MECHANICAL ANISOTROPY OF THE LITHOSPHERIC MANTLE AND CONTINENTAL RIFTING: OBSERVATIONS AND MODELS

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Summary. The close temporal and spatial association between flood basalt extrusion and continental breakup suggests that mantle plumes play an important role on the rifting process. There is, however, a paradox between the pinpoint thermal and stress perturbation generated by an upwelling mantle plume and the linear geometry of rifts. Analysis of various plume-rift systems also highlights that rifts are offset relative to the plume head apex, where extensional stresses are highest. Rift propagation is not random; it tends to follow the trend of the pre-existing orogenic fabric of the plates, systematically reactivating ancient lithospheric structures. Moreover, continental rifts often display a clear component of strike-slip deformation, in particular during the early rifting stage. The source of this structural inheritance lies in a mechanical anisotropy of the lithospheric mantle due to the preservation of a lattice preferred orientation (LPO) of olivine crystals formed during major orogenic episodes. We use a polycrystal plasticity model to calculate the viscoplastic deformation of a pre-structured lithospheric mantle in response to various tensional stress fields. Model results show that the interaction between the extensional stress field and the LPO-induced mechanical anisotropy of the lithospheric mantle may explain both the structural inheritance and the onset of transtension within continental rifts.

Continents breakup parallel to ancient orogenic belts

Most of the major rifts have propagated parallel to the trend of the pre-existing orogenic fabric of the plates. This systematically triggered a reactivation of ancient lithospheric structures (Vauchez et al. 1997, 1998). The tectonic fabric of the Gondwana and Laurentia continents, for instance, largely guided the Atlantic Ocean opening. The initial South Atlantic rift (Fig.1a) propagated over more than 3000 km parallel to the Hercynian Cape fold belt, then to the Malmesbury, Kaoko, Dom Feliciano, Ribeira and West Congo Neoproterozoic belts, and also to the Palaeoproterozoic Itabuna belt in the São Francisco craton. This striking parallelism is maintained even south of Africa where the relative displacement of continents, which allowed a connection between the Atlantic rift and the Indian Ocean, was essentially transtensional.

The North Atlantic initial rift (Fig.1b) propagated from the Central Atlantic along the Hercynian belt until the relative displacement was transferred towards the Mediterranean basin along a major Hercynian transcurrent fault that linked the Newfoundland with the south Iberian Hercynian segments. The reactivation of this fault accommodated a differential displacement between the North African and the Iberian branches of the Hercynian belt. Northward, the opening of the Bay of Biscay started when the North Atlantic rift, following the curvature of the Ibero–Armorican Hercynian segment, wrapped around Iberia and produced the rupture between Iberia and Europe along the North Pyrenean fault which reactivated Hercynian structures. Finally, as the direction of the Hercynian belt curved to almost E–W, a direction unfavorable to opening, the North Atlantic rift followed the Caledonides belt northward.

Continental-scale steep transcurrent faults (or shear zones) are preferentially reactivated during rift propagation, even when they are oblique on the general trend of the orogenic belts. This was already highlighted by Daly et al. (1989), for instance, for the upper Palaeozoic Karoo basins of South Africa: Proterozoic shear zones closely controlled the location, orientation and tectonic styles of these basins. Another example lies in the West African rift system (e.g, Fairhead and Binks 1991), where the Benoue Trough, the Central African basins and the Cameroon volcanic line reworked the transcontinental strike-slip fault system formed by the Sanaga and Adamawa Neoproterozoic faults and their Brazilian counterparts (Vauchez et al. 1995). Finally, in the East African rift system, the southern part of the Gregory rift follows a Neoproterozoic lithospheric shear zone oblique on the general trend of the Mozambique belt (e.g., Cardon et al. 1997). A similar process may account for other basins oblique on the general orientation of the rift system, that otherwise follows the N–S Neoproterozoic Mozambique belt.

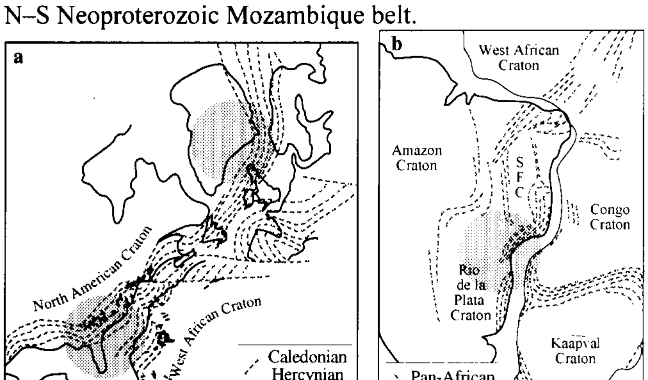

Fig. 1. Schematic map of (a) circum-North Atlantic Caledonian-Hercynian belts and (b) circum South-Atlantic Pan-African belts before rifting. Grey circles indicate the supposed positions of the major plumes (Courtillot et al. 1999) associated with the Central and North Atlantic, and the South Atlantic rifting

