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Asymmetric ocean basins

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ABSTRACT

While the superficial expression of oceanic ridges is generally symmetric, their deeper roots may be asymmetric. Based on a surface-wave tomographic 3D model of the Earth's upper 300 km, we construct a global cross-section parallel to the equator of the net-rotation of the lithosphere, the so-called tectonic equator. Shear wave velocities indicate a difference between the western and eastern flanks of the three major oceanic rift basins (Pacific, Atlantic and Indian ridges). In general, the western limbs have a faster velocity and thicker lithosphere relative to the eastern or northeastern one, whereas the upper asthenosphere is faster in the eastern than in the western limb. We interpret the difference among the two flanks as the combination of mantle depletion along the oceanic rifts and of the "westward" migration of the ridges and the lithosphere relative to the mantle. The low-velocity zone (LVZ) in the upper asthenosphere at the depth of 120–200 km is assumed to represent the decoupling between the lithosphere and the underlying mantle. It is also well defined by the distribution of radial anisotropy that reaches minimum values close to the rifts, but with an eastward offset. These results could be explained in the frame of the "westward" drift of the lithosphere relative to the underlying mantle.

INTRODUCTION

The mantle is thought to rise adiabatically along oceanic ridges and to melt, generating new oceanic crust (e.g., Cann et al., 1999 and references therein). Since the recognition of magnetic anomalies on both sides of the ridges, oceanic basins have generally been associated to symmetric spreading. However, it has been shown that rift zones are moving on the Earth's surface relative to the underlying mantle, i.e., they are decoupled with respect to the mantle. Plate boundaries move to the west relative to Antarctica and to the hotspot reference frame (e.g., Le Pichon, 1968, Garfunkel et al., 1986).

In fact, a number of papers have described some asymmetric spreading, differences in geometry and subsidence between the two ridge, as well as heterogeneities in the underlying mantle tomography (e.g., Morgan and Smith, 1992; Zhang and Tanimoto, 1993; Calcagno and Cazenave, 1994; Cande and Kent, 1995; Bonatti et al., 2003; Pilidou et al., 2005; Muller et al. 2008).

Subduction zones show a marked asymmetry as a function of their geographic polarity (Doglioni et al., 2007); in this research we tested whether a worldwide asymmetry holds for oceanic rifts as well.

For this purpose, we extracted sections across the S-wave tomographic model of the Earth's lithosphere-asthenosphere system (Shapiro and Ritzwoller, 2002). The sections are perpendicular to the three main oceanic ridges, i.e., East Pacific Rise (EPR), Mid Atlantic Ridge (MAR) and Indian Ridge (IR), as shown in Figure 1. The first global cross-section coincides with the so-called "tectonic equator" (TE), which is the ideal line along which plates move over the Earth's surface with the fastest mean angular velocity toward the "west" relative to the mantle (Crespi et al., 2007). The coordinates of the sections are in Table 1 of the data repository.

3-D SHEAR VELOCITY MODEL

We considered a 3D shear velocity model of the Earth's upper mantle, CUB2 (Shapiro and Ritzwoller, 2002; http://ciei. colorado.edu/~nshapiro/MODEL) obtained by tomographic inversion of seismic surface waves generated by earthquakes and recorded by numerous seismic stations across the world. It provides a quite detailed (at 2° by 2° geographical grid) shear-wave velocity (Vs) image of the uppermost 300 km of the Earth. This model is the result of the Monte-Carlo inversion of dispersion data-group velocities of fundamental Rayleigh and Love modes, in the range of periods 16–200s (Levshin et al., 1989; Ritzwoller and Levshin, 1998; Ritzwoller et al., 2002**[[Not in reference list?]]**) and phase velocities, in the range of period 40–200s, (Trampert and Woodhouse, 1995, and Ekstrom et al., 1997). The procedure allows for the recognition of the radial anisotropy of shear velocities in the upper mantle down to 220 ± 30 km depth and provides estimates of the uncertainty in the inversion.

To obtain Vs radial cross-sections across this model we use bispline interpolation of velocities at fixed depths levels (on a 4 km grid) with subsequent gaussian smoothing. Here the *Vs* is taken here as an average of *Vsv* and *Vsh* along two sections (tectonic equator, TE, and along a sort of perturbed tectonic equator, TE-pert), covering 10° width (Fig. 1). The magnitude of the radial anisotropy (*Vsh-Vsv*)/*Vs* predicted by the model is shown in Figure 1.

