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Reply

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Vauchez *et al.* [this issue] (hereinafter refered to as VBN) interpret the petrologic, tomographic, and anisotropy data from continental rifts to support a model of continental rifting [*Nicolas*, 1993; *Nicolas et al.*, 1994] in which the lithosphere splits along the rift axis and asthenosphere flows in from the sides to fill the resulting gap. We suggest here that the data can also be described by a model in which the lower lithosphere is modified or eroded by active mantle upwelling over a region of significantly greater dimensions than the rift graben and that partial melt developing in the upwelling region can account for the widespread volcanism, as well as the seismic properties. Nicolas [1993] argued that rift-aligned anisotropy could be explained by rift-parallel mantle flow. We thank VBN for bringing this relevant paper to our attention.

Volcanism about the East African Rift and the Rio Grande is not confined to the rifts but extends hundreds of kilometers from the rift axes (Mount Kilimanjaro, Mount Elgon, Mount Kenya in East Africa, The Jemez Lineament on the Rio Grande) in regions uplifted relative to their surroundings. The low-velocity tomographic anomalies also extend beneath the uplifted regions and are thought to be related to the uplift possibly supporting it by thermostatic buoyancy. The size of the P and S velocity contrasts and attenuation of high frequencies have led to the suggestion that large regions of the anomalous bodies have temperatures at or above the solidus [*Achauer et al.*, 1994; *Slack et al.*, 1994, 1996]. The wide extent of the anomalous regions is not explicable as resulting from an abyssal lithospheric dike beneath the rift intruded by asthenosphere. The extension of the East African, Baikal, and Rio Grande rift grabens has been estimated to be about 10 km [*Baker et al.*, 1972; *Baldridge et al.*, 1984; *Morgan and Golombek*, 1984; *Logatchev and Florensov*, 1978]. Passive influx of asthenosphere into a 10 km lithospheric dike is insufficient to explain the tomographic anomalies [*Davis*, 1991]. In addition, the amount of finite strain from lithospheric diking is insufficient to explain the anisotropy anomalies. Active replacement or modification of lower lithosphere either prior to, or contemporaneous with, rifting could generate tomographic anomalies of this magnitude.

1. Rift Model

We will mainly focus on the East African Rift where the anomalies are greatest. In Africa the continent wide basin and swell topography has been attributed to small scale convection in the mantle [*Burke and Wilson*, 1972; *McKenzie and Weiss*, 1975; *Burke*, 1996]. Rifting in East Africa is thought to have a 30 Myr history possibly related to Africa's coming to rest in the mantle reference frame [*Burke*, 1996] and impingement on the lithosphere by upwelling mantle [*Burke*, 1996; *Ebinger and Sleep*, 1998; *George et al.*, 1998; *Davies*, 1998]. VBN cite the tomographic results of *Achauer et al.* [1994] for the East African rift to support a rift model [*Nicolas*, 1993; *Nicolas et al.*, 1984] in which asthenospheric intrusion occurs within a narrow steep conduit in the lithosphere, the asthenospheric wedge model. *Nicolas et al.* [1994] used results presented by *Green et al.* [1991] which give the appearance of steep vertical sides. However, part of this appearance results from using blocks to represent tomographic anomalies, as well as inherent lack of vertical resolution of the method and the limited extent of the array. A thin vertical conduit would not be observable by teleseismic tomography because diffracted waves in the low-velocity channel would obscure its influence on surface delays. Furthermore, the *Green et al.* [1991] study was based on a subset of the data collected from the East African Rift. Subsequent measurements from a wider array have shown that the first-order pattern of teleseismic delays attributable to mantle effects is more widespread, peaking at the rift and extending hundreds of kilometers on either side, a pattern that is not consistent with a narrow steep conduit. The travel

