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# How many mantle plumes in Africa? The geochemical point of view

R. Pik [a,*], B. Marty [a,b], D.R. Hilton [c]

[a] Centre de Recherches Pétrographiques et Géochimiques, CRPG, CNRS-UPR 2300, BP 20, 54 501 Vandoeuvre-Lès-Nancy Cedex, France
[b] Ecole Nationale Supérieure de Géologie, rue du Doyen Marcel Roubault, BP 40, 54501 Vandoeuvre-Lès-Nancy Cedex, France
[c] Geosciences Research Division, Scripps Institution of Oceanography, La Jolla, California 92093-0244, USA

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## Abstract

The association of anomalous topographic swells and widespread Cenozoic volcanism within the African plate (Hoggar, Tibesti, Darfur, Ethiopian highlands, Kenyan dome) may reflect either the involvement of one, or several, deep mantle plumes, or, alternatively, be attributed to tectonic processes involving only the lithosphere or the shallow asthenosphere. We present here new helium isotopic measurements that, added to existing data, allow us to restrict the spatial extent of a high-$^3$He component (up to 20 Ra) to the Ethiopia–Afar volcanic province, for places where large volumes of Oligocene pre-rift flood basalts and ignimbrites erupted within a short (1–2 Ma) time interval. All other investigated African volcanic provinces display MORB-type, and/or continental lithosphere-like, $^3$He/$^4$He signatures (7 ± 2 Ra) often modified by a contribution of crustal He. The distribution of He isotopic signatures in Africa, together with other isotopic (Sr–Nd–Pb) tracers measured in Miocene to Plio–Quaternary alkaline lavas in East-Africa, is fully consistent with the occurrence of two types of mantle plumes: (i) a large, deep-sited mantle plume characterized by a high-$^3$He signature, possibly originating from the core–mantle boundary according to seismic mantle tomography, which triggered the flood basalt eruptions 30 Ma ago and which subsequently interacted with shallower mantle sources to produce the syn-rift volcanism of the Ethiopia–Afar province; and (ii) a second-order type of shallow mantle upwelling, presumably originating from depths shallower than 400 km as suggested by seismic wave imaging, distinct from the main Afar plume and disseminated within the African plate under the uplifted and rifted swells. The above conclusions do not support the view of a unique large mantle plume feeding all Cenozoic African volcanic provinces. The fact that high-$^3$He signals are associated with the largest lava volumes erupted in Africa since the beginning of the Cenozoic argue against models advocating a shallow origin for high $^3$He/$^4$He signatures. Instead, they confirm that such signatures characterize hot material coming from the deep mantle.

*Keywords:* Mantle plumes; Helium isotopes; East African Rift; African volcanism; Afar plume; Kenyan plume

## 1. Introduction

Eastern Africa, as well as other smaller areas across the African plate, are characterized by the association of Tertiary to Recent volcanism and anomalous topographic swells (Fig. 1). Along the East African Rift System (EARS), as far as Southern Africa, high plateaus rising above the surrounding low-lands by more than 1 km form what has been called the African Superswell (Nyblade and Robinson, 1994; Lithgow-Bertelloni and Silver, 1998). To account for the relationship between African intraplate volcanism, topographic elevation and seismic velocity anomalies, the presence of one or several mantle plumes has been put forward in various models (Ebinger and Sleep, 1998; George et al., 1998; Ritsema et al., 1999; Gurnis et al.,

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[*] Corresponding author. Tel.: +33 3 83 59 42 27; fax: +33 3 83 51 17 98.
*E-mail address:* rpik@crpg.cnrs-nancy.fr (R. Pik).

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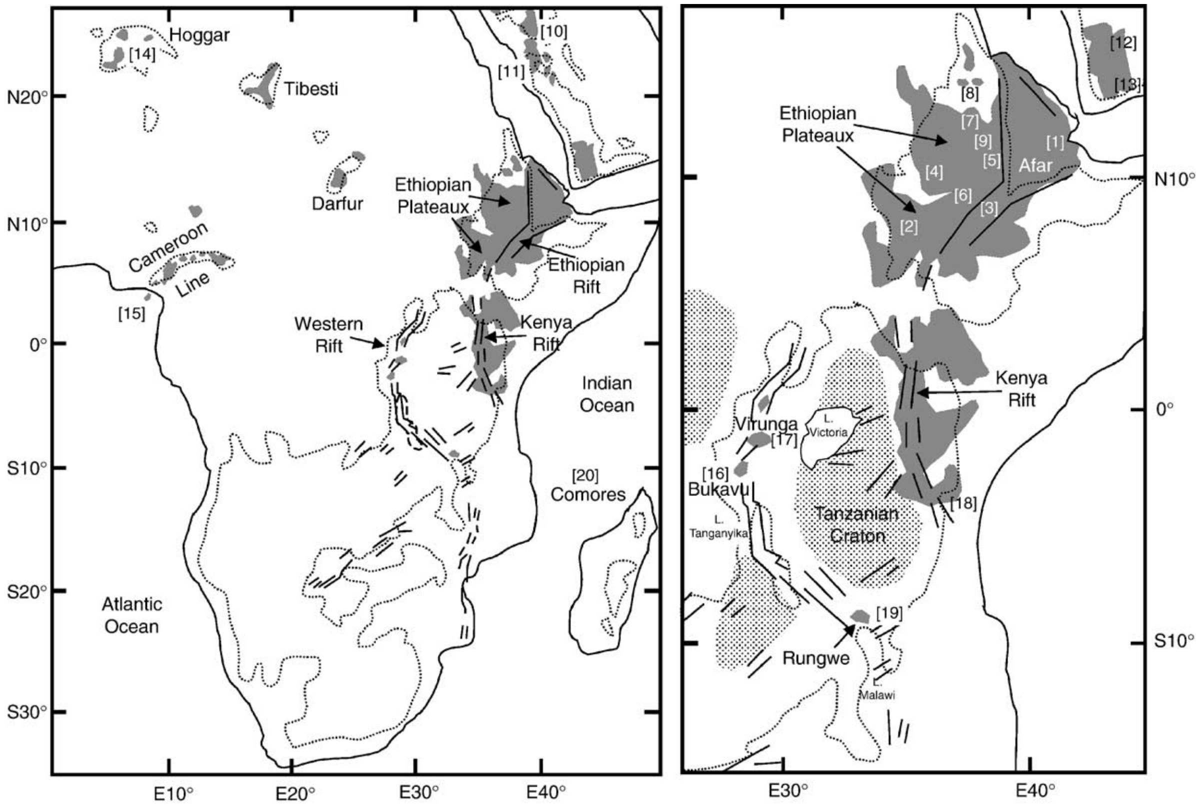

Fig. 1. Geological and tectonic map of Africa showing the anomalous topographic swells surrounding hotspots and rifted African provinces (dashed lines, elevation >1000 m), as well as the main tectonic features (Kampunzu et al., 1998), the location of Archean cratons (field with dots) and the main Cenozoic volcanic provinces (grey field). The numbers in square brackets refer to samples in the Tables.

