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Upper mantle heterogeneities in the Indian Ocean from waveform inversion

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Abstract. A waveform inversion method is applied to 156 Love and Rayleigh wave seismograms to build up a 3-D model of the shear velocity in the upper mantle beneath the Indian Ocean. The first step of the method consists in finding, for each path, a radially stratified upper mantle model compatible with the Love and Rayleigh wave seismograms relative to that path. The fundamental mode and few higher modes are modelled in the waveform inversion. In a second step, the models related to the different paths are used in a tomographic inversion to map the 3-D upper mantle structure. The 3-D velocity model has a lateral resolution of 1000 km. No significant velocity anomalies are found below 300 km, although the resolution is still good. Continental roots are confined to the upper 300 km and low velocities below mid-oceanic ridges to the upper 250 km, depending on their spreading rates. At shallow depths (< 80 km), we find a positive velocity anomaly beneath the West Indian ridge near the Rodriguez triple junction, where gravimetric and bathymetric data indicate a reduced volcanic activity. At greater depth (around 200 km), a low velocity signature is found beneath the hot-spot of Réunion-Mauritius islands and the Central Indian ridge. It could reflect a real connection between the two structures.

1. Introduction

During the past 15 years, long period surface waves have been commonly used to image the structure of the upper mantle. Due to the increasing amount of digital data, the lateral dimensions of structural features that can be resolved in global S velocity models have progressively decreased from 5000 km [*Woodhouse and Dziewonski,* 1984] to around 1000 km [*Zhang and Tanimoto,* 1993]. In regional studies, lateral resolution can now reach locally 250 km in regions where a dense coverage is available [*Zielhuis and van der Hilst,* 1996]. In the Indian Ocean, the previous regional studies [*Montagner,* 1986a;b; *Roult et al.,* 1987; *Montagner and Jobert,* 1988] have a lateral resolution limited to 2000 km, due to the poor distribution of stations. These latter studies, based on the analysis of fundamental mode dispersion curves, show a good correlation of the deep structure with surface tectonics down to about 100 km depth, except in the Central part of the Southeast Indian Ridge. In addition, *Montagner* [1986a;b] and *Montagner and Jobert* [1988] find a slow structure shifted eastward of the Central Indian ridge below 100 km depth.

In this paper, we present a 3-D S-velocity model for the upper mantle in the Indian Ocean with improved lateral and depth resolution. The model is obtained from a larger dataset than in previous studies and a different methodological approach. New data recorded on Géoscope stations DRV, CRZ and HYB allow us to improve the lateral resolution to 1000 km with a more homogeneous path coverage. Instead of analysing dispersion curves, we use a waveform inversion method designed to match directly surface-wave seismograms, possibly including several higher modes. It is based on the waveform inversion technique of *Cara and Lévêque* [1987] adapted to process simultaneously a set of seismograms with close epicenters, recorded at a single station. In this approach called "multi-seismogram technique", the epicenters of a given cluster must be close enough so that we can consider the waves travel the same path and can be explained with a single model. The inverted model, compatible with all the observed seismograms available for that path, can be interpreted as the average Earth's structure beneath the path. A regionalization of the models obtained for the different paths leads to tomographic images of the upper mantle.

2. Data Selection

We use Love and Rayleigh wave long-period seismograms at 11 stations in the Indian Ocean, for earthquakes occurring from 1988 to 1994. The selected events have magnitudes ranging from 4.8 to 7.2 Msz and the corresponding seismograms are inverted using observables covering the 20-300 s period range. Most of these earthquakes are shallow events located on mid-oceanic ridges of the Indian Ocean. The few deep earthquakes we use are located in the Indonesian subduction zone. We have discarded seismograms with a poor signal-to-noise ratio or for which the initial phase at the source was not stable with respect to small perturbations of the path azimuth. Finally, we keep only the paths for which at least one Rayleigh wave and one Love wave seismograms can be inverted simultaneously. For some paths, up to 4 seismograms (2R+2L) have been inverted simultaneously. The whole set of data consists of 156 seismograms related to 71 different paths. For 11 of these paths, higher modes are taken into account up to the fifth overtone for Rayleigh waves. Love wave higher modes are included in the inversion for 53 paths. The path coverage is shown on Fig.1a.

