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Elevated mantle temperature beneath East Africa

Tyrone O. Rooney[1]*, Claude Herzberg[2], and Ian D. Bastow[3]
[1]Department of Geological Sciences, Michigan State University, East Lansing, Michigan 48824, USA
[2]Department of Geological Sciences, Rutgers University, Piscataway, New Jersey 08855-1179, USA
[3]Department of Earth Sciences, University of Bristol, Bristol BS8 1RJ, UK

ABSTRACT

The causes of magmatism at magmatic rifted margins and large igneous provinces (LIPs) are uncertain because the condition of the mantle that underlay them during formation can no longer be directly observed. Therefore, whether the mantle was characterized by elevated potential temperatures (T_P), small-scale convection, or anomalously fertile composition is debated. East Africa is an ideal area in which to address this problem because it contains both the young African-Arabian LIP and the tectonically and magmatically active East African Rift system. Here we present mantle T_P estimates for 53 primitive magmas from throughout the region to reveal that thermal anomalies currently peak in Djibouti (140 °C above ambient upper mantle). Slightly warmer conditions accompanied the Oligocene African-Arabian LIP, when the T_P anomaly was 170 °C. These values are toward the low end of the global temperature range of LIPs, despite the markedly slow seismic velocity mantle that underlies the region. Mantle seismic velocity anomalies in East Africa cannot, therefore, as is often assumed, be attributed simply to elevated mantle temperatures. We conclude that CO_2-assisted melt production in the African superplume contributes to the markedly slow seismic velocities below East Africa.

INTRODUCTION

The origins of voluminous magmatism observed at magmatic rifted margins and large igneous provinces (LIPs) is a matter of considerable debate because it can often be explained by a variety of models, including shallow convection, anomalously fertile mantle, and in particular elevated mantle temperatures (e.g., White et al., 2008). In regions of very young volcanism, seismic tomographic imaging of the mantle can place fundamental constraints on the morphology and depth extent of low-velocity regions intimately linked to the observed magmatism; however, there are many causes of seismic heterogeneity. Of fundamental importance in discriminating between these mechanisms of melt generation is constraining the temperature of the upper mantle. A new generation of petrologic models may be used to yield estimates of mantle thermal state (Herzberg and Asimow, 2008) and provide constraints as to the potential sources of mantle seismic heterogeneity, facilitating an integrated approach to mantle melting at magmatic rifted margins.

East Africa, which is characterized by Cenozoic flood basalts and magmatic rifting above one of the most significant seismically defined mantle structures on the planet (Ritsema et al., 2011), offers a unique opportunity to develop our understanding of the relationship between mantle temperature, compositional heterogeneity, seismic velocity, and the production of melt. Here we present petrologically derived estimates of mantle potential temperature (T_P; McKenzie and Bickle, 1988) for a suite of primitive magmas erupted in East Africa. These data are interpreted in light of seismic tomographic images to clarify the possible thermal and compositional contributions to mantle heterogeneity in the African mantle. Our results show that while the East African mantle is characterized by temperatures that are elevated above ambient values, it is nevertheless toward the cooler end of LIPs within the global database.

*E-mail: rooneyt@msu.edu.

TECTONIC SETTING

The Cenozoic geological record in East Africa is dominated by flood basalt magmatism and the subsequent development of a magmatic rift. Initial activity began with a 45–30 Ma volcanic episode that was restricted to southern Ethiopia and Kenya (George and Rogers, 2002; Furman et al., 2006). This initial magmatism was soon followed by the volumetrically and spatially more significant 29–31 Ma African-Arabian continental flood basalt province (e.g., Baker et al., 1996; Pik et al., 1999). From 29 Ma until ca. 10 Ma, volcanic activity in East Africa was restricted to isolated shield volcanoes on the Ethiopian Plateau (e.g., Kieffer et al., 2004) and episodic activity in southern Ethiopia and Turkana (George and Rogers, 2002; Furman et al., 2006). Subsequently rift-related magmatism became widespread throughout East Africa, and is evident in Afar (e.g., Barrat et al., 1998), along the length of the East African Rift in Ethiopia (e.g., Rooney et al., 2011), and in both the eastern (e.g., Furman et al., 2004) and western branches (e.g., Rosenthal et al., 2009) of the rift. The volcanic products of the region therefore preserve a spatial and temporal record that samples an ~2800 km cross section of the Cenozoic African upper mantle.

