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IMPORTANCE OF THE REFERENCE MODEL IN LINEARIZED TOMOGRAPHY AND IMAGES OF SUBDUCTION BELOW THE CARIBBEAN PLATE

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Abstract. In linearized delay time tomography the choice of a one-dimensional reference model is very important for correct mapping of seismic anomalies. We demonstrate that the use of an inadequate background model results in artifacts in tomographic images which may give rise to erroneous interpretations. Particularly the absence or presence of upper mantle discontinuities in the reference model, influences the mapping of structures (e.g. subducting slabs) at the transition between upper and lower mantle. New tomographic images of the mantle below the Caribbean Region are presented. These show the extent of the Lesser Antilles subduction zone down to 600 km which is well below the seismic zone. A high velocity anomaly is imaged from the Mid American trench to lower mantle depths (1400 km).

Introduction

In the past decade, tomographic studies have provided us with images of the three-dimensional structure of the Earth's interior [e.g. Nolet, 1987]. Body wave data have been used in many regional studies [e.g. Hirahara, 1981; Grand, 1987; Spakman 1988; Zhou, 1988]. In these investigations the non-linear problem of travel time inversion is linearized using Fermat's Principle (FP), leading to a description of the tomographic problem relative to a reference model of seismic velocities. The reference velocity model determines the source locations, delay times and, together with the distribution of earthquakes and seismological stations, the ray geometry, and thus the system of equations representing the tomographic problem. The assumptions underlying the application of FP impose restrictions on the reference model and may cause the inversion results to be biased towards this reference model.

Notwithstanding the obvious importance of the reference model usually little attention is paid to the choice of a proper model. In this paper we emphasize upon the influence of the reference model on images resulting from linearized tomographic inversions. With data errors, poor ray coverage, model discretization, and numerical approximations [Spakman and Nolet, 1988; Spakman et al., 1989] choice of an inappropriate reference model may lead to artifacts in the image and it is important to distinguish between these and the "true" velocity perturbations. Reference model artifacts are illustrated by new results from a tomographic investigation of the P-velocity structure of the mantle beneath the Caribbean Region.

Linearization and reference model: assumptions and implications

In delay time tomography we invert delay times for estimates of the slowness deviations $\Delta s(\mathbf{r})$ of the actual Earth's slowness field $s(\mathbf{r})$ with respect to a reference slowness model $s_o(\mathbf{r})$. The delay time can be defined as the difference between the observed travel time T and the reference travel time T_o, which is computed from the reference model s_o. Representing travel time by a ray integral we can write for delay time d:

$$d = T - T_o = \int_{L(s)} s(\mathbf{r})\,dl - \int_{L_o(s_o)} s_o(\mathbf{r})\,dl_o \approx \int_{L_o(s_o)} \Delta s(\mathbf{r})\,dl_o \qquad (1)$$

where L is the actual (unknown) ray path and L_o the ray path in the reference model. In linearized delay time tomography Fermat's Principle (FP) is applied to the first integral of (1). FP states that small perturbations in ray path L lead to a second-order error in T. In linearized tomography this second-order error is neglected and L(s) can be replaced by $L_o(s_o)$. The delay time d is now linearly related to the unknown slowness anomaly field $\Delta s(\mathbf{r})$. In a more subtle derivation of (1) additional source mislocation and station correction terms appear on the right hand side [e.g. Spakman, 1988]. In our tomographic inversions these extra terms are included. For a discussion about algorithms commonly used to solve the linear system of equations we refer to Nolet [1985] and Spakman and Nolet [1988].

In the present paper we qualitatively discuss the choice of the reference model and whether second order effects due to ray bending can be neglected. If published residual times are used, we are not free in our choice of a reference model but have to adopt the velocity structure used for the computation of the data.

