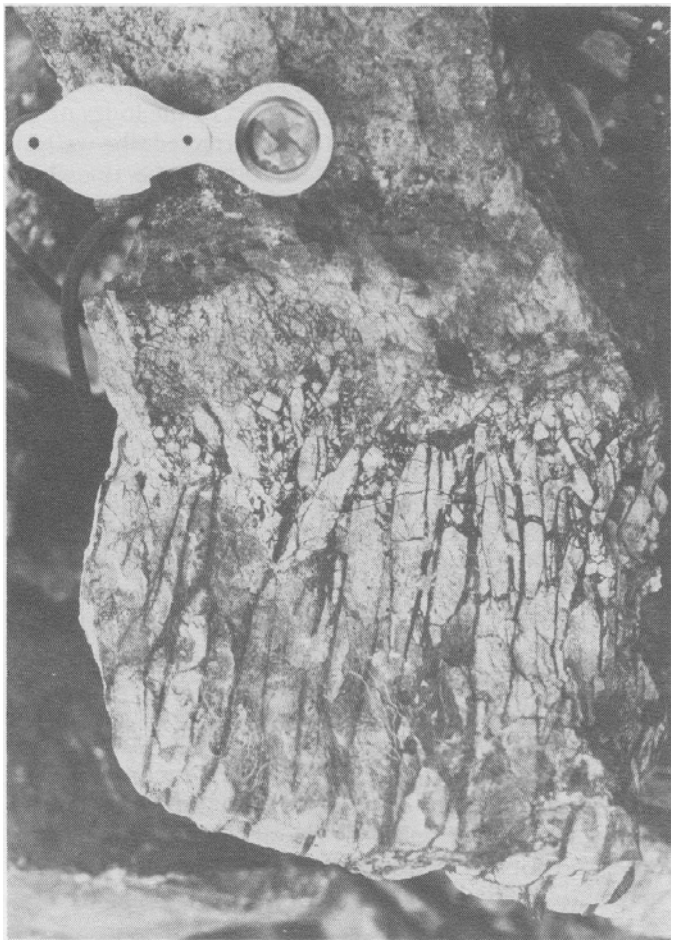

Figure 6. Photograph of a Section on the margin of the Towanroath Lode from Wheal Coates, St. Agnes, showing the "decrepitative" fragmentation produced hydraulically in the metamorphosed and deformed Ladock Beds. The dark hydrothermal cement is schorlitic tourmaline.

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of dilation of the lode-fractures were accompanied by differential movements of the lode walls which then acted as normal, strike-slip or, occasionally, as reverse faults. The constituent layers of gangue and mineral were deposited to form a succession of plates, each showing a development of bilateral symmetry by the growth of opposed combs of quartz; to this Pryce (1778) gave the name "rampant spar".

It is within lodes at this stage of development that the main generations of copper and zinc mineralization were deposited and structures of this type were figure by De la Beche (1839) and Collins (1873). The movement of fluids in the structures, now behaving as fault-lodes, was seismically triggered and at this stage, as the structure acted either as a seismic pump (Sibson *et al.* 1975) or a seismic tap (Boast *et al.* 1981), the initial flux of fluid could be maintained for a period by thermal convection, subject to the constraints on permeability imposed by progressive crystallisastion.

The distinct paragenetic/structural habitats of tin, arsenic and copper in the major composite lodes has often been turned to advantage during the history of mining in Southwest England when fluctuations in the metal market or the exhaustion of reserves threatened the viability of operations. Dines (1956) records that when the copper located in the central part of the lodes of the United Mines in St. Day had been extracted, the walls of the structures were stripped to obtain the tin which occurred chiefly as impregnations in the adjacent tourmalinized wall-rock. In the case of Devon Great Consols Mine, when the copper market went into decline in 1865, operations were rapidly converted for the production of arsenic from arsenopyrite which had been left standing in the margins of the copper lodes where, in places, it reach.ed a thickness of 5 feet (Booker 1967).

The crustified and locally brecciated textures characteristic of seismically controlled fluid circulation and mineral deposition are well-illustrated by the central section of the Wheal Cock Lode, Botallack, shown in the photograph, Figure 8. Structures of this type provide the classical criteria by which polyascendent mineralization is defined (Kutina, 1965). Because the movement of fluids by seismic mechanisms is not dependent on magmatically generated hydraulic pressures, the contribution of magmatic fluids to the hydrothermal system is not a prerequisite. Seismic and magmatically autogenous mechanisms are not, however, mutually exclusive; in the early stages of seismic evolution the input of magmatic fluid to the system may have been'significant, but with time, and notably during post-Variscan events, the role of magmatic fluids must have become negligible.

During the later stages of their evolution the tault-lodes could tap the fluids from the killas as well as formational brines from the Late Palaeozoic and Mesozoic basins adjacent to the Cornish Platform (Alderton 1975). Permo-Triassic extensional tectonics accompanied by

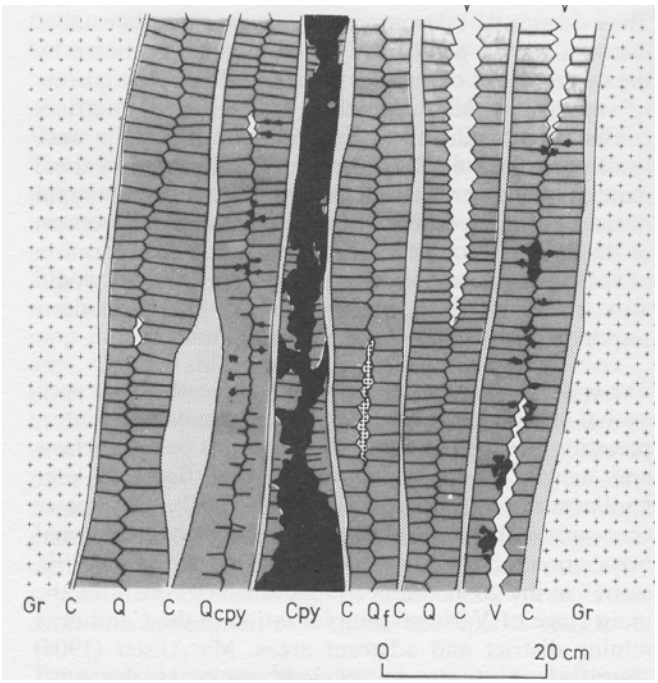


Figure 7. Diagram of a comby quartz lode with copper mineralization, redrawn from the illustration of a vein from the granite at Carn Marth described by Collins (1873). Gr - granite, C - clay gouge, Q - quartz with chalcopyrite, Cpy - more massive chalcopyrite, Qf - quartz with purple flourite, V - vugh.

alkaline basic magmatism may, in addition, have granted access to fluids from which the exotic Bi-Co-Ni-As paragenesis was deposited (Halls 1970). The persistence of tectonic and hydrothermal activity through later Mesozoic and Tertiary time is recorded by the transcurrent movements on the major cross-course structures (Dearman 1963) within which a paragenetic record of tantalizing complexity remains to be resolved in detail.