3. Method

3.1. The Waveform Fitting

One important problem in a waveform inversion technique is the highly non-linear dependence of the recorded

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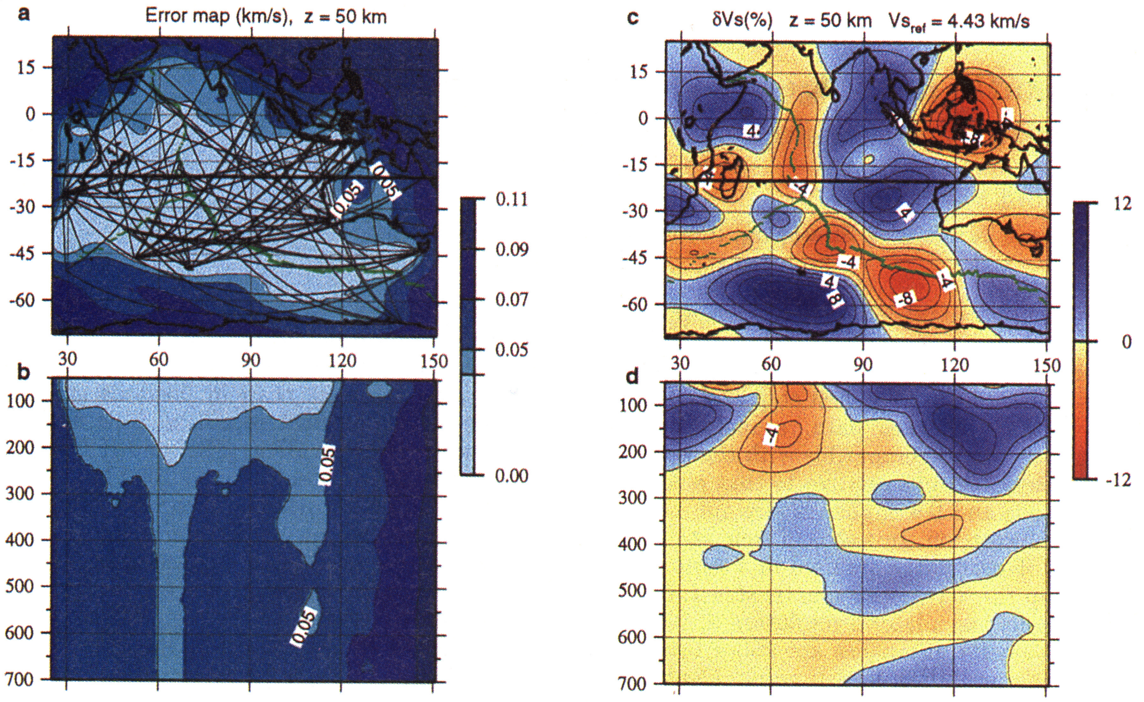

Figure 1. a) A posteriori error map (in km/s) at 50 km depth and path coverage. b) vertical East-West cross-section at 20°S in the 3-D error model. c) Map of lateral perturbations in percent (with respect to the value Vref indicated on the map) for the S-velocity at 50 km depth. d) vertical East-West cross-section at 20°S in the 3-D S-velocity model. The oceanic ridges of the Indian Ocean are plotted in green on the maps.

