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# DEVONIAN AND CARBONIFEROUS VOLCANIC ROCKS ASSOCIATED WITH THE PASSIVE MARGIN SEQUENCES OF S W ENGLAND; SOME GEOCHEMICAL PERSPECTIVES.

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Altered mafic volcanic rocks form a major component of the Palaeozoic sequences filling passive margin basins in SW England. They were generated by Devonian and Dinantian intracontinental rifting and form submarine lava flows and pyroclastic deposits as well as minor intrusions. Trace element and Sm-Nd isotope data indicate that three types of mafic magma were erupted. Lower Devonian basalts represent both subalkaline magmas and within-plate alkaline magmas. Middle Devonian through to Lower Carboniferous basalts are mostly derived from within-plate alkaline magmas. Metabasic schists of uncertain protolith age from Start Point appear to represent depleted N-type MORB. The subalkaline magmas were generated during initial extension of the rift system, and are probably alkaline magmas contaminated by crustal material. However, they might also represent magmas derived from subcontinental lithosphere modified by an earlier subduction event. With establishment of the rifting process, OIB-type alkaline magmas sourced in asthenospheric mantle dominated the volcanism. The lack of crustal contamination shown by these magmas probably reflects high rates of extension in the rift system. Contraction of the rift system inverted the passive margin basins and emplaced a family of southerly-derived nappes over the sublithospheric source of the magmas. MORB-type metabasic schists derived from Rhenohercynian oceanic lithosphere were emplaced as part of the rift closure.

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## INTRODUCTION AND GEOLOGICAL SETTING

The alkaline character of the Upper Devonian and Lower Carboniferous mafic volcanic rocks of north and central Cornwall, and the tholeiitic character of south Cornish rocks, were identified by Floyd (1982). By assigning the south Cornish rocks to the Lower Devonian, Floyd (1982) was able to propose changes in magma compositions with time across the peninsula. Subsequently, most of the rocks of south Cornwall proved to be of Upper Devonian age (Turner *et al.* 1979; Le Gall *et a1.* 1985; Wilkinson and Knight, 1989). The contrasting geochemical character of the tholeiitic rocks (Floyd, 1984) was subsequently related to a division between those erupted in a parautochthonous continental margin sequence and those in sequences forming nappes derived from a southerly oceanic environment (Holder and Leveridge, 1986a). The latter include the Start metabasic schists which have normal mid-ocean ridge basalt (MORB)-type characteristics (Rice-Birchall and Floyd, 1988), an affinity they share with the Landewednack Hornblende Schists of the Lizard Complex (Kirby, 1979; Floyd, 1984). Mapping of the Plymouth 1:50,000 geological sheet (Leveridge *et al,* in press) suggests that the volcanic rocks were erupted on a rifted continental margin within a series of E-W parallel extensional half-graben and graben basins that developed sequentially northwards throughout the Devonian and into the Dinantian. The latest Visean volcanism characterised the early extensional phase of the Culm Basin development and was the last volcanic expression prior to progressive closure and inversion of the rift system following Late Devonian-Early Dinantian collision to the south (Holder and Leveridge, 1986b; Leveridge *et al*., 1990).

This paper uses geochemical data obtained by instrumental neutron activation (INA), X-ray fluorescent (XRF), and Sm-Nd isotope analysis of 27 representative samples of metabasic rock to explore how changes in mafic magma composition may have been influenced by crustal extension and subsequent closure of the Rhenohercynian Zone in SW England.

## PETROLOGY

Although samples showing minimum secondary alteration were selected for the analyses discussed below, in varying degrees all have been altered subsequent to igneous emplacement. This ranges from early sea-water reactions resulting from submarine emplacement, that produced secondary assemblages equivalent to the zeolite facies, to prehnite-pumpellyite facies alteration caused by burial metamorphism, to high-greenschist facies assemblages related to nappe emplacement tectonics. Highest grades assemblages are found in samples from the Start Schists, collected from Prawle Point and near Salcombe, to the west of Start Point (Fig. 1). They are schistose rocks consisting of quartz + albite + actinolite + epidote + chlorite ± muscovite ± hornblende. These greenschist facies rocks show a pronounced foliation and crude mineral banding. Lower Devonian metabasic lava samples used for Sm-Nd isotope analyses were collected from coastal outcrops close to St Anchorite's Rock, South Devon (Fig. 1). Secondary alteration is typical of the prehnite-pumpellyite facies. They show primary textures of feldspar phenocrystic and microphenocrystic basalts with the plagioclase replaced by albite + pumpellyite ± epidote ± prehnite ± white mica, and the groundmass replaced by chlorite + epidote + quartz + titanite (sphene).

Core samples of the Middle Devonian in Higher Ludbrook boreholes 1 and 2, SE of Ivybridge (Fig. 1), are vesicular basalt lavas showing sparse plagioclase microphenocrysts in a crude flow-aligned groundmass. All the samples are replaced by carbonate and some show a crude cleavage. Extensive carbonation has suppressed the development of diagnostic hydrous calc-silicate assemblages and the grade of alteration is indeterminate, though probably no higher than the prehnite-pumpellyite facies. Samples of the Upper Devonian, from outcrops south of the Tamar Bridge Toll and at Wearde Quay, Saltash (Fig. 1), are vesicular basalt lavas and include one hyaloclastite. All are extensively carbonated, with calcite filling vesicles and replacing primary plagioclase, while chlorite ± titanite