METHODS

We collated an extensive geochemical data set from East Africa using the GEOROC database (http://georoc.mpch-mainz.gwdg.de/georoc/), adding additional location and age information from the original publications where necessary. These data were filtered to exclude all differentiated samples that had undergone augite and or plagioclase fractionation as indicated by depletions in CaO and Al_2O_3 (e.g., Herzberg and Asimow, 2008). The remaining samples were assumed to have been affected only by variable amounts of olivine addition and subtraction. We applied PRIMELT-2 software (Herzberg and Asimow, 2008) to our filtered database to obtain primary magma compositions and mantle T_P values. The software is calibrated from melting experiments on fertile peridotite, and its application to lavas assumes a similar fertile peridotite source. Uncertainties in fertile peridotite composition do not propagate to significant errors in mantle T_P (Herzberg and Asimow, 2008). Melting of iron-rich peridotite will propagate to MgO and mantle T_P that are too low (Herzberg and O'Hara, 2002). PRIMELT-2 software provides solutions for both batch and accumulated fractional melting, and we use the results for the latter. PRIMELT-2 contains filters that reduce uncertainties that arise from pyroxenite source lithology, source volatile content from metasomatized peridotite, and clinopyroxene fractionation. Mantle T_P is inferred from the MgO content of the primary magma, and MgO typically correlates with FeO. The calculations require that FeO be obtained from FeO_T (total iron reported as a single oxide), and this was estimated assuming $Fe_2O_3/TiO_2 = 1$ (see Herzberg and Asimow, 2008). A more reducing ratio of $Fe_2O_3/TiO_2 = 0.5$, suitable for some oceanic islands, will increase FeO in the primary magma, yielding higher MgO and higher mantle T_P. The 0.5–1.0 range in Fe_2O_3/TiO_2 usually propagates to Fe^{2+}/Fe_T values that vary from 0.80 to 0.90. Uncertainties in Fe^{2+}/Fe_T propagate to uncertainties in mantle T_P of ~±36 °C for low-Ti type lavas to ±58 °C for high-Ti types. Uncertainties arising from the partitioning of Fe and Mg between olivine and liquid (Herzberg and O'Hara, 2002) will contribute an additional ±44 °C uncertainty in mantle T_P. Total uncertainty will be <±72 °C at the 2σ level, based on the most Ti- and Fe^{3+}-rich samples, and our adoption of a more oxidized Fe_2O_3/TiO_2 value will likely provide a minimum estimate of mantle T_P below East Africa.