ISC delay times (published in monthly Bulletins of the International Seismological Centre), which are widely used in tomographic studies, are computed relative to the Jeffreys-Bullen travel time tables [Jeffreys and Bullen, 1940]. The JB velocity structure (dashed curve in Figure 1a) is therefore often used as a reference model in tomographic inversions. It is a global model, averaging velocity structures of continental and oceanic, and tectonically active and stable areas. The JB model lacks a low velocity layer and first order discontinuities in the upper mantle. Using ISC delay times we compute the ray geometry in the JB model. Some JB ray paths are plotted in Figure 1b. For comparison, also the PREM model ray paths are plotted.

On applying FP to linearize the inversion problem, we implicitly assume the reference ray paths to be close to the ray paths in the true Earth. From Figure 1b we infer that in the lower mantle JB and PREM ray paths are close to each other. In the upper mantle, however, differences between JB and PREM ray paths may be as large as 100 km [also Zielhuis et al., 1989], which is comparable to cell dimensions typically used in regional tomographic studies [Hirahara, 1981; Spakman 1988; Zhou, 1988]. Both JB and e.g. PREM can be used as reference models for tomographic imaging. However, that usage of a model that inappropriately describes the average Earth for a particular tomographic problem, leads to

- mapping of anomalies relative to incorrect reference velocities
- substantial differences between true and reference raypaths, resulting in a non-linearity possibly too strong to neglect second order errors in the derivation of (1), and mapping of anomalies at incorrect locations.

Derivation of a new reference model

Can the global JB model adequately be used as a reference model for the mantle below the Central American region? An important indication that JB may not be the most appropriate model for this study is given by the data set itself. In our tomographic study we use ISC data (1964 - June 1985) and an additional set of NEIC data (July 1985 - July 1987). The distribution of delay times versus epicentral distance is given in Figure 2a. We note that if the JB model were an adequate description of the average mantle structure of the studied area we would expect the data to be evenly distributed around the line delay = 0 marked by the horizontal dashed line. From Figure 2a we infer, however, systematic deviations with epicentral distance. The observation that in particular distance intervals, body waves arrive

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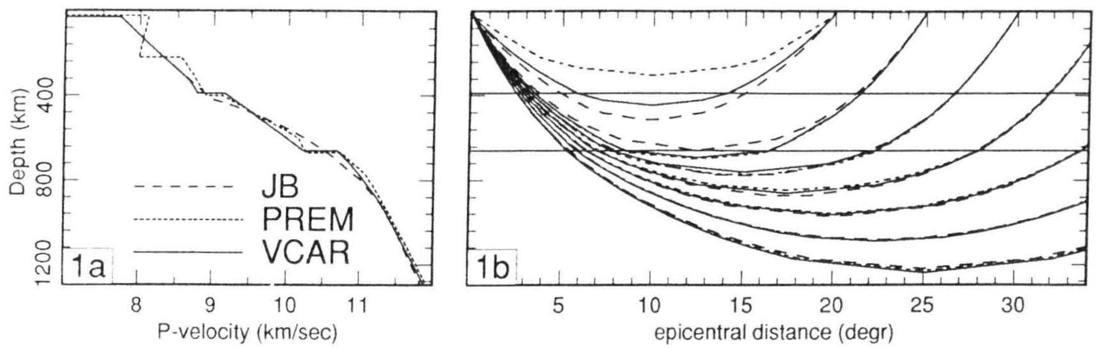

Fig. 1. a: Differences between JB, PREM and the regional VCAR velocity structures. b: Ray geometry.

