

The Role of Crustal Contamination During the Evolution of Continental Rift-Related Basalts: A Case Study from the Vogelsberg Area (Central Germany)

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ABSTRACT. The Cenozoic basaltic province of the Vogelsberg area (Central Germany) is mainly composed of intercalated olivine to quartz tholeiites and near-primary to slightly differentiated alkaline basaltic rocks. The inferred mantle source for the alkaline and tholeiitic rocks is asthenospheric metasomatized garnet peridotite containing some amphibole as the main hydrous phase. Previously published trace element modelling indicates 2 to 3% partial melting for the alkaline rocks and 5 to 7% partial melting for the olivine tholeiites. Incompatible trace element abundances and ratios as well as Nd and Sr radiogenic isotope compositions lie between plume compositions and enriched mantle compositions and are similar to those measured in Ocean Island Basalts (OIB) and the Central European Volcanic Province elsewhere. The mafic olivine tholeiites have similar Ba/Nb, Ba/La and Nd-Sr isotope ratios than the alkaline rocks indicating derivation of both magma types from chemically comparable mantle sources. However, Zr/Nb ratios are slightly higher in olivine tholeiites than in basanites reflecting some fractionation of Zr relative to Nb during partial melting. Quartz tholeiites have higher Ba/Nb, Zr/Nb, La/Nb, and higher initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios but lower Ce/Pb ratios and lower Nd isotope ratios than the alkaline rocks which can be explained by interaction of the basaltic melt with lower (granulite facies) crustal material or partial melts thereof during stagnation within the lower crust. It appears most likely that upwelling of hot, asthenospheric material results in the generation of primitive alkaline rocks at the base of the lithosphere at depths of 75–90 km. Lithospheric extension together with minor plume activity and probably lower lithosphere erosion induced melting of shallower heterogeneous upper mantle thereby generating a spectrum of olivine tholeiitic melts. These olivine tholeiitic rocks evolved via crystal fractionation and probably limited contamination to quartz tholeiites.

KEY WORDS: alkaline basalts, tholeiites, crustal contamination, mantle source, Vogelsberg.

Introduction

In recent years, volcanic rocks of continental rifts have received considerable attention and trace element data in conjunction with isotope data are now available from a significant number of continental rift zones (Western Africa: Halliday et al. 1988; Fitton and Dunlop 1985; Eastern Africa: Class et al. 1994; Furman 1995; Stewart and Rogers 1996; Arabia: Altherr et al. 1990; Asia: Zhi et al. 1990; Liu et al. 1994; Zhou and Mukasa 1997; Europe: Downes 1984; Alibert et al. 1987; Blusztajn and Hart 1989; Wilson and Downes 1991; Embey-Istzin et al. 1993; Harangi 1994; Wedepohl et al. 1994; Cebria and Lopez-Ruiz 1995; Downes et al. 1995). Rift-related alkaline magmatism, especially that which generated relatively large masses of magma, is usually derived from chemically anomalous mantle sources associated with hot spot activity (e.g. McKenzie and O'Nions 1983) and Wilson and Downes (1991) suggested that at least two components, a lithospheric and an asthenospheric one, are involved in the petrogenesis of continental rift-related volcanic rocks from Central Europe. In their view, the lithospheric component originates from partial melting of a phlogopite/amphibole-bearing spinel lherzolite whereas the asthenospheric component partly represents old (Variscan) subducted oceanic lithosphere. This asthenospheric component has recently been described as the European Asthenospheric Reservoir (EAR) by Cebria and Wilson (1995). The geochemical characterization of melts from asthenospheric and lithospheric sources places important constraints on the dynamics of melting within and movement of melt through the mantle and on geodynamic models of crustal recycling within the convecting mantle (Hofmann et al. 1986; Zindler and Hart 1986). Silica-undersaturated volcanic rocks are often believed to originate in the deeper parts of the mantle (asthenosphere), although, based on geochemical (Hawkesworth and Vollmer 1979; McKenzie and Bickle 1988;

Hawkesworth et al. 1990; Bradshaw et al. 1993) and thermal considerations (e.g. McKenzie 1989), it can be suggested that metasomatized lithospheric mantle can also be a viable source for small-volume undersaturated mafic liquids. The lithospheric mantle may contribute in several ways to the chemical characteristics of alkaline, intra-plate volcanic rocks. These contributions may include (1) incorporation of partial melts at the site of partial melting, i.e. at the upper surface of a plume, (2) contamination by partial melting of lithospheric material as an asthenosphere-derived magma moves through the mantle, (3) the lithosphere serves as a source component as detached fragments within the asthenosphere and (4) direct melting of the lithosphere. As the subcontinental lithosphere is heated during extension or above an ascending mantle plume, melts of metasomatized peridotite can mix with asthenospheric melts. However, numerical modelling (e.g. Arndt and Christensen 1992) indicates that the volumetric contribution of continental lithosphere melts, relative to melts from the asthenosphere, is small. Because most of the trace element and isotopic signature of the volcanics from the European Volcanic Province (EVP) is broadly similar to ocean-island basalts (OIB) with HIMU affinity, these geochemical signatures were used to constrain a sub-lithospheric source for these basalts. Several genetic relationships have been proposed including partial melting of the asthenosphere, melting of enriched (metasomatized) lower lithosphere, melting of subducted Hercynian oceanic lithosphere, and melting of small mantle diapirs (Wörner et al. 1986; Blusztajn and Hart 1989; Wilson and Downes 1991; Wilson et al. 1995; Hegner et al. 1995).