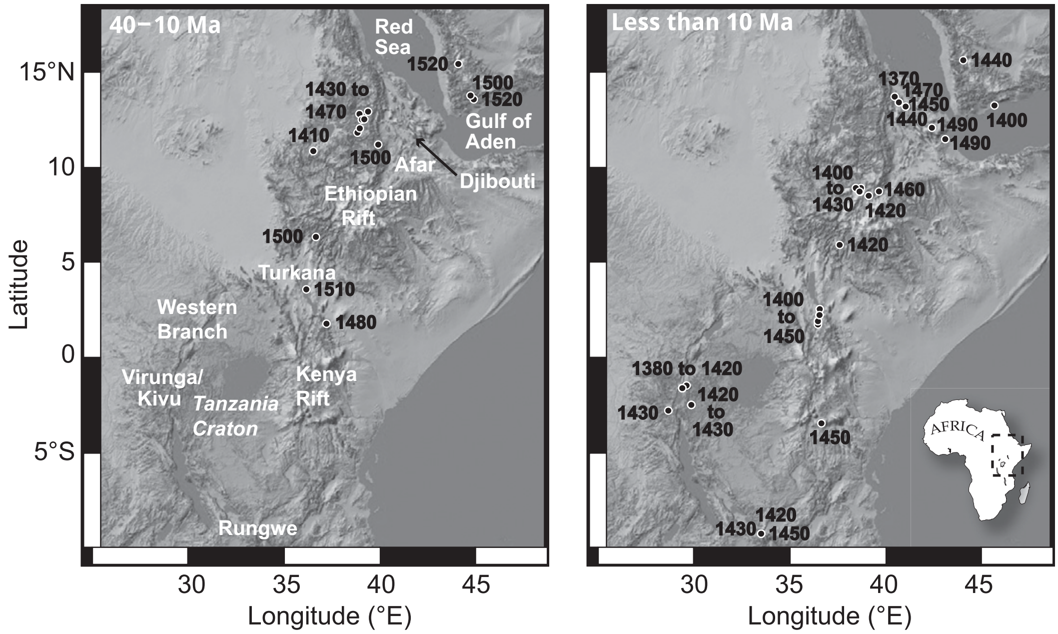

Figure 1. Spatial distribution of mantle potential temperatures (T_P) in East Africa overlain on digital elevation model derived from Radar Shuttle Tomography Mission. T_P values are in Table DR1 (see footnote 1) and are rounded to nearest 10 °C. Left: T_P values for rocks erupted between 40 and 10 Ma. Right: T_P values for lava erupted since 10 Ma.

THERMAL STATE OF THE EAST AFRICAN UPPER MANTLE

A consensus from independent disciplines is now emerging that ambient mantle T_P is 1350 ± 50 °C (e.g., Courtier et al., 2007; Herzberg et al., 2007; Ono, 2008; Katsura et al., 2010). Previous studies in East Africa have placed rough constraints on the thermal conditions of the mantle and have suggested that mantle T_P is elevated above these ambient values (e.g., Rogers et al., 1998; Beccaluva et al., 2009). Our results are consistent with these earlier studies and show that the T_P of the East African upper mantle has remained elevated above ambient mantle values over the past 40 m.y. (Fig. 1; Table DR1 in the GSA Data Repository[1]). Mantle T_P values reached a maximum during the volumetrically significant Oligocene African-Arabian flood basalt eruptions (1520 °C), but in comparison to other LIPs it is among the coolest known (Fig. 2).The values of mantle T_P (~1500 °C) apparent in the ca. 40 Ma Amaro unit of southern Ethiopia and in 23–10 Ma lavas from Turkana (1480–1510 °C) indicate that mantle thermal conditions at least in southern Ethiopia and northern Kenya were elevated before and after the Oligocene flood basalt event.

Younger magmatism (after 10 Ma) throughout East Africa was generally cooler, recording T_P that ranges from ambient mantle to 1490 °C, and is only slightly elevated in comparison to other hotspot-influenced regions globally (Fig. 2). The increased sample density during this time period has revealed spatial variability in the mantle T_P values. Most notably T_P is elevated throughout Afar and Djibouti, while the most consistently cool regions are in southern Ethiopia and along the western branch of the East African Rift (Fig. 1). Around the margins of the Tanzania craton, T_P values for the Kenya Rift and Rungwe (1400–1450 °C) are elevated in comparison to activity along the western flank of the craton at Kivu and Virguna (1380–1430 °C). These variations in T_P during the past 10 m.y. may be explained by the tapping of magmas from the hotter plume core and cooler peripheries (Herzberg and Gazel, 2009), generation of magma by conductive melting of the compositionally heterogeneous lithospheric mantle (e.g., Rogers et al., 1998; Leeman et al., 2005), cooling of the plume by thermal conduction to the lithosphere, and uncertainties in the petrological modeling.

[1]GSA Data Repository item 2012012, Table DR1, and supplementary references to data sources used in generating the T_P model, is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

IMPLICATIONS FOR THE STRUCTURE OF THE EAST AFRICAN MANTLE

Numerous global-scale geophysical studies have shown that the mantle structure beneath the African plate is characterized by a significant low-velocity seismic zone (e.g., Ritsema et al., 2011). This African superplume, which is a dominant feature of the lower mantle, likely extends across the mantle transition zone into the upper mantle (Montelli et al., 2004). The upper mantle beneath East Africa is similarly characterized

