The origins of ultrapotassic rocks as inferred from Sr, Nd and Pb isotopes

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Abstract—Pb, Nd and Sr isotopic compositions are reported for ultrapotassic rocks from a variety of tectonic settings. Olivine leucitites located within the Palaeozoic Lachlan Fold Belt of southeastern Australia have a range in initial 87Sr/86Sr of from 0.7042 to 0.7056, 143Nd/144Nd values of +1.5 to −4.1 and 207Pb/204Pb of 15.55 to 15.60. These isotopic characteristics overlap with those of contemporaneous alkali basalts and suggest derivation of the leucitites from sources which have been variably contaminated by either the hotspot which initiated volcanism or during earlier enrichment events. Lamproites from the West Kimberley region of Western Australia and leucitites from Gausberg intrude stabilised Precambrian continental crust and have low 206Pb/204Pb (<17.60 and <17.60 respectively) and high 207Pb/206Pb (>15.60 and >15.65). Pb isotopic correlations displayed by the Western Australian lamproites are consistent with the mixing of an ancient (>2.1 byr old) high 207Pb/206Pb, low 206Pb/204Pb component with more typical mantle Pb. These ancient components probably evolved within the subcontinental lithosphere. Lamproites from southeastern Spain, which have geochemical features (e.g. negative Ti and Nb-anomalies) suggesting a subduction-related origin, possess isotopic compositions (87Sr/86Sr = 0.7173 to 0.7207, 206Pb/204Pb = 18.66 to 18.81, 207Pb/206Pb = 15.67 to 15.74 and 143Nd/144Nd = −11.2 to −12.6) and isotopic correlations consistent with contamination of their sources by a component resembling modern oceanic sediments. This component is isopetrically similar to that previously identified in the potassic rocks of Italy. A leucitite from a back-arc setting in the Sea of Japan has Pb isotopic composition similar to some ocean islands such as Kerguelen. The available isotopic data from this and other studies implicate enrichment processes frequently involving ancient, isotopically evolved components in the generation of continental potassic magmatism. These components are probably polygenetic with possible sources including subducted sediments, "megaliths" of recycled crust or the subcontinental lithosphere.

INTRODUCTION

A VARIETY of mechanisms have been proposed to explain the unusual and diverse chemistry of representatives of the ultrapotassic rock suite, yet no single mechanism has so far proved entirely satisfactory. Although many examples of ultrapotassic volcanism possess geochemical features consistent with a mantle origin, it is also apparent that the characteristic feature of ultrapotassic rocks, their high K/Na ratios, is unlikely to result from the direct partial melting of unmodified or 'primitive' mantle peridotite. Experimental work (e.g. ECGER, 1978; WENDLANDT, 1984; FOLEY et al., 1986) has demonstrated that melts of peridotite formed in the presence of CO2 at pressures ~27 kb would be carbonatitic, while the presence of H2O or F may enhance the stability of phlogopite. These studies suggest that small degrees of partial melting of phlogopoite-bearing peridotite at depths below the level of amphibole stability and in the presence of CO2 might produce a high K2O liquid with high Mg/Ca. The prerequisite modification (i.e. by the addition of volatiles) of the mantle sources of ultrapotassic rocks has commonly been attributed to metasomatic processes, often considered to be associated with either intraplate rifting or subduction (e.g. CUNDARI, 1979; EDGAR, 1980).

A number of recent studies of ultrapotassic rocks (VOLLMER and NORRY, 1983; MCCULLOCH et al., 1983; COLLERSON and MCCULLOCH, 1983; VOLLMER et al., 1984; FRASER et al., 1985) have found Sr and Nd isotopic compositions indicating long histories of high Rb/Sr and Nd/Sm. As the generally very high abundances of trace elements (including Sr, Nd and Pb) of ultrapotassic lavas make them insensitive to bulk crustal contamination processes, these isotopic signatures have been interpreted as indicating derivation from ancient incompatible element enriched mantle. For example, diamond-bearing lamproites from Western Australia have Sr and Nd isotopic compositions indicating enrichment in Rb/Sr and Nd/Sm for at least 8 byr (MCCULLOCH et al., 1983), yet their major and trace element geochemistry argues against substantial assimilation or anatectic of continental crust. Most occurrences of highly potassic volcanism with these unusual isotopic features are found in old continental regions, suggesting that enriched components may exist within some regions of subcontinental lithosphere. The discovery of isotopic compositions indicating ancient enrichment in sub-calcic garnet inclusions in diamonds from African kimberlites led RICHARDSON et al. (1984) to propose that a harzburgitic subcontinental lithosphere, stabilised to depths within the diamond stability field since the Archaean, is the source of diamonds and by implication, diamond-bearing kimberlites and lamproites themselves. The low velocity zone, defined by the attenuation of s-wave velocity and where the geothermal gradient approaches or intersects the melting curve, may contain small amounts of melt which are likely to be highly enriched in incompatible elements (e.g. GREEN, 1976). Cooling of the lithosphere may result in the incorporation of such incompatible element enriched material within
the base of the subcontinental lithosphere, allowing its long term storage and eventually producing isotopically evolved, “enriched” mantle.

Several authors (CHASE, 1981; HOFMANN and WHITE, 1982; RINGWOOD, 1982) have suggested that ancient mantle enrichments such as those identified by isotopic studies of some ocean island basalts may be the result of the recycling of oceanic crust and sediments into the mantle via subduction. Highly incompatible element enriched partial melts of the subducted “megolith” generated as it attains thermal equilibrium with the surrounding mantle are envisaged to rise as magma diapirs, contaminating the overlying mantle and producing the alkali basaltic volcanism of ocean islands (RINGWOOD, 1982). Such plumes could conceivably also be the sources of ultrapotassic magmas, providing an explanation for the radiogenic Sr and Pb and unradiogenic Nd isotopic signatures found in some ultrapotassic suites.

Apart from models invoking origins from mantle reservoirs enriched in incompatible elements, it is also apparent from isotopic studies that members of the ultrapotassic suite may be derived from primitive or even originally incompatible element depleted mantle. As ultrapotassic magmas are believed to originate from considerable depths (as evidenced by the presence of diamonds in lamproites from Western Australia), they provide a direct means of sampling the deep subcontinental lithosphere. The origins of enriched mantle components are of particular interest because of their implications for both the Earth’s trace element and isotopic budget and recent proposals of crustal recycling via subduction. In the following study, we present isotopic analyses of ultrapotassic rocks from a variety of tectonic settings in an attempt to investigate these models.