Another section slightly deviates from the TE, along a sort of perturbed tectonic equator (TE-pert). Along the TE-pert, following a sort of funneling, the low-velocity layer (LVZ), corresponding to the upper asthenosphere, has shear wave velocity lower than 4.5 km/s everywhere, i.e., all across the Earth at a depth of ~130–200 km.

The Vs model shows an asymmetry in the uppermost 100 km between the western side (4.5–4.8 km/s), which is faster with respect to the eastern side of the rift (4.4–4.6 km/s). The upper asthenosphere (100–200 km) of the western flank is slow (Vs = 4.2–4.4 km/s) compared to the eastern flank (Vs = 4.3–4.5 km/s). Therefore, the difference in Vs between the western and the eastern flanks of the rift, both in the lithosphere and in the asthenosphere, is significant and in the range of 0.1–0.3 km/s. The LVZ shows an asymmetric pattern, it is deeper and thicker on the west than on the east side of the ridge. This is particularly evident in the Eastern Pacific Ridge (EPR). In the western lithosphere of the Mid Atlantic Ridge (MAR) the Vs horizontal gradient is much larger than the one in EPR, in agreement with the slower spreading rate of the MAR.

GEODYNAMIC MODEL

The bathymetry of rift zones is, in general, asymmetric: the eastern flank is in average slightly shallower (100–300 m) than the western flank (Doglioni et al., 2003). See Fig. A in the data repository. Since the mantle becomes depleted in Fe when it melts beneath a ridge (Oxburgh and Parmentier, 1977), and it moves "eastward" relative to the lithosphere, the shallower bathymetry to the east has been interpreted in terms of an isostatic adjustement, i.e., a lower thermal subsidence in the eastern flank of the ridge (Doglioni et al., 2005). Due to the net rotation of the lithosphere (Gripp and Gordon, 2002; Crespi et al., 2007; Husson et al., 2008), the subridge depleted and lighter mantle will eventually transit beneath a continent to the east, if any, and uplifting it (e.g., Africa, Doglioni et al., 2003).

Since rifts show a difference that appears to be chiefly controlled by the geographical distribution of the anomalies (Vs, bathymetry), we interpret the asymmetry in terms of the "westward" drift of the lithosphere relative to the mantle (Scoppola et al., 2006), along the tectonic equator (TE) of Crespi et al. (2007), which makes an angle of ~30° relative to the geographic equator.

The hot mantle rising along ridges is decompressed, thus melts and delivers fluids. This process determines a chemical depletion of the pre-melting mantle: the residual mantle undergoes a modification of its physical properties, such as the decrease in density (20–60 kg/m^3, Oxburg and Parmentier, 1977**[[Oxburg or Oxburgh? See reference list as well.]]**) and consequent natural increase of Vs due to Fe depletion, increase of 1–2 orders of magnitude of viscosity and temperature decrease of around 100 °C. At shallower lithospheric depths, in the range 0–80 km, due to cooling and associated with its westward motion relative to the underlying mantle, the lithosphere is forming from depleted mantle, and has naturally lower velocities than on the western side of the ridge.

Ridges move relative to the mantle, with velocity *Vr* given by (*Va*+*Vb*)/2, where *Va* and *Vb* are the velocities relative to the mantle of the two plates (a) and (b), separated by the rift. The ridge is the seat of mantle depletion due to melting, to form new oceanic crust (Fig. 2). The melting region of the mantle gradually shifts westward, affecting new sections of undepleted mantle. This process delivers depleted mantle to the eastern side of the rift. In other words, the residual asthenosphere shifts "eastwards", with the upper part cooled to form the lithospheric mantle of the eastern flank. Therefore, the ridge is permanently transiting "westward" over a "fertile" mantle able to steadily supply MORB melts. However, once transited, there will be a compositional depletion in the mantle that should appear when comparing the lithosphere/asthenosphere of the western side of the rift with its eastern conjugate counterpart. This would explain the difference in Vs observed at both sides of the rift.

Zoomed-in images of cross-sections along the TE at rift zones (EPR, MAR, IR) show this asymmetry (Fig. 3). In order to test whether this observation is a local occasional asymmetry, a number of sections perpendicular and parallel to the ridge have been constructed along TE (Fig. 3) and far away from it (Figs. B, C and D in the data repository). They are still supportive an asymmetric pattern in the upper mantle when comparing the western and the eastern sides of the rift, particularly in the Pacific and Indian ridges.

