Mantle upwellings and convective instabilities revealed by seismic tomography and helium isotope geochemistry beneath eastern Africa

Jean-Paul Montagner, Bernard Marty, Eléonore Stutzmann, Déborah Sicilia, Michel Cara, Raphael Pik, Jean-Jacques Lévêque, Geneviève Roult, Eric Beucler, Eric Debayle

Mantle upwellings and convective instabilities revealed by seismic tomography and helium isotope geochemistry beneath eastern Africa

Jean-Paul Montagner,[1] Bernard Marty,[2] Eléonore Stutzmann,[1] Déborah Sicilia,[1] Michel Cara,[3] Raphael Pik,[2] Jean-Jacques Lévêque,[3] Geneviève Roult,[1] Eric Beucler,[4] and Eric Debayle[3]

Received 15 July 2007; revised 19 September 2007; accepted 8 October 2007; published 9 November 2007.

[1] The relationship between intraplate volcanism and continental tectonics has been investigated for North and East Africa using a high resolution three-dimensional anisotropic tomographic model derived from seismic data of a French experiment "Horn of Africa" and existing broadband data. The joint inversion for seismic velocity and anisotropy of the upper 400 km of the mantle, and geochemical data reveals a complex interaction between mantle upwellings, and lithosphere. Two kinds of mantle upwellings can be distinguished: The first one, the Afar "plume" originates from deeper than 400 km and is characterized by enrichment in primordial ^{3}He and ^{3}He/^{4}He ratios higher than those along mid-ocean ridges (MOR). The second one, associated with other Cenozoic volcanic provinces (Darfur, Tibesti, Hoggar, Cameroon), with ^{3}He/^{4}He ratios similar to, or lower than MOR, is a consequence of shallower upwelling. The presumed asthenospheric convective instabilities are oriented in an east-west direction, resulting from interaction between south-north asthenospheric mantle flow, main plume head and topography on the base of lithosphere. **Citation:** Montagner, J.-P., B. Marty, E. Stutzmann, D. Sicilia, M. Cara, R. Pik, J.-J. Léévêque, G. Roult, E. Beucler, and E. Debayle (2007), Mantle upwellings and convective instabilities revealed by seismic tomography and helium isotope geochemistry beneath eastern Africa, *Geophys. Res. Lett.*, *34*, L21303, doi:10.1029/2007GL031098.

1. Introduction

[2] The African continent is characterized by extensive intraplate volcanism. A first phase of active volcanism related to the breakup of Gondwana continent during Mesozoic (245–66 Ma) was followed by a quiet interval of time during the early Cenozoic (66–30 Ma) [*Burke*, 1996]. Since Oligocene (33–23 Ma), renewed volcanic activity [*Wilson and Guiraud*, 1992] was particularly important in the Horn of Africa where $\sim 1 \times 10^6$ km^3 continental flood basalts (CFB) in Ethiopia erupted 30 Ma ago in a time interval of 1 Ma or less [*Hofmann et al.*, 1997; *Ayalew*, 2002]. The Afar volcanic province, still magmatically active though with large temporal variations, is thought to represent the surface expression of a deep mantle plume [*Morgan*, 1971], originating either in the transition zone [*Debayle et al.*, 2001] or even deeper in the lower mantle [*Nyblade and Robinson*, 1994; *Montelli et al.*, 2004]. A deep mantle plume origin for Ethiopian CFBs was independently suggested by the occurrence of ^{3}He/^{4}He ratios up to 20 Ra [*Marty et al.*, 1996], where Ra is the ^{3}He/^{4}He ratio of atmospheric helium, much higher than those of mid-ocean ridge basalts (on average, 8 ± 1 Ra [e.g., *Graham*, 2002]) and is thought to characterize mantle material originating from below the 660 km discontinuity. However, a deep mantle origin for "high ^{3}He" material is currently questioned by some models which rather ascribe a lithospheric or shallow asthenospheric origin for such He component [*Anderson*, 1998].

