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REGIONS OF SEISMIC WAVE SCATTERING IN THE EARTH'S MANTLE AND PRECURSORS TO PKP

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ABSTRACT

The characteristics of precursors to PKP as analyzed at the Norwegian Seismic Array give evidence for the existence of scattering structures, situated at a wide range of depths in the lower mantle.

INTRODUCTION

Observational limits usually prevent the resolution of irregular structures acting as seismic wave scatterers. The scattered energy will be relatively small and it will, generally, be masked by the coda of the primary wave. Special conditions, though, may be present in seismic shadow zones. The major shadow zone in the earth is formed by the presence of the core. In the most simple core model, phases, travelling through the outer core (PKP_1 and PKP_2) form a caustic surface which intersects the core-mantle boundary and the earth's surface at epicentral distances of about 117.5^o and 143^o respectively. At the earth's surface a shadow zone is formed from 143^o down to about 100^o.

This shadow is only with respect to PKP_1 and PKP_2 and later phases still arrive, of which PKIKP, the phase which is refracted through the inner core, is the first to be expected. Therefore, the observation of precursors to PKIKP in the approximate distance range 125^o-143^o has since long caused confusion and interpretations in terms of more complicated core models have been put forward. A discussion has been given by Doornbos and Husebye[1)], in the light of data in a limited distance range from the Norwegian Seismic Array (NORSAR).

More recently Haddon[2] and Cleary and Haddon[3] proposed precursors to represent scattered waves from the lower 200 km of the mantle (the D"-layer of Bullen). The precursors then would originate at the intersection of this scattering layer and the caustic surface, thus ensuring a large primary wave field. This would imply time-distance curves for precursors with a minimum travel time at 117.5°. The proposed mechanism is both attractive and plausible, though not strongly supported by the data presented. These data are substantially the same as those used before to support other hypotheses. In particular, no new evidence is presented that will rule out any of the following possibilities:

(1) Energy diffracted from the caustic as predicted theoretically by Jeffreys[4] and Scholte[5] is present in a limited distance range near the caustic.

(2) Scattering is not necessarily confined to the D"-layer, but can set in also in other parts of the mantle near the caustic surface.

(3) Scattering occurs in the lower mantle under the source region. A scattering structure, acting as a secondary radiator, then forms a caustic at the surface in the shadow zone. Near this point the focusing effect will thus advance the observability of a precursor. Fig. 1 (which is a similar figure as given in Ref. 3) illustrates the scattering as a cause of precursors.

In this paper evidence will be presented for the simultaneous existence of the several possibilities. Also the location of some specific scattering regions will be determined. The results are based on NORSAR data which have been subjected to a spectral analysis method which extracts detailed information. An outline of the method is given in this paper. A more detailed description will be presented elsewhere.