Recent shear wave splitting surveys in the Kenya and the Baikal rifts (Gao et al. 1997) show that at the rift margin, where large-scale modification of the lithospheric mantle by upwelling asthenospheric mantle is unlikely, fast shear waves are polarized parallel to the trend of the Mozambique and Sayan-Baikal orogenic belts respectively. These observations suggest that the Kenya and Baikal rifts formed parallel not only to crustal structures of the Mozambique and Mongolian belts, but also to a pre-rift fabric frozen in the upper mantle since these orogenies.

In addition, the close temporal and spatial association between flood basalt extrusion and continental breakup suggests that mantle plumes play an important role on the rifting process. Episodes of fast development of the Atlantic ocean, for instance, are closely related to the extrusion of large volumes of basalts. There is, however, a paradox between the pinpoint thermal and stress perturbation generated by an upwelling mantle plume and the linear geometry of rifts.

Large-scale intraplate rheological heterogeneities, especially cratonic nuclei, may favor strain localization and control the rift location (Tommasi and Vauchez 1997, Tommasi et al. 1995, Vauchez, et al. 1998,). Yet, rheological heterogeneities fail to explain why rifts developed far away from any cratonic nuclei follow the trend of ancient orogenic belts (e.g., the South Atlantic rift and the northern East African rift). They cannot also explain why continental rifts often display a component of strike-slip deformation, in particular during the early rifting stage (e.g., the East African rift (Doser and Yardwood 1991), the North Atlantic (Geoffroy et al. 1994), and the Baikal (Delvaux et al. 1995)).

An alternative (and complementary) model to explain the structural inheritance was proposed by Vauchez et al. (1997) based on the analysis of shear-wave splitting data in the Appalachians and the Pyrenees. In this model, the source of the structural inheritance lies in a mechanical anisotropy of the lithospheric mantle due to the preservation, within the uppermost mantle, of a lattice preferred orientation (LPO) of olivine crystals formed during the main tectonic episodes that shaped the plate.

Upper mantle deformation and anisotropy

Olivine, the main constituent of the upper mantle, is mechanically anisotropic. Microstructural analysis of deformed peridotites (e.g., Nicolas et al. 1971) and experimental axial compression of olivine single crystals in different crystallographic orientations (Bai et al. 1991, Durham and Goetze 1977) provide evidence that (1) few slip systems are available to accommodate plastic deformation, and (2) these systems display a significantly different resistance to flow. Analysis of more than 200 lattice-preferred orientations of naturally deformed peridotites from various geodynamic environments (Ben Ismail and Mainprice 1998) also clearly indicates that olivine deforms predominantly by glide on the (010)[100] slip system with subsidiary glide on other systems of the {0kl}[100] family. All these observations suggest that, under upper mantle conditions, (010)[100] is the weakest slip system for olivine; it should therefore accommodate most of the strain.

Upper mantle rocks develop crystallographic preferred orientations of olivine during deformation by dislocation creep; they should therefore display a significant mechanical anisotropy. Recent experimental axial compression tests of textured dunites under high temperature and pressure (P. Chopra, pers. commun., 1995; Wendt et al. 1998) confirm this hypothesis: the strength of textured dunites depends on the orientation of the compression relative to the foliation. Thus mechanical anisotropy is also observed at the aggregate scale. Do we have any evidence that this anisotropy is also manifested at the scale of the lithospheric mantle? Although it is not possible to answer this question with certainty, geophysical and geological observations point toward an anisotropic behavior of the lithosphere.

Tectonic fabric of the continental lithospheric mantle

Direct observation of the continental mantle is possible in several lherzolite massifs, which often retain in their cores undisturbed lithospheric mantle structures. This is, for instance, the case of the Lanzo massif and lherzolite bodies of the Ivrea zone in the Alps (Boudier 1978), the Ronda massif in the Betic Cordillera (Tubia and Cuevas 1987), and the Lherz massif in the Pyrenees (Avé-Lallemant 1967). A consistent tectonic fabric (foliation, lineation, crystallographic preferred orientation), formed under lithospheric conditions (900°C < T < 1200°C), has been mapped over these massifs. This suggests that the lithospheric mantle, before it was incorporated into the crust, already displayed a fabric consistent at the scale of several tens of kilometres at least.

