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Jurassic alkali-rich volcanism in Victoria (Australia): lithospheric versus asthenospheric source

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ABSTRACT—An alkali-rich set of dykes near Freestone, eastern Victoria (Australia) has an age and geochemical signature similar to alkali basalts in western Victoria, which are found interbedded with low-Ti tholeiites of the Ferrar magmatic province. Both occurrences of alkali basalts are shown to have EM1 mantle-type trace element and Nd isotopic signatures, while the Sr isotopic signature in the Freestone basalts is likely to have been affected by secondary processes. The Jurassic alkali basalts are also similar to the Cenozoic alkali basalts of the Newer Volcanic Province in West Victoria. This suggests that the source for both the Jurassic and Cenozoic alkali basalts may have resided in the subcontinental lithospheric mantle. This has also been suggested as the source for the low-Ti tholeiites, which are likely to have come from a shallower part of the lithosphere than the alkali basalts. Alternatively, both the Jurassic and Cenozoic alkali basalts could have had a plume source, in which case the geochemical similarity between these two periods of magmatism is presumably coincidental. © 1999 Elsevier Science Limited. All rights reserved.

RÉSUMÉ—Un faisceau de filons alcalins près de Freestone (Australie) possède un âge et une signature géochimique semblables aux basaltes alcalins de Victoria occidental, qui sont interstratifiés avec les tholéites de la province magmatique de Ferrar. Ces deux occurrences de basaltes alcalins possèdent une signature EM1 sur la base des éléments en traces et des isotopes du Nd; les isotopes du Sr des basaltes de Freestone ont probablement été affectés par des processus secondaires. Les basaltes alcalins jurassiques sont également semblables aux basaltes cénozoïques de la province volcanique nouvelle en Victoria occidental. Ceci suggère que les sources des basaltes jurassiques et cénozoïques ont toutes les deux résidés dans le manteau lithosphérique sous-continental. Cette source a également été envisagée pour les tholéites pauvres en Ti, qui provinrent probablement d'une partie moins profonde de la lithosphère que les basaltes alcalins. Alternativement, aussi bien les basaltes jurassiques que cénozoïques pourraient avoir une source de type panache mantellique, auquel cas la similitude géochimique entre ces deux périodes de magmatisme est purement une coïncidence. © 1999 Elsevier Science Limited. All rights reserved.

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INTRODUCTION

The break-up of the Gondwana supercontinent has been preceded and accompanied by voluminous outpourings of continental flood basalts (Fig. 1). Two main episodes of magmatism have been recognised, the first one in the Early to Mid-Jurassic, affecting southern Africa, Antarctica and southeast Australia (Hergt *et al.*, 1991; Cox, 1992; Elliott, 1992; Duncan *et al.*, 1997), as well as Patagonia and west Antarctica (Pankhurst *et al.*, 1998). The second episode took place in the Early Cretaceous and produced the Paraná and Etendeka flood basalt provinces in South America and southwestern Africa,

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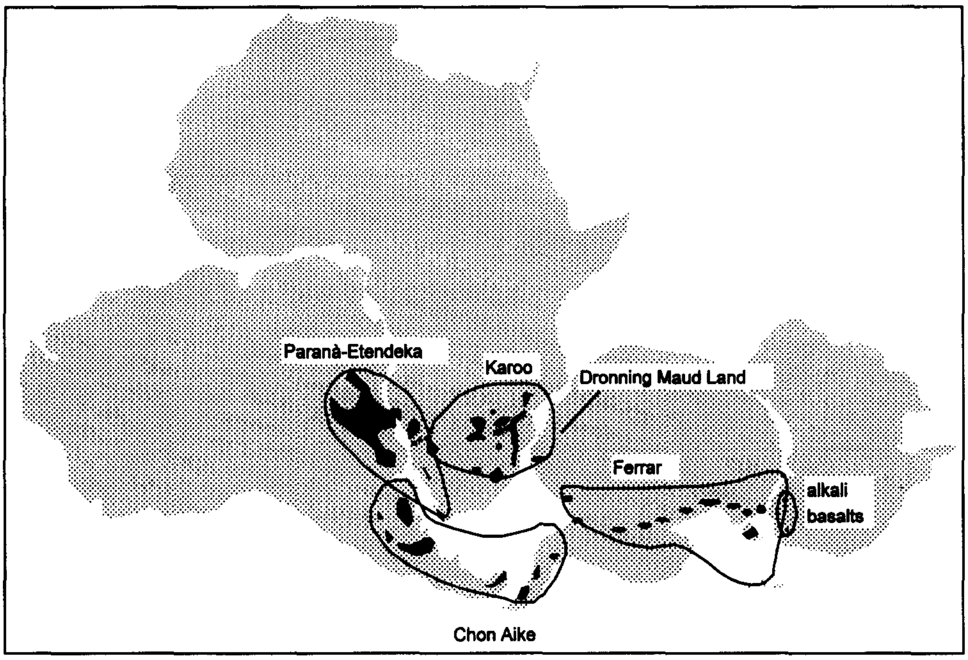

Figure 1. Schematic representation of Gondwana with the four main igneous provinces and the area of the alkali basalts described in this paper. Map and provinces after Hergt et al. *(1991), Duncan* et al. *(1997) and Pankhurst* et al. *(1998).*

respectively (Petrini *et al.*, 1987; Hawkesworth *et al.*, 1992; Renne *et al.*, 1996; Ewart *et al.*, 1998).

Provinciality in the geochemical signatures of this magmatism has been recognised, and many workers have discussed its cause (Cox *et al.*, 1967; Sweeney and Watkeys, 1990; Brewer *et al.*, 1992; Elliott, 1992; Pankhurst *et al.*, 1998). The two main groups of lavas are the so-called high-Ti and low-Ti tholeiites, recognised in flood basalts from both magmatic episodes. Jurassic magmatism in the Transantarctic Mountains, New Zealand, and southeastern Australia (here referred to as the Ferrar Province, following Tingey, 1991) belongs almost exclusively to the low-Ti group (Hergt *et al.*, 1989a, b, 1991). An exception is provided by some samples from Coleraine, western Victoria (Australia), which are alkali basalts (Hergt *et al.*, 1991). It is as yet unclear how these alkali basalts fit into the overall picture.