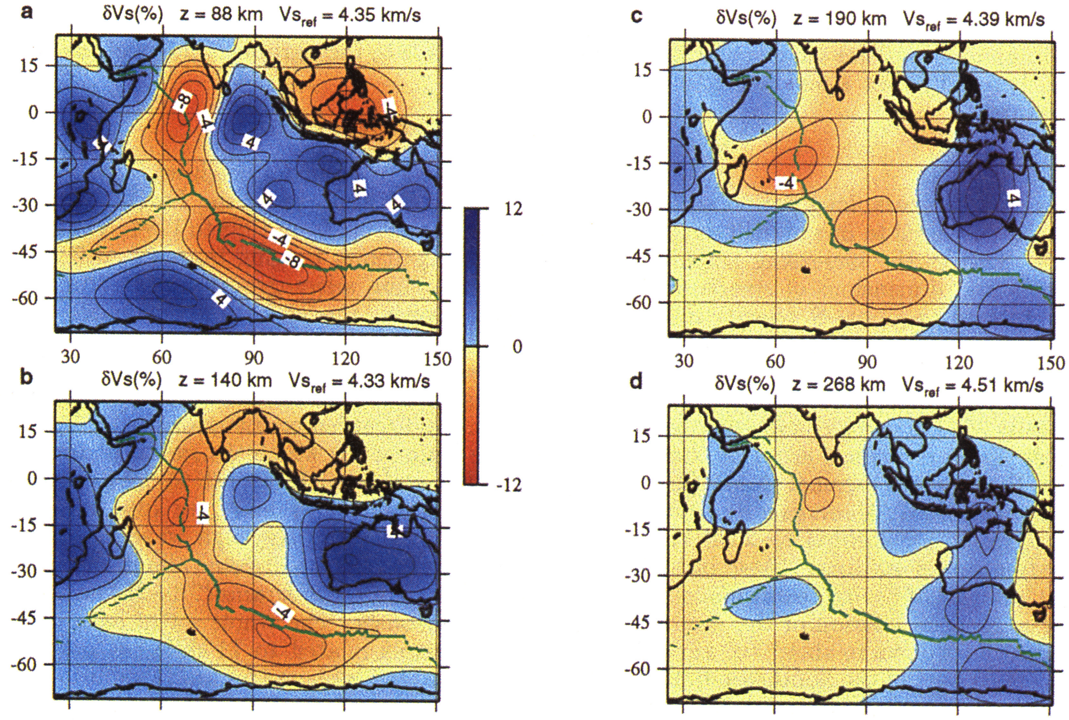

Figure 2. Maps of lateral perturbations for the S-velocity in the Indian Ocean at increasing depths. The variations are given in percents with respect to the value Vref indicated on each map a) depth 88 km. b) depth 140 km. c) depth 190 km. d) depth 268 km.

signal on the model parameters. The originality of the method developped by *Cara and Lévêque* [1987], compared with other waveform inversion techniques [e.g. *Nolet,* 1990], is the introduction of secondary observables, built up from the seismograms, having only a slightly non-linear dependence upon the model parameters, allowing for an inversion with a classical non-linear scheme. In the multi-seismogram approach used here, the secondary observables are computed for all seismograms related to a same path, and then inverted using the same scheme as in *Cara and Lévêque* [1987].

Using several seismograms simultaneously in one inversion reduces the influence of errors on fixed parameters, such as focal mechanism or focal depth, and allows to use simultaneously data containing non-redundant information on the mantle structure. For example, we can invert simultaneously data from shallow and deep earthquakes as in *Stutzmann and Montagner* [1993], or data from Love and Rayleigh waves.

In most cases, Love and Rayleigh waves are not compatible with a single isotropic structure. We adress this Love/Rayleigh discrepancy by inverting for the S-wave anisotropic parameter ξ as defined in *Takeuchi and Saito* [1972] for a transversely isotropic medium. We also invert for the shear wave velocity β_v, the attenuation factor Q_β^{-1} and for M_0, the scalar seismic moment of the source, to ensure an adequate scaling of the signal. In this paper, we present and discuss results on β_v only. Significant anisotropy is found in the upper 250-300 km, but the trade-off between β_v and ξ is found very small. Results on anisotropy and Q_β^{-1} will be discussed in a separate paper.

The a priori information used in this study is similar to the one used in *Lévêque et al.* [1991]: the a priori β_v model in particular is a smoothly depth-varying isotropic model in the mantle with a crustal structure adapted for each path. The a priori standard-deviations are fixed to 0.05 km/s for β_v and 0.03 for ξ according to the expected variation range for these parameters in the Indian Ocean. The vertical correlation length is fixed to 50 km and the uncertainty on the data to 10 % for amplitude data, and 5 % for phase data.

3.2. Regionalization of Shear Velocities

The average β_v models are obtained for each path shown in Fig.1a. A regionalization of these models is performed using the continuous regionalization algorithm of *Montagner* [1986a]. To constrain the lateral smoothness of the model and according to our path coverage, we use gaussian functions with length of 1000 km as correlation functions. The a priori standard deviation which controls the amplitude of heterogeneities in the inverted model is set to 0.10 km/s. This value allows velocity contrasts in the final model as large as 15 % , in agreement with velocity contrasts observed in previous oceanic studies [e.g. *Montagner,* 1986a;b or *Nishimura and Forsyth* 1989].

The S-velocity map at 50 km depth and an East-West cross section at latitude 20^oS are shown on Fig.1, together with the corresponding a posteriori error maps (Fig.1a,b). Dark blue areas indicate an a posteriori error close to the a priori error (0.1 km/s), indicating a total lack of resolution. This unresolved area is limited to the outer zone of the map. In most part of the Indian Ocean, and at least down to 300 km depth, the error is less than 0.05 km/s, indicating a very good resolution. Below 300 km depth (Fig.1b), we still observe locally an error smaller than 0.05 km/s in two regions, one located below the Central Indian ridge (60^oE), and the other one around 110^oE. They correspond to areas where the paths associated to deep events in the eastern part of the indonesian subduction zone cross the latitude 20^oS. This is a direct consequence of the increased resolution for these paths, as compared with paths where no higher mode data were available.

