GEOPHYSICAL RESEARCH LETTERS, VOL. 7, NO. 5, PAGES 345-348, MAY 1980

LARGE SCALE THREE DIMENSIONAL P VELOCITY STRUCTURE BENEATH THE WESTERN U.S. AND THE LOST FARALLON PLATE

Barbara A. Romanowicz

Department of Earth and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Mass. 02139 and Institut de Physique du Globe de Paris, 4 Place Jussieu, Tour 14,75230 Paris Cedex 05, France

Abstract. The results of a recent large scale three-dimensional study of P velocity beneath North America are analyzed from the point of view of the search for the fossil Farallon plate in the mantle beneath the western edge of the North American continent.

The large scale velocity structure obtained in the western U.S. is compatible with independent finer scale seismic studies and suggests that the Farallon plate can be traced to depths of 300 to 450 km along the entire North-South extent of the area. At greater depth, no clear evidence is found for its presence: it has either not reached it or is no longer distinguishable from the surrounding mantle.

On the basis of the 3-D velocity study we also venture to predict that, whereas in the central and southern part of the western U.S. the top of the plate seems to have sunk to depths in excess of 200 km, it should still be present at shallower depths beneath the Northwestern region. This is in agreement with the progressive migration to the North of the Mendocino transform-transform-trench triple junction and its present day position.

Introduction

According to the tectonic history of the Pacific margin of the North American continent, the present triple junction/transform fault regime was initiated about 10 to 20 million years ago (Atwater, 1970). At that time, a ridge trench collision caused the Farallon plate, (formerly separating the Pacific plate from the North American plate) to disappear under the North American continent. If any remains of this hypothetical fossil plate are still present in the mantle, the study of lateral variations of seismic velocities in the western United States should provide a means of locating them.

Indeed, studies of the azimuthal variation of teleseismic P travel times have shown evidence for an elongated zone of earlier arrivals (high velocities) roughly parallel to the Pacific coast, and originating in the mantle. This has been observed in central and northern California (Otsuka, 1966; Nuttli and Bolt, 1969; Solomon and Butler, 1974), as well as in northern Nevada (Koizumi et al., 1973). Although these observations can be interpreted as due to variations of thickness of the upper mantle low velocity zone (Nuttli and Bolt, 1969), they are compatible with an interpretation in terms of the presence of the dead subducted plate (Koizumi et al., 1973; Solomon and Butler, 1974). More recently, a three-dimensional study of P velocities beneath central California to a depth of 225 km (Cockerham and Ellsworth, 1979; 1980) extending earlier studies (Husebye et al., 1976; Zandt, 1978), has provided a more detailed picture of the P velocity structure under this particular part of the western United States. It has revealed, in particular, the existence of a NW-SE trending, east dipping low velocity body, which, under the Sierra Nevada, reaches a depth of 200 km. This has been interpreted in terms of the "slab-window" model (Dickinson and Snyder, 1979), whereby the void left behind by the Farallon plate, as it sunk into the mantle, has been filled by low velocity asthenospheric material.

In this paper, we first review the results of a large scale three-dimensional inversion of teleseismic P travel times in North America (Romanowicz, 1979a,b). This study yielded large scale velocity anomalies in the mantle, down to a depth of 700 km and showed their relation to the main tectonic features of the continental United States. We then analyze the results obtained for the part of the United States situated roughly west of longitude 105°W, from the point of view of the search for the dead Farallon plate.

Large-Scale 3-D Structure Under the Western U.S.

The large scale three-dimensional inversion was preformed using P wave arrival times to North American stations, as given by the ISC bulletins for the ten year period 1964-1973, and adapting the original 3-D velocity modelling method of Aki et al. (1977). A detailed description of the data and modelling is given in our earlier paper (Romanowicz, 1979a). Three layers of thickness 200 to 250 km divided into 5° by 5° blocks were resolved in the depth range 0 to 700 km. A series of models was generated, modifying input parameters such as initial velocity model, amount of data, block boundaries, thicknesses and number of layers. Although values of velocity anomalies for individual blocks showed some variation from model to model, the large scale pattern of low and high velocities as well as their average magnitude remained stable. The common features of all the models are presented in Figure 1, where we have shown the results for the entire United States as the inversion method yields velocity anomalies relative to the average velocity in each layer. These anomalies are here expressed in % of the average velocity in each layer and given for the most stable blocks. The regions of consistently negative or positive velocity anomalies are delineated by contours. The western United States, where the density of stations is largest, shows the most stable

Copyright 1980 by the American Geophysical Union.