Similarly, a slower asthenosphere in the western side of the EPR has been identified in the Melt experiment, interpreted as due to more pronounced melting in the western asthenospheric mantle (e.g., Scheirer et al., 1998). There are areas where this asymmetry is not evident, or possibly sections where it is even reverse. However, it appears as a dominant feature.

The partial melting in the mantle beneath ridges varies as a function of a number of parameters, such as the tectonic setting (e.g., smaller along transtensive rifts), the original mantle composition and fluids content, the temperature of the mantle, etc. The variation in Vs is by definition associated to the variation of the square root of the ratio between rigidity (μ) and density (ρ). However it remains unsolved, at least to our knowledge, how to relate in detail the variation of those parameters with the mantle modification at ridges. Oxburg and Parmentier (1977) suggested that there is mantle depletion along ridges, regardless the rift is symmetric or asymmetric. From tomography images (see also Pilidou et al. 2005), all we can say is that the ratio μ/ρ is different between at the two sides of the ridges. Moreover the mean bathymetry is slightly shallower in the eastern flank of the rifts. Therefore, due to the westerly migration of ridges and of the lithosphere relative to the underlying mantle, we propose to interpret the asymmetry as the result of an oblique upraising of the mantle and the distribution of the related depletion.

RADIAL ANISOTROPY

Detailed information on the seismic anisotropy of the Earth's mantle provides insight into paleo and recent deformation processes and therefore mantle dynamics. Radial anisotropy of shear velocities in the upper mantle is usually characterized by the ratio η = (Vsh-Vsv)/Vs,%, where Vsh and Vsv are velocities of two types of shear waves of different polarization and Vs = (Vsh+Vsv)/2.

In the anisotropy sections, both along TE and TE-pert, the minimum value of radial anisotropy is reached, in general at a depth of ~200 km, with outstanding exceptions in proximity of the ridges. The level at which radial anisotropy is low, say below 1%, may well represent the decoupling level between the lithosphere and the underlying asthenospheric LVZ, due to the presence of a relevant fraction of melt that inhibits the formation of preferential orientations in the texture of mantle rocks. In particular, along TE-pert very low values of radial anisotropy (< 1%) reach the top of the section (20 km below surface) with an eastward shift of ~20° with respect to EPR and MAR, and a smaller shift is seen along TE, with respect to EPR, all in agreement with the notion of westward drift of the lithosphere relative to the underlying mantle (first order flow). From Figure 1 one can infer that the shift between the geographical ridges axis and the vertical stripes of radial anisotropy <1% - the "anisotropy ridge" - axis varies from ~1250 km to 2500 km (eastward). The formation of a sizeable solid lid at the ridge sides requires not more than 10–20My (e.g., Leeds et al., 1974; Forsyth, 1975, Panza, 1980) and both a systematic increase in velocities with the age of the seafloor and anisotropy of propagation are observed (Forsyth, 1975). From the above values one gets an average westward lithosphere velocity of ~12.5 cm/y. This value is the result of the ratio between the extremes of the space and time intervals.

The exception of MAR along TE section, is only apparent; in fact, the relatively high radial anisotropy there can be explained by the fact that TE intersects the MAR where the ridge makes an almost 90° bend, thus giving rise to apparent anisotropy, related to geometry rather than rock texture.