In this paper another locality of Jurassic alkali basalts is reported on from southeastern Australia – the Freestone dykes. New geochemical and Sr-Nd isotope data is presented on this alkali-rich magmatism, and these are contrasted with the low-Ti tholeiites of the area. The possible source is also discussed.

REGIONAL GEOLOGY, DATING AND MINERALOGY

The regional geology for the Freestone dykes has already been described by Soesoo *et al.* (1999). There are at least 15 dykes, with individual thicknesses of 1 to 3 m, exposed in a creek bed in East Gippsland, Victoria, Australia (see Soesoo *et al.*, 1999, for exact location). The dykes intruded Ordovician sediments of the Lachlan Fold Belt during north-northeast–south-southwest extension.

K/Ar dating of the Freestone dykes was performed on a separate of kærsutitic amphibole following procedures described by Webb *et al.* (1986). This yielded an age of 191.4 ± 1.5 Ma (Table 1). Partially molten enclaves of red granite are present within the dykes, and zircon from these enclaves was dated by the evaporation technique on a Finnigan MAT 261 thermal ionisation mass spectrometer at the University of Adelaide, following procedures described by Dougherty-Page and Foden (1996) and Bartlett *et al.* (1998). This gave an age of 196 ± 3 Ma (Table 2). The error on the age is the standard deviation of the common Pb-corrected ages for three separate multiloads, while a fourth measurement yielded an age of 161 Ma and was discarded as an outlier. It is felt that the quoted error may be overly optimistic, considering the error introduced by common Pb correction (14-50 Ma) for these young zircons. Including the 161 Ma analysis in the average decreases the age to 187 ± 18 Ma, which is analytically indistinguishable from the age of the enclosing basalt.

The Freestone alkali basalts contain phenocrysts of ortho- and clinopyroxene, olivine, plagioclase, kaersutitic amphibole and Fe-Ti-oxide, which are set

Table 1. K/Ar dating for sample FS6

Sample	mineral	%K	$^{40}Ar^*/^{40}Ar_{tot}$	mol ^{40} Ar*/gram	age (Ma)	error (Ma)
FS6	kaersutite	1.29	0.952	4.51×10^{-10}	191.4	1.5

Error quoted is one standard deviation.

Table 2. Pb/Pb zircon evaporation characteristics of partially molten granitic enclave within the Freestone basalts

analysis #	$^{207}Pb/^{206}Pb$	error	$^{204}Pb/^{206}Pb$	error	uncorrected age	error
1	0.051231	0.000023	0.000134	0.000058	251.1	1.0
2	0.053959	0.000086	0.000272	0.000045	368.7	3.6
3	0.050674	0.000134	0.000040	0.000008	226.0	6.1
4	0.050618	0.000240	0.000041	0.000050	223.5	10.9
analysis #	**corrected $^{207}Pb/^{206}Pb$**	**error**	**corrected age**	**error**	**average 2-4**	**error 2-4**
1	0.049261	0.001060	160.9	49.1	**196.2**	**2.8**
2	0.049963	0.001063	193.6	48.3	average 1-4	error 1-4
3	0.050086	0.000296	199.2	13.6	187.4	17.8
4	0.050016	0.001061	196.0	48.2		

Note the large error introduced by correcting for common Pb. The age of 196 Ma (average of analyses 2-4) is preferred. The error on the age is the standard deviation on the average of these three analyses, but is likely to be higher (see text for discussion).

in a fine-grained groundmass. Secondary(?) calcite is present in most samples, and olivine can be altered to iddingsite. More details of the mineralogy are given by Soesoo *et al.* (1999).

ANALYTICAL TECHNIQUES

All major and most trace elements were analysed by XRF at the School of Earth Sciences, LaTrobe University, and REE and selected trace elements (Th, U, Pb, Hf) by HR-ICP-MS at the Department of Earth Sciences, Monash University, following procedures described by Soesoo *et al.* (1999). Sr and Nd isotope ratios were measured on a Finnigan MAT 262 thermal ionisation mass spectrometer at the Centre for Isotope Geology and Geochronology following procedures outlined by Elburg and Nicholls (1995). The long-term average for the LaJolla $^{143}Nd/^{144}Nd$ standard is 0.511858 ± 10 (1σ of total population), and the $^{87}Sr/^{86}Sr$ ratio for SRM987 is 0.71023 ± 4.

WHOLE ROCK GEOCHEMISTRY

The SiO_2 contents of the Freestone basalts range from 46.3 to 48.3% (after normalisation to 100% with all Fe as Fe_2O_3), and *mg* ($Mg/Mg+Fe_{tot}$) from 41 to 57 (Table 3). The latter values indicate that the basalts are unlikely to represent primary magmas, and that they have undergone some differentiation en route to the surface. This agrees with the interpretation by Soesoo *et al.* (1999) that clinopyroxene in the samples forms three populations which crystallised at different pressures (1 to 1.5 GPa, 0.2-0.5 GPa and <0.2 GPa). A peculiar characteristic of the basaltic Freestone samples is their K_2O/Na_2O ratio of approximately 1, whereas this is <1 for most alkali basalts. All basaltic samples but one are nepheline normative. The two more silica-rich samples analysed are a partially molten granitic enclave (FS5G), and a felsic dyke associated with the basalts (FS55). These samples are not included in the Harker variation diagrams.