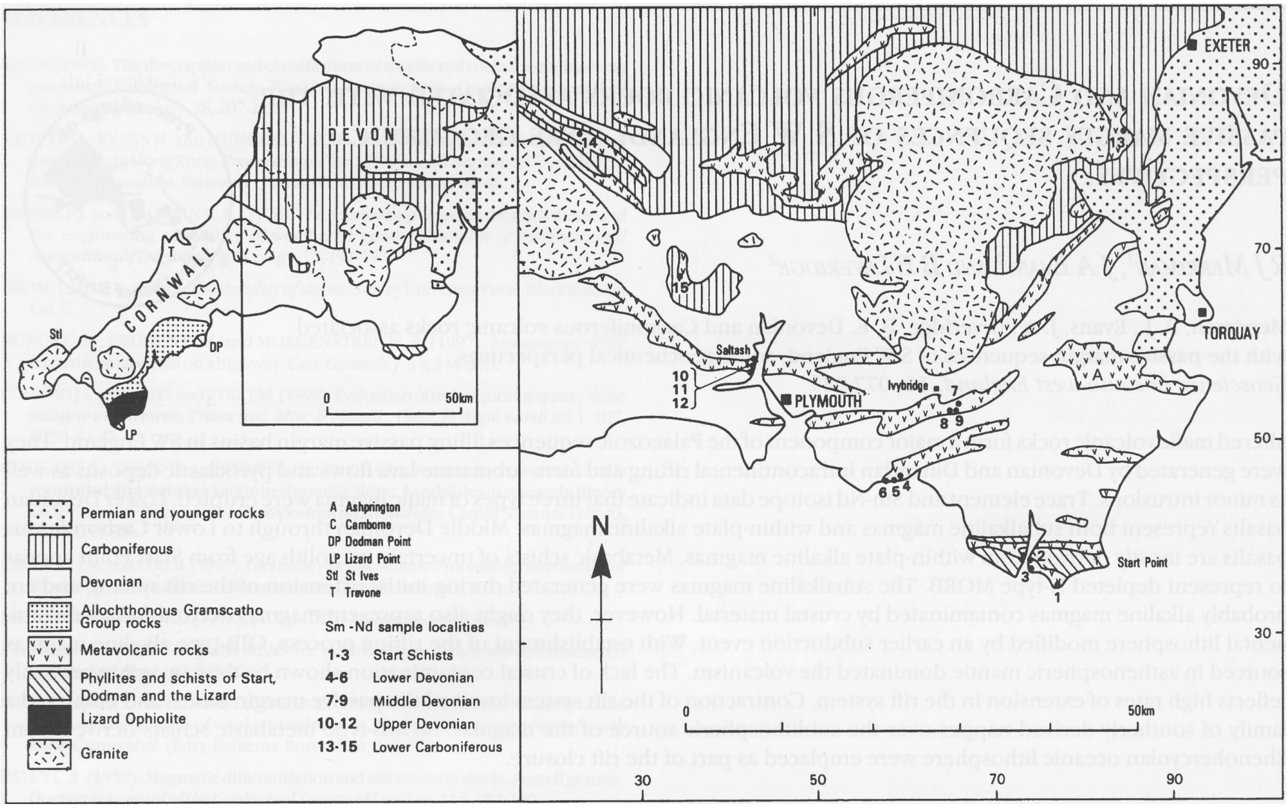

***Figure 1.*** *Geological sketch map of SW England showing sample location. Details of sample location numbers are given in Table 1.*

replaces ferromagnesian minerals and the groundmass. Again, the grade of alteration cannot be determined from these non-diagnostic secondary assemblages, but is probably sub-greenschist facies. The samples of pillowed lavas from the Lower Carboniferous are vesicular aphyric basalts, typically showing variolitic textures. Two samples, from Sannicliffe Copse and Newbridge (Nos. 13 and 15, Fig. 1), are extensively carbonate-replaced and are essentially calcite + albite + chlorite + titanite assemblages. The occurrence of bright-green, notably birefringent chlorite suggests the presence of corrensite, mixed-layer chlorite/smectite, and possibly indicates very low-grade (zeolite-facies?) alteration. A third sample, from St Clether (No. 14, Fig. 1), is a hornfelsed basalt consisting of granular epidote, albite, titanite and calcite with decussate biotite and chlorite.

The nature of the alteration products provides useful guidelines for the interpretation of the geochemical composition of the mafic rocks. For example, most of the primary plagioclase has been altered to albite, and this may result in a net loss of calcium unless it is completely taken up in Ca-bearing secondary minerals such as epidote, calcite or titanite. Depletion in trace amounts of strontium is an indicator of calcium loss and is a feature of the MORB-normalised data. Despite carbonate replacement of some samples, none showed enrichment in Sr, so that the dilution effect on other trace elements is assumed to be very minor or insignificant. Albitized plagioclase is also commonly altered to white mica (sericitized), resulting in a net gain in potassium. This type of alteration was probably initiated by reaction with seawater soon after emplacement or extrusion. Initially the potassium was captured as the glassy groundmass was converted to clay minerals, particularly celadonite, and zeolites (e.g. Alt, 1999). Sericitization resulted from burial metamorphism of the altered basalt leading to recrystallisation of early formed celadonite to form chlorite and white mica. Potassium enrichment is usually accompanied by enrichment in the trace elements rubidium and barium.

## GEOCHEMISTRY

The primary composition of the lavas, prior to secondary alteration, can be explored by means of MORB-normalized and chondrite-normalized rare earth element (REE) diagrams (Fig. 2). Many of the elements used to construct these diagrams tend to have very limited mobility during secondary alteration, particularly the REEs and most of the high field strength (HFS) elements. Hence these elements retain concentrations originally generated by magmatic processes (e.g. Pearce and Cann, 1973; Winchester and Floyd, 1977; Merriman *et al.,* 1986). As noted above, some of the light-ion lithophile (LIL) elements are easily mobilized during alteration, particularly K, Rb, Ba and Sr, and are therefore unreliable indicators of primary composition. In contrast, the LIL element Th is relatively immobile and is used in conjunction with other immobile HFS elements to discriminate between the various basaltic magmas (Wood, 1980; Wood *et al.,* 1979).

Chondrite-normalized REE plots show that the Start schists are light rare earth element (LREE)-depleted, with (Ce/Yb)cn ratios in the range 0.51-0.62, and with La/Ta ratios of 21.7-36.7, typical of depleted normal or N-type MORB (Fig. 2A). Data normalized to MORB show the flat patterns of N-type MORB, but with marked depletions in HFS elements Ta and Nb, and LIL element Th, which is below detection limits (Fig. 2B). Depletion in these highly incompatible elements suggests that the parental magmas were derived from a source that had already undergone a previous melt extraction event, i.e. a typical MORB source.

Chondrite-normalized REE plots for the Lower Devonian metabasalts are LREE-enriched with (Ce/Yb)cn ratios of 2.454.75. A negative Eu anomaly indicative of plagioclase fractionation (Fig. 2C) is consistent with the plagioclase phenocrysts observed in thin sections of the samples. MORB-normalized data show strong enrichment in HFS elements Zr to Nb, and in immobile LIL elements Ce, La and Th, resulting in progressive enrichment patterns characteristic of alkalic basalts (Fig. 2D). Nb/Y ratios in the range 0.47-0.71 indicate that these are transitional subalkaline-alkaline basalts (Winchester and Floyd, 1977).

