Rare earth element, Sr- and Nd-isotope evidence for petrogenesis of Permian basaltic and K-rich volcanic rocks from south-west England

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ABSTRACT. Permian basic/ultrabasic lavas from south-west England may be divided into a 'basaltic' and a K-rich group. Both groups have enrichment of large-ion lithophile (LIL) elements relative to high field strength (HFS) elements, and the K-rich group show large degrees of LIL enrichment (c.50–500 times primordial mantle) in association with varied transition element concentrations. Samples from both groups $^{87}Sr/^{86}Sr_i = 0.704-0.705$ and $^{143}Nd/^{144}Nd_i = 0.5123-0.5127$ and plot close to the mantle array on an $\varepsilon_{Sr}-\varepsilon_{Nd}$ diagram. These data are interpreted in terms of derivation of the lavas from magmas resulting from partial melting of mantle which had experienced less (for the basaltic group) or more (for the K-rich group) enrichment in LIL elements as a result of migration of mantle melts. Such enrichment accompanied or followed subduction of oceanic lithosphere below south-west England. The resultant magmas experienced fractional crystallization of olivine and pyroxene prior to eruption.

KEYWORDS: rare earth elements, strontium isotopes, neodymium isotopes, Permian lavas, south-west England.

THE Peninsula of south-west England comprises deformed Palaeozoic (Devonian and Carboniferous) sedimentary rocks intruded by Upper Carboniferous (Armorican) granites and unconformably overlain by Permian and younger rocks (Edmonds et al., 1969). The Permian and Triassic rocks are generally unfossiliferous red-coloured breccias, conglomerates, sandstones, and marls. Volcanic rocks comprise scoriaceous lavas and agglomerates which occur near to the base of Permian sediments occupying two major east–west trending troughs around Exeter (fig. 1). These are termed the Exeter Volcanic Series (Knill, 1969, 1982; Cosgrove, 1972). A representative rock (the Killerton Park minette) has given a K–Ar age of 279 ± 6 Ma (Miller et al., 1961) which has been recalculated at the Open University to a preferred age of 291 ± 6 Ma using decay constants recommended by Steiger and Jäger (1977). A mean K–Ar age for seven lamprophyres of 296 ± 5 Ma has been

determined by C. C. Rundle (Hawkes, 1981). These ages are similar to the oldest ages determined for the Cornubian batholith which has recently been dated at c.280–290 Ma by Darbyshire and Shepherd (1986).

The lavas were divided into a basaltic group and a K-rich group by Knill (1969, 1982) who suggested that the lavas resembled certain high-K associations of the western USA. Cosgrove (1972) established that the lavas could be chemically subdivided into regional groups and suggested that the association has affinities with orogenic shoshonitic lavas. In this paper we present rare earth element (REE) trace element data, $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios for samples studied by Cosgrove and use these to propose that the lavas are products of partial melting of heterogeneous mantle below south-west England.

Regional tectonic setting. The Permian lavas were restricted to fault-bounded troughs or graben developed within the Palaeozoic basement during uplift at the close of the Variscan orogeny (Whittaker, 1974, p. 75). Magmatism associated with the Variscan orogeny occurred over a period of c.110 Ma, from the Devonian to the Carboniferous. The Variscan orogeny of western Europe has been interpreted, in terms of plate tectonic processes (e.g. see Hancock, 1983). Orogenic activity is interpreted to have been associated with northward subduction of oceanic lithosphere below an active continental margin, either in northern or in central Europe. The subduction may have been accompanied by strike-slip motion (e.g. Badham and Halls, 1975), and is believed to have ceased as a result of collision between northern and southern European continental plates, during the late Carboniferous. The tectonic evolution of the northern plate was accompanied by eruption of dominantly tholeiitic within-plate basaltic magmas characterized by increasing alkalinity from the Devonian to Permian, interrupted by emplacement of acid
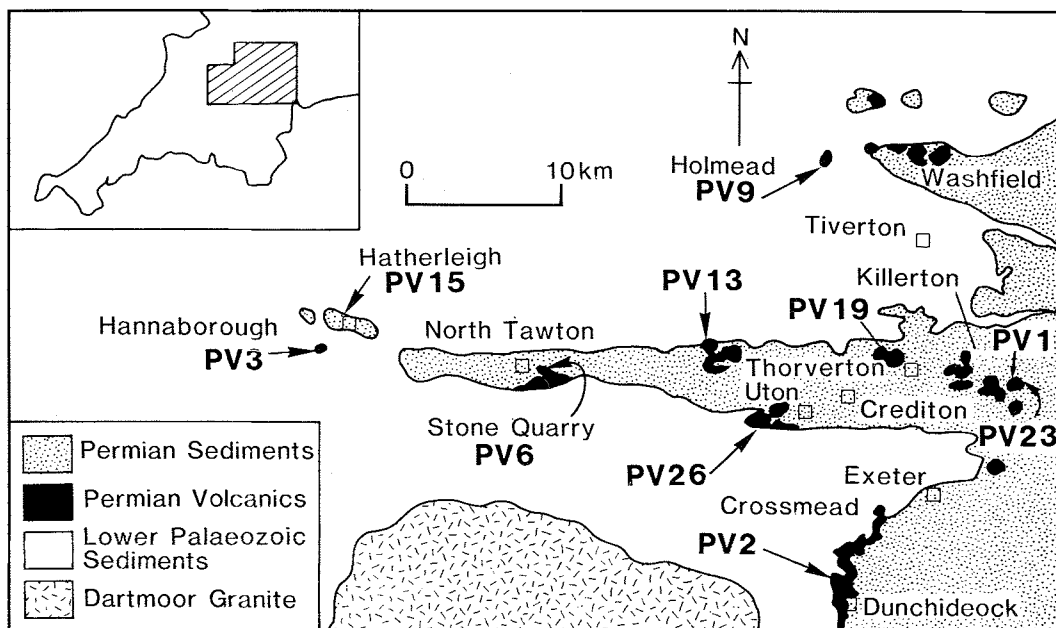
FIG. 1. Geological map of part of south-west England showing locations of analysed samples.

plutonic and volcanic rocks during the late Carboniferous (Exley *et al.*, 1983; Floyd *et al.*, 1983).

