GEOPHYSICAL RESEARCH LETTERS, VOL. 11, NO. 7, PAGES 625-627, JULY 1984

A TOMOGRAPHIC IMAGE OF MANTLE STRUCTURE BENEATH SOUTHERN CALIFORNIA

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Abstract. We determined the variations in seismic structure beneath southern California by using a tomographic method of inversion on teleseismic P delays recorded with the Southern California Array. The algorithm employed was a modified form of an Algebraic Reconstruction Technique (ART) used in medical X-ray imaging. Deconvolution with an empirically estimated point spread function was also used to help in focusing the image.

The inversion reveals two prominent features beneath the region. The first is a thin, vertical wedge directly beneath the Transverse Ranges that is 2-3% faster than the surrounding region. This feature deepens to the east, attaining a maximum depth of about 250 km beneath the San Bernardino Mountains. The second feature is a major zone of low velocity material that is 2-4% slow under the Salton Trough rift valley, extending to a depth of about 125 km. Two possible explanations for the spatial association of the Transverse Ranges with the velocity anomaly below are lithospheric subduction or small-scale sublithospheric convection in the region of the Big Bend of the San Andreas Fault. The low velocity anomaly beneath the Salton Trough is consistent with convective upwelling there.

Introduction

The Southern California Array consists of approximately 200 stations distributed over a 400 by 500 km area. With this array it is possible to investigate local upper mantle and crustal structure using teleseismic P arrivals. The first such study (Hadley and Kanamori, 1977) determined that PKIKP arrivals from a single earthquake were 0.5-1.0 seconds early in the Transverse Ranges relative to other southern California stations. The anomalous region was thought to extend to a significant depth because the delay pattern extended across the surface trace of the San Andreas Fault.

Local refraction data suggested to Hadley and Kanamori that the anomalous region extends upward to about 40 km below the base of the crust. Other studies based on P arrivals by Raikes (1980) and Walck and Minster (1982) determined that the anomalous region extends to at least a few hundred kilometers in depth.

In this study, a large data set is used to construct an image of the upper mantle velocity variations beneath southern California. The upper mantle, to a depth of 500 km, is divided into blocks that are 30 x 30 km in horizontal extent and 50 km in depth. This discretization allows for significantly greater detail than did the previous studies. The inversion is done with a tomographic back-projection method. In a paper to follow, we will give a complete discussion of the tomographic method used, as well as a more detailed presentation of the results (Humphreys and Clayton, in preparation).

Paper number 4L6029.
0094-82/76/004L-6029$03.00

Data Reduction

The raw data consist of P, PKP, and PKIKP arrival times, with the direct P wave data taken from the study of Walck and Minster (1982). Approximately 200 sources generate a data set of nearly 10,000 rays. The azimuth and ray parameter of each observation are calculated from the NEIS locations using the Herrin Tables (Herrin, 1968). These data cover all azimuthal quadrants, with ray parameters in the range 0-10 sec/deg. The south and northeast azimuths, however, are not as well covered as the northwest and southeast azimuths.

To reduce the data to a set of travel time delays, several standard corrections are applied. Initial delays are calculated as differences from the Herrin Tables where both $dt/d\Delta$ and $d^2t/d\Delta^2$ corrections are used. The average delay for each source is removed to reduce the effect of errors in source parameter estimation. For the core phases, $dt/d\Delta$ was found to be consistently underestimated by the Herrin Tables. Therefore, the travel time delays for these arrivals are corrected with a nearly antipodal event (Indian Ocean; Jan. 23, 1981; $m_b = 6.1$; $\Delta = 175\ ^\circ$). This is accomplished by determining the reduction velocity that gives the closest match to the antipodal event, in a least squares sense.

A correction for variable crustal thickness is also applied. These corrections are determined from the station P_n time-terms of Hearn (1984). In general, these corrections are in the range ±0.37 sec. (The figure presented below does not have these corrections added back into the crustal layer.)

Tomographic Method

The relatively large data and model spaces used in this study (their product is $3x10^7$) make a direct least-squares inversion (c.f. Aki et al, 1977; Raikes, 1980) impractical. Instead, we use a modified back-projection algorithm similar to one used in medical X-ray imaging. This method processes the observations sequentially. Consequently it is rapid and requires storage proportional only to the model size. A drawback of this method is that the resolution matrix is not readily available. To apply the back-projection algorithm, the travel time equation is linearized by perturbing the model slownesses about a reference slowness. The reference slowness, which in this study is chosen to be a smooth decrease with depth, is used only to guide the ray paths and its precision is therefore not critical. Using this reference slowness, each ray is back-projected and a portion of the ray's observed delay is put into each block hit by the ray. The superposition of all such back-projections reconstructs an image.

