Surface wave tomography of the Gulf of California

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[1] We measured interstation fundamental mode Rayleigh wave phase velocities using data from the NARS-Baja seismic network located around the Gulf of California. A region-average, shear velocity model and a set of azimuthally anisotropic phase velocity maps are obtained from these data. The average shear velocity structure shows a strong low-velocity zone underlying a thin lid and the data are suggestive of low velocities down into the transition zone. The phase velocity maps display signatures of sedimentary layers, crustal thickness variations, upwelling under the plate boundary, and the presence of the subducted Farallon microplate remnants beneath the Gulf. The upper mantle features inferred from this study provide new seismic evidence on the tectonic evolution of the region. **Citation:** Zhang, X., H. Paulssen, S. Lebedev, and T. Meier (2007), Surface wave tomography of the Gulf of California, *Geophys. Res. Lett.*, *34*, L15305, doi:10.1029/2007GL030631.

1. Introduction

[2] In the Gulf of California the Pacific-North America plate boundary changes character from an oceanic-type spreading center and transform fault system in the south to a region of diffuse continental extensional deformation in the north [*Nagy and Stock*, 2000]. The system is a result of tectonic interaction between the Pacific, Farallon and North America plates [e.g., *Lonsdale*, 1991; *Nicholson et al.*, 1994; *Bohannon and Parsons*, 1995; *Atwater and Stock*, 1998]. As the Pacific-Farallon spreading ridge reached the North American plate (ca. 28 Ma), the character of the plate boundary contact changed from Farallon-North America oblique subduction to Pacific-North America transcurrent motion with an extensional component taken up by the North American continent. With time the Rivera triple junction migrated southward and the intervening Farallon plate started to fragment into various microplates. Subduction of the Guadalupe and Magdalena microplates (Figure 1) beneath Baja California ceased ca. 12 Ma. The Pacific-North America plate motion was largely accommodated along the right-lateral San-Benito-Tosco-Abreojos fault zone west of Baja, but over time the relative plate motion was increasingly accommodated by strike-slip motion and extension in the future gulf area. This was to become the Gulf Extensional Province, bordered west by the more rigid Baja California Range and east by the unextended block of the Sierra Madre Occidental. Around 6 Ma, almost all of the

Pacific-North America plate motion was accommodated inside of the Gulf [e.g., *Lonsdale*, 1991; *Oskin and Stock*, 2003]. Global and regional tomographic studies have revealed a pronounced low-velocity anomaly in the top 250 km of the mantle beneath the Gulf of California area [e.g., *Godey et al.*, 2003; *van der Lee and Frederiksen*, 2005; S. Lebedev and R. D. van der Hilst, Global upper-mantle tomography with the automated multi-mode inversion of surface and S waveforms, submitted to *Geophysical Journal International*, 2007, hereinafter referred to as Lebedev and van der Hilst, submitted manuscript, 2007]. However, these tomographic images do not have sufficient resolution to interpret the tectonic process active in this region. The NARS-Baja stations deployed around the Gulf of California [*Trampert et al.*, 2003] allow us to explore the
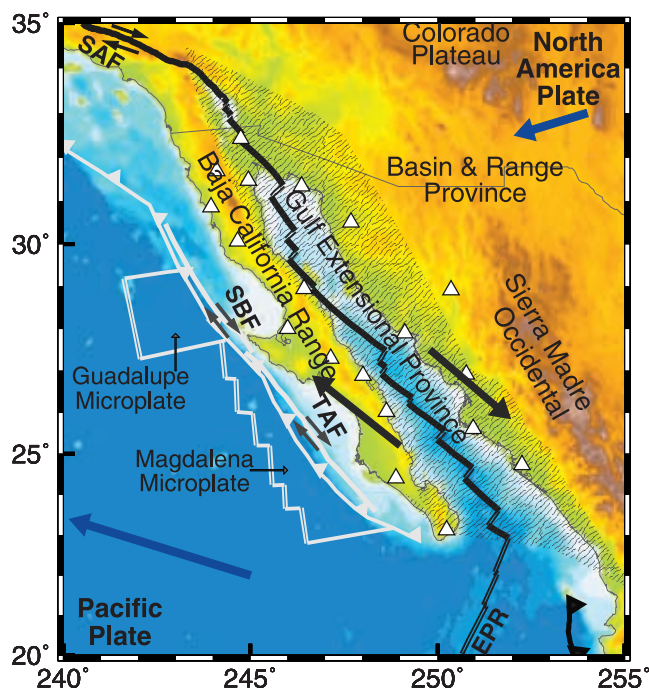