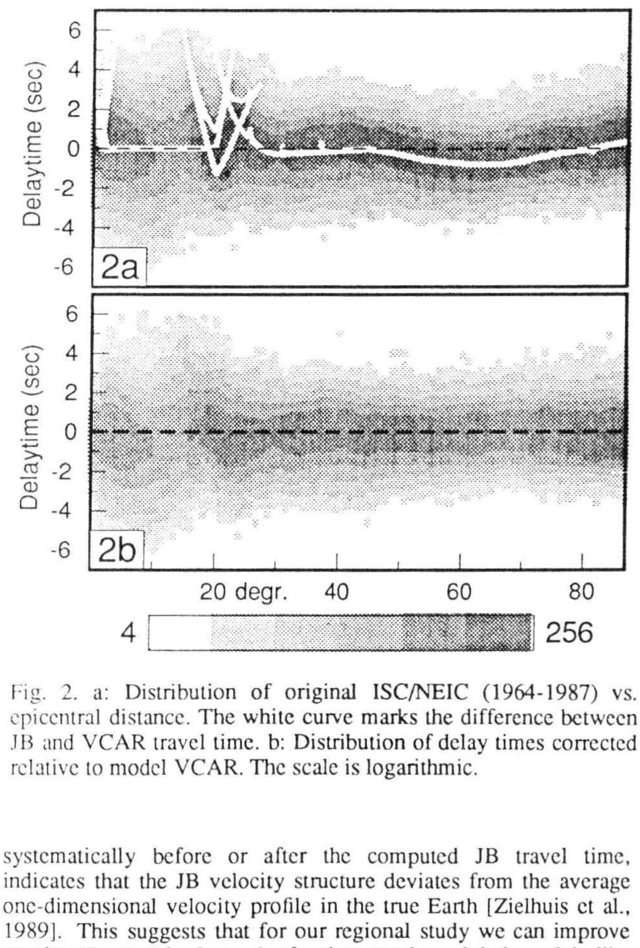

Fig. 2. a: Distribution of original ISC/NEIC (1964-1987) vs. epicentral distance. The white curve marks the difference between JB and VCAR travel time. b: Distribution of delay times corrected relative to model VCAR. The scale is logarithmic.

systematically before or after the computed JB travel time, indicates that the JB velocity structure deviates from the average one-dimensional velocity profile in the true Earth [Zielhuis et al., 1989]. This suggests that for our regional study we can improve on the JB model. Instead of using another global model, like PREM, we modified existing P-velocity models [Jeffreys-Bullen,1940; Burdick, 1981; Dziewonski et al., 1975] with the objective of removing the mentioned trends in the data. We remark that, in contrast to Grand [1987], we use one reference model although the studied region comprises both tectonic stable and active areas. We maintained JB for shallow depths and did not consider a low velocity zone. We computed travel time curves from updated models, reduced these curves relative to the Jeffrey-Bullen tables and matched the trends in the data with the resulting reduced travel time curves [Zielhuis et al., 1989]. By trial and error we arrived at model VCAR (Figure 1a), the reduced travel time curve of which is given in Figure 2a. In this curve we recognize triplication branches between 14° and 28° epicentral distance due to large gradients or discontinuities in the upper mantle velocity structure. Part of the spreading in ISC data in this distance range is due to picking (later) arrivals (with larger amplitudes than first arrivals) associated with these triplications: reading errors are not random. The trends for distances beyond 30° are well fitted by the reduced travel time curve of VCAR.

Subsequently, with the ray geometry computed in the new model, the ISC/NEIC delay times (Figure 2a) were corrected relative to the new reference model VCAR. These corrections are in the same order of magnitude as the values of delay times used in the inversion. The distribution of the delay times relative to VCAR is shown in Figure 2b. Evidently, for epicentral distances exceeding 30°, a substantial part of the ISC/NEIC delay time values is explained by the difference between the JB and VCAR lower mantle structures and need thus not be explained in terms of lateral heterogeneities. Although the data between 14° and 28° are corrected the previously mentioned triplication branches are not removed, because in the correction procedure we could not distinguish between first arrivals and later arrivals associated with triplications. The correction of ISC data relative to VCAR reduced the data variance, prior to inversion, with 10%.
VCAR ray paths are shown in Figure 1b. Differences between JB and VCAR ray paths may be as large as 100 km. We assume that VCAR ray paths are closer to the true ray paths than the JB rays and that the non-linearity of the inverse problem is smaller than in the case of the JB model.