In a previous study (Jung and Masberg 1998) the nature and composition of the sources of alkaline basalts from the Vogelsberg, a part of the central European rift system has been evaluated. The present study focuses on the role of crustal contamination for temporally and spatially associated tholeiitic rocks

mainly based on incompatible trace element ratios and Sr and Nd isotopes. Trace element and Nd and Sr isotope data for the alkaline rocks do not indicate a significant contribution of crustal material, however, for the quartz tholeiitic rocks a small amount of contamination of probably lower crustal material has been suggested (Wittenbecher 1992). The Vogelsberg area of

central Germany is an excellent locality for determining the relative importance of crustal components in continental basalts because (1) the intercalated tholeiitic and alkalic basalts provide a geochemical diversity that is not available elsewhere in the Central European Volcanic Province and (2) the occurrence of mantle xenoliths within the alkalic basalts but not in the tholei-

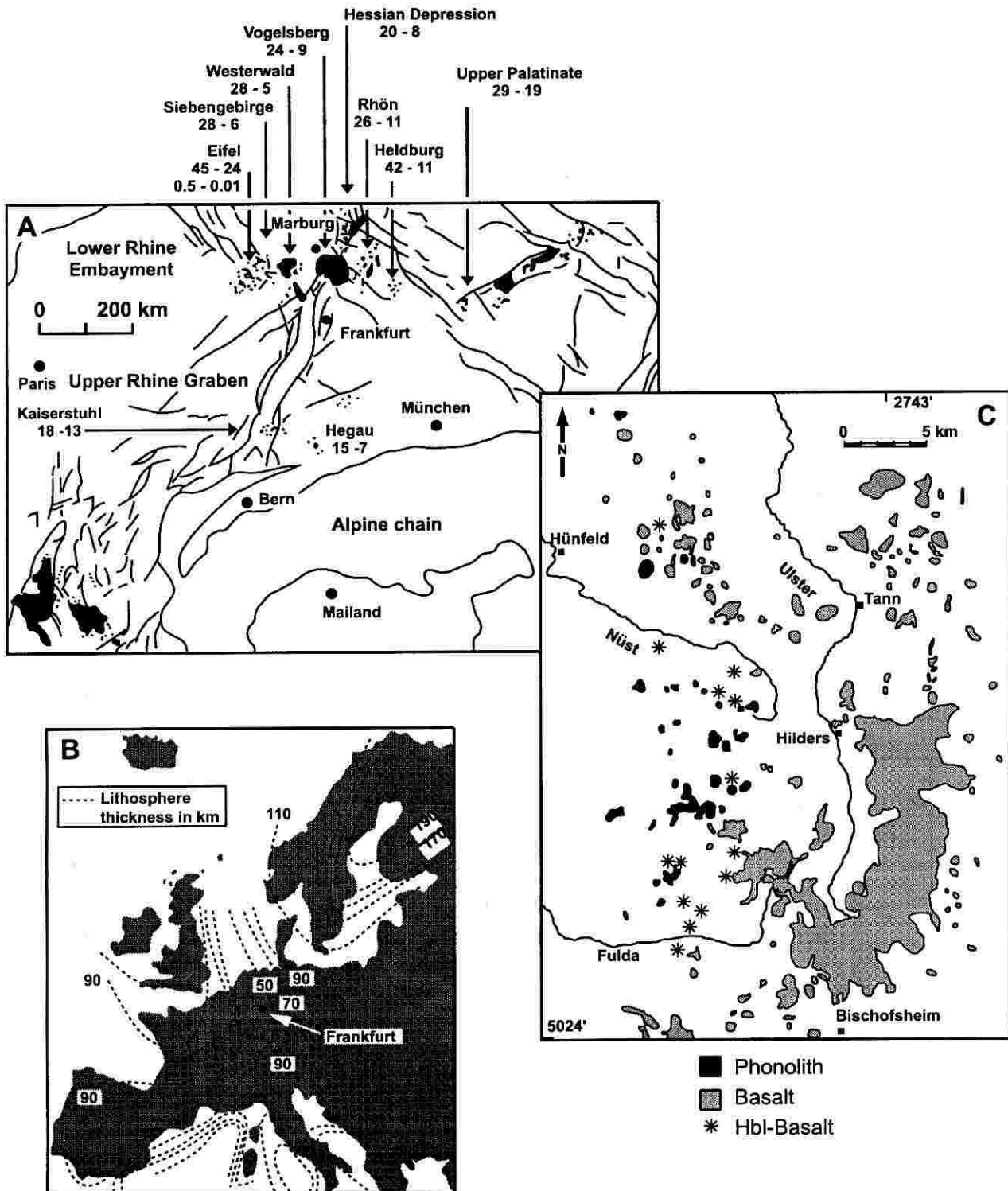


Fig. 1. A – A map (slightly modified from Wedepohl 1985) showing distribution of some Cenozoic volcanic rocks in Central Europe. Numbers denote K-Ar ages from Lippolt (1982); B – Contour map of lithosphere thickness in Europe (Wedepohl et al. 1994); C – Location of the Vogelsberg volcanic province in Germany. Numbers denote sample locations: 1 – Quarry Zeidler & Wimmel; 2 – Bühnfeld; 3 – Kürle; 4 – Kaff; 5 – Reugenstein; 6 – Wernerstein.

itic rocks indicates that the alkali basalts ascended rapidly from their source whereas the tholeiites probably resided for some time during their ascent within the continental crust.

Geological setting

The Vogelsberg volcanic province with an areal extent of ca. 2,500 km² is one of the largest Cenozoic volcanic provinces in Central Europe. It is located approximately 400 km north of the Alps, and its southern end overlaps the northern part of the Upper Rhine depression (Fig. 1A). The onset of volcanic activity was probably related to mass movements within the upper mantle mainly as a result of plate collision processes in the Alpine region during Cenozoic times (Illies et al. 1981). Depression of lithospheric material into the mantle was compensated mainly by uplift of the lithosphere in Central Europe. During Palaeocene, Eocene and Oligocene times subsidence of the NNE-trending graben of the upper Rhine valley was initiated but during Miocene and Pliocene times, activation of a NW-trending system which formed the lower Rhine embayment had important consequences in the development of the tectonic stress field. At this time the tectonic evolution was mainly represented by the formation of continental rifts and graben structures, accompanied by basaltic volcanism along the rift systems. Prodehl (1981) reported a depth of approximately 28–30 km for the Moho beneath the Vogelsberg area whereas the base of the lithosphere is located at roughly 50 km depth (Fig. 1B). Vogelsberg volcanism started at about 17 Ma and lasted until 9 Ma (Lippolt 1982). Phonolites and trachytes are considered to be the oldest volcanic rocks since they underlie the basalt flows and, in one place, are separated from them by a thick layer of Neogene sandstone. Most of the alkali olivine basaltic and tholeiitic volcanism occurred during the late Miocene (17.2 Ma to 13.0 Ma, Kreuzer et al. 1973; 1974). Samples from a borehole in the central Vogelsberg area show that the flood-like sequence of alternating tholeiitic and alkali olivine basalts erupted as a sequence 300 m thick from 17.2 to 16.2 Ma (Harre et al. 1975; Ehrenberg et al. 1977). Schricke (1975) and Diederich et al. (1988) suggested, based on rare K/Ar ages and outcrop evi-

dence, that the volcanism within the Vogelsberg area consists of two main sequences in which each sequence started with the eruption of tholeiitic rocks followed by the extrusion of alkali olivine basaltic rocks. The maximum thickness of the basaltic pile is believed to be 700–800 m in the central Vogelsberg and an average volume of 500 km³ has been suggested (Ehrenberg 1986). Local basement rocks consist of folded Palaeozoic low-grade metasediments, overlain by flat-lying Mesozoic and Cenozoic clastic sediments and minor carbonates (Fig. 1C).