Figure 1. Tectonic map of the Gulf of California region. The NARS-Baja stations are depicted by white triangles. The main tectonic provinces are Baja California Range, Gulf Extensional Province (dotted), Basin and Range Province, Sierra Madre Occidental and Colorado Plateau. Present-day plate boundaries shown as dark lines. Inactive plate boundaries shown as white lines. SAF–San Andreas Fault; EPR–East Pacific Rise; SBF–San Benito Fault; TAF–Tosco Abreojos Fault. Thick arrows indicate plate motions (absolute plate motion in blue, relative plate motion in black) predicted by global plate motion model HS3-NUVEL1A [*Gripp and Gordon*, 2002].

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upper mantle structure at a more detailed level. Here we present a set of azimuthally anisotropic, fundamental mode Rayleigh wave phase velocity maps and the results of a one-dimensional, shear velocity inversion of the phase velocity measurements averaged over the Gulf of California region. The results give us insight into the driving forces under this dynamic plate boundary system.

2. Data and Interstation Phase Velocity Measurements

[3] We adopted the method described by *Meier et al.* [2004] to measure the dispersion curves of fundamental mode Rayleigh waves along up to 139 interstation paths (see auxiliary material).[1] The phase velocity measurements were obtained from seismograms recorded by NARS-Baja stations between April 2002 and the end of 2004. The data set included 6075 vertical component seismograms of 543 strong events (moment magnitude $\geq$ 5.0) recorded at NARS-Baja stations. For each station pair, we cross-correlated the two vertical component seismograms excited by an event, whose epicenter is located along the great circle path ($\pm 7°$) determined by this station pair. Frequency-dependent filtering and weighting are applied to the cross-correlation function before the reliable part of the phase velocity curve is interactively selected in the frequency domain. This process was repeated for all the events and the final dispersion curve is obtained as the average of all the phase velocity curves. Our interstation dispersion measurements have been averaged over 10–189 individual phase velocity curves.

[4] Finite-frequency effects due to heterogeneity outside the interstation path, such as off great-circle propagation, multipathing and scattering [e.g., *Zhang et al.*, 2003; *Prindle and Tanimoto*, 2006] can cause biased estimates of interstation phase velocities. These effects are reduced by the averaging process, but for some station pairs systematic differences were observed between the measurements for the two opposite propagation directions at periods shorter than 30 s. This is suggestive of off great-circle propagation, particularly since these station pairs are oriented along the strike of the peninsula where a significant influence from the ocean-continent transition is expected for events from the north-west. We discarded these biased measurements recognized by their higher phase velocities to obtain more reliable estimates of the dispersion curves.

3. One-Dimensional Shear Velocity Model Space Search

[5] The interstation phase velocity measurements of our data set span the period range of 9–250 s and are sensitive to shear velocity structure from the crust down to the mantle transition zone. We explored shear velocity models with corresponding phase velocity curves within one standard deviation from the average over all measured phase velocities. Detailed information about the model space search can be found in the auxiliary material. Figure 2 shows the result of the model space sampling. A persistent feature is a strong
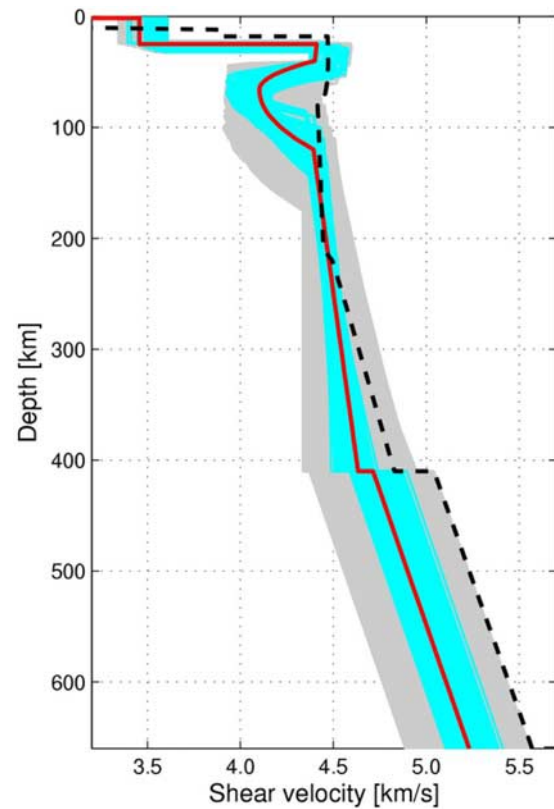
Figure 2. 1-D model space search results. The gray lines show all models whose phase velocity curve is within one standard deviation away from the mean of all interstation phase velocity measurements. The cyan lines represent the 1000 best fitting models. The best fitting model is shown in red. Model AK135 is shown with a dashed black line.