Paper number 80L0329.
0094-8276/80/0080L-0329$01.00

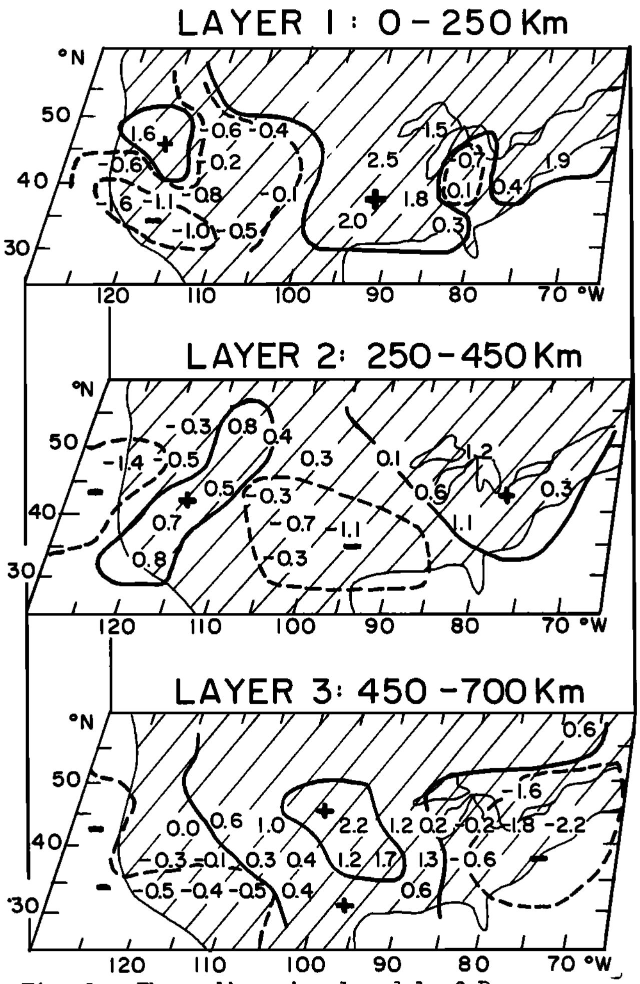

Fig. 1. Three-dimensional model of P wave velocities beneath North America. Velocity anomalies are given for the most stable blocks in % of average P-velocity in the layer. Contours indicate regions of constantly positive or negative velocity anomalies.

results and their reliability is reflected in the values of the resolution for the corresponding blocks, given in Figure 2 and of the standard deviations in the model parameters, given in Figure 3 and expressed in % of average velocity in the layer.

As can be seen in Figure 1, in the first layer (depth range 0 to 250 km), two regions can be distinguished in the western United States. To the North (latitude 45° to 50°N, longitude 115° to 125°) a region of high velocity spreads out towards the East, decreasing in magnitude in this direction. To the South, beneath California and roughly the Basin and Range province, there is a region of low velocities which also decrease in magnitude towards the East. All the features described so far are significantly above the standard deviations, as can be seen from Figure 3. It is important to bear in mind that, given the large size of blocks in this study, the results represent averages of velocity anomalies over very large volumes, so that one would expect a smearing out of the structure to accomodate the imposed boundaries of the blocks. In particular, the velocity contrasts are expected to be smaller than in a more localized, smaller scale study.

The overall low velocities obtained in the southwestern United States (latitude 30° to 35°N) are compatible with other results obtained in the Basin and Range province, in particular the low P and PL velocities found by York and Helmberger (1973) and the evidence for a well-developed upper mantle low velocity zone (Archambeau et al., 1969; Wiggins and Helmberger, 1973). The central California area studied by Cockerham and Ellsworth (1979; 1980) would fit into this first layer and roughly into the block situated between latitude 35° to 40°N and longitude 120° and 125°W, where the velocities are lowest in our model. The results of both studies are thus compatible, and the eastward decrease in magni-