Petrography of analysed samples. The distribution of outcrops of Permian lavas and the locations of analysed samples are shown in fig. 1 and Appendix 1. The Permian volcanic rocks of Devonshire are all extensively altered and are carbonated and hydrated, with much of the iron oxidized to hematite, commonly pseudomorphing earlier ferromagnesian silicates. Because of this high degree of alteration, identification of the groundmass minerals in thin section is difficult. The volcanic rocks comprise lava flows and related subvolcanic intrusive bodies which are typically vesicular or amygdaloidal and commonly porphyritic with fluidal-textured groundmass.

The main group of lavas in this study are of basaltic composition and are represented by samples PV2, PV6, PV19, PV23 and PV26. (Table I, fig. 1). These contain corroded basic plagioclase and olivine phenocrysts (pseudomorphed by Fe–Ti oxide). The plagioclase is often mantled by a narrow rim of alkali feldspar, which also occurs as a groundmass mineral sometimes displaying a trachytic texture. Small augite crystals are usually pseudomorphed by bastite, Fe–Ti oxide or smectite clays. The groundmass comprises Fe–Ti oxides, and patches of low refractive index/isotropic meso-

stasis which is probably analcite. Occasional quartz xenocrysts occur.

The remaining samples have more varied mineralogy. A minor group of lavas (represented by samples PV9 and PV13) is characterized by olivine (fresh in PV9; Fo_{85}, Velde, 1971) and biotite phenocrysts associated with augite and analcite set poikilitically in an alkali feldspar (orthoclase)-rich groundmass. Electron microprobe analyses show that the biotite in PV9 is a titaniferous member ($TiO_2 = 3.2$–3.5%) of the phlogopite–siderophyllite series. The composition (*c.* $Al_3Mg_{62}Fe_8$) corresponds to a magnesian phlogopite ($Mg/Fe = c.0.88$) with chemical characteristics similar to biotite in calc-alkaline lamprophyres (Rock, 1984). In PV9 the analcite is euhedral which suggests that it may be pseudomorphing leucite. Samples PV1 and PV3 have the characteristics of minettes. They contain abundant biotite (commonly corroded), together with augite (sometimes fresh but more often pseudomorphed by carbonate) and apatite. PV3 also contains altered olivine. The groundmass consists of alkali feldspars; both orthoclase and sodic plagioclase seem to be present.

The mineralogy of the Permian lavas is consistent with formation from compositionally varied volatile-rich mantle-derived basic and/or ultrabasic magmas. These locally experienced minor crustal contamination prior to eruption and under-

TABLE I. Major and trace element analyses of basaltic lavas

	PV2	PV6	PV19	PV23	PV26
SiO_2	54.79	44.08	42.90	46.69	46.97
TiO_2	1.17	1.83	2.50	2.07	1.61
Al_2O_3	15.32	14.88	11.42	18.15	16.48
Fe_2O_3	9.47	10.85	11.12	13.14	12.89
MgO	5.81	1.79	4.38	2.17	2.53
CaO	5.73	10.92	11.91	2.03	5.39
Na_2O	3.45	3.99	2.55	0.29	2.71
K_2O	2.00	1.08	1.63	9.40	4.37
P_2O_5	0.18	0.36	0.32	0.30	0.20
CO_2	0.23	6.45	7.92	1.77	2.49
H_2O	2.81	3.37	2.24	3.47	2.40
Total	100.96	99.60	98.89	99.48	98.40
Ba	345	242	314	827	347
Rb	97	67	33	77	45
Sr	278	94	218	70	164
Cs	8.1	61.7	n.d.	n.d.	n.d.
La	22.2	21.9	26.5	21.2	21.1
Ce	43.8	48.0	53.6	51.3	40.4
Nd	21.7	29.4	29.3	27.8	25.1
Sm	4.2	6.6	7.0	5.9	5.8
Eu	1.25	1.97	1.89	1.89	1.80
Gd	n.d.	6.40	6.9	6.3	6.6
Tb	0.74	0.92	1.01	0.94	1.03
Tm	(0.33)	(0.23)	0.45	n.d.	0.51
Yb	1.96	1.41	2.33	1.95	2.96
Lu	0.26	0.20	0.35	0.31	0.47
Y	17	21	26	22	44
Ce_N/Yb_N	5.7	8.7	5.8	6.5	3.5
Th	7.18	5.77	5.00	5.24	4.51
Ta	1.27	1.69	1.46	1.51	1.10
Hf	3.28	2.66	4.51	4.39	3.64
Zr	115	89	182	165	134
Nb	11	19	20	17	9
Sc	18.1	11.3	22.7	23.0	22.3
V	118	122	255	185	175
Cr	205	199	n.d.	n.d.	n.d.
Co	41.4	33.0	33.7	56.1	48.6
Ni	148	116	113	134	160

The major elements and Ni are by XRF (Cosgrove, 1972); other elements are by INAA (this study). Major elements in weight per cent and trace elements in parts per million; n.d. = not determined.

went intense hydrothermal alteration and/or weathering during/after crystallization in the Permian desert environment.