Application to the mantle below the Caribbean Region

In our tomographic study, the mantle below Central and South America is discretized into 48,750 cells with constant horizontal dimensions of 1.25° by 1.25° and vertical dimensions increasing from 33 km (top) to 225 km (bottom). Together with relocation parameters and station corrections we solved for nearly 80,000 unknowns. We only considered earthquakes (mb > 2) which were recorded at at least ten stations. This resulted in a data set of 700,000 ISC/NEIC delay times. All tomographic images to be discussed in this section are obtained after 20 iterations. The inversions are slightly damped and the solutions smoothed (for details about the inversion scheme see Spakman and Nolet [1988]). To investigate the effect of the reference model on tomographic images we performed two computations: in one we used the original ISC/NEIC data (Figure 2a) and the JB ray geometry, in the other the corrected data (Figure 2b) and VCAR ray geometry were used. Hereafter the two inversions are referred to as JB and VCAR inversions, respectively. We illustrate the influence of the reference model with two mantle cross sections through the 3D velocity structure, the locations of which are given in Figure 3.

Figure 4a represents the result of the JB inversion for a section across the Lesser Antilles arc. The most striking feature in this image is the high velocity structure dipping steeply from the top of the model to a depth of about 600 km, although the seismic zone is restricted to the upper 200 km. This structure may be interpreted as the (blurred) image of the subduction of the Atlantic Plate below the eastern part of the Caribbean Plate. At the transition between upper and lower mantle the dip decreases and the high velocity anomaly changes to a subhorizontal position.
The apparent continuation and flattening of the velocity structure in this image may give rise to erroneous interpretations with regard

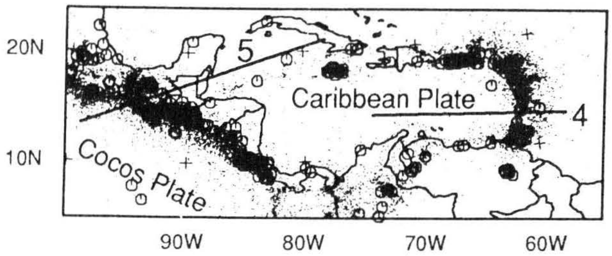

Fig. 3. Seismicity and the location of sections of Figures 4 and 5.

to mantle dynamics. Figure 4b shows the result of the VCAR inversion for the same section. This result does not show the continuation and flattening of the high velocity structure associated with the subduction zone as was suggested by the JB image.

The left hand side of the JB image (Figure 4a) suggests an alternation of layers with velocities lower and higher than the JB reference model at a depths of about 670 km. Just above this depth level low velocities are visible whereas just below this interface high velocities (relative to JB) can be seen. Similar features are present in tomographic images of Zhou [1988, e.g. Figure 4b] and Spakman et al. [1989]. The alternation can be understood by studying the differences between the velocity structures given in Figure 1a. Compared with model VCAR, JB velocities are higher just above the discontinuity and lower just below. The suggested stratification of the upper mantle are images of these discontinuities. Using the updated reference model we were able to remove features in the images that can be attributed to the inadequacy of the JB model as a one-dimensional starting model for this particular area. Below the Caribbean Plate the 400 km discontinuity is not recovered. Due to poor ray coverage this part of the model is hardly illuminated with rays resulting in poor resolution. Recall that not only the velocity perturbations are displayed relative to model VCAR but that also the data set and ray geometry used in the inversions differ. We were not able to reproduce the image of Figure 4b by simply adding the velocity differences between JB and VCAR to Figure 4a, and conclude that the effect of the corrections discussed above is not restricted to the linear domain.

The absence of the 670 km discontinuity in the JB model also affects the structures in the section across the Mid American trench (Figure 5). In the JB image (Figure 5a) the arrow points to a gap in the rather continuous zone of high velocities which extends from the surface to the bottom of the model (at a depth of over 1300 km). The low velocities we expect to image (relative to JB) just above the discontinuities (as discussed above) are superimposed on the positively valued perturbations that may be associated with a cold slab. In Figure 5b the VCAR image shows the velocity anomaly being almost continuous across the discontinuity, suggesting that the gap in Figure 5a may be regarded as an artifact of using JB to compute data and ray paths (assuming that artifacts of smoothing and resolution are the same for both sections).