[3] The origin of other Cenozoic volcanic provinces in Africa is less clear. It has been suggested from large-scale tomographic models with a lateral resolution of 2000 km [*Hadiouche et al.*, 1989] that the Afar plume might feed other hotspots in Central Africa. Using geological data and numerical methods of *Ebinger and Sleep* [1998] delineated areas of ponding plume material and proposed that a single plume can explain the uplift throughout East Africa and magmatism up to the Darfur swell and Cameroon line in the West and the Comores islands in the southeast. In order to investigate the origin of African magmatism and, specifically, a possible connection between the Afar plume and other intraplate volcanic provinces in Africa, a high resolution ($\sim$500 km) anisotropic tomographic investigation of central and east Africa was carried out in the framework of the International program "Horn of Africa" (France, Djibouti, Ethiopia, Yemen). *Sebai et al.* [2006] presented a tomographic upper mantle model at the scale of the whole African plate with a lateral resolution of 500 km for isotropic velocity and of 1000 km for azimuthal and radial anisotropies. In the present paper, we focus on the investigation of the eastern and central part of Africa where a resolution of 500 km is achievable for both velocity and anisotropies due to a good spatial and azimuthal coverage. A comparison with geochemical data is also presented and a geodynamical interpretation of the different kinds of data is proposed.

2. Surface Wave Tomographic Results

[4] Since the station coverage is very poor in Eastern Africa, five STS2 broadband stations provided by the RLBM (French Broadband seismic portable network) were

[1]Seismological Laboratory, Institut de Physique du Globe, UMR7154 CNRS, Paris, France.
[2]Centre de Recherches Pétrographiques et Géochimiques, Centre National de la Recherche Scientifique, Vandeuvre-les-Nancy, France.
[3]Ecole et Observatoire des Sciences de la Terre, UMR, Centre National de la Recherche Scientifique, Université Louis Pasteur, Strasbourg, France.
[4]Laboratoire de Planétologie et Géodynamique, UMR/CNRS, Université de Nantes, Nantes, France.

0094-8276/07/2007GL031098

installed from 1999 to 2002 in the Horn of Africa, in order to enhance lateral resolution around the Afar hotspot and to complement data collected from global and regional permanent broadband FDSN networks and from temporary PASSCAL experiments in Tanzania and Saudi Arabia (see the coverage by *Sebai et al.* [2006]). By using 3-component broadband seismic data, it was possible to derive the phase velocities of fundamental Rayleigh and Love waves and the azimuthal dependence of Rayleigh waves. In a second stage, we simultaneously retrieve and separate the distribution of "isotropic" S-wave velocity and anisotropy anomalies (see *Montagner and Tanimoto* [1991] for the complete tomographic technique and *Sebai et al.* [2006] for its improvements). The spatial and azimuthal coverage is very good in eastern and central Africa due to the increase in the number of stations. So, it is possible to jointly invert for seismic velocities, Sv-azimuthal anisotropy (G parameter) and radial anisotropy $\xi = (\frac{V_{SH}}{V_{SV}})^2$ (by including Love wave data) with a lateral resolution of 500 km instead of 1000 km for anisotropy in the whole African plate [*Sebai et al.*, 2006], down to an approximate depth of 400 km (with a poor resolution below 300 km). It is a significant improvement compared with previous models [*Hadiouche et al.*, 1989; *Ritsema and van Heijst*, 2000; *Debayle et al.*, 2001].

[5] Figure 1 shows maps of lateral variations of S-wave velocity V_S, of its G-azimuthal dependence and of radial anisotropy $\Delta\xi$ at depths of 100, 200 and 310 km with respect to PREM. The most prominent anomaly is associated with the Afar hotspot, where slow velocities can be traced down to 400 km. The West African and Congo cratons are characterized by high velocities, as previously observed [*Ritsema and van Heijst*, 2000; *Sebai et al.*, 2006]. A slow elongated anomaly in south-north (SN) direction around 40°E follows the East African rift in the whole depth range, whereas in the east-west (EW) direction, slow S-velocity anomalies extend down to about 150–200 km along the West and Central African rift systems. The hotspots of Darfur, Tibesti, Cameroon are located at the boundaries of slow velocities anomalies. An asymmetry between EW and SN trending structures can be observed on anisotropy: the direction of G anisotropy, direction of the fastest propagating S-waves is, north of the Equator, primarily SN, except in the Afar-Ethiopia region where an east-west direction can be observed with a large amplitude around 200 km depth. This SN predominance of azimuthal anisotropy persists at large depth but with a smaller amplitude. The pattern of radial $\Delta\xi$ anisotropy obtained from the simultaneous inversion of Rayleigh and Love wave "isotropic" terms displays as well the elongated SN structure along the Red sea and the East African rift with a negative value suggesting upwelling. The $\Delta\xi$ extremum migrates southwards at larger depth. At 20–25°E, zones of fast velocity which extend to larger depths (300 km), seem to separate these slow velocity anomalies. In contrast, the Afar hotspot displays large slow velocity down to 400 km depth as well as the Victoria hotspot (−3°S, 36°E) in Tanzania though of smaller lateral extent. East of the Afar hotspot, another slow velocity anomaly is observed below the Gulf of Aden ridge down to 200 km depth, indicating a likely interaction between this ridge and the Afar upwelling. The depth extent of the Afar upwelling cannot be solved by the present study, but the regional models of *Debayle et al.* [2001] and *Benoit et al.* [2006], as well as several global models [*Romanowicz and Gung*, 2002; *Montelli et al.*, 2004] show that its origin could be tracked down to at least the transition zone, though its connection with the so-called south African superplume is controversial [*Davaille et al.*, 2005].