**SAMPLES**

Samples have been selected from a variety of tectonic settings, including both relatively young fold-belt terrains and stable cratons. The southeast Australian olivine leucitites occur as minor flow remnants along a north-south trending line extending from central New South Wales to Cosgrove in Victoria (Fig. 1). The geochemistry and mineralogy of the New South Wales occurrences have been described by CUNDARI (1973) and the Cosgrove occurrence by BIRCH (1978). The leucitites are located within the Lachlan Fold Belt, which consists of Palaeozoic geosynclinal sediments and granites and is possibly underlain by Lower Palaeozoic basement. Leucite outcrop distribution was noted by CUNDARI (1973) to conform to regional north–south structural trends, characterised by block-faulting and regional uplift. Potassic volcanism is temporally and spatially closely associated with alkali basalts, which several studies (e.g. WASS and ROGERS, 1980; O'REILLY and GRIFFITH, 1984) have shown to have been derived from metasomatised mantle. WELLMAN and MCDougall (1974) demonstrated a prominent southward temporal migration of Cainozoic igneous activity, a feature also displayed by the leucitites, and attributed it to the northward migration of the eastern part of the Australian continent over several hotspots. Sutherland (1983) proposed that the southerly migration of volcanism may have been caused by movement of the continent over former sites of sea-floor spreading.

A vitrophyric analcimite occurrence at Inglewood in south-

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**FIG. 1. Generalised geology of the Kimberley region (upper diagram), northwest Australia, showing localities of the Elendale (E), Calwynyardah (C) and Noonkanbah (N) fields, and the distribution of leucitite volcanism in southeast Australia (lower diagram) relative to Tertiary-Recent alkali basaltic volcanism. H—Harden analcimite (Early Jurassic age). Inset: BH—Beagoo Hill, BU—Burgooney, BY—Byagore, CO—Condobolin, FH—Flagstaff Hill, GH—Gorman Hill, LC—Lake Cargelligo, TL—Tullibigeal.**

eastern Queensland (see Fig. 1) was described by Wilkinson (1977), who considered the analcimite to be an alteration product of leucite. The analcimite is believed to be of Cainozoic age (probably Late Oligocene-Early Miocene) and is possibly related to the extensive Cainozoic alkali basaltic volcanism of southeastern Queensland.

The Harden olivine analcimite, located ≈200 km southeast of the New South Wales leucitite occurrences (see Fig. 1), is of Early Jurassic age (WELLMAN et al., 1970). Major and trace element analyses reported by CUNDARI (1973; analysis HAR II) suggest affinities with nepheline-bearing mid-Mesozoic intrusions and minor flows which occur throughout the southeastern highlands region of New South Wales.

The location, geochemistry and mineralogy of the ultrapotassic rocks from southeastern Spain is given in VENTURELLI et al. (1984). The tectonic evolution of the region is controversial, but most models invoke recent subduction processes. ARANA and VEGAS (1974) proposed that the increasing K content of calc-alkaline volcanism from south to north indicates that a northward-dipping subduction zone was active during the Lower Miocene. The ultrapotassic rocks were re-
garded as the most northerly and therefore deepest expression of arc volcanism resulting from the subduction of the African plate under the Iberian plate. A possible association between potassic volcanism and post-Nappe block faulting during the Miocene was suggested by Nixon et al. (1984).

Ulung-do (Utsuryoto) Island is located in the western part of the Sea of Japan, 130 km off the eastern coast of Korea. Petrological studies by Tsunou (1970) recognised several stages of volcanism, commencing with predominantly basaltic volcanism followed by trachytic and phonolitic flows and pyroclastics. Leucite-bearing lavas were described from an intra-caldera dome at Arpung Hill, and were interpreted by Tsunou (1920) to be the products of the final stage of volcanism on the island.

The early Miocene Western Australian lamproites consist of some 100 bodies intruding the Precambrian to Mesozoic rocks of the King Leopold Mobile Zone, the Lennard Shelf and the Fitzroy Trough, immediately south of the South western margin of the Precambrian Kimberley Block (Atkinson et al., 1984, see Fig. 1). Many of the intrusions are localised along deep west northwest-trending tensional faults and fractures with long histories of activity. Details of the geochemistry and mineralogy of the lamproites can be found in Jaques et al. (1984a). The samples analysed for Pb isotopic composition in this study are the same as those analysed by McCulloch et al. (1983) for Nd and Sr isotopic composition.

Gaussberg is an isolated volcano located on the eastern margin of the Antarctic continent. Gaussberg leucitites are characterised by extreme K$_2$O (up to 12 wt%) and incompatible element contents, high TiO$_2$ (averaging 3.4 wt%) and Mg/ (Mg + Fe) values = 0.70 (Sheraton and Cundari, 1983). Attempts have been made to relate Gaussberg volcanism to hotspot activity (Duncan, 1981) but, as emphasised by Sheraton and Cundari (1980), there is no evidence relating the volcanism to any other area of Caiozoic volcanic activity. Isotopic analyses of granitic crustal xenoliths indicate their derivation from early Proterozoic or late Archean crust (Collerson and McCulloch, 1983), suggesting that Gaussberg is sited on stable continental basement.

The trace element geochemistry of the suites investigated in this study is summarised and compared to average kimberlite values in Fig. 2. Complete trace element data are not available for the southeast Australian suite or Ulung-do Island leucitites. The available data indicate that New South Wales leucitites have overall abundances of the highly incompatible elements Pb, Rb and Ba (average 90, 230 and 260 times primitive mantle values, respectively) intermediate between average kimberlite values and those of Spanish and Western Australian lamproites and Gaussberg leucitites. Noteworthy is the remarkable similarity in the trace element characteristics of leucitites from Gaussberg and those of the Western Australian lamproites. Isotopic studies of Gaussberg (Collerson and McCulloch, 1983) and of the Western Australian lamproites (McCulloch et al., 1983) indicates that the suites also have similar Nd and Sr isotopic character. The patterns display extremely high abundances of all trace elements with pronounced positive barium spikes. The patterns of the Spanish lamproites are characterised by similar overall abundances but with negative anomalies of niobium and titanium—features commonly observed in island arc lavas. Nixon et al. (1984) contrasted the chemistry of the Western Australian and Spanish lamproites, noting the higher K$_2$O/Al$_2$O$_3$, $\text{K}_2\text{O}$ and incompatible elements Ba, Sr, and Nb of the Western Australian lavas. The Spanish lavas also have lower abundances of the LREE, negative Eu anomalies and higher abundances of the HREE, leading Nixon et al. (1984) to propose that they were derived from shallower depths than the Western Australian suite.