Although there appear to be some geochemical distinctions between samples FS4 and FS6 on the one hand, and FS22 on the other, all Freestone basalts are characterised by strong enrichment in incompatible elements on mantle normalised trace element patterns (Fig. 2), and a small negative anomaly for Pb. This pattern roughly matches that of ocean island basalts (OIBs) with enriched mantle (EM1 or EM11) characteristics. It also resembles the Jurassic alkali basalts from Coleraine, western Victoria (Hergt *et al.*, 1991), but bears no similarity to the low-Ti tholeiites that are found in the remainder

Table 3: Whole rock geochemical data for Freestone samples

sample	FS111	FS3-2	FS54	FS51	FS22	FS04	FS1	FS16	FS06	FS55	FS5G
SiO_2	46.76	46.38	46.71	46.36	46.64	46.30	47.99	47.45	48.28	63.93	67.45
TiO_2	2.51	3.10	2.96	2.79	2.70	2.70	2.70	2.59	2.62	0.05	0.23
Al_2O_3	15.20	15.59	16.57	15.20	14.11	14.93	14.77	15.61	15.56	19.16	16.23
Fe_2O_3*	11.40	14.39	12.85	13.52	12.95	13.78	12.07	11.60	11.73	4.27	3.55
MnO	0.19	0.14	0.19	0.21	0.22	0.19	0.20	0.19	0.19	0.20	0.07
MgO	7.82	6.28	4.61	6.70	7.22	7.97	6.50	6.02	6.43	0.33	1.79
CaO	8.88	7.01	8.47	8.79	9.52	8.45	8.82	8.61	8.64	0.17	1.96
Na_2O	2.11	2.97	4.20	3.46	4.60	2.09	3.23	3.95	2.54	11.43	8.55
K_2O	2.86	3.04	1.91	2.23	1.32	2.81	2.76	2.87	2.93	0.39	0.11
P_2O_5	0.67	1.11	1.53	0.74	0.92	0.79	0.96	1.09	1.08	0.06	0.06
LOI		7.07	5.52	5.00	4.15	1.88	5.23	3.37	2.26	2.69	2.90
Total		100.30	98.97	99.72	100.28	100.19	100.29	99.91	100.23	100.33	100.16
mg	57.60	46.36	41.55	49.51	52.48	53.40	51.60	50.69	52.03	13.43	49.95
Ba	1054.0	1101.6	80.9		991	1010.0	978.9	1376.4	1406.0	250.0	122.0
Rb	78.0	87.2	44.9	62.1	40.0	75.0	82.2	42.4	92.0	21.2	92.4
Sr	846.0	814.3	1401.7	817.7	1345.2	806.0	976.9	1281.0	1037.0	128.0	52.1
Pb	1.0	15.7	6.1	4.8	*13.1*	*0.8*	16.1	8.7	*1.0*	16.0	16.0
La		78.4	70.3		*145.0*	*28.1*	64.5	43.6	*46.2*	114.0	105.0
Ce	111.0	139.8	216.8	30.9	*237.0*	*60.4*	119.4	144.0	*97.6*	180.0	176.0
Pr					*25.8*	*8.6*			*13.5*		
Nd	50.0		106.1	39.4	*84.3*	*34.5*			*51.3*	53.0	
Sm	9.28				*14.00*	*7.88*			*10.44*		
Eu	3.06				*4.15*	*2.52*			*3.22*		
Gd	7.57				*12.50*	*6.93*			*8.91*		
Tb					*1.62*	*0.86*			*1.04*		
Dy	5.01				*7.78*	*4.03*			*4.75*		
Ho					*1.43*	*0.67*			*0.81*		
Er	2.11				*3.35*	*1.44*			*1.75*		
Tm					*0.45*	*0.18*			*0.23*		
Yb	1.51				*2.73*	*1.03*			*1.29*		
Lu					*0.37*	*0.14*			*0.18*		
Y	24.0	33.2	31.4	23.9	*42.7*	23.0	30.9	38.6	*29.0*	33.0	23.0
Th	4.0	14.6	13.3	11.7	*11.8*	*1.0*	13.8	19.9	*1.4*	53.0	11.0
U		3.5	-	0.6	*3.9*	*0.3*	2.1	4.9	*0.4*	20.0	2.0
Zr	301.0	392.2	393.1	343.1	338.2	294.0	380.7	368.7	*358.0*	158.0	66.0
Hf					*6.4*	*5.4*			*6.4*		
Nb	67.0	104.1	106.0	65.5	96.0	61.0	90.1	92.8	*102.0*	138.0	4.0
Sc	20.0	26.7	20.5	20.8	11.9	21.0	17.5	14.9	*13.0*		2.0
Ni	117.0	127.4	32.4	134.2	152	122.0	116.6	146.3	*84.0*	7.0	11.0
Cr	156.0	285.3	21.3	165.2	170	164.0	172.1	128.7	*131.0*	2.0	-
V	234.0	205.6	136.0	165.9	178	248.0	168.7	163.3	*221.0*	6.0	2.0

Numbers in italic determined by HR-ICP-MS, others by XRF. -: below detection. FS5G is a partially molten granitic enclave, and FS55 is a felsic dyke.

of the Ferrar Province in Antarctica.

Chondrite normalised REE patterns of the Freestone basalts show LREE enrichment and moderately steep slopes for HREE (Fig. 3), similar to the alkali basalts from Coleraine. The low-Ti tholeiites show less LREE enrichment, and shallower slopes for the HREE.

Sr AND Nd ISOTOPES

Initial $^{87}Sr/^{86}Sr$ ratios for unleached samples range from 0.7048 to 0.7067 and, as far as can be judged from three analyses, increase with increasing Sr content (Table 4). These ratios are high for alkali basalts in general and fall outside the field for most