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time delays have been interpreted as due to a broadening low-velocity anomaly over several hundred kilometers wide in the uppermost mantle extending down to depths between 150 and 200 km (Figure 7 of *Achauer et al.* [1994] and Figures 6-8 of *Slack et al.* [1994] for the African rift; *Parker et al.* [1984], *Halderman and Davis* [1991], *Davis* [1991], and *Slack et al.* [1996] for the Rio Grande Rift; and *Gao et al.* [1994b], *Gao* [1995] for the Baikal rift). While the conduit model may apply for the ophiolites that have been studied by VBN, it is uncertain whether ophiolites are the best description of the uppermost mantle beneath continental rift zones in the pre-seafloor spreading phase. Continental rifts lie in regions of uplift presumed to be a thermostatic response to asthenospheric erosion of the lower lithosphere [*Davis,* 1991; *Morley,* 1994; *Smith,* 1994] with limited surface extension largely confined to the rift. Ophiolites are associated with the extreme extension associated with seafloor spreading with regional uplift dependent on (half-space) cooling of the upper lithosphere. Ophiolite mantle may be depleted in basalt and volatiles compared to fertile mantle such as that thought to underlie the Kenya Rift.

2. Rift Anisotropy

With regards to three mechanisms for generating mantle anisotropy beneath rift zones, *Gao et al.* [1997, p. 22,794] state that "resolving between fossil anisotropy, recent mantle flow, or aligned magmatic cracks is sufficiently difficult that favoring one over the other cannot be made with a high degree of certainty." VBN respond that the parallelism between the polarization azimuth of the fast split waves and the trend of the rift may "be explained by olivine LPO either due to rift-parallel asthenospheric mantle flow, to an inherited lithospheric tectonic fabric, or to a combination of both," thereby favoring the first two mechanisms over the third. VBN bring their extensive petrologic experience to bear on the problem, and we welcome this interdisciplinary exchange. We concede that LPO in olivines may develop above the solidus but remain persuaded that aligned magmatic cracks must still be viewed as a strong candidate for the observations. In East Africa fast directions extend well past the rift width of 50 km to cover a distance of 180 km, that is, well onto the rift shoulders. The small (6%) finite strain associated with a 10 km opening is probably too small to dominate fossil anisotropy over this large region.

VBN rule out anisotropy caused by a bias in magma filled cracks because for it to become dominant would require "several percent of melt concentrated in coherently aligned melt pockets displaying high aspect ratio." There is no theoretical basis for this percentage. A much smaller fraction of melt in aligned cracks could be a very sensitive generator of S wave anisotropy as has been shown by numerous studies [*Garbin and Knopoff,* 1973, 1975a, b; *Anderson et al.,* 1974; *Budiansky and O'Connell,* 1976; *Mavko,* 1980]. The perturbation in seismic shear wave velocity is governed by the product of porosity and aspect ratio of the cracks [*Thomsen,* 1986; *Anderson,* 1989]. A slight bias in orientations of magma filled cracks could easily dominate the anisotropy of S waves. For example, *Anderson et al.* [1974] show that 0.1% of cracks of aspect ratio 100 causes several percent anisotropy. An extreme case of circular cracks of zero porosity and infinite aspect ratio is treated by *Garbin and Knopoff* [1973, 1975a, b] for which *Crampin* [1978] gives examples of SV SH velocity anisotropy as high as 20%. Melt in grain-grain boundaries can have low porosities and high aspect ratios. Laboratory melts are often confined to grain-grain triple junctions. Sheared rock exhibits much greater wetting with melt distributed in thin films that wet grain boundaries [*Jin et al.,* 1994], which is much more effective in reducing the rigidity modulus. Admitting that it is difficult to choose between fossil, flow, or crack mechanisms, we favored cracks for the Rio Grande and East Africa cases because a flow producing this direction seemed more ad hoc and the fast direction fits recent estimates of regional strain [*Gao et al.,* 1997]. Laboratory experiments in which seismic anisotropy is measured in partially melted peridotites under triaxial stress conditions are needed to compare observations with calculations.