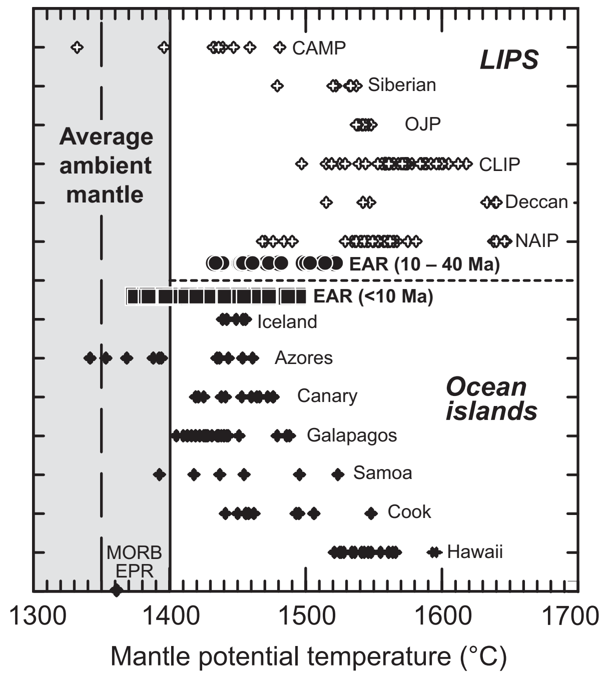

Figure 2. Mantle potential temperature for a selection of oceanic islands and large igneous provinces (LIPs). New results from East Africa (Table DR1; see footnote 1) are compared to existing data sets (Herzberg and Gazel, 2009). EAR—East African Rift; CAMP—Central Atlantic Magmatic Province; OJP—Ontong Java Plateau; CLIP—Caribbean large igneous province; NAIP—North Atlantic igneous province; MORB EPR—Mid-oceanic ridge basalt at East Pacific Rise.

by low-velocity seismic anomalies best imaged beneath the Tanzania craton (e.g., Park and Nyblade, 2006) and the Ethiopian rift (e.g., Bastow et al., 2008). The thermo-chemical nature of the African superplume in the lower mantle is well established (Forte et al., 2010); however, the interpretations of upper mantle tomographic structures more commonly cite only thermal hypotheses to explain the observations of low velocities (e.g., Benoit et al., 2006; Park and Nyblade, 2006).

Tomographic studies in East Africa vary in their estimates of the amplitude and precise morphology of the region's anomalously low velocity mantle; however, a simple observation remains: teleseismic P-wave arrival times at permanent station AAE in Addis Ababa are among the latest worldwide, meaning that seismic wave speeds in the Ethiopian upper mantle are likely the slowest worldwide (e.g., Bastow et al., 2008). In addition, vertically averaged upper mantle seismic velocity anomalies in the tomographic model of Ritsema et al. (2011) also show that the Ethiopian mantle is markedly slower than beneath other hotspots such as Hawaii and Iceland (Table 1).

Although temperature variations are often cited as the main cause of seismically imaged heterogeneity in the upper mantle (e.g., Goes et al., 2000), the relationship between temperature and $dV_{P,S}$ can vary greatly depending on seismic attenuation, Q. Following Karato (1993), we express the dependence of seismic wave velocity, V, on temperature in the upper mantle as:

$$\partial \ln V / \partial T = \partial \ln V_0 / \partial T - F(\alpha)\left[Q^{-1}(\omega,T)/\pi\right]\left(H^*/RT^2\right), \quad (1)$$

where $\partial \ln V/\partial T$ is the observed velocity perturbation ($\partial \ln V_{P,S}$) with temperature change (∂T). H^* is the activation enthalpy, R is the gas constant, and F describes the dependence of Q on frequency. The two terms on the right side of Equation 1 are the elastic and anelastic contributions to the velocity perturbation, respectively. We assume $\partial \ln V_0/\partial T \approx -5 \times 10^{-5}$ K^{-1}, $H^* \approx 500$ kJ/mol for olivine, $T \approx 1600$ K (after Karato, 1993), and $F(\alpha) = 1$ (constant Q). Detailed constraints on seismic attenuation are lacking for Ethiopia, but beneath the East African Rift in Tanzania, $Q_P \approx 80$ (Venkataraman et al., 2004). Thus, the petrologically determined 140 °C T_P anomaly for Ethiopia using Equation 1 likely results in only an ~2% V_P anomaly, significantly lower than that observed in the region (e.g., Bastow et al., 2008). Factors other than elevated temperature must therefore be contributing to the exceptionally slow seismic velocity Ethiopian mantle.