Petrography

The tholeiitic lavas are coarse-grained and light to medium grey whereas the dark grey and massive alkaline rocks are porphyritic with abundant phenocrysts of olivine and Ti-rich clinopyroxene. Upper mantle xenoliths have been observed within the alkaline rocks but the tholeiites are xenolith-free rocks. Olivine-normative tholeiites are subophitic or slightly porphyritic and contain phenocrysts of olivine and, less abundant, augitic clinopyroxene, set in a groundmass containing zoned and twinned plagioclase, clinopyroxene and Fe-Ti-oxides. Quartz-normative tholeiites are usually composed of rare olivine phenocrysts, plagioclase, Ca-poor pyroxene (pigeonite), augitic clinopyroxene and subordinate Fe-Ti oxides and exhibit subophitic to ophitic textures. Some samples show glomerophyric clots of plagioclase probably as a consequence of plagioclase accumulation. Generally, both tholeiite types are distinguished from the alkali basalt rocks by their lack of titanite.

Results

Representative analyses of the alkalic and tholeiitic lavas from the Vogelsberg area are given by Wittenbecher (1992) and Jung and Masberg (1998). According to the TAS classification of Le Bas et al. (1986) the samples are nephelinites, basanites and basalts. Using the criteria proposed by Irvine and Baragar (1971), the basalts are tholeiites (Fig. 2). Alkali basalts are nepheline normative whereas the tholeiites are either olivine normative or quartz normative. As usual, FeO_{tot}, MgO, and CaO decrease and Al₂O₃ increases with increasing SiO₂ contents. The nephelinites

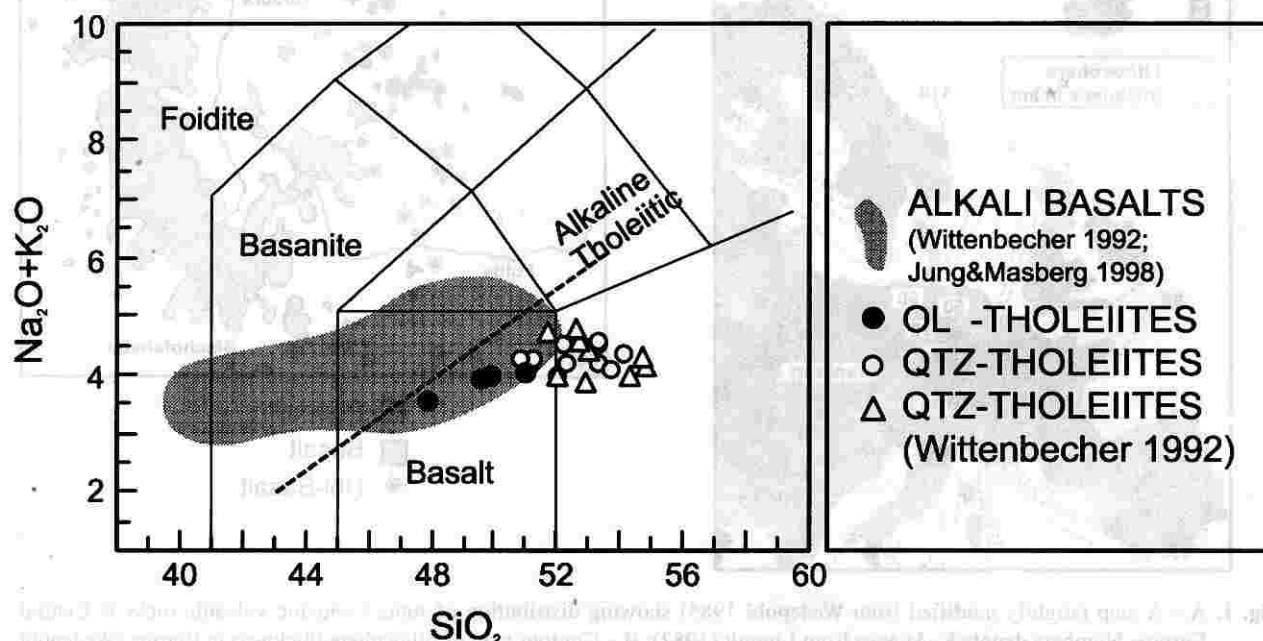


Fig. 2. Total alkali-silica diagram according to Le Bas et al. (1986). The boundary between alkaline and tholeiitic rocks (dashed line) is taken from Irvine and Baragar (1971). Data from Wittenbecher (1992) and Jung and Masberg (1998).

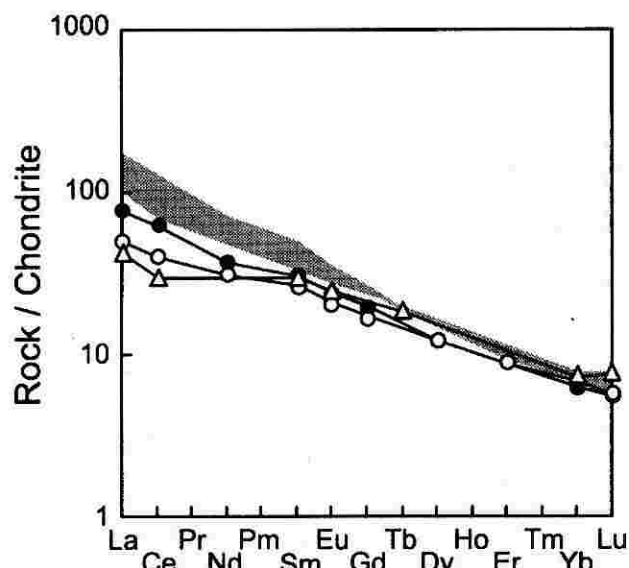


Fig. 3. Chondrite-normalized REE diagram for alkaline rocks (shaded area; Wittenbecher 1990; Jung and Masberg 1998), averages of olivine tholeiites ($n = 4$; Jung and Masberg 1998) and quartz tholeiites ($n = 9$, Wittenbecher 1992; $n = 14$, Jung and Masberg 1998). Normalization values from Boynton (1984).

and most basanites have high mg-numbers (> 0.68) but olivine tholeiites and quartz tholeiites have lower mg-numbers ($0.62-0.67$ and $0.62-0.66$).