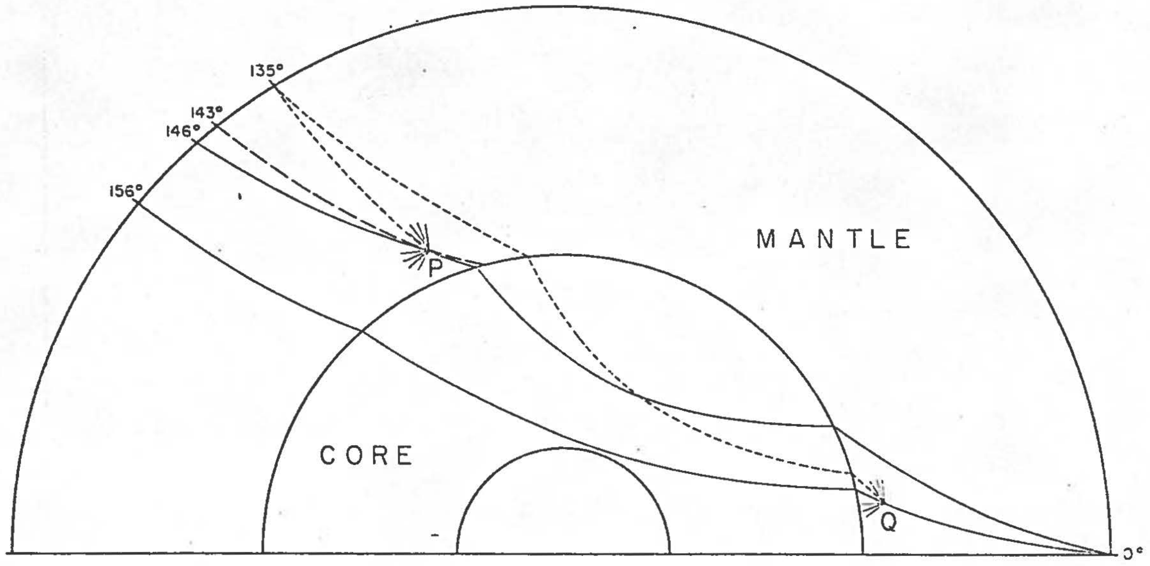

Fig. 1 Schematic picture of generation of precursors (here at 135° from the source), with direct PKP rays (———) scattered rays(-----) and the caustic in the mantle (— — — —). In P: Scattering from the caustic surface. In Q: Scattered rays form a "secondary" caustic which cuts the earth's surface at 135°.

ARRAY-SPECTRAL ANALYSIS OF BODY WAVES

The use of a seismic array to extract characteristic signal parameters as the slowness $dT/d\Delta$ and the azimuth of the direction of wave propagation, is well established. For signals which can be regarded as representing a stationary process, such information is often obtained from a frequency-wavenumber analysis, e.g. in a way as demonstrated by Smart and Flinn[6)] for acoustic gravity waves. They constructed so-called slowness- and azimuth spectra by adding to every given frequency slice the polar coordinates $dT/d\Delta$ and azimuth of the maximum in the corresponding wavenumber plane. We have used a similar procedure, taking into account the character of short-period body waves. This will require minimization of the noise and the energy in the coda of the signal, and corrections for wavefront deformations due to the local structure under the array. Figs. 2 and 3 give the spectra for some representative examples of precursors. The reliability curves in these figures are indispensable in appreciating the results. They are based on the ratio of the maximum power in the wavenumber plane and the total power at the given frequency, thus determining a value in dB. The 4 dB level has been found to be a stable "detection threshold".

For the purpose of this paper this spectral analysis method has two advantages over the conventional "broadband" techniques. Firstly the solution can always be based on the frequency interval with maximum signal-to-noise ratio, which is especially important in the case of weak signals. Secondly interfering signals sometimes can be separated on the basis of a different frequency content. Figs. 2 and 3 illustrate both points. On the other hand, this method may sometimes obscure interfering signals whose dominant frequencies are not sufficiently different. Especially in these cases methods as described in Ref. 1 will provide the supplementary information.