It is not the intention of this discussion to detract from the role which convective circulation must have had during the later stages of hydrothermal evolution. The extended life of the hydrothermal activity associated with the Cornubian granites is a distinctive feature attributable to the high content of the heat-producing elements K, Th and U (Tammemagi and Wheildon 1974). The significant burden of dissolved components in the hot springs which issue into the workings at a number of mines (Wheal Jane, South Crofty) show that hydrothermat transport continues to the present day (York 1872, Tilley 1873), but whether mineralization is now continuing at depth remains to be proven by further investigation. Ir/this context the arguments in favour of continuing kaolinization of the Cornish granites as a result of the thermal circulation of meteoric waters at the present day must be taken into account (Durrance and Heath 1985, Durrance and Bristow 1986).

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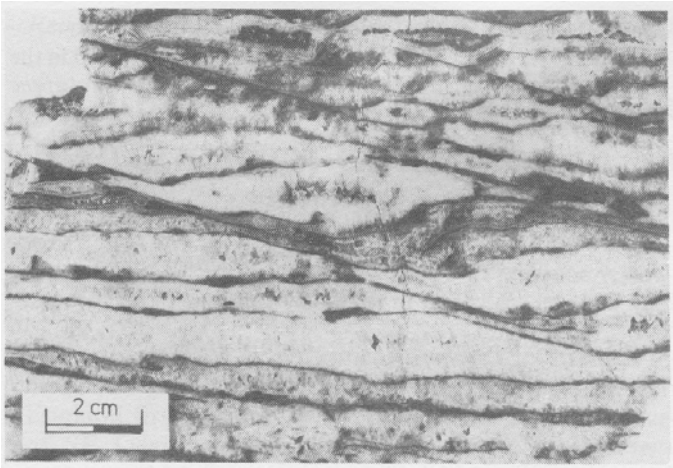


Figure 8. Photograph of a section of the central part of the Wheal Cock Lode from Botallack, showing the succession of lenticular plates formed as successive dilations of the vein took place in response to fault movement. The main sulphide minerals deposited with the quartz were chalcopyrite and pyrite. Arsenopyrite occurs in the earliest stage of opening adjacent to, and impregnating the chloritised metabasic wallrocks. Cassiterite, and locally scheelite, are found chiefly as veinlets and impregnations in the wallrocks.

The metalliferous region of Southwest England evidently remains an area of the greatest importance for testing theories of the transitional processes in the evolution of hydrothermal fluids from granite magmas, and for Studying the persistence of hydrothermal circulation in ancient, geochemically specialised granites. It is, however important to constrain general concepts of mineral deposition and fluid circulation by the rigorous analysis of paragenetic relationships so that compatible mechanisms can be invoked. The general principles outlined in this paper can help in resolving some of the problems which are faced in attempting a paragenetic subdivision of the Cornish lodes and can also provide a basis for understanding the distinction which can be made between the intrinsic metallogenic signature originating from the granites, and those contributions inherited from the surrounding Palaeozoic rocks or imposed subsequently during Post-Variscan events.

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## References

Alderton, D.H.M. 1975. Fluid inclusion studies in SW England. *Proceedings of the Ussher Society, 3,* 214-217.

Allman-Ward, P., Halls, C., Rankin, A.H. 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.

Baumann, L. 1970. Tin deposits of the Erzgebirge. *Transactions of the Institution of Mining and Metallurgy,* Section 5, 79, B68-B75.

Baumann, L. and Schlegel, G. 1967. Zur Geologie und Mineralisation der Zinnerzlagerstfitten Altenberg. *Freiberger Forschung-sherle, C218,* 9-34.

Boast, A.M., Coleman, M.L. and Halls, C. 1981. Textural and stable isotopic evidence for the genesis of the Tynagh base metal deposit, Ireland. *Economic Geology, 76,* 27-55.

Booker, F. 196T *The industrial archaeology of the Tamar Valley.* David and Charles, Newton Abbot, 303pp. Collins, J.H. 1912. Observations on the West of England Mining region. *Transactions of the Royal Geological Society of Cornwall, 14,* 683pp.

Collins, J.H. 1873. The mining districts of Cornwall and West Devon. *Proceedings of the Institution of Mechanical Engineers,* 89-118.

Darbyshire, D.P,F. and Shepherd, T.J. 1985. Chronology of granite magmatism and associated mineralization, SW England. *Journal of the Geological Society of London, 142,* 1159-1177.

Daubrée, G.A. 1841. Sur le gisement, la constitution et l'origine des amas de minerai d'6tain. *Annales des Mines (Troisième Série), 20,* 65-112.

Dearman, W.R. 1963. Wrench faulting in Cornwall and South Devon, *Proceedings of the Geologists' Association, 74,* 265-287. De la Beche, H.T. 1839. Report on the geology of Cornwall, Devon and West Somerset. *Memoir of the Geological Survey, London,* Longmans, Orme, Brown, Green and Longmans, 648pp.

Dines, H.G. 1956. The metalliferous mining region of South-West England. *Memoir of the Geological Survey of Great Britain.*

Durrance, E.M. and Bristow, C.M. 1986. Kaolinisation and isostatic readjustment in south-west England. *Proceedings of the Ussher Society. 6,* 318-322.

Durrance, E.M. and Heath, M.J. 1985. Thermal groundwater movement and radionuclide transport in SW England. *Mineralogial Magazine, 49,* 289-299.

Flett, J.S. 1903. Notes on some brecciated stannfferous veinstones from Cornwall. *Summary of Progress of the Geological Survey for 1902.* 150-162.

Halls, C. 1970. Comparative aspects of the genesis of the arsenide-silver veins of Cobalt, Ontario. p. 414-443. In: The geology of the Silverfields and Hi-Ho Mines, Cobalt, Ontario. *Unpublished, Ph.D. Thesis University of London.*

Halls, C. and Allman-Ward, P. 1986. The role ofdecompressive shock and "hydraulic decrepitation" in the formation of hydrothermal breccias and composite lode structures: a discussion. Abstract, In: *Mineral Deposits Studies Group Annual Meeting, 15-16 December t986, University of Southampton,* Information and abstracts, p 11.

