

# Seismic evidence for a deep upper mantle thermal anomaly beneath east Africa

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## ABSTRACT

Upper mantle seismic velocity variations beneath northern Tanzania coupled with the structure of the 410 and 660 km discontinuities reveal a 200–400-km-wide thermal anomaly extending into but not necessarily through the transition zone beneath the eastern branch of the East African rift system. This finding is not easily explained by small-scale mantle convection induced by passive stretching of the lithosphere or by a broad thermal upwelling extending from the lower mantle into the upper mantle, but it can be attributed to a mantle plume, provided that a plume head is present under the lithospheric keel of the Tanzania craton. A plume interpretation for the deep thermal anomaly is supported by evidence for mantle having the geochemical characteristics of a plume at >150 km depth beneath northern Tanzania.

**Keywords:** plume, rift, east Africa, craton.

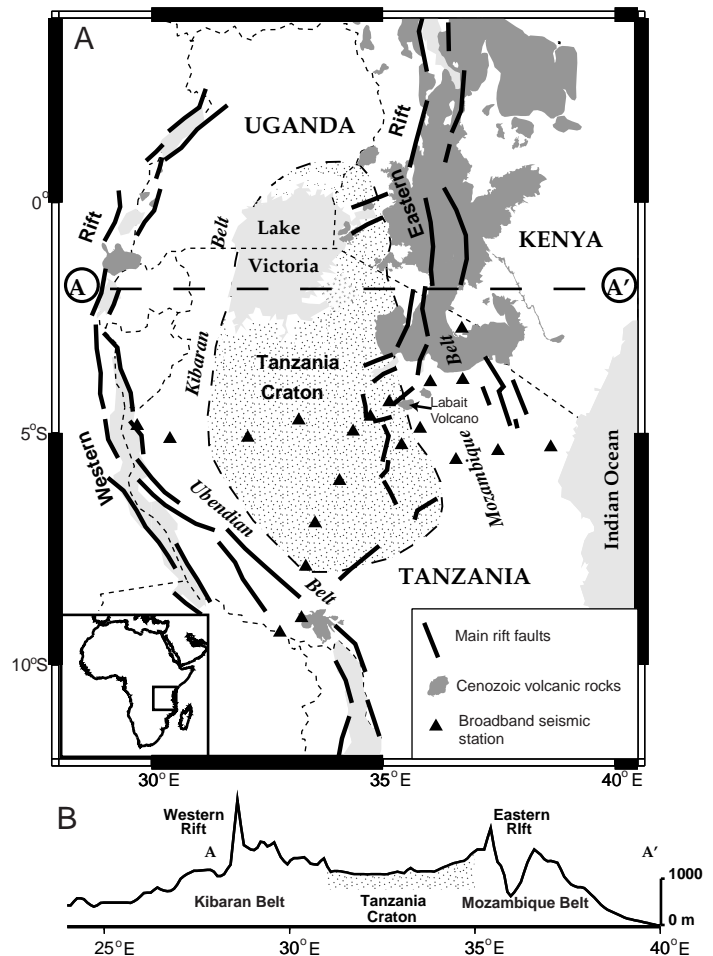
## INTRODUCTION

Although east Africa has long been regarded as a classic area in which to study the early stages of continental breakup, the origin of the Cenozoic rifting, volcanism, and plateau uplift found there is still poorly understood (Fig. 1). The east African rifts can be linked to extensional stresses associated with the development of the Afar triple junction (Baker et al., 1972), but it is unlikely that the small amount of crustal extension ( $\leq 10$ –15 km) across east Africa could have led to (1) sufficient pressure-release melting to account for the large volume of extrusive rock present in some parts of the rift system or (2) enough thinning of the lithosphere to cause significant ( $\geq 1$  km) plateau uplift (McKenzie and Bickle, 1988; Ebinger, 1989). Consequently, a purely passive origin for the Cenozoic tectonism has been frequently rejected; instead, the tectonism has been commonly attributed to one or more mantle plumes or to passive rifting above a mantle plume (e.g., Green et al., 1991; Latin et al., 1993; Macdonald, 1994; Slack et al., 1994; Achauer et al., 1994; Prodehl et al., 1994; Paslick et al., 1995; Burke, 1996; Fuchs et al., 1997). However, whether a plume exists beneath east Africa has been contended because geochemical and geophysical data from there, until recently, have provided little information on mantle composition and thermal structure beneath the lithosphere where the plume is hypothesized to be.