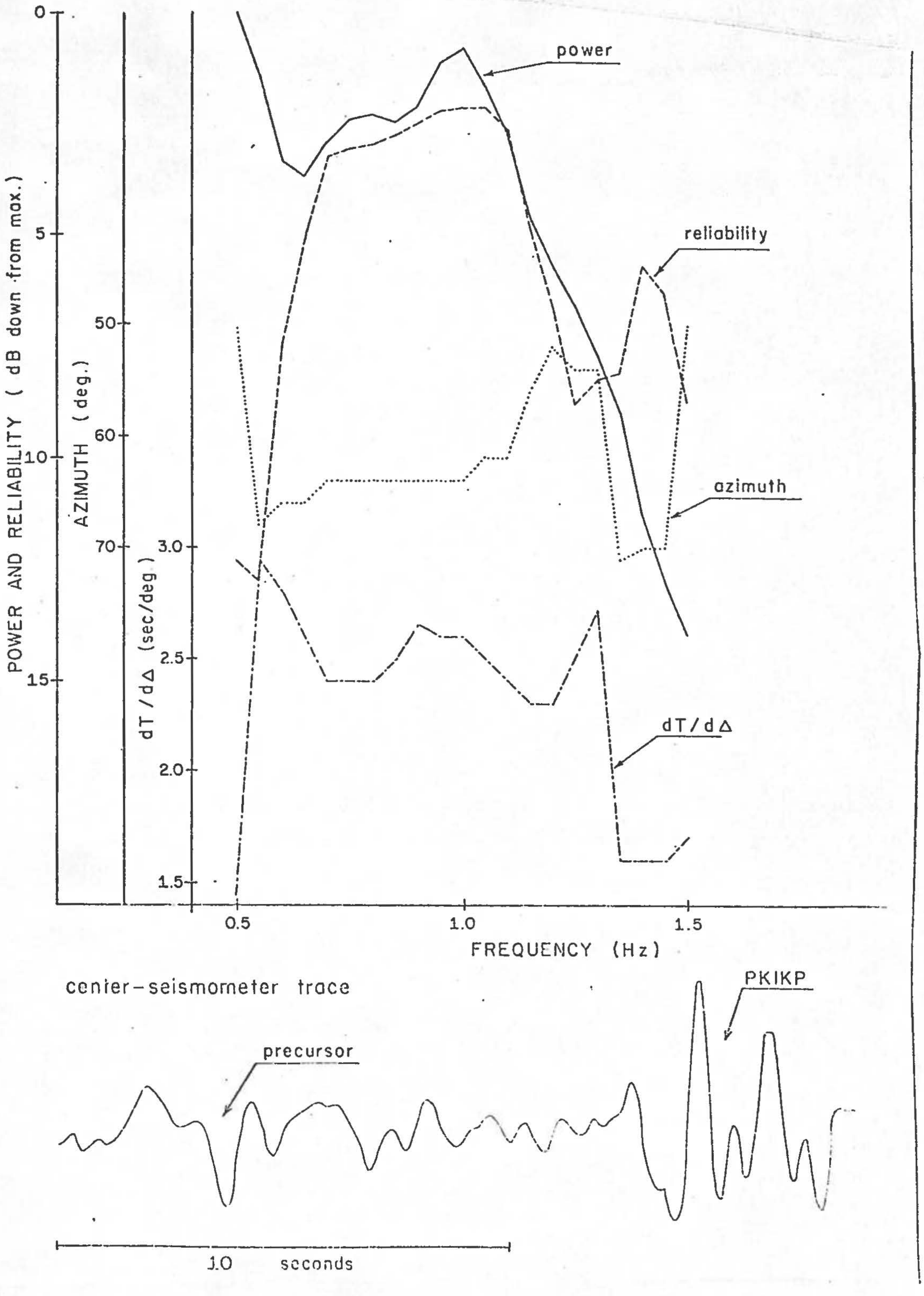

Fig. 2 Spectral analysis of precursors (see seismogram) from event with Δ=131.7°, depth=118 km, magnitude=5.4.