2000; King and Ritsema, 2000; Davis and Slack, 2002). To the north of the EARS, the voluminous Ethiopian flood basalts and subsequent volcanism (probably more than $1\times10^6$ km$^3$ in total, (Mohr, 1983; Mohr and Zanettin, 1988) as well as geological, geochemical, and geophysical characteristics of the Afar area, have long been attributed to the activity of a mantle plume (Schilling, 1973; White and McKenzie, 1989; Marty et al., 1993; Courtillot et al., 1999). However, geochemical identification of such a mantle plume is difficult due to the diversity of the different mantle and crustal sources and variations in their respective contributions through time (Hart et al., 1989; Vidal et al., 1991; Chazot and Bertrand, 1993; Deniel et al., 1994; Baker et al., 1996, 1997; Pik et al., 1999). The possible relationship between volcanism in Ethiopia and that in Kenya has been investigated from a geochemical point of view by Rogers et al. (2000), who proposed that two distinct plumes are present under these two bordering volcanic provinces, and by Furman et al. (2004) who instead advocated the occurrence of a unique long-lived plume component under the Ethiopian and Kenyan domes.

One of the major issues in such a debate concerning hotspot mantle sources is what constitutes a “plume” (e.g., Courtillot et al., 2003). Indeed, mantle plumes which impinge upon the base of the continental lithosphere may range in size from large-scale (~1000 km) plume heads, inferred to trigger continental flood basalt provinces, to smaller wavelength convective instabilities. These two types of mantle plume are expected to sample deep and shallow mantle regions, respectively. For the Afar mantle plume, the geochemical argument used to support a deep mantle origin (Marty et al., 1993, 1996) is the occurrence of $^3$He/$^4$He ratios up to 20 Ra (Ra is the $^3$He/$^4$He ratio of atmospheric helium) in the lavas—much higher than the homogeneous values of mid-ocean ridge basalts (on average, $8\pm1$ Ra) or of the continental lithosphere (5–7 Ra) (Dunai and Porcelli, 2002; Graham, 2002). These high $^3$He/$^4$He ratios are thought to characterize mantle material originating from below the convective part of the mantle feeding mid-ocean ridge basalts (MORB).

In the general debate linking mantle plume concepts and hotspot surface expressions, a deep mantle origin for “high-$^3$He” material is currently questioned by some models which rather ascribe a lithospheric or shallow asthenospheric origin to the high-$^3$He end-member (Anderson, 1998, 2001). In one of these models (Meibom et al., 2003; Meibom and Anderson, 2004), the MORB $^3$He/$^4$He ratio of 8 Ra is regarded as resulting from averaging a highly heterogeneous lithosphere or shallow asthenosphere having a heterogeneous He isotope signature. One of the consequences of such a view is that high $^3$He/$^4$He ratios (that is, higher than the mean MORB of 8 Ra), as well as low $^3$He/$^4$He values, should be observed in volcanic provinces characterized by low degrees of partial melting which result in poorly homogenized magmas at a province scale. In contrast, $^3$He/$^4$He ratios close to MORB's values would characterize volcanism with high degrees of partial melting having sampled and averaged large portions of the shallow mantle (Meibom et al., 2003). For Cenozoic volcanic provinces associated with the African plate, the highest (and lowest) $^3$He/$^4$He values should be found in volcanic provinces showing the lowest partial melting rates (e.g. undersaturated volcanism). Conversely, high partial melting rate lavas, such as tholeiitic CFB, should produce $^3$He/$^4$He values in the MORB range. Furthermore, a shallow origin for helium signals also implies that the source of all magmas, even those that fed the Ethiopian flood basalts, have a shallow mantle origin. This scenario is at odds with the one proposed by Ebinger and Sleep (1998) which links most of the Cenozoic African plate volcanism to a single large mantle plume channeled along lithosphere discontinuities beneath a moving African plate.

Here we use new helium isotopic data together with published data for different African volcanic provinces in order to test the above-mentioned models and to investigate the relationship between African volcanic provinces and mantle dynamics. He isotope data were previously published for Ethiopian lavas (Marty et al., 1993, 1996; Scarsi and Craig, 1996), for Darfur lavas (Franz et al., 1999), for geothermal fluids from the EARS (Darling et al., 1995), and for both lavas and fluids from the Cameroon line (Barfod et al., 1999). The newly sampled areas include Yemen (CFB), the Red Sea coast in the Arabian plate, the Hoggar the Comores and volcanic regions along the EARS such as Tanzania and Zaire.

## 2. Geological setting and samples

The African Superswell rises to about 2 km above the basement in Eastern and Southern Africa (Fig. 1). Several studies have proposed that part of the uplift was triggered by dynamic processes associated with the presence of seismically imaged low-velocity anomalies in the underlying mantle, originating either in the lower mantle for the Southern African plateau or at shallower depths (250 to 500 km) for the East African plateaus (Lithgow-Bertelloni and Silver, 1998; Gurnis et al., 2000; Davis and Slack, 2002; Weeraratne et al., 2003; Benoit et al., submitted for publication). Gravity data and crustal structures under the EARS and surrounding plateaus (Ebinger et al., 1989; Dugda et al., 2005), as well as the domal-shape and long-lived stability of the Northern Ethiopian plateau uplift (Pik et al., 2003), also support a combination of dynamic compensation and crustal underplating of magma bodies as the predominant control on these large topography anomalies. On a larger scale, Ritsema et al. (1999) have proposed, based on a global seismic tomography approach, that a deep mantle anomaly originating from the mantle–core boundary rises until it impinges the Earth's lithosphere beneath the Afar volcanic province.

The African Superswell is capped in its northern part–where the low-velocity seismic anomaly is located in the upper mantle–by large volumes of lavas erupted since the Eocene. Both the volumes and lava compositions vary significantly along the EARS. Large volumes of flood tholeiites and ignimbrites (~10$^6$ km$^3$, Mohr and Zanettin, 1988; Pik et al., 1998; Ayalew et al., 2002) were erupted ~30 Ma ago in Ethiopia over a short time interval of possibly 1–2 Ma or less (Hofmann et al., 1997; Rochette et al., 1998; Ayalew et al., 2002). This major phase of flood volcanism has shaped the Northern and Southern Ethiopian plateaus. It has been preceded in SW Ethiopia by limited volumes of Eocene volcanism (Ebinger et al., 1993; George et al., 1998) spatially associated with a rifted zone connecting the Mesozoic NW Anza rift to the current NE Main Ethiopian Rift (Cerling and Powers, 1977; Ebinger et al., 2000). Volcanic activity continued from Miocene to Present in Ethiopia, with much smaller volumes and no flood basalt volcanism, with the exception of the Stratoid formation (5–2 Ma) in Afar. This subsequent Miocene and Plio–Quaternary volcanism consists of large shield volcanoes on the plateaus (Piccirillo et al., 1979; Kieffer et al., 2004) and in variably differentiated stratovolcanoes within rifted areas in the Main Ethiopian Rift and in Afar (Mohr and Zanettin, 1988). Southward along the Kenya Rift, significant volumes of alkaline to transitional basic and evolved lavas have also been emplaced since the Miocene (Macdonald et al., 2001). In contrast, limited volumes of undersaturated nephelinites and carbonatites (Paslick et al., 1995; Kalt et al., 1997) erupted in the Western and Southern parts of the EARS, with a general tendency for lavas to