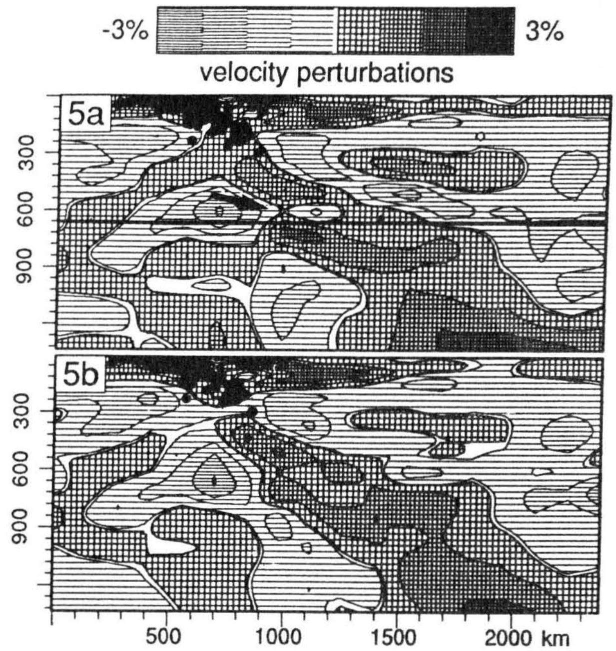

Fig. 5. Vertical mantle cross section across the Mid American subduction zone. a: JB inversion. The arrow points to a gap in the velocity structure at the transition between upper and lower mantle. b: result of VCAR inversion. (See text for uncertainties about resolution in the transition zone.)

A continuous high velocity anomaly down to lower mantle depths

The presence of anomalously high velocities in the lower mantle below the western part of the Caribbean Plate has been reported by several authors. Analyzing S-ScS and P-PcP differential times Jordan and Lynn [1974] discovered strong lateral velocity gradients in the lower mantle below this region. This conclusion was confirmed by Lay [1983], Vidale and Garcia-Gonzalez [1988] and Grand [1987]. Grand's tomographic inversion of S and SS delay times revealed a steeply dipping high velocity anomaly continuous from the Caribbean area to the southern border of Canada, ranging from 700 to 1700 km in depth. Grand found little heterogeneity in the shear wave velocity structure of the upper mantle.

The question whether or not the reported high velocity anomaly in the lower mantle exists and can be continued across the transition zone, between 400 and 670 km, to the surface, as is suggested by Figure 5b, cannot be answered without analyzing the spatial resolution in the image. We inverted data derived from known velocity anomalies in order to obtain upper estimates for

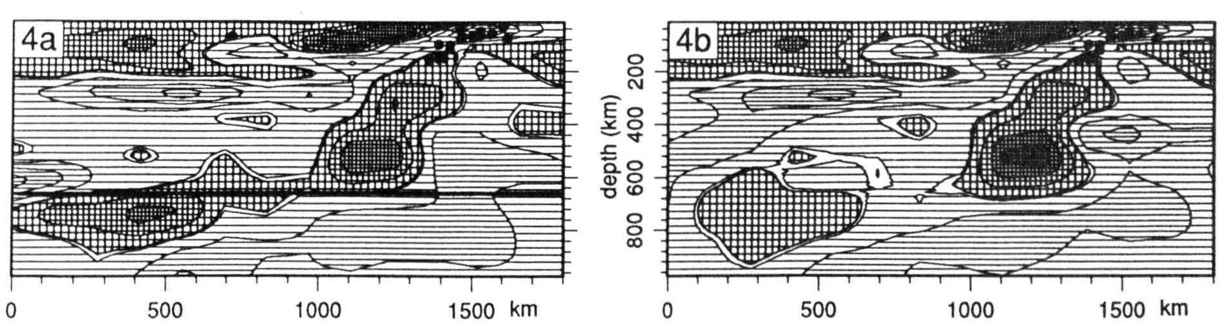

Fig. 4. Vertical mantle cross section across the Lesser Antilles Arc. For the scale key used in this graph see Figure 5. Small dots in the upper right corner represent earthquake hypocentra. a: Result of JB inversion. b: VCAR inversion.