New light is shed on the east African plume debate in this paper by (1) showing how results from two recent studies using broadband seismic data, when combined, reveal a deep (>400 km) thermal anomaly in the upper mantle beneath northern Tanzania, and (2) using the structure of the thermal anomaly to evaluate several models (plume and nonplume) advanced previously to explain the Cenozoic tectonism.

## SEISMIC EVIDENCE

The seismic data come from teleseismic earthquakes recorded at 20 stations deployed across Tanzania between June 1994 and May 1995 (Nyblade et al., 1996) (Fig. 1). In the first study, relative traveltimes from P and S waves were inverted for upper mantle seismic velocity variations (Ritsema et al., 1998). The patterns of P- and S-wave velocity variation obtained are similar, and so we limit our discussion to the S-wave velocity model. A vertical cross section through the S-wave model is shown in Figure 2A to illustrate the main features. The model shows higher than average



**Figure 1. A:** Schematic map of east Africa showing political boundaries, large rift lakes, Precambrian terranes, main rift faults, volcanic provinces, and locations of broadband seismic stations. Tectonic framework of east Africa is characterized by Archean Tanzania craton within center of east African plateau surrounded by Proterozoic mobile belts. Two rift-system branches (eastern and western rifts) have been formed by Cenozoic rifting primarily in mobile belts. Eastern rift terminates in northeastern Tanzania within 300-km-wide region of block faulting. **B:** West-east cross section showing topography across east African plateau.

velocities beneath the Tanzania craton and predominantly lower than average velocities beneath the rifted mobile belts surrounding the craton. The low-velocity region under the eastern rift extends vertically to depths greater than 400 km and laterally over a region ~300 km wide. The lithospheric keel beneath the craton, as defined by the relatively fast velocities, extends to a depth of ~200–250 km (the continuation of fast velocities to 300–400 km depth in Fig. 2A is due to limited vertical resolution). Between depths of 200 and 300 km the low-velocity structure associated with the rifts begins to extend westward under the fast structure of the cratonic lithosphere.

There are two likely causes for the contrast in the upper mantle S-wave velocities between the craton and eastern rift. High S-wave velocities (~3%–6%) commonly characterize cratonic lithosphere to depths of at least 200 km in other Precambrian shields (e.g., Grand, 1994; Grand et al., 1997; Van der Lee and Nolet, 1997; Ekstrom and Dziewonski, 1998) and are expected for the cold, chemically depleted structure of the cratonic keel (Jordan, 1979, 1988). The contrast in velocities could also result from elevated temperatures in the mantle beneath the eastern rift. Because the seismic model shows only relative velocities beneath east Africa, it is unclear whether the mantle under the rift is abnormally slow or the mantle under the craton is abnormally fast. Additional information on the thermal and/or compositional structure of the upper mantle is needed to partition the velocity variation between cold, depleted mantle under the craton and warm mantle under the rift.

A study of the topography on the 410 and 660 km discontinuities beneath Tanzania provides the required information (Owens et al., 2000). The 410 and 660 km discontinuities are generally interpreted as transitions in the  $\alpha$ -phase to the  $\beta$ -phase of  $(\text{Mg}, \text{Fe})\text{SiO}_4$  and from  $\gamma$ - $(\text{Mg}, \text{Fe})\text{SiO}_4$  to perovskite + magnesiowustite, respectively. The Clapeyron slopes of the equilibrium phase boundaries indicate that the depth of the 410 km discontinuity should be deflected downward in regions of warmer temperature and the 660 km discontinuity should be deflected upward (Bina and Helffrich, 1994). Therefore, topography on the discontinuities can provide information about upper mantle thermal structure in the 400–700 km depth range.

Topography on the 410 and 660 km discontinuities beneath Tanzania has been estimated by geographically stacking receiver functions (Owens et al., 2000). Results show that the transition zone (e.g., the region between the discontinuities) is thinned by 30–40 km over an area 200–400 km wide beneath the eastern rift. The transition-zone thinning, which corresponds to a temperature increase of about 200–300 K, is primarily due to a wide depression of the 410 km discontinuity (Fig. 2A and 2B) and coincides directly with the low-velocity anomaly seen beneath the eastern rift (Fig. 2A). In comparison to the 410 km discontinuity, little relief is observed on the 660 km discontinuity (Fig. 2A).