Table 1
Helium isotopic analysis of olivine from alkaline lavas

| | Sample # | Location Fig. 1 | Latitude | Longitude | $^4$He ($10^{-12}$ mol/g) | R/Ra | ± |
|---|---|---|---|---|---|---|---|
| Djibouti–Assal Rift[a] | DR14 | 1 | 11.53 | 42.52 | 0.04 | 15.0 | 0.3 |
| Ethiopia[a] | | | | | | | |
| SW plateau—Tepi | 19–98 | 2 | 7.52 | 35.42 | 0.80 | 3.8 | 0.1 |
| SW plateau—Tepi | 17–98 | 2 | 7.52 | 35.42 | 0.33 | 3.0 | 0.1 |
| Rift-Zway | 63–98 | 3 | 8.03 | 38.72 | 0.14 | 7.7 | 0.3 |
| Tana-Injibara | AD67 | 4 | 11.36 | 37.11 | 0.17 | 8.1 | 0.2 |
| Termaber-Dessie | 60–98 | 5 | 10.97 | 39.49 | 0.87 | 6.0 | 0.1 |
| Termaber-Fiche | AD70 | 6 | 9.80 | 38.59 | 1.45 | 7.0 | 0.1 |
| Termaber-Ras Dashen | PM252 | 7 | 13.25 | 38.19 | 0.35 | 11.3 | 0.2 |
| NW plateau CFB-low-Ti | E216 | 8 | 14.25 | 39.34 | 0.45 | 4.4 | 0.1 |
| NW plateau CFB-high-Ti | E38 | 9 | 11.96 | 39.40 | 0.08 | 16.4 | 0.5 |
| Saudi Arabia[a] | AS32 | 10 | 24.80 | 38.01 | 0.29 | 7.0 | 0.2 |
| | AS54 | 11 | 22.53 | 40.24 | 0.05 | 8.6 | 0.3 |
| Yemen[a] | Y5 | 12 | 15.68 | 45.31 | 0.23 | 3.4 | 0.2 |
| | Y6 | 12 | 15.68 | 45.31 | 0.52 | 2.4 | 0.1 |
| | Y118 | 13 | 13.70 | 46.25 | 0.04 | 6.5 | 0.4 |
| | Y112 | 13 | 13.70 | 46.25 | 0.21 | 16.2 | 0.5 |
| Hoggar[a] | BM1 | 14 | 23.25 | 5.75 | n.d. | 8.6 | 3.3 |
| | BM3 | 14 | 23.25 | 5.75 | n.d. | 8.7 | 0.6 |
| | BM4 | 14 | 23.25 | 5.75 | n.d. | 8.9 | 1.1 |
| Fernando Po Island[a] | BM-FP | 15 | 3.61 | 8.78 | n.d. | 6.2 | 0.2 |
| Zaire–Bukavu Field[a] | He7 | 16 | −2.53 | 28.72 | 0.06 | 8.9 | 0.3 |
| | He5 | 16 | −2.53 | 28.72 | 0.11 | 7.6 | 0.3 |
| | He2 | 16 | −2.53 | 28.72 | 0.09 | 6.4 | 0.2 |
| Zaire–Virunga Field[a] | | | | | | | |
| Nyiragongo | AP30 | 17 | −1.57 | 29.17 | 1.32 | 7.4 | 0.1 |
| | AP31 | 17 | −1.57 | 29.17 | 0.31 | 7.1 | 0.2 |
| | AP40 | 17 | −1.57 | 29.17 | 0.65 | 8.4 | 0.1 |
| | AP148b | 17 | −1.57 | 29.28 | 0.69 | 7.8 | 0.1 |
| | AP149b | 17 | −1.57 | 29.28 | 0.50 | 7.2 | 0.2 |
| | AP114 | 17 | −1.49 | 29.28 | 0.97 | 8.5 | 0.1 |
| | AP107b | 17 | −1.49 | 29.28 | 1.42 | 7.6 | 0.1 |
| Visoke | OT19 | 17 | −1.28 | 29.48 | 0.41 | 6.1 | 0.2 |
| | OT25 | 17 | −1.28 | 29.48 | 0.40 | 6.9 | 0.1 |
| | OT27 | 17 | −1.28 | 29.48 | 0.47 | 6.8 | 0.1 |
| Tanzania[b] | | | | | | | |
| Arusha | ARU-1 | 18 | −3.10 | 37.20 | 0.59 | 7.8 | 0.2 |
| Rungwe | RNG-13 | 19 | −9.33 | 34.08 | 0.49 | 7.7 | 0.2 |
| Lashaine | LAS-10A | 18 | −3.37 | 36.43 | 10.20 | 5.9 | 0.1 |
| Kilimanjaro (Himo) | KMJ-5 | 18 | −3.40 | 37.53 | 0.31 | 6.7 | 0.1 |
| Lake Manyara | MAN-4 | 18 | −3.75 | 35.83 | 0.99 | 5.9 | 0.1 |
| Arusha (Kivitek) | KIV-1 | 18 | −3.60 | 37.13 | 1.01 | 5.7 | 0.1 |

Analysis from: a = noble gas laboratory, CRPG b = Isotope Laboratory, Scripps Institute of Oceanography.

Table 2
Helium and neon isotopic analysis from geothermal fluids

| | Sample # | Location Fig. 1 | Latitude | Longitude | He/Ne | R/Ra |
|---|---|---|---|---|---|---|
| Kilambo springs[b] | Kil-1A | 19 | −9.33 | 33.67 | 1895 | 2.38 |
| | Kil-1B (dup) | 19 | −9.33 | 33.67 | 1211 | 2.31 |
| | Kil-2B | 19 | −9.33 | 33.67 | 2325 | 2.43 |
| Ikama village (Katumba area)[b] | Kat-1A | 19 | −9.31 | 33.68 | 138 | 7.34 |
| | Kat-1B | 19 | −9.31 | 33.68 | 86 | 7.20 |
| | Kat-2A | 19 | −9.31 | 33.68 | 105 | 7.76 |
| | Kat-2B | 19 | −9.31 | 33.68 | 80 | 7.48 |
| Kalambo area[b] | Kmb-1 | 19 | −9.28 | 33.70 | 10 | 1.16 |
| | Kmb-2 | 19 | −9.28 | 33.70 | 28 | 0.72 |
| | Kmo-1 | 19 | −9.28 | 33.70 | 17 | 0.60 |
| | Kmo-2 | 19 | −9.28 | 33.70 | 130 | 0.22 |
| Kiblia[b] | Kib-1 | 19 | −9.33 | 34.08 | 75 | 6.65 |
| | Kib-2 | 19 | −9.33 | 34.08 | 1937 | 6.67 |
| Songwe river[b] | Son-1 | 19 | −9.00 | 33.00 | 33 | 2.27 |
| | Son-2 | 19 | −9.00 | 33.00 | 27 | 2.65 |
| | Son-3 | 19 | −9.00 | 33.00 | 66 | 1.56 |
| | Son-4 | 19 | −9.00 | 33.00 | 44 | 2.30 |
| Ivuna[b] | Ivu-1 | 19 | −8.35 | 32.52 | 167 | 0.26 |
| | Ivu-2 | 19 | −8.35 | 32.52 | 214 | 0.23 |
| Lake Manyara[b] | Lmn-1 | 18 | −3.75 | 35.83 | 328 | 0.10 |
| | Lmn-2 | 18 | −3.75 | 35.83 | 1914 | 0.06 |
| Comores Island[a] | OV17 | 20 | −12.00 | 44.00 | 5 | 5.37 |
| | OV23 | 20 | −12.00 | 44.00 | 30 | 5.62 |

Analysis from: a = noble gas laboratory, GRPG b = Isotope Laboratory, Scripps Institution of Oceanography.

become more alkaline and less voluminous as rifts developed between cratonic blocks to the south and west during the Miocene (George et al., 1998; Kampunzu et al., 1998; Nyblade and Brazier, 2002). An association between crustal uplift and recent volcanism is also observed in Darfur, Hoggar, and Tibesti volcanic provinces where lavas are also generally undersaturated (Fig. 1, Franz et al., 1999).