**ANALYTICAL PROCEDURE**

Approximately 500 mg of sample chips or powder was dissolved using hydrofluoric and perchloric acids in teflon bombs at 200°C for at least 48 hours. The resulting solution was

![Fig. 2. Averaged trace element abundances in lamproites from Western Australia and SE Spain and leucitites from Gaussberg, normalised to estimated primitive mantle abundances (shown in ppm). Normalised trace element abundances in "average" kimberlite shown for comparison. Data sources: Spanish lamproites, Vestre Nissum (1984), Nixon et al. (1984), this study; Western Australian lamproites, Jaques et al. (1984a), McCulloch et al. (1983), this study; Gaussberg leucitites, Sheraton and Cundari (1980), Collerson and McCulloch (1983); "average" kimberlite, Wedepohl and Muramatsu (1979).](attachment:image.png)
converted to chloride form using hydrochloric acid and split into 3 aliquots, one of which was spiked with both mixed $^{138}$Rh, $^{146}$Sm and $^{150}$Nd spikes, the second with $^{234}$U-$^{208}$Pb spike and the third aliquot used for Pb isotopic composition. The remaining procedure for Pb-Sr and Sm-Nd analysis follows that of MCCULLOCH and CHAPPELL (1982). Mineral separates were leached in 6 N HCl for 10 minutes to remove surface contamination. Pb was isolated from the spiked and unspiked aliquots by 2 passes through 2 gm Dowex-1 anion exchange columns using HBr-HCl for the first pass and HCl only for the second pass. About one microgram of Pb was then loaded onto an outgassed single rhenium filament and analysed using the silica-gel/phosphoric acid technique. A correction factor, determined by comparison of multiple analyses of NBS-982 with the corrected values of CATANZARO et al. (1968), was applied to the raw measurements to correct for mass fractionation. The correction factor averaged 0.15% $\mu g^{-1}$. The total processing blank was $<$10 for those-rock samples and $=$3 ng for mineral separates and is insignificant for samples analysed. As analytical precision for each run was typically better than $\pm$0.008 ($2\sigma$, total) for $^{208}$Pb/$^{208}$Pb, the main source of analytical error is due to variable mass fractionation. In order to obtain a meaningful estimate of the total error, 30 of the 40 Pb analyses listed in Table 2 were performed in duplicate. For duplicated analyses, quoted ratios refer to means of both analyses. Two way analysis of variance indicates that duplicate analyses of samples agree within the following errors at the 1σ level, $^{208}$Pb/$^{208}$Pb error $\pm$0.011, $^{206}$Pb/$^{206}$Pb error $\pm$0.014, $^{207}$Pb/$^{207}$Pb error $\pm$0.033. The values obtained for NBS-981 common Pb standard during this study (average of 7 analyses, error $2\sigma$, total) are $^{208}$Pb/$^{208}$Pb = 0.1735 $\pm$0.0007, $^{206}$Pb/$^{206}$Pb = 0.1546 $\pm$0.013, $^{207}$Pb/$^{207}$Pb = 0.27668 $\pm$0.0044.

RESULTS

SE Australian leucites

The results of Rh/Sr, Sm/Nd and U/Pb concentration and isotopic analysis are presented in Tables 1 and 2 and compared with other relevant data in Figs. 3, 4 and 5. K/Ar dating of the suite gave ages ranging from 10–16 m.y. for the New South Wales representatives and 6 m.y. for the Cosgrove occurrence (WELLMAN et al. 1970; WELLMAN, 1974; SULLIVAN, 1983). Where necessary, quoted ages have been re-calculated using the constants of STEGER and JAGER, 1971. The correction for radiogenic decay since emplacement is within or just outside analytical uncertainty for Sr and Nd isotopic systems. Ages for the Pb isotope analyses of Nd/Sr range from 5.4 to 7.1 (chronometric $\approx$3), indicating that the leucites are highly LREE-enriched. Nd and Sr isotopic compositions lie within the mantle array (Fig. 3), extending from the "depleted" quadrant for the most southerly New South Wales occurrence at El Capitan (Nd = -4.1, $^{143}$Nd/$^{144}$Nd = 0.7057). As thorium concentrations were not determined for the southeast Australian rocks, the small age corrections to $^{208}$Pb/$^{208}$Pb were made assuming Th/U = 4. The Condobolin leucite (CIA-3476) has high U/Pb and the age correction to $^{208}$Pb/$^{208}$Pb and $^{206}$Pb/$^{206}$Pb is significant compared to the analytical error. Age-corrected Pb isotope compositions show little variation, with the exception of the Cosgrove sample which has significantly lower $^{207}$Pb/$^{206}$Pb than the other members of the suite, and El Capitan which has slightly lower $^{207}$Pb/$^{206}$Pb. The Pb isotopic compositions of the New South Wales leucites are characterised by relatively high $^{206}$Pb/$^{206}$Pb and $^{207}$Pb/$^{207}$Pb compared to those of MORB but are similar to those determined by COOPER and GREEN (1969) for contemporaneous Tertiary-Recent continental alkali basalts from western Victoria.

The Cosgrove leucite is chemically and petrographically distinct from the New South Wales leucites, being poorer in olivine and plagioclase and richer in clinopyroxene (BIRCH, 1978), reflected in its lower Ms, K, Rh, Ni, and higher in Ca, Fe, Na, and possibly Ti contents and lower LREE/HREE. These features imply derivation of the Cosgrove leucite from a more depleted source than the New South Wales leucites, consistent with the isotopic data (i.e. the lower $^{206}$Pb/$^{206}$Pb and $^{207}$Pb/$^{207}$Pb and higher $^{143}$Nd/$^{144}$Nd of the Cosgrove leucite). The Cosgrove leucite has Pb, Sr and Nd isotopic compositions within the range determined for the southeast Australian Tertiary.