Several modifications of the standard back-projection algorithm are used. First, to deal with the effects of non-isotropic ray coverage, the blocks are partitioned into azimuth and ray parameter windows which are separately averaged for slowness estimates. A final slowness for a given block is an average over the windows. This procedure tends to diminish the bias introduced by preferentially sampled ray directions. The second modification is the use of deconvolu-

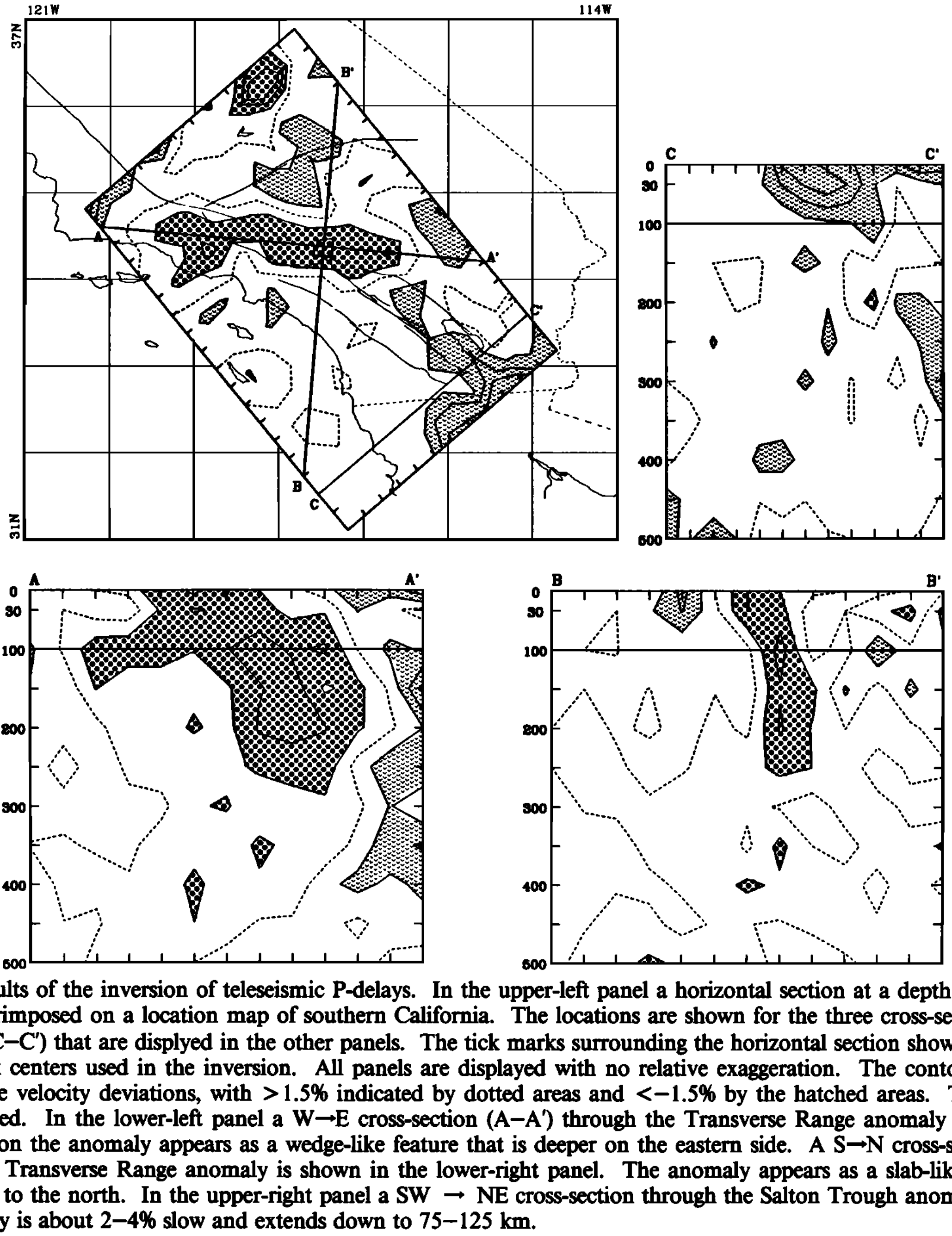

Fig. 1. Results of the inversion of teleseismic P-delays. In the upper-left panel a horizontal section at a depth of 100 km is shown superimposed on a location map of southern California. The locations are shown for the three cross-sections (A–A', B–B', and C–C') that are displyed in the other panels. The tick marks surrounding the horizontal section show the locations of the block centers used in the inversion. All panels are displayed with no relative exaggeration. The contour interval is 1.5% relative velocity deviations, with >1.5% indicated by dotted areas and <−1.5% by the hatched areas. The zero contour is dashed. In the lower-left panel a W→E cross-section (A–A') through the Transverse Range anomaly is shown. In this projection the anomaly appears as a wedge-like feature that is deeper on the eastern side. A S→N cross-section (B–B') through the Transverse Range anomaly is shown in the lower-right panel. The anomaly appears as a slab-like feature that dips slightly to the north. In the upper-right panel a SW → NE cross-section through the Salton Trough anomaly is shown. The anomaly is about 2–4% slow and extends down to 75–125 km.

tion with an estimated point spread function to decrease image blurring. This modification is similar in principle to the deconvolutional techniques used in medical X-ray imaging (Rowland, 1979). The point spread function is estimated by examining the point response of the inversion in various regions of the model domain. Finally, an iteration scheme similar to the ART method of medical X-ray imaging is applied (Herman et al., 1973). The method back-projects the difference between the observed delays and the delays predicted by the latest inverse, then uses the result to update the inverse. This can be formally related to Jacobi iteration on the linear system (Clayton, in preparation).