Within the Afar–Ethiopia volcanic province, $^3$He/$^4$He ratios (Marty et al., 1993, 1996; Scarsi and Craig, 1996) range from near crustal values (<1 $R_A$) through normal upper mantle values (observed for MORBs ~7–8 Ra, Graham, 2002)), to values higher than MORB (up to 19.6 Ra) reflecting a $^3$He-rich component interpreted as diagnostic of a lower mantle contribution during the genesis of magmas (Graham, 2002). The highest $^3$He/$^4$He ratios have been observed in the high-Ti pre-rift Oligocene flood basalts (Marty et al., 1996) identified by Pik et al. (1999) as best representing the Afar plume component composition (HT2 group of lavas). These results strongly suggest that a deep plume-type component was already present during the genesis of the 30-Ma old CFB, which predated regional extension and rifting. The proposed lateral extent of high $^3$He/$^4$He ratios is consistent with an approximate radius of ~1000 km for the flattened Afar plume head. More recent data from Darfur (Franz et al., 1999) have confirmed this estimate of the plume radius as it displays normal upper-mantle helium isotopic ratios.

In order to extend helium isotopic data to other African plate volcanic provinces, $^3$He/$^4$He ratios have been measured in olivine-bearing alkaline lavas from most of the volcanic areas from which data were missing: Hoggar, Zaire (Virunga and Bukavu fields), Tanzania (Northern area volcanoes and Rungwe field) and Fernando Po Island (Cameroon line) (Fig. 1, and Table 1). Late-Miocene to Plio–Quaternary alkaline lavas from the Arabian plate (Yemen and Saudi Arabia, Fig. 4) are also included.

Geothermal fluids from Tanzania and the Comores Islands have also been analyzed to extend our record of helium isotope signatures to the Southeast part of the EARS and beyond. In Tanzania, fluids from the Mbeya Highlands in southern Tanzania, situated between Lake Malawi and Tanganyika, and from the Lake Manyara area in Northern Tanzania, were sampled (Fig. 1 and Table 2).

Additional data for the Ethiopian province have been obtained for the Miocene shield volcanoes emplaced on the NW-plateau and known as the Termaber Formation (Mohr and Zanettin, 1988), as well as for Quaternary off-axis volcanism on the NW-plateau south of Lake Tana and on the SW-plateau near the Tepi area (Fig. 1

and Table 1). Two samples from the Low-Ti and High-Ti flood basalts sub-provinces have been analyzed to complement existing data in pre-rift flood volcanics.

For the lavas, helium was extracted from olivine phenocryst separates by in vacuo crushing in order to minimize the contribution of radiogenic and nucleogenic matrix-sited helium. Purification and mass spectrometry procedures and calibrations are detailed in Marty et al. (1996). Helium in geothermal fluids from Tanzania was extracted and analyzed using a split flight-tube mass spectrometer following techniques described in Hilton and Craig (1989).

## 3. Results

### 3.1. New isotopic data

New He isotopic data from this study are presented in Tables 1 and 2. Lavas from the western branch of the EARS (Zaire), Tanzania, Comores, Hoggar and Fernando Po Island (Cameroon Line) display a limited range of $^{3}He/^{4}He$ ratios from 5.7 to 8.9 Ra. These values are typical of the upper mantle signature as observed in MORBs (Graham, 2002) and other continental and arc volcanoes (Dunai and Porcelli, 2002; Hilton et al., 2002).

For the new Ethiopian data, the range of measured $^{3}He/^{4}He$ is considerably wider, from 3 to 16.4 Ra, and overlaps the distribution of He isotope ratios previously determined for this volcanic province (Fig. 2). Helium isotopic values lower than 6 Ra already identified in Ethiopian lavas (Marty et al., 1996) correspond to either (i) accumulation of radiogenic $^{4}He$ in aged lavas (a few million years ago) depleted in volatiles, or (ii) crustal contamination, a process that could also affect old as well as young lavas. Low $^{3}He/^{4}He$ ratios in low-Ti Oligocene samples (E216) are consistent with crustal contamination for these

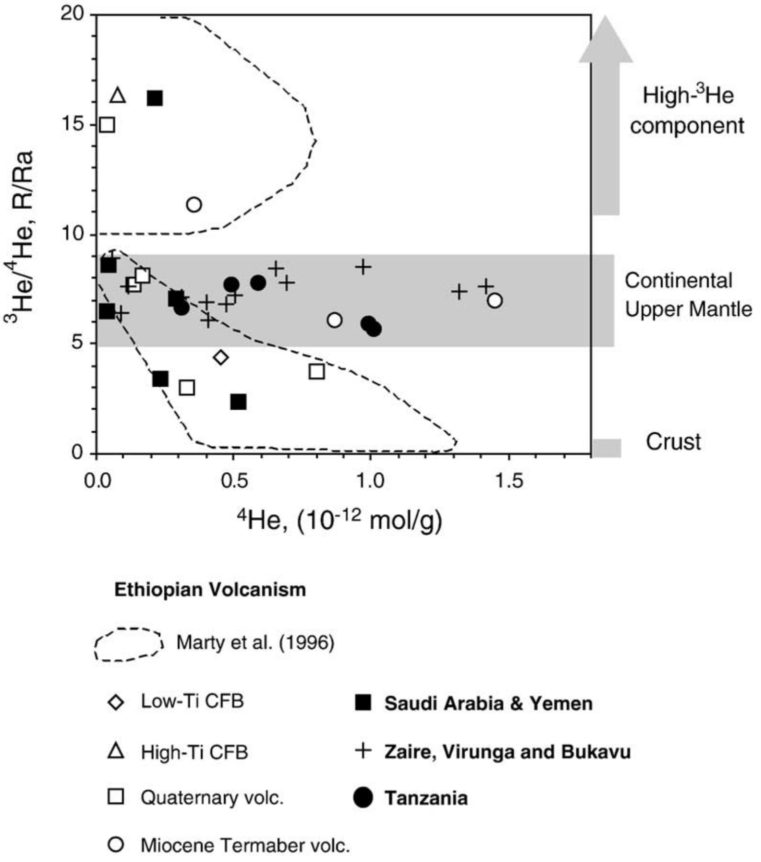

Fig. 2. Helium isotopic data for African and Arabian olivine-bearing alkaline lavas measured in this study. The data are compared to previous work on the Ethiopian volcanic province (Marty et al., 1996), as well as to the isotopic composition of the crust and mantle domains. $^{4}He$ enrichment by lava ageing or crustal contamination in Ethiopian and Yemeni lavas is supported by the negative correlation of the isotopic ratio (R/Ra) with the helium abundance.

lavas as inferred from other geochemical evidence (trace elements, Sr–Nd–Pb isotopic ratios, (Pik et al., 1999)). A low $^3He/^4He$ value of 4.4 Ra for the Quaternary alkaline lavas from the Tepi area (SW-plateau, Fig. 1) is more difficult to interpret. It could either represent an initial (uncontaminated) end-member for the Southern Ethiopian plateau, or, alternately, a case for crustal contamination that has also been advocated for low-Ti Oligocene flood basalts (Marty et al., 1996). Other Quaternary (Tana and main Rift) and Miocene lavas (Fiche and Dessie Termaber volcanoes) display $^3He/^4He$ from 6 to 8 Ra, and are consistent with an upper mantle origin. Values from the Assal Rift (Djibouti), high-Ti flood basalts and the Miocene Ras-Dashen shield volcano (NW-Plateau) range from 11.3 to 16.4, and confirm the occurrence of a high-$^3He$ component in the Ethiopian lavas from Oligocene to Present.