Analytical methods. From the samples analysed by Cosgrove (1972), ten were selected for study, chosen to cover the range of rock types described and to include relatively fresh rocks. The samples were analysed by instrumental neutron activation analysis (INAA) for *REE*, Th, Ta, and Hf by the method of Potts *et al.* (1983) and the results are reported in Tables I and II. Five samples were separately analysed for Cs by INAA. Three samples were analysed for $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ using a VG Isomass 54E automated mass spectrometer and the results are reported in Table III.

For isotope analysis, the samples were dissolved in open Teflon beakers with $HF \cdot HNO_3$ mixtures; Sr and Nd were separated on a cation exchange column. Sr was loaded on single Ta filaments and normalized to $^{86}Sr/^{87}Sr = 0.1194$; NBS 987 gives

$^{87}Sr/^{86}Sr = 0.71018 \pm 2$ and no further normalizations were applied. Nd was loaded on the side filaments of a triple filament assemblage and analysed as Nd^+, normalized to $^{146}Nd/^{144}Nd = 0.7219$; BCR-1 gives $^{143}Nd/^{144}Nd = 0.51262 \pm 2$ and no further normalization was performed. ε values were calculated with respect to a reservoir with $^{87}Rb/^{86}Sr = 0.0847$, $^{87}Sr/^{86}Sr = 0.70475$, $^{147}Sm/^{144}Nd = 0.1967$; $^{143}Nd/^{144}Nd = 0.512638$.

Geochemical data. The volcanic rocks were classified by Knill (1969) into an earlier group of olivine basalts and a later group of K-rich lavas. On the basis of comprehensive major and trace element data, the lavas were classifed into four groups by Cosgrove (1972). The samples in Table I include rocks classified by Knill (1969) as 'olivine basalt' (PV2, PV6), olivine dolerite (PV19), 'syenite lamprophyre' (PV23) and 'trachybasalt' (PV26) and belong to the 'Dunchideock–Crediton trough

TABLE II. Major and trace element analyses of K-rich lavas

	PV1	PV3	PV15	PV9	PV13
SiO_2	48.93	50.53	57.00	47.73	51.45
TiO_2	1.24	0.79	0.86	1.65	1.27
Al_2O_3	13.78	16.12	22.13	13.42	14.16
Fe_2O_3	7.05	7.03	9.82	8.85	8.56
MgO	5.72	3.46	0.15	10.71	7.50
CaO	7.52	6.12	0.15	5.52	5.09
Na_2O	1.74	3.65	0.12	2.63	2.64
K_2O	7.72	3.17	0.05	5.37	4.61
P_2O_5	0.86	1.04	1.02	1.72	0.91
CO_2	4.43	6.94	0.23	0.14	1.54
H_2O^+	1.82	3.02	7.87	2.81	1.82
Total	100.81	101.87	99.40	100.10	99.95
Ba	3625	4845	4527	3748	2299
Rb	112	93	2	417	181
Sr	2508	1835	2770	978	1078
Cs	n.d.	6.6	n.d.	75.1	n.d.
La	n.d.	326.2	n.d.	75.7	67.9
Ce	442.6	636.0	954.1	179.6	138.7
Nd	209.3	239.3	361.3	96.5	65.6
Sm	19.6	28.8	32.2	19.4	10.2
Eu	7.24	6.23	9.00	4.55	2.72
Gd	18.3	n.d.	n.d.	n.d.	n.d.
Tb	1.98	1.87	2.51	2.31	1.16
Tm	0.46	(0.28)	0.49	n.d.	0.41
Yb	2.92	(1.7)	(2.9)	(2.9)	2.34
Lu	0.42	(0.22)	0.35	(0.3)	(0.32)
Y	21	26	20	42	27
Ce_N/Yb_N	38.5	95.5	83.6	15.8	15.1
Th	24.08	54.36	89.81	27.89	20.74
Ta	1.26	0.70	1.16	1.90	2.00
Hf	15.60	6.80	9.50	18.60	10.8
Zr	412	282	259	650	425
Nb	8	4	5	28	21
Sc	16.1	14.5	11.9	22.5	18.3
V	91	11	31	79	145
Cr	n.d.	115	n.d.	500	n.d.
Co	27.9	21.1	26.7	41.8	38.0
Ni	162	82	89	384	207

The major elements and Ni are by XRF (Cosgrove, 1972); other elements are by INAA (this study). Major elements in weight per cent and trace elements in parts per million; n.d. = not determined.

group' of Cosgrove (1972). The samples in Table II include rocks classified by Knill (1969) as 'minette' and 'olivine minette' (PV1, PV3, PV15) and 'mafic syenite' (PV13). The rock represented by sample PV9 in this group was regarded by Knill (1969) as an 'olivine leucitite' but it has also been termed an 'analcite lamproite' (Velde, 1971). These belong to the 'Hatherleigh Group' (PV3, PV15), the 'Tiverton Group' (PV9) and a separate group (PV1, PV13) in the classification of Cosgrove (1972). The characteristics and distinction between the 'basaltic' group (Table I) and the 'K-rich' (Table II) are discussed below.