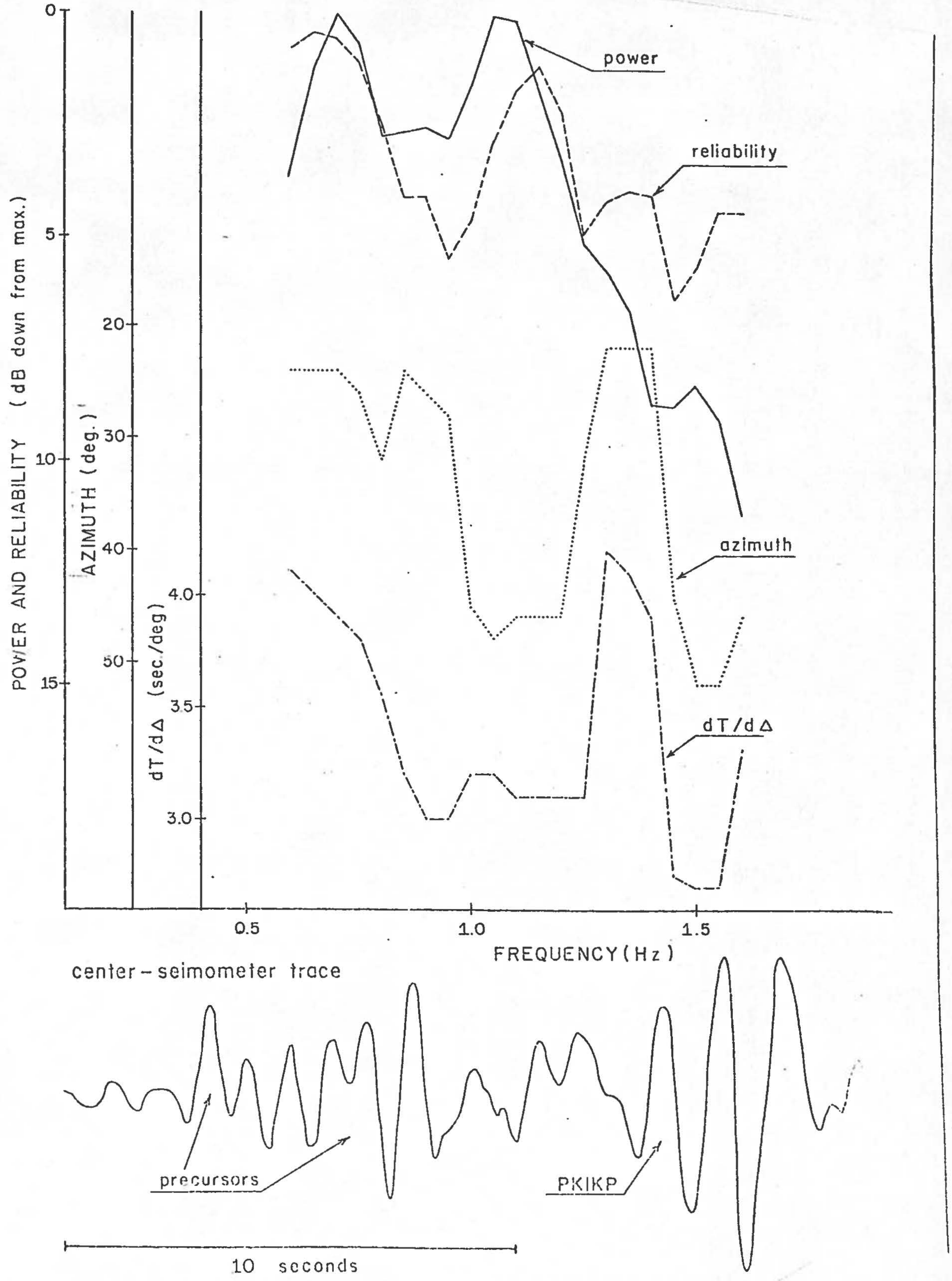

Fig. 3 Spectral analysis of precursors (see seismogram) from event with Δ=136.7^{o},depth 548 km, magnitude=5.7.

CHARACTERISTICS OF PRECURSORS

An analysis has been made of events during the years 1971 and 1972 in the Solomon and Fiji Islands regions. With regard to the reliability criteria used, 30 of these events gave accepted solutions for precursors. The event locations have been plotted in Fig. 4. We shall use the information on travel times and slowness vectors to characterize the precursors.