In Ethiopia, plate stretching at different times during rift development has likely produced large volumes of decompression melt in the asthenosphere that markedly lower mantle seismic velocities observed beneath the region (e.g., Bastow et al., 2010; Bastow and Keir, 2011). At depths >~200 km, however, substantial volumes of decompression-driven partial melting in the ambient mantle are not expected, and alternate mechanisms are thus required to account for the markedly low seismic wave speeds that are likely contiguous with the African superplume in the lower mantle (e.g., Montelli et al., 2004).

TABLE 1. MEAN MANTLE SEISMIC WAVE-SPEED ANOMALIES FOR THE DEPTH RANGES 50–410 AND 50–200 km

Region	Longitude	Latitude	δ*Vs*, 410 km (%)	δ*Vs*, 200 km (%)
Ethiopian rift	40°E	9°N	–4.24	–5.11
Afar	42°E	11°N	–4.19	–5.15
Iceland	17°W	64°N	–3.31	–3.12
Hawaii	155°W	19°N	–1.50	–1.04
Samoa	168°W	15°S	–1.58	–0.90
Cook Islands	158°W	22°S	–0.83	–0.58
Azores	26°W	38°N	–1.60	–2.25
Canaries	18°W	28°N	–0.32	+0.32
Galapagos	92°W	0°N	–3.10	–5.46

Note: Values are calculated using the global tomographic model of Ritsema et al. (2011).

Seismic studies have established that the African superplume is a thermochemical structure in the lower mantle, raising the possibility that some part of the observed seismic anomaly in the upper mantle is also compositionally based. The source of the compositional heterogeneity within the superplume in the lower mantle is likely related to recycled slab materials that have been converted into eclogites and pyroxenites (e.g., Kogiso et al., 2003), consistent with bulk modulus of the African superplume (Tan and Gurnis, 2005; Forte et al., 2010). While pyroxenites and eclogites are typically thought of as more dense than peridotite, yielding anomalously high values of V_P and V_S (Tan and Gurnis, 2005), the potentially wide range of compositions and densities associated with subducted materials and their reactions to form pyroxenites within the mantle (Herzberg, 2011) make it difficult to constrain the effect of such lithologies on seismic velocity.

In the absence of dramatically elevated T_P, the role of recycled materials in facilitating deep partial melting is of critical importance for developing an understanding of the seismically deduced physical properties of the upper mantle below East Africa. Pyroxenites and eclogites typically generate melt at depths greater than that of peridotite (Kogiso et al., 2003); however, it is the combined effect of CO_2 and H_2O that can dramatically increase the melting depth range of mantle lithologies (Dasgupta et al., 2007a). While water is present in the source of ocean island basalts (Dixon et al., 2002), CO_2 is likely the dominant volatile phase during small degrees of partial melting (Dasgupta et al., 2007b). Carbonate melts are a volumetrically minor component of the mantle, but such melts can cause sufficient dissolution and reprecipitation of olivine to influence the mantle seismic properties (Dasgupta and Hirschmann, 2006).

The presence of active carbonatite volcanism in the East African Rift cannot be considered evidence for a particularly CO_2-enriched mantle source in the region (Fischer et al., 2009); however, xenoliths derived from the East African Rift lithospheric mantle exhibit the metasomatic imprint of carbonatite melts and CO_2-rich fluids derived from the asthenosphere (Rudnick et al., 1993; Frezzotti et al., 2010). Studies of fluid inclusions preserved within the Ethiopian lithospheric mantle show evidence for chlorine-rich metasomatic H_2O-CO_2 fluids that may originate from the degassing of deep carbonate melts, and exhibit signatures consistent with a contribution from recycled altered oceanic crust (Frezzotti et al., 2010). The recycling of crust into the mantle may carry with it carbonate, and this CO_2 can trigger deep melting in both the recycled crust and associated peridotite host (e.g., Dasgupta and Hirschmann, 2006). We thus suggest that given the absence of a thermal anomaly of sufficient magnitude, CO_2-assisted melt production in the African superplume likely contributes significantly to the low seismic wave speeds that characterize the East African mantle.