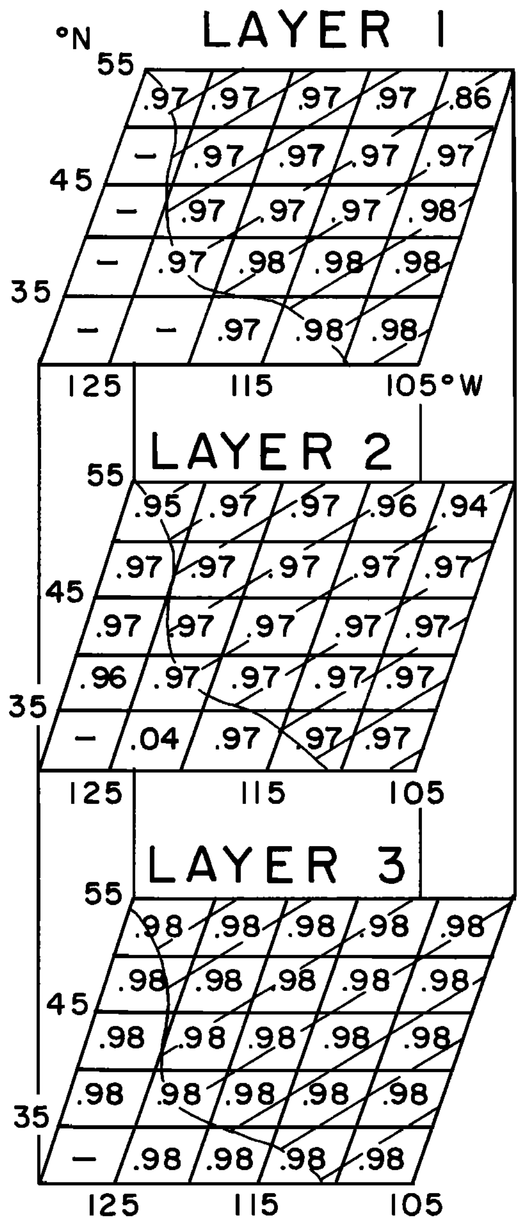

Fig. 2. Diagonal elements of the resolution matrix for the 3D inversion beneath North America: only blocks corresponding to the western U.S. are shown.

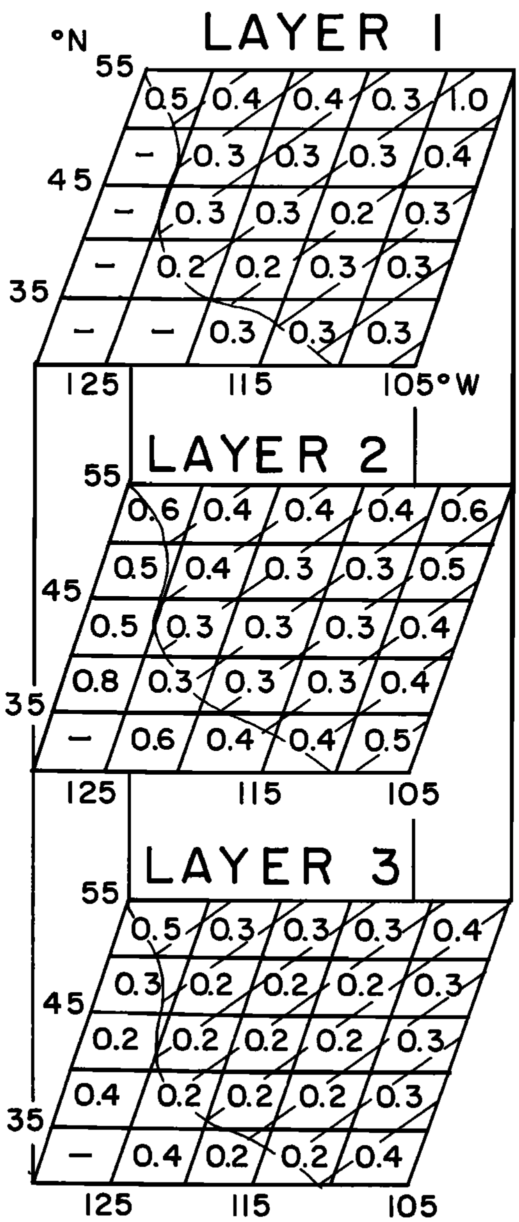

Fig. 3. Standard deviations in the model parameters for the 3-D inversion beneath North America. The standard deviations are expressed in % of average P-velocity in each layer and are shown here for the western U.S.

tude of the low velocities in the large scale study would correspond to the displacement of the low velocity body to greater depths towards the East (Cockerham and Ellsworth, 1979, 1980). The particularly high velocities in the Northwest, as well as their spreading out towards the East with a loss of magnitude are compatible with the travel time studies (Solomon and Butler, 1974), and the interpretation in terms of the east dipping Farallon plate.