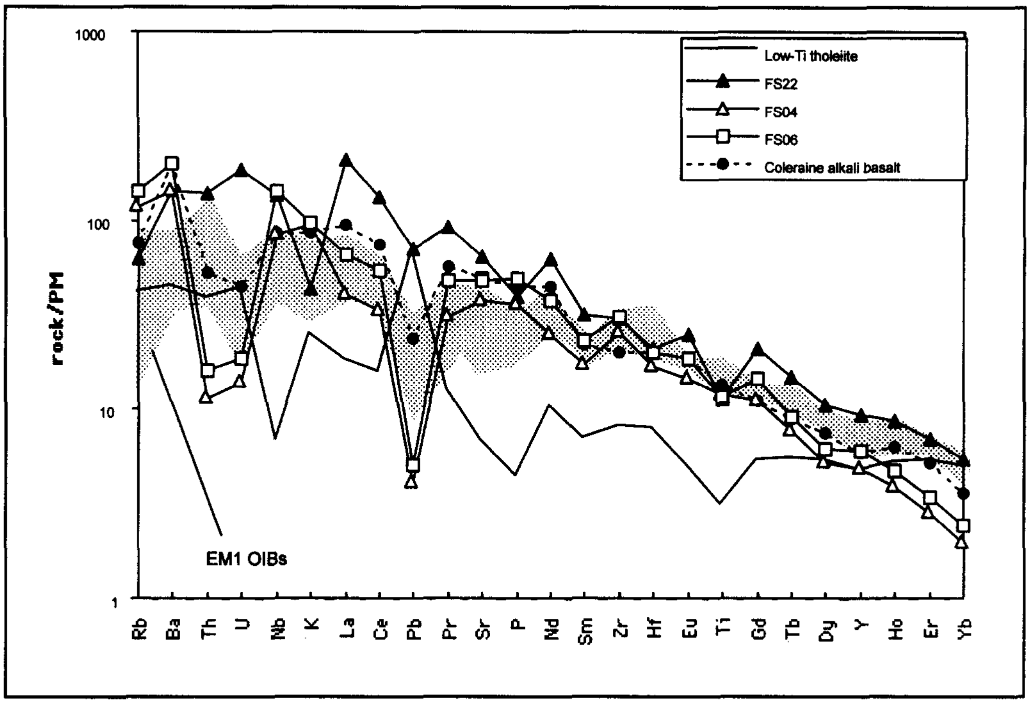

Figure 2. *Primitive mantle (PM) normalised trace element patterns for selected Freestone basalts, average Coleraine alkali basalt and low-Ti tholeiite (Hergt* et al., *1991). Field in the background is for EM1 basalts from Kerguelen (Yang* et al., *1998), Pitcairn (Woodhead and McCulloch, 1989), Tristan da Cunha (Le Roex* et al., *1990) and Inaccessible Island (Cliff* et al., *1991). Normalisation values and element ordering from Sun and McDonough (1989).*

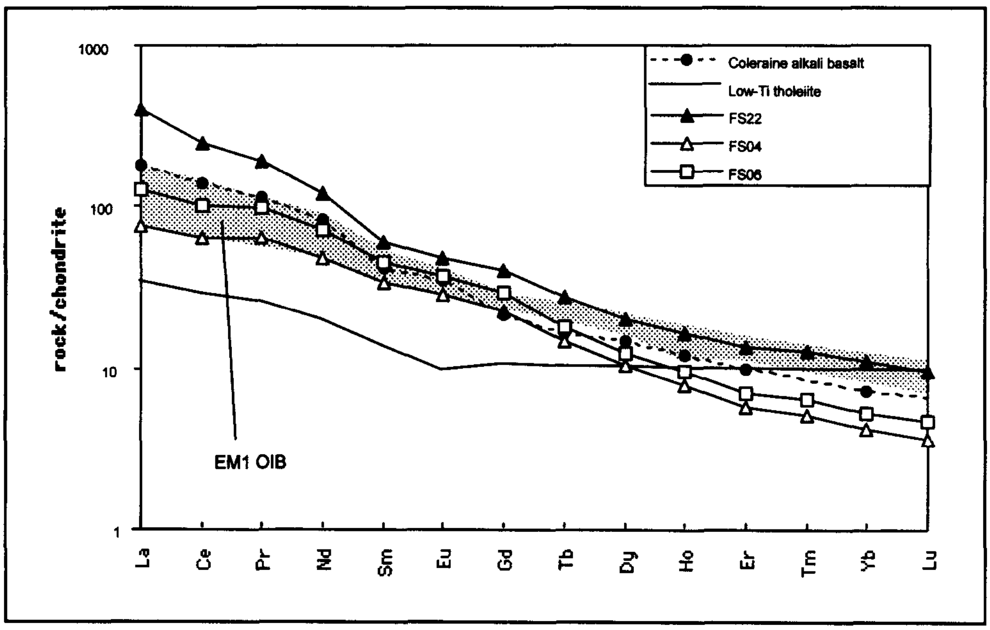

Figure 3. *Chondrite-normalised REE patterns for Freestone basalts. Background for EM1 samples as in Fig. 2. Normalisation values from Taylor and McLennan (1985).*

EM1 OIBs (Fig. 4). The alkali basalts from Coleraine have lower initial $^{87}Sr/^{86}Sr$ ratios of 0.7043-0.7044 (Hergt *et al.*, 1991). As calcite was present in some samples, some leaching experiments were performed on the sample with the highest $^{87}Sr/^{86}Sr$ ratio, sample FS22. Fresh-looking rock chips of this sample were first ultrasonically cleaned in distilled water, and then leached in warm 6N HCl for 30 minutes. The

Table 4. Sr and Nd isotope data for the Freestone samples

sample	Rb	Sr	$^{87}Sr/^{86}Sr_i$	Nd	Sm	$^{143}Nd/^{144}Nd_i$	εNd	T_{DM}	T_{CHUR}
FS4	75	806	0.705126	34.54	7.88	0.512449	1.4	940	29
FS6	90.3	1070.4	0.705735	57.02	9.8	0.512427	0.65	720	133
FS22	50.3	1327.3	0.706668	81.79	13.46	0.512444	0.99	680	110
FS22 ld1	38.5	1338.4	0.706250						
FS22 ld2	29.7	1125.4	0.705310						
FS22 lt1	3.3	166.4	0.710162						
FS22 lt2	7.35	123.2	0.712644						
FS51 ld	43.6	550.0	0.704634	12.62	2.92	0.512486	1.83	843	-62
FS51 lt	38.6	642.5	0.709231						

Constants for mantle extraction ages from Faure (1986). Mantle extraction ages in Ma. ld: leached sample; lt: leachate. See text for description of leaching process. The Rb and Sr concentrations of the leached sample and the leachate were calculated with respect to the weight of the unleached sample.