3. Constraints From Geochemical Data

[6] The connection between the different slow velocities areas can be addressed by geochemical data. A compilation of available helium isotope data among African volcanic regions is presented in Figure 2 [*Pik et al.*, 2006]. The distribution of high $^3He/^4He$ ratios, indicates the influence of the Afar hotspot in the Gulf of Aden lavas as well as along the Red Sea ~1000 km away from the inferred location of the hotspot center [*Marty et al.*, 1996; *Moreira et al.*, 1996]. All other African Cenozoic volcanic regions exhibit $^3He/^4He$ ratios that are equal to, or lower than, the mean MORB ratio of 7–9 Ra (Cameroon: 5–7 Ra; Hoggar: 8 Ra; Darfur: 5.4–7.5 Ra; West African rifts: 5–8.5 Ra; Comores: 6.5 Ra).

[7] The suggestion that the Afar plume originates from the transition zone or deeper is fully consistent with geochemical mass balance proposing that the Afar volcanic province results from thermal diffusion across the transition zone that mobilized upper mantle material with limited material transfer from below the 660 km discontinuity [*Marty et al.*, 1996] characterized by high $^3He/^4He$ ratios. Although the origin of elevated $^3He/^4He$ ratios have been assigned recently to the shallow lithospheric or asthenospheric mantle [*Anderson*, 1998], such a model cannot explain the spatial and temporal association of long-lived high $^3He/^4He$ ratios of other flood basalts where magma compositions indicate high partial melting and therefore elevated thermal regime. These characteristics are fully consistent with the outbreak of a thermal and geochemical plume at the Earth's surface that originated deep in the mantle [*Courtillot et al.*, 2003].

4. Discussion: Geodynamical Interpretation

[8] The birth of the Afar hotspot around 30 Ma ago [*Hofmann et al.*, 1997] completely perturbed the upper mantle flow circulation below Africa. At the same time, volcanism was reactivated in Central Africa [*Burke*, 1996]. The observed slowing down of African plate motion since 30 Ma might be related to the Afar birth [*O'Connor et al.*, 1999]. Even though tomography only provides present-day image of convective flow, the simultaneous use of seismic velocity, anisotropy and geochemical data enables new insight into the interaction between the Afar upwelling, the African lithospheric plate and the underlying asthenosphere and to draw some geodynamic consequences of this major event.

[9] The strong and deep signature of the Afar hotspot in the whole depth range is characterized by slow S-wave velocities which trend southwards with increasing depth and by a strong stratification of azimuthal and radial anisotropy. If we accept the interpretation [see, e.g., *Montagner*, 2002] that the fast direction given by G azimuthal anisotropy (Figure 1) is closely related to flow aligning anisotropic crystals such as olivine through lattice preferred orientation

