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Review Article

# Heterogeneity and anisotropy in the lithospheric mantle

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ABSTRACT

The lithospheric mantle is intrinsically heterogeneous and anisotropic. These two properties govern the repartition of deformation, controlling intraplate strain localization and development of new plate boundaries. Geophysical and geological observations provide clues on the types, ranges, and characteristic length scales of heterogeneity and anisotropy in the lithospheric mantle. Seismic tomography points to variations in geothermal gradient and hence in rheological behavior at scales of hundreds of km. Seismic anisotropy data substantiate anisotropic physical properties consistent at scales of tens to hundreds of km. Receiver functions imply lateral and vertical heterogeneity at scales <10 km, which might record gradients in composition or anisotropy. Observations on naturally deformed peridotites establish that compositional heterogeneity and Crystal Preferred Orientations (CPOs) are ubiquitous from the mm to the km scales. These data allow discussing the processes that produce/destroy heterogeneity and anisotropy and constraining the time scales over which they are active. This analysis highlights: (i) the role of deformation and reactive percolation of melts and fluids in producing compositional and structural heterogeneity and the feedbacks between these processes, (ii) the weak mechanical effect of mineralogical variations, and (iii) the low volumes of fine-grained microstructures and difficulty to preserve them. In contrast, olivine CPO and the resulting anisotropy of mechanical and thermal properties are only modified by deformation. Based on this analysis, we propose that strain localization at the plate scale is, at first order, controlled by large-scale variations in thermal structure and in CPO-induced anisotropy. In cold parts of the lithospheric mantle, grain size reduction may contribute to strain localization, but the low volume of fine-grained domains limits this effect.



**Contents**



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## 1. Introduction

Tectonic plates are dominantly composed of peridotites — the lithospheric mantle. The shallowest and coldest part of this layer is, in most cases, the strongest part of the plates. It plays therefore an essential role in plate tectonics. For simplicity sake, the lithospheric mantle is usually defined as a stable, homogeneous and isotropic layer. Geophysical observations show nevertheless that the lithospheric mantle is neither homogeneous nor isotropic. Seismic tomography models highlight a strong heterogeneity in seismic velocities at depths between 50 and 150 km (e.g., Trampert and Van Der Hilst, 2005; Ritsema et al., 2011; Debayle and Ricard, 2012; Simmons et al., 2012; Obayashi et al., 2013). These velocity contrasts reflect, to the first order, lateral variations in the thermal structure of the mantle at scales ranging from tens to hundreds of km. Seismic refraction/reflection data, receiver function analysis, or waveform modeling predict still sharper (at the scale of a few km or even less) contrasts in elastic properties, which may result from variations in composition or in the deformation fabric within the lithospheric mantle. Splitting of teleseismic shear waves and the azimuthal anisotropy of Pn and Rayleigh wave velocities indicate that seismic anisotropy is ubiquitous in the shallow mantle (e.g., Montagner, 1998; Savage, 1999; Smith and Ekström, 1999). This anisotropy implies coherent orientation of olivine crystals at scales of tens to hundreds of kilometers, formed in response to active or past deformation episodes (e.g., Nicolas and Christensen, 1987; Savage, 1999; Silver et al., 1999; Vauchez and Nicolas, 1991).

Heterogeneity and anisotropy are fundamental properties that modify the mechanical response of rocks to applied forces and thus shape the strain field. They also affect the propagation of seismic waves as well as thermal and electrical conduction. Heterogeneity arises from spatial variations in composition or physical parameters. It may be thermal, corresponding to either a lateral variation in the stationary geothermal gradient or local, transient changes of the geotherm due to advective processes or enhanced heat production. Compositional heterogeneity arises from changes in the mineralogical composition or from more subtle variations in the trace-element contents. Among the latter, only variations in the hydration state of olivine may significantly affect physical properties. Heterogeneity may also be structural, arising from a spatial variation in the microstructure of the rock, such as gradients in grain size, changes in the crystallographic or shape preferred orientations, or in the spatial arrangement of the rock-forming minerals. If any of these heterogeneities result in significant variation in the rheological properties of the lithospheric mantle, it may trigger strain localization.