The Yemenite CFBs, which were continuous with the Ethiopian traps before the opening of the Afar triple junction, display $^3He/^4He$ ratios varying from 2.4 to 16.2 Ra, overlapping the full compositional range of Ethiopian lavas (Marty et al., 1996). In contrast, the two samples which represent Miocene volcanism along the Red Sea coast (Saudi Arabia) display $^3He/^4He$ (7.0–8.6 Ra) in the range of normal upper mantle compositions.

The isotopic compositions measured in Tanzanian and Comores geothermal fluids (Table 2 and Fig. 3) display $^3He/^4He$ and $^4He/^{20}Ne$ ratios showing mixing between crustal, atmospheric and mantle components, as were fluids previously sampled in other parts of the East African Rift such as Kenya by Darling et al. (1995). Some of the samples display $^3He/^4He$ isotopic ratios as high as 6–7 Ra, in the same range as the 7.7 Ra value measured for the Rungwe field alkaline lava (Table 1). Other samples from Southern and Northern Tanzania geothermal fields highlight mixing of mantle-derived gases with a crustal component that can dominate the isotopic signatures. This Manyara–Ivuna–Kalambo trend does not mix back to the atmosphere, but somewhere along the atmosphere–mantle mixing array, suggesting that interaction with a crustal component occurred after mixing between atmosphere and the magma-derived fluids, in approximately constant proportions. Such strong crustal signatures have not been observed in Kenyan fluids (Fig. 3), and could reflect the scarcer volcanic activity and smaller volumes of magmas that characterize Tanzania and the southern part of the EARS.

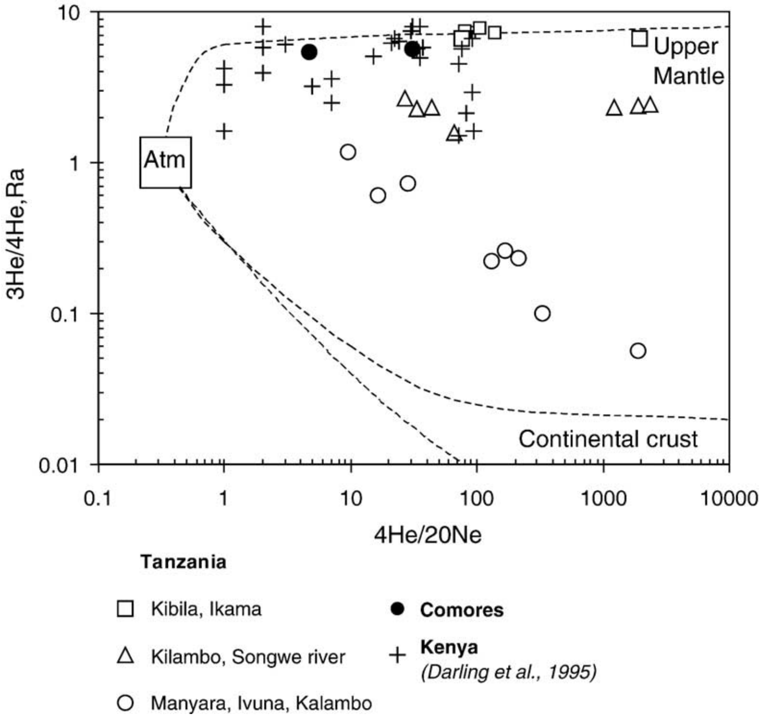

Fig. 3. Helium and neon isotopic data for geothermal fluids from Tanzania and Comores. Data are compared to geothermal fluids from Kenya rift (Darling et al., 1995). The composition of such complex geothermal fluid is also compared to calculated mixing lines between air, crust and mantle compositions.

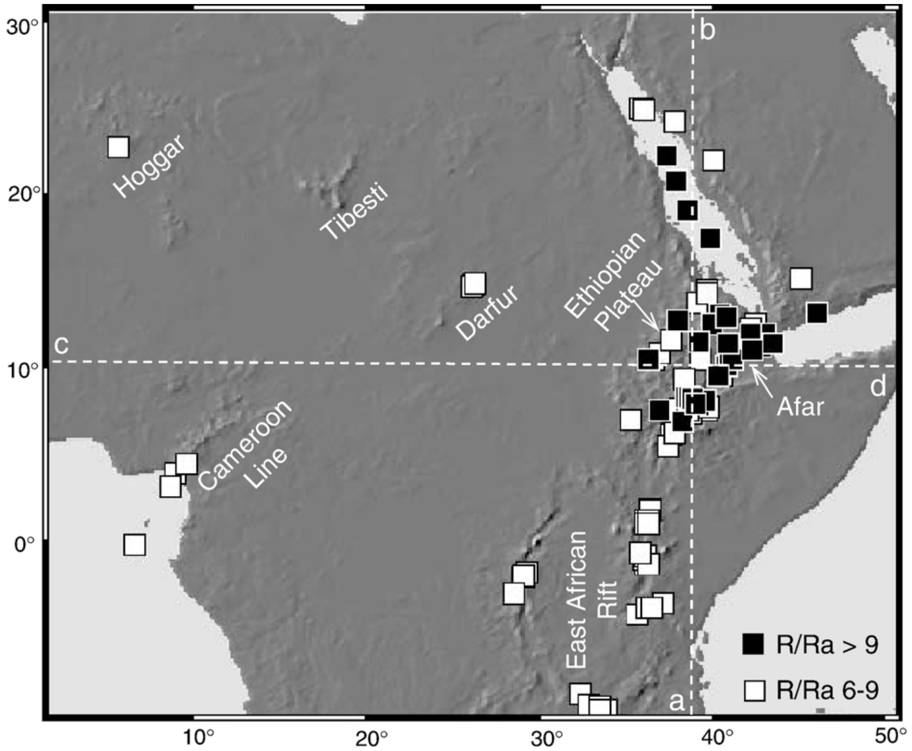

Fig. 4. Distribution of helium isotopic ratios R/Ra (with Ra the ratio of atmosphere) over the African plate. Data from this study and from (Marty et al., 1993, 1996; Darling et al., 1995; Moreira et al., 1996; Scarsi and Craig, 1996; Barfod et al., 1999; Franz et al., 1999).

### 3.2. Extension of the high $^3He/^4He$ signature over the African plate

Helium isotopic data from this study and from previous work (Figs. 4 and 5) allow us to highlight the distribution of high $^3He/^4He$ ratios over the African plate. These data clearly document the presence of a high-$^3He$ component (>9 Ra) in the Afar volcanic province (up to 20 Ra, Fig. 5, Ethiopia, Yemen and Djibouti) and, to a lesser extent, along the axis of the Red Sea (9–10 Ra, Fig. 5, Moreira et al., 1996). All the other Westward and Southern volcanic fields, distributed along the EARS or isolated within the plate (Darfur, Hoggar), are characterized by values of $7 \pm 2$ Ra that can be regarded as pinpointing the predominance of a MORB-like component more or less affected by crustal contamination or lava ageing (≤0.05 Ra end-member). The Cameroon line and associated islands also exhibit values between 5 and 7 Ra and do not show any evidence of a high-$^3He$ component. In the Arabian plate, values of 7.0–8.6 Ra in Saudi Arabia place a geographic limit on the Northeast extension of the high-$^3He$ component identified in the Afar area.