The major element analyses in Tables I and II are characterized by varied SiO_2 (42.9–57.0%), TiO_2 (0.79–2.50%), Fe_2O_3, MgO and highly varied Na_2O and K_2O and Na_2O/K_2O ratios. However many samples are K_2O-rich with $K_2O > Na_2O$ (cf. Cosgrove, 1972) and the abundance of K-rich mica and alkali feldspar in the rocks indicates that this is an original characteristic of the lavas. The lavas are volatile-rich: samples analysed by Cosgrove (1972) have $H_2O = 1.1$–7.9% and $CO_2 = 0.1$–10.0%.

Before considering the application of the new trace element data to the petrogenesis of the lavas, it
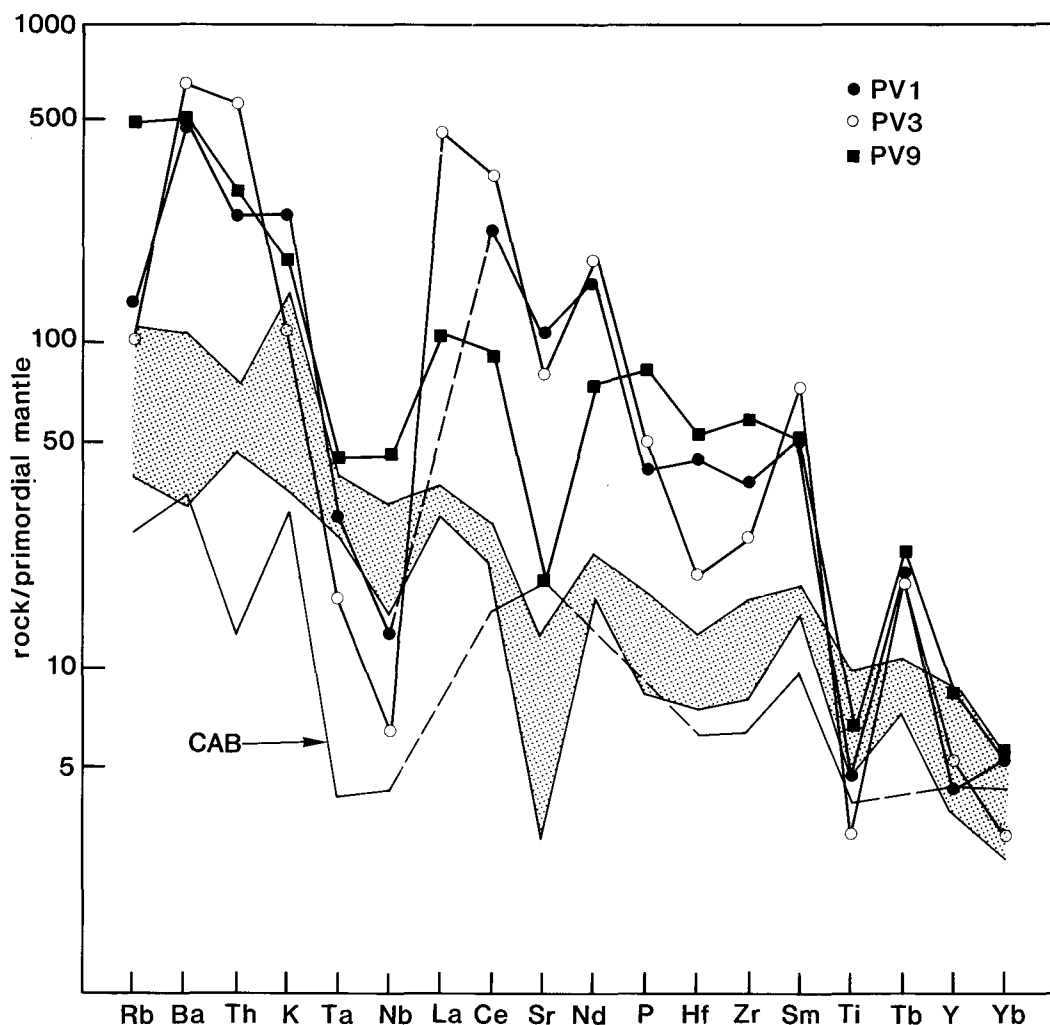

FIG. 2. Primordial mantle-normalized trace element patterns (Wood, 1979) for Permian lavas from south-west England. The stippled area encloses the basaltic lavas PV2, PV6, PV19, PV23, and PV26 and three representative samples from the K-rich group (PV1, PV3, PV9) are shown. For PV23, potassium (K) is not plotted. A representative calc–alkaline basalt (CAB) is plotted for comparison (Pearce, 1982). See text for further discussion.

is important to consider the possible effects of alteration on trace element mobility. The Permian lavas are extensively altered and hydrated and have carbonate minerals (dolomite and calcite) both replacing silicate minerals and infilling vesicles. The analysed samples in Tables I and II have 1.8–7.9 % H_2O and 0.1–7.9 % CO_2 and some have compositions that are unlikely to be magmatic in character (e.g. PV15 in Table II). Although variation in alkali/alkaline earth elements may reflect alteration, the occurrence of high Ba, Th, and *LREE* in some samples (e.g. Table II; PV3, PV15) may be a primary characteristic of these rocks.