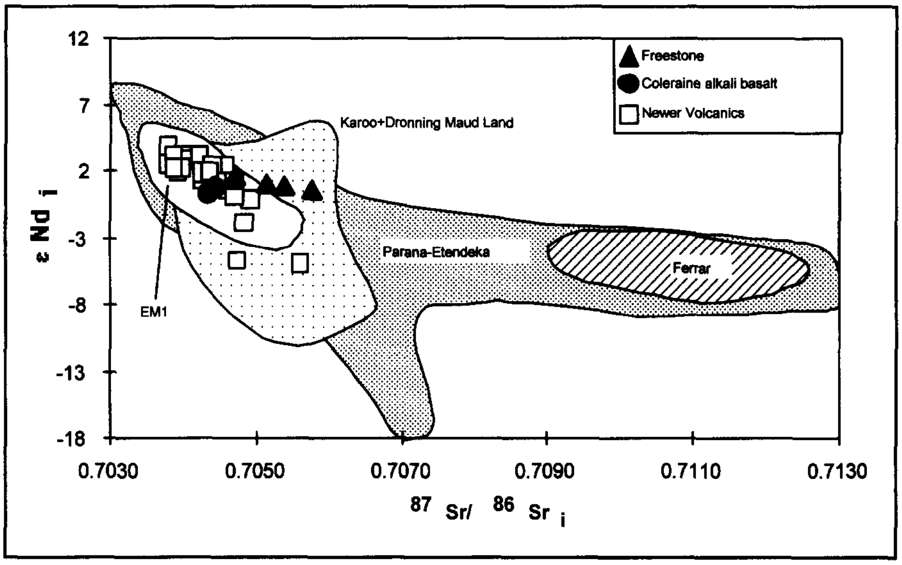

Figure 4. Initial $^{87}Sr/^{86}Sr$ versus εNd for the Freestone basalts, Coleraine alkali basalts (Hergt et al., *1991) and Cenozoic Newer Volcanics from western Victoria (McDonough* et al., *1985). Shown for reference are the fields for EM1 OIBs (references as in Fig. 2), Ferrar magmatic samples (Hergt* et al., *1989a, b, 1991; Mortimer* et al., *1995; Molzahn* et al., *1996), Karoo-Dronning Maud Land (Duncan* et al., *1990; Harris* et al., *1990; Ellam and Cox, 1991; Sweeney* et al., *1994; Grantham, 1996) and Paranå-Etendeka (Hawkesworth* et al., *1986, 1988, 1992; Duncan* et al., *1990; Gibson* et al., *1995; le Roex* et al., *1996; Ewart* et al., *1998).*

supernatant was pipetted off, and, after the normal separation procedures, it was analysed for Rb and Sr isotopes (FS22 lt1, Table 4). The leached chips were washed and dried, and crushed in an agate mortar. Half of the crushed sample was dissolved and analysed as FS22 ld1. The other half of the crushed sample was again leached in 6N HCl for 30 minutes, and the supernatant was analysed as FS22 lt2. The doubly-leached sample was analysed as FS22 ld2. Both leachates have initial $^{87}Sr/^{86}Sr$ ratios grater than 0.710, suggesting that secondary processes were responsible for the elevated $^{87}Sr/^{86}Sr$ ratio of this sample. The leached samples gave ratios of 0.7062 and 0.7053, appreciably lower than the value of 0.7067 for the unleached sample. The lowest Sr isotope ratio is closest to that of the pristine rock. Note that the Rb/Sr ratio of this sample is very low, so that the applied age correction only brought the ratio down from 0.7055 to 0.7053.

Sample FS51 was leached in a similar fashion to the second leaching step of FS22, and gave an $^{87}Sr/^{86}Sr$ ratio of 0.7046 for the leached sample, and 0.7092 for the leachate.

$^{143}Nd/^{144}Nd$ initial ratios for the Freestone basalts vary within a small range (0.512427-0.512486), and $εNd_i$ values vary between 0.68 and 1.83. These

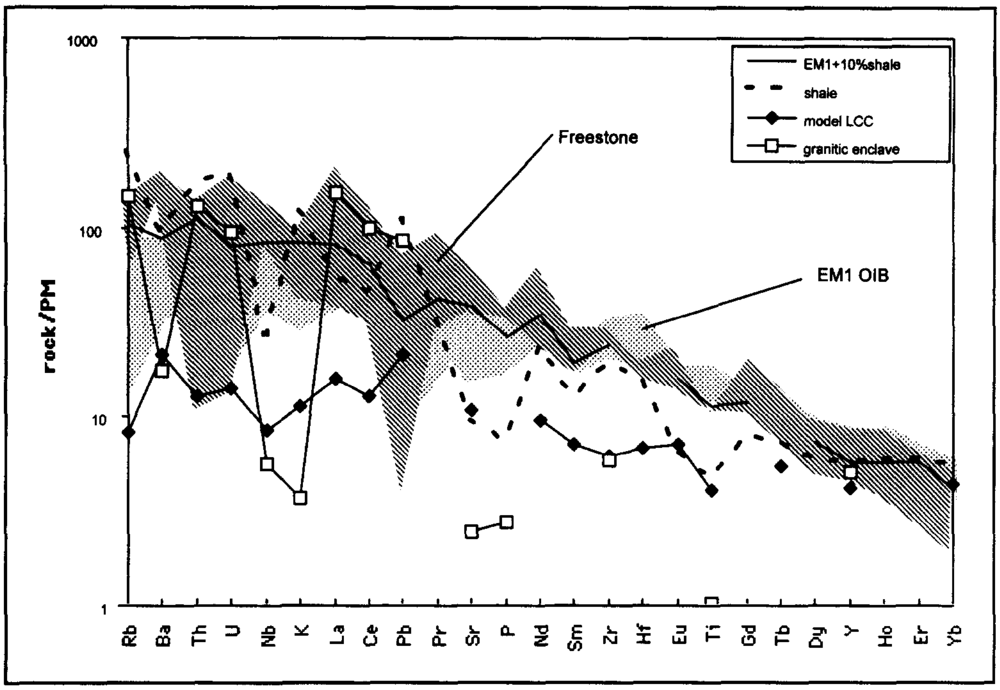

Figure 5. Primitive mantle (PM) normalised trace element diagram illustrating the effect of crustal contamination on EM1-type magmas. Fields shown are for EM1 OIBs and Freestone samples. The thick continuous line shows the pattern for a typical crustal contaminant (shale from Taylor and McLennan, 1985), and the stippled line is the pattern for a typical EM1 OIB with 10% shale; showing that the trace element pattern is insensitive to moderate amounts of crustal contamination. Contamination by lower continental crust will have even less effect, due to the low trace element contents of this contaminant. Digestion of the partial molten granitic enclave (FS5G) does not seem to have influenced the trace element pattern of the basalts either.

