GEOPHYSICAL RESEARCH LETTERS, VOL. 20, NO. 21, PAGES 2371-2374, NOVEMBER 5, 1993

SEISMIC DISCONTINUITY AT THE TOP OF D": A WORLD-WIDE FEATURE ?

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Abstract. Considering the growing number of observations of a seismic discontinuity at the top of D", some 300 km above the core-mantle boundary, we investigate the scenario of whether this feature could be global. We show that the mean first arrivals of P-waves, as used to build global models, can be fit by the two branches of a discontinuous model. We argue that the intermittence of the detection of the reflector is due to lateral variations of a global discontinuity. These observations put strong constraints on the type of chemical layering that could explain the discontinuity. We speculate that the properties of the D" discontinuity are better explained in terms of a new phase transition.

A wide-spread discontinuity

Ten years ago, Lay & Helmberger (1983) showed evidence from S waves for a seismic discontinuity, some 300 km above the core-mantle boundary (CMB), at the top of D". Since then, the discontinuity has been searched for in many places, with both P and S waves, at short and long periods. Of course, the discontinuity has not been found everywhere (e.g. Schlittenhardt et al., 1985; Vidale & Benz, 1992, 1993), and we will get back to this, but it has now been observed in many different regions, and by various authors, as shown in Figure 1. In most cases, the evidence comes from observing, at epicentral distances 76-82°, a secondary arrival between P (S) and PcP (ScS), whose move-out with epicentral distance is also intermediate between that of those two waves. Traditional global models, such as PREM (Dziewonski & Anderson, 1981), iasp91 (Kennett & Engdahl, 1991), and SP6 (Morelli & Dziewonski, 1993) do not predict any such secondary arrival. It is best explained by models in which velocity increases rather abruptly with depth by 2-3%, some 250-300 km above the CMB. Figure 2a compares a model of this kind, here the PWDK P-velocity model of Weber & Davis (1990), with a traditional global model, here PREM.

Matching first arrival times

At first sight, it seems difficult to reconcile the two structures proposed so far: in PREM, the D" layer is characterized by "lower-than-adiabatic" velocities, while in PWDK it is marked by an abrupt velocity increase. In global models, the main constraint on the velocity structure at the base of the mantle stems from the average arrival time of first arrivals as a function of distance. In Figure 2b, we have drawn the mean first P-arrival data used to derive PREM. Of course PREM fits these data points very well. In particular, the pronounced decrease of $p=dT/d\Delta$ for Δ beyond 85° is the reason for the low velocity gradient in D" found for this model. More interesting are the continuous lines drawn in Figure 2b: they represent the two travel-time branches (direct and transmitted) computed for the PWDK model. Quite surprisingly, the mean first arrivals are very well matched by this model. However, PWDK was not meant as a global model: it was proposed by Weber & Davis (1990) to explain P secondary arrivals for bounce points on a small spot of D" beneath Northern Siberia. We are not proposing that it is a good global model, but we are pointing out that a class of models with a velocity jump some 300 km above the CMB, as suggested by many observations of secondary arrivals, should be considered when building global models. We further speculate that it is likely that models with a D" discontinuity can fit the travel times of first arrivals as well as current global models.

Intermittent detection of the discontinuity

The main reason why the discontinuity at the top of D" is usually thought not to be a global feature, is that its detection is often intermittent. Striking examples of this intermittence are found in Weber (1993) and Vidale & Benz (1993). It is then tempting to connect the presence (absence) of detection with the presence (absence) of the discontinuity, and conclude that the discontinuity is rather discontinuous. While we think this line of thinking is perfectly reasonable, we are disturbed by the following points: i) even though we observe a large intermittence in our own detection at individual stations for individual events, the global trend given by all positive detections shows a great coherency over the whole region we sample beneath Northern Siberia (Houard & Nataf, 1993). ii) Similarly, on both sides of a clear "hole of detection", Weber (1993) finds reflections from a similar-looking discontinuity. iii) Also, it seems that the larger the period of the wave, and the spacing of the stations, the larger the region of "coherent reflections" (Weber, 1993; Houard & Nataf, 1993; Gaherty & Lay, 1992). iv) Finally, there are now several examples where, for a given D" region, the effect of the discontinuity is seen on long-period S seismograms, while not observed with short-period P waves, as discussed by Gaherty & Lay (1992), and Vidale & Benz (1992). The detectability of the discontinuity depends on many local factors, such as its topography (Weber, 1993), its thickness and velocity contrast, in addition to observational conditions, such as noise level, source complexity, and epicentral distance. Therefore, we are inclined to think that the intermittent detections we referred to are better explained by a widespread discontinuity with laterally varying local properties. We should point out that intermittence is often observed for accepted global discontinuities, such as the Moho, 410 and 660 km, and even the CMB (see Benz & Vidale, 1993, for a beautiful example of intermittence of the