DISCUSSION AND CONCLUSIONS

We show relevant horizontal Vs variations both in the lithosphere (uppermost say 100 km of the Earth) and in the upper asthenosphere (LVZ, from say 100–200 km of depth). However, the LVZ in the upper asthenosphere is recognized all across the Earth as a persistent layer at the depth of 120–200 km, as shown in a modified path of the tectonic equator. Across rift zones the main velocity variation is of the order of 0.1–0.3 km/s, where the western flank has a faster lithosphere and a slower asthenosphere relative to the eastern or northeastern flank. Whatever the cause, rift zones show a worldwide mean signature in terms of asymmetry, with a stronger Vs contrast between lithosphere and asthenosphere in the western limb when compared to the eastern one. We interpret it as the depletion of the asthenosphere along the rift, while the ridge is moving "westward" relative to the mantle. The lithosphere to the east would represent the cooling of the more depleted asthenosphere, abandoned after the ridge migration to the west. This process is consistent with the net rotation of the lithosphere relative to the underlying mantle. This decoupling is postulated by the sizeable amount of melting that can be inferred from Vs and radial anisotropy sections at ~190–220 km (Fig. 1). In this interpretation, beneath the decoupling, the mantle shifts "eastward" relative to the lithosphere (first order flow). This relative motion could be responsible for the main anisotropy recorded by shear-wave splitting analysis (e.g., Debayle et al. 2005). Along ridges, the oblique rising mantle could be responsible for the asymmetric pattern (second order flow, Fig. 4). The heterogeneity among the flanks of ocean basins mirrors the differences of subduction zones as a function of their geographic polarity. This polarization along the tectonic equator points to an asymmetric Earth, as expected for a complete net rotation of the lithosphere (1.20°/Myr, Crespi et al., 2007).

