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

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Introduction

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

Geological setting

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

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

In the past, insufficient faunal evidence for the age of enclosing sediments led to many volcanic rocks in the area being tentatively identified as Upper Devonian in age (e.g. Selwood, 1974). However, recently recovered conodont faunas (Stewart, 1981b, 1981c) indicate that most of the volcanic rocks of the study area are late Tournaisian to late Viséan in age.
The association of dolerite intrusions with the volcanic rocks and the similar restriction of the bulk of the intrusions to the Greystone Nappe is thought to indicate a temporal association between the two. More specifically the phase of basic magmatism these two groups represents is contained with allochthonous sediments between the lower part of the typicus Zone and top of the texanus Zone, a period of about 19 m.a. from 357 to 338 m.a. (estimated from Paproth 1969; Lane and others 1980; and from radiometric data given in George and others, 1976).

Field relations and sampling

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

Metamorphism and alteration

Both the intrusive and extrusive igneous rocks have undergone, along with the surrounding sediments, very low grade regional metamorphism. Clay mineral assemblages in the Lower Carboniferous metasediments of the Greystone Nappe indicate that the higher part of the ordered mixed-layer zone (Zone III of Velde 1977, Fig. 5I) and the lower part of the illite-chlorite zone was reached (Isaac, 1982). This represents temperatures of about 250°C and very low pressures, less than 2 Kbar, and corresponds approximately to the prehnite-pumpellyite zone in igneous and volcanogenic sedimentary rocks. We have tentatively identified pumpellyite in thin sections of vesicular lavas from southeast of Launceston but overall both the intrusive and extrusive lithologies are dominated by phyllosilicates (chlorites with minor illite), albite and carbonate minerals (calcite, ankerite, siderite).
Figure 1. Map showing tectonic setting of sampled localities. L=Launceston, T=Tavistock, P=Plymouth and E=Exeter. Sample localities (all grid references lie within National Grid 100km square SX); 1) Trewinnow Plantation (303788) and Lower Larnick (307780), 2) Greystone Quarry (365806), 3) South Hill (330723), 4) Newbridge (346697 and 347681) 5), Tavistock (478745, 478747, 485745 and 493756) and 6) Asheltor (475827)
It has been inferred that the fluid phase evolution of the surrounding sediments was dominated by conditions in which $P_{\text{H}_2\text{O}}$ was considerably less than $P_{\text{fluid}}$ (Isaac, 1982). Many of the sediments are rich in graphite and contain metamorphic carbonate porphyroblasts suggesting that they were originally rich in organic matter which has undergone degradation during diagenesis and metamorphism. The degradation of organic matter in the sediments may have played a key role in the carbonatisation and albitionisation of the interbedded and intruded igneous rocks during metamorphism.

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

Methods

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

Major oxide geochemistry

The brief appraisal above of the effects of very low grade metamorphism demonstrates that these rocks have suffered extensive alteration. A large loss on ignition (>2%) was found in all the samples analysed and reached values of 21%. Work in progress indicates that the largest component of the loss can be attributed to CO$_2$. The values of loss on ignition are related to the high degree of carbonatisation and hydration as indicated by the presence of carbonate minerals and hydrous phyllosilicates in the metamorphic mineral assemblages.

The major oxide compositions of both the intrusive and extrusive rocks are extremely variable. A plot of Na$_2$O + K$_2$O against SiO$_2$ for all samples (Fig. 2) shows no recognisable distribution patterns and a complete spread of points into the alkali and tholeiitic basalt fields of Macdonald and Katsura (1964). This is further emphasised by an examination of the CIPW norms calculated from selected analyses (Table 2). All these analyses are from a single sill and have olivine tholeite, tholeite and alkali basalt normative compositions. This variation cannot be explained by different magmatic sources but must be due to the effects of the very low grade metamorphism and associated carbonisation and hydration. This large variation in the major oxide compositions is seen throughout all the samples analysed and it is suggested that the major oxide compositions cannot be used here as an indicator of original petrologic type.

