Elevated mantle temperature beneath East Africa

Tyrone O. Rooney1*, Claude Herzberg2, and Ian D. Bastow3
1Department of Geological Sciences, Michigan State University, East Lansing, Michigan 48824, USA
2Department of Geological Sciences, Rutgers University, Piscataway, New Jersey 08855-1179, USA
3Department 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. Melt 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.

TEC TONIC 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., Duller 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$_2$O$_3$ (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$_{TOT}$ (total iron reported as a single oxide), and this was estimated assuming FeO$_{TOT}$/TiO$_2$ = 1 (see Herzberg and Asimow, 2008). A more reducing ratio of FeO$_{TOT}$/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 FeO$_{TOT}$/TiO$_2$ usually propagates to Fe$^{3+}$/Fe$^{2+}$ values that vary from 0.80 to 0.90. Uncertainties in Fe$^{3+}$/Fe$^{2+}$ 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 FeO$_{TOT}$/TiO$_2$ value will likely provide a minimum estimate of mantle $T_p$ below East Africa.

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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 Repository1). 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 Virunga (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.

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

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1GSA 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.
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 relation between temperature and dVp/dT 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:

\[
\frac{\partial \ln V}{\partial T} = \frac{\partial \ln V_0}{\partial T} - F(\alpha) \left( \frac{Q}{\alpha} \right) \left( \frac{\partial \ln \tau}{\partial T} \right)
\]

where \(\partial \ln V/\partial T\) is the observed velocity perturbation (\(\partial \ln V_p/\partial T\)) with temperature change (\(\partial T\)), \(H^*\) is the activation enthalpy, \(R\) is the gas constant, and \(F(\alpha)\) 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 \(\partial \ln V/\partial T = -5 \times 10^{-4} \text{ K}^{-1}\), \(H^* = 500 \text{ kJ/mol for olivine}, T = 1600 \text{ K}\) (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, \(Q_\alpha = 80\) (Venkataraman et al., 2004). Thus, the petrologically determined 140 °C \(T_p\) anomaly for Ethiopia using Equation 1 likely results in only an \(\sim 2\%\) \(V_p\) 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 \(>200\text{ km}\), 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).

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 melts at depths greater than that of peridotite (Kogiso et al., 2003); however, it is the combined effect of CO2 and H2O 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), CO2 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 CO2-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 carbonate melts and CO2-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 H2O-CO2 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 CO2 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, CO2-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.

**ACKNOWLEDGMENTS**

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

<table>
<thead>
<tr>
<th>Region</th>
<th>Longitude</th>
<th>Latitude</th>
<th>(\delta V_s, 410\text{ km} (%))</th>
<th>(\delta V_s, 200\text{ km} (%))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethiopian rift</td>
<td>40°E</td>
<td>9°N</td>
<td>-4.24</td>
<td>-5.11</td>
</tr>
<tr>
<td>Afar</td>
<td>42°E</td>
<td>11°N</td>
<td>-4.19</td>
<td>-5.15</td>
</tr>
<tr>
<td>Iceland</td>
<td>17°W</td>
<td>64°N</td>
<td>-3.31</td>
<td>-3.12</td>
</tr>
<tr>
<td>Hawaii</td>
<td>155°W</td>
<td>19°N</td>
<td>-1.50</td>
<td>-1.04</td>
</tr>
<tr>
<td>Samoa</td>
<td>168°W</td>
<td>15°S</td>
<td>-1.58</td>
<td>-0.90</td>
</tr>
<tr>
<td>Cook Islands</td>
<td>158°W</td>
<td>22°S</td>
<td>-0.83</td>
<td>-0.58</td>
</tr>
<tr>
<td>Azores</td>
<td>26°W</td>
<td>38°N</td>
<td>-1.60</td>
<td>-2.25</td>
</tr>
<tr>
<td>Canaries</td>
<td>18°W</td>
<td>28°N</td>
<td>-0.32</td>
<td>+0.32</td>
</tr>
<tr>
<td>Galapagos</td>
<td>92°W</td>
<td>0°N</td>
<td>-3.10</td>
<td>-5.46</td>
</tr>
</tbody>
</table>

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

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