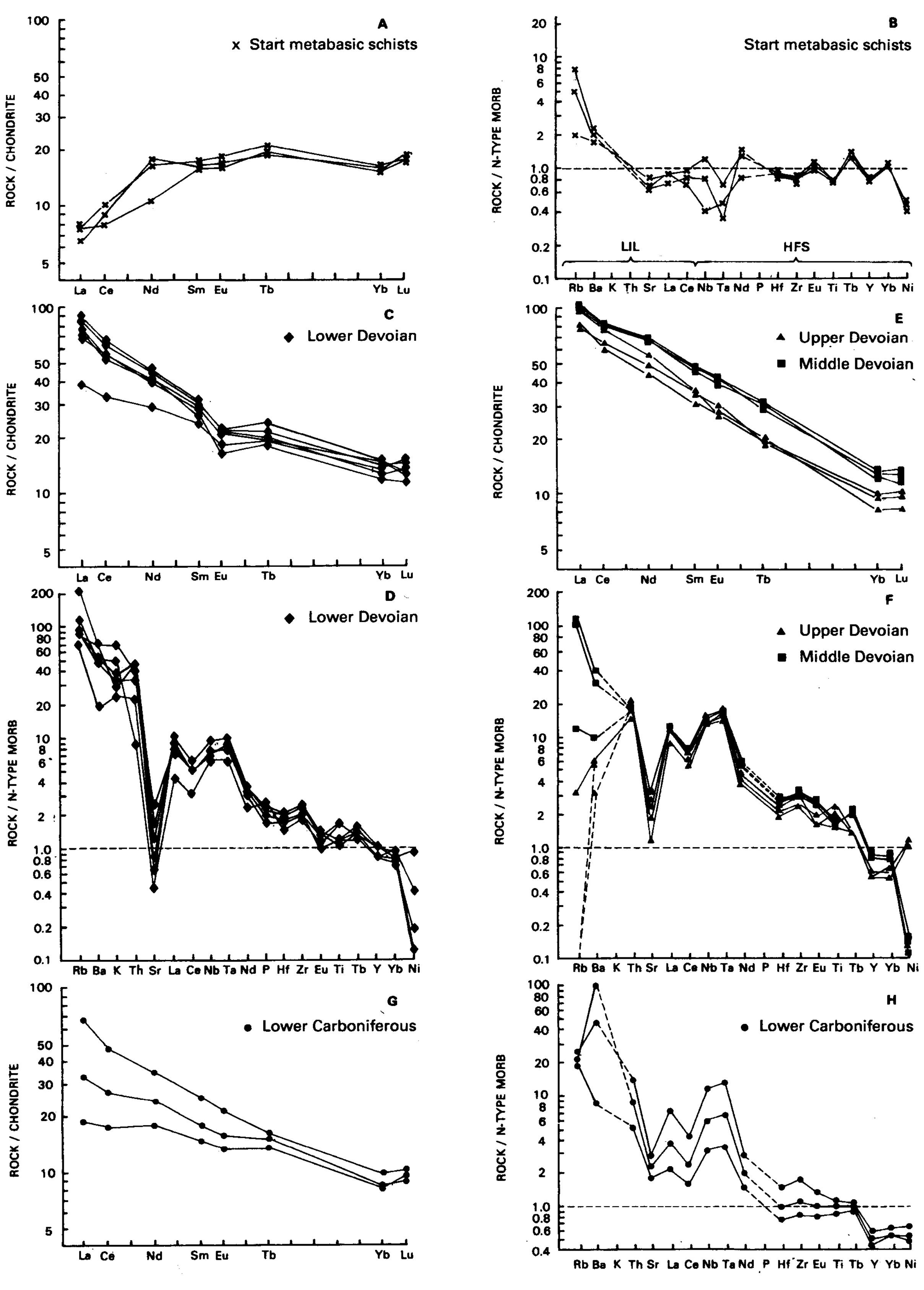

***Figure 2.*** *N-type MORB normalized multi-element and chondrite-normalized rare-earth element patterns for Devonian and Lower Carboniferous metabasic volcanic rocks from SW England. MORB normalizing values from Saunders and Tarney (1984) and chondrite normalizing values from Wakita* et al., *(1971).*