Hosking, K.F.G. 1964. Permo-carboniferous and later primary mineralisation of Cornwall and south-west Devon. In:

Table of Contents

Hosking, K.F.G. and Shrimpton, G.J. (eds.) Present views of some aspects of the geology of Cornwall and Devon, 150th Anniversary Volume, Royal *Geological Society of Cornwall,* 201-245.Hunt, R. 1884. *British Mining.* Crosby Lockwood and Company, London, *944pp,*

Jackson, N.J., HaUiday, A.N., Sheppard, S.M.F. and Mitchell. J.G. 1982. Hydrothermal activity in the St. Just Mining district, Cornwall, England. In: Evans, A.M. (ed.) *Metallization associated with acid magmatism.* John Wiley and Sons, Chichester, 137-179.

Kutina, J. 1965. The concept of Monoascendent and poly-ascendent zoning. In: Stemprok, M. (ed.) *Symposium problems of postmagmatic ore deposition, Volume 2, Geological Survey of Czechoslovakia, Prague,* 47-55.

Le Neve Foster, C. 1884. What is a mineral vein or lode? *Geological Magazine (New Series, Decade III), 1,* p513. MacAlister, D.A. 1906. Part II Mining. In: Hill, J.B. and MacAlister, D.A. The geology of Falmouth and Truro and of the mining district of Camborne and Redruth (Sheet 352). *Memoir of the Geological Survey of England and Wales.*

MacAlister, D.A. 1908. Geological aspect of the lodes of Cornwall. *Economic Geology, 3,* 363-380. Manning, D.A.C. and Exley, C.S. 1984. The origins of late stage rocks in the St. Austell granite - a reinterpretation. *Journal of the Geological Society of London, 141,* 581-591.

Moore, J. McM. 1975. A mechanical interpretation of the vein and dyke systems of SW England orefield. *Mineralium Deposit, 10,* 374-388.

Niggli, p. 1920. Die Leichtflüchtigen Bestandteile im Magma. *Preisschriften der Fürstlich Jablonowskischen Gesellschaft zu Leipzig, XLVII,* 272pp.

Niggli, P. 1929. *Ore deposits of magrnatic origin: their genesis and natural classification.* Thomas Murby and Co., London.

Puce, W. 1778. *Mineralogia Cornubiensis.* James Phillips (Printer), London.

Reid, C. and Scrivenor, J.B., with Flett, J.S., Pollard, M.A. and MacAlister, D.A. 1906. The geology of the country near Newquay (sheet 346). *Memoir of the Geological survey of England and Wales.*

Scrivener, R.C., Shepherd, T.J. and Garrioch, N. 1986. Ore genesis at Wheal Pendarves and South Crofty Mine, Cornwall -a preliminary fluid inclusion study. *Proceedings of the Ussher Society, 6,* 412-416.

Shepherd, T.J., Miller, M.F., Scrivener, R.C. and Darbyshire, D.P.F. 1985. Hydrothermal fluid evolution in relation to mineralization in Southwest England with special reference to the Dartmoor-Bodmin area. In: *High Heat Production (HHP) Granites, hydrothermal circulation and ore genesis;* papers presented at an international conference, St. Austell, September 1985, London: The Institution of Mining and Metallurgy, 345-364.

Sibson, R.H., Moore, J. McM. and Rankin, A.H. 1975. Seismic pumping - a hydrothermal fluid transport mechanism. *Journal of the Geological Society of London, 131,* 653-659.

Sillitoe, R.H. 1985. Ore-related breccias in volcanoplutonic arcs. *Economic Geology, 80,* 1467-1514.

Smirnov, S.S. 1937. On the question of zoning of ore deposits (in Russian). *Izvestya Akademii nauk SSSR (Seriya Geologiceskya),* 6, 1071-1083.

Tammemagi, H.Y. and Wheildon, J. 1974. Terrestrial heat flow and heat generation in south west England. *Geophysical Journal of the Royal Astronomical Society, 38,* 83-94.

Tilley, H. 1873. Particulars of a thermal spring at Wheal Seton in the Parish of Cambome, with a comparative table of analyses of similar springs in the United, Balleswidden, Botallack and Crown Mines. *Report of the Miners' Association of Cornwall and Devon (1872-1873), 53-56.*

Tuttle, O.F. and Bowen, N.L. 1958. Origin of granite inthelight of experimental studies in the system $NaA1Si_3O_8$ - $K A1Si_3O_8$ - $SiO_2$ - $H_2O$, *Geological Society of America. Memoir 74.*

York, P. 1872. Note on the quantity of caesium contained in the water of the hot spring found in Wheal Clifford. *Journal of the Chemical Society [Second Series/, 10.* 273-274.

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# Helium and radon transport mechanisms, heat flow and hydrothermal circulation in SW England

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The use of $^{222}Rn$ activity measurements in streams for mapping groundwater flow within fractures in SW England first became apparent in the results of a survey of SE Devon. Anomalies were found to occur in a position which is now known to coincide with major NW-SE transcurrent faulting. Further studies of $^{238}U$ decay series disequilibrium showed that the $^{222}Rn$ anomaly also coincided with a zone of recent addition of U from ascending groundwater (Durrance and Heath, 1985). Other similar zones were found along E-W fractures. On Dartmoor the distribution of $^{222}Rn$ activities is also controlled by major fractures and is to related heat flow. This was taken as evidence for active hydrothermal circulation within the Dartmoor granite (Durrance *et al.* 1982). Mathematical modelling by Fehn (1985) shows that a fracture zone of ultra-high permeability, cutting a radiothermal pluton, will control the distribution of the circulation cells by determining the position of a descending limb. Where more than one such zone is present the most important fracture exercises this control, and other fracture zones may become sites of upward flow. This pattern of circulation was identified using $^{222}Rn$ by Gregory and Durrance (1987) in the Carnmenellis granite. Therefore, as $^{222}Rn$ has a half-life of only 3.8 days, either groundwater flow is very rapid or there is a large, shallow source of $^{222}Rn$ which owes its distribution to heat flow. However, there are no thermal springs at ground level and no large concentrations of $^{226}Ra$ in the areas of high $^{222}Rn$ to support either of these hypotheses, so interpretation is ambiguous. For this reason, a complementary $^{4}He$ survey of the Carnmenellis was carried out. The problem of the short $^{222}Rn$ half-life does not arise with $^{4}He$. The results showed that the pattern obtained using $^{4}He$ was similar to that given by $^{222}Rn$ and heat flow, and indicate that a gaseous transport mechanism, more efficient than groundwater flow alone, could resolve the ambiguity.