The present data set allows us to restrict the presence of a high-$^3He$ component to the Afar volcanic province. The spatial extension of this component corresponds to the area affected by large volumes of Oligocene pre-rift flood volcanism around the East African triple junction, and is compatible with the diameter of a large flattened plume head (~1000 km). In detail, we cannot distinguish between a pancake-like distribution of plume material under the Horn of Africa, or a thinner array of mantle flows radiating from the center of the plume head.

## 4. Discussion

### 4.1. The geochemical identification of East African plumes

The nature of mantle sources beneath the African plate has been investigated in numerous geochemical studies and has led to variable, sometimes contradictory, conclusions concerning the presence and composition of underlying mantle plumes. Despite their general OIB-like trace element compositions, previously attributed to a “plume-type” component as opposed to a MORB composition (Schilling, 1973), lavas from the whole East African region display variable and contrasted isotopic signatures. One of the most controver-

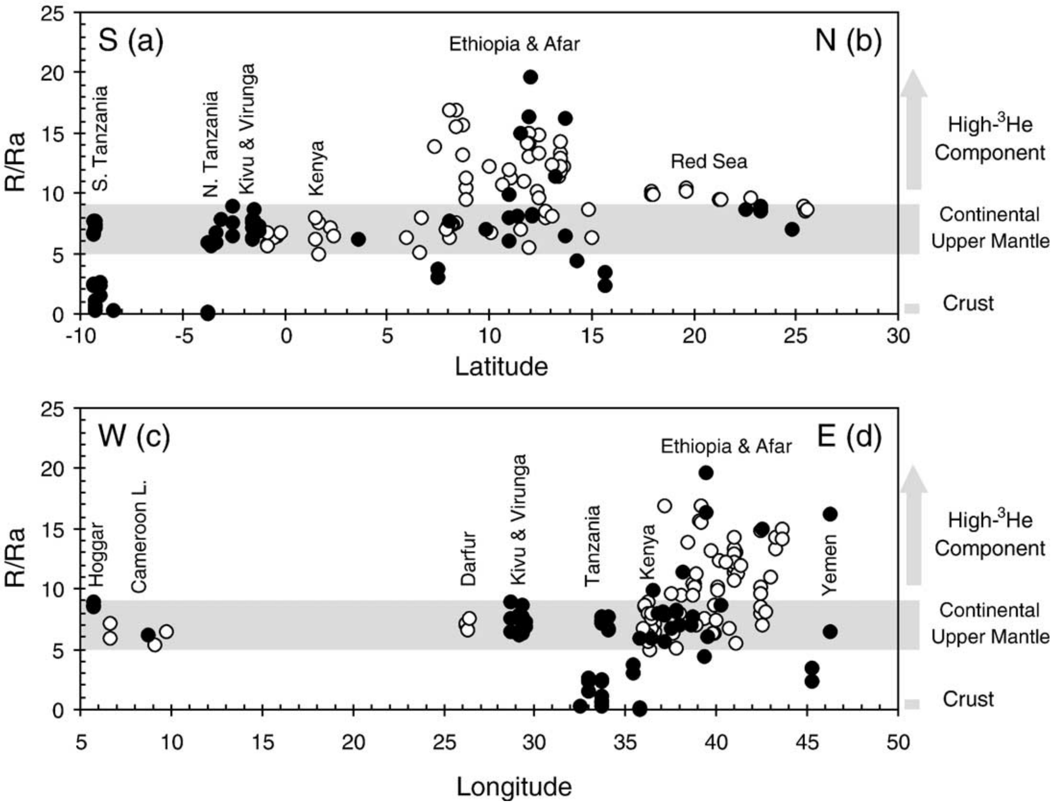

Fig. 5. Distribution of helium isotopic ratios R/Ra (with Ra the ratio of atmosphere) over the African plate. Data are plotted as a function of their latitude or longitude. Data from this study corresponds to filled dots and data from previous work to open dots (Marty et al., 1993, 1996; Darling et al., 1995; Moreira et al., 1996; Scarsi and Craig, 1996; Barfod et al., 1999; Franz et al., 1999).

sial arguments concerns the high $^{206}$Pb/$^{204}$Pb ratios exhibited by a large proportion of Miocene and Quaternary lavas (Fig. 6A). This radiogenic Pb character is compatible with a high time-integrated U/Pb ratio (HIMU) in the source of magmas, and has been variously attributed in East Africa to: (i) the Afar mantle plume itself (Schilling et al., 1992; Deniel et al., 1994), (ii) a common Kenyan–Afar mantle plume (Furman et al., 2004), and (iii) the heterogeneous East African lithospheric mantle (Paslick et al., 1995; Simonetti and Bell, 1995; Kalt et al., 1997).

In line with the last hypothesis, Pik et al. (1999) proposed that this HIMU signature, which is not observed in the composition of the widespread pre-rift flood basalts from Northern Ethiopia (Fig. 6A), cannot be part of the plume head that triggered this important volcanic crisis (Marty et al., 1996), but rather resides in the Ethiopian continental mantle lithosphere. More recently, the widespread occurrence of the HIMU character among alkaline lavas all over the Arabian plate led Bertrand et al. (2003) to reach a similar conclusion. In the African plate the HIMU volcanism is also very widespread, characterizing Miocene to Plio–Quaternary volcanism at Darfur, Ethiopia, Kenya, Tanzania and Cameroon (Fig. 6A). The highest $^{206}$Pb/$^{204}$Pb have been measured in alkaline and carbonatitic magmas from the EARS, inferred to be derived from the continental lithosphere (Fig. 6A, Paslick et al., 1995; Simonetti and Bell, 1995; Kalt et al., 1997). This view is also strongly supported by analyses of mantle xenoliths from Tanzania (Fig. 6A, Cohen et al., 1984) which display the full HIMU-type compositional trend exhibited by East African alkaline lavas. The shallow mantle sampled by these xenoliths therefore represents a straightforward candidate for the source component of these magmas.

However, this view is not shared by Kieffer et al. (2004) who proposed that the radiogenic Pb component is present in the head of a large composite Ethiopian mantle superswell which triggered both the Oligocene flood basalts and the subsequent Miocene and Quaternary volcanism by melting of compositionally distinct regions. This inference is in contrast to the view of Pik et al. (1999) who proposed that the Afar