\begin{table}[h]
\centering
\caption{Strontium and Neodymium Isotopic Data}
\begin{tabular}{lcccccccc}
\hline
Sample & Nb & Sr & Sm & Nd & $^{87}$Sr/$^{86}$Sr & $^{143}$Nd/$^{144}$Nd & $^{147}$Sm/$^{144}$Nd & $^{183}$W/Pb & \hline
NEW SOUTH WALES & & & & & & & & \\
GA-3970 & Beagalo Hill & 719 & 2065 & 14.5 & 89.9 & 0.250 & 0.705624 & 0.70507 & 0.0959 & 0.15182z & -0.3 & \\
GA-3971 & Beagalo Hill & 781 & 1351 & 14.1 & 88.2 & 0.185 & 0.705141 & 0.70519 & 0.0953 & 0.15186z & -0.7 & \\
GA-3972 & Beagalo Hill & 159 & 1779 & 24.6 & 150.0 & 0.258 & 0.705236 & 0.70519 & 0.0928 & 0.15177z & -1.3 & \\
GA-3973 & Beagalo Hill & 128 & 1577 & 20.0 & 124.9 & 0.234 & 0.705251 & 0.70518 & 0.0973 & 0.15181z & -0.6 & \\
GA-3974 & Gomar Hills & 147 & 1136 & 20.7 & 191.5 & 0.305 & 0.705024 & 0.70486 & 0.0921 & 0.15181z & -0.4 & \\
GA-3975 & Kulnibegal & 173 & 1353 & 18.9 & 119.1 & 0.159 & 0.705945 & 0.70546 & 0.0952 & 0.15178z & -1.1 & \\
GA-3976 & Condobolin & 135 & 1494 & 14.9 & 93.0 & 0.260 & 0.705606 & 0.70501 & 0.0957 & 0.15185z & +0.3 & \\
GA-3977 & L. Cowper & 173 & 1670 & 17.3 & 107.1 & 0.210 & 0.706201 & 0.70620 & 0.0973 & 0.15161a & 0.2 & \\
GA-3980 & Bungaroo & 135 & 1424 & 14.6 & 86.5 & 0.229 & 0.705124 & 0.70508 & 0.0998 & 0.15184z & +0.1 & \\
GA-3981 & Flapstaff & 145 & 1265 & 15.1 & 92.7 & 0.423 & 0.705522 & 0.70515 & 0.0986 & 0.15177a & -1.2 & \\
GA-3979 & El Capitan & 265 & 974 & 17.3 & 106.3 & 0.596 & 0.705712 & 0.70541 & 0.0851 & 0.15163z & -8.1 & \\
VICTORIA & & & & & & & & \\
ET1900 & & & & & & & & \\
KE1900 & & & & & & & & \\
QUEENSLAND & & & & & & & & \\
NB-321 & Inglewood & 56.1 & 1492 & 15.9 & 90.9 & 0.109 & 0.705185 & 0.70515 & 0.1057 & 0.15172z & -1.5 & \\
\hline
\end{tabular}
\end{table}

1 All errors quoted refer to within run precision at the 2σ level. Uncertainty in $^{143}$Nd/$^{144}$Nd is 0.25% (1σ) in $^{147}$Sm/$^{144}$Nd, 0.1% (2σ).
2 Initial Sr calculated using the (re-calculated) K/Ar ages of WELLMAN et al. (1970), WELLMAN (1974) and SULLIVAN (1983) for New South Wales samples and of 22 m.y. for the Ilimaussaq suite. Age correction to Nd isotopic compositions is within analytical error for all samples except Harden (see text).
3 Nd isotopic ratios calculated using $^{143}$Nd/$^{144}$Nd = 0.5118352 at 1%. The value obtained for MORB standard is 0.7020014, K & R standard carbonate value is 0.7080253.
Origin of ultrapotassic rocks

Recent Newer alkali basalts (COOPER and GREEN, 1969; MCDONOUGH et al., 1985).

Although the exact age of emplacement of the Ingledew anacitite is not known, an age of 22 m.y. has been assumed, based on 40Ar/39Ar studies of nearby volcanism with which the Ingledew leucite is associated (WELLMAN and MCDONOUGH, 1974). Despite the uncertainty in the exact age of volcanism, the age corrections to the measured Nd, Sr and Pb isotopic ratios are within or close to the analytical error. Initial Sr and Nd isotopic ratios overlap with those of the New South Wales olivine leucitites, but the anacitite has slightly higher initial \(^{207} \text{Pb}/^{206} \text{Pb}\) and substantially higher initial \(^{208} \text{Pb}/^{206} \text{Pb}\). The combined data therefore indicate that the Ingledew anacitite and the New South Wales suite were derived from isotopically similar sources, but with the Ingledew anacitite source having higher recent \(U/Pb\).

After correction for an age of 22 m.y. (WELLMAN et al., 1970, as 180 ± 3 m.y.) Nd and Sr isotopic data indicate that the Harden anacitite was derived from a depleted source with \(e_{Nd} = -2.4\) and \(e_{Sr} = 0.63\) (1). 0.7042. Uranium and thorium abundances have not been determined so it is not possible to correct precisely for their radioactive decay since emplacement. Assuming reasonable values of \(^{238} \text{U}/^{206} \text{Pb}\) of 20 and Th/U of 4 results in age-corrected \(^{207} \text{Pb}/^{206} \text{Pb}\) of 18.45, \(^{207} \text{Pb}/^{206} \text{Pb}\) of 15.55 and \(^{208} \text{Pb}/^{206} \text{Pb}\) of 37.65. Although \(^{207} \text{Pb}/^{206} \text{Pb}\) and \(^{208} \text{Pb}/^{206} \text{Pb}\) estimated in this way is subject to considerable uncertainty, the correction to \(^{207} \text{Pb}/^{206} \text{Pb}\) is small (−0.03). The Pb isotopic data therefore indicate that the source of the Harden anacitite had \(^{207} \text{Pb}/^{206} \text{Pb}\) lower than that of the New South Wales olivine leucite suite but not comparable to that of the Cosgrove olivine leucite.

Spanish lamproites

Whole-rock and mineral K/Ar data on several of the Spanish ultrapotassic rocks indicates ages of \(\sim 6-8\) m.y. (BELLON and LETOUZEY, 1977; NOBEL et al., 1981). The high Rb/Sr ratios require small but significant age corrections to be applied to the Sr isotopic data. Initial Sr isotopic compositions show a wide range and are highly radiogenic (61/41-42.70), similar to the values reported by BELLON and LETOUZEY (1977) for samples from Ingledew. Nd/Sm is variable from 10.2 to 14.3, suggesting mod-
erate LREE-enrichment. Nd isotopic compositions are un-
radiogenic and fall within the narrow range of εNd of from
−11.2 to −12.6, indicating that the sources of these rocks
have had long-term LREE-enrichment (>1 byrs). These iso-
topic features are like those of the Western Australian lam-
proites (McCulloch et al. 1983) and the micaceous South
African kimberlites (Smith, 1983; see Fig. 3). The measured
Pb isotopic compositions are within the range 208Pb/204Pb of
18.66 to 18.81, 207Pb/204Pb of 15.67 to 15.74 and 208Pb/206Pb
of 39.0 to 39.2. Of present-day reservoirs, the Pb isotopic
compositions of the Spanish ultrapotassic rocks most closely
resemble that of pelagic oceanic sediments (e.g. Sun, 1980).

Ullung-do Island leucitite

The Ullung-do Island leucitite has 206Pb/204Pb within the
range observed for MORB (Fig. 4), but has slightly higher
208Pb/204Pb and significantly higher 205Pb/204Pb than is found
in MORB, plotting within the Kerguelen field. The high 206Pb/
204Pb suggests a mantle source resembling that of ocean islands
rather than that of MORB. Several other Pb isotopic studies of
alkali basalts from the southwestern Japan region (Ku-
kasawa, 1968; Tatsumuji and Kusuh, 1969; Allégre et al., 1979)
have found Pb isotopic compositions comparable to some ocean islands. The relatively unradiogenic 208Pb/206Pb of
the leucitite implies that its source was not substantially
contaminated by Pb derived from subducted sediments.