There are a number of gases which could act as carriers of $^{4}He$ and $^{222}Rn$. However, carrier movement must occur as a free-phase in the groundwater. Gases fall into two well-defined solubility groups: (1) those with low solubility, such as CO and $CH_4$, and (2) those which rapidly react with water and have high'solubilities, such as $CO_2$. Most soluble gases are unlikely to be present in sufficient concentrations to exist as a free phase, but as $CO_2$ will be produced from CO or $CH_4$ where deep groundwaters meet shallow oxic groundwaters, $CO_2$ may be present as a carrier in the mixing zone. Also important is the fact that gas solubilities decrease with rise in temperature. Consequently, gas concentrations may occur which flush trace gases from solution where groundwater temperatures are high, but do not in cooler ground-waters at similar depth. The most likely carrier gases for transporting $^{4}He$ and $^{222}Rn$ in SW England are CO, $CH_4$ and $CO_2$.

Little information is available on these gases in SW England, although there are several pointers to gas migration taking place. For example, oxidised CO or $CH_4$ occur as high levels of $CO_2$ with depleted $O_2$ in soil gases above important fractures. Furthermore, in a deep borehole in the Carnmenellis granite, the concentration of $CO_2$ was found to be about $0.7 cm^3 kg^{-1}$ (R.H. Parker, pers. comm.). Although this is well below the level required for $CO_2$ to exist as a separate phase, and contamination may have occurred, it is possible that some represents oxidised CO or $CH_4$ from depth. Of more interest is the $CH_4$ concentration of about $1.0 cm^3 kg^{-1}$ found in the same borehole. This approximates to the solubility of $CH_4$ in water at the temperature found. Consequently, it is likely that some $CH_4$ has existed as a separate phase. Contamination from near-surface sources is again possible, but a reasonable alternative is that some $CH_4$ originated at depth.

In SE Devon the $^{222}Rn$ anomaly could partly owe its origin to transport from depth, but since activities in this area are low and the rocks contain reasonable levels of $^{238}U$, a deep source does not appear essential. Nevertheless, movement of CO, $CH_4$ and $CO_2$ could take place along NW-SE faults. Moreover, if the $^{222}Rn$ has a shallow origin then the E-W fractures, which cut the same succession, should also show $^{222}Rn$ anomalies. That they do not, implies the $^{222}Rn$ has a deep origin.

If trace gases move within carrier gases, the association of high heat flow with high levels of $^{4}He$ and $^{222}Rn$ suggests that either carrier gas migration is controlled by heat flow, or carrier gases act as a means of heat transfer. Certainly, hot gas can transfer heat, and ascending groundwater in a hydrothermal system will increase the speed of the carrier gas movement. Indeed, this is supported by the fact that the correlation between $^{4}He$ and $^{222}Rn$ indicates a system which controls the bulk quantity of gas transported as well as the rate of

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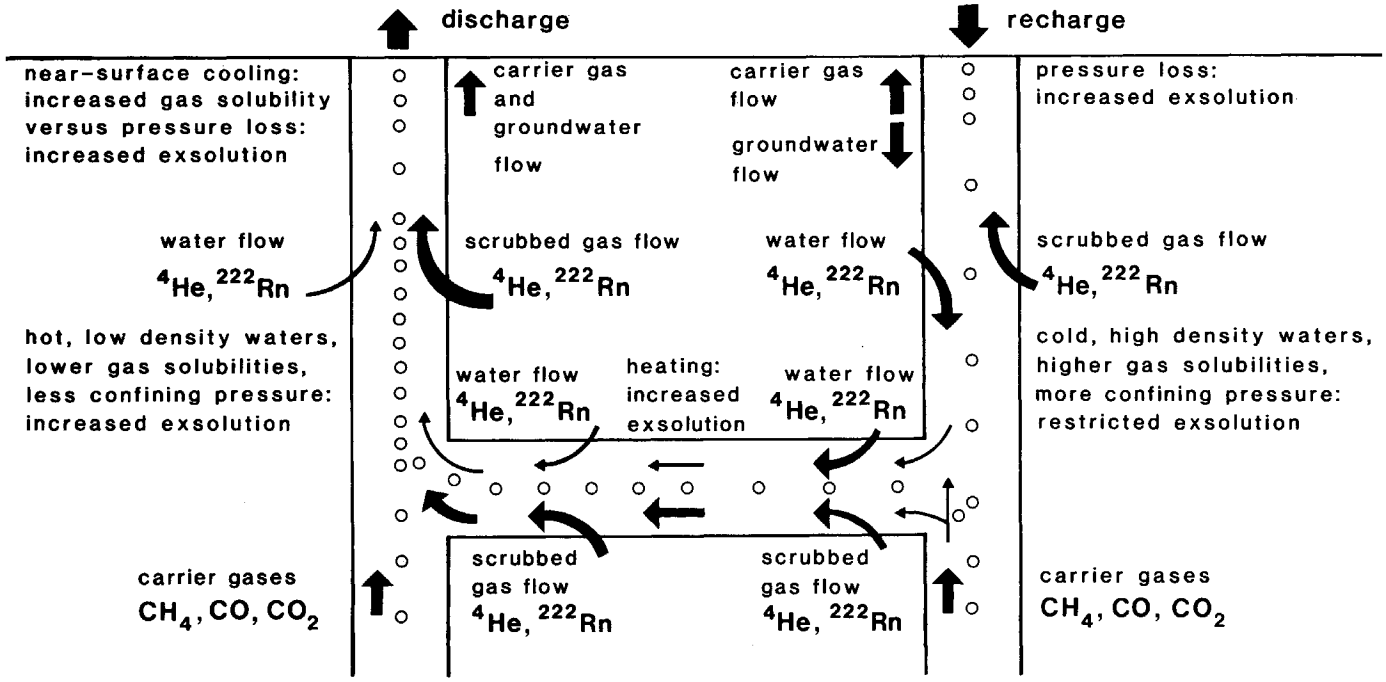


Figure- 1. Model of carrier gas - trace gas migration in a hydrothermal circulation system. The relative concentrations of the free-phase carrier gases are indicated by the frequency of bubbles in the fracture zones. The relative efficiencies of entrapment of $^4$He and $^{222}$Rn by 'water flow', and the degree of removal of $^4$He and $^{222}$Rn by 'scrubbed gas flow', are shown by variations in the size of the flow arrows.

transport. However, because the cold descending limbs of hydrothermal cells become located in major fractures, carrier gases may not be an important means of heat transfer. Nevertheless, it is possible that an indirect mechanism linking hydrothermal circulation and gas transport is acting.As already discussed, free-phase concentrations of carrier cases will vary with position in a hydrothermal cell. Descending cold water will contain more carrier gas in solution than is possible in ascending warm water at similar depth. Thus degassing must occur on heating and ascent. Temperature differences within a groundwater circulation system will thus give rise to variations in the free-phase abundances of the carrier gases and the rate at which they move towards the surface of the Earth. In turn, this will lead to differences in the efficiency with which $^4$He and $^{222}$Rn are scrubbed from the groundwater (Figure 1).