Paper number 93GL02686
0094-8534/93/93GL-02686$03.00

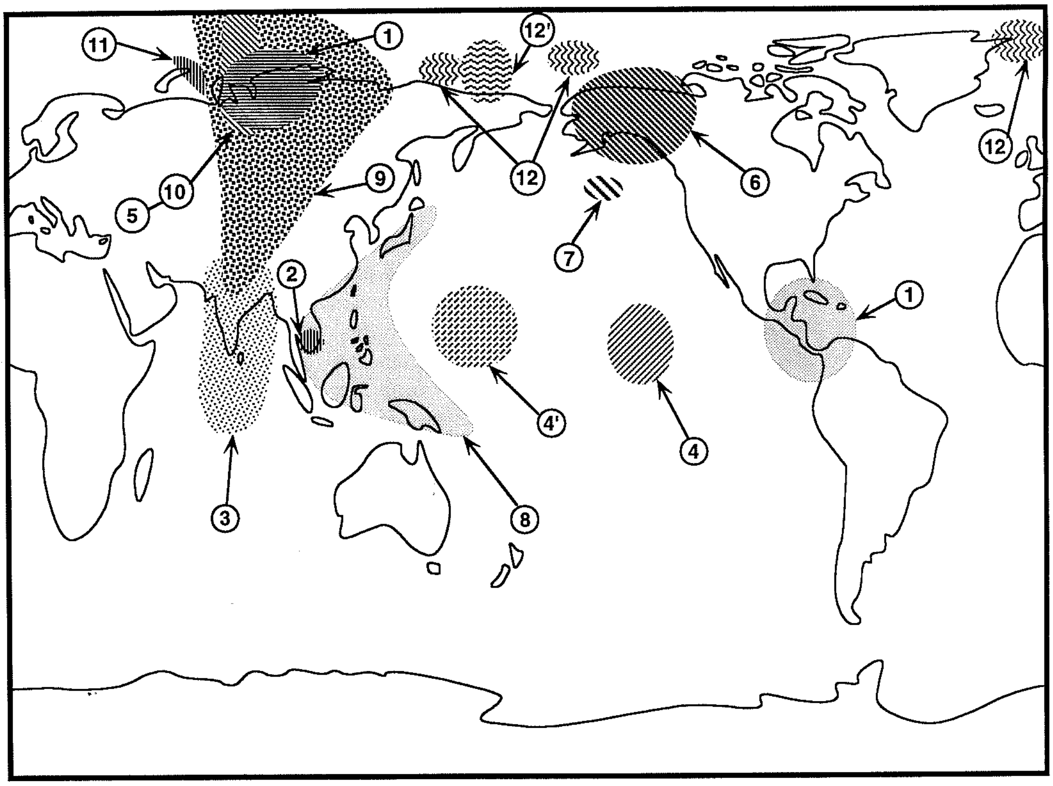

Fig. 1. World map representing different areas of D" for which a discontinuity has been looked for. Each area is referred to by a number. Right of the numbers are the corresponding authors' names, date of study and type of data used (*LP* = long-period - *SP* = short-period - *BB* = broad-band). Reflection points for the study by Baumgardt (1989) (*SP* P) are not drawn. They would plot in northern Siberia mostly. In almost all studies, a discontinuity at the top of D" is needed to explain the data. The exceptions are Vidale & Benz (1992), and the patches of Vidale & Benz (1993) with an unprimed number.The discontinuity is seen for only one third of the paths in Revenaugh & Jordan (1991). The discontinuity is found closer to the CMB in the primed patches of Vidale & Benz (1993) and Garnero et al. (1993). Michael Weber (personal communication, Sept. 1993) pointed out to us that the published bounce points in Vidale & Benz (1993) were incorrect. The ones we draw have been recomputed.

1 : Lay & Helmberger (1983) - *LP* SH.
2 : Wright et al. (1985) - *SP* P.
3 : Young & Lay (1987) - *LP* SH.
4 : Garnero et al. (1988, 1993) - *LP* S, SKS, SKKS.
5 : Weber & Davis (1990) - *BB* S & P.
6 : Young & Lay (1990) - *LP* S, sS, SKS, SKKS.
7 : Vidale & Benz (1992) - *SP* ScP.
8 : Revenaugh & Jordan (1991) - *LP* ScS.
9 : Gaherty & Lay (1992) - *LP* SH.
10 : Weber (1993) - *BB* S, P, pP.
11 : Houard & Nataf (1992, 1993) - *SP* P.
12 : Vidale & Benz (1993) - *SP* P.