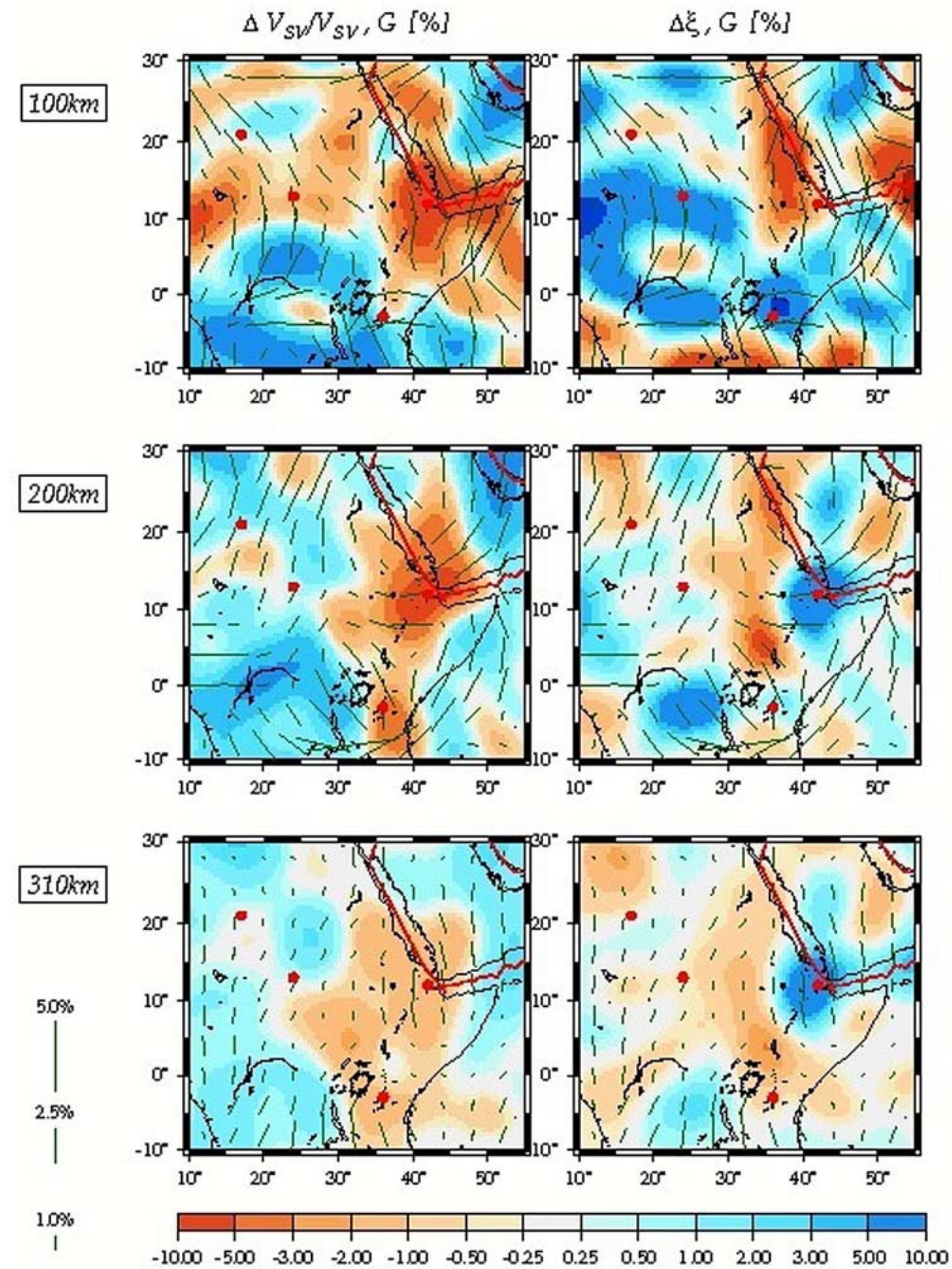

Figure 1. Tomographic images of S-wave velocity (ΔV_{SV}) and radial anisotropy ($\Delta\xi$) at 3 different depths: (top) 100, (middle) 200, and (bottom) 310 km. The perturbations of S- velocity and $\Delta\xi$ are expressed with respect to PREM [Dziewonski and Anderson, 1981] and plotted with the same color scale. The azimuthal anisotropy of Sv-wave velocity (G-parameter) is superimposed to S-wave and ξ anomalies and the bar length is proportional to its amplitude normalized with respect to S-wave velocity (scale of G at the bottom left). Dots refer to the location of hotspots in Africa.