The coincidence of the depressed 410 km discontinuity and the low-velocity region beneath the eastern rift indicates that at least some of the S-wave velocity variation between the craton and eastern rift is due to temperatures beneath the eastern rift elevated by 200–300 K. According to laboratory measurements of the temperature derivatives of wave speeds in olivine (Isaak, 1992), a 200–300 K temperature increase in the upper mantle would reduce S-wave velocities by ~2%.

## DISCUSSION

The depth extent of thermally perturbed mantle beneath the eastern rift, the wide depression of the 410 km discontinuity, and the relatively flat 660 km discontinuity can be used to evaluate candidate models (plume and nonplume) for the Cenozoic tectonism in east Africa. The depth extent of the upper mantle thermal disturbance is not readily explained by small-scale convective upwelling induced by passive stretching of the lithosphere. In passive rift models, sublithospheric mantle flow fills in voids created by the stretched lithosphere. This process leads to small-scale convective instabilities near the base of the lithosphere, but likely not throughout the upper mantle (e.g., Buck, 1986; Mutter et al., 1988). In addition, in fast-spreading oceanic rifts, anomalously slow mantle structure caused by upwelling and decompression melting extends to depths of only a few hundred kilometers (Toomey et al., 1998; Webb and Forsyth, 1998). Thus, in northern Tanzania, where the total amount of lithospheric extension during the past 5–8 m.y. has been only 10 km over an area 300 km wide (Foster et al., 1997; Ebinger et al., 1997), it seems highly improbable that small-scale convective upwellings induced by lithospheric stretching could extend from the transition zone all the way to the base of the lithosphere.

On the basis of tomographic images of the mantle beneath Africa that show a broad S-wave velocity anomaly in the upper mantle beneath

Tanzania possibly connecting with low-velocity structure in the lower mantle beneath southern Africa, it has been suggested that a broad (i.e., several hundred kilometers wide) thermal upwelling extends from the core-mantle boundary all the way to the uppermost mantle beneath the rift system (Ritsema et al., 1999; Lithgow-Bertelloni and Silver, 1998). Although the depth extent of the thermal anomaly and the wide depression of the 410 km discontinuity in Figure 2 (A and B) are consistent with a broad thermal upwelling, the flat 660 km discontinuity under Tanzania and the average thickness of the transition zone are not easily explained by a broad thermal upwelling that is continuous across the transition zone, at least not by one beneath Tanzania. The average thickness of the transition zone beneath Tanzania (253 km; Owens et al., 2000) is consistent with estimates of the global average transition-zone thickness (e.g., Flanagan and Shearer, 1998; Chevrot et al., 1999), indicating that there is no broad thinning of the transition zone. Whereas the lower mantle low-velocity structure beneath southern Africa may somehow be linked geodynamically to the upper mantle low-velocity structure beneath east Africa, there appears to be little evidence to support a throughgoing mantle thermal anomaly beneath Tanzania.

A third model for the Cenozoic tectonism in east Africa invokes the presence of one or more mantle plumes. Models with a plume located beneath the eastern branch of the rift system in Kenya have been proposed by many authors (e.g., Simiyu and Keller, 1997; Ebinger et al., 1997; Green et al., 1991; Smith, 1994; Slack et al., 1994). In contrast to the models discussed here, the depth extent of thermally perturbed structure beneath northern Tanzania, the wide depression of the 410 km discontinuity, and the relatively flat 660 km discontinuity can all be attributed to a plume head beneath Kenya, provided that the plume head came up under the eastern side of the Tanzania craton and then flowed laterally along the craton margin into northern Tanzania. In this interpretation (Fig. 2C), the thermal structure beneath the eastern rift is caused by buoyant (warm) plume head material that has migrated around and laterally along the eastern side of the cratonic keel, modifying the mantle lithosphere beneath the eastern rift. Plume head temperatures are estimated to be 100–300 K above ambient mantle temperatures (McKenzie and Bickel, 1988; Campbell and Griffiths, 1990; Farnetani and Richards, 1994), sufficient to reduce S-wave velocities by a few percent.