Western Australian lamproites

The correction for radiogenic decay since emplacement of
the Fitzroy lamproites during the Early Miocene (Wellman,
1973; Jacque et al., 1984b) is small for 207Pb/204Pb (t = −0.04
for the highest U/Pb sample analysed, WAK-6L) and insig-
ificant for the other Pb isotope ratios. The lamproites have
relatively low 206Pb/204Pb of from 17.24 to 17.88, extremely
high and variable 208Pb/204Pb values ranging from 15.69 to
15.80 and 208Pb/204Pb of 37.80 to 38.59. Acid-washed chlo-
opyroxene separated from the 'P Hill lamproite intrusion
(WAK-13L) has Pb isotopic composition within the range
displayed by the Western Australian lamproite suite. In ad-
dition, acid-washed phlogopite separated from the Mt. Percy
lamproite (WAK-10L) has Pb isotopic composition within
analytical error of the host lava. These mineral isotopic data
indicate that the unusual Pb isotopic compositions of the
Western Australian lamproites represent magmatic compos-
itions and are unlikely to have been significantly affected by
post-emplacement alteration. A distinctive feature of the Pb
compositions is their unusual position to the left of the zero
age geochron (Fig. 4).

Gaussberg leucitites

Fission track data and geomorphological studies suggest
that Gaussberg volcanism is of Late Pleistocene-Recent age
(Sheraton and Cundari, 1980) so corrections to the Pb
isotopic data for age of emplacement are unnecessary. Leu-
citites from Gaussberg have similar Pb isotopic signatures to
those displayed by the Western Australian lamproites but
with slightly lower 206Pb/204Pb (Fig. 4). Nd and Sr isotopic
characteristics (Collerson and McCulloch, 1985) of Gaussberg
leucitites are also similar to those of the Western
Australian suite except for the slightly lower 87Sr/86Sr (0.7097,
compared to 0.710-0.720; McCulloch et al., 1983). A crustal
 xenolith (82-24) has Pb isotopic composition distinct from
the host leucite, with significantly higher 206Pb/204Pb. The
very high 208Pb/235U of the xenolith indicates that it is unlikely
that the Pb isotopic compositions of the leucitites have been
substantially modified by assimilation of crustal material like
that of the xenolith.
Origin of ultrapotassic rocks

DISCUSSION

S.E. Australian leucitites

Although the evolved isotopic characteristics of the New South Wales leucitites may be attributed to contamination by continental crust, there is no compelling evidence for the assimilation of crustal material in the major and trace element characteristics of the lavas. The suite has high Ni (average \( \approx 375 \) ppm), Cr (\( \approx 400 \) ppm), MgO (12.4 wt%), Mg/(Mg + Fe\(^{2+}\)) (excluding some of the fractionated Begargo Hill samples, averaging \( \approx 0.71 \) recalculated assuming Fe\(^{3+}\)/Fe\(^{2+}\) + Fe\(^{3+}\) = 0.15), combined with low SiO\(_2\) (44.3 wt%) and Al\(_2\)O\(_3\) (8.7 wt%) (Cundari, 1973), consistent with their derivation from the mantle. In addition, while the El Capitan leucitite (GA-3479) has the most radiogenic Sr and least radiogenic Nd and is therefore the most likely candidate to have been contaminated by continental crust, there is no evidence of this in its major and trace element chemistry. Taylor et al. (1984) analysed the same samples used in this study for \(^{18}\)O/\(^{16}\)O, and found that the whole-rock and leucite phases are enriched in \(^{18}\)O but that the clinopyroxenes have \( \delta^{18}\)O of \( \approx +6.5 \), considered to represent primary magmatic values. They attributed the high \(^{18}\)O of the leucites to interaction with late-stage K-rich magmatic fluids with high \( \delta^{18}\)O (\( \approx +8 \)), although they did not discount the possibility of the involvement of small amounts of meteoric water which had isotopically equilibrated with magmatic fluid. The primary \( \delta^{18}\)O values estimated from the clinopyroxenes are similar to the values of alkali basalts and argue against the assimilation of upper crustal material. It is unlikely that the possible involvement of small amounts of meteoric water could have significantly affected the Sr, Nd and Pb isotopic compositions. The variation in isotopic characteristics of the New...
South Wales leucitites may therefore be the result of either: a) contamination of their sources by a component having radiogenic \(^{87}\text{Sr}/^{86}\text{Sr}\), unradiogenic \(\epsilon_{\text{Nd}}\) and \(^{207}\text{Pb}/^{204}\text{Pb} \geq 15.6\); or b) derivation from variably enriched mantle sources which have evolved the observed isotopic compositions since the enrichment events. The latter alternative is considered less likely as a period of at least \(~300\) myrs is required to produce the observed range in Nd isotopic compositions of 4 \(\epsilon\) units from closed system decay within source regions which have undergone varying degrees of incompatible element enrichment (i.e. increase in Nd/Sm and Rb/Sr accompanied by a decrease in U/Pb), assuming a source Sm/Nd like that of the leucitites themselves. As the source Sm/Nd is likely to be considerably higher than that of the leucite melt, this time estimate is probably greatly underestimated. The El Capitan leucite has the highest measured Rb/Sr and Nd/Sm ratios and significantly more radiogenic Sr and less radiogenic Nd compared to the other New South Wales leucitites, consistent with greater contribution of an incompatible element enriched, high \(^{87}\text{Sr}/^{86}\text{Sr}\), low \(\epsilon_{\text{Nd}}\) component to its source, but also has identical \(^{207}\text{Pb}/^{204}\text{Pb}\) to the other New South Wales leucite occurrences. This suggests that either the Pb isotopic compositions of the leucitites are dominated by that of the added component, or that the added component and the invaded mantle had similar \(^{207}\text{Pb}/^{204}\text{Pb}\). The less radiogenic \(^{207}\text{Pb}/^{204}\text{Pb}\) of the El Capitan leucite compared to the other New South Wales occurrences may be due to some variation in the timing or degree of enrichment in the leucite sources, or may indicate differences in the \(^{206}\text{Pb}/^{204}\text{Pb}\) of the added components involved at El Capitan and the other occurrences.