410 km discontinuity as seen by P'P' precursors).

Chemical pools ?...

Figure 3 shows a layer of chemically denser material in a convecting system representing the lower mantle (Hansen & Yuen, 1989). The layer could be due to the 'sedimentation' of oceanic crust that transformed into eclogite (U.R. Christensen & A.W. Hofmann, submitted to JGR, 1993). The layer is discontinuous, with pools of dense material forming beneath hot uprising currents. This peculiar geometry was one of the reasons for seeing in an intermittent D" discontinuity the top of a chemically distinct layer. With the new evidence for a rather global D" discontinuity, the analogy is less appealing. Weber (1993) shows that syncline-like structures with slopes as gentle as 3 degrees are enough to defocus D"-reflected waves, so as to make them invisible. In addition, the discontinuity can be followed on distances as large as 1500 km (Gaherty & Lay, 1992), with only small depth variations. Finally, the regions where the discontinuity is found do not seem to be restricted to 'hot regions' of the deep mantle. It is therefore quite unlikely that seismologists have detected pools of denser material of the kind shown in Figure 3. While such pools might exist, they would be very difficult to detect seismologically (also see Jeanloz, 1991). If the D" discontinuity is a chemical boundary, the present seismological observations put strong constraints on the type of chemical layering allowed. Indeed, evidence is for a rather flat and thick global layer. The interface in Figure 3 has a very large topography. One way to reduce it is to increase its density contrast with the lower mantle. Values as large as 5% are then probably needed. Together with the 3% velocity contrast, this would produce a rather strong impedance contrast. It is not sure that this is compatible with the reported scarceness of detection in small incidence reflection studies (Revenaugh & Jordan, 1991).

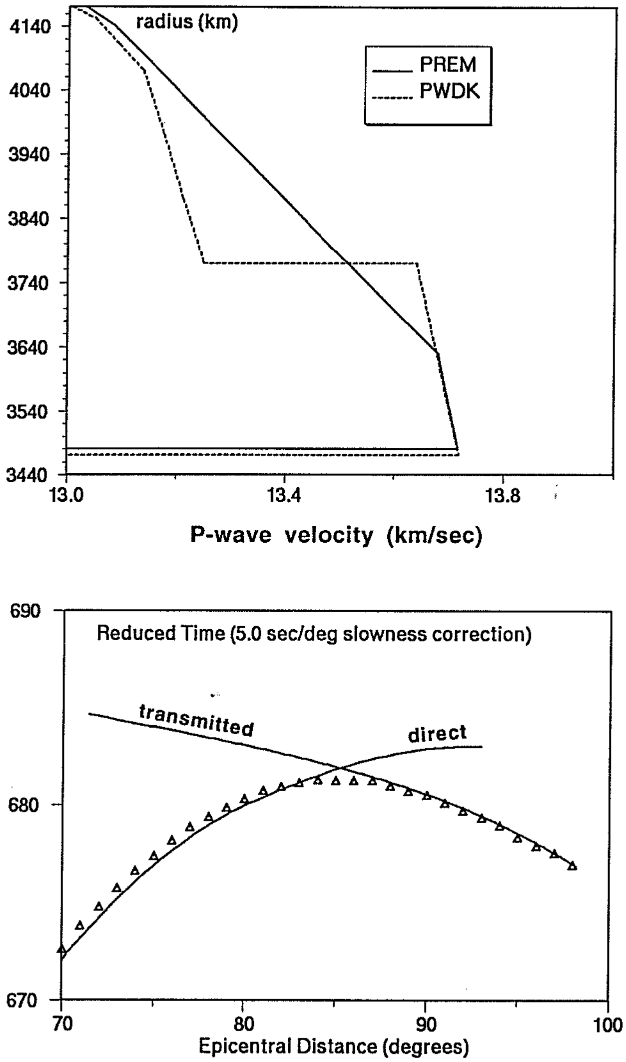

Fig. 2. a) P velocity distributions in the lowermost mantle. PREM is the Preliminary Reference Earth Model of Dziewonski & Anderson (1981). PWDK is the D" model derived by Weber & Davis (1990). A 3% P velocity discontinuity is present at a radius of 3770 km.

b) Travel times for direct P-waves sampling the lowermost mantle. The data points are 1° interval mean travel times used to invert global Earth model PREM. The continuous lines are the travel-time branches computed for the PWDK model.