values are similar to those for the Coleraine alkali basalts. Depleted mantle extraction ages for the Freestone and Coleraine alkali basalts range from 680 to 940 Ma, and T_{CHUR} from -62 to 150 Ma.

IMPORTANCE OF CRUSTAL CONTAMINATION AND ALTERATION

The *mg* of the Freestone basalts indicates that they are not primary magmas,and have undergone fractionation during their ascent through the crust. This, together with the presence of partially molten granitic xenoliths, indicates that they could have experienced crustal contamination. It is therefore necessary to investigate whether crustal contamination has taken place at any stage during their ascent. The Freestone basalts are characterised by a small negative Pb anomaly and a positive Nb anomaly. Upper continental crust, as exemplified by the pattern for a shale in Fig. 5, typically has a pronounced negative Nb and Sr-P anomaly, and a positive Pb anomaly. Despite these obvious differences in trace element patterns, the high concentrations of incompatible elements in the alkali basalts makes them very insensitive to small amounts of crustal contamination. Simple bulk mixing modelling shows that only at a contamination percentage of more than 10% can one start to see some influence on the trace element pattern of an EM1 basalt, the main result being the development of a negative Sr anomaly. Likewise, crustal contamination will not have a profound influence on the Sr and Nd isotopic ratios of alkali basalts, due to the high contents of these elements in alkali basalts. Contamination with lower crustal material is equally unlikely to be noticeable, as the lower crust of southeast Australia has a rather unradiogenic Sr and radiogenic Nd isotopic signature (Rudnick, 1992). Also, there is no correlation between the isotopic signature of the samples analysed and any index of fractionation, whereas this would be expected if the suite of samples had experienced crustal contamination combined with fractionation.

A third potential contaminant is the red granite of which partially molten enclaves are found within the Freestone dykes. The trace element pattern of the enclave analysed is somewhat similar to that of upper crust (negative Nb, Sr, P anomaly), so it must be concluded that contamination would not be noticeable in either the trace element pattern or the Sr

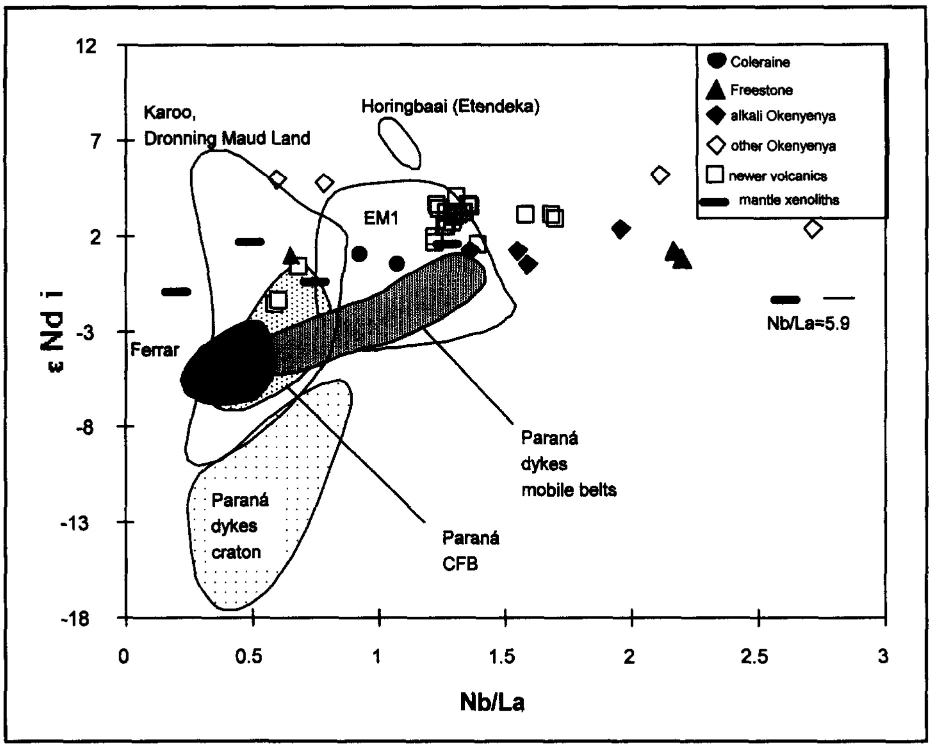

Figure 6. *Nb/La versus εNd$_i$. The Freestone and Coleraine alkali basalt resemble EM1 OIBs, the Newer Volcanics and alkali gabbros from the Okenyenya Complex (Milner and le Roex, 1996), as well as mantle xenoliths from Victoria (Griffin* et al.*, 1988; O'Reilly and Griffin, 1988).*

and Nd isotopic data unless it was more than 10%. The very low K_2O contents of this enclave suggests that contamination of the basalts with this material cannot be responsible for the elevated K_2O/Na_2O ratios of the Freestone basalts. It is therefore concluded that these high K_2O/Na_2O ratios are likely to be a characteristic of the source of the Freestone basalts.

The high loss on ignition of most Freestone samples suggests that they have suffered some alteration, and this may have affected the contents of some mobile elements such as Rb, Ba, Sr and U. An element on which alteration seems to have had a pronounced effect is U, which is quite variable in the three Freestone basalts for which ICP-MS analyses were obtained. The leaching experiments show that the $^{87}Sr/^{86}Sr$ ratios of the unleached Freestone samples have been influenced by secondary processes. The fact that the leached sample with the lowest $^{87}Sr/^{86}Sr$ ratio virtually overlaps with the Coleraine samples in a Sr-Nd isotopic diagram (Fig. 4) suggests that the leaching has been effective in removing the secondary imprint.