In the second layer (depth range 250 to 450 km), the large scale study shows an elongated region of higher velocities which encompasses the whole North-South extent of the United States (Figure 1). It is displaced by about 300 to 500 km to the East, as compared to the region of high velocities in the Northwestern part of the first layer. The velocity contrasts, while still significantly above standard deviations (Figure 3), show less contrast with respect to the surrounding mantle. In the third layer (depth range 450 to 700 km), the velocity anomalies west of 105° to 110°W appear to have evened out and do not exhibit any distinct structure, while the high velocities beneath the central part of the United States appear to belong to a much larger scale unit (Romanowicz, 1979a) which we shall not discuss here.

A tentative interpretation of the above features, in the deep layers beneath the western United States, has been proposed in terms of the presence of the dead Farallon plate (Romanowicz, 1979b). The region of high velocities in the second layer would represent a continuation of the high velocities in the Northwest, marking the location of the fossil plate, plunging towards the East, down to a depth of at least 300 to 400 km, but no longer distinguishable from the surrounding mantle below a depth of 450 km. The zone of high velocities in the second layer appears to be about 500 to 600 km wide, which can hardly correspond to the thickness of a lithospheric plate, but can be accounted for by a combination of two effects. The velocity anomalies tend to be smeared out, as mentioned before, to accomodate the boundaries of the blocks, and also, the cold plate may have a cooling effect on the mantle around it, causing the velocities to somewhat increase in the vicinity of the plate, thus broadening the zone of high velocities.

The 3-D velocity pattern in the western U.S. can now be discussed in the framework of current plate tectonics schemes proposed for that region (Atwater and Molnar, 1973; Stewart, 1978) and the "slab window" model (Dickinson and Snyder, 1979). Since the encounter of the East Pacific Rise with the North American plate, subduction has ceased along the San Andreas fault, which has developed between two migrating triple junctions (Atwater and Molnar, 1973). We shall be interested in particular in the Mendocino triple junction, situated at roughly 40°N, North of which the small Juan de Fuca plate is still being subducted beneath the North American continent.

The high velocities observed in our 3-D study in the Northwestern United States are compatible with the presence, near the surface, of a subducting slab. In our study, the transition from high to low velocities is situated between 40 and 45°N, the poor resolution of boundaries of contrasted regions accounting for the imperfect agreement with the position of the Mendocino triple junction. To the south of 40°N, the low velocities in the first layer indicate that the former slab must have sunk deeper into the mantle. Its top is now separated from the continental lithosphere by low velocity material which may have originated simply from the subduction of a portion of the East Pacific Rise, or, by a different mechanism, from the filling up of the void left by the sinking plate with asthenospheric material (Stewart, 1978).

Dickinson and Snyder (1979) recently proposed a model for the geometry of this void According to them, it would be an expanding triangular "window" dipping along the dip of the subduction and one side along the San Andreas fault. These authors propose that the triangle be isosceles with one of the equal sides along the San Andreas fault. It is to be noted that the zone of high velocities in the second layer of our 3-D study seems to extend beneath the coast of southern California. Taking into account the spread of velocity anomalies to accomodate the boundaries of blocks, this would still imply a somewhat more complicated geometry for the slab window. The triangle could no longer be isosceles and would expand much faster in the direction of the San Andreas fault than perpendicular to it. The ridge subduction hypothesis might thus still be a simpler explanation for the low velocities obtained in southwestern U.S.

Conclusion

Our large scale 3D velocity model suggests that the dead Farallon plate can be traced to depths of about 300 to 400 km in the mantle beneath the western United States, but probably not any deeper. In the first 250 km of the mantle, while it may have been replaced in the region of central California, by low velocity material from the ridge which produced it, it would indeed still be present at shallow depths beneath the northwestern part of the United States, where subduction is said to be still active.