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FIGURE CAPTIONS

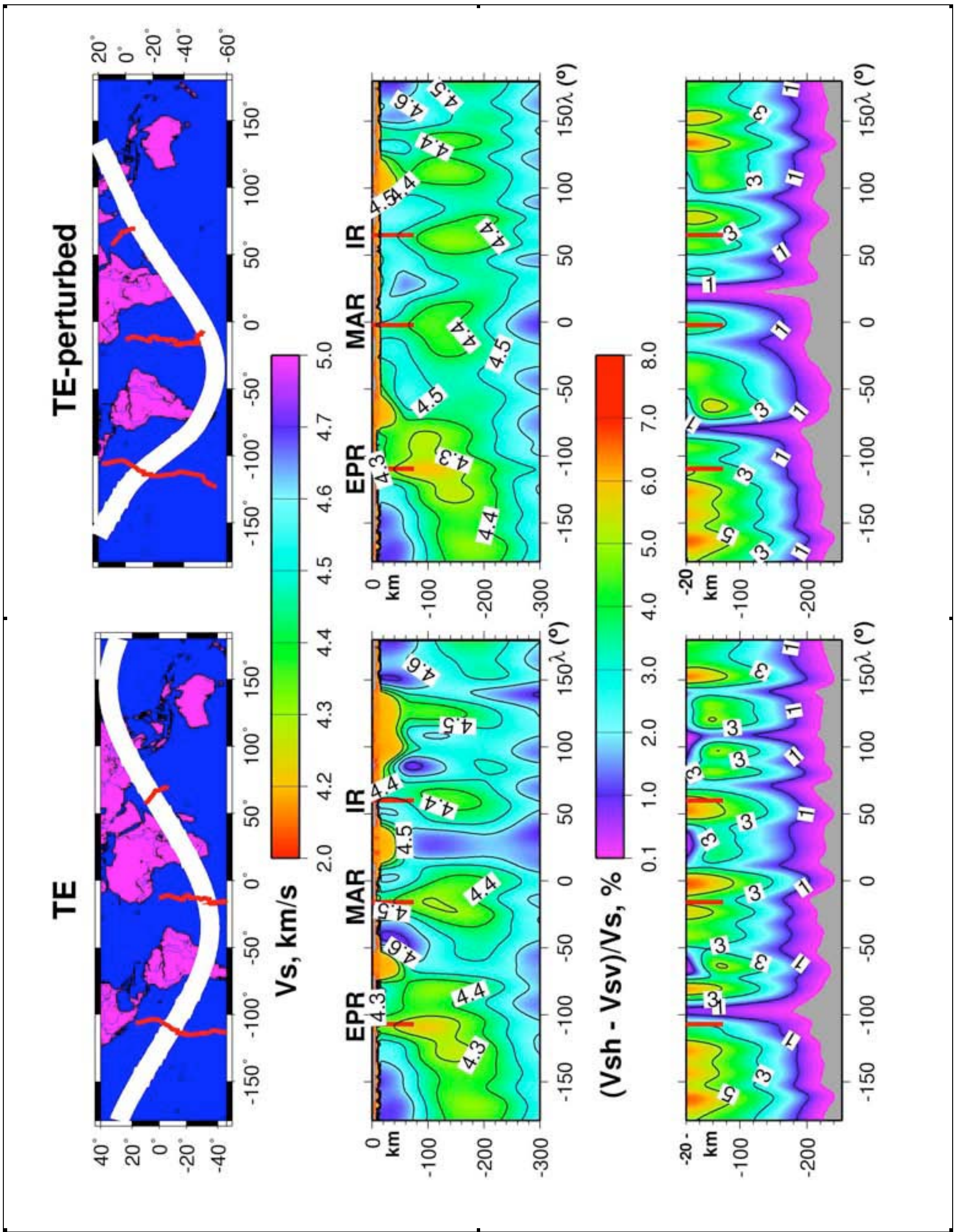

Figure 1. Shear-wave Earth's section along the tectonic equator (TE) proposed by Crespi et al. (2007) to the left, and along a perturbed path (TE-pert). Note the generalized asymmetry across oceanic ridges: the lithosphere (0–100 km) in the western side of the rift is faster than in the eastern or northeastern side, whereas the upper asthenosphere (LVZ, 100–200 km) is slower in the western side with respect to the conjugate counterpart. Red lines correspond to elements of Eastern Pacific, Mid Atlantic and Indian ridges. The lower panels show the radial anisotropy along these sections. To obtain Vs radial cross-sections we used bispline interpolation of velocities at fixed depths levels (on a 4 km grid) with subsequent gaussian smoothing. The Vs is taken here as an average of Vsv and Vsh along a section covering 10° width. The radial anisotropy sections are without crust, since crust is assumed isotropic.