Comparison with other Mesozoic samples

The Freestone and Coleraine alkali basalts are geochemically and isotopically very different from the low-Ti tholeiites of the Ferrar province of Antarctica, New Zealand and southeastern Australia. While the low-Ti tholeiites display a trace element pattern similar to that of sediments (negative Nb anomaly, positive Pb), and have high initial $^{87}Sr/^{86}Sr$ and low $^{143}Nd/^{144}Nd$ ratios, the alkali basalts show more similarity to EM-type OIBs with respect to the trace elements and isotopic compositions measured here. Although the isotopic signature of the Freestone basalts is similar to that of some other Mesozoic basalts related to the break-up of Gondwana, most notably those from the Karoo and Dronning Maud Land Provinces, their trace element signature has few equals. None of the Jurassic basalts in the Karoo, Ferrar or Dronning Maud Land Provinces displays the same type of enriched mantle signature, exemplified by high Nb/Zr and Nb/La ratios (Fig. 6). The only match in trace element and isotopic signature comes from Cretaceous basalts related to the opening of the south Atlantic. Alkali basalts from the Okenyenya Complex in the Etendeka Province of Namibia have a similar trace element signature (le Roex *et al.*, 1996; Milner and le Roex, 1996; Fig. 6), which has been interpreted to reflect an asthenospheric plume source.

Comparison with the Newer Volcanics

The trace element signature of the Freestone and Coleraine alkali basalts shows a strong resemblance

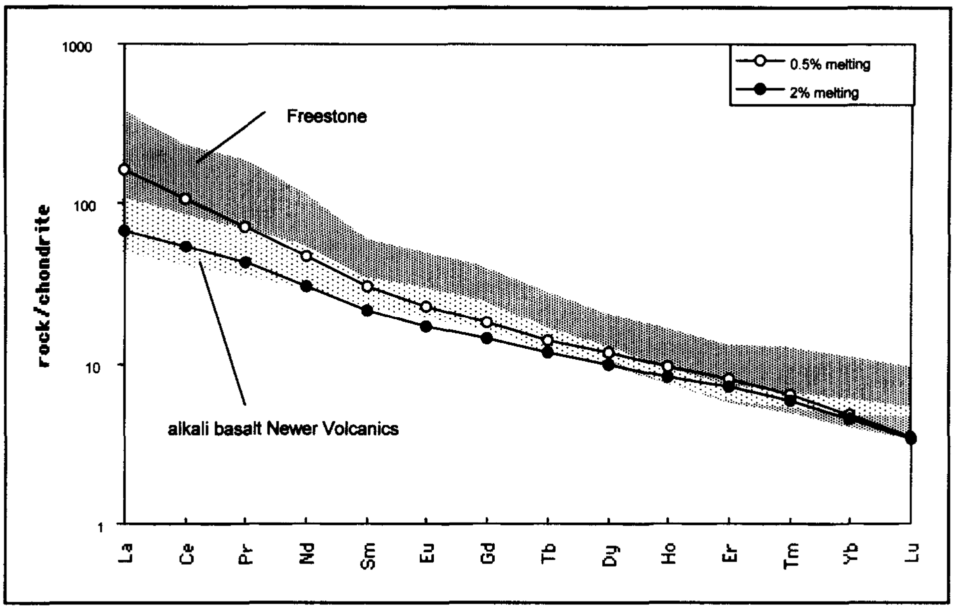

***Figure 7.** REE patterns of the Freestone and Coleraine basalts compared to that of alkali basalts from the Cenozoic Newer Volcanics. Curves shown are modelled melts in equilibrium with a garnet lherzolite source. Elemental concentrations of E-MORB from Sun and McDonough (1989); distribution coefficients used from McKenzie and O'Nions (1991).*

to those of the alkali basalts belonging to the Cenozoic Newer Volcanics Province in western Victoria (Fig. 6; McDonough *et al.*, 1985; Price *et al.*, 1997). The isotopic signature of the Freestone and Coleraine alkali basalts falls within the range of those measured for the Newer Volcanics (Fig. 4), but it must be noted that they bear more isotopic resemblance to the Newer Volcanics tholeiites than to the alkali basalts, which have on average lower $^{87}Sr/^{86}Sr$ and higher $^{143}Nd/^{144}Nd$ ratios (or εNd). The slightly shallower REE pattern of the Newer Volcanics compared to that of the Freestone basalts suggests that the Newer Volcanics were formed by larger degrees of melting (Fig. 7). This agrees with the greater volume of the Newer Volcanics compared to the scarcity of Jurassic alkali basalts.

Petrogenesis of the Freestone basalts: lithospheric versus asthenospheric source

The moderately steep HREE pattern of the Freestone basalts suggests that the melts were in equilibrium with a garnet-bearing residue at some stage. They can be modelled as a 0.5% batch melt of an E-MORB source in equilibrium with a residue of olivine (67%), orthopyroxene (21%), clinopyroxene (8%) and garnet (4%) (Fig. 7). Such a small melt fraction may just be able to collect and ascend from its mantle source (McKenzie, 1989). Modelling these basalts as melts from an N-MORB gives a poorer fit for the REE patterns, and requires even smaller degrees of partial melting. The REE pattern of the Newer Volcanics shows more similarity to a 2% melt of the same source.

Alternatively, the Freestone basalts can be interpreted as larger degree melts from a more enriched source. Apatite-bearing mantle xenoliths found in the Newer Volcanics indicate that parts of the subcontinental lithospheric mantle underneath Victoria have REE patterns and isotopic signatures similar to the Freestone alkali basalts (Griffin *et al.*, 1988; O'Reilly and Griffin, 1988), and they also plot in the same area as the Freestone basalts with respect to Nb/La and εNd at 191 Ma (Fig. 6). The geochemical signature of these mantle xenoliths could, of course, also be interpreted as reflecting metasomatism by basaltic melts similar to those that formed the Freestone dykes.