[*Nicolas and Christensen*, 1987], the flow pattern in the asthenosphere below the African lithosphere is to first order oriented south-north which corresponds to the orientation of the relative motion between the African and Eurasian plates of NUVEL1A and not to the absolute plate motion of the African plate (HS3-NUVEL1A [*Gripp and Gordon*, 2002]) (Figure 3). South of equator, the pattern of G-anisotropy around the East Africa Rift system is complex, due to the existence of Victoria and Rovuma microplates [*Calais et al.*, 2006]. At shallow depth (Figure 1, 100 km) and large depth (Figure 1, 310 km), the orientation of flow in the Afar-Ethiopia region is in agreement with SKS splitting measurements [*Kendall et al.*, 2005]. In the uppermost mantle, this direction is primarily explained by oriented melt inclusions on mantle flow [*Kendall et al.*, 2005, 2006], and at large depth, this direction reflects the average deep upper mantle flow. But the asthenospheric flow (Figure 1, 200 km) is strongly perturbed when it encounters the strong Afar plume (probably its head) and it seems to turn around it, This deflection is translated into an EW direction of anisotropy to

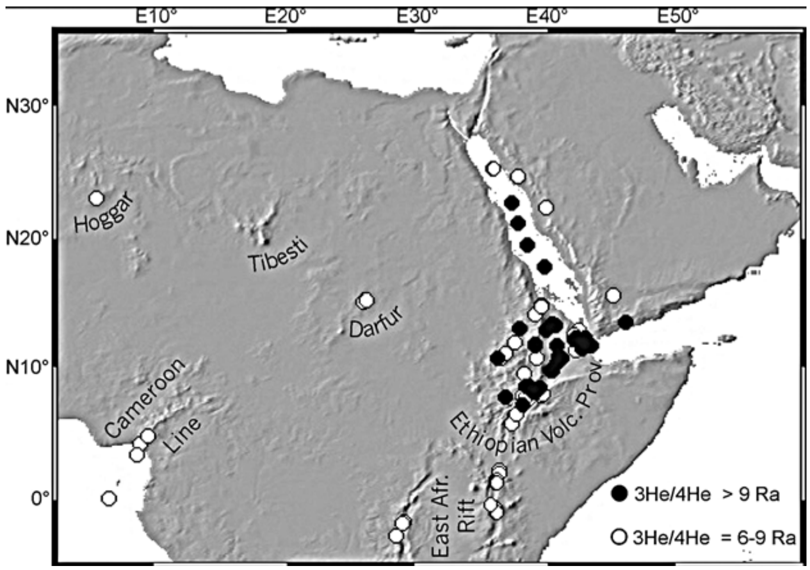

Figure 2. Geochemical $^3He/^4He$ ratios in central and east Africa. White circles are for normal ratios (Mid-Ocean Ridge basalts values). Black circles are for higher than normal ratios (MORB ratios).

the west of Afar hotspot. On the eastern side of Afar the flow can escape below the lithosphere towards the Indian Ocean and could have played a role in the opening of the Gulf of Aden, with the ridge propagating toward Afar [*Courtillot et al.*, 1999].

[10] Around 40°E, a slow S-velocity anomaly extends from the eastern side of the Red Sea through Afar down to 10°S with a local extremum below the Victoria hotspot (eastern side of the Tanzania craton). Other slow anomalies associated with the Darfur and the Tibesti hotspots are only visible down to 150–200 km. These results, therefore, show 2 types of upwellings as displayed on tomographic cross-sections through eastern Africa (Figure 3). Another fundamental boundary condition for asthenospheric flow in Central and East Africa is provided by the deep roots of the Congo craton in the South and the West African craton down to 250 km [*Sebai et al.*, 2006]. Outside cratonic areas, the lithosphere is thinner and some lines of weakness persist from the past tectonics of Africa. The Central African shear zone (CASZ in Figure 3) from Cameroon to Sudan [*Wilson and Guiraud*, 1992] is a Mesozoic rift reactivated about 30 Ma ago. The thick root of African cratons and the thinner lithosphere between them might give rise to convective instabilities with a mechanism similar to edge-driven con-