A finer scale three-dimensional study conducted in the Northwest, in the same fashion as for central California, with a dense network of stations, should make it possible to delineate the slab more precisely in the depth range 0 to 250 km, this time indeed as a high velocity body.

Acknowledgements. I wish to thank Professor Aki for showing me the results of the central California study by Cockerham and Ellsworth, before their publication, and I am grateful to Rob Cockerham and Bill Ellsworth for allowing me to make reference to their work. This study was conducted under partial support of NSF grant 77-13632 EAR and of C.N.R.S., France.

References

Aki, K., N. Christofferson, and E. Husebye, Determination of the three dimensional structure of the lithosphere, J. Geophys. Res., 82, 277-296, 1977.

Archambeau, C.B., E.A. Flinn, and D.G. Lambert, Fine structure of the upper mantle, J. Geophys. Res., 74, 5825-5865, 1969.

Atwater, T., Implications of plate tectonics for the Cenozoic tectonic evolution of western North America, Bull. Geol. Soc. Am., 81, 3513-3536, 1970.

Atwater, T. and P. Molnar, Relative motion of the Pacific and North American plates deduced from sea-floor spreading in the Atlantic, Indian and South Pacific Oceans, in Proc. Conf. Tectonic Problems of the San Andreas Fault System, eds. R.L. Kovach and A. Nur, Stanford Univ. Publ., Geol. Sci., 13, 136-148, 1973.

Cockerham, R.S., and W.L. Ellsworth, Three-dimensional large scale mantle structure in Central California, E.O.S. Trans. A.G.U., 60, 875, 1979.

Cockerham, R.S. and W.L. Ellsworth, Remnants of the subduction process in the mantle beneath Central California, Seis. Soc. Am., 80, Abstract, 1980.

Dickinson, W.R. and W.S. Snyder, Geometry of subducted slabs related to the San Andreas transform, submitted to J. Geophys. Res., 1979.

Husebye, E.S., A. Christofferson, K. Aki, and C. Powell, Preliminary results on the three-dimensional seismic structure of the lithosphere under the USGS central California seismic array, Geophys. J.R. astr. Soc., 46, 319-340, 1976.

Koizumi, C.J., A. Ryall, and K.F. Priestley, Evidence for a high velocity lithosphere plate under Northern Nevada, Bull. Seis. Soc. Am., 63, 2135-2146, 1973.

Nuttli, O. and B.A. Bolt, P wave residuals as a function of azimuth. 2 - Undulations of the mantle low velocity layer as an explanation, J. Geophys. Res., 74, 6594-6602, 1969.

Otsuka, M., Azimuth and slowness anomalies of seismic waves measured on the central California seismographic array, Part II Interpretation, Bull. Seism. Soc. Am., 56, 655-675, 1966.

Romanowicz, B.A., Seismic structure of the upper mantle beneath the United States by three-dimensional inversion of body wave arrival times, Geophys. J.R. astr. Soc., 57, 479-506, 1979a.

Romanowicz, B.A., Ondes de volume et structure tridimensionelle du manteau superieur: le cas des Etats-Unis d'Amerique, These d'Etat, Univ. Paris 7, France, 1979b.

Solomon, S.C., and R.T. Butler, Prospecting for dead slabs, Earth Planet. Sci. Lett., 21, 421-430, 1974.

Stewart, J.H., Basin and range structure in western North America, in Smith, R.B. and Eaton, G.P., eds., Cenozoic tectonics and regional geophysics of the western Cordillera, Geol. Soc. Am. Mem., 152, 1-32, 1978.

Wiggins, R.A. and D.V. Helmberger, Upper mantle structure of the Western United States, J. Geophys. Res., 78, 1870-1880, 1973.

York, J.E., and D.V. Helmberger, Low velocity zone variations in the Southwestern United States, J. Geophys. Res., 78, 1883-1886, 1973.

Zandt, G., Study of three-dimensional heterogeneity beneath seismic arrays in central California and Yellowstone, Wyoming, Ph.D. Thesis, M.I.T., Cambridge, MA, 1978.

(Received February 28, 1980;
accepted March 10, 1980.)