The similarity of the Freestone basalts and EM1 OIBs, such as those from Tristan da Cunha and Kerguelen, suggests that they could be derived from within a deep-seated mantle plume. This interpretation has been favoured by other authors for the EM1 signature seen in magmatism associated with the break-up of Africa and South America (Milner and le Roex, 1996). In the case of the Etendeka Province this is a logical interpretation, as there is strong evidence that the present-day Tristan Plume was underneath that area at the time of continental break-up (Gallagher and Hawkesworth, 1994; Turner *et al.*, 1994). There is, however, no clear evidence for the presence of a plume underneath Australia in Jurassic times.

The similarities between the geochemistry of the Freestone basalts and that of the Cenozoic Newer Volcanics could be a coincidence, but it could also indicate that they had similar sources. As the Australian continent has moved appreciably northwards since the Mesozoic, it is unlikely that the Freestone basalts and Newer Volcanics could have had the same asthenospheric or plume source. If they had the same source, this source must reside in the part of the mantle that is coupled to the Australian Plate, i.e. the lithospheric mantle.

It has been argued that the Jurassic low-Ti tholeiites of the Ferrar Province were derived from the subcontinental lithospheric mantle (Hergt *et al.*, 1991). If both the low-Ti tholeiites and the Freestone alkali basalts were derived from the lithospheric mantle, this could mean that there is a geochemical boundary in the lithospheric mantle in the area of Coleraine, western Victoria, where both low-Ti tholeiites and alkali basalts are found (Hergt *et al.*, 1991). An alternative option is that both areas contain this alkali-rich source, but that it is overwhelmed by the larger-degree low-Ti tholeiitic melts in the main part of the Ferrar area, and that the alkali-rich basalts are only seen at the periphery of the magmatic province.

The depth of melting of the alkali basalts can be estimated from the degree of silica saturation of their primary melts (O'Reilly and Zhang, 1995; Rogers *et al.*, 1995). The Si_8 (SiO_2 at 8% MgO) of the Freestone basalts is approximately 46.5%, and nearly all basalts are nepheline normative. This roughly corresponds to melting depths of 2.7 GPa (Rogers *et al.*, 1995), which falls within the garnet lherzolite field of the lithospheric mantle (McDonough *et al.*, 1990; Muirhead and Drummond, 1991). The Fe_8 of the basalts is quite high at 13, also indicative of high pressure melt generation (Turner and Hawkesworth, 1995). The Si_8 of the Ferrar low-Ti tholeiites, on the other hand, is 52%, corresponding to a depth of only 1 GPa, which would place the depth of melt generation near the crust-mantle boundary (McDonough *et al.*, 1990). It is, however, likely that the depth estimate for the low-Ti tholeiites is affected by the presence of water in the source (Hergt *et al.*, 1991; Turner and Hawkesworth, 1995), as water in the source will increase the Si_8 at a certain depth, so that 1 GPa is only a minimum pressure estimate. However, it appears that the different depths of melting may have caused some of the geochemical distinctions between the low-Ti tholeiites and alkali basalts. Unlike the situation in the Paraná, where the magma source region becomes shallower through time (Garland *et al.*, 1996), the low-Ti tholeiites and alkali basalts in western Victoria must have erupted at the same time, as the two magmas have been found interbedded in Coleraine (Hergt *et al.*, 1991).

The depleted mantle extraction ages for the Freestone and Coleraine alkali basalts are 680 to 940 Ma. As there is no unequivocal evidence for the presence of crust older than 600 Ma in southeast Australia (Coney, 1992), these ages appear to be slightly older than the crust in the area. It is therefore unlikely that the Nd isotopic signature, and by inference the trace element signature, was wholly generated from the depleted mantle by localised melting and storage for prolonged periods of time. So, even if the source for the alkali basalts was within the lithospheric mantle, it is likely that a component different from depleted mantle or partial melts thereof, was added to the lithospheric mantle. This could have come from a plume in an earlier stage of the lithosphere's history, or it could be the dehydrated residue of a subducting slab, which is one of the interpretations for the origin of the EM signature (Weaver, 1991). In this respect, the Jurassic alkali basalts are complementary to the low-Ti tholeiites of the area, which have been interpreted to represent a sedimentary addition to the subcontinental lithosphere, related to subduction prior to Jurassic times (Hergt *et al.*, 1991).

CONCLUSIONS

The Freestone basalts have the same trace element characteristics as the Jurassic alkali basalts from Coleraine. Their Nd isotopic composition is also the same, but the $^{87}Sr/^{86}Sr$ ratios of the Freestone basalts are higher than those of the Coleraine alkali basalts. This may reflect secondary processes.

The (isotope) geochemistry of the Freestone and Coleraine alkali basalts shows no resemblance to that of the basalts from the Antarctic-Australian Ferrar Province.

The trace element pattern (positive Nb anomaly, negative Pb anomaly) and Nd isotopic signature of the Freestone and Coleraine alkali basalts are similar to those of the EM1 component seen in some OIBs, and to the Cenozoic Newer Volcanics in western Victoria.

The Freestone and Coleraine alkali basalts could represent a plume component, but there is no independent evidence for a plume in the area in Jurassic times, such as a subsequent hot spot trace.

The similarity between the Jurassic and Cenozoic alkali basalts could mean that they have the same source, which should then be located in the subcontinental lithospheric mantle.

The location of this source in the lithospheric mantle agrees with the occurrence of apatite-bearing mantle xenoliths with REE and Nd isotopic signatures similar to that of the Freestone basalts.

The mantle extraction ages for the alkali basalts appear to be slightly older than the age of the crust in the area, indicating that, if the source for the alkali basalts resides within the lithospheric mantle, it is likely that extraneous material has been added to the lithospheric mantle. It is interesting to note that the interpretation of the EM1 signature (dehydrated residue of subducted crust) is complementary to that of the low-Ti tholeiites (sediment addition during subduction).

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