...or a new phase transition ?

At this stage, we should point out that, in our view, the D" discontinuity shares many properties with the other discontinuities in the mantle: it is global, rather flat, with a velocity contrast of a few percents, and shows some lateral variability. It is then tempting to propose a common origin for all: a phase transition. No major phase transition has been found for perovskite/magnesiowüstite at lower mantle conditions. However some structural change of the perovskite mineral has been discovered recently (Wang et al., 1992). It is not clear yet that such a change occurs in the lower mantle, at the appropriate depth, nor that it can produce a 3% velocity increase, as suggested by the seismological observations. Nevertheless, this an important track to be followed. Incidently, mapping this transition could help constraining temperatures in the lower mantle. Seismological observations suggest a topography of +- 50 km for the discontinuity (Gaherty & Lay, 1992; Houard & Nataf, 1993). It is somewhat larger than the inferred topography of the 410 and 660 km discontinuities. This could indicate a larger Clapeyron slope. This, in turn, would lead to important dynamic effects. At present, it is not clear what the sign of the Clapeyron slope should be. One difficulty with the phase transition hypothesis, is the observation, in a few regions, of the D" discontinuity at a depth much closer to the CMB. Vidale & Benz (1993) show convincing evidence for a discontinuity some 130 km only above the CMB, while Garnero et al. (1993) need a smeared discontinuity about 180 km above the CMB. If these all have a common origin, and are due to a phase transition, this would require a very large Clapeyron slope. An alternative is that we need not one but two new phase transitions ! Indeed, Gaherty & Lay (1992) report evidence for a double discontinuity, with velocity jumps at 160 km and 300 km above the CMB.

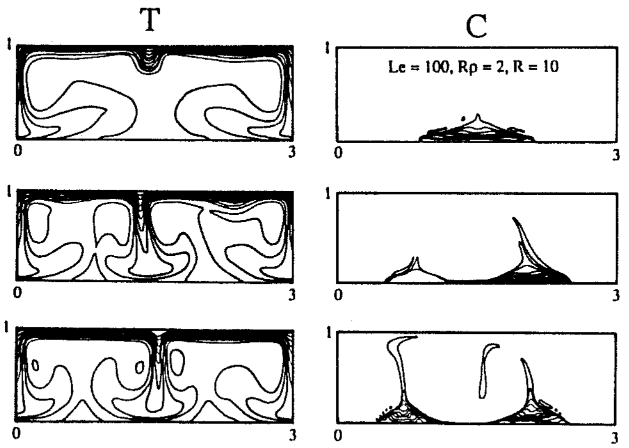

Fig. 3. Interaction of a 100 km thick dense layer at the base of the mantle with thermal convection. Rayleigh number is 10^5. The left panels (T) show the temperature distribution for non-dimensional times of 0.01, 0.03 and 0.05. The right panels (C) show the evolution of the chemical anomaly. The initial dense horizontal layer is swept by the convective currents, accumulates near the center of the cell, and separates into two distinct pools. From Hansen & Yuen (1989).

Conclusion

Lay & Helmberger (1983) were the first to propose a seismic discontinuity at the top of D" as a global feature. Ten years later, we point out several elements that give credit to their original suggestion.

1) The discontinuity has been found in many places around the world, for both P and S waves, at short and long periods.

2) The triplicated branches of a discontinuous model, such as PWDK, fit the first arrivals of P waves, as well as present global models, which display on the contrary a "lower-than-adiabatic" velocity in D".

3) The intermittence of the detection of the discontinuity is better explained by lateral variations of its properties (topography, thickness, contrast), rather than by the

intermittence of its existence.

We discuss two scenarios for the origin of the D" discontinuity: chemical or physical. Present seismological observations put constraint on these two possible cases:

1) If the D" discontinuity is the top of a chemically distinct layer, this layer does not resemble the discontinuous chemical pools predicted by convective models. On the contrary, a global and rather flat layer is needed. This suggests that the density contrast across the discontinuity should be larger than commonly assumed.

2) Because many of the features of the D" discontinuity are similar to those of other discontinuities in the mantle, a common origin is plausible. One then needs a new phase transition in the lowermost mantle. Lateral variability of the discontinuity suggests a large Clapeyron slope.

Acknowledgements. This work was supported by CNRS-INSU "Tomographie". We thank two anonymous reviewers for useful comments. ENS-Géologie contribution # 277.

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(Received July 8, 1993;
accepted July 29, 1993.)