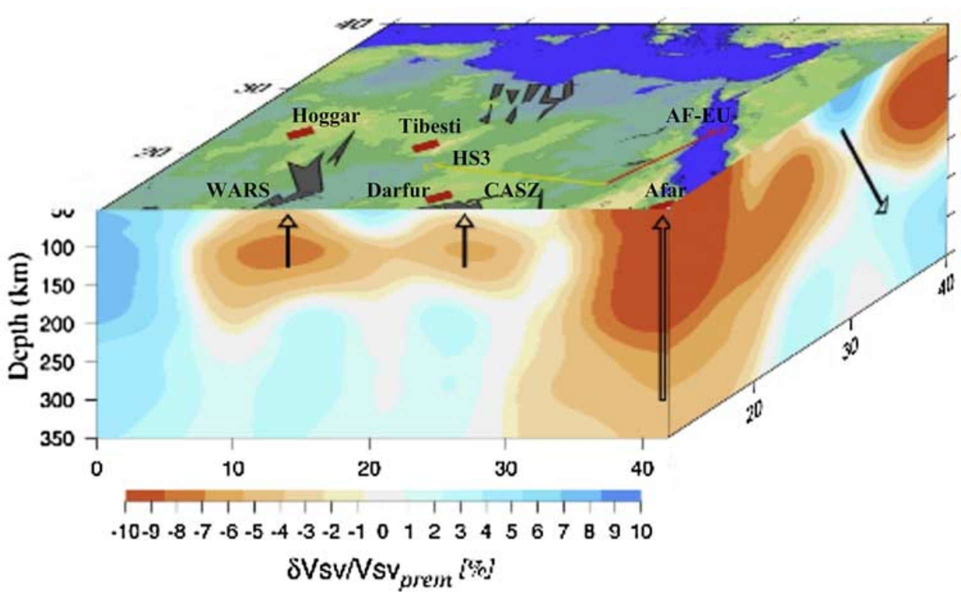

Figure 3. E-W and N-S cross-sections in 3D tomographic model of the northeast Africa between 0–42°E and 12°–40°N. Arrows indicate the direction of the upwellings in the lithosphere and asthenosphere as inferred from the sign of Vs anomalies and G anisotropy. WARS, West African Rift System; CASZ, Central African Shear Zone. The red arrow corresponds to the relative motion between African plate and Eurasian plate of model NUVEL1A, and the yellow arrow corresponds to the absolute plate motion of the African plate of model HS3-NUVEL1A ([*Gripp and Gordon*, 2002]).

vection [*Guillou and Jaupart*, 1995; *King and Ritsema*, 2000]. These convective instabilities develop upwellings, imaged by tomographic results. We propose that intraplate, hotspot-like volcanism can develop when asthenospheric upwelling flow encounters an inherited line of weakness in the lithosphere, such as the CASZ. Darfur and indirectly Tibesti hotspots might be the volcanic expressions of these crossing points and a similar asthenospheric origin can be inferred for the Hoggar and Cameroon hotspots from the whole Africa tomographic investigation of *Sebai et al.* [2006]. These convective instabilities are probably confined in the asthenosphere since the distribution of azimuthal anisotropy at larger depths (Figure 1, 310 km) is almost uniform in the SN direction.

[11] The present model of secondary convective instabilities triggered by interaction of flowing asthenosphere with the Afar hotspot and around cratons is supported by the distribution of available helium isotopic data (Figure 2) among nearby African Cenozoic volcanic regions, characterized by $^3He/^4He$ ratios equal to, or lower than, the mean MORB ratio of 7–9 Ra. Although low $^3He/^4He$ ratios in intraplate volcanic provinces might result from crustal recycling in the mantle and remobilisation of recycled crust during plume uprise, the upper range of $^3He/^4He$ values within the field of MORB values points to the strong involvement of asthenospheric mantle and limited interactions of magmas with the aged African crust. Furthermore, these "low^{-3}He" volcanic provinces are characterized by alkaline to undersaturated volcanism indicative of low degrees of partial melting and a thermal regime of the asthenosphere cooler than the one that gave rise to transitional to tholeiitic Ethiopian CFBs [*Pik et al.*, 2006]. These geochemical observations conflict with models that advocate channelling of the Afar hotspot material by pre-existing tectonic features to account for all these African volcanic provinces [*Ebinger and Sleep*, 1998]. Afar with its deep origin played a peculiar role, whereas other African hotspots have a shallow origin and are separated from the Afar upwelling by convective instabilities. This study further demonstrates a direct relationship between mantle depth origin inferred from seismic tomography and $^3He/^4He$ ratios of erupted magmas at a continental scale.