Nickel, Cr and Co contents of the alkaline rocks are equal to or higher than the values commonly assumed for primary magmas (Ni: 300–400 ppm, Cr: 300–500 ppm, Co: 50–70 ppm; e.g., Frey et al. 1978). The tholeiites have lower Ni and Cr contents. Abundances of V (and Ti) and Sc are higher in the alkaline rocks than in the tholeiites. K/Rb ratios of most of the alkaline rocks (K/Rb: 160) are close to K/Rb ratios for primitive alkaline rocks from Germany (K/Rb: 160–250; Wedepohl et al. 1994). The tholeiites show K/Rb ratios between 166–440 with an average of 270, typical of continental tholeiites from Central Germany (Wedepohl 1985). The chondrite-normalized REE patterns of the alkali basalts show a pronounced LREE enrichment and a strong fractionation between LREE and HREE. La_N/Yb_N ratios are 22–32 in the alkaline rocks whereas this ratio drops to 10–16 in the olivine tholeiites and to 5–10 in the quartz tholeiites (Fig. 3).

The pattern of incompatible element abundances normalized to the primordial mantle of most continental alkali basalts and many OIBs is remarkably similar from La to Y but among the highly incompatible elements such as Rb, Ba, and K there is a considerable variation in abundances. The depletion in K relative to Ba and Nb is evident from the alkaline rocks (Fig. 4). Maximum normalized abundances occur for Ba and Nb with La/Nb ratios < 1 . This feature is similar in basanites and nephelinites and typical of OIBs and many continental alkali basalts (Thompson et al. 1984). Olivine tholeiites have lower element abundances than the alkaline rocks and their negative K anomaly is less pronounced. Unlike the alkaline rocks, the tholeiites display positive anomalies at Sr. For the alkaline rocks the positive Nb anomaly, high Ba but low Zr contents result in low Zr/Nb ratios, low La/Nb ratios but high Ba/Nb ratios. The olivine tholeiites have higher Zr/Nb ratios but rather similar Ba/Nb and

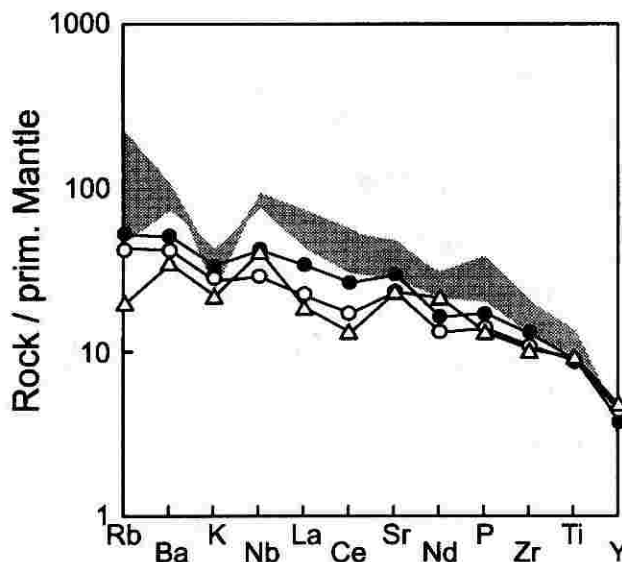


Fig. 4. Primitive mantle-normalized incompatible element patterns for alkaline basalts (shaded area; Wittenbecher 1992; Jung and Masberg 1998), olivine tholeiites ($n = 4$, Jung and Masberg 1998) and quartz tholeiites ($n = 9$, Wittenbecher 1992; $n = 14$, Jung and Masberg 1998). Normalization values from Sun and McDonough (1989).

La/Nb ratios. Quartz tholeiites have higher Zr/Nb and Ba/Nb ratios but similar La/Nb ratios although the spread of data is generally wider for tholeiites than for the alkaline rocks.

Some radiogenic isotope analyses are given by Wittenbecher (1992) and in Tab. 1 which was adopted from Jung and Masberg (1998). $^{87}Sr/^{86}Sr$ ratios are low and $^{143}Nd/^{144}Nd$ ratios are high and the negative correlation between the isotope ratios plots in the depleted field relative to bulk Earth in the Sr–Nd diagram. This trend is similar to trends of other mafic alkaline rocks from the Eifel, Massif Central, Poland and the Pannonian Basin (e.g. Wörner et al. 1986; Blusztajn and Hart 1989; Wilson and Downes 1991; Embey-Isztin et al. 1993). The alkali basalts have a restricted range in Nd and Sr isotopes whereas the tholeiites display a wider spread of data. Three of four olivine tholeiites have an isotopic signature comparable to the isotope composition of the alkaline rocks with low Sr and high Nd isotope concentrations close to a depleted source. One olivine tholeiite has higher Sr and lower Nd isotope composition. All quartz tholeiites have lower Nd isotope ratios at a given $^{87}Sr/^{86}Sr$ ratio than the alkaline basalts. Alkaline rocks exhibit no obvious correlation between MgO and $^{143}Nd/^{144}Nd$ (Fig. 5) but the tholeiites show decreasing $^{143}Nd/^{144}Nd$ ratios with decreasing MgO.

Discussion

Petrogenesis of the Vogelsberg lavas

Compositional differences between the alkali basaltic and tholeiitic lavas may reflect differences in the degree of melting, source composition, and post-melting fractionation and contamination processes. The major and trace element data characterize the alkaline rocks as dominantly mafic, sodium-rich and silica-undersaturated rift-related intraplate volcanic rocks. Limited geochemical variation suggests that extensive fractionation in high-level magma chambers and contamination by country rocks was not important and the composition must be explained largely by mantle processes or mantle compositions.