In addition to explaining the $^4$He and $^{222}$Rn distributions in SW England, carrier gases can also explain $^3$He/$^4$He ratios in terms of the history of gas transport (Gold, 1986). $^3$He/$^4$He ratios are usually taken to indicate the contribution of mantle heat to total heat flow because most $^3$He that is lost from the Earth is of primordial origin. On that basis, the very low $^3$He/$^4$He ratios found in the groundwaters of the Cammenellis granite suggest only normal levels of mantle heat in SW England. However, $^3$He/$^4$He ratios may also indicate the extent to which primordial $^3$He has been flushed from the mantle during past orogenic and volcanic episodes. Major fracture zones in SW England show episodic reactivation throughout the Mesozoic and Cenozoic. These zones are associated with nearby volcanism and it is likely that hydrothermal circulation systems have been operating since the late Carboniferous (Durrance *et al.,* 1982). If carrier gases are an important transfer mechanism, SW England must be considered a well-flushed system. Low $^3$He/$^4$He ratios are consistent with this interpretation.


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

Durrance, E.M. and Heath, M.J., 1985. Thermal groundwater movement and radionuclide transport in south west England. *Mineralogical Magazine 49,* 289-299.

Fehn, U., 1985. Post-magmatic convection related to high heat production in granites of south west England: a theoretical study. *In:* Halls, C. (ed.). *High heat production (HHP) granites, hydrothermal circulation and ore genesis* 99-112. London, Institution of Mining and Metallurgy.

Gregory, R.G. and Durrance, E.M., 1987. Helium, radon and hydrothermal circulation in the Carnmenellis radiothermal granite of Southwest England. *Journal of GeophysicalResearch, in press.*

Gold, T., 1986. The origin of terrestrial helium, its association with hydrocarbons and the interpretation of its isotopic composition. Atomic Energy of Canada cohference on Isotope Geochemistry of groundwater and fracture material in plutonic rock. Mont Ste Marie, Quebec, October 1-3.


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*Read at the Annual Conference of the Ussher Society, January 1987*

# Notes on the distribution of Sarsen Stones in South Somerset and West Dorset

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Sarsens are silcretes, hard silica-cemented sedimentary rocks, and are thus resistant to physical disintegration and chemical weathering; they persist in the landscape in many parts of Southern and Eastern England, notably forming the larger stones of Stonehenge. However, this present distribution owes much to both physical and human factors, especially as people have moved and/or attacked them for many centuries. A few are still to be found on the interfluves of the Dorset Heights (e.g. at ST517034 by the side of the A356 at Toller Down) and in the Sidmouth area (Isaac 1979).

It is generally assumed that sarsens found on lower topographic features have descended from the hill-tops during valley widening and deepening; the processes of solifluction and landsliding have been very active where · the Cretaceous rocks are underlain by Mercia Mudstones and Lower Lias Clay to the south and east of Taunton, and on Fullers Earth Clay north of Beaminster Down. Several loose sarsens, in association with chert gravels rucked into the Lower Lias Clay, were observed in a cutting from the Hatch Beauchamp by-pass (ST294199). Another remnant of a sarsen has been observed in valley gravels below the flood plain of the River Isle near Ilton (ST362180).

Intensification of agriculture between 1960 and 1980 has led to many sarsens being moved from fields to hedgerows, where they will hopefully remain for future study. However, some have been destroyed with explosives and the future safety of those remaining should not be assumed. Recently-moved sarsens may be seen at the following sites: Staple Fitzpaine, 7km SSE of Taunton; in the car park behind The Greyhound (ST264184); Halstock, 9 km SSW of Yeovil (ST522072); Beaminster Down, 5 km NE of Beaminster (ST513044); Nunney, 3 km SW of Frome (ST745461).

The use of sarsen material in prehistoric monuments and later buildings indicates that even very large stones were moved by man, and this should be borne in mind when considering specific locations of sarsens. A lump of sarsen (0.25 x 0.20 x 0.20 m) resting on top of some 3.4 m of peat was discovered recently in a soil pit at South Petherton, 12 km west of Yeovil (ST290630) and must surely have been dumped at the spot by human agency; the top of the peat has a radio-carbon date of around 500 A.D. but is more likely to be early mediaeval. Colluvium to a depth of 0.71 m overlay the sarsen (S. Staines, pers. comm.).

The recently issued explanatory memoir for sheet 295 (Taunton) (Edmunds and Williams, 1985) suggested that a "hard quartzitic grit ... rounded boulder ... about 0.9 x 0.5 x 0.5 m" was ice-ra fted to its present position at Court Farm, Hillfarrance (ST169244) across a conjectural Lake Maw in Wolstonian times. Whilst this sarsen is rather more smooth and tapering than many examples, there can be little doubt that it is part of the suite of sarsens found south and south west of Taunton.

On a wider view, the sarsens extend in a fairly narrow belt from south and east of Taunton via Beaminster Down, whence there is a much broader spread eastward on the Chalk dip-slope east of Dorchester. Silcretes are also found in the Sidmouth area (Isaac, 1979) but do not appear to be reported in the Vale of Marshwood, Lower Axe Valley or Honiton areas. The alignment of the Taunton-Beaminster Down trail of sarsens appears to be discordant to the present-day drainage pattern and this suggests that silicification may have taken place before the initiation of that pattern. Possibly silicification was influenced by local variations in relief and ground water (Summerfield and Goudie 1980).