The mobility of the *REE* under conditions of alteration and low-*T* metamorphism have been summarized by Hellman et al. (1979) who distinguished several types of *REE* mobility. In view of the alteration of the lavas the *REE* and other stable incompatible element contents may have been diluted by up to c.10% by post-magmatic hydration and carbonation. However, this may be an overestimate of trace element dilution since alkaline, minette, and lamprophyre magmas may have high magmatic H_2O and CO_2 contents (Rock, 1984). The smooth chondrite-normalized *REE* patterns, their similarity with less altered analagous lavas elsewhere, and the correlation of *REE* and Y abundances in the two groups with less mobile high field strength elements such as Zr, Hf, Ta, and Nb all suggest that these elements record primary magmatic patterns and are hence used below to interpret the petrogenesis of the lavas.

The geochemical characteristics of the Permian lavas are summarized in a primordial mantle-normalized trace element diagram in fig. 2 (cf. Wood, 1979). The stippled area shows the range in variation in the 'basaltic' group (Table I; PV2, PV6, PV19, PV23, and PV26), which show enrichment of
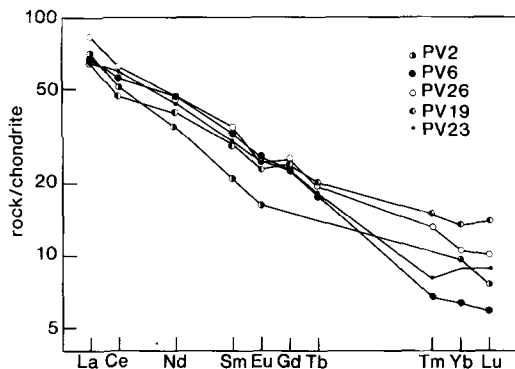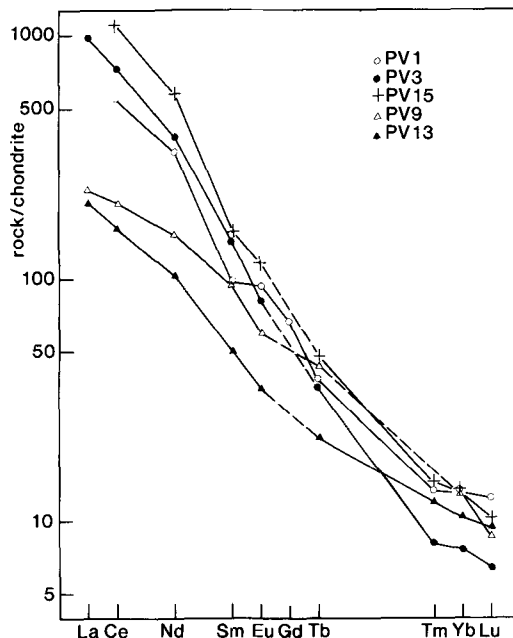

FIG. 4. Chondrite-normalized *REE* abundances in high-K Permian lavas. Chondrite-normalizing values are given in Potts et al. (1983).

Rb, Ba, Th, and K (c.50 times primordial mantle values) relative to elements from Ta–Yb (c.5–20 times primordial mantle values) in fig. 2. In comparison with a calc-alkaline basalt (Pearce, 1982) the basalts are enriched in most elements plotted in fig. 2, and have a high ratio of Rb–Nb in relation to Ce–Yb. By contrast, the representatives of the K-rich group plotted (PV1, PV3, PV9) show a high degree of enrichment in Ba, Th, K, and La–Sm (c.50–500 times primordial mantle values) in relation to Ta, Nb, and Ti. These lavas are also characterized by high compatible element concentrations (cf. Tables I and II, and Cosgrove, 1972) and despite the range in MgO contents (and hence FeO/MgO ratios), they all have relatively high Cr and Ni concentrations (Cosgrove, 1972). The basaltic rocks (Table I) have Ni = 113–160 ppm, Cr = 119 and 205 ppm, and the K-rich group has a wide range with Ni = 82–384 ppm and Cr = 115 and 500 ppm, the latter in PV9 which has 10.71 % MgO. The analyses of Cosgrove (1972) show Ni = 40–549 ppm.

The basaltic group of lavas (Table I, fig. 3) is characterized by relatively low *REE* concentrations with Ce_N = 47–62, Yb_N = 6–14 and Ce_N/Yb_N = 3.5–8.7. The samples have small negative Eu anomalies with Eu/Eu* = 0.83–0.94. The high-K samples (Table II, fig. 4) have Ce_N = 160–1100,

FIG. 3. Chondrite-normalized *REE* abundances in basaltic Permian lavas. Chondrite-normalizing values are given in Potts et al. (1983).

Table III

Sample Number	Sm(ppm)*	Nd(ppm)*	Sm/Nd	$^{143}Nd/^{144}Nd$	ε_{291}
PV1	19.6	209.3	0.0936	0.512491 ± 12	2.3
PV2	4.2	21.7	0.1935	0.512437 ± 5	-1.0
PV9	19.4	96.5	0.2010	0.512273 ± 10	-4.4

Sample Number	Rb (ppm)**	Sr(ppm)**	Rb/Sr	$^{87}Sr/^{86}Sr$	ε_{291}
PV1	112	2508	0.0447	0.704303	-8.3
PV2	97	278	0.3489	0.708554	0.3
PV9	417	978	0.4264	0.710702	17.6

*determination by INAA analysis (this paper)

**determination by XRF analysis (Cosgrove, 1972)

$Yb_N = 8$–13 and $Ce_N/Yb_N = 15.1$–95.5 and although Gd is not determined for four samples, some may have negative Eu anomalies with $Eu/Eu^* = 0.8$–1.0. Fig. 4 shows that samples PV1, PV3, and PV15 have similar REE profiles and high Ce_N/Yb_N ratios, but although PV9 and PV13 have similar Ce_N/Yb_N ratios, they have different profiles such that PV9 has higher intermediate REE than PV13. The basaltic group have low Th (4.51–7.18 ppm) and Hf (2.66–4.51) concentrations in comparison with the high K-group (Th = 20.74–89.81, Hf = 6.80–18.60 ppm).