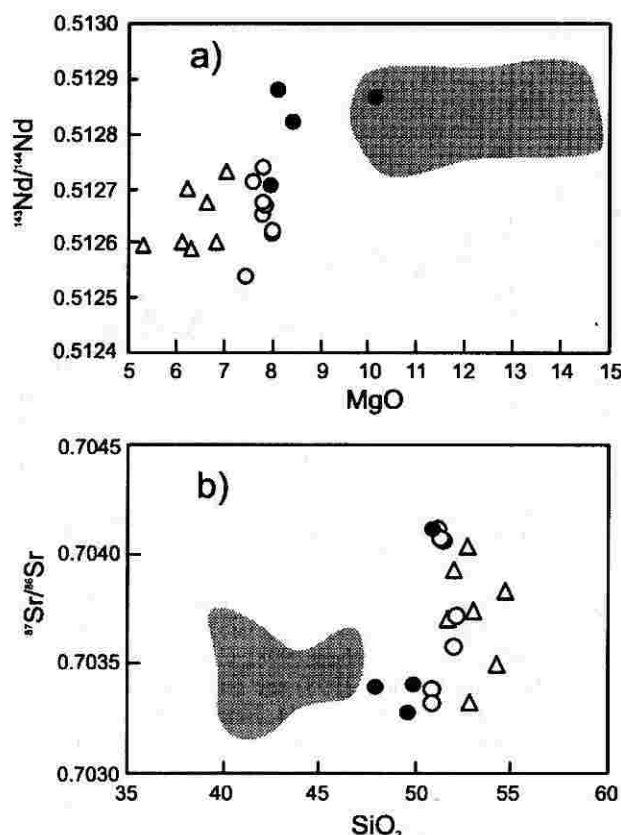


Fig. 5. $^{143}\text{Nd}/^{144}\text{Nd}$ vs. MgO and $^{87}\text{Sr}/^{86}\text{Sr}$ vs. SiO_2 for the Vogelsberg lavas. Data sources: Wittenbecher (1992), Jung and Masberg (1998).

Partial melting processes

Generally, the increasing degree of undersaturation in SiO_2 within the sequence olivine tholeiite–alkali basalt principally results from decreasing degrees of partial melting at increasing depth in the mantle (e.g., Kay and Gast 1973; Sun and Hanson 1975; Frey et al. 1978). It has been shown (Jung and Masberg 1998) that the alkaline rocks and olivine tholeiites have undergone only very minor crystal fractionation. Therefore, in agreement with the results from experimental investigations, the decrease in CaO and MgO accompanied by an increase in Al_2O_3 from nephelinites and basanites to olivine tholeiites similarly corresponds to an increase in the degree of partial melting. Furthermore, the $\text{Al}_2\text{O}_3/\text{TiO}_2$ and CaO/TiO_2 ratios increase from the alkali basaltic rocks to olivine tholeiites consistent with an increasing degree of partial melting (Jaques and Green 1980). Trace element ratios as La/Yb , La/Sm or Ba/Sr where the numerator has a higher degree of incompatibility exhibit a regular decrease from nephelinite and basanite to olivine tholeiite which is also in agreement with the increasing degrees of partial melting. Using Ce and Yb abundances of metasomatized lherzolite xenoliths (I-Group from Hartmann and Wedepohl 1990) and varying clinopyroxene/garnet ratios (from 13.2 to 14.5:0.5) in the source, the degree of partial melting of 2–3 % for the alkali olivine basaltic rocks and 5–7 % for the olivine tholeiites has been calculated (Jung and Masberg 1998).

Nature of the source

The major and trace element evidence (high $\text{CaO}/\text{Al}_2\text{O}_3$ ratios,

nearly constant Y and Yb contents, high La_N/Yb_N ratios, and high Zr/Y ratios) suggests that the alkali basaltic magmas were derived from a garnet-bearing mantle source (Brey et al. 1979; Frey et al. 1978).

The depletion in K relative to Ba and Nb on a primitive mantle-normalized plot (Fig. 4) is evident from the alkali basaltic rocks and indicates the presence of a residual LILE-bearing mineral phase. This mineral phase, which was progressively eliminated during partial melting, is more likely to be amphibole than phlogopite giving rise to positively correlated Rb/Nb and K/Nb ratios. Alkaline and tholeiitic lavas have positively correlated Rb/K ratios and Rb concentrations and their variation has essentially the same slope and is colinear with the variation exhibited by amphibole analyses from the literature (Jung and Masberg 1998). The striking correspondence between the array defined by the lavas and that of the amphiboles suggests that amphibole rather than phlogopite controlled the observed Rb/K systematics.

The Vogelsberg alkaline lavas have Ba/Nb and Zr/Nb (and La/Nb) characteristics intermediate between those from plume-type sources (HIMU) and enriched mantle (EM) sources (Fig. 6). The high incompatible trace element ratios in alkaline volcanic rocks are usually explained as having originated from recycled oceanic lithosphere plus sediment or from sub-continental lithosphere (Weaver 1991; Liu et al. 1994; Zhi et al. 1990). Many examples show similar isotope signatures for ocean island basalts and some continental basalts (e.g., Fitton and Dunlop 1985 and Halliday et al. 1988, among many others). Our results confirm this similarity, the Sr and Nd isotope ratios lie within the fields of many OIB. Most of the data points form an elongated array between a high ϵ_{Nd} –low ϵ_{Sr} endmember and a low ϵ_{Nd} –high ϵ_{Sr} endmember which could be interpreted in terms of mixing of discrete mantle source components or partial melts thereof. In view of the primitive nature of the alkaline rocks and because these rocks exhibit no correlation between MgO and Nd isotopes (Fig. 5), this trend is unlikely to have been generated by crustal contamination. The similarity in isotope composition between the continental basalts and OIB implies that the alkaline rocks have been derived from a deep mantle source relatively homogeneous on a broader scale. The alkaline rocks studied here have mostly a depleted isotopic signature and low incompatible trace element ratios, therefore, we favour an asthenospheric derivation for these rocks. For the tholeiites, the situation is more complex. We suggest that the olivine tholeiites originate at the asthenosphere–lithosphere boundary having both enriched and depleted isotopic signatures. The problem of derivation from enriched sources or contamination by lower crustal material with low values of Sr and Nd isotopes is evident from most of the quartz tholeiites. Zr/Nb ratios are as high as 22 in the quartz tholeiites and are significantly higher than estimates of the Zr/Nb ratio in the lower crust and partial melts from this material (Taylor and McLennan 1985; Hawkesworth and Clarke 1994). We therefore favour a lithospheric mantle origin for the quartz tholeiites because the overlap of Zr/Nb ratios of the quartz tholeiites with those of samples from the lower crust beneath Central Europe (Fig. 7) implies that direct contamination with lower crustal material would have reached an unreasonable degree if it had been the sole controlling process. However, the tholeiitic rocks show different abundances of, and ratios between, highly incompatible trace elements. These features suggest modification during fractionation by processes linked with storage in crustal magma chambers.