Trace element geochemistry

All the samples were analysed for 18 trace elements. However, only data for titanium (Ti), yttrium (Y), zirconium (Zr), niobium (Nb) and strontium (Sr) are considered here. Four of these elements, (Ti, Y, Zr and Nb) are generally regarded as being immobile and consequently are unaffected by such processes as weathering and greenschist facies metamorphism (Cann, 1970). Our analysis of the trace element data follows the scheme of Pearce and Cann (1973) and Pearce (1975) who devised a series of graphical plots on which the tectonic setting of the samples could be identified according to their position on the plot. These diagrams have been widely used by other authors. The principal criticism of the method lies in the assumption that Ti, Y, Zr and Nb have remained immobile during subsequent alteration (Hynes, 1980; Williams and Floyd, 1981) and this aspect will be considered below.
SiO₂  48.69  48.28  47.03  47.55  45.84  48.2  48.43  45.81  44.91  45.33
TiO₂  2.14  1.91  1.73  1.54  3.26  2.6  3.43  3.01  0.26  0.26
Fe₂O₃  1.4  2.6  2.84  0.68  3.18  1.76  2.36  1.33  2.15  8.13
FeO  10.57  8.85 10.35 11.1  7.4  7.55 10.4  9.14 10.35  6.21
MnO  0.19  0.17  0.19  0.18  0.26  0.23  0.26  0.26  0.43  0.18
MgO  9.11 11.02 14.87 11.8  4.99  4.56  5.68  5.1  5.56  4.73
CaO  4.7  6.49  6.28  8.77  8.97  7.9  7.3  8.48  9.05  3.13
Na₂O  3.45 1.79  0  0  2.69  2.8  1.97  1.42  1.65  3.39
K₂O  0.03 0.01  0  1.82  2.96  2.55  1.37  2.34  1.97  2.99
P₂O₅  0.34 0.03 0.26 0.15  0.62  0.5  0.67  0.67  0.75  0.65
Sr  281 245  191 187  271 306 192 269 261 177
Y  35  37  34  27 43  42  51  47  45  43
Zr  149 144 118 98 180 200 221 206 224 207
Nb  23  22  19 14 34  32  36  36  36  33
Q  -  3.26  5.58  -  - -  4.04  -  -  0.39
C  5.85  3.49  5.63  -  -  -  1.72  3.42  0.49  7.3
Or  0.18  0.06  - 10.76 17.51 13.9 8.1 13.84 11.65 17.69
Ab  29.16 15.14  - 16.25 23.66 16.65 12 13.95 28.65
An  21.31 30  29.48 39.34 33.2 36.78 31.87 37.73 40.04 15.54
Ne  -  -  - 3.52  -  -  -  -  -  -
Di  -  -  -  1.28  2.9  0.98  -  -  -  -
Hy  33.58 38.78 51.31 35.59  5.37 26.14 22.39 12.9 11.83
Ol  3.14  -  7.43 11.31 9.93  -  2.26 10.13  -  -
Mt  2.03  3.78  4.12 0.99  4.61 2.55  3.42 1.93 3.12 10.62
Hm  -  -  -  -  -  -  -  -  -  0.8
I  4.07  3.63  3.29 2.93  6.19  4.94  6.52  5.72  6  6.54
Ap  0.68  0.74  0.57 0.33  1.35  1.09 1.46 1.46 1.64 1.42

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

**Yttrium/nioibium ratio**

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

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

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

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

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

**Titanium-zirconium diagram (Fig. 5)**

Sixty-four percent of the samples plot in the ocean floor basalt field in this diagram. Points falling outside this field can be attributed to samples representing residual liquids enriched in Ti and Zr formed during progressive differentiation of the dolerites and basalts.
Figure 3. Bar diagram showing the Y/Nb ratios of all the sampled basic volcanic classes from Pearce and Cann (1973).

Figure 4. Discriminant diagrams (Pearce and Cann, 1973). a) Ti-Y-Zr: Within-plate basalts plot in field D, ocean-floor basalts in field B, low-potassium tholeiites in fields A and B, and calc-alkali basalts in fields C and B. Symbols as for fig. 2. b) Ti-Sr-Zr: Ocean-floor basalts plot in field C, low-potassium tholeiites in field A, and calc-alkali basalts in field B. Symbols as for fig. 2.
Interpretation
To what extent the so called "immobile" elements Ti, Y, Zr and Nb, can be regarded as immobile is uncertain. Hynes (1980) studied a series of carbonatised metabasalts from the Ascot Formation in south-east Quebec and concluded that the Ti, Y and Zr variation patterns were not primary in origin. Evidence for mobility of these elements was not found in our data because, a) the range of values is considerably less than an order of magnitude, b) no unusually low values of Ti or Zr are present and c) comparison of Figs. 4 and 5 with Hynes's diagrams shows that our data has a markedly closer grouping.

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

Figure 5. Ti-Zr discriminant diagram (Pearce and Cann, 1973). Ocean-floor basalts plot in fields D and B, low-potassium tholeiites in fields A and B, and calc-alkali basalts in fields C and B. Symbols as for fig. 2.
The complete overlap of the intrusive and extrusive basic volcanic rocks on all the figures may suggest a common magmatic source with, perhaps, the intrusive rocks forming the feeders to the extrusive basaltic volcanism. The two analyses from autochthon plotted within the main group of samples, likewise the four samples from the higher Tredorn Nappe, (Isaac, Turner and Stewart, 1982), inferring that they are probably part of the same phase of igneous activity.

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

**Discussion**

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

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

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

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

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

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

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

In southwest England the Lizard Complex of possible Devonian age is generally regarded as being an ophiolite (Thayer, 1967; Strong and others, 1975). Kirby and Styles (1980) reviewed the evidence for an ophiolite origin for the Lizard Complex and concluded that certain aspects of the petrology and field relations of the igneous rocks and the close association with continental sediments were different from other well known ophiolites. They envisaged a short-lived ocean which formed temporarily along a transform fault close to a continental margin.
The field relations of the igneous rocks indicate that intrusion and extrusion occurred in a restricted pelagic zone bounded on one side, presumably the south, by a neritic carbonate platform. Both the platform and the pelagic zone were buried firstly by gravity nappes of Viséan flysch (Isaac, Turner and Stewart, 1982) and then by Namurian flysch deposition. The basic magmatism appears to have immediately preceded and indeed heralded the beginning of overthrusting and deformation.

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

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Reference


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