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Letters

Microstructural and seismic properties of the upper mantle underneath a rifted continental terrane (Baja California): An example of sub-crustal mechanical asthenosphere?

L.N. Palasse [a,1], R.L.M. Vissers [a,*], H. Paulssen [a], A.R. Basu [b], M.R. Drury [a]

[a] Department of Earth Sciences, Utrecht University, P.O. Box 80.021, 3508 TA Utrecht, The Netherlands
[b] Department of Earth and Environmental Sciences, University of Rochester, Rochester, NY 14627, USA

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ABSTRACT

The Gulf of California rift is a young and active plate boundary that links the San Andreas strike-slip fault system in California to the oceanic spreading system of the East Pacific Rise. The xenolith bearing lavas of the San Quintin volcanic area provide lower crust and upper mantle samples from beneath Baja California peninsula. The microstructures, crystallographic preferred orientations (CPO) and petrology of the San Quintin xenoliths suggest that the continental lithosphere in this region has undergone several stages of deformation, recrystallisation and melt–rock interaction. Melt–rock interactions have led to enrichment in olivine while fine-grained microstructures suggest intense deformation in an active shear zone in the shallow upper mantle. In this study we highlight the effect of the fine-grained mylonitic shear zone development in the upper mantle as an important process of weakening of continental lithosphere. The results of the microstructural study show a reduction in CPO strength with increasing grain size reduction. Most CPOs are consistent with dominant slip on the {0kl}[100] system. As a consequence, corresponding seismic anisotropies decrease for both P- and S-waves with increasing grain size reduction. The shallow crystallographic fabric can be related to active shear zones, which accommodate the relative motion between the Northern Baja terrane and the Pacific plate. Estimates of the strain rate, stress and viscosity indicate that the shallow mantle beneath Northern Baja is thermally and chemically lithospheric but mechanically has similar viscosity as the asthenosphere. The Northern Baja terrane is an interesting case of continental crust lying directly on low viscosity upper mantle.

1. Introduction

The Gulf of California is an active trans-tensional rift zone where the plate boundary evolves from continental extension in the north to an oceanic spreading system with transform faults in the south (Fig. 1). The upper mantle structure associated with this complex tectonic interaction between the Pacific, North American and now largely subducted Farallon plates has been recently studied using surface wave tomography (Zhang et al., 2007, 2009; Wang et al., 2009) inferred from the NARS-Baja seismic network (Trampert et al., 2003). The study of Zhang et al. (2009) using Rayleigh wave phase velocities suggests the presence of remnants of the Farallon microplate beneath the central and southern Gulf, whereas the existence of a low velocity zone in the northern part could be related to upwelling within a slab window. Zhang et al. (2009) found fast propagation directions of surface waves in the crust and uppermost mantle that are plate boundary parallel in the north and perpendicular in the south. Because olivine develops strong lattice preferred orientations during plastic deformation that may well account for this seismic anisotropy, there is a potential link between seismic anisotropy and upper mantle flow. Mantle xenoliths from the Holocene San Quintin volcanics in Baja California (Basu, 1975a, 1975b, 1977; Cabanes and Mercier, 1988; Storey et al., 1989; Luhr et al., 1995; Luhr and Aranda-Gomez, 1997) provide a unique opportunity to constrain the current petrophysics of this active area, and to test models for the regional variations in anisotropy.

The xenoliths exhibit a wide range of microstructures from deeper upper mantle coarse-porphyroclastic to shallow upper mantle fine-grained material. The objective of this study is to characterise the deformation history of the San Quintin xenoliths by performing a microstructural study, with measurements of the Crystallographic Preferred Orientation (CPO), to infer the anisotropic seismic properties of the mantle beneath the northern part of Baja California.

* Corresponding author. Tel.: +31 30 2535051.
E-mail address: rvissers@geo.uu.nl (R.L.M. Vissers).
[1] Present address: Bruker Nanoanalysis, Berlin.

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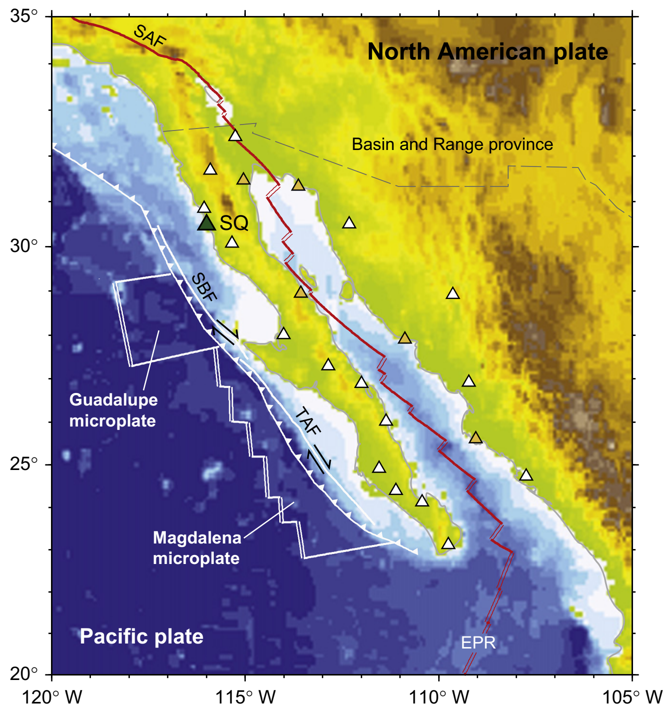

Fig. 1. Tectonic sketch map of the Gulf of California rift region, and location of the San Quintin volcanic field (indicated as "SQ") where upper mantle xenoliths have been brought up during Plio-Pleistocene volcanism. Present-day plate boundaries are shown. SAF: San Andreas Fault, EPR: East Pacific Rise, SBF: San Benito Fault, TAF: Tosco Abreojos Fault (modified after Zhang et al. (2007)). Triangles show locations of the NARS-Baja seismic network (Trampert et al., 2003).