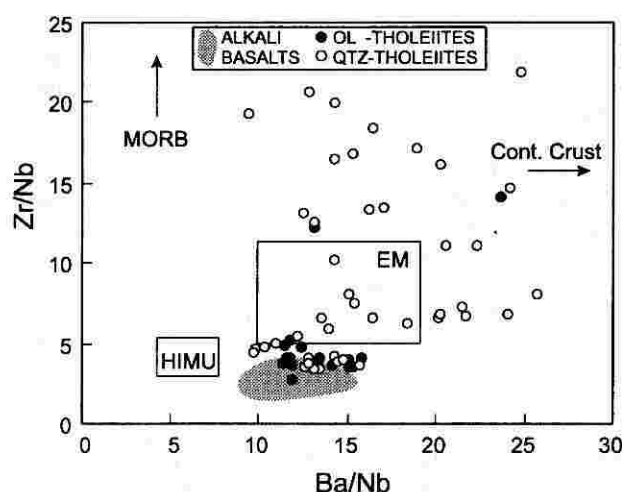


Fig. 6. Zr/Nb vs. Ba/Nb plot of the alkaline and tholeiitic volcanic rocks from the Vogelsberg area. Compositions of HIMU-OIB, EM-OIB, MORB and CC according to Weaver (1991). Data from Schricke (1986), Diederich et al. (1988), Wittenbecher (1992) and Jung and Masberg (1998).

Role of crustal contamination

Continental basalts often show enriched trace element and isotopic characteristics relative to their oceanic counterparts and the present debate continues as to the importance of processes operating at crustal levels determining the composition of these rocks. Therefore, given the continental environment in which the basaltic lavas erupted, it is essential to evaluate the possible effects of crustal contamination. Previous geochemical studies on the Cenozoic volcanic rocks from Central Germany (e.g., Wörner et al. 1986; Wilson and Downes 1991; Wedepohl et al. 1994) have shown that the majority of the alkaline rocks have not been contaminated by crustal material. Principally, contamination of basalts by lower crustal rocks is possible (e.g., Glazner et al. 1991; Peng et al. 1994). In this case the density contrast between the mafic lower crust and the upper mantle makes the Moho zone an ideal place for magma to accumulate due to the decreasing density contrast between mafic lower crust and upper mantle. Advanced fractional crystallization together with heat input from an ascending plume may support assimilation of lower crustal rocks. Large gabbroic intrusions at the base of the crust may be abundant due to magma underplating as a result of lithospheric extension (e.g., Furlong and Fountain 1986) and some old, underplated mafic rocks may develop an enriched isotopic signature over time and provide a source for the contaminated endmember.

The different and often higher K/Nb, Rb/Nb, Ba/Nb and La/Nb ratios of the Vogelsberg quartz tholeiites relative to the alkali basaltic rocks and olivine tholeiites are not easily explained by different degrees of partial melting, extensive crystal fractionation or a metasomatic imprint from the mantle source. Therefore, it seems likely that these different trace element ratios are the product of crustal contamination. The Ce/Pb ratio which is relatively high and uniform in MORB and OIB (25 ± 5 ; Hofmann et al. 1986) is low in the quartz tholeiites (average: 6.8, Jung and Masberg 1998) and may also suggest the involvement of crustal material. Figure 7 shows the variation of the Zr/Nb ratio with Nb concentration for the volcanic rocks and the field for published trace element data for lower crustal xenoliths from

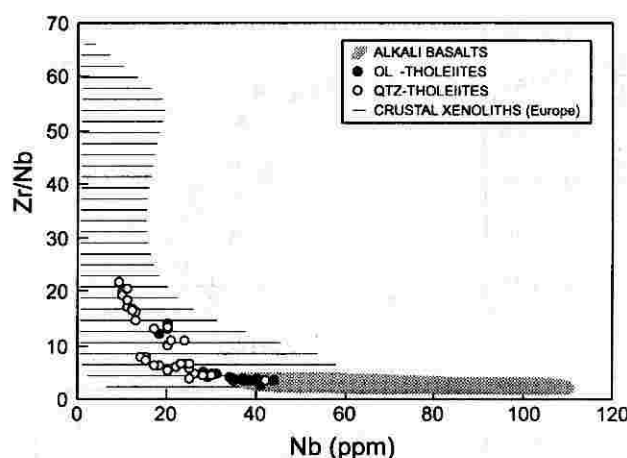


Fig. 7. Zr/Nb vs. Nb plot for the alkaline and tholeiitic rocks from the Vogelsberg area. Data from Schricke (1986), Diederich et al. (1988) and Jung and Masberg (1998). The hatched area represents crustal xenolith analyses from Europe (Dostal et al. 1980; Wörner et al. 1982; Mengel 1990; Downes et al. 1990).

Europe. It is evident that the Zr/Nb ratios are constant within the alkali basaltic rocks and only moderately fractionated in the case of the olivine tholeiitic rocks. The quartz tholeiites have strongly fractionated Zr/Nb ratios. These results indicate that contamination with a crustal endmember with a high Zr/Nb ratio and low Nb concentration is likely at least for the tholeiites with the highest Zr/Nb ratio. Mixing trajectories between a basalt and any crustal endmember are hyperbolic based on the different contents of Zr and Nb in basaltic and crustal rocks. The range in Zr/Nb ratios and Nb concentrations of most quartz tholeiites, the shape of the data array in Figure 7 as well as the large range of Zr/Nb and Ba/Nb ratios (Fig. 6) might indicate that contamination must have occurred to some extent. From Fig. 5 it is evident that the Nd isotopic composition decreases with decreasing MgO contents whereas the Sr isotopic composition increases with increasing SiO_2 contents in the tholeiites. This feature cannot be explained by simple crystal fractionation and must be somewhat related to an unspecified AFC (assimilation-fractional crystallization) process. Low values of ϵ_{Nd} and low $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and elevated La/Nb, Ba/Nb, Ba/La and Zr/Nb ratios can be found in enriched magmas from the continental mantle lithosphere and in lower crustal rocks (e.g., Rudnick and Goldstein 1990) and, therefore, these ratios are not unequivocal. The lower $^{143}\text{Nd}/^{144}\text{Nd}$ isotope compositions of some quartz tholeiites can be explained by contamination with a LREE-enriched but $^{87}\text{Sr}/^{86}\text{Sr}$ -depleted endmember, similar to granulite-facies gneisses from the Lewisian complex, Scotland (Carter et al. 1978; Wittenbecher 1992). Additionally, positive correlation between $^{143}\text{Nd}/^{144}\text{Nd}$ and MgO (Fig. 5) and the negative correlation between $^{143}\text{Nd}/^{144}\text{Nd}$ and Zr/Nb, Ba/La and Ba/Nb ratios (Fig. 8) may reflect crustal contamination. Similarly, in a plot of $^{143}\text{Nd}/^{144}\text{Nd}$ isotope ratio vs. the Sm/Nd ratio (Fig. 9), the alkaline rocks show a horizontal trend which can be explained by different degrees of partial melting and/or fractional crystallization. The quartz tholeiites define a slightly inclined trend, compatible with binary mixing between components of the common source of the basalts and a component from the crust.