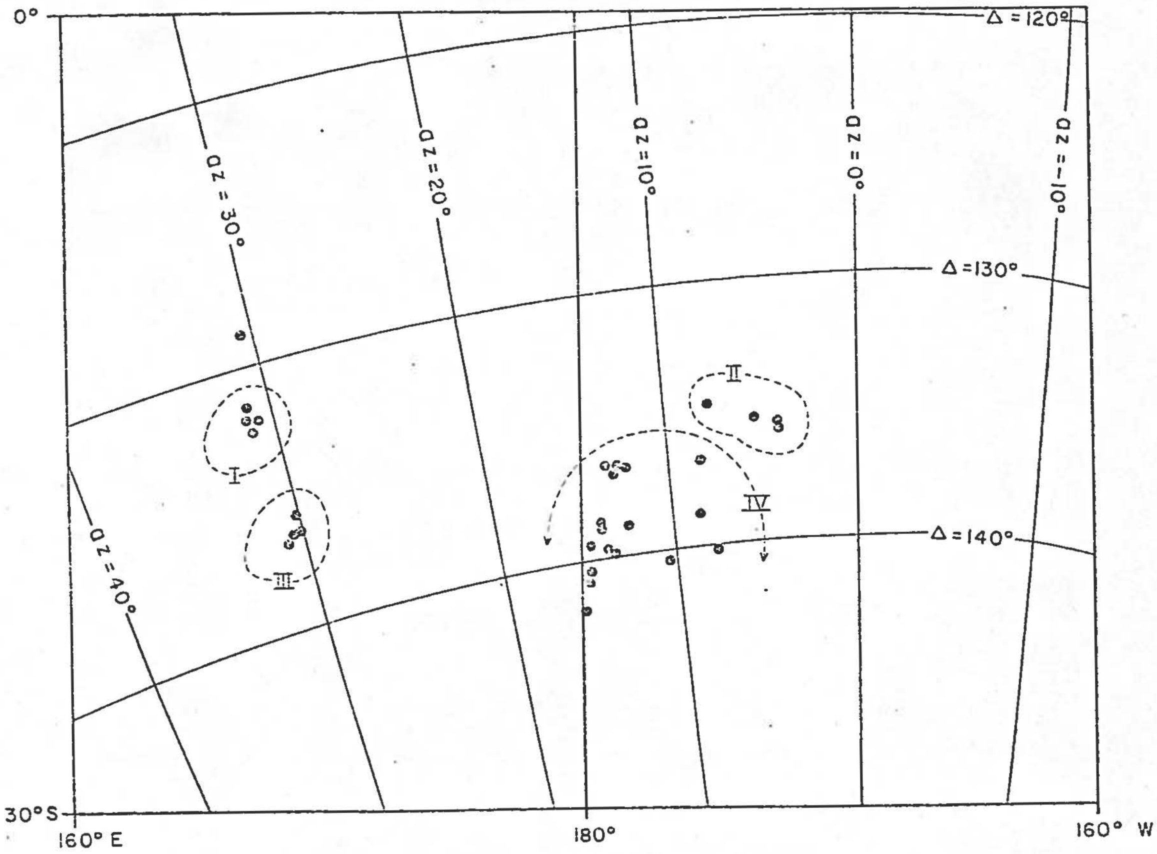

Fig. 4 Locations of events used in this study, with epicentral distances and azimuths from NORSAR.

Travel times, relative to PKIKP, have been plotted in Fig. 5 (some data, where PKIKP could not be sufficiently identified, have been deleted here). The figure reflects the fact that in a precursor wave train often more than one identifiable phase is present. However, by using the