## Table 1. Trace element concentrations in Devonian and Lower Carboniferous metabasic rocks

| Sample | SD | SD | SD | SD | SD | SD | SD | SD | SD | UAR | UAR | UAR | UAR | UAR | UAR | UAR | DCD | DCD | SD | SD | SD | SD | SD | SD | SD | SD | SD |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 344 | 345 | 346 | 317 | 318 | 319 | 325 | 326 | 328 | 11 | 68 | 78 | 91 | 109 | 122 | 238 | 3147 | 3533 | 71 | 74 | 75 | 341 | 342 | 343 | 338 | 339 | 340 |
| | Start | Start | Start | L.Dev. | L.Dev. | L.Dev. | L.Dev. | L.Dev. | L.Dev. | L.Dev. | L.Dev. | L.Dev. | L.Dev. | L.Dev. | L.Dev. | L.Dev. | L.Dev. | L.Dev. | M.Dev. | M.Dev. | M.Dev. | U.Dev. | U.Dev. | U.Dev. | L.Carb. | L.Carb. | L.Carb. |
| By XRF | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| ppm | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Ba | 21 | 27 | 25 | 802 | 581 | 646 | 617 | 232 | 838 | n.d. | 358 | 1072 | 396 | 160 | 490 | n.d. | n.d. | n.d. | 120 | 463 | 372 | 67 | 36 | 71 | 570 | 99 | 1236 |
| Nb | 3 | 1 | 2 | 24 | 18 | 23 | 16 | 19 | 18 | 30 | 24 | 38 | 9 | 20 | 23 | 6 | 35 | 18 | 37 | 34 | 38 | 31 | 38 | 32 | 29 | 8 | 15 |
| Ni | 55 | 65 | 66 | 14 | 25 | 16 | 134 | 55 | 25 | 44 | 59 | 19 | 110 | 109 | 201 | n.d. | n.d. | n.d. | 19 | 14 | 18 | 137 | 145 | 15 | 89 | 72 | 68 |
| Rb | 2 | 8 | 5 | 89 | 92 | 92 | 117 | 69 | 220 | 41 | 85 | 99 | 147 | 33 | 166 | n.d. | n.d. | n.d. | 12 | 118 | 106 | 0 | 0 | 3 | 24 | 19 | 21 |
| Sr | 109 | 93 | 87 | 201 | 322 | 162 | 56 | 82 | 114 | 358 | 58 | 56 | 19 | 76 | 94 | n.d. | n.d. | n.d. | 243 | 414 | 305 | 336 | 153 | 224 | 363 | 241 | 298 |
| Y | 28 | 27 | 27 | 34 | 29 | 34 | 34 | 28 | 28 | 34 | 45 | 52 | 34 | 37 | 41 | n.d. | n.d. | n.d. | 28 | 28 | 29 | 17 | 18 | 19 | 20 | 15 | 17 |
| Zr | 75 | 73 | 71 | 209 | 168 | 210 | 155 | 212 | 176 | 197 | 225 | 311 | 130 | 200 | 192 | n.d. | n.d. | n.d. | 268 | 259 | 274 | 193 | 234 | 202 | 153 | 71 | 92 |
| TiO2 % | 0.64 | 0.63 | 0.63 | 1.69 | 1.6 | 1.89 | 2.16 | 2.13 | 1.38 | 3.93 | 2.55 | 3.13 | 1.18 | 2.87 | 2.73 | n.d. | n.d. | n.d. | 1.45 | 1.3 | 1.44 | 1.2 | 1057 | 1.87 | 0.93 | 0.7 | 0.8 |
| by INAA | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| ppm | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| La | 2.6 | 2.7 | 2.2 | 29.4 | 25.3 | 30 | 13.1 | 23.3 | 26.2 | 0 | 21.4 | 25 | 19.9 | 23.6 | 18.9 | 8 | 52.9 | 15.8 | 35.3 | 33 | 34.8 | 27.2 | 32.9 | 27.1 | 21.9 | 6.43 | 11.1 |
| Ce | 9.1 | 7.2 | 8.2 | 57.5 | 48.2 | 58.4 | 29.5 | 49.9 | 50.6 | 28.7 | 49.3 | 55.6 | 35.2 | 53 | 40.8 | 17.5 | 81.3 | 38.3 | 75.8 | 73 | 75.6 | 53 | 68.3 | 57.4 | 42.1 | 15.9 | 24.4 |
| Nd | 10.4 | 6.8 | 11.2 | 28.8 | 25.3 | 29 | 18.2 | 26.6 | 25.4 | 18.4 | 28.8 | 36.1 | 29.4 | 34.1 | 27 | 14.1 | 67.3 | 26.1 | 44.5 | 42.6 | 43.6 | 27.2 | 33.6 | 30.7 | 22.2 | 11.5 | 15.5 |
| Sm | 3.37 | 3.09 | 3.2 | 5.96 | 5.43 | 6.1 | 4.56 | 5.55 | 5.1 | 6.25 | 6.82 | 8.42 | 6.95 | 7.17 | 5.74 | 4.13 | 14.3 | 6.25 | 9.26 | 9.03 | 9.33 | 5.75 | 6.69 | 6.62 | 4.95 | 2.87 | 3.48 |
| Eu | 1.32 | 1.16 | 1.22 | 1.61 | 1.58 | 1.6 | 1.31 | 1.48 | 1.19 | 2.24 | 1.8 | 1.96 | 1.87 | 1.92 | 1.76 | 1.7 | 3.22 | 1.83 | 3.09 | 2.87 | 3.1 | 1.94 | 1.89 | 2.11 | 1.56 | 0.97 | 1.16 |
| Tb | 0.98 | 0.9 | 0.89 | 0.99 | 0.93 | 1.11 | 0.88 | 0.9 | 0.84 | 1.02 | 1.18 | 1.48 | 1.08 | 1.05 | 1.12 | 0.96 | 1.97 | 1.21 | 1.36 | 1.42 | 1.47 | 0.89 | 0.88 | 0.85 | 0.76 | 0.64 | 0.71 |
| Yb | 3.56 | 3.42 | 3.58 | 3.05 | 2.72 | 3.17 | 2.91 | 3.18 | 2.57 | 2.59 | 4.12 | 5.45 | 3.13 | 3.31 | 3.58 | 3.14 | 7.11 | 3.76 | 2.83 | 2.68 | 2.88 | 1.71 | 2.1 | 1.97 | 2.19 | 1.85 | 1.86 |
| Lu | 0.6 | 0.59 | 0.62 | 0.48 | 0.45 | 0.44 | 0.5 | 0.43 | 0.38 | 0.47 | 0.63 | 0.83 | 0.43 | 0.5 | 0.59 | 0.48 | 1.19 | 0.58 | 0.44 | 0.38 | 0.46 | 0.27 | 0.33 | 0.31 | 0.35 | 0.33 | 0.31 |
| Co | 43.8 | 46.8 | 44.9 | 24.6 | 25.1 | 26.3 | 48.5 | 44.4 | 34.3 | 44.5 | 39.8 | 32.6 | 46.3 | 54.9 | 54.6 | 51 | 18.7 | 36.7 | 39.6 | 32.7 | 37.9 | 46.8 | 51.6 | 47.8 | 40.3 | 48 | 44.2 |
| Cr | 177 | 268 | 268 | 22 | 58 | 18 | 334 | 85 | 67 | 72 | 106 | 23 | 253 | 263 | 411 | 309 | 100 | 126 | 46 | 46 | 51 | 386 | 427 | 28 | 325 | 254 | 218 |
| Cs | 2 | 4.23 | 2.22 | 0.68 | 1.21 | 1.56 | 1.71 | 1.08 | 2.92 | 14.5 | 3.56 | 2.23 | 3.13 | 7.01 | 1.95 | 1.6 | 8.91 | 2.92 | 7.68 | 9.12 | 9.04 | 4.17 | 4.9 | 10.7 | 1.32 | 2.36 | 3.79 |
| Hf | 2.26 | 2.25 | 2.14 | 4.09 | 4.25 | 5.16 | 3.63 | 5.17 | 4.48 | 3.95 | 4.35 | 7.48 | 3.44 | 4.45 | 4.43 | 2.55 | 10.5 | 5.11 | 6.79 | 6.38 | 6.64 | 4.59 | 5.56 | 4.95 | 3.63 | 1.87 | 2.44 |
| Sc | 48.5 | 48.7 | 47.5 | 20.5 | 22.8 | 20.5 | 35.2 | 38.1 | 24.4 | 24.5 | 32 | 38.2 | 28.4 | 32.9 | 40.7 | 40.2 | 67.3 | 34.9 | 21.5 | 20.3 | 21.5 | 26.6 | 30.4 | 23.7 | 26 | 33.6 | 34.5 |
| Ta | 0.12 | 0.08 | 0.06 | 1.65 | 1.39 | 1.68 | 1.08 | 1.33 | 1.46 | 1.73 | 1.49 | 2.38 | 0.65 | 1.11 | 1.41 | 0.43 | 2.08 | 1.07 | 3.03 | 2.87 | 2.95 | 2.29 | 2.89 | 2.5 | 2.21 | 0.58 | 1.12 |
| Th | 0.3 | 0.3 | 0.3 | 8.8 | 6.86 | 9.21 | 1.74 | 4.44 | 7.7 | 1.64 | 4.5 | 4.79 | 3.46 | 2.78 | 2.3 | 0.79 | 6.64 | 2.08 | 3.62 | 3.4 | 3.48 | 3.32 | 4.1 | 2.85 | 2.69 | 1.03 | 1.79 |
| U | 0.4 | 0.4 | 0.4 | 2.54 | 1.66 | 2.57 | 0.61 | 0.81 | 1.88 | 200 | 1.09 | 1.94 | 0.95 | 2.46 | 0.95 | 0.53 | 3.4 | 1.11 | 1.43 | 1.58 | 1.39 | 0.63 | 0.96 | 1.13 | 1.43 | 0.7 | 0.59 |