Some problems remain for investigation and speculation concerning sarsens. Additional analyses of sarsen fabrics would be of interest, especialy with regard to titanium-rich silcrete (Isaac 1983; Summerfield and Goudie 1980). It is possible that silicification never occurred in the areas of West Dorset and East Devon from which sarsens have not beenreported, or has the evidence been destroyed by erosion? Is it possible that tectonic movements may have influenced the localization Of silicification and/or subsequent erosion? The thick cover of residual angular flint gravel on some Chalk hill-tops (e.g. Batcombe Hill, ST615034) shows deep pitting similar to that of many sarsens; to what extent may these features be attributable to weathering during the Tertiary Period? Is it possible that sarsens exist elsewhere in the SW Peninsula, but remain unrecognized or misidentified? The answers to these questions may not be easily obtained, but they should throw more light on the Tertiary history of South Somerset and West Dorset.

Edmonds, E.A., and Williams, B.J., 1985, Geology of the country around Taunton and-the Quantock Hills: *Memoir British Geological Survey, Sheet 295.*

Isaac, K.P. 1979. Tertiary silcretes of the Sidmouth area, East Devon: *Proceedings of the Ussher Society, 4,* 341-54.

Isaac, K.P. 1983. Silica diagenesis of Palaeogene kaolinitic residual deposits in Devon, England: *Proceedings of the Geologists' Association, 94,* 181-6.

Summerfield, M.A., and Goudie, A.S. 1980. *In the Shaping of Southern England.* Academic Press.

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*Read at the Annual Conference of the Ussher Society, January 1987*

# Mineralogy and paragenesis of the Haytor iron ore deposit

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Workings at Haytor Vale are the most extensive of the group of stratiform iron ore deposits to the east of the village of Ilsington, BoveyTracey, Devon. Both opencast and drift mining were pursued in the 19th and early 20th centuries and records indicate the production of `lode stones' in the 16th century or earlier.

Haytor Iron Mine is situated within the metamorphic aureole of the Dartmoor Granite, with the contact lying some 500m to the east. The ores are hosted in siliceous metapelite of Upper Carboniferous (Namurian) age; the scarcity of quartzite beds contrasts with hornfels exposed elsewhere in the vicinity and suggests that the hostrocks may be a pelitic and slightly calcareous part of the lowest Crackington Formation, locally termed the Ashton Shale. At adit level, the ore occurs in three beds which dip 30° to 35° NE. Total thickness of the ore zone is 11.5m and this includes 4.3m of barren metapelite. A high-angle fault, apparently trending NE-SW and visible in the adit, throws the ore-bearing strata on the eastern side into contact with a barren metamorphosed sandstone/shale sequence.

The ore consists of finely intergrown magnetite and hornblende which may be massive, or show banding marked by varying proportions of the two minerals. Coarse hemioctahedra of magnetite are present on some joint surfaces and the hornblende forms coarse fibroradiate aggregates in places. Locally, sparse discontinuous layers and irregular pockets of coarse garnet crystals occur. In thin section, each garnet crystal shows a core with an irregular, corroded margin, and a paler coloured outer zone. Both garnet phases show anomalous anisotropy. X-ray diffraction studies and SEM-EDA work have shown that the core is endmember andradite and the outer zone andradite 90 - grossularite,o. Minor axinite, siderite, calcite and apatite are present and pseudomorphs of chalcedony after datolite, originally termed 'Haytorite', have been recorded. Traces of sulphides are present in the ore beds and include arsenopyrite, pyrite, sphalerite and chalcopyrite.

The paragenesis of this deposit is typical of infiltration exoskarns elsewhere in the region, with an early phase of silicate grown succeeded by the development of ore minerals. Garnet is the earliest silicate with two growth stages of slightly different composition separated by a regressive episode. The main growth of hornblende immediately postdates garnet, though some amphibole is present as inclusions, particularly in the later garnet. Hornblende is also present as impregnations in the wallrock and in reaction veins in a narrow pre-skarn aplite sill emplaced within the ore zone. Magnetite overgrows hornblende and fills fractures and joints within the orebodies. The latest stage of mineralisation is the development of small pods and fracture fillings of sulphides, carbonates and chalcedonic quartz.

Fluid inclusion studies of quartz from rare aggregates and veinlets in the magnetite-hornblende orebodies show a population of very small, equant inclusions with liquid, vapour, and a number of solid salt phases. Similar inclusions were noted in quartz intergrown with the hornblende reaction veins in the aplite sill noted above, but are absent from other parts of the intrusion. Microthermometric studies were precluded due to the small inclusion size, but oil immersion microscopy showed vapour bubble sizes indicating temperatures of homogenisation between 350° and 475°C. The number and type of solid daughter salts indicate salinities in excess of 50 wt % NaCI equivalent. This type of inclusion population has been described in tourmalinite wallrock in the nearby Dartmoor Granite. In the absence of later, lower salinity inclusions, it is concluded that the main stage mineralisation at Haytor resulted from high salinity, high temperature fluids migrating from the granite into a suitable host. These fluids, depleted in boron and tin but rich in iron reacted with the slightly calcareous Ashton Shale hornfelses to produce localised exoskarn orebodies.

*This contribution is published with the approval of the Director, British Geological Survey, (NERC).*

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# Late Pleistocene and Holocene radiocarbon dates from the Penzance district, Cornwall

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During recent BGS work in the Penzance district a number of samples was processed to obtain radiocarbon dates. The resulting determinations are listed here in chronological order. Dates are in radiocarbon years B.P.±1

| Lab. No. | Date | Locality | NGR | Ht.(m:O.D.) |
|---|---|---|---|---|
| SRR-3022 | 12070±80 | Mount's Bay | SW506273 | -32 |
| SRR-315 | 10202±50 | Trink Cottage | SW51613737 | c.+102 |
| SRR-713 | 4919±55 | Higher Try Farm | SW45973606 | 184 |
| SRR-714 | 4278±50 | Gulval | SW48373092 | c.1-6 |
| SRR-314 | 1810±45 | Trannack | SW56473297 | c.+17 |
| ST3694 | 1805±100 | Praa Sands | SW578280 | 0 |

The radiocarbon ages from this area indicate a history of peat accumulation and fluvial activity from the end of the Devensian and through much of the Holocene that might repay further study.

The following are brief comments on the occurrence of the dated material:

SRR-3022. The specimen was obtained from Mount's Bay during exploration for alluvial tin by Billiton UK Ltd. The peat was situated at -32m O.D. in a buried channel cut in the submerged rock platform at -28.5m. O.D. The late Devensian sea level at this time, as indicated by projection of the curve for post-glacial sea-level rise constructured by Heyworth and Kidson (1982), is lower than the height of the peat, and because the peat is covered by 3.5m of alluvial deposits it is probable that peat accumulation had ceased prior to sea-level reaching this height. An examination of the sample by Dr M.J. Tooley showed that it contained only herbaceous pollen, which implied an age greater than 10,000 B.P.