the resolution. Random noise was added to the synthetic data. A discussion about this method is beyond the scope of this paper and we refer to Spakman and Nolet [1988]. The subject of resolution will be addressed to in a separate paper about the three-dimensional structure of the Mid American subduction zone. Here we suffice with giving some conclusions. Comparison of the inversion response to synthetic velocity models with the exact model revealed that smoothly varying anomalies are well resolved in the lower mantle part of the image and at shallow levels just below the seismic active area. Between the discontinuities, resolution is worse. With respect to the reference model we recall that, (1) the geometry of rays bottoming in the transition zone strongly depends on the velocity structure and, (2), corresponding data are contaminated with later arrivals associated with triplications. This is not taken into account in the performed synthetic tests. It is important to realize, that the resolving power of a fixed reference geometry is tested and only random noise is added to the data. Consequently, inversion of synthetic data does not provide additional information about possible inadequacies of the reference model, and gives upper estimates of the true resolution, particularly for structures in the transition zone.

From Figure 5b it is evident that the slab like velocity anomaly is broader in the lower than in the upper mantle. This is partly be due to the use of larger cells to discretize the lower mantle. Both in the upper and lower mantle the images are blurred due to data errors, image distortion by the inversion algorithm and smoothing [Spakman and Nolet, 1988]. Also the use of a ray geometry derived from shooting in a 1D reference model neglecting 3D ray bending effects may overestimate the width of the anomaly [Engdahl and Gubbins, 1987]. Consequently the width of the actual anomaly is difficult to determine and the structure may be narrower than imaged. We remark that absolute values of the imaged amplitudes are systematically underestimated due to smoothing, damping and event relocation.

Discussion and concluding remarks

We showed that in linearized tomographic inversions the 1D reference model plays a very important role. A substantial part of the values of ISC delay times can be explained by the use of a one-dimensional reference model different than JB. Some important features in the tomographic images can be attributed to the inadequacy of the JB model for the studied mantle region. Particularly images that represent the transition from upper to lower mantle are sensitive to whether or not the reference model contains upper mantle discontinuities. This becomes especially important when tomographic images are used for the study of the subduction process. The imaged change in dip of a high velocity anomaly at the base of the upper mantle (Figure 4) does not necessarily mean that the subducting slab behaves in a similar way and one should be very careful in interpreting such an observation. The flattening of the anomaly in Figure 4 appeared to be an artifact of the JB reference model. The effect may be enhanced if lack of resolution occurs in directions of dominant ray illumination, which causes velocity perturbations to be "smeared out" in this direction [Spakman et al., 1989]. Reference model artifacts and lack of resolution may provide alternative explanations for the feature of slab fingering in the transition zone.

In both examples the high velocity structures extend well below the seismic zones. The occurrence of a-seismic subduction [e.g. Wortel, 1982] may have important implications for the reconstruction of the Neotectonic history of the Caribbean area. The image across the Mid American trench confirms earlier observations of lower mantle velocity anomalies below the western Caribbean Plate [e.g. Jordan and Lynn, 1974]. However, from resolution analyses it can not unambiguously be concluded that the high velocity feature is continuous across the transition zone to the site where presently the Cocos Plate subducts beneath Middle America. The lower mantle structure may tentatively be interpreted as the image of the subducted Farallon Plate [e.g. Jordan and Lynn, 1974; Grand, 1987]. If so, the broadening of the slab below the transition zone may also be explained by advective thickening due to the increase in viscosity [Fischer and Jordan, 1988]. With respect to slab penetration, one should realize that tomographic images provide us with velocity perturbations and that continuity of velocity structure does not automatically mean continuity of tectonic structures.

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