***Table 1.*** *Trace element analyses of Devonian and Carboniferous metabasic rocks*

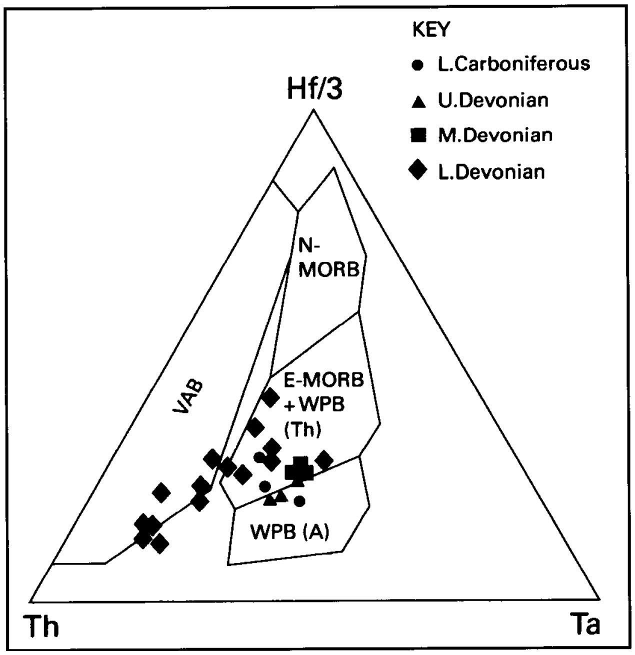

*Figure 3. Hf-Th-Ta discriminant plot (after Wood, 1980) of Devonian and Lower Carboniferous metabasic volcanic rocks from SW England. Field names: N-MORB = normal mid-ocean ridge basalt; E-MORB = enriched mid-ocean ridge basalt; WAB(Th) = tholeiitic within plate basalt; WAB(A) alkalic within plate basalt; VAB = volcanic arc basalt.*

The altered basalts from the Middle and Upper Devonian are generally more enriched in incompatible elements than those from the Lower Devonian. MORB-normalized patterns show pronounced enrichment in elements Tb to La, with slightly humped patterns peaking at Nb-Ta (Fig. 2F). Compared with the Lower Devonian samples, Th is slightly less enriched in the Middle and Upper Devonian samples and Th/Ta ratios (1.14-1.45) are significantly lower than those in the Lower Devonian samples (1.61-5.48). Middle and Upper Devonian REE patterns are strongly LREE-enriched, with (Ce/Yb)cn ratios of 6.3-7.9 (Fig. 2E). Patterns for both groups of samples lack negative Eu anomalies, suggesting that plagioclase fractionation was not the dominant process in the magmatic evolution of these lavas, as indicated by the scarcity of plagioclase phenocrysts. Nb/Y ratios in the range 1.21-2.11 indicate that these are alkaline basalts (Winchester and Floyd, 1977).

The REE patterns for the Lower Carboniferous basalts (Fig. 2G) show variable LREE enrichment [(Ce/Yb)cn 2.08-4.63], but enrichment is less marked than is the case for the Devonian basalts. Minor negative Eu anomalies are shown by two samples. MORB-normalized data show enriched patterns (Fig. 2H), but in general the Lower Carboniferous basalts are slightly less enriched in most incompatible elements than are the Devonian basalts. The progressive divergence of the sub-parallel patterns with increasing incompatiblity of elements from Ti to Th, may reflect variable partial melting processes, if the samples had a common source. Nb/Y ratios in the range 0.53-1.45 indicate that these are generally alkaline basalts (Winchester and Floyd, 1977).

## TECTONIC SETTING

The tectonic setting of the mafic rocks is characterized using discrimination diagrams (Figs. 3 and 4) constructed from ratios of immobile trace elements La, Hf, Ta and Th Wood, 1980; Leat and Thorpe, 1988). These elements are also highly incompatible, with bulk distribution coefficients of less than 0.01 in basaltic melts, and therefore ratios are least affected by fractionation during partial melting or low-pressure crystallization. Note that because of very low concentrations of Th and Ta (Table 1) data from the Start schists could not be plotted on Figs 3 and 4, but on an Nb-Zr-Y discriminant diagram (Meschede, 1986; not shown), they plot in the field of MORE.