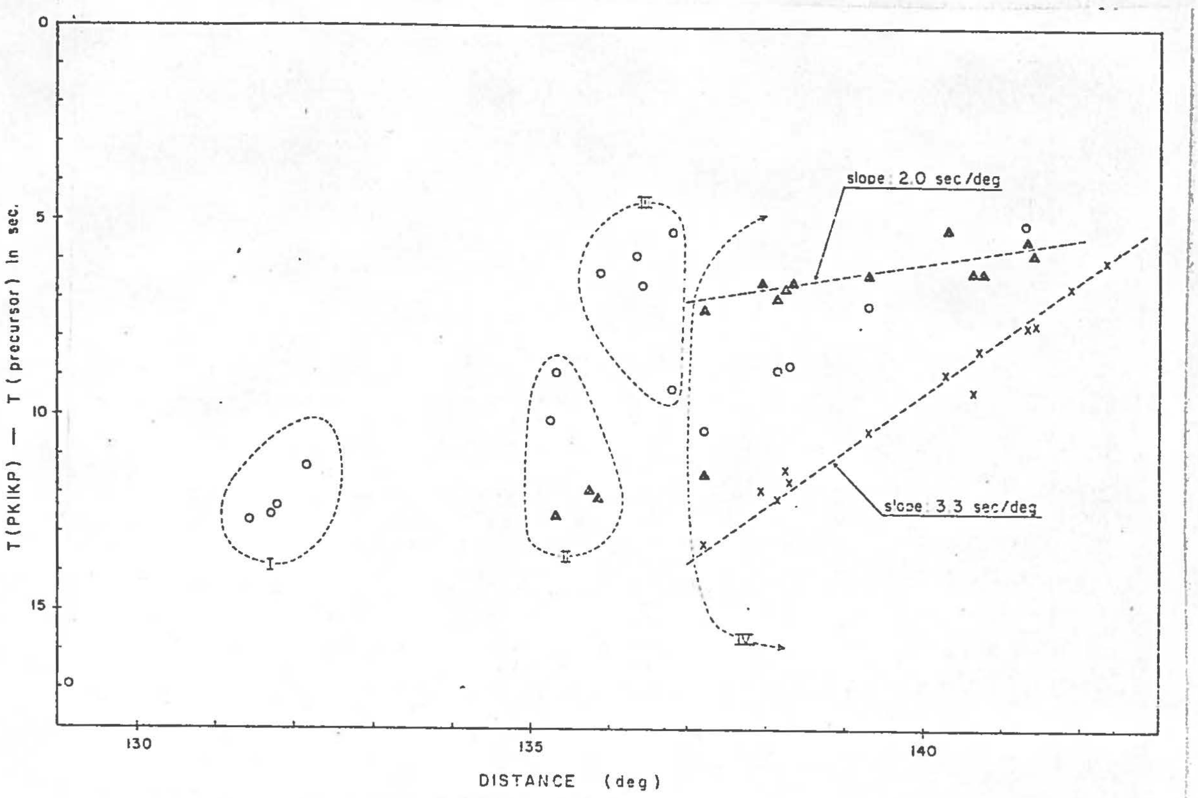

Fig. 5 Residual travel times of precursors, relative to PKIKP. The distances adjusted to surface focus. Note that dT/dΔ of PKIKP is about 1.8 in this distance range.

Phase identifiers: x - first onsets at 137°-143°
▲ - dT/dΔ > 3.3 sec/deg
O - dT/dΔ < 3.3 sec/deg azimuth deviation > 5°.

relation with the slowness vectors it can be shown that the origin of the individual phases is not the same. A slowness vector points in the direction of wave propagation and has a length given by dT/dΔ. It is necessary to correct the "observed" vectors for effects of near-array structure, since bias due to these effects is often considerable. In the following, slowness vectors will always be assumed to be corrected. It would then be expected that they give the direction from source to receiver. This is true within reasonable limits for only part of the phases in Fig. 5.

On the basis of characteristics concerning $dT/d\Delta$ and azimuth there is reason for a subdivision in three classes (Fig. 5):

(1) First arrivals from $\Delta = 143^{\circ}$ with decreasing amplitude down to about 138°. Standard methods applied to the phases in the range 140°-143° yield a $dT/d\Delta$ around 3.3 sec/deg (Fig. 6), the same as found at the caustic, whereas deviations from the true azimuth of the event are within 2°. The slope of a (tentative) curve through the travel time points is consistent with the value 3.3.

(2) Phases with anomalously low $dT/d\Delta$ (1.6-3.0 sec/deg) especially at shorter epicentral distances. More striking even are the extremely large azimuth deviations, ranging from 10° to 40°. The solutions for these phases are given in Fig. 7, where the azimuth deviations are represented by the angles between the vectors and the vertical.

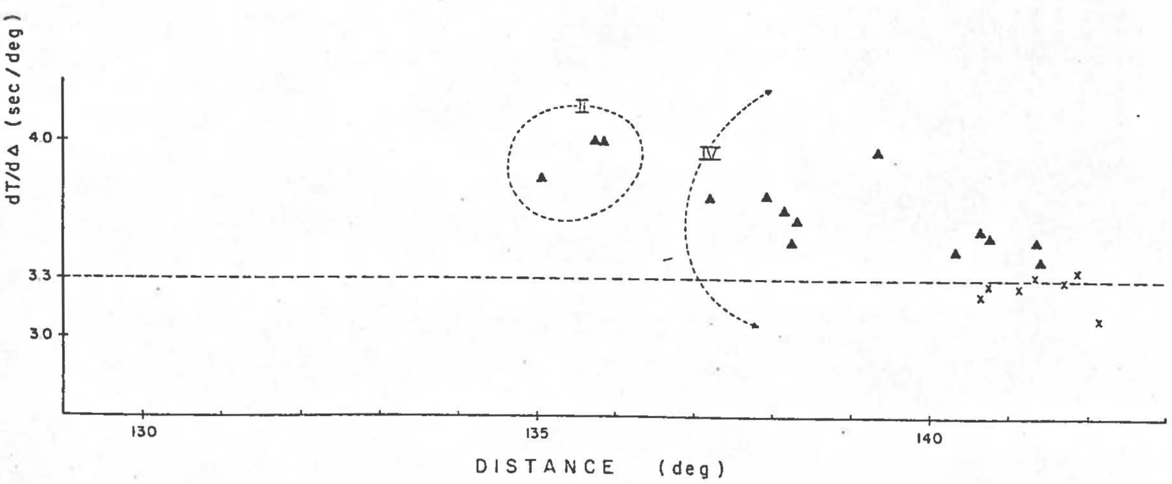

Fig. 6 $dT/d\Delta$ of precursors with azimuth deviation < 5°. The distances adjusted to surface focus. Phase identifiers correspond to those in Fig. 5.