[12] We come up with the conclusion that the simultaneous use of tomographic and geochemical data confirm the existence of at least 2 kinds of plumes in Africa, the first one (the Afar plume) originating at least in the transition zone and the second one being a kind of "baby plume" resulting from the interaction between the asthenosphere and the base of the lithosphere by convective instabilities.

[13] **Acknowledgments.** We would like to thank IRIS and GEOSCOPE for the FDSN data, INSU/CNRS for supporting the "Corne de l'Afrique" Project, two anonymous reviewers for their useful critics and many others colleagues for discussions which helped to improve the manuscript. IPG-UMR CNRS 7154 contribution 2284.

References

Anderson, D. (1998), The helium paradox, *Proc. Natl. Acad. Sci. U.S.A.*, *95*, 4822–4827.

Ayalew, D. (2002), Source, genesis, and timing of giant ignimbrite deposits associated with Ethiopian continental flood basalts, *Geochim. Cosmochim. Acta*, *66*, 1429–1448.

Benoit, M., A. Nyblade, and J. VanDecar (2006), Upper mantle P- wave speed variations beneath Ethiopia and the origin of the Afar hotspot, *Geology*, *34*, 329–332, doi:10.1130/G22281.1.

Burke, K. (1996), The African plate, *S. Afr. J. Geol*, *99*, 339–410.

Calais, E., C. Ebinger, C. Hartnady, and J. Nocquet (2006), Kinematics of the East African Rift from GPS and earthquake slip vector data, in *The Afar Volcanic Province Within the East African Rift System*, edited by G. Yirgu, C. J. Ebinger, and P. K. H. Maguire, *Geol. Soc. Spec. Publ.*, *259*, 9–22.

Courtillot, V., C. Jaupart, I. Manighetti, and P. Tapponnier (1999), On causal links between flood basalts and continental breakup, *Earth Planet. Sci. Lett.*, *166*, 177–195.

Courtillot, V., A. Davaille, J. Besse, and J. Stock (2003), Three distinct types of hotspots into the Earth's mantle, *Earth Planet. Sci. Lett.*, *205*, 295–308.

Davaille, A., E. Stutzmann, G. Silveira, J. Besse, and V. Courtillot (2005), Convective pattern under the Indo-Atlantic box, *Earth Planet. Sci. Lett.*, *239*, 233–252.

Debayle, E., J. Leveque, and M. Cara (2001), Seismic evidence for deeply rooted low-velocity anomaly in the upper mantle beneath the northeastern Afro/Arabian continent, *Earth Planet. Sci. Lett.*, *193*, 423–436.

Dziewonski, A., and D. Anderson (1981), Preliminary reference Earth model, *Phys. Earth Planet. Inter.*, *25*, 297–356.

Ebinger, C., and N. Sleep (1998), Cenozoic magmatism throughout East Africa resulting from impact of a single plume, *Nature*, *395*, 788–791.

Graham, D. (2002), Nobles gases in geochemistry of mid-ocean and ocean island basalts, in *Noble Gases in Geochemistry and Cosmochemistry, Rev. Mineral Geochem.*, vol. 47, edited by D. Porcelli, C. J. Ballentine, and R. Wieler, pp. 247–318, Mineral. Soc. of Am., Washington, D. C.

Gripp, A., and R. Gordon (2002), Young tracks of hotspots and current plate velocities, *Geophys. J. Int.*, *150*, 321–351.

Guillou, L., and C. Jaupart (1995), On the effects of continents on mantle convection, *J. Geophys. Res.*, *100*, 24,217–24,238.

Hadiouche, O., N. Jobert, and J.-P. Montagner (1989), Anisotropy of the African continent inferred from surface waves, *Phys. Earth Planet. Inter.*, *58*, 61–81.

Hofmann, C., V. Courtillot, G. Féraud, P. Rochette, G. Yirgus, E. Ketefo, and R. Pik (1997), Timing of the Ethiopian flood basalt event and implications for plume birth and global change, *Nature*, *389*, 838–841.

Kendall, J.-M., G. Stuart, C. Ebinger, I. Barstow, and D. Keir (2005), Magma-assisted rifting in Ethiopia, *Nature*, *433*, 146–148.