low-velocity zone in the upper 200 km, in which the shear velocity can be up to 10% lower than in the global reference model AK135 [*Kennett et al.*, 1995]. The detailed character of the low-velocity zone of the average model is uncertain, as illustrated by the ensemble of gray curves in Figure 2. Thus, we do not to interpret the low-velocity zone in terms of melt, water, and/or variations in grain size, although fluids or melt have been suggested by *Goes and van der Lee* [2002] for this region. Another noticeable feature is that the best fitting models have lower velocities in the transition zone than the reference model AK135. In the model space search, the transition-zone shear velocities reaches the reference value (AK135), but it is the upper limit of the possible models, and requires very low velocities in the upper 400 km. Thus the low average phase velocities in the period range of 100 to 250 s suggest that the shear velocity in the transition zone is substantially lower than the global average, which could imply the presence of a deep seated heat source affecting processes at shallower levels.

4. Phase Velocity Maps With Azimuthal Anisotropy

[6] Our data yields sufficient coverage to map both isotropic and anisotropic phase velocity variations. In a plane layered medium and in the presence of weak general

anisotropy, phase velocities vary as a function of horizontal propagation direction [*Smith and Dahlen*, 1973]:

$$\frac{dc}{c}(T, \Psi) = \alpha_0(T) + \alpha_1(T)\cos 2\Psi + \alpha_2(T)\sin 2\Psi$$
$$+ \alpha_3(T)\cos 4\Psi + \alpha_4(T)\sin 4\Psi \qquad (1)$$

where dc/c is the local relative phase velocity perturbation, T the period and Ψ the azimuth of wave propagation. The coefficient α_0 is the isotropic phase velocity perturbation; α_1, α_2, α_3 and α_4 parameterize azimuthal anisotropy.

[7] We constructed phase velocity maps for the period range of 10–100 s (for ray coverage, see auxiliary material). The inversion, which includes the isotropic as well as the 2Ψ and 4Ψ terms, is performed with LSQR [*Paige and Saunders*, 1982] with smoothing and (slight) norm damping as described by Lebedev and Van der Hilst (submitted manuscript, 2007). The triangular model grid has knot spacing of around 100 km. We calculated resolution matrices and show the results only for the well-sampled areas— defined as those with grid points whose diagonal element of the isotropic term of the resolution matrix has a value larger than 0.10. Analysis of the resolution matrices showed that leakage between the isotropic and anisotropic terms is small. This is confirmed by resolution tests with synthetic input data containing no anisotropy, but the inversion allowing for anisotropy. Furthermore, the measured data requires anisotropy as inferred from a statistically significant increase in variance reduction. The isotropic coefficients are better resolved than the 2Ψ and 4Ψ terms which require more smoothing. Thus, the resolution lengths of the isotropic coefficients are approximately 100–200 km, whereas they are 200–400 km for the anisotropic coefficients. A resolution test which illustrates the robustness of the results is shown in the auxiliary material.

[8] Figure 3 presents the results of the inversion only for the isotropic and the 2Ψ terms. We have allowed for 4Ψ heterogeneity but verified that our main results and conclusions—concerning isotropic and "2Ψ" structure—are robust with respect to the amount of the 4Ψ signal allowed in the models by the regularization.