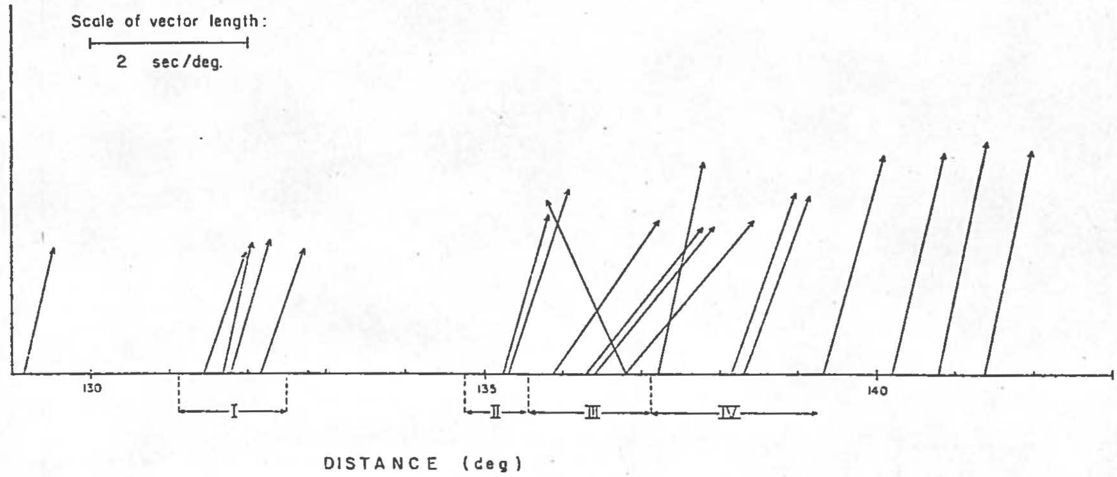

Fig. 7 Rotated slowness vectors of precursors with azimuth deviation > 5^{o}. The distances adjusted to surface focus. Length of vector $\equiv dT/d\Delta$, deviation from the vertical $\equiv$ azimuth deviation.

(3) Phases with anomalously high $dT/d\Delta$ (3.4-4.0 sec/deg) particularly at shorter epicentral distances (Fig. 6). These values are moreover apparently inconsistent with the travel times, which is especially clear in Fig. 5 in the range 137^{o}-142^{o}: One is tempted to draw a travel time branch with a slope of about 2 sec/deg, but the average $dT/d\Delta$ of these phases is measured to be about 3.6 sec/deg. This discrepancy was noted already in Ref. 1. Azimuth deviations are within limits of 5^{o}.

Despite the classification given, Figs. 5-7 still show significant differences within the classes (2) and (3). It is important, however, to note the correlation with differences in event location. For the purpose of demonstrating this, some groups of data in Figs. 5-7 are numbered in correspondence with numbered source regions in Fig 4. There are many possible reasons why ambiguities can always be expected to remain. (The weak first arrival from an event at 136.8^{o}, which supplied the only "negative" azimuth deviation in Fig. 7, is only one example of this.) Nevertheless, the correlation implied is sufficient to suggest that the measurements themselves are reasonably "repeatable" and that systematic differences should be attributed to earth's structure effects.

SCATTERING STRUCTURES IN THE MANTLE

Without introducing any structural complexities, precursors are still predicted by diffraction from the caustic according to classical Airy theory[4,5], even if radial heterogeneity of the earth is not accounted for. The characteristics of the first arrivals (class (1)) from 143^{o} to 140^{o} and possibly further down to about 138^{o}, give us no reason for a different explanation than by means of this type of diffraction.