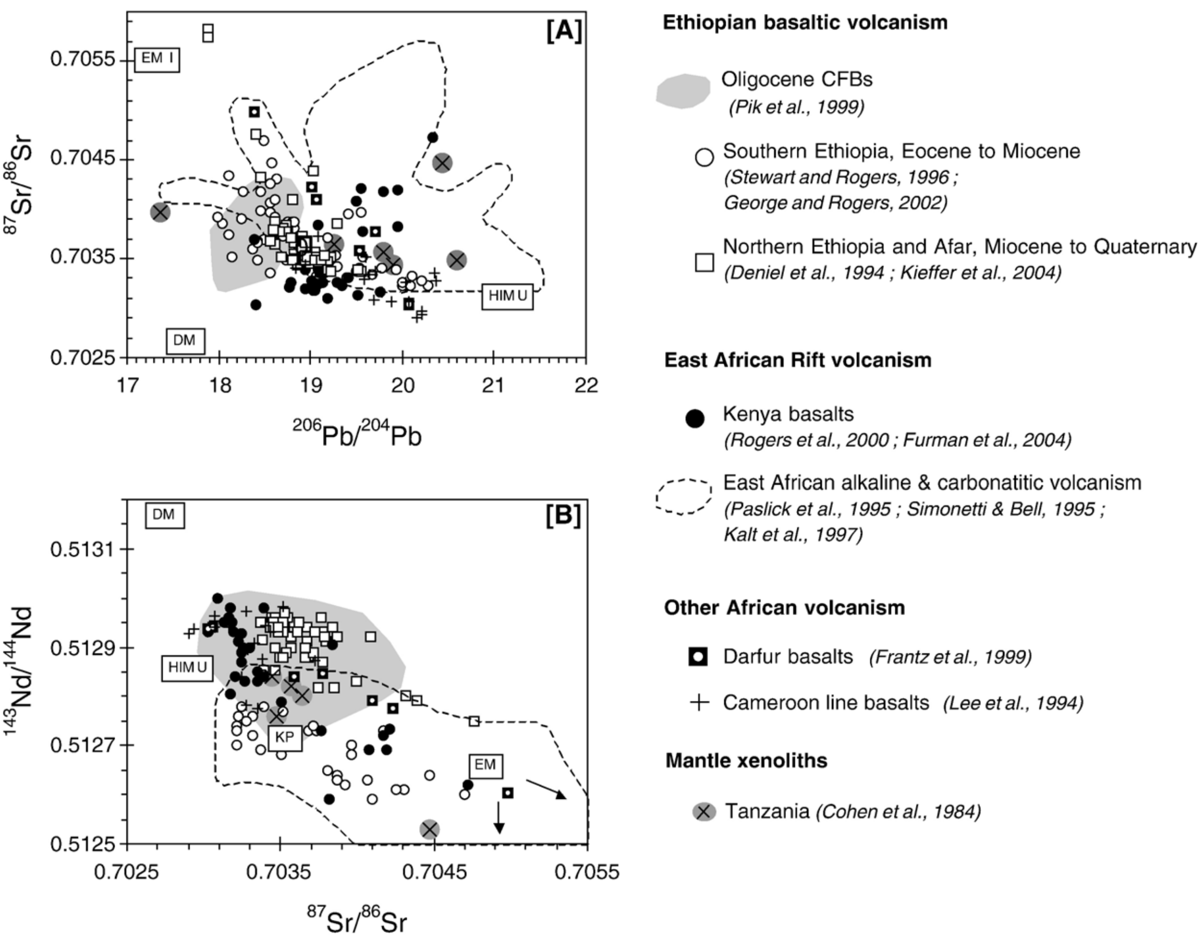

Fig. 6. Compilation of Sr–Nd–Pb isotopic data from the main volcanic provinces of Africa. Mantle domains are indicated, DM: depleted mantle, EM: Enriched mantle, HIMU: high time-integrated U/Pb ratio, KP: proposed Kenyan plume composition after Rogers et al. (2000).

plume composition is represented by the less-contaminated high-Ti and low-Ti flood basalts which define two very close, but isotopically distinct, end-members (Fig. 6a and b). These CFB compositions do not show any contribution from the HIMU component, which strongly suggests that this component did not contribute significantly to magma genesis during the pre-rifting stage in Northern Ethiopia. Rogers et al. (2000) defined a Sr–Nd composition for the Kenyan plume different from that of the Afar plume proposed by Pik et al. (1999). Likewise, this Kenyan plume composition cannot account in the same Sr–Nd space for the signatures of most of the modern lavas in the Afar province (Fig. 6B). Despite these differences, the lead isotopic compositions are rather indicative of a genetic link between the Kenyan basalts and the Ethiopian Miocene to Plio–Quaternary Basalts (Fig. 6A). Furthermore, a possible link between this Kenyan plume composition and lavas erupted by Miocene shield volcanoes emplaced onto the NW-Ethiopian plateau is supported by recent Sr–Nd data (Kieffer et al., 2004). Whatever the origin of this isotopic end-member characterized by low $^{143}Nd/^{144}Nd$ ratios (Fig. 6B, crustal contamination (Pik et al., 1999) or heterogeneous continental mantle lithosphere), it cannot be used to define a different sub-lithospheric Kenyan plume composition as it is also clearly involved in the genesis of some of the Ethiopian lavas.

Volcanism from the Cameroon Line in western Africa also displays isotopic signatures typical of the involvement of a HIMU component (Halliday et al., 1990; Lee et al., 1994). In Sr–Nd–Pb isotopic spaces, these lavas overlap the compositions of other Miocene to Plio–Quaternary African volcanics (Fig. 6). In the case of the Cameroon Line, this HIMU signature has been regarded as originating from a plume head emplaced in the upper mantle ~100 Ma ago (Halliday et al., 1990; Barfod et al., 1999).

Besides the debate concerning the interpretation of isotopic signatures, the major observations pertinent to the above discussion can be summarized as follows:

(1) The unique magma group in East Africa that: (i) displays limited isotopic compositional variations (when corrected for crustal contamination), (ii) corresponds to the largest volumes erupted in the Cenozoic magmatic history of the African plate and (iii) displays petrological and chemical characteristics compatible with a deep origin of the magmas (Pik et al., 1998; Kieffer et al., 2004), is represented by the pre-rift Oligocene flood basalts from the NW-Ethiopian plateau (and from the Yemeni Plateau, Chazot and Bertrand, 1993; Baker et al., 1996). Moreover this lava group does not show any contribution of an HIMU component.

(2) All Miocene and Plio–Quaternary alkaline lava groups, from rifted areas or localized intraplate volcanic provinces, display larger compositional trends (Fig. 6A and B) in which a HIMU-type component is variously mixed with other enriched or depleted mantle component(s).

(3) The widespread occurrence of similar compositional trends among African Miocene and Plio–Quaternary alkaline lavas prevents the identification of the separate "plumes" that has been proposed in the literature based on Sr–Nd–Pb isotope arguments (Rogers et al., 2000). On the other hand, such shared geochemical trends cannot reflect the contribution of a unique Afar plume feeding all African Cenozoic magmatism, because the African Miocene to Plio–Quaternary alkaline lavas display chemistries and isotopic signatures different from the homogeneous composition of the Oligocene Ethiopian flood basalts. It must be noted that the Ethiopian CFBs correspond to the most important magmatic episode–in terms of lava volume–and therefore must be central in a model which would propose a unique giant plume.

### 4.2. The use of helium isotopes for identifying mantle plumes in Africa

The distribution of helium isotopes over the African plate, discussed below (Figs. 4 and 5), delivers a simple message: the only place where high $^3He/^4He$ ratios have been observed–whatever the age of volcanism–corresponds to areas affected by the eruption of pre-rift Oligocene flood basalts in Ethiopia and Yemen. This observation is consistent with the following: (i) high $^3He/^4He$ ratios trace the involvement of a deep primitive mantle component (Graham, 2002), and (ii) the eruption of continental flood basalts corresponds to the impingement under the lithosphere of a large mantle plume head having a temperature higher than that of the ambient mantle (e.g. Richards et al., 1989; Courtillot et al., 2003). The unique geochemical signature of Ethiopian CFB, their considerable volume, and their high $^3He/^4He$ ratios (the highest values measured among African lavas and fluids) lead us to propose that the Ethiopian flood basalts represent the best candidate for a surface fingerprint of the deep-sited mantle upwelling imaged under South and East Africa (Ritsema et al., 1999). Moreover, their Sr–Nd–Pb isotopic composition is compatible with the proposed end-members for such deep material (FOZO, C, PHEM, etc....), as is also the case in other plume-related volcanic provinces such as Iceland for example (see for example the Discussion in Hilton et al., 1999).