CONCLUSIONS

Our new T_P estimates show that elevated mantle temperatures are a pervasive feature of the upper mantle beneath East Africa. A maximum temperature anomaly of 140 °C above ambient mantle is recorded from magmas younger than 10 Ma erupted in Djibouti, though Oligocene flood basalts display anomalies as great as 170 °C. These modest temperature anomalies coincide with some of the most significant seismic low-velocity anomalies on the planet, highlighting the role of volatile-driven partial melting and heterogeneous mantle composition in controlling mantle density variation beneath East Africa.

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REFERENCES CITED

Baker, J., Snee, L., and Menzies, M., 1996, A brief Oligocene period of flood volcanism in Yemen: Implications for the duration and rate of continental flood volcanism at the Afro-Arabian triple junction: Earth and Planetary Science Letters, v. 138, p. 39–55, doi:10.1016/0012-821X(95)00229-6.

Barrat, J.A., Fourcade, S., Jahn, B.M., Cheminee, J.L., and Capdevila, R., 1998, Isotope (Sr, Nd, Pb, O) and trace-element geochemistry of volcanics from the Erta'Ale range (Ethiopia): Journal of Volcanology and Geothermal Research, v. 80, p. 85–100, doi:10.1016/S0377-0273(97)00016-4.

Bastow, I.D., and Keir, D., 2011, The protracted development of the continent-ocean transition in Afar: Nature Geoscience, v. 4, p. 248–250, doi:10.1038/ngeo1095.

Bastow, I.D., Nyblade, A.A., Stuart, G.W., Rooney, T.O., and Benoit, M.H., 2008, Rifting at the edge of the African low velocity anomaly: Geochemistry Geophysics Geosystems, v. 9, Q12022, doi:10.1029/2008GC002107.

Bastow, I.D., Pilidou, S., Kendall, J.M., and Stuart, G.W., 2010, Melt-induced seismic anisotropy and magma assisted rifting in Ethiopia: Evidence from surface waves: Geochemistry Geophysics Geosystems, Q0AB05, doi:10.1029/2010GC003036.

Beccaluva, L., Bianchini, G., Natali, C., and Siena, F., 2009, Continental flood basalts and mantle plumes: A case study of the Northern Ethiopian Plateau: Journal of Petrology, v. 50, p. 1377–1403, doi:10.1093/petrology/egp024.

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

Courtier, A.M., and 14 others, 2007, Correlation of seismic and petrologic thermometers suggests deep thermal anomalies beneath hotspots: Earth and Planetary Science Letters, v. 264, p. 308–316, doi:10.1016/j.epsl.2007.10.003.

Dasgupta, R., and Hirschmann, M.M., 2006, Melting in the Earth's deep upper mantle caused by carbon dioxide: Nature, v. 440, p. 659–662, doi:10.1038/nature04612.

Dasgupta, R., Hirschmann, M.M., and Smith, N.D., 2007a, Water follows carbon: CO_2 incites deep silicate melting and dehydration beneath mid-ocean ridges: Geology, v. 35, p. 135–138, doi:10.1130/G22856A.1.

Dasgupta, R., Hirschmann, M.M., and Smith, N.D., 2007b, Partial melting experiments of peridotite + CO_2 at 3 GPa and genesis of alkali ocean island basalts: Journal of Petrology, v. 48, p. 2093–2124, doi:10.1093/petrology/egm053.

Dixon, J.E., Leist, L., Langmuir, C., and Schilling, J.G., 2002, Recycled dehydrated lithosphere observed in plume-influenced mid-ocean-ridge basalt: Nature, v. 420, p. 385–389.

Fischer, T.P., Burnard, P., Marty, B., Hilton, D.R., Furi, E., Palhol, F., Sharp, Z.D., and Mangasini, F., 2009, Upper-mantle volatile chemistry at Oldoinyo Lengai volcano and the origin of carbonatites: Nature, v. 459, p. 77–80, doi:10.1038/nature07977.