In this paper we will use the terms asthenosphere and lithosphere in a mechanical sense, with "asthenosphere" to describe the low-viscosity upper mantle and "lithosphere" for the high-viscosity shallow upper mantle. In a tectonically active region, both lithosphere and asthenosphere may be actively deforming and the high-viscosity, mechanically defined lithosphere may not correspond to the seismically, chemically, or thermally defined boundary layers.

2. Tectonic setting of the San Quintin volcanics

The Gulf of California region is the result of tectonic interaction between the Pacific, Farallon and North American plates (Atwater and Stock, 1998; Plattner et al., 2007). The evolution of the oceanic tectonic plates is well known from the analysis of magnetic patterns on the ocean floor in combination with geological observations. The evolution after subduction is constrained by tomographic images of the present seismic velocity structure and modelling experiments (Zhang et al., 2009; Wang et al., 2009; Plattner et al., 2009).

Closely following the progressive south to north termination of subduction, the Pacific–Farallon spreading ridge reached the North American plate (28 Ma), and the plate boundary character changed from Farallon–North America oblique subduction to transcurrent motion with an extensional component taken up by North America (Stock and Hodges, 1989). Then, the Rivera triple junction migrated southward and the Farallon plate started to fragment into microplates. Subduction of the Guadalupe and Magdalena microplates beneath the region ceased at 12 Ma. The Pacific–North America plate motion was accommodated by strike-slip motion and extension in the future Gulf area, currently the Gulf Extensional Province. Over the last 10 Ma, the Gulf of California experienced a complex tectonic evolution subsequent to a complicated mountain building process along the western margin of the American plate and progressive interaction with the Pacific Ridge system. Present-day movements are thought to have been persistent over the last 5 Ma, with dextral transtension and movement of the Baja California Peninsula similar to the Pacific plate.

In zones of active deformation, direct information from the upper mantle can be obtained from upper mantle xenoliths. In the Gulf of California area upper mantle xenoliths were brought up during late Cenozoic volcanism in Baja California and Mexico (Fig. 1). In this study, we investigate 9 xenoliths of a previous study (Basu, 1977) from the San Quintin Volcanics along the Pacific coast of Baja California Norte. The Northern Baja crust is a continental terrane that rifted away from North America, and is currently also moving relative to the Pacific plate along faults like the San Benito (SBF) and Tosco Abreojos (TAF) faults (Plattner et al., 2007). The San Quintin volcanics consist of basaltic cinder cones with associated lava flows of late Pleistocene to recent age. This volcanic complex is the only one in the region where intraplate-type mafic alkalic magmas have erupted, carrying upper mantle and lower crustal xenoliths. We have selected seven peridotites with different microstructures and two pyroxenites. These latter are plagioclase-bearing pyroxenites, which likely represent the shallower mantle underneath the region and allow us to investigate possible relationships between different microstructures for different pressure and temperature conditions, to interpret these microstructures in terms of dominant deformation and recrystallisation mechanisms, and to estimate their seismic properties.

3. Microstructures of the xenoliths

About 80% of the ultramafic xenoliths from San Quintin are spinel lherzolites, with lesser harzburgites, dunites, and pyroxenites (Luhr et al., 1995). The suite is remarkable for the ubiquitous microstructural evidence of strong deformation (Basu, 1977; Luhr et al., 1995). Following Mercier and Nicolas (1975), the San Quintin xenoliths have been classified by Basu (1977) according to their increasing deformation, and include coarse granular, porphyroclastic, tabular mosaic and equigranular mosaic microstructures. The selection for the present study contains 9 samples, including 4 porphyroclastic, 3 tabular (with 2 pyroxenites) and 2 equigranular ones.

The porphyroclastic microstructure (samples SQ1-8-12, SQ2-69, SQ2-67 and SQ2-60) is the most abundant (Basu, 1977). It displays a bimodal grain size distribution, with large elongate porphyroclasts of olivine and pyroxenes (4–5 mm) and smaller spinel and clinopyroxenes in a finer matrix composed of neoblasts of the same mineral phases with grain sizes of up to ~1.2 mm. The olivine porphyroclasts show undulatory extinction (Fig. 2) with well developed subboundaries. Many crystals have concave boundaries suggesting grain boundary migration, while the grain boundaries show triple junctions with near 120° angles. The neoblasts of the finer matrix are bimodally distributed with (1) a relatively large grain size of ~1.2 mm similar to the subgrains within coarse olivines and (2) smaller grains of generally ~0.6–0.3 mm and even smaller. Elongate olivine grains and aligned spinels define a foliation. Orthopyroxenes are not elongated but more rounded with irregular grain boundaries and kink bands, and seem to have a lattice preferred orientation, since exsolution lamellae (100) are often oriented parallel to the olivine elongation. Spinels have curvilinear boundaries without elongation. The neoblasts are free of deformation structures and exsolutions. In some samples (e.g. SQ2-60) the pyroxene porphyroclasts are rounded and occur within clusters.