Seismological and magnetotelluric observations allow an extension of this conclusion at a larger scale. Rock-forming minerals (especially olivine) are seismically anisotropic, their crystallographic preferred orientation therefore produces a significant seismic anisotropy of upper mantle rocks (Nicolas and Christensen, 1987, Mainprice and Silver 1993)) and is regarded as the main source of teleseismic shear wave splitting. Short-scale spatial variations of splitting parameters on continents and a good correlation with surface geology (e.g., Silver 1996, Vauchez and Barruol 1996, Barruol et al. 1997) point to a dominant contribution of continental lithospheric mantle fabric to the splitting of shear waves. Most commonly, the fast split shear wave is polarized subparallel to orogenic structural trends (see review in Silver 1996). The difference in arrival time between the fast and slow waves is usually around 1s and may exceptionally exceed 2s. Considering the intrinsic anisotropy of mantle xenoliths, such time lags require a layer of anisotropic mantle 100 km thick at least, with a preferred orientation of the [010] and [100] axes of olivine, respectively perpendicular and close to the strike of the orogen (Mainprice and Silver 1993). These measurements hint at the existence of a coherent crystallographic fabric over the entire thickness of the lithospheric mantle. Pn azimuthal anisotropy, although more sensitive to lateral heterogeneity, leads to a similar conclusion. Pn waves propagate just beneath the Moho and the fast propagation direction is parallel to the olivine [100]-axes, i.e., to the frozen flow direction. Azimuthal variations in Pn travel time therefore reflect the structure of the uppermost lithospheric mantle only. Consistent patterns are found over large areas and display a good correlation with both shear wave splitting parameters and tectonic features at the surface (e.g., Hearn 1996, Smith and Ekström 1999). The good consistency between shear wave splitting and Pn anisotropy strongly support that the lithospheric mantle displays a tectonic fabric consistent over its entire thickness and this fabric is laterally coherent over several tens to several hundreds of kilometers. As the lithospheric mantle displays a pervasive tectonic fabric and olivine single-crystals and aggregates are mechanically anisotropic, it may be expected that the lithosphere will also behave anisotropically when submitted to tectonic forces.

Constraints from polycrystal plasticity models

Polycrystal plasticity models offer an insight on how the aggregate strength or deformation depends on the active slip systems and thus on the orientation of the grains. They allow therefore an investigation of the mechanical anisotropy induced by a pre-existing LPO.

Anisotropic viscoplastic self-consistent modeling (Lebensohn and Tomé 1993) applied to textured olivine polycrystals indicates that small textural variations induce significant changes in the aggregate mechanical behavior. Simulation of axial compression of textured olivine polycrystals reproduces qualitatively the experimental results: textured aggregates compressed at 45° to the foliation display significantly lower strengths than those compressed normal to the foliation.

In order to investigate the effect of a pre-existing mantle fabric on the continental break-up process, we approach the deformational response of an anisotropic continental lithosphere to an axi-symmetric tensional stress field produced by an upwelling mantle plume. The deformation of textured olivine polycrystals representative of the lithospheric mantle was computed at different positions above a plume head. Preliminary results indicate a very heterogeneous strain distribution: the higher strain rates are observed in domains where the initial LPO is oblique to the extension direction. In these domains the aggregates deform by transtension, i.e., a combination of extension normal to the pre-existing structural trend, vertical shortening and simple shear parallel to the pre-existing structure. A LPO-induced mechanical anisotropy of the upper mantle may thus explain the reactivation of the pre-existing lithospheric fabric. In addition, the proposed transtensional deformation within the lithospheric mantle will result in SKS splitting oblique to the trend of the rift (Tommasi et al. 1999, Vauchez et al., in press), in good agreement with observations in the East African rift (Gao et al. 1997).

Conclusion

Mechanical anisotropy of the lithospheric mantle is suggested from (1) the plasticity anisotropy of olivine single crystal and aggregates during experimental deformations and numerical simulations, (2) the observation of a strong crystallographic orientation of olivine and other mantle rock-forming minerals in mantle xenoliths and lherzolite massifs, and (3) widespread seismic anisotropy (shear wave splitting, Pn azimuthal anisotropy, P-residuals etc.) and electrical conductivity anisotropy (magnetotelluric soundings) which require a consistent tectonic fabric in the upper mantle over large areas.

Our preliminary model results suggest that an LPO-induced mechanical anisotropy of the lithospheric mantle results in a directional softening within the lithosphere, controlling the strain localisation. This phenomena may therefore explain the plume-rift paradox, the structural inheritance, and the onset of transtension within continental rifts.

Yet, in most cases, both mechanical anisotropy and rheological heterogeneity will combine to control the strain localization during the deformation of continents. The evolution of the Baikal rift or the East African rift, for instance, probably integrates the rheological effect of the stiff Siberian or Tanzanian cratons and an anisotropy factor due to the tectonic fabric of the lithospheric mantle in the Mongolian and Mozambique belts, as suggested by shear wave splitting, results (Gao et al. 1997, Vauchez et al. 1999).

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