The geochemical and isotopic data are therefore consistent with the derivation of the New South Wales leucitites from mantle which has been contaminated by a component with \(^{87}\text{Sr}/^{86}\text{Sr} \approx 0.7057\), \(\epsilon_{\text{Nd}} = -4\) and...
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{207\text{Pb}}/{204\text{Pb}} \approx 15.6. \text{ Compared to the Tertiary-Recent Victorian Newer alkali basalts (McDonough et al., 1985), the Cosgrove leucite has similar Sr, Nd and Pb isotopic compositions whereas the New South Wales leucitites have higher }^{87}\text{Sr}^{86}\text{Sr} \text{ and lower }^{143}\text{Nd}^{144}\text{Nd}, \text{ forming an extension of the array displayed by the Newer basalts into the enriched quadrant on the }{208\text{Pb}}/{204\text{Pb}}-{^{87}\text{Sr}}^{86}\text{Sr} \text{ diagram. The New South Wales leucitites have similar }{207\text{Pb}}/{204\text{Pb}} \text{ and }{208\text{Pb}}/{204\text{Pb}} \text{ but have lower }{206\text{Pb}}/{204\text{Pb}} \text{ than the Newer basalts (Cooper and Green, 1969; Fig. 4). Although these features may simply reflect regional isotopic heterogeneity within the subcontinental lithosphere beneath southeastern Australia, they may also be interpreted as mixing trends, with the addition of a component having isotopic characteristics like those of the New South Wales leucitites to the sources of the Newer basalts responsible for their isotopic variation. Wellman and McDougall (1974) and Sutherland (1983) showed that the locations and eruption ages of the southeast Australian leucitites and Newer basalts are consistent with the initiation of volcanism by the passage of the Australian continent over a hotspot. As the isotope variation found in the Newer basalts was attributed by McDonough et al. (1985) to mixing between a component derived from the hotspot plume component and the subcontinental lithosphere, it is conceivable that the hotspot plume represents the enriched, low }{206\text{Pb}}/{204\text{Pb}} \text{ end-member component. Further Pb isotope analyses of the Newer basalts are required in order to assess this possibility.}
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A number of studies of Cainozoic alkali basaltic volcanism and incorporated xenoliths from the eastern margin of New South Wales (e.g. Kesson, 1975; Wass and Rogers, 1980; O'Reilly and Griffin, 1984) have argued that the mantle from which the products of volcanism were derived was chemically and isotopically heterogeneous. The widespread occurrence of amphibole ± mica ± apatite-bearing mantle xenoliths has been interpreted as evidence for the operation of metasomatic processes in the source regions of the host lavas. O'Reilly and Griffin (1984) found a range of Sr isotope compositions of from 0.7031 to 0.7054 for New South Wales alkali basalts, and attributed the isotope variation to the metasomatic addition of varying amounts of radiogenic Sr to their sources. Much of the New South Wales alkali basaltic volcanism considered by O'Reilly and Griffin (1984) and others to be derived from metasomatised subcontinental lithosphere predates, and is therefore unrelated to, the passage of the hotspot responsible for the leucite volcanism. Although leucite volcanism was probably activated by the hotspot, metasomatism of the leucite sources may have been related to that of the sources of the New South Wales alkali basalts and may have occurred prior to the passage of the hotspot.

**Spanish lamproites**

The large range in 
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{207\text{Pb}}/{204\text{Pb}} \text{ displayed by the Spanish lamproites is notable, especially as it is accompanied by a relatively limited range in }{206\text{Pb}}/{204\text{Pb}} \text{ (Fig. 4). Such a correlation is unlikely to have resulted directly from closed system decay of uranium, as the range in }{207\text{Pb}}/{204\text{Pb}} \text{ requires the existence of long term variation in }U/{\text{Pb}}, \text{ which would result in large variation in }{206\text{Pb}}/{204\text{Pb}}. \text{ The correlation is most readily explained by the mixing of highly radiogenic Pb with that of a source with low }{207\text{Pb}}/{204\text{Pb}}, \text{ such as the depleted mantle source of MORB. An origin of the Spanish suite involving mixing is consistent with trace element relations (Venturelli et al., 1984).}
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Comparison between Pb and Sr isotopes of ultrapotassic rocks from this and other studies are displayed in Fig. 6. Lavas from Spain and Western Australia resemble those from the Virungan volcanic field described by Vollmer and Norry (1983) in possessing large ranges in Sr isotopic compositions but limited variation in Pb compositions, particularly 
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{206\text{Pb}}/{204\text{Pb}}, \text{ and very high }{208\text{Pb}}/{204\text{Pb}}. \text{ An interesting aspect of the Spanish lamproite isotopic data is that it lies on an extension of the Sr-Pb isotopic correlations displayed by ultrapotassic rocks from Italy (Fig. 6). The Pb isotopic compositions of the Spanish lavas are identical to those of the Vico-Vulsini-Sabatini region, which has among the most radiogenic Sr and un radiogenic Nd of the Italian lavas (i.e. most like the Spanish lamproites). This may indicate that the metasomatic component invoked to explain the isotopic correlations of lavas from the southern region of Italy (Hawkesworth and Vollmer, 1979) is similar to that identified in the Spanish lamproites. This component has the Sr, Nd and Pb isotopic characteristics of continental crust or sediments derived from continental crust.}

**Ullung-do Island leucitite**

Nakamura et al. (1985) found that the island arc character, indicated by enrichment in K, Ba, Sr and Rb and depletion of Ta and Ti, of alkali basalts across the Japanese island arc to Korea and Eastern China becomes progressively weaker, and that the trace element patterns of islands from the Sea of Japan show no evidence of the influence of subduction processes. The relatively un radiogenic Pb isotopic composition of the Ullung-do Island leucitite limits the possible involvement of subducted oceanic crust and sediments as a source of their high potassium, as has been proposed to explain the well-documented relationship between potassium and depth to Benioff zone evident in some island arcs (c.f. Dickinson and Hattori, 1967). Geochemical and isotopic studies of lavas from the west Sunda arc, Indonesia, (Whitford, 1975; Whitford et al., 1981) demonstrated that although tholeiitic and calc-alkaline lavas display evidence of contamination by a component derived from subducted lithosphere, the leucite-bearing lavas of Mt. Muriah, situated \( \approx 300 \text{ km above the Benioff zone, manifest least evidence of such contamination. However, leucite-normative lavas from the east Sunda arc region have radiogenic Sr compared to calc-alkaline lavas from the same region (Whitford et al., 1978),}
suggesting that they may have been more strongly contaminated by a component derived from the subducted slab. It is therefore evident that the direct chemical influence of the subducted lithosphere on leucite-bearing lavas located in or near subduction zones, such as those of Ullung-do Island and the west and east Sunda arcs, varies considerably.

In contrast with most continental potassic volcanism, leucitites from island arcs frequently have low TiO₂, Nb and Zr, characteristics in common with arc volcanism. Although the source of the potassium in high-K island arc volcanism is controversial, a number of studies (e.g. Nicholls and Whitford, 1978; Foden and Varne, 1980) favour the derivation of high-K arc lavas from mantle which has been modified by the addition of a LIL-rich component to their source regions. It seems likely that melts or fluids derived from the subducted slab are involved, but that in some cases these may not be isotopically distinguishable from the invaded mantle. Lloyd and Barry (1975) attributed the scarcity of highly potassic volcanism in oceanic settings to the effects of generally steeper geotherms in ocean basins compared to the continental geotherm, reducing the depths to which phlogopite persists without amphibole also being stable.