Forte, A.M., Quere, S., Moucha, R., Simmons, N.A., Grand, S.P., Mitrovica, J.X., and Rowley, D.B., 2010, Joint seismic–geodynamic-mineral physical modelling of African geodynamics: A reconciliation of deep-mantle convection with surface geophysical constraints: Earth and Planetary Science Letters, v. 295, p. 329–341, doi:10.1016/j.epsl.2010.03.017.

Frezzotti, M.L., Ferrando, S., Peccerillo, A., Petrelli, M., Tecce, F., and Perucchi, A., 2010, Chlorine-rich metasomatic H_2O-CO_2 fluids in amphibole-bearing peridotites from Injibara (Lake Tana region, Ethiopian plateau): Nature and evolution of volatiles in the mantle of a region of continental flood basalts: Geochimica et Cosmochimica Acta, v. 74, p. 3023–3039, doi:10.1016/j.gca.2010.02.007.

Furman, T., Bryce, J.G., Karson, J., and Iotti, A., 2004, East African Rift System (EARS) plume structure: Insights from Quaternary mafic lavas of Turkana, Kenya: Journal of Petrology, v. 45, p. 1069–1088, doi:10.1093/petrology/egh004.

Furman, T., Kaleta, K.M., Bryce, J.G., and Hanan, B.B., 2006, Tertiary mafic lavas of Turkana, Kenya: Constraints on East African plume structure and the occurrence of high-m volcanism in Africa: Journal of Petrology, v. 47, p. 1221–1244, doi:10.1093/petrology/egl009.

George, R.M., and Rogers, N.W., 2002, Plume dynamics beneath the African plate inferred from the geochemistry of the Tertiary basalts of southern Ethiopia: Contributions to Mineralogy and Petrology, v. 144, p. 286–304, doi:10.1007/s00410-002-0396-z.

Goes, S., Govers, R., and Vacher, P., 2000, Shallow mantle temperatures under Europe from P and S wave tomography: Journal of Geophysical Research, v. 105, p. 11153–11169, doi:10.1029/1999JB900300.

Herzberg, C., 2011, Identification of source lithology in the Hawaiian and Canary Islands: Implications for origins: Journal of Petrology, v. 52, p. 113–146, doi:10.1093/petrology/egq075.

Herzberg, C., and Asimow, P.D., 2008, Petrology of some oceanic island basalts: PRIMELT2.XLS software for primary magma calculation: Geochemistry Geophysics Geosystems, v. 9, Q09001, doi:10.1029/2008GC002057.

Herzberg, C., and Gazel, E., 2009, Petrological evidence for secular cooling in mantle plumes: Nature, v. 458, p. 619–622, doi:10.1038/nature07857.

Herzberg, C., and O'Hara, M.J., 2002, Plume-associated ultramafic magmas of Phanerozoic age: Journal of Petrology, v. 43, p. 1857–1883, doi:10.1093/petrology/43.10.1857.

Herzberg, C., Asimow, P.D., Arndt, N., Niu, Y.L., Lesher, C.M., Fitton, J.G., Cheadle, M.J., and Saunders, A.D., 2007, Temperatures in ambient mantle and plumes: Constraints from basalts, picrites, and komatiites: Geochemistry Geophysics Geosystems, v. 8, Q02006, doi:10.1029/2006GC001390.

Karato, S., 1993, Importance of anelasticity in the interpretation of seismic tomography: Geophysical Research Letters, v. 20, p. 1623–1626, doi:10.1029/93GL01767.

Katsura, T., Yoneda, A., Yamazaki, D., Yoshino, T., and Ito, E., 2010, Adiabatic temperature profile in the mantle: Physics of the Earth and Planetary Interiors, v. 183, p. 212–218, doi:10.1016/j.pepi.2010.07.001.

Kieffer, B., Arndt, N., Lapierre, H., Bastien, F., Bosch, D., Pecher, A., Yirgu, G., Ayalew, D., Weis, D., Jerram, D.A., Keller, F., and Meugniot, C., 2004, Flood and shield basalts from Ethiopia: Magmas from the African superswell: Journal of Petrology, v. 45, p. 793–834, doi:10.1093/petrology/egg112.