In the following section, two major anomalies are presented and discussed. Although the details will be given elsewhere (Humphreys and Clayton, in preparation), we have addressed the question of how well resolved these features are by computing several synthetic examples with the rays from the actual data set and the delays calculated from a known, artificial slowness structure. Also, the point spread function of a block can be used to show the ability to resolve the slowness of that block. The synthetic examples, along with the use of point spread functions determined in many regions of the model, indicate that the two anomalies shown in the next section are very well resolved in their lateral extent. Their vertical resolution is not as well defined, but it is usually within ±50 km.

Results and Discussion

Results of the tomographic inversion are shown in Figure 1. The most prominent feature is the high-velocity anomaly below the Transverse Ranges. This anomaly is a nearly vertical, slablike feature trending east-west. It is located directly below the Transverse Ranges and is deepest on the eastern side, where it extends to approximately 250 km. The anomalous region is a maximum of about 3% fast, which contrasts with the 6% fast found for the subducted slab below Japan using a much coarser block size (Hirahara, 1977). An additional data set consisting of P waves from two regional sources confirms the results of the inversion. The rays intersect the Transverse Range anomaly at moderately shallow angles, and hence show that the anomaly is primarily due to velocity heterogeneity and not to anisotropy.

A common interpretation is that the kinematics of the Big Bend of the San Andreas Fault, in conjunction with right lateral displacement, results in north-south compression. Local fault patterns and earthquake mechanisms support this interpretation (Pechmann, 1983). Bird and Rosenstock (1984), furthermore, suggest that this compression produces crustal shortening and sympathetic lithospheric subduction to accommodate the strain, thus accounting for both the Transverse Ranges and the velocity anomaly beneath. One possibility, suggested by the results of the inversion, is that the Big Bend has been developing at approximately a steady rate for the last four million years, and that relative to North America, the northern portion of the Big Bend has migrated to the west about 150 km. This would account for the offset now present in the San Andreas Fault. As the northern bend moved westward, progressively more of the north-moving Pacific Plate lithosphere would be subducted at the Big Bend. If the relative plate motion has been a constant 5 cm/yr, the result would be the creation of a wedge of subducted material below the Transverse Ranges extending down to about 250 km on the eastern side. This assumes that only one plate was subducted and that the subducted slab has not experienced vertical compression or extension.

A second possibility is that the velocity anomaly is the manifestation of a cold convective downwelling beneath the Transverse Ranges. In this interpretation, the (viscous) base of the thermal lithosphere has undergone a convective instability, resulting in a localized downwelling. The sinking of this high density material produces a circulation that, in turn, drives the lithosphere towards the Transverse Ranges. In this view, convergence at the Transverse Ranges and formation of the Big Bend is due to active mantle processes rather than horizontal "plate forces" within the lithosphere. Some observations in support of this interpretation over the subducted slab model are the lack of subcrustal seismicity beneath southern California and the small amplitude of the velocity anomaly, suggestive of temperature contrasts of only a few hundred degrees.

The Salton Trough anomaly has a straightforward interpretation based on its geologic setting. The Salton Trough is a rift basin, as well as the northern terminus of the East Pacific Rise (Elders et al., 1972). Figure 1 shows that, relative to the rest of southern California, there is indeed a pronounced region of low velocity material below the Salton Trough. This anomaly, in agreement with the study of Raikes (1980), is mainly confined to depths shallower than 125 km, although there is a suggestion in Figure 1 that a thin zone of low velocity material continues to a much greater depth. This feature may be real, but because of the sparsity of rays in this region, it is also possible that the feature is simply an artifact of the inversion.

The presence of low-velocity, and presumably low-density material beneath the Salton Trough would produce local upwelling, tending to maintain and reinforce the convective downwelling proposed below the Transverse Ranges. The greater depth extent of the eastern part of the Transverse Range anomaly may be due to its proximity of the Salton Trough. It may also be possible that the opening of the Gulf of California about 5 my ago initiated the proposed convective flow, and that the downwelling below the Transverse Ranges was is natural result of the rifting (Humphreys and Hager, 1984). We will develop the convective model further in another paper (Humphreys and Hager, in preparation).

Acknowledgements. We thank Sue Raikes for providing most of the teleseismic direct P wave data used in this study, and Marianne Walck for the regional P wave data. Tom Hearn kindly made available his P_n time-term results. This work was supported under USGS contract #14-08-0001-21210 and NASA contract NAG-5315. Contribution #4022, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125.

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(Recieved January 18, 1984;
revised March 15, 1984;
accepted March 16, 1984.)