The wide depression of the 410 km discontinuity beneath northern Tanzania is explained in this model by the bottom of a plume head being across the 410 km discontinuity. Fluid dynamic studies of plumes suggest that plume heads can be several hundred kilometers across and as thick as 200 km (Griffiths and Campbell, 1991). Hence, if a plume head impinged on thick (200–250 km) cratonic lithosphere, it is possible that the bottom of the plume head could extend to depths of  $\geq$ 400 km, giving rise to a depression of the 410 km discontinuity that is several hundred kilometers across. The structure of the plume-head bottom could be very complicated because of the thermal and mechanical interaction of plume-head material with the surrounding mantle, and so the model depicted in Figure 2C should be viewed as somewhat schematic and general. The 660 km discontinuity beneath Tanzania is not disrupted by the plume tail in this interpretation because the tail is to the north beneath Kenya.

A plume head situated beneath the eastern side of the craton could also explain why there is little volcanism in the western rift compared to the eastern rift. For a plume head located under the eastern margin of the craton, most of the plume material would flow around the craton lithosphere to the east and a lesser amount would make its way around the craton lithosphere to the west.

Ebinger and Sleep (1998) proposed a similar plume model and argued that a large plume head impinged on the lithosphere in southern Ethiopia, as opposed to Kenya, and that the plume material flowed outward from this location channeled by topography on the lithosphere-asthenosphere boundary. Considering that warm material spreading outward from the plume center in the Ebinger and Sleep model is only 50–100 km thick, it is not easy to explain with their model the  $>$ 400 km deep thermal anomaly beneath northern Tanzania, unless for some unknown reason the plume material has