Kogiso, T., Hirschmann, M.M., and Frost, D.J., 2003, High-pressure partial melting of garnet pyroxenite: Possible mafic lithologies in the source of ocean island basalts: Earth and Planetary Science Letters, v. 216, p. 603–617, doi:10.1016/S0012-821X(03)00538-7.

Leeman, W.P., Lewis, J.F., Evarts, R.C., Conrey, R.M., and Streck, M.J., 2005, Petrologic constraints on the thermal structure of the Cascades arc: Journal of Volcanology and Geothermal Research, v. 140, p. 67–105, doi:10.1016/j.jvolgeores.2004.07.016.

McKenzie, D., and Bickle, M.J., 1988, The volume and composition of melt generated by extension of the lithosphere: Journal of Petrology, v. 29, p. 625–679, doi:10.1093/petrology/29.3.625.

Montelli, R., Nolet, G., Dahlen, F.A., Masters, G., Engdahl, E.R., and Hung, S.H., 2004, Geophysics: Finite-frequency tomography reveals a variety of plumes in the mantle: Science, v. 303, p. 338–343, doi:10.1126/science.1092485.

Ono, S., 2008, Experimental constraints on the temperature profile in the lower mantle: Physics of the Earth and Planetary Interiors, v. 170, p. 267–273, doi:10.1016/j.pepi.2008.06.033.

Park, Y., and Nyblade, A.A., 2006, P-Wave tomography reveals a westward dipping low velocity zone beneath the Kenya rift: Geophysical Research Letters, v. 33, L07311, doi:10.1029/2005GL025605.

Pik, R., Deniel, C., Coulon, C., Yirgu, G., and Marty, B., 1999, Isotopic and trace element signatures of Ethiopian flood basalts: Evidence for plume-lithosphere interactions: Geochimica et Cosmochimica Acta, v. 63, p. 2263–2279, doi:10.1016/S0016-7037(99)00141-6.

Ritsema, J., Deuss, A., van Heijst, H.J., and Woodhouse, J.H., 2011, S40RTS: A degree-40 shear-velocity model for the mantle from new Rayleigh wave dispersion, teleseismic traveltime and normal-mode splitting function measurements: Geophysical Journal International, v. 184, p. 1223–1236, doi:10.1111/j.1365-246X.2010.04884.x.

Rogers, N.W., James, D., Kelley, S.P., and de Mulder, M., 1998, The generation of potassic lavas from the eastern Virunga Province, Rwanda: Journal of Petrology, v. 39, p. 1223–1247, doi:10.1093/petroj/39.6.1223.

Rooney, T.O., Bastow, I.D., and Keir, D., 2011, Insights into extensional processes during magma assisted rifting: Evidence from aligned scoria cones and maars: Journal of Volcanology and Geothermal Research, v. 201, p. 83–96, doi:10.1016/j.jvolgeores.2010.07.019.

Rosenthal, A., Foley, S.F., Pearson, D.G., Nowell, G.M., and Tappe, S., 2009, Petrogenesis of strongly alkaline primitive volcanic rocks at the propagating tip of the western branch of the East African Rift: Earth and Planetary Science Letters, v. 284, p. 236–248, doi:10.1016/j.epsl.2009.04.036.

Rudnick, R.L., McDonough, W.F., and Chappell, B.W., 1993, Carbonatite metasomatism in the Northern Tanzanian mantle—Petrographic and geochemical characteristics: Earth and Planetary Science Letters, v. 114, p. 463–475, doi:10.1016/0012-821X(93)90076-L.

Tan, E., and Gurnis, M., 2005, Metastable superplumes and mantle compressibility: Geophysical Research Letters, v. 32, L20307, doi:10.1029/2005GL024190.

Venkataraman, A., Nyblade, A.A., and Ritsema, J., 2004, Upper mantle Q and thermal structure beneath Tanzania, East Africa from teleseismic P wave spectra: Geophysical Research Letters, v. 31, L15611, doi:10.1029/2004GL020351.

White, R.S., Smith, L.K., Roberts, A.W., Christie, P.A.F., Kusznir, N.J., and the ISIMM Team, 2008, Lower-crustal intrusion on the North Atlantic continental margin: Nature, v. 452, p. 460–464, doi:10.1038/nature06687.

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