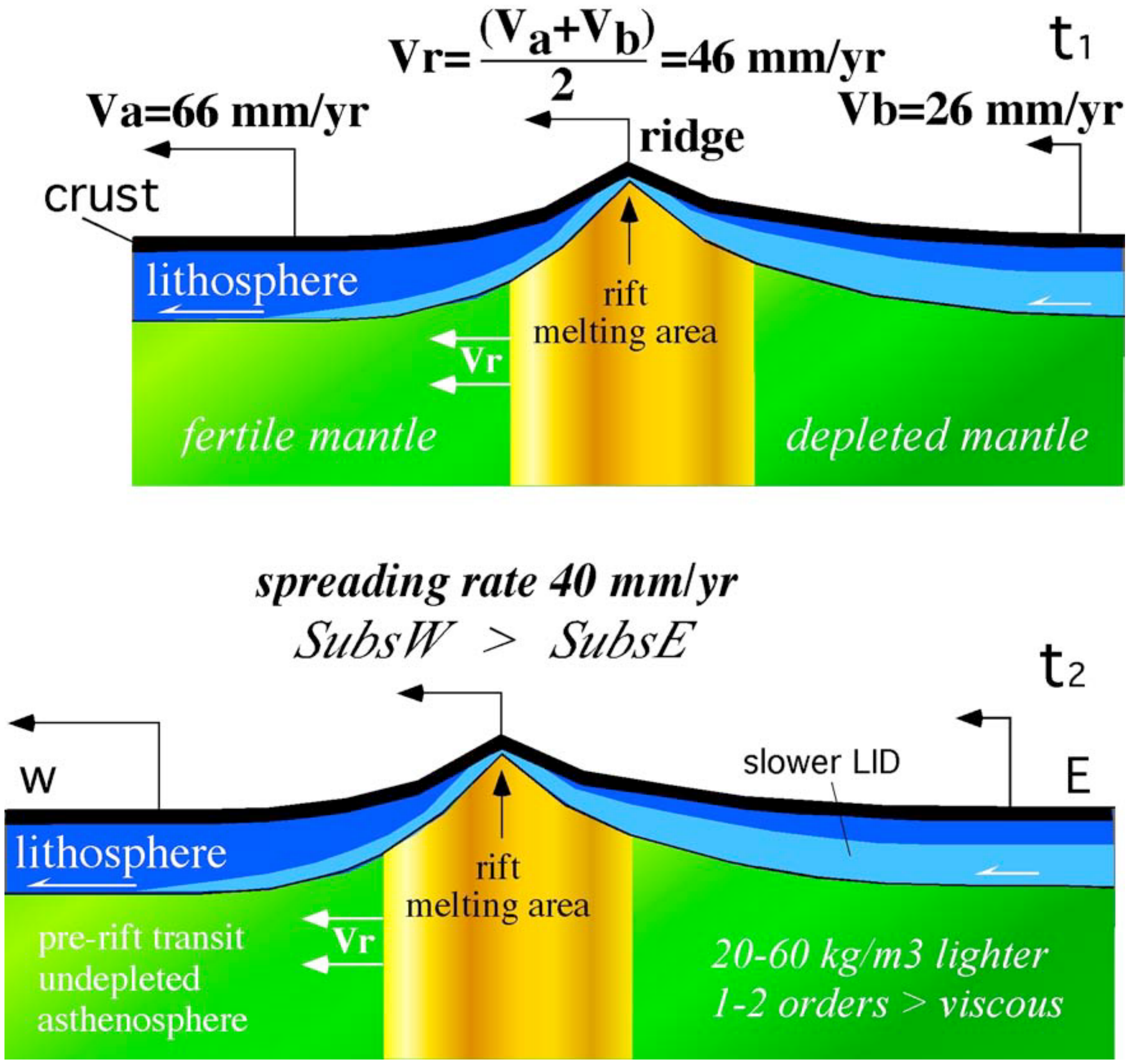

Figure 2. Cartoon of an oceanic rift with hypothetic velocities of plates a and b relative to the fixed mantle. The ridge moves west at the velocity of the ridge (Vr). The separation between plates triggers the uplift of undepleted mantle previously located to the west. In the melting area, the mantle loses Fe, Mg, and other minerals to form oceanic crust, while the residual mantle is depleted. Since the melting area moves west it gradually transits toward the undepleted mantle, releasing to the east a depleted mantle. This can explain the slightly shallower bathymetry of the eastern limb, but it should also generate an asymmetry of seismic waves velocity seen in Figure 1. In this model, the differential velocity among plates is controlled by LVZ viscosity variations generating variable decoupling between the lithosphere and the mantle. Modified after Doglioni et al. (2005).

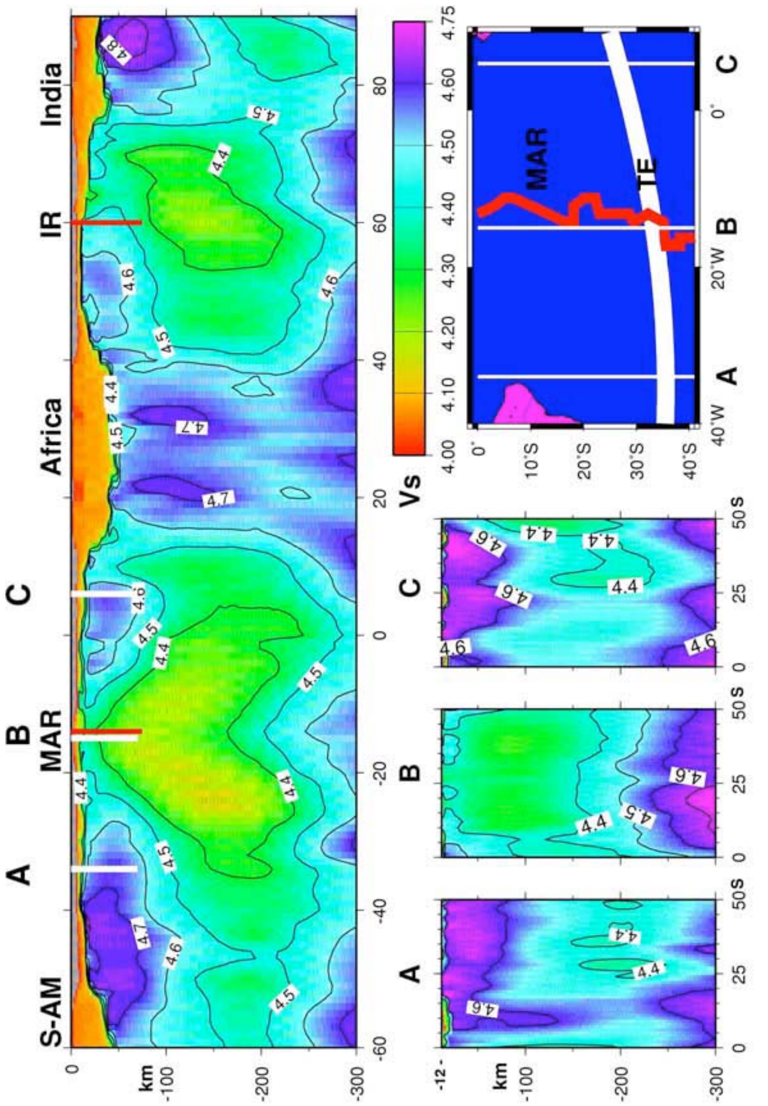

Figure 3. Above, enlarged shear-wave cross-section of the Mid Atlantic and the Indian ridges along the tectonic equator (TE). Unlike Figure 1, the velocities are unsmoothed. A-B-C are N-S cross-sections parallel to the southern Mid Atlantic ridge (see small map with MAR in red). The western side of the ridge shows faster lithosphere and slower asthenosphere, both moving perpendicularly and parallel to the ridge. Data from CUB2 model, see text.