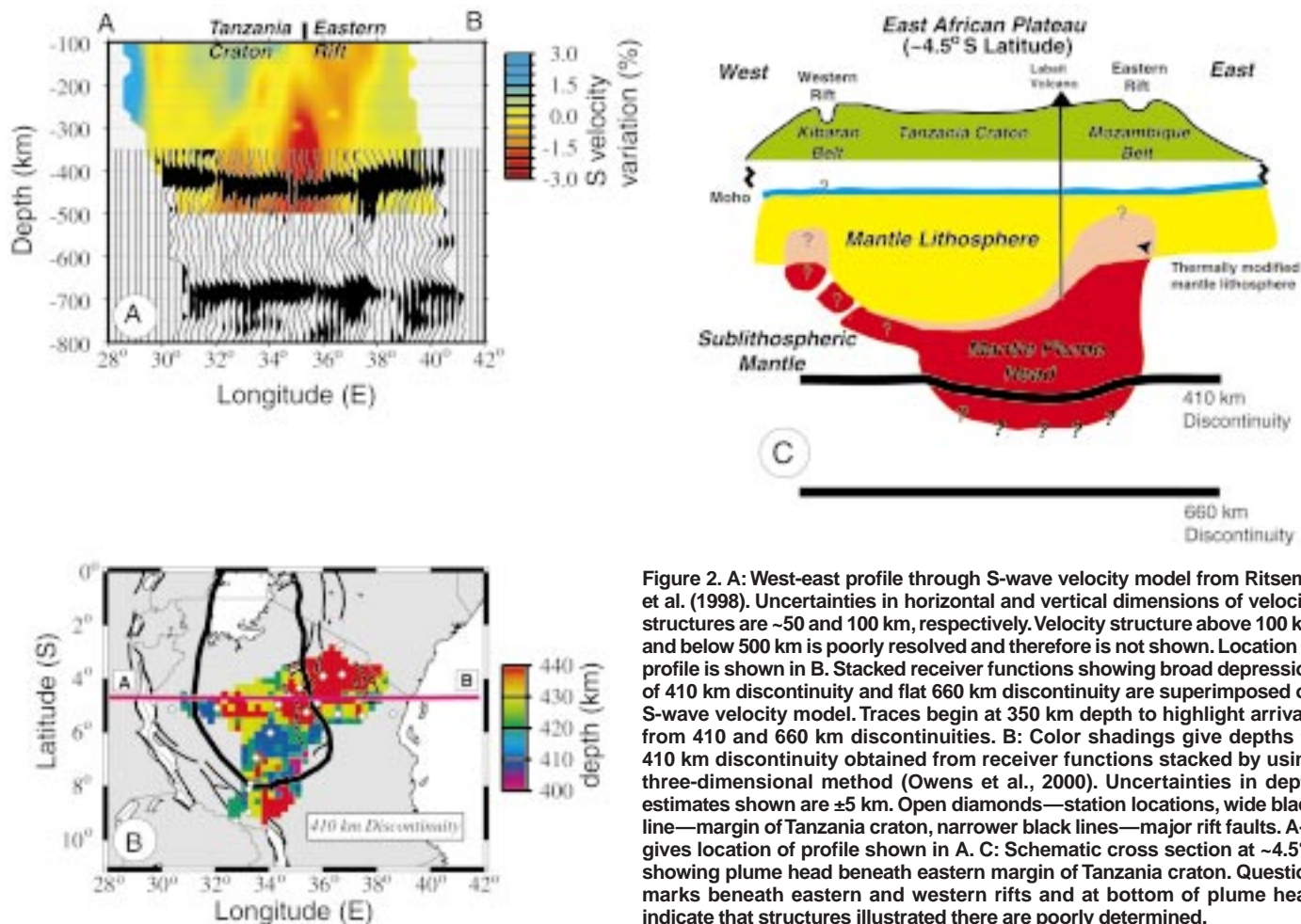


Figure 2. A: West-east profile through S-wave velocity model from Ritsema et al. (1998). Uncertainties in horizontal and vertical dimensions of velocity structures are ~50 and 100 km, respectively. Velocity structure above 100 km and below 500 km is poorly resolved and therefore is not shown. Location of profile is shown in B. Stacked receiver functions showing broad depression of 410 km discontinuity and flat 660 km discontinuity are superimposed on S-wave velocity model. Traces begin at 350 km depth to highlight arrivals from 410 and 660 km discontinuities. B: Color shadings give depths to 410 km discontinuity obtained from receiver functions stacked by using three-dimensional method (Owens et al., 2000). Uncertainties in depth estimates shown are  $\pm 5$  km. Open diamonds—station locations, wide black line—margin of Tanzania craton, narrower black lines—major rift faults. A-B gives location of profile shown in A. C: Schematic cross section at  $\sim 4.5^\circ$ S showing plume head beneath eastern margin of Tanzania craton. Question marks beneath eastern and western rifts and at bottom of plume head indicate that structures illustrated there are poorly determined.

ponded there beneath the lithosphere. George et al. (1998), in a related study, suggested that the tail from the Ethiopian plume is now located beneath Kenya because of the northward motion of the African plate. This model has the same problem as the Ebinger and Sleep model in that it requires a mechanism to get the warm material from the plume tail to pond beneath northern Tanzania in order to explain the depth extent of the upper mantle thermal anomaly.

Our plume interpretation is in good agreement with several recent geochemical studies of lavas and mantle xenoliths from northern Tanzania. A detailed investigation of basalts and nephelinites from northern Tanzania concluded that the trace element, Sr, Nd, and Pb isotopic compositions of these magmas were similar to those of ocean island basalts (Paslick et al., 1995). A recent study of mantle xenoliths from the Labait volcano, on the eastern edge of the craton (Figs. 1 and 2C), concluded that the sublithospheric mantle there has radiogenic Os isotopic compositions similar to those observed in ocean island basalts (Chesley et al., 1999). In addition, the deepest xenolith (~160 km depth) has a major element composition close to primitive mantle and could therefore be a sample of plume-like mantle (Chesley et al., 1999).

## SUMMARY AND CONCLUSIONS

Seismic velocity models of the upper mantle combined with topography on the 410 km discontinuity provide evidence for a deep thermal anomaly in the upper mantle beneath the eastern rift. We attribute this thermal anomaly to a mantle plume, because the structure of the thermal anomaly can be readily explained by a plume head under the eastern margin of the Tanzania craton. The Cenozoic uplift and volcanism found in east

Africa can be attributed to a plume head under the eastern margin of the Tanzania craton. Warm plume material spread out under the craton could generate lithospheric uplift across the east African plateau, and decompression melting of warm plume material could give rise to the observed volcanism.

The extent to which the rifting may be influenced by a plume under the eastern margin of the Tanzania craton, however, remains uncertain. The timing between plateau uplift and rifting is needed to unravel the relative contributions to the extensional stress field from the plume (i.e., membrane stresses due to lithosphere uplift) versus far-field plate-boundary forces associated with the opening of the Afar triple junction. The history of plateau uplift in east Africa relative to the timing of rifting is poorly understood, and thus it is difficult to determine how much influence a plume may have had on rifting. Information on the timing of uplift needed to address further the cause of rifting may be obtained in the future from fission-track, cosmogenic isotope, or other types of data that are sensitive to lithospheric uplift.

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