Anisotropy, on the other hand, results from a regular arrangement of 'objects' with different properties, such as the atomic bonds in a crystal or, at a larger scale, the repetition of layers of materials with different composition or structure. Even if produced at the crystal scale, anisotropy may be transferred at much larger scales provided the anisotropic objects are themselves arranged in a regular way. Anisotropy of mechanical properties (and, in an indirect way, thermal properties) changes the strain field produced by an applied stress, since some directions are easier to deform than others. It may therefore produce strain localization. The scale of observation is crucial for discriminating between anisotropy and heterogeneity. If the periodicity of the variation in physical parameters is much smaller than the observation length scale, the medium is seen as homogeneous, but anisotropic. On the other hand, if the observation length scale is similar to the one at which the changes in physical parameters occur, the medium will be described as heterogeneous.

In this article, we review the geophysical observations that constrain heterogeneity and anisotropy in the lithospheric mantle. Then, based on observations on peridotite massifs and xenoliths, we discuss the processes that may produce and destroy heterogeneity and anisotropy in the lithospheric mantle and try to define characteristic spatial and temporal scales for the various types of heterogeneity and anisotropy in the lithospheric mantle. Finally, the geodynamical consequences of the different types of heterogeneity and anisotropy are analyzed.

## 2. Geophysical observations

### 2.1. Heterogeneity in the lithospheric mantle

Seismology samples the elastic properties of the lithospheric mantle over a large range of scales, from the global distribution of seismic velocities to local contrasts in seismic properties producing seismic conversions and reflections. It is therefore our best tool to 'map' heterogeneity in the lithospheric mantle. However, relating the observed contrasts in elastic properties to variations in temperature, composition, or deformation is not always straightforward.

Global seismic tomography models highlight variations of $\pm 7\%$ for S waves and $\pm 3\%$ for P waves between 50 and 200 km depth (e.g., Debayle and Ricard, 2012; Obayashi et al., 2013; Ritsema et al., 2011; Simmons et al., 2012; Trampert and Van Der Hilst, 2005). These large-scale variations in seismic velocities correlate well with the surface heat flow distribution at the global scale (cf. the recent compilation by Davies, 2013 and the global heat flow database: http://www.heatflow.und.edu/). This correlation supports that global tomography models image, to the first order, lateral variations in the thermal structure of the plates, that is, thermal heterogeneity in the lithospheric mantle. They provide consistent 3D representations of cratonic domains, major continental rifts, and volcanic arcs (Fig.1a).

Depletion in Fe of residual mantle rocks due to partial melting (or enrichment due to metasomatism) may also enhance (reduce) seismic velocities (James et al., 2004; Jordan, 1975, 1979; Tommasi et al., 2004). Compositional heterogeneity is not often invoked to explain velocity anomalies at the scale of hundreds to thousands of km, because petrological processes have usually smaller characteristic spatial length-scales (cf. Section 3.2). However, in cratonic roots, low temperatures and Fe-depletion add up to produce high seismic velocities, but low densities (Baptiste and Tommasi, 2014; James et al., 2004; Jordan, 1979). The opposite effects of Fe-depletion on seismic velocity and density make the joint analysis of gravity and seismic data a powerful tool for discriminating between thermal and compositional heterogeneity in the lithospheric mantle (e.g., Afonso et al., 2008; Tesauro et al., 2014).

Regional scale tomography models better define the geometry of the velocity anomalies, as, for instance, the broadening and intensification of the low anomaly associated with the East African rift approaching the Afar region (e.g., Bastow et al., 2008). They also provide evidence for smaller wavelength (tens to hundreds of km) variations in seismic velocities superposed to the large-scale structure. Such variations in seismic velocities were imaged, for instance, in the lithospheric mantle beneath Australia (Fig. 1b; Fishwick et al., 2005) and the Baltic shield (Fishwick et al., 2005; Pedersen et al., 2013). They might have a compositional origin, as suggested for the relatively lower velocities observed beneath the Bushveld complex in the Kaapvaal craton (Fouch et al., 2004; James et al., 2001). Small-scale heterogeneities were also imaged in the broad low velocity domain beneath the Afars, where they were interpreted as due to the presence of melts (Hammond et al., 2014). Analysis of Vp/Vs ratios obtained from joint P- and S-wave tomography may further constrain compositional heterogeneity in the lithospheric mantle. For instance, the association of low Pn velocities and low Vp/Vs ratios in the mantle lid beneath Sierra Nevada implies a compositional origin for the observed velocity reduction (Buehler and Shearer, 2014).

Seismic refraction/reflection data, receiver function analysis, and waveform modeling point to sharp contrasts (at scales of a few km or even less) in elastic properties within the lithospheric mantle. Shallowly dipping reflectors have been observed at various depths in the lithospheric mantle. The best studied among these reflectors are