Strontium and neodymium isotope data and related trace elements for 'olivine basalt' (PV2), the Killerton Park minette (PV1) and the 'analcite lamproite' (PV9) are given in Table III. Initial $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios have been calculated using the recalculated K–Ar age of 291 Ma (cf. Miller et al., 1961). The initial isotope ratios show significant variation with $(^{87}Sr/^{86}Sr)_{291} = 0.704$–$0.705$ and $(^{143}Nd/^{144}Nd)_{291} = 0.5123$–$0.5127$. On a ε_{Sr}–ε_{Nd} diagram the data points plot close to the 'mantle array' near the bulk earth value (fig. 6).

Discussion. Here we attempt to identify the affinities of the magmas erupted to form the Permian lavas, and to comment on the tectonic setting and petrogenesis of these rocks. The mafic mineralogy and high compatible element concentrations (e.g. Cr and Ni) in the lavas indicate that the volcanic rocks are largely or totally derived from the mantle and we discuss their petrogenesis in terms of mantle processes below.

The geochemical features of the lavas summarized in the primordial mantle-normalized plot (fig. 2) show some features of basic lavas erupted above subduction zones. Both the basaltic and particularly the K-rich groups show enrichment of lithophile elements Cs, Rb, Ba, Th, K, and LREE

relative to the high field strength elements Ta, Nb, Zr, Hf, and Ti. The enrichment of Th relative to Ta and Hf is shown by a Th–Ta–Hf plot (fig. 5) in which both groups of lavas plot within or near the field of volcanic arc basalts (cf. Wood et al., 1979). These characteristics of subduction-related basic lavas (e.g. Bailey, 1981; Pearce, 1982, 1983) indicate derivation from mantle which experienced subduction before or during the episode of Permian volcanism.

The enrichment of LIL elements and Nb, Ta in relation to other HFS and REE elements in the basaltic group is consistent with incorporation of a within-plate magmatic component with relatively high HFS/LIL element ratios prior to subsequent enrichment and/or partial melting within the influence of a subduction zone (cf. Macdonald et al., 1985).

The enrichment of large-ion lithophile (LIL) relative to high field strength (HFS) elements in subduction-related magmas may reflect enrichment of LIL elements as a result of the subduction process and/or retention of the HFS elements by a refractory phase (cf. Pearce, 1982, 1983; Thompson et al., 1984). In this model, the K-rich group may be derived from a more LIL-enriched mantle source and/or by a smaller degree of partial melting in comparison with the basaltic group. However the high LIL-element concentrations within the K-rich group suggest derivation by such small degrees of partial melting of 'primordial' mantle or an 'enriched' mantle source (such as that postulated for the basaltic group) that we regard the K-rich lavas as being derived by partial melting of a more LIL-enriched mantle source than that of the basaltic group (cf. Venturelli et al., 1984). The trace element and isotope data may be used to comment on the mineralogy and the type or age of postulated enrichment processes.