At 50 km depth (Fig.1c), S-velocities are strongly correlated to surface tectonics. Low velocities are associated with mid-oceanic ridges. Old oceanic basins display high velocities. Two unexpected features however show up in the well resolved area: a positive anomaly beneath the West Indian ridge, near the Rodriguez triple junction, and high velocities beneath the Carlsberg ridge. On the cross-section at latitude 20^oS (Fig.1d), fast S-velocities are found down to 250 km below Africa and down to 300 km below Australia. The low velocity signature of the Central Indian ridge does not extend beyond 250 km depth. This is probably a reliable feature in the model since the resolution is good in this area (Fig.1a). Below 300 km, the amplitude of the anomalies remains small everywhere. Note also that the low velocity beneath the island of Madagascar can be an artefact due to a poor knowledge of the crustal structure in this region; this negative anomaly does not extend deeper than 50 km.

Figure 2 displays the velocity maps at increasing depths, showing that features observed on the 20^oS cross-section are more general. The correlation with surface tectonics is still very clear at 88 and 140 km depth. At 88 km, a positive velocity contrast is present beneath the West Indian ridge near the Rodriguez triple junction. At 140 km depth, this positive contrast disappears and the slow signature of the West Indian ridge itself vanishes while it remains beneath the two other ridges. At 190 km depth, low velocities beneath mid-oceanic ridges and the Indonesian arc nearly disappear. At this depth, the largest negative anomaly is centered on the Central Indian ridge, close to Mauritius and La Réunion islands. High velocities are still present beneath continents, and a north-south positive anomaly connects the Australian continent to Antarctica. At 268 km, the low velocity signature of the ridge completely vanishes, but the high velocity pattern is similar to that found at 190 km depth, although if attenuated.

4. Discussion

The depth extent of the seismic anomalies we have found (Fig.1d,2c) is slightly shallower than in most other surface wave studies of the Indian Ocean [e.g. *Montagner and Tanimoto,* 1991]. These observations agree with a more recent global S-velocity model [*J. Woodhouse and J. Trampert,* submitted to Earth Planet. Sci. Lett., 1996] and support the idea developed in *Ricard et al.* [1996] that most seismological observations are compatible with the 3-SMAC "geodynamical" model where upper mantle anomalies are no deeper than 300 km. However, in our model, the low-velocity signature beneath mid-oceanic ridges is apparent down to 200 km in the most part of the Indian Ocean (Fig. 2c,d), a greater value than in 3-SMAC where ridge anomalies are present in the first 100 km only.

Despite the enhanced lateral resolution of our study, no eastward shift is observed at any depth beneath the Central Indian ridge: we find low velocities in the Central Indian basin at 190 km depth as in *Montagner* [1986a;b] or *Montagner and Jobert* [1988] but the strongest velocity anomaly is well centered beneath the Central Indian ridge (Fig.2). Another feature, more classical [e.g. *Montagner and Tanimoto,* 1991], of our model is the correlation between the low velocity signature of oceanic ridges and their spreading rates.

At shallow depths, we find a positive anomaly that does not appear in previous 3D S-velocity models beneath the West Indian ridge near the Rodriguez triple junction, suggesting a relatively cold mantle in that part of the ridge (Fig.1c,2a). This can be related to recent bathymetric [*Mendel and Sauter,* 1996] and gravimetric [*Rommevaux et al,* submitted to Marine Geophys. Res., 1996] results that conclude to a weak volcanic activity between the fracture zone of Melville (around 60^oE) and the Rodriguez triple junction. It could also help explaining the high phase velocities obtained at this location by *Roult et al.* [1987] for Rayleigh waves at periods 61s and 102s. Another interesting new feature is the deep low velocity anomaly that persists to 190 km depth beneath the Central Indian ridge, and spreads toward the hot-spot of Réunion-Mauritius islands. This westward spreading is also apparent on the cross-section (Fig.1d) and at shallower depth (88 and 140 km, Fig.2a,b) beneath the Mascareignes plateau. Due to a lack of lateral resolution, this low velocity anomaly could be the coalescence of two distinct anomalies beneath the hot-spot of Réunion-Mauritius islands and beneath the Central Indian ridge. Another possible interpretation is to associate this low velocity signature with the hot-spot trace between the Central Indian ridge and Mauritius island. The well-known Australian-Antarctic discordance appears clearly on our maps at all depths as a structure abnormally fast for a ridge (Fig.2). This result is in agreement with those of *Forsyth et al.* [1987], who found high S velocities down to 150 km depth, and *Kuo et al.* [1996] who favour a deep asthenospheric origin of the AAD from considerations on the geoid. The oceanic plateaus, which are one of the striking characteristics of the Indian Ocean, do not systematically correspond to clear velocity anomalies. This may be due to the fact that some of these structures (e.g. Ninety-east and Broken ridges) are much narrower than the lateral resolution or, where the plateau structure is larger (Kerguelen), to the poor path coverage near the border of our maps.

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