It is noteworthy, however, that Marty et al. (1996) have shown that He–Sr correlations could not be explained only by mixing of deep mantle material with shallower enriched or depleted sources, and required a very limited contribution from a deep mantle reservoir. Indeed such mixing can only be seen in He isotopic ratios due to the unique enrichment in primordial $^3He$ whereas radiogenic isotope signatures are dominated by shallow mantle and recycled component contributions. The authors proposed limited mass transfer of deep mantle material at the 660 km seismic discontinuity together with efficient heat transfer and material upwelling above this discontinuity. This idea, which has been generalized for other OIB by Marty and Tolstikhin (1998) and Ellam and Stuart (2004), is apparently consistent with global seismic tomography imaging proposed by Ritsema et al. (1999) in which the connection between lower mantle and upper mantle low velocity zones under East Africa is not clear. Therefore, there might exist a barrier at this depth for transfer of deep mantle material whereas heat (and enough helium to create a high-$^3He$ anomaly) could readily traverse the discontinuity and contribute to the seismic anomaly imaged below Ethiopia (Debayle et al., 2001; Benoit et al., submitted for publication). However, other authors have argued that there is no physical mechanism that can achieve this (Keken and Ballentine, 1998, 1999; Hunt and Kellogg, 2001). Further work, especially on deep mantle seismic tomography, is needed to resolve this important issue for which East Africa offers an exceptional natural laboratory.

In the Ethiopian volcanic province, the high-$^3$He signature is not restricted to the Oligocene flood basalts. Rather, it is present in many of the Ethiopian Miocene to Plio–Quaternary lavas that display a HIMU signature (Marty et al., 1996). Such mixing between a high-$^3$He deep plume-type component and other shallower enriched or depleted components (the common HIMU trends of Fig. 6a) is not observed in any of the other Cenozoic African volcanics because of the lack of $^3$He anomalies in these provinces. In our view, these common coherent HIMU trends, which are widely distributed over Africa and Arabia, represent the involvement of a common type of mantle reservoir (HIMU) for all the rifted zones and localized intraplate volcanoes. Because such a common HIMU mantle reservoir scales with the African and Arabian plates, its is more reasonable to envision its location in the continental mantle lithosphere–or in the shallow upper mantle–rather than in a gigantic superswell. This hypothesis is in perfect agreement with the composition of mantle xenoliths from the EARS (Fig. 6a). This HIMU component is variously mixed with depleted or enriched components that account for the involvement of other mantle sources. On the basis of isotopic data, it is not easy to be precise about the location of such other components in the mantle. However, in most of the African volcanics–except those of the Ethiopian volcanic province–the helium isotopic ratios suggest that these components are located in the upper mantle.

### 4.3. The origin of the Afar plume and other African hotspots

The helium isotopes and other geochemical data constrain the areal extent of the initial deep plume material that impinges under the East African lithosphere to the area covered by Oligocene flood volcanism in Ethiopia and Yemen (Figs. 4 and 5). This geochemical approach is not consistent with models which link all the Cenozoic Eastern and Central African volcanism to the impact and channeling of a single mantle plume. Our view also contradicts the hypothesis of Kieffer et al. (2004), which attributes the composition of flood and post-flood volcanism throughout the Horn of Africa to melting of anomalously hot material in a large, compositionally heterogeneous, slowly upwelling, superswell. Indeed, this hypothesis does not explain why parts of this large superswell material exhibits high-$^3$He signatures and others do not.

The lack of a high-$^3$He signal outside the Ethiopian–Yemeni volcanic province strongly suggests that magmas from the other African volcanic provinces (Hoggar and Darfur hotspots, East African Rift system) were not generated from the same deep mantle source. However, all the post-CFB African volcanics (including the Ethiopian–Yemeni province) display common Sr–Pb isotopic trends which suggests that they share identical mantle sources, most probably located in the shallow mantle.

These constraints call for two distinct types of mantle plumes:

(1) a large, deeply sited mantle plume characterized by high-$^3$He signature (i.e. originating from the transition zone or below), which triggered the flood basalt eruptions 30 Ma ago and which subsequently interacted with shallower mantle sources to produce syn-rift volcanism in the Ethiopian province.
(2) second-order shallow upwellings, isolated from the main plume according to He isotope data, and possibly originating from depths less than 500 km as suggested by seismic tomography under the EARS (King and Ritsema, 2000; Owens et al., 2000; Davis and Slack, 2002; Weeraratne et al., 2003). Such a second-order type of upwelling could account for intraplate volcanism and crustal uplift across the African plate.

### 4.4. The origin of the high $^3$He/$^4$He signature

The highest $^3$He/$^4$He ratios are documented in tholeiitic CFB from Ethiopia, which correspond to the largest partial melting rates and highest volumes of magmas erupted through the African plate during the Cenozoic. In contrast, other volcanic provinces, which systematically represent lower degrees of partial melting (alkaline to undersatured magmatism) as well as smaller lava volumes, display $^3$He/$^4$He signatures that are all equal to, or lower than, those characterizing the MORB range and presumably the convective mantle. These observations are at odds with the predictions of models ascribing a shallow mantle origin to high $^3$He/$^4$He ratios as well as those calling for a statistical mantle assemblage to produce MORB He isotope ratios (Meibom et al., 2003; Meibom and Anderson, 2004). From seismic tomography studies which propose a deep mantle plume originating at the core–mantle boundary and reaching the Earth's surface under East Africa (Ritsema et al., 1999), we conclude that the high $^3$He/$^4$He signals seen now in this region originate from deep in the mantle, possibly from the core–mantle boundary and/or the core itself.

## 5. Conclusions

The distribution of helium isotopic data for Cenozoic volcanism over the African plate lead us to draw the following conclusions concerning the relationships between rift- and hotspot-related volcanism and the potential presence of underlying mantle plume(s):

(1) The spatial extent of the high-$^3$He component (up to 20 Ra) is restricted to the Ethiopian–Yemeni volcanic province and corresponds to the area affected by large volumes of Oligocene pre-rift flood volcanism around the East African triple junction. All other African volcanics display MORB-type $^3$He/$^4$He signatures (7 ± 2 Ra).

(2) A critical re-evaluation of the isotopic signatures (Sr–Nd–Pb) of African hotspot or rift magmatism highlight the fact that these Miocene to Plio–Quaternary alkaline lavas exhibit the same type of shallow lithospheric or sub-lithospheric mantle sources involved in their genesis (compositional trends involving a dominant HIMU-type component and other variously enriched components). The only singular (non HIMU) and homogeneous source composition is represented by the pre-rift Ethiopian flood basalts and has been attributed to the Afar plume head.

(3) Considered together, these geochemical and petrological constraints require the presence of two types of mantle plume under the African plate: (i) a large, deeply sited mantle plume characterized by high-$^3$He signature (i.e. originating from the transition zone), which triggered the flood basalts 30 Ma ago and which subsequently interacts with shallower mantle sources to produce the syn-rift volcanism of the Afar province, and (ii) a second-order type of shallow mantle upwelling, $<500$ km as image seismically, isolated from the main plume, and disseminated in the African plate under the uplifted and rifted swells.

(4) The above considerations do not support the view that a unique large mantle plume has fed all Cenozoic African volcanic provinces, nor the view that high-$^3$He signatures originate in the shallow mantle.

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