Both the basaltic and high-K groups show a high degree of variation of LREE ($Ce_N = 47$–1100) in comparison with the HREE ($Yb_N = 6$–14) such that LREE/HREE ratios show variation between 3.5–95.5 (cf. Tables I and II). Such a large variation of LREE in relation to HREE has been observed in other volcanic associations, such as a suite of basanitoids and alkali basalts from Grenada (Shimizu and Arculus, 1975), and is consistent with the presence of a mineral with high HREE partition coefficients such as garnet within the mantle source of the volcanic rocks. Assuming that the mantle source of the lavas may have originally contained 2–3 times chondritic REE abundances (e.g. Kay and Gast, 1973; Sun and Hanson, 1974) the formation of basic lavas with $Yb_N = 6$–14 times chondrite implies partial melting and/or fractional crystallization involving garnet and/or some other
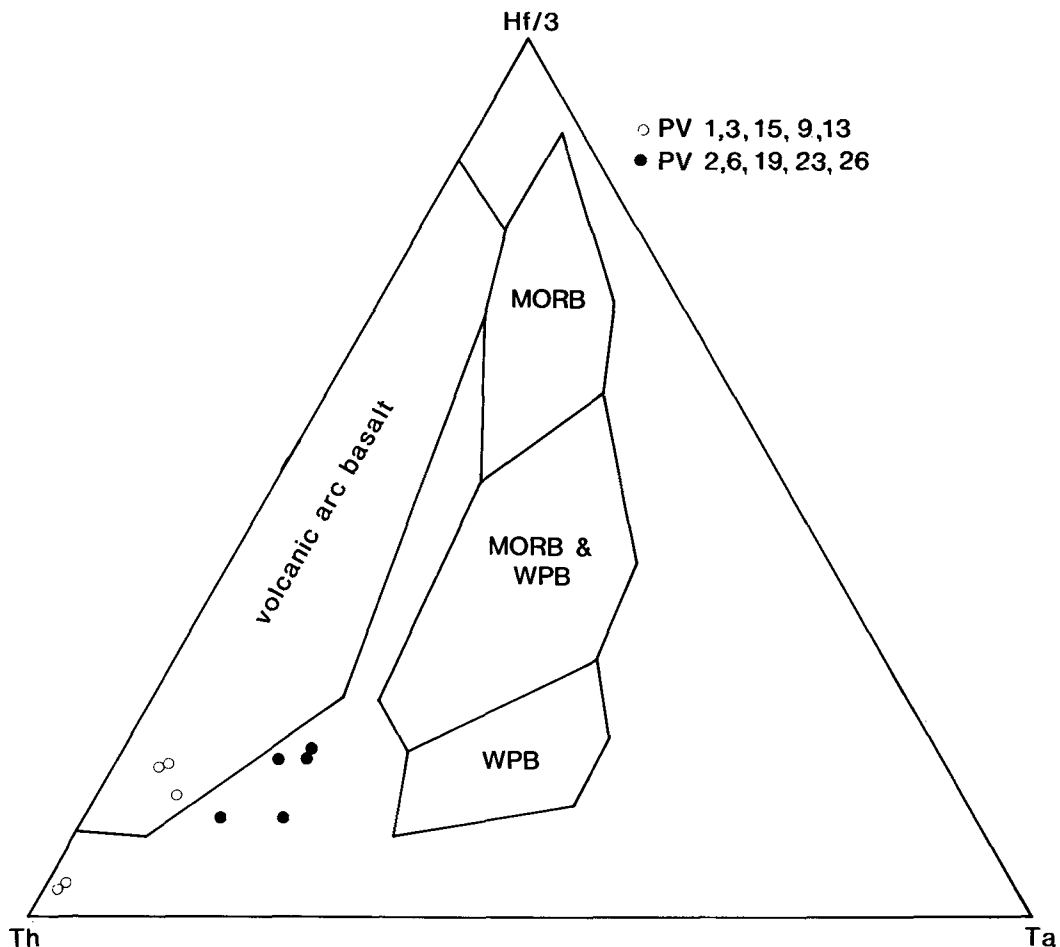
FIG. 5. Plot of Hf/3-Th-Ta for analysed Permian lavas. (cf. Wood *et al.*, 1979). WPB = Within-plate basalt, MORB = mid-ocean ridge basalt.

minerals with high *HREE* partition coefficients (cf. Floyd *et al.*, 1983, p. 179). The presence of garnet throughout partial melting (or similar degrees of partial melting of a *LIL*-heterogeneous source) is therefore consistent with the constant *HREE* concentrations and the varied Ce_N/Yb_N ratios.

Although the parent magmas of basaltic and high-K lavas may have been derived by partial melting of heterogeneous garnet-bearing peridotite mantle, the variation in the shapes of the *REE* profiles (figs. 3 and 4) may also reflect the presence of other minerals with high *REE* partition coefficients (such as amphibole, apatite or sphene) within the melting residue. Finally, although the basaltic rocks have similar Ni concentrations (Table I) and may have been derived by similar degrees of fractional crystallization from melts in equilibrium

with mantle peridotite, the large variation in Ni (and Cr) concentration in samples from the K-rich group (Ni = 82–384 ppm) indicates that these magmas are likely to have experienced varying degrees of fractional crystallization of olivine (and pyroxene±spinel) prior to eruption. The Sr–Nd isotope data (Table III and fig. 6) indicate that the Permian lavas cannot have been derived from an isotopically homogeneous source region although the three samples plot close to the 'mantle array' on a ε_{Sr}–ε_{Nd} diagram (fig. 5). Some of the variation could reflect crustal contamination of lavas derived from a source on the mantle array with $^{87}Sr/^{86}Sr = c.0.704$ and $^{143}Nd/^{144}Nd = c.0.5125$ (cf. PV1), but the high Sr and Nd contents of samples PV1 and PV9 make this unlikely. In terms of the Sr and Nd isotope composition of the mantle source of the
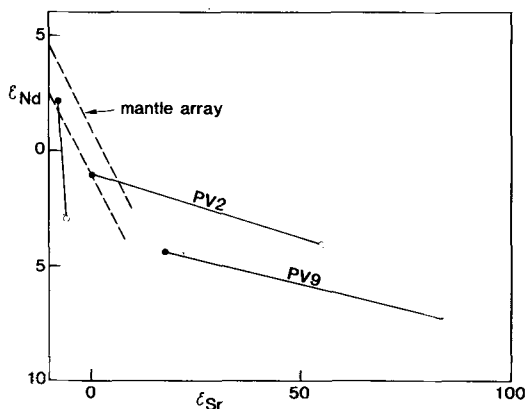
FIG. 6. Plot of ε_{Nd} against ε_{Sr} for analysed Permian lavas. The open circles correspond to present day values and the closed circles correspond to values at 291 Ma (see text for discussion).

volcanic rocks, the chemical composition of the 'analcite lamproite' PV9 (cf. Velde, 1971) is significant. Sample PV9 contains olivine, phlogopite, clinopyroxene, alkali feldspar, Fe–Ti oxide and analcite (possibly after leucite) has MgO = 10.71 %, Cr = 500 ppm and Ni = 384 ppm (Table II). These characteristics are consistent with a mantle origin, in which case the high *LIL* (inc. *LREE*) concentrations and initial $^{87}Sr/^{86}Sr$ (c.0.7054) and $^{143}Nd/$ ^{144}Nd (c.0.5123) indicate derivation from an enriched mantle source. The enrichment processes responsible for the characteristics of the mantle sources of the basaltic and K-rich lava groups may have involved melts of fluids derived from heterogeneous mantle sources close to the (Permian) mantle array. Such enrichment may correspond to the low Ti/K, high Rb/Sr (and subsequently low ε_{Sr}) style of enrichment attributed by Hawkesworth *et al.* (1984) to 'infiltration of H_2O and alkali-rich fluids . . . related to subduction'.