5. Interpretation and Discussion

[9] Phase velocity maps are commonly inverted for shear velocity structure to allow a direct interpretation of the structural features. Such an inversion requires an accurate crustal model in order to obtain reliable estimates of the mantle structure. The crustal structure in this area is, however, very complex and insufficiently known to currently warrant a 3-D shear velocity inversion. We therefore interpret the phase velocity maps. Overall, these maps show a difference between the northern part of the gulf and south of roughly 29°N. This is first observed for the maps at periods of 10 and 14 s. In the northern part, effects of a thick layer of low-velocity sediments [*González-Fernández et al.*, 2005] are visible for short period phase velocities (10 s). Variations in crustal thickness dominate at 14 s. The crust beneath the southern part of the Gulf of California is oceanic and thinner than beneath the northern part. The large contribution of the high mantle velocities beneath the thin oceanic crust explains the relatively high phase velocities at periods of 10 and 14 s in the southern part of the

area. These high phase velocities extend onto the western part of the Mexican mainland, indicating that its crust is thinner than beneath the Baja California peninsula. The area of high phase velocities at 14 s matches the Gulf Extensional Province [e.g., *Stock and Hodges*, 1989] in Figure 1, confirming the crustal thinning as inferred from geological data. The sharp transition along the eastern margin of the Baja California peninsula marks the western boundary of the Gulf Extensional Province. The low phase velocity anomalies on the Mexican mainland at 30°N can be explained by a thick crust (40 km), according to a receiver function study using NARS-Baja data by *Persaud* [2003].

[10] The fast anisotropic directions in the 10–14 s period phase velocity maps are approximately NNW–SSE in the northern part of the gulf and Baja California. This direction is roughly parallel to the plate boundary which has a transtensional character in this region of diffuse continental deformation [*Nagy and Stock*, 2000]. In contrast, in the southern part of the gulf the fast-propagation directions are NE–SW to E–W, close to being perpendicular to the plate boundary. This direction corresponds to the direction of opening of the gulf, which is similar to the direction of past subduction. At a period of 30 s (max. sensitivity at a depth interval around 50 km), low velocities are found directly beneath the plate boundary over the entire length of the gulf. These low anomalies could be caused by melt and/or fluids feeding the ridge system in the gulf. Noticeably, the azimuthal anisotropy becomes smaller in amplitude at this period, which, speculatively, could be related to local upwelling beneath the plate boundary reducing the horizontal component of flow. The north–south contrast is seen again in the phase velocity maps in the 50–80 s period range (max. sensitivity ~50–150 km). Relatively high phase velocities (although still lower than the global average) are observed at latitudes roughly 24°–28°N. We suggest that these high phase velocity anomalies are associated with remnants of the stalled Guadalupe and Magdalena microplates [*Nicholson et al.*, 1994; *Bohannon and Parsons*, 1995] (see also Figure 1) which ceased to subduct 12 Ma ago. Although these young slab remnants must be very warm, possibly near the solidus, they can still be identified by their higher velocity compared to their surroundings. The low velocities beneath northern Baja California, on the other hand, match the area of the suggested "slab window" [*Dickinson and Snyder*, 1979; *Severinghaus and Atwater*, 1990; *Atwater and Stock*, 1998], and may be attributed to shallow asthenospheric material in this region. In summary, the phase velocity maps at 30 to 100 s suggest that the upwelling of low velocity asthenospheric material occurs around the northern and southern edge of the microplate remnants under Baja California, to fill the region of melt directly beneath the ridge under the gulf.