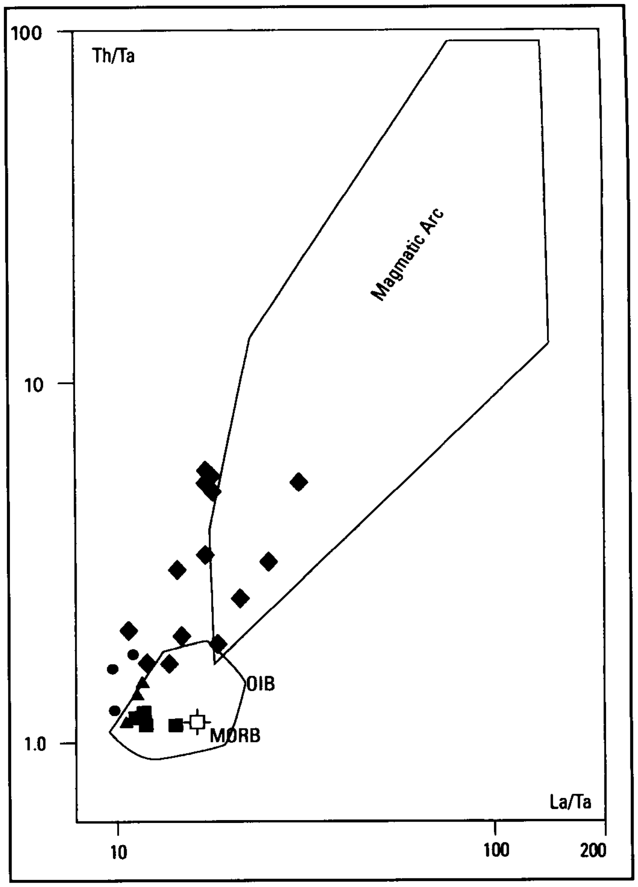

*Figure 4. La/Ta vs Th/Ta discriminant plot (after Leat and Thorpe, 1988) of Devonian and Carboniferous metabasic volcanic rocks from SW England. The key to symbols is shown in Figure* 3. *IOB = field of ocean island basalt; MORB = mid-ocean ridge basalt*

In Fig. 3, data from the Lower Devonian basalts range across the fields of volcanic arc basalt (VAB) and within-plate basalt (WPB), reflecting the transitional subalkaline-alkaline character of these rocks. The same group of rocks plotted on Fig. 4 show that 65% of the samples possess La/Ta ratios of 15 or greater, and plot within or close to the field of magmatic arc basalts. High La/ Ta and Th/Ta ratios are characteristic of LIL element enrichment resulting from the generation of basaltic magmas during subduction processes (e.g. Leat and Thorpe, 1988). The remaining 35% of Lower Devonian samples plot within the ocean island basalt (OIB) field or range between OIB and magmatic arc basalts in Fig. 4. These samples have low ratios of Th/Nb (0.10-0.13) and La/Nb (0.89-2.21), more typical of OIB-source magmas (Weaver, 1991).

The Middle and Upper Devonian, and the Lower Carboniferous lavas plot entirely in the field of WPB on Fig. 3, and tend to be more tightly grouped than the Lower Devonian basalts. On Fig. 4 these WPBS plot within or close to the field of OIB, with low Th/ Ta and La/Ta ratios indicating a lack of involvement in subduction zone magma genesis. A similar conclusion was reached by Rice-Birchall and Floyd (1988) from a geochemical study of the Lower Carbonifeous Tintagel Volcanic Formation.

OIB has a source in the asthenospheric mantle which underlies both continental and oceanic crust. Although eruption of this basalt typically forms within-plate oceanic islands, considerable volumes of OIB-type magmas are also generated along intraplate continental rifts (Fitton and Dunlop, 1985). The association of subalkaline basalts and

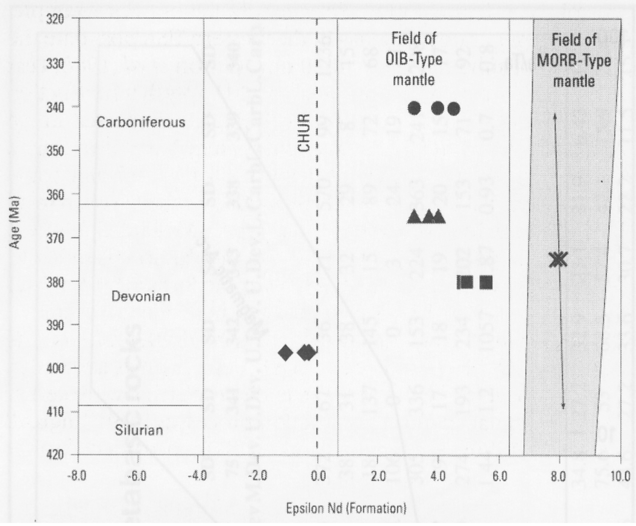

***Figure 5.*** *Plot of stratigraphic age against* $\varepsilon Nd_{formation}$ *for Devonian and Lower Carboniferous metabasic volcanic rocks from SW England. The fields of MORB and OIB are calculated from the mean and 1 standard deviation of modern day MORB and OIB data (Richardson* et al., *1982; Stille et al., 1983; Palacz and Saunders, 1986; Davies* et al., *1987; Dupay* et al., *1987; Ito et al., 1987; Gerlach* et al., *1988; Hart, 1988; Chaffey et al., 1989; Storey* et al., *1989). Symbols are the same as those used in Figs. 2 and 3.*

OIB found in the Lower Devonian of SW England is unusual but has been recorded elsewhere, for example from the Cenozoic of western USA (Ormerod *et a1*., 1988; Fitton *et al.,* 1988), and from the Ordovician of North Wales (Leat and Thorpe, 1988). The association has been interpreted as a transition from magmas generated in subduction-modified lithospheric mantle, to magmas derived from unmodified asthenospheric mantle in an extensional setting (Fitton *et al.,* 1988). Such a transition requires the removal of subduction-modified oceanic lithosphere, possibly into deeper mantle (Leat and Thorpe, 1988; Leat *et al.,* 1988), accompanied by progressive continental lithospheric extension, allowing upwelling of the asthenosphere and generation of OIB magmas (McKenzie and Bickle, 1988). Alternatively, the subalkaline character of some of the Lower Devonian basalts may reflect crustal contamination of alkaline magmas. This possibility is explored using Sm and Nd isotope data.

## SM AND ND ISOTOPE DATA

Sm and Nd abundance and isotope data are shown in Table 2, and the assumed ages together with derived $\varepsilon Nd_{formation}$ values are plotted in Fig. 5. Three groups of samples can be distinguished on the basis of their isotopic composition and trace element geochemistry (Fig. 5). Firstly, the Start metabasic schists lie within the field of typical MORB-type mantle, consistent with their general depletion in incompatible elements. Secondly, the Lower Devonian metabasalts are the only group of samples that show negative $\varepsilon Nd_{formation}$ values, indicating that crustal contamination occurred during magma evolution. For the third group, comprising the Middle and Upper Devonian and Lower Carboniferous metabasalts, $\varepsilon Nd_{formation}$ values lie within the field of OIB-type mantle. Such a source is consistent with the low La/Nb (0.740.97) and Th/Nb (0.09-0.13) ratios shown by these rocks, which result from Nb and Ta enrichment during genesis of OIB (Weaver, 1991). The Middle and Upper Devonian lavas are distinguished from the Lower Carboniferous lavas, in having higher Ce/Yb ratios (Fig. 2).