In order to constrain the crustal contamination process, we have utilized a simple two-component mixing model which may

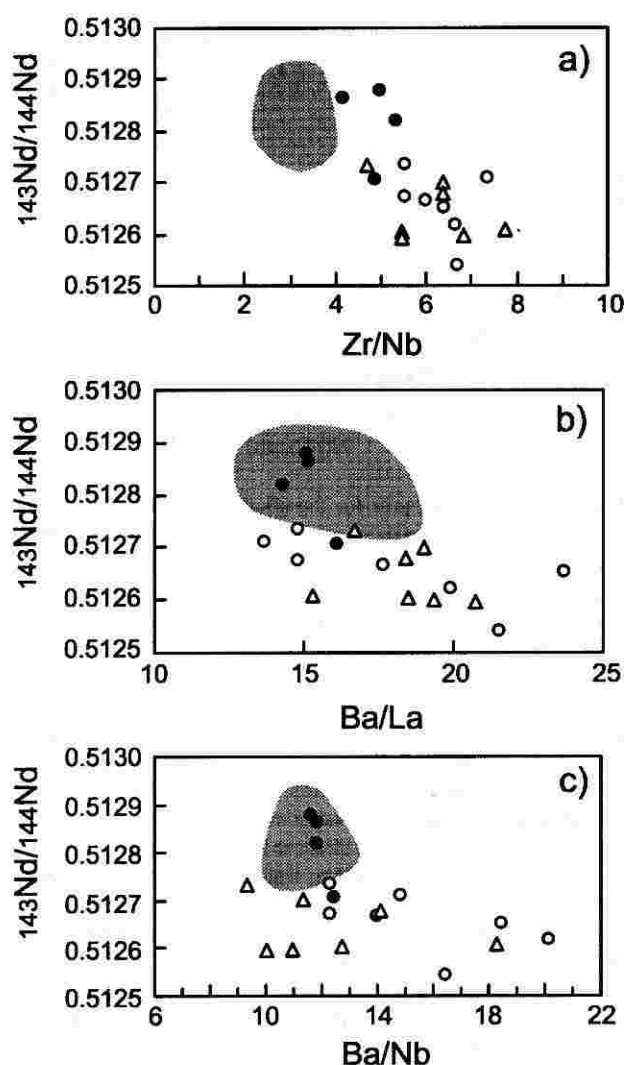


Fig. 8. $^{143}\text{Nd}/^{144}\text{Nd}$ vs. Ba/Nb, Ba/La, and Zr/Nb ratios. Data sources: Wittenbecher (1992), Jung and Masberg (1998). Because Wittenbecher (1992) did not report Nb concentration, an average Nb content of 22 ppm from Jung and Masberg (1998) was used for calculation of trace element ratios.

help to provide first-order constraints on the proportions of mantle and crustal components (Patchett and Bridgewater 1984; Chauvel et al. 1987). Principally, the interaction of mantle-derived magmas with continental crust can be described by AFC (assimilation–fractional crystallization; DePaolo 1981) models or by more complex MASH (melting–assimilation–storage–homogenization; Hildreth and Moorbath 1988) models. However, any attempt to use these models would involve several unconstrained parameters which introduces severe difficulties. Additionally, the MASH scenario results in a close approximation to simple mixing provided that there is enough time for the mantle-derived melt and the crustal component to be homogenized. Table 2 gives the ϵ_{Nd} values and Nd concentrations of the inferred mantle source (Hartmann and Wedepohl 1990) as well as the ϵ_{Nd} values and Nd concentrations of several possible crustal components (Stosch and Lugmair, 1984; Lee et al., 1993) which provide a rough estimation of the Nd isotope composition and Nd concentration of the lower crust beneath central Europe. From Table 2 it can be seen that the crustal contamination in

quartz tholeiites with an ϵ_{Nd} value of c. 1.0 ranges between 3.4 and 10.9 %. Quartz tholeiites with an ϵ_{Nd} value of c. -1.1 require crustal contamination between 6.3 and 25.8 %. In view of the rather primitive character of the quartz tholeiites, we suggest that contamination with crustal rocks with less strong negative ϵ_{Nd} values and/or high Nd concentrations seems to be less likely. It seems more likely that the contaminant is a lower crustal component with strong negative ϵ_{Nd} values but moderate high Nd concentrations, similar to the Lewisian xenoliths investigated by Lee et al. (1993). Considering a Lewisian-like lower crustal component is also in line with the inferred high Zr/Nb ratios (Fig. 7), a feature observed in Lewisian lower crustal rocks (Rollinson and Fowler 1987).

Conclusions

The geodynamic setting of the volcanism of Central Europe has been discussed in detail by Wilson and Downes (1991). They noted that the main volcanic centres are located on uplifted Variscan basement and that the major graben systems show only minor igneous activity. Magmatism in the Vogelsberg area is therefore difficult to link simply to lithospheric thinning during rifting and must be related somehow to plume activity. A major contribution from asthenospheric sources in terms of a rising diapir is also indicated by the enriched trace element signature but depleted Nd–Sr–Pb isotopic signature of the primitive basalts from Europe (Wörner et al. 1986; Wilson and Downes 1991; Cebria and Wilson 1995; Wilson et al. 1995). Several authors have shown that the source rocks of OIB-like alkaline lavas are a constituent of the asthenosphere due to dispersion of mantle plumes (Galer and O’Nions 1986; White 1993) and delamination of lithospheric mantle (McKenzie and O’Nions 1995). Melting of the shallow asthenosphere can account for the chemistry of these magmas (Zindler et al. 1984) and we propose that the chemical characteristics of the alkaline basalts originate from melting of enriched OIB-like sources at the top of the asthenosphere. Estimates of lithosphere thickness are between 100–140 km prior to the onset of volcanism (Babuška and Plomerová 1988); therefore, partial melting at c. 90 km is located within the thermal boundary layer of the lower lithosphere (Wilson et al. 1995). Melting within this region with amphibole and