The Sr and Nd isotope composition of the mantle source for the volcanic rocks deduced above result from time-integrated decay of ^{87}Rb and ^{147}Sm. The $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios may result from melts derived from ancient lithosphere enriched in Rb/Sr and Nd/Sm (cf. McCulloch *et al.*, 1983). However, in view of the active tectonic environment preceding eruption of the lavas (Edmonds *et al.*, 1969), the spatial association with Palaeozoic subduction and the likely absence of Precambrian crust below south-west England (Hampton and Taylor, 1983; Thorpe *et al.*, 1984), the enrichment process is likely to have involved fluids/melts associated with subduction of oceanic lithosphere (possibly including continent-derived sediment)

during pre-Permian (Palaeozoic), ocean closure (cf. Thompson *et al.*, 1984; Venturelli *et al.*, 1984). This model is consistent with the concept, deduced from trace element characteristics of Devonian to Carboniferous basaltic rocks, of mantle heterogeneity below south-west England (Floyd *et al.*, 1983), although the lavas all occur within one of the two types of mantle ('Mantle B') identified by these authors (op. cit. Fig. 9.2, p. 181). Our data therefore support and extend the model of Exley *et al.* (1983) for the petrogenesis of the Exeter Volcanic Series in which the lavas 'represent separate, small volume, magma batches melted from variably metasomatized mantle . . . crustal contamination was probably minimal' (op. cit. p. 173).

In summary, the mafic mineralogy and high transition element concentrations in both the basaltic and K-rich groups indicates formation from mantle-derived parent magmas. The high ratio of *LIL* elements to Nb and Ta indicates derivation from a mantle source which had experienced earlier and/or contemporaneous subduction. However, the enrichment of *LIL* and *HFS* elements in both groups in comparison with subduction-related calc–alkaline basalts (cf. figs. 2 and 3) indicates that the mantle source was enriched by (i) a within-plate partial melt component enriched in *HFS* elements and (ii) a subduction-related component characterized by a high *LIL/HFS* element ratio. The latter component is more enriched in source of the K-rich group, and these two components correspond respectively to components B and C of Macdonald *et al.*, 1985. The position of the samples analysed for $^{87}Sr/^{86}Sr$ and $^{143}Nd/$ ^{144}Nd, near to the mantle array indicates that the fluids responsible for the enrichment of Sr and Nd were dominated by components derived by mantle partial melting, rather than by dehydration of subducted oceanic lithosphere.

Conclusions

(i) Permian basic/ultrabasic lavas from south-west England may be divided into a 'basaltic' and a K-rich group. Both groups are characterized by enrichment of large-ion lithophile (*LIL*) elements in relation to high field strength (*HFS*) elements, and have high and varied concentrations of transition elements. The high-K group show a high degree of *LIL* (including light *REE*) enrichment (c.50–500 times primordial mantle), and more varied transition element concentrations in comparison with the basaltic group.

(ii) Initial $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratio plot close to the 'mantle array' on an ε_{Sr}–ε_{Nd} diagram.

(iii) The chemical and isotopic characteristics are interpreted in terms of derivation of the basaltic

and high-K groups from mantle under the influence of pre-Permian (Palaeozoic) subduction.

(iv) The mantle source of the Permian lavas experienced smaller (for the basaltic group) and larger (for the high-K group) degrees of enrichment of *LIL* relative to *HFS* elements. The magmas derived by partial melting of this chemically and mineralogically heterogeneous mantle experienced fractional crystallization of olivine and pyroxene prior to eruption at the surface.

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Appendix 1 locations of analysed samples (rock names are from Knill, 1969, 1982)

1. **Low – REE group** (Table I)

PV2 Olivine basalt ? lava, Dunchideock quarry, *ca*. 400 m. S.W. of Webberton Cross (SX 875 872).

PV6 Olivine basalt ? lava, Stone Quarry, nr. N. Taunton (SS 682 014).

PV19 Olivine dolerite lava, Raddon Quarry, nr. Raddon Court, *ca*. 1.5 km west of Thorverton Church (SS908 020).

PV23 Syenitic lamprophyre ? lava, Budlake Quarry, *ca*. 400 m. west of Budlake (nr. Silverton) (SS 980 001).

PV26 Trachybasalt lava, Uton Quarry, *ca*. 500 m. west of Uton (SX 824 985).

2. **High – REE group** (Table II)

PV1 Minette plug, Killerton Park, nr. Silverton (SS 976 004).

PV3 Olivine minette ? plug, Hannaborough quarry, nr. Hatherleigh (SS530 028).

PV15 Olivine minette ? plug, Lydbridge, nr. Hatherleigh (SS 517 018).

PV9 Analcite lamproite ? lava, Holmead Farm (cf. Knill,1969; SS 889 157).

PV13 Mafic syenite lava, Knowle Quarry (south of Brandirons Corner), *ca*. 800 m north-east of Knowle village (SS 789 020).