SRR-315. The sample was obtained from a temporary trench in an alluvial terrace about lm above the present stream. The section exposed was: soil 0.18m, gravel 0.08m, clay and silt 0.17m, peat 0.27m, gravel 0.3m (Wilson, 1974). The peat is of similar age to a horizon on Bodmin Moor which was considered by Brown (1977) to indicate a period of cooling at the end of the Devensian.

SRR-713. The sample was from the lowest part of a peat horizon formed in a basinal area near the source of the Trevaylor stream. The section exposed was: peat 0.75m, purplish grey clay with plamt fragments 0.3 to 0.7m, sub-angular granite cobbles with clay matrix > 0.1m.

SRR-714. The sample of wood was taken from the submerged torest when it was exposed in 1974, trees, both fallen and rooted, with trunk diameters up to 0.2m lie on the surface of a peat layer c.0.3m thick just above mean low-water mark. The peat rests on head. The date could reflect the Flandrian sea level at this time, but it is possible that the trees were destroyed by the advance of sand dunes ahead of the rising sea. Remnants of dunes SRR-314. A sample of wood was taken from a trench exposing alluvial sand and clays in which a portion of a tree trunk lm x 0.5m x 0.25m was embedded 3.m below the surface. Most streams in the area no longer flood, and alluvial accumulation appears to have ceased during the period after this date (Wilson 1974).

ST 3694. The Peat at Praa Sands probably accumulated in water populated by reeds, which was ponded behind the advancing sand dunes that subsequently buried it. See also Welin *et al.* (1973).

Brown, A.P. 1977. Late-Devensian and Flandrian vegetational history of Bodmin Moor, Cornwall. *Philosophical Transactions of the Royal Society of London, Series, B, 276,* 251-320.

Heyworth, A. and Kidson, C. 1982. Sea-level changes in south west England and in Wales. *Proceedings of the Geologists' Association, 93,* 91-111.

Welin, E., Engstrand, L. and Vaczy, S. 1973. Institute of Geological Sciences Radiocarbon Dates IV. *Radiocarbon, 15,* 299-302.

Wilson, A.C. 1974. Some aspects of Quaternary fluvial activity in south-west Cornwall, England. *Proceedings of the Ussher Society, 3,* 120-122.

*This contribution is published with the approval of the Director, British Geologial Survey (N.E.R.C.).*

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# Abstracts of other papers read at the Annual Conference, January 1987

**A new look at the sense of facing and thrusting during the Hercynan evolution of Cornwall.** CF. *Pamplin, A.J. Barker, J.R. Andrews. Department of Geology, The University, Southampton, S09 5NH*

.Recent contributions (eg. Selwood and Thomas 1986) have suggested that the facing confrontation at Polzeath is the product of local refolding, and as such is of limited regional significance. This contention rests on the reinterpretation of the facing directions associated with early (D1) folds. Our detailed work along the north Cornish coast reaffirms that all observed D1 structures north of the Camel Estuary face south as previously recorded (Roberts and Sanderson 1971, Shackleton *et al.* 1982). We confirm the existence of the "facing confrontation", where early northern structures overprint earlier southern structures. Early structures both north and south of the estuary are overprinted by D2 ductile shearing. Succeeding more brittle N.N.W.-directed movements followed as part of the progressive sequence of events.

Paradoxically, we find that shear sense indicators present within the high strain zone around Tintagel clearly indicate northwards directed movement. Pyrite pressure shadow fringes in the hinge zones of D2 folds indicate that most tectonic strain was accumulated during the D2 event. The intense strain traditionally associated with southward transport is now interpreted as largely resulting from early D2 N.N.W. - directed ductile shear, superimposed upon the earlier south facing structures.

Whilst greenschist facies conditions may have been achieved during the generation of the early (D1) structures, the assemblage quartz-chlorite-actinolite in pyrite pressure shadows aligned within S2 clearly demonstrates that greenschist conditions prevailed synchronous with D2 N.N.W. - directed ductile shearing.

The structural history of the area can be summarised as follows:-
l) Earliest north facing folds developed south of the Camel Estuary (Dl-south).
2) Early south facing folds developed north of the Camel Estuary (D 1-north).
3) A progressive D2 deformation characterised by early N.N.W.-directed ductile strain, and later by N.N.W.-directed brittle thrusting overprinted Fl folds both north and south of the Camel Estuary.

The tectonic history recorded in this classic coastal section can now be reconciled with evidence for northwards directed thrusting inland (eg. Selwood and Thomas 1985, Isaac *et al.* 1982) by correlation with the D2 deformation.

**Early Devonian macrofaunas of north and south Devon.**
*K.M. Evans. Huish Episcopi School, Langport, Somerset.*

The marine Devonian beds of south-west England are usually regarded as having been deposited to the (present day) south of the Old Red Sandstone continent. An examination of the marine faunas reveals that this model is somewhat oversimplified. Beds of Emsian age are represented by the Lynton Formation (north Devon) and the Meadfoot Group (south Devon) and have yielded faunas dominated by brachiopods, corals and bivalves. Although the faunas are consistent with a nearshore, subtidal environment, there are few elements which are common to each area, moreover there is widely recognised evidence for a regression around the Emsian/Eifelian boundary in north Devon in contast to deepemng conditions in south Devon (with only localised episodes of shallowing).

The faunal and sedimentological evidence for the isolation of the two areas is reviewed and it is concluded that although both outcrops may be referred to the Rhenish magnafacies, with affinities to Belgium and Germany, there is little indication that the present day location of the outcrops is significant. It would seem best to regard the Lynton Formation and the Meadfoot Group as representing two distinct basins of deposition.

**Alluvial fan sequence development at the base of the Rozel Conglomerate Formation, Jersey, Channel Islands.**
D.J. *Went and M.J. Andrews. Dept. of Geology, University College of Wales, Aberystwyth, Dyfed SY23 3DB.*

The Rozel Conglomerate, of probable Cambro-Ordovician age shows many characteristics of alluvial fan deposits.

At the base of the formation, a spectacular unconformity is made with the underlying, often spherulitic rhyolites. The rhyolites are in places smoothly but irregularly eroded, whereas in others they show deep ancient weathering profiles. Locally breccia is preserved spalling from the profiles as talus wedges, interbedded with exotic fine pebble gravels. Elsewhere this local breccia is hydraulically sorted, resting on the basement rhyolites.Overlying the breccia is an upwards coarsening sequence 4m thick of thin silty sands and exotic fine pebble gravels, succeeded by a 25m upwards fining sequence of coarse debris flow and streamflood gravels. The lower unit is interpreted as representing the progradation of a secondary fan lobe sourced from an abandoned fan sector whilst the upper unit reflects the incision of a pirated canyon with the subsequent initiation of a constructional fan lobe sourced from a northerly hinterland.