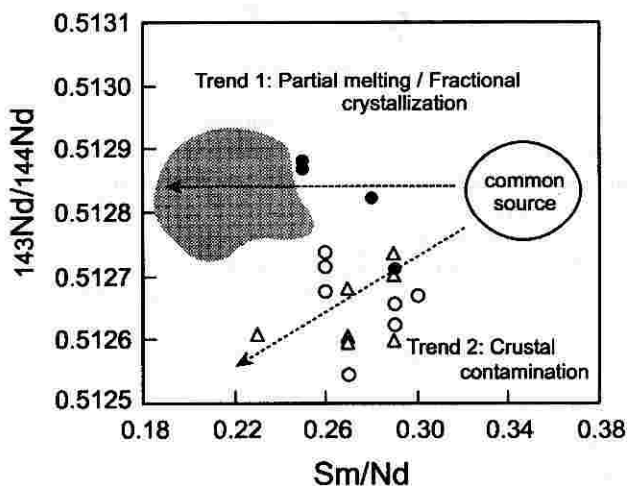


Fig. 9. $^{143}\text{Nd}/^{144}\text{Nd}$ vs. Sm/Nd for the Vogelsberg alkaline and tholeiitic rocks. Data sources: Wittenbecher (1992), Jung and Masberg (1998). A horizontal trend represent the partial melting/fractional crystallization path and an inclined path is consistent with crustal contamination.

garnet present, as suggested from the K-Rb and HREE systematics, is also compatible with the stability fields of both minerals (e.g. Wilson et al. 1995).

Compositional effects of lithosphere extension on the magmas derived beneath the lithosphere may be important because the lithosphere may act as a barrier to continuing upwelling of asthenospheric material undergoing adiabatic decompression (McKenzie and Bickle 1988). Upwelling may be passive in response to lithosphere thinning or active in response to an ascending plume. Because the plume is hotter than the ambient mantle, it will intersect the solidus at greater depth and requires much less lithospheric thinning to produce relatively large volumes of melt. In this indirect lithospheric control, the composition of magmas may be influenced by lithosphere thickness prior to the melting episode. During ascent of a plume, upper mantle material will be progressively heated above the plume head which, in turn, will result in partial melting of the uppermost mantle above that plume. If initial partial melting started at the lithosphere-asthenosphere boundary, it might therefore be expected that initial magmatism would have a lithospheric signature followed by melts with a plume signature. Schricke (1975) and Diederich et al. (1988) suggested, based on outcrop evidence, that in some areas within the Vogelsberg volcanic province tholeiitic rocks erupted before the alkaline rocks. The late appearance of plume-derived melts is consistent with models that invoke first melting of a more easily fusible lithosphere by conductive heating followed by melting of the plume due to thinning of the lithosphere. During the initial stages of volcanism the upper part of the lithosphere is rather rigid and intruding melts are forced to reside some time in lower crustal magma chambers. The view that the quartz tholeiites represent contaminated basaltic melts is also supported by the nearly equal densities of tholeiitic melts (2.8 g/ccm, Kushiro, 1982) and granites, granodiorites and felsic granulites (2.7 g/ccm, Herzberg et al., 1983) which constitute much of the lower crust beneath Central Germany (Mengel 1990). It is therefore very likely that the majority of tholeiitic melts will intrude into the lower crust instead of reaching the earth's surface.

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Appendix

The proportion of continental crust (x) added to one part of the mantle component is calculated using:

$$X = \frac{C_{\text{Nd}(m)}(\epsilon_{\text{Nd}(\text{final})} - \epsilon_{\text{Nd}(m)})}{C_{\text{Nd}(cc)}(\epsilon_{\text{Nd}(cc)} - \epsilon_{\text{Nd}(\text{final})})}$$

where m = mantle component, cc = continental crust, $\epsilon_{\text{Nd}}(\text{final})$ = ϵ_{Nd} of the resultant magma, and C Nd is the concentration of Nd. The percentage of the crustal component is given by:

$$\% \text{ crust} = \frac{100 X}{(1+X)}$$

These equations correspond to those given by Patchett and Bridgwater (1984) and Chauvel et al. (1987)

Analytical methods

The samples were prepared by crushing in an agate shatterbox. Aliquots were analysed for major and trace elements by fused lithium-tetraborate glass beads using standard XRF techniques at the Mineralogical Petrological Department at the University of Bonn. Several trace elements (Cr, Ni, Co, Pb) were verified by flameless atomic absorption spectrometry using the graphite furnace technique and by flame atomic absorption spectrometry.

etry (Rb) at the Mineralogical Department at the University of Marburg. Contents of Ba, Sr, Zr, Nb, and Y were verified by inductively coupled plasma emission spectrometry (ICP-AES) following Heinrichs and Herrmann (1990). The precision of each technique is better than 5–10% for all trace elements and the agreement between XRF and atomic absorption spectrometry is generally better than 5%. REE have been analysed by inductively coupled plasma emission spectrometry following separation of the matrix elements by ion exchange (Heinrichs and Herrmann, 1990). LOI (loss on ignition) was determined gravimetrically at 1050 °C (Lechler and Desilets, 1987) and FeO was measured titrimetrically with standard techniques. Accuracy was controlled by repeated measurements of international and in-house standards.

Sr and Nd isotope analyses were carried out at the Max-

Planck-Institut für Chemie at Mainz using thermal ionization mass spectrometry with a Finnigan MAT 261 multiple sample, multicollector mass spectrometer operating in the static mode. Samples were leached in 6N HCl for at least 6 hours and leachates were treated separately. Sr and REE were separated by using standard cation exchange columns with a DOWEX AG 50 W-X 12 resin using 2.5N HCl for Sr and 6N HCl for the REE. Nd was separated from the other REE by using HDEHP coated teflon columns and 0.12 N HCl. Nd isotopes were normalized to $^{146}\text{Nd}/^{144}\text{Nd}$: 0.7219. Repeated measurements of the La Jolla Nd standard gave $^{143}\text{Nd}/^{144}\text{Nd}$: 0.511848 ± 0.000021 (2σ ; $n = 28$). The reproducibility of the Sr standard (NBS 987) is $^{87}\text{Sr}/^{86}\text{Sr}$: 0.710224 ± 0.000024 (2σ ; $n = 14$) and the fractionation was corrected to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$.