## MAGMA GENESIS AND RIFTING

In his review of basalt geochemistry, Floyd (1995) identified the presence of both MORB and WPB within the Rhenohercynian Zone of SW England and Germany. Three main groups of basaltic magma, N-type MORB, T-type (transitional) MORB and WPB (OIB) could be defined in terms of chondrite-normalized incompatible element patterns. Although tholeiitic basalts form part of the WPB group, none of these were identified as subalkaline in character. Floyd (1995) interpreted the coexistence of MORB and WPB as indicative of an ensialic basin that evolved by early crustal attenuation and, in the process, developed a narrow zone of oceanic crust. The Gulf of California, an atypical back-arc basin, is seen as a possible modern analogue. A more extensive oceanic basin is envisaged by Franke (in press), who suggest that parts of the Rhenohercynian include relicts of the Rheic Ocean.

Both Badham (1982) and Barnes and Andrews (1986) considered basin development in SW England to be the result of intracontinental rifting in a dextral strike-slip fault zone. The model considered by Badham (1982) is an analogue of western North America, where microplate collision and accretion characterize the Cordillearn strike-slip orogen. Subduction-generated Cenozoic and Mesozoic calc-alkaline volcanism is widespread in the western USA, extending eastwards as far as the western margin of the great plain (Snyder *et al.,* 1976). Predominantly easterly directed subduction in the western

| sample | thin section | locality Figure 1 | NGR | age* | Sm ppm | Nd ppm | 174Sm/144Nd | 143Nd/144Nd | epsilon Nd |
|---|---|---|---|---|---|---|---|---|---|
| SD 338 | E61968 | 13 | SX8448 8630 | 340 | 4.734 | 21.16 | 0.1353 | 0.5127 | 4.5 |
| SD 339 | E61969 | 14 | SX2030 8450 | 340 | 2.999 | 10.58 | 0.1714 | 0.5128 | 4 |
| SD 340 | E61970 | 15 | SX3463 6790 | 340 | 2.679 | 9.44 | 0.1716 | 0.5127 | 3.2 |
| SD 341 | E61971 | 10 | SX4380 5850 | 365 | 5.899 | 28.17 | 0.1266 | 0.5127 | 3.7 |
| SD 342 | E61972 | 11 | SX4385 5844 | 365 | 6.822 | 33.93 | 0.1216 | 0.5126 | 3.2 |
| SD 343 | E61973 | 12 | SX4288 5783 | 365 | 6.499 | 29.95 | 0.1312 | 0.5127 | 4 |
| SD 345 | E61975 | 2 | SX7383 3800 | 375 | 4.26 | 10.96 | 0.235 | 0.5132 | 8.2 |
| SD 346 | E61976 | 3 | SX7383 3998 | 375 | 4.626 | 11.56 | 0.242 | 0.5132 | 8.1 |
| SD 71 | E66801 | 7 | SX6677 5403 | 380 | 8.95 | 40.51 | 0.1336 | 0.5127 | 4.9 |
| SD 74 | E66802 | 8 | SX6643 5380 | 380 | 8.495 | 37.8 | 0.1359 | 0.5128 | 5.5 |
| SD 75 | E61967 | 9 | SX6643 5380 | 380 | 9.548 | 42.29 | 0.1365 | 0.5127 | 4.8 |
| SD 317 | E61285 | 4 | SX5911 4727 | 396 | 6.345 | 30.61 | 0.1253 | 0.5124 | -0.5 |
| SD 318 | E61286 | 5 | SX5891 4713 | 396 | 5.739 | 26.13 | 0.1328 | 0.5124 | -1 |
| SD 319 | E61252 | 6 | SX5887 4709 | 396 | 5.846 | 27.84 | 0.1269 | 0.5124 | -0.3 |

***Table 2.*** *Results of Sm and Nd analyses. Samples were run on a VG 354 multicollector mass spectrometer which gave a value for the La Jolla international* $^{143}Nd/^{144}Nd$ *standard of 0.511827 ± 0.000020 (2s), average of 7 determinations. Epilson values were calculated using* $^{143}Nd/^{144}Nd_{CHUR} = 0.51264$, $^{147}Sm/^{144}Nd_{CHUR} = 0.1967$ *and* $^{147}Sm = 654 \times 10^{-12}a$.

**Assumed age for calculations of epsilon values, based on the stratigraphic age of the rocks using the timescale of Harland* et al. *(1990). Samples SD 345 and SD 346 are stratigraphically unconstrained and their age is estimated as penecontemporaneous with the Lizard Complex dated at 375±34 Ma (Davis, 1984).*

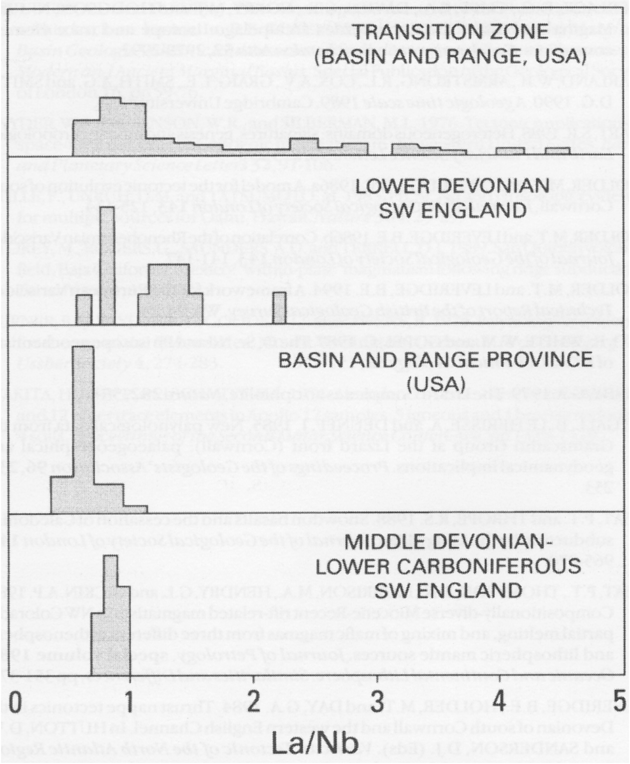

***Figure 6.*** *La/Nb ratios from Devonian and Lower Carbonifeous metabasic volcanic rocks from SW England contrasted with those from Tertiary basalts from the Basin and Range Province, western USA (Fitton* et al., *1988).*

USA was intersected by a major oceanic spreading centre, the East Pacific Rise, 20-30 m.y. ago and resulted in the northward-propagating San Andreas transform zone along the western coast of the USA. Late Cenozoic basaltic volcanism around the Basin and Range Province has been related to extension in the lithosphere caused by spreading and asthenospheric upwelling beneath the western USA (Fitton *et al.* 1988). An unusual feature of the volcanism is the association of calc-alkaline basalts with typical OIB in an extensional setting.