Western Australian lamproites and Gaussberg leucitites

The distinctive Pb isotopic signature of the Western Australian lamproites and Gaussberg leucitites is indicative of an extremely ancient component which had high U/Pb early in its history, followed by a lowering of U/Pb more recently, relative to the observed array displayed by oceanic islands and MORB. This is in contrast to the sources of most MORB and many ocean islands, which have undergone (either progressively or episodically) an increase in their U/Pb ratios. As with the Spanish suite, the Western Australian lamproites display little variation in 206Pb/204Pb for the correspondingly large variation in 207Pb/204Pb. McCulloch et al. (1983) modelled the correlation between Nd and Sr isotopes displayed by the Western Australian lamproites by mixing of enriched and depleted components. This is consistent with the Pb isotopic variation, which is most readily explained by mixing. However, rather than trending towards the present-day MORB field on the 206Pb/204Pb-207Pb/204Pb diagram (Fig. 4) as in the case of the Spanish lamproites, the Western Australian lamproite array (excluding WAK-16L) appears to extend to more primitive 206Pb/204Pb values. The array may result from the mixing, at some time in the past, of a high 207Pb/204Pb component with a MORB component (i.e., when the MORB reservoir had 207Pb/204Pb = 15.5 like the present-day value but 206Pb/204Pb less than ~17.00). A primitive or (more probably) depleted mantle component which dominates the major elements can account for the high MgO, Ni, Cr and low Al, Ca and Na contents, while a “metasomatic” component enriched in incompatible elements and which dominates the isotopic characteristics can account for the trace element contents (Jaques et al., 1984a). If produced at depth, the metasomatic component may pass through isotopically different regions of the mantle and subcontinental lithosphere, resulting in the observed isotopic correlations.
Origins of the high $^{207}\text{Pb}/^{204}\text{Pb}$, low $^{206}\text{Pb}/^{204}\text{Pb}$ component

That ultrapotassic rocks from Gaussberg and Western Australia possess similar unusual isotopic compositions is strong evidence for their generation by a common process. Although their Sr, Nd and $^{207}\text{Pb}/^{206}\text{Pb}$ isotopic characteristics are more like those of the upper continental crust, many aspects of their major and trace element characteristics, such as their high Mg/(Mg + Fe) and Ni and Cr contents, and in the case of the Western Australian lamproites, the presence of mantle xenocrysts and diamonds, are more consistent with a mantle origin. In the following modelling of the isotope data, some general inferences about the long term histories of the sources of the Western Australian lavas are made.

The unusual Pb isotopic compositions of the Western Australian and Gaussberg leucitites require an evolution involving at least two stages. A general model of the evolution of their Pb is shown in Fig. 7. Modelling of the high $^{207}\text{Pb}/^{206}\text{Pb}$, low $^{206}\text{Pb}/^{204}\text{Pb}$ component recognised in the Western Australian lamproites allows the ranges of possible values of $\mu_1$ and $\mu_2$ and minimum age for $t_1$, the time of differentiation of the component from the mantle, to be determined. Figure 7 shows, for selected values of $t_1$, the range of possible values for $\mu_1$ and $\mu_2$ plotted against $t_2$, the time at which the U/Pb ratio was lowered. The modelling uses the Pb composition of the Western Australian lamproite having the highest $^{207}\text{Pb}/^{206}\text{Pb}$ and relatively low $^{206}\text{Pb}/^{204}\text{Pb}$ (WAK-27L), regarded as the least contaminated by Pb from other sources. In the case of an evolution involving two stages (where $t_1 = t_0$), the range of possible values for $\mu_1$ and $\mu_2$ is given by the $t_1 = 4.5$ byr curves. For decreasing values of $t_2$, $\mu_1$ approaches 8.6 while $\mu_2$ approaches zero, until at $t_2 \approx 0.5$ byr, $\mu_2$ becomes negative and it is not possible to generate the measured Pb composition of WAK-27L. Because a two stage model requires the existence of an extremely ancient, moderately high U/Pb reservoir, perhaps the only instance where a two stage model could be applied is when the first stage reservoir is known to be very ancient sialic crust.

A more general and geologically plausible three stage model differs from the two stage case in having an earlier period prior to the high U/Pb stage during which the Pb evolves in the “normal” mantle reservoir with $\mu_0 \approx 8.0$. It can be seen from Fig. 7 that younger values of $t_1$ require higher $\mu_1$ and lower $\mu_2$, until at $t_1 \approx 2.1$ byrs $\mu_2 < 0$ and it becomes impossible to produce the Pb isotopic composition of WAK-27L. A first stage $\mu_0 = 8.0$ has been used, based on ore Pb isotope data from Archean greenstone belts (Tilton, 1983; Rod-
dick, 1984; Dupré et al., 1984; Brevart et al., 1986) although the three stage modelling is not particularly sensitive to the value of $\mu_0$. For example, all solutions are possible for $t_1 < 2.1$ byrs using the Cumming and Richards (1975) Model 3 growth curve based on conformable ores, which is considered to provide a reasonable upper limit of the value of time integrated $\mu_0$ evolution for the mantle (as ores are likely to contain some Pb derived from the crust), while using values of $\mu_0 < 8.0$ will tend to increase the minimum allowable values of $t_1$.

The three stage modelling establishes that the Pb component identified in the Western Australian lamproites cannot have differentiated from primitive mantle at times less than 2.1 byrs ago. From Fig. 7 it is apparent that for older values of $t_1$, lower and more geo logically reasonable values of $\mu_1$ are possible. Younger values of $t_1$ require higher values for $\mu_1$ or longer periods between the events $t_1$ and $t_2$.

Additional information about the source history of the Western Australian lamproites is provided by their Nd isotopic systematics. For example, Zindler et al. (1984) estimated that during low degrees of modal melting (≈ 1%) of a garnet lherzolite source, the Sm/Nd ratio of the melt will be at least one half that of the source. The measured Sm/Nd values of the Western Australian lamproites are relatively constant at ≈ 0.11 (McCulloch et al., 1983), implying a source Sm/Nd of at least 0.22. A minimum period of 2.1 byrs is re-
quired for a source with Sm/Nd ratio equal to or greater than this value to evolve the Nd isotopic compositions observed in the Western Australian lamproites from an initially depleted mantle source. As the Pb isotope data indicates a more complex history, probably involving at least two stages, the calculated Nd depleted mantle model source ages should be regarded as an estimate of the minimum age of first differentiation of the lamproite sources from primitive mantle (cf. McCulloch et al., 1983). The minimum estimate of \( \approx 2.1 \) byrs for the differentiation event is in accord with the value determined from the Pb systematics.