VBN argue that "... the asthenospheric wedge beneath the rift axis, where melting may occur, is usually narrow ... . Consequently, a large volume of preferentially oriented melt pockets is unlikely beyond the rift axis, especially beneath the rift shoulders." For both the Rio Grande and East Africa the volcanism, and presumably partial melting associated with it, extends past the rift shoulders as does the tomographic and anisotropy anomaly. Baikal has little cenozoic volcanism (6000 km^3 as compared to 500,000 km^3 in East Africa [*Baker et al.,* 1972]), but there too the tomographic anomaly extends well past the rift shoulders and has been variously attributed to thinning of the lithosphere [*Zorin,* 1979; *Gao et al.,* 1994b; *Gao,* 1995]. A narrow asthenospheric wedge is also not supported by that data. The narrowness has yet to be demonstrated for continental rifts.

3. Stability of Anisotropy

Gao et al. [1997] citing *Vinnik et al.* [1992] suggested that above 900^{o}C, mobility of olivine crystals is high and therefore survival of fossil anisotropy is very unlikely in the sheared mantle beneath the rifts, especially if the tomographic interpretation for low-velocity anomalies is correct in that the mantle is at temperatures near or above the solidus. VBN give examples in which LPO develops in mantle rocks heated to the point of recrystallization but which may be weaker or stronger than the LPO of the unrecrystallized samples. In particular, peridotites deformed under asthenospheric conditions ($T \geq 1200$ °C) in the Oman Ophiolite were found to display a strong fabric [*Nicolas*, 1989]. Indeed, *Nicolas* [1989] suggests that large scale homogeneous deformation representative of asthenospheric flow occurs only above 1200°C. Replacement of lower lithosphere by convective shearing over a time period of 30 Myr requires a strain rate of at least 10^{-15} s^{-1}. VBN state that "the deviatoric stress necessary to deform olivine aggregates at 900°C and strain rates $\geq 10^{-15}$ s^{-1}, computed using experimental data [*e.g., Chopra and Paterson,* 1981], is higher than 100 MPa, a value so high that within the lithosphere, the deformation is confined to restricted areas." We counter that this estimate is highly dependent on the rheology chosen, in particular on water content. For example, flow laws for wet and dry dunite [*Chopra and Paterson,* 1984, Table 3] give much lower stresses of 1.7 MPa and 16 MPa, respectively [also *Kohlstedt et al.,* 1995, Figure 9]. If the stresses associated with mantle upwelling are supporting the 1 km of topography, these values are not unreasonably high. Given uncertainty as to whether a wet or dry olivine rheology applies to the upper mantle beneath a rift, it is not clear at what temperature the lithosphere would flow and be engulfed in the convection of the underlying asthenosphere.

While we argue against the wedge model, when discussing structures at depths of up to 200 km and processes that have developed over the last 30 Myr, it behoves us to discuss the uncertainties in our interpretation. The combination of surface extension and tomography does not favor a dike but does not have to be explained by thinning of the lithosphere with replacement by asthenosphere. A lateral contrast in composition may explain the data. For example, lithosphere modified by volatiles from an upwelling convection cell in the asthenosphere could also cause the velocity reduction by increasing the homologous temperature, perhaps to the point of raising it above the solidus and generating volcanism. In that case, no major deformation of the lower lithosphere need take place and the anisotropy could indeed be fossil as VBN suggest. However, petrologic studies of volcanic products in East Africa have favored mantle upwelling there [*Latin et al.,* 1993], but it is beyond the scope of this paper whether those models can also be accommodated by a volatilized lithosphere. In continental regions of much greater extension than the rifts described here, the inflow could occur over a much greater region and the asthenospheric wedge model [*Nicolas,* 1993] may well apply provided the inflow is orthogonal to the extension.

In conclusion, the widespread volcanism in East African and Rio Grande rifts, and the widespread tomographic anomalies beneath Baikal, Rio Grande and East African rifts, have suggested to us that the lithosphere has been thinned beneath the rifts. Wet or dry olivine creep laws place the isotherm above which lithosphere might be entrained in an associated mantle flow at about 900°C. The tomography suggests this isotherm upwarps beneath rifts. Shearing associated with this process generates finite strain over a greater volume than that associated with just the rift opening. Whether the measured anisotropy is due to those strains, fossil strain, or magmatic cracks is uncertain. However, to rule out magmatic cracks on the basis of a conservative quantitative assessment, or the asthenospheric wedge model which is not demanded by the data is premature at this stage in our understanding.

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