Kendall, J.-M., S. Pilidou, D. Keir, I. Barstow, G. Stuart, and A. Ayele (2006), Mantle upwellings, melt migration and the rifting of Africa: Insights from seismic anisotropy, in *The Afar Volcanic Province Within the East African Rift System*, edited by G. Yirgu, C. J. Ebinger, and P. K. H. Maguire, *Geol. Soc. Spec. Publ.*, *259*, 55–71.

King, S., and J. Ritsema (2000), African hotspot volcanism: Small-scale convection in the upper mantle beneath cratons, *Science*, *290*, 1137–1140.

Marty, B., R. Pik, and Y. Gezahegn (1996), Helium isotopic variations in Ethiopian plume lavas: Nature of magmatic sources and limit on lower mantle contribution, *Earth Planet. Sci. Lett.*, *144*, 223–237.

Montagner, J. (2002), Low anisotropy channels below the Pacific plate, *Earth Planet. Sci. Lett.*, *202*, 263–274.

Montagner, J.-P., and T. Tanimoto (1991), Global upper mantle tomography of seismic velocities and anisotropies, *J. Geophys. Res.*, *96*, 20,337–20,351.

Montelli, R., G. Nolet, F. Dahlen, G. Masters, E. Engdahl, and S. Hung (2004), Finite-frequency tomography reveals a variety of plumes in the mantle, *Science*, *303*, 338–343.

Moreira, M., P. Valbracht, T. Staudacher, and C. Allegre (1996), Rare gas systematics in Red Sea ridge basalts, *Geophys. Res. Lett.*, *23*, 2453–2456.

Morgan, J. (1971), Convection plumes in the lower mantle, *Nature*, *230*, 42–43.

Nicolas, A., and N. Christensen (1987), Formation of anisotropy in upper mantle peridotites—A review, in *Composition, Structure and Dynamics of the Lithosphere/Asthenosphere System*, *Geodyn. Ser.*, vol. 16, edited by K. Fuchs and C. Froideveaux, pp. 111–123, AGU, Washington, D. C.

Nyblade, A., and S. Robinson (1994), The African Superswell, *Geophys. Res. Lett.*, *21*, 765–768.

O'Connor, J., P. Stoffers, P. van den Bogaard, and M. McWilliams (1999), First seamount age evidence for significantly slower African plate motion since 19 to 30 Ma, *Earth Planet. Sci. Lett.*, *171*, 575–589.

Pik, R., B. Marty, and D. Hilton (2006), How many plumes in Africa? The geochemical point of view, *Chem. Geol.*, *226*, 100–114.

Ritsema, J., and H. van Heijst (2000), New seismic model of the upper mantle beneath Africa, *Geology*, *28*, 63–66.

Romanowicz, B., and Y. Gung (2002), Superplumes and the core-mantle boundary to the lithosphere: Implications for heat flux, *Science*, *296*, 513–516.

Sebai, A., E. Stutzmann, J.-P. Montagner, E. Beucler, and D. Sicilia (2006), Hotspot and superswell beneath Africa as inferred from surface wave anisotropic tomography, *Phys. Earth Planet. Inter.*, *155*, 48–62.

Wilson, M., and R. Guiraud (1992), Magmatism and rifting in western and central Africa from late Jurassic to recent times, *Tectonophysics*, *213*, 203–225.

E. Beucler, Laboratoire de Planétologie et Géodynamique, UMR/CNRS, Université de Nantes, BP92205, 2 rue de la Houssinière, F-44322 Nantes, France.

M. Cara, E. Debayle, and J.-J. Lévêque, EOST, UMR/CNRS, Université Louis Pasteur, F-67084 Strasbourg, France.

B. Marty and R. Pik, Centre de Recherches Pétrographiques et Géochimiques, CNRS, BP20, rue Notre-Dame des Pauvres, F-54501 Vandeuvre-les-Nancy, Cedex, France.

J.-P. Montagner, G. Roult, D. Sicilia, and E. Stutzmann, Seismological Laboratory, CNRS UMR7154, Institut de Physique du Globe, 4 Place Jussieu, F-75252, Paris cedex 05, France. (jpm@ipgp.jussieu.fr)