**Implications for the origins of the ultrapotassic suite**

The remarkable diversity of isotopic characteristics displayed by representatives of the ultrapotassic suite is apparent from Figs. 3 and 5. However, the available geochemical and isotopic data taken from this and other earlier studies favour the generation of many examples of continental potassic volcanism by the invasion of regions of the subcontinental mantle by an isotopically foreign incompatible element enriched "metasomatic" component. In many cases these components possess high \(^{207}\)Pb/\(^{204}\)Pb, radiogenic Sr and unradiogenic Nd relative to MORB, indicating that the sources of these components have had long and complex histories. The trace element and isotopic identity of the resulting melts is strongly influenced by that of the added component, resulting in isotopic/abundance relations indicative of mixing. Examples include the Spanish and Western Australian lamproites and probably the New South Wales leucitites. In view of their remarkable geochemical and isotopic similarity with Western Australian lamproites, leucitites from Gaussberg may also have been generated by a similar process. The isotopic characteristics of the Virungan lavas (Vollmer and Norry, 1983) are also consistent with the addition to their sources of a similar radiogenic \(^{207}\)Pb/\(^{204}\)Pb and \(^{87}\)Sr/\(^{86}\)Sr, unradiogenic \(^{143}\)Nd/\(^{144}\)Nd component, but the sources of the Virungan lavas may have evolved variable \(^{87}\)Sr/\(^{86}\)Sr since the mixing event. There is no consensus about the origins of the Italian potassic lavas, although \(^{18}O/\(^{16}O\), Nd, Sr and Pb isotopic studies (e.g. Taylor and Urai, 1976; Hawkesworth and Vollmer, 1979; Vollmer and Hawkesworth, 1980; Holm and Munksgaard, 1982 and others) favour the involvement of crustal material, either by assimilation within high level magma chambers or by magmatism of the sources of the magmas by subducted sediments.

The metasomatic components of many potassic occurrences possess high \(^{207}\)Pb/\(^{204}\)Pb, radiogenic Sr and unradiogenic Nd, limiting the sources of these components to only a few geological reservoirs;

1. **Old subcontinental lithosphere**—the Western Australian, Gaussberg, Leucite Hills and Virungan suites are situated on stable, thick Precambrian base-

ment which may have had the specific long-term history required. A major difficulty is that many ultrapotassic suites are generated at great depths; within the diamond stability field in the case of the Western Australian lamproites. The depths to which the continental lithosphere extends beneath old continents is unknown but if, as speculated by Richardson et al. (1984), it is in some circumstances stable to depths within the diamond stability field, then the subcontinental lithosphere could be an important reservoir for the storage of ancient, isotopically evolved components. Spanish lamproites have geochemical features which suggest that they were generated at shallower depths than the Western Australian lamproites (Nixon et al., 1984) but are located on relatively young Proterozoic basement which may not have had sufficient prior history to have evolved the isotopic characteristics required.

2. **Subducted sediments**: The findings of this study are consistent with the recent proposal of Thompson et al. (1984) that some potassic volcanism is derived from subducted sediments. In particular, the trace element characteristics of the Spanish lavas resemble those of arc lavas and isotopic compositions overlap with those of modern sediments. Although Western Australian, Gaussberg and Virungan ultrapotassic volcanism cannot be obviously related to any modern subduction zone, the antiquity of the source enrichments indicated by the isotopic data suggest that subduction processes cannot be discounted. Isotopic modelling and further discussion of the possible involvement of subducted sediments in the genesis of ultrapotassic magmatism will be published at a later date.

3. **Subducted 'megaliths'**: Oceanic crust and sediments subducted into the mantle and having residence times of \( \approx 1 \) byrs (Hofmann and White, 1982; Ringwood, 1982). Partial melting of the megalith may cause incompatible element enriched diapirs to rise upward, contaminating the overlying regions of the mantle and eventually manifesting as hotspots in oceanic regions or, in the continental environment, as alkaline volcanism. The involvement of sedimentary material or the long timescales involved during storage of the megalith in the mantle could result in isotopic characteristics indicative of long term incompatible element enrichment. While many ocean islands bear little isotopic resemblance to continental potassic volcanism, lavas from Kerguelen and Society islands have Sr and Nd isotopic compositions extending into the "enriched" quadrant on the Sr-Nd isotope diagram and have generally higher \(^{207}\)Pb/\(^{204}\)Pb than MORB (White, 1985). These isotope characteristics are similar to those of the New South Wales leucitites, which may also be products of hotspot volcanism.

It is probable that no single origin is responsible for all of the various ancient components identified in representatives of the ultrapotassic suite. That most isotopically evolved potassic volcanism (e.g. Western Australian, Gaussberg, Virungan, Leucite Hills, mi-
caceous South African) is confined to old cratons is strong indirect evidence that the continental lithosphere acts as a site of long term storage of enriched mantle components. In a discussion of models of subcontinental lithospheric growth, BROOKS et al. (1976) suggested that mantle plumes rising beneath continents may underplate the subcontinental lithosphere and are later reactivated, appearing as isotopically evolved continental alkaline magmatism. Differences in the time elapsed between underplating and reactivation events might then explain the range in isotopic characteristics observed in continental alkaline lavas. Alternatively, mantle plumes may be responsible for the reactivation of pre-existing enriched subcontinental lithosphere. In this case, the age of the subcontinental lithosphere will determine the isotopic character of subsequent volcanism.

The Sr, Nd and Pb isotopic characteristics of Gaußberg leucitites and Western Australian lamproites are unlike any previously identified, lying off the mantle plane of ZINDLER et al. (1982). Their high $^{207}\text{Pb}/^{206}\text{Pb}$ and low $^{206}\text{Pb}/^{204}\text{Pb}$ contrasts with the Pb isotopic compositions found in ocean islands, which define a linear array of positive slope extending from the unradiogenic Pb field of MORB to the high $^{207}\text{Pb}/^{206}\text{Pb}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ of St. Helena and Tubuai. The ocean island array lies to the right of the geochron (on which all present-day single stage Pb should lie, assuming an initial Pb isotopic composition like that of Canyon Diablo troilite lead), indicating that the sources of ocean islands have undergone an increase in U/Pb within the last $\approx 2.5$ byrs or less. The geochemical history of the metasomatic components of Gaußberg leucitites and Western Australian lamproites inferred from their Pb isotopic characteristics differs from that inferred for ocean islands because of the ancient fractionation events which lowered U/Pb. Although the position of MORB and ocean island Pb to the right of the geochron has been attributed to the progressive loss of Pb from the mantle to the Earth's core, the existence within the subcontinental lithosphere of substantial reservoirs of low $^{207}\text{Pb}/^{206}\text{Pb}$ components with moderate to high $^{206}\text{Pb}/^{204}\text{Pb}$ like those identified in this study may also explain the position of the ocean island array relative to the geochron, as such low U/Pb reservoirs can also compensate for the general increase of U/Pb in the sources of ocean islands.

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