We then are left with explaining the precursors in the classes (2) and (3). The characteristics of both types rule out the hypotheses in terms of core complexities proposed so far. However, an explanation is possible if scattering in the mantle is accepted. We then are able to locate the scattering structures. Rather than discussing all data individually, we shall give results only in those cases where averaging of comparable data from closely spaced events is possible.

Phases with relatively small $dT/d\Delta$ and large azimuth deviations (class(2)) are expected to be generated by scattering on or near the caustic surface, in analogy to the mechanism proposed before[2,3]. Knowing the slowness vector of a precursor, the ray can be traced back to the intersection with the caustic surface, thus locating the scattering structure. By combining this ray with the PKP ray which is tangent to the caustic surface at this point, a total travel time for the precursor can be computed. Given the slowness vector of the precursor, this time is a minimum with respect to the times of all other possible combinations of P and PKP rays. It is strongly in favour of the proposed mechanism that the minimum time leads to a striking agreement between computed and observed travel time differences with PKIKP.

From the data (Figs. 5 and 7) near 132°, 136°-137° and 138°, scattering regions are found in the lower mantle at distances from the core-mantle boundary of about 250, 500 and 600 km respectively. We realize that there is an uncertainty in these results due to the possibility of systematic errors occurring at the varous stages of the procedure: There could be bias in the measurements, the slowness corrections and the ray tracing in the reference model (a revised Jeffreys' model[7] has been used), and estimates for these uncertainties are mainly based on intuitive arguments; for example, in the case of slowness corrections arguments as used in[8] should be invoked. If allowance is made for a possible bias of ± 0.2 sec/deg in the slowness vector, of ± 1.5 sec in the travel time difference with PKIKP, and of ± 1° in the lateral position of the scatterer (away from the caustic surface), the resulting maximum depth mislocation is about 100 km for the data near 132° and 150 km in the other two cases. While these values indicate that the uncertainties are not negligible, neither are they large enough to explain the differences in depth location.

A similar procedure can be followed to find the origin of the precursors in class (3). The relatively large slownesses indicate that their origin cannot be in the mantle at the receiver side. They can be generated, however, by scattering in the mantle at the source side.

Computations show that this hypothesis will satisfactorily explain both dT/dΔ and travel time if the location of scattering is such that scattered rays form a caustic near the receiver. Indeed, if scattering in the mantle does occur, this mechanism would be expected along with scattering from the caustic surface; this is clear from the reciprocity of both possibilities, which can be seen in Fig. 1 by interchanging source and receiver.

From the data (in Figs. 5 and 6) at 135-136^o, near 138^o and at 140-141^o scattering structures are inferred in the lower mantle at distances from the core-mantle boundary of about 200, 800 and 900 km respectively, where it must be added that these values are considered as much more uncertain than in the former case. The same criteria as used before would lead here to possible bias of several hundreds of kilometers in the depth.

Some comments can be made: The results indicate that scattering is not confined to the D" layer. How instead scattering structures could fit in a global pattern, is still very much an open question. Only a limited part of the mantle can be "seen" from NORSAR, since it is to be expected that scattering in directions close to the direction of the primary wave is most likely to be observed. This will favour the observability of deeper structures, especially at shorter epicentral distances. The data give an indication for this. Also, scattering from directions along the azimuth of the event will be favoured. In this respect the azimuth deviations in Fig. 7 are rather striking. They imply the existence of lower mantle "irregularities" in a laterally limited region, as indicated by the range of azimuths of arrival.

We now arrive at the following conclusions:

(1) Precursors are not the effect of proposed complexities in the structure of the core.

(2) As far as not explainable by diffraction from the caustic, they represent scattered energy from irregularities in the lower mantle, both at the receiver and at the source side of the core.

(3) Scattering structures exist from the base of the mantle (the D" layer) to at least 600 km from the core-mantle boundary (values of 800 and 900 km at the source side have been obtained). Possible structural detail higher in the mantle is unlikely to be revealed because of the nature of scattering in the shadow zone.

We finally remark that the presented evidence is of a purely observational nature. At present we do not enter into speculations concerning tectonic and physical implications of our findings. Also, the scattering phenomenon observed has still to be theoretically justified.

ACKNOWLEDGEMENTS

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