In Fig. 6, the distribution of La/Nb ratios in metabasic volcanic rocks from SW England (excluding the Start samples), is compared with those of basalts from two of the magmatic provinces in the western USA, detailed by Fitton *et al.* (1988). Rocks from the Basin and Range Province are typical OIB with a narrow range of low La/Nb ratios, reflecting an asthenospheric mantle source. All of the analysed basalts from the Middle Devonian through to the Lower Carboniferous fall within this range. Basalts from the Transition Zone of Fitton *et al.* (1988), represent a belt of voluminous lava fields between the Basin and Range Province and the Colorado Plataeu, and show affinities with typical calc-alkaline basalts. These basalts are characterized by a wide range of La/Nb values, reflecting variable LIL element enrichment and/ or depletion of Nb and Ta during subduction-related modification of lithospheric mantle. Although data from the Lower Devonian metabasalts do not cover such a wide range as the Transition Zone basalts, they clearly show a greater range than the Middle Devonian-Lower Carboniferous metabasalts. This suggests that crustal contamination, identified from the Sm and Nd isotope data (Fig. 5), has enriched OIB magmas in LREE and other LIL elements relative to Nb and Ta.

A less likely possibility, but one worth considering, is that some of the earliest (Lower Devonian) melts produced during the early stages of extension were derived from subcontinental lithospheric mantle that had high ratios of La/Nb, La/Ta and Th/Ta resulting from previous subduction modification of the mantle. Modification of the subcontinental lithospheric mantle beneath SW England may have occurred considerably earlier than extension, possibly in relation to Caledonian subduction. For example, extension-generated magmas in the western USA post-date the cessation of subduction by 10-20 m.y. (Fitton *et* a1., 1988; Leat *et al.,* 1988). A similar time interval would imply that subduction modification of the mantle under SW England occurred in the Llandovery or Wenlock. Such a process may have been linked with the eruption of the concealed calc-alkaline volcanic rocks which form a seismic marker horizon north of the Variscan front in southern Britain (Pharaoh *et al.,* 1991). Modification of the mantle due to northerly subduction in the Variscan is unlikely, given the lack of abundant andesitic volcanic rocks in SW England (Floyd *et al.,* 1983). However, limited southerly-directed Variscan subduction in SW England was proposed by Holder & Leveridge (1986a; 1994). Recognition of calc-alkaline magmas associated with MORE within accreted sedimentary rocks that were generated and emplaced during obduction processes in SW England (Barreiro, 1996; Sandeman *et al*., 2000), provided further support for such a process.

## DISCUSSION

The geochemical evidence considered above suggests that much of the Devonian and Carboniferous volcanism in SW England can be accounted for largely in terms of intracontinental rifting. Extension appears to have been initiated in the rocks of South Devon early in the Lower Devonian by asthenospheric upwelling beneath continental lithosphere. Isotopic evidence of crustal contamination of the Lower Devonian magmas supports an intracontinental setting for the initiation of extension. Some of the earliest melts produced in the zone of extension are transitional subalkaline-alkaline basalts, and show high ratios of La/Nb, La/Ta and Th/Ta. These ratios and their transitional character probably reflects contamination of alkalic WPB magmas by crustal rocks. However the possibility that some of these magmas were derived from subduction-modified subcontinental lithosphere cannot be discounted in terms of the history of the subcontinental lithospheric mantle beneath SW England prior to Devonian magmatism. No evidence of crustal contamination was found in lavas erupted from the Middle Devonian through to the Lower Carboniferous, indicating that for a considerable period of time, perhaps 50-60 m.y., extension allowed partial melts generated in asthenospheric mantle to be erupted unmodified as OIB. According to McKenzie and Bickle (1988), this suggests that the amount of extension was such that the stretching factor $S > 2$ and that the potential mantle temperature Tp exceeded 1380°C. The eruption of typical continental tholeiites in this setting (Floyd, 1982) may indicate a considerably greater stretching factor or higher Tp, and greater degrees of melting of the asthenosphere.

As a result of rifting, Palaeozoic oceanic crust appears to have developed along the southern margin of the Rhenohercynian Zone in SW England (e.g. Kirby, 1979; Floyd, 1984; Barnes and Andrews, 1986). Rocks with MORB-type compositions, which are thought to represent the oceanic crust, occur within the thrust nappe stack associated with the obducted Lizard ophiolite (Leveridge *et al.,* 1984). They include the metabasic schists of the Start and other mafic volcanic rocks of south Cornwall with similar affinities, particularly the metavolcanic Landewednack Schists of the Lizard (Floyd, 1984). The Start metabasic schists have La/Ta ratios (21.7-36.7) that are considerably higher than typical N-type MORE (Saunders, 1984), and suggest that the parental basic magmas may have been derived from a mantle source strongly depleted in incompatible elements. A source of this nature would probably require 15-20% partial melting to generate basaltic magma (e.g. Merriman *et al.,* 1988), and a higher than usual potential mantle temperature, i.e. $Tp > 1380°C$, as discussed above. Sm-Nd data for the Start samples (Fig. 5) show no evidence of crustal contamination, implying that the source was suboceanic lithospheric mantle, a possibility previously suggested by Davis (1984) as a source for the Lizard ophiolite. U-Pb dates of 397 ± 2 Ma obtained from magmatic zircons in plagiogranite within the Lizard ophiolite (Clark *et al*., 1998) indicates that the oceanic (MORB) magmatism considerably predates the obduction and emplacement of the ophiolite.

The closure of the Gramscatho Basin was completed by the late Devonian/early Carboniferous with the expulsion of flysch sediment fill and obduction of the Lizard ophiolite. Closure was a soft collision, and compressional deformation continued to migrate northwards across the rifted margin (Holder and Leveridge, 1986a; 1994; Leveridge *et al*., in press), which became a fold and thrust foreland. This deformation is the D1 event of Warr (1991), to which he attributes the inversion of the Trevone Basin and the southward verging folding and thrusting of the adjacent Lower Carboniferous at the end of the Lower Carboniferous. These events mark the cessation of rift volcanism in the Carboniferous.

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