[11] The fast-propagation anisotropic directions in northern Baja California change from NW–SE at 50 s to nearly E–W at 100 s. This E-W direction agrees with the fast directions inferred from SKS splitting measurements in southern California [e.g., *Polet and Kanamori*, 2002] as well as those in northern Baja California [*Obrebski et al.*, 2006], with the exception of the station NE70 which is located at the plate boundary and has an approximately NW-SE direction. At long periods (80–100 s), the fast anisotropic directions in the southern part are not well
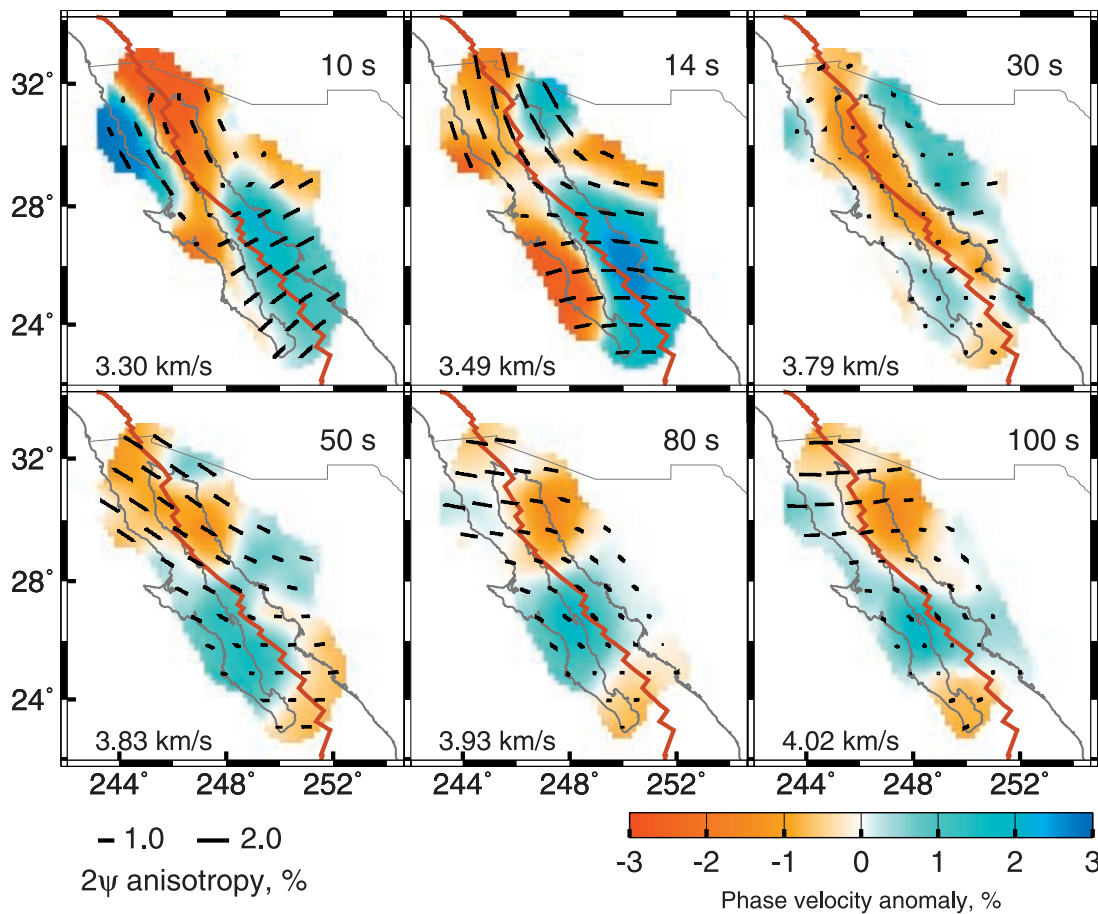
Figure 3. Tomographic images of Rayleigh wave phase velocities at different periods. The period is shown in the upper right corner and the reference phase velocity is in the lower left corner of each phase map. The colors indicate the isotropic anomalies and the black bars indicate the fast-propagation directions and the strength of the azimuthal anisotropy. The purple line marks the location of the plate boundary.

resolved due to the poor azimuthal ray path coverage and relatively long wavelengths considered.

6. Conclusions

[12] Data of NARS-Baja network allow the determination of high-resolution anisotropic Rayleigh wave phase-velocity maps between 10–100 s. These detailed phase–velocity maps provide new insight into the geodynamics of the Gulf of California region. The fast anisotropic directions of phase velocities with crustal sensitivity (10–14 s) change from predominantly plate-boundary parallel in the north to plate-boundary perpendicular in the south. The transition occurs where the plate boundary changes character from a region of diffuse transtensional continental deformation to a system of oceanic-type spreading centers and transform faults [*Nagy and Stock*, 2000]. The low-velocity anomaly directly beneath the plate boundary and small values for azimuthal anisotropy in the 30 s phase velocity map suggest ridge associated upwelling beneath the gulf. The maps at longer periods (50–100 s) suggest that the low-velocity material flows from below, around the relatively high velocity anomaly corresponding to the location of Guadalupe and Magdalena slab remnants. If this interpretation is correct, it could imply that the slab is effectively attached to the Baja California peninsula and remains in place, possibly extending across the Gulf (see Figure 3, 100 s). The region of low velocities in the north matches the area of the proposed slab window beneath northern Baja California.

[13] An intriguing question is whether there is a deep seated (>300 km) source of low-velocity mantle material that feeds the low-velocity features imaged in our phase velocity maps. The results of the model space search show considerable uncertainty in the transition zone, but the phase velocity measurements do favor a low-velocity transition zone. If confirmed by additional data, this could explain the overall low velocities of the region as well the origin of the upwelling beneath the Gulf of California.

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