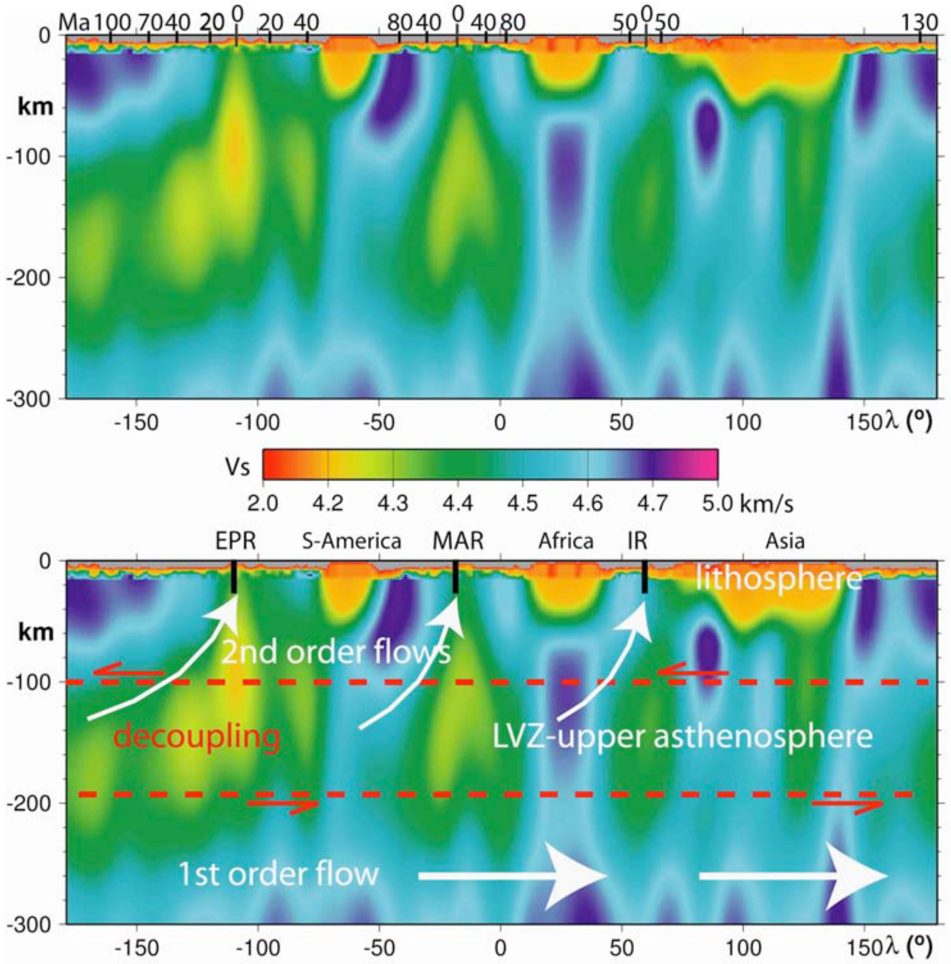

Figure 4. Unininterpreted (above) and interpreted sections along the tectonic equator of the Earth's first 300 km. The upper asthenosphere contains the LVZ, i.e., what is supposed to be the main decoupling surface between the lithosphere and the mantle, allowing the net rotation of the lithosphere, i.e., the first order relative "eastward" relative mantle flow, or "westward" drift of the lithosphere. Secondary flow should be related to the mantle obliquely upraised along oceanic ridges. The asymmetry among the two sides of the ridges is independent from the age of the oceanic lithosphere shown at the top in million years (Ma, ages from Müller et al., 2008).

[1]GSA Data Repository item 2009xxx, [Please provide a brief description of your data repository items], is available online at www.geosociety.org/pubs/ft2008.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.