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**Integrated microbiostratigraphy of the Turonian in Devon.** *B.A. Tocher. and M.B. Hart. Dept. of Geological Sciences, Plymouth Polytechnic, Plymouth PL4 8AA.*

The Turonian chalk exposed in the area around Beer has been investigated for its macrofauna, Foraminifera and dinoflagellates. This attempt at an integration of two independent microbiostratigraphic schemes is primarily intended as a recognition of the microflora of the internationally used *Praeglobotruncana helvetica* Zone. Changes in foraminiferal and dinoflagellate abundance will be used to further discuss the palaeoenvironmental interpretation of the Turonian.

**A reconnaissance geochemical study of Little Sark, Channel Islands.** *Nicholas dA. Laffoley, Simon R.N. Chenery, A. Murray O'Keefe. Dept. of Geology, University of Leicester. Leicester LEI 7RH.*

The results of a soil sampling grid on Little Sark, Channel Islands are described. The samples reveal an area of loess concealed by residual soils, and analysis of the samples for 28 elements by inductively-coupled plasma spectroscopy (ICP) shows the elements to be divisible into two groups: those with a uniform distribution and those forming a characteristic pattern related to the loess, depressed values occurring over the loess. Possible explanations for this behaviour are discussed, and the suggestion is made that soil geochemistry could be used as a quick, cheap means of mapping drift and solid geology m areas with little exposure.

**Uranium-series disequilibrium studies of granite core from Carwynnen Quarry, Toon, Cornwall**. M. *Broderick.*

Alpha-particle spectrometry studies of the $^{238}$U-decay series from the 700m of granite core obtained from Carwynnen quarry near Troon show that disequilibrium is present in all samples, irrespective of their depth. Because of the relatively short half-lives of $^{234}$U (2.5 x $10^5$a) and $^{230}$Th (8 x $10^4$a), rock-water interaction processes have given rise to this disequilibrium in fairly recent geological time. Six samples were examined using thin source alpha-particle spectrometry. The shallowest sample from a depth of 137m showed a $^{234}$U/$^{238}$U ratio of 0.981 and a $^{230}$Th/$^{234}$U ratio of 1.109, while progressively deeper samples from 231m, 295m, 368m, 529m and 601m have ratio values of 1.003, 0.973; 1.194, 1.120; 0.930, 1.099; 1.045, 0.872 and 1.102, 0.783 respectively. The various competing processes that give rise to this disequilibrium are defined using a $^{238}$U$^{234}$U/$^{230}$Th ternary diagram.

The measured mobility of $^{238}$U and its daughter products on a whole rock scale is very useful in evaluating the geochemical integrity of granites and for providing a sensitive indicator of incipient low temperature alteration.

**Mineralisation at Wheal Jane: a progress report.** *A. Bromley, J. Holl, M. Thorne, M. Walters. Camborne School of Mines, Trevenson, Pool, Cornwall TRI5 3SE.*

Wheal Jane Mine is developed on a northerly dipping lode system which lies in the eastern part of the St. Day mineralised district. A set of gently dipping lodes ("B" Lode, North Lodes) is located on thc footwall of a porphyry sheet system and occupies structures which appear to pre-date the mineralisation and may be related to regional Variscan deformation. A more steeply dipping structure (South Lode) branches downwards from the footwall of the "B" Lode - North Lode system. It appears to have been propagated by hydraulic failure as a result of internal hydrothermal overpressure in an underlying granite body.

Three distinct mineralising events are recognised:
*1. Greisen mineralisation* which pre-dates the emplacement of the porphyry sheets.
*2. Tourmalinite-breccia mineralisation,* which was the principal tin-mineralising event, was emplaced penecontemporaneously with the intrusion of the Porphyry sheets.
Both of these assemblages are believed to have been emplaced from immiscible magmatic-hydrothermal fluids which originated in a density stratified hydrothermal column.
*3. Cassiterite-Sulphide assemblage.* This assemblage originated as a result of mixing between waning, outgoing magmatic-hydrothermal fluids and downgoing exogranitic waters of formation and/or meteoric origin.

A period of deeply-penetrating oxidative alteration separated early and late sulphide deposition.

Preliminary studies at South Crofty Mine and elsewhere in South Cornwall suggest that the paragenetic sequences discovered at Wheal Jane may have province-wide significance.

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**High-resolution seismic investigations of Plymouth Sound and the River T amar**. *K. MacCallum, J.M. Reynolds. Dept. of Marine Science, Plymouth Polytechnic, Plymouth PL4 8AA.*

High-resolution marine seismic surveys have been undertaken in Plymouth Sound and the River Tamar since the early 1980s as part of a field-training programme of the Diploma in Hydrographic Surveying, run by the Department of Marine Sciences. Plymouth Polytechnic. Historically, the emphasis was on data acquisition and navigation, but since 1983, data have been obtained for specific geological research purposes for the Department of Geological Sciences.

The polytechnic research vessel 'Catfish' provided the marine platform from which the surveys were conducted. Navigation fixes were measured to within 2m or better, while seabed bathymetry was determined using a Raytheon echo sounder. A side-scan sonar provided information about seabed texture.

The seismic instrument system comprised an EG&G Uniboom 230 13.5 kHz) seismic source with an 8-element hydrophone streamer linked via a filter to a precision recorder. Seismic sections were produced as analogue paper records. Seismic energy to fire the Uniboom source was provided by a triggered capacitor bank.

To date about 130 line-kilometres of high quality seismic profiles have been acquired and are in the process of detailed geological interpretation.

**A review of geophysical results in S.W. England.** A.J. *Burley and J.D. Cornwell. British Geological Survey, Keyworth, Notts, NG12 5GG.*

This review is an attempt to summarise the results of the principal geophysical investigations which have been made into the structure of the land area of S.W. England. Such investigations have provided information on large scale structures, such as the form of the concealed granite batholith, and more recently seismic studies have revealed the presence of deep-seated discontinuities in the crust. However there is a great deal to be learnt from smaller scale studies designed to investigate problems relevant to geological mapping, particularly as a result of improvements to the regional geophysical data. Examples are presented to illustrate the range of problems which can be solved by various methods.

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# The Ussher Society

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