ROYAL NORWEGIAN COUNCIL FOR SCIENTIFIC AND INDUSTRIAL RESEARCH

PROCEEDINGS FROM THE SEMINAR ON

SEISMOLOGY AND SEISMIC ARRAYS

OSLO, 22–25 NOVEMBER 1971

Editors: E S Husebye and H Bungum

Arranged in connection with the opening of The Norwegian Seismic Array (NORSAR) 1972

ARRAY ANALYSIS OF CORE PRECURSOR WAVES

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INTRODUCTION

Our present understanding of the state of the earth's core is primarily based on the observations and interpretations of the seismic core waves, notably the PKP phases. More recently, the research interest has been focused on the waves preceding PKIKP in the distance range 125-142 deg. These precursors have puzzled seismologists for many years and a correct interpretation has turned out to be problematic as witnessed by the many papers treating this subject. For example, Bolt's (1962, 1964) hypothesis, in which the precursors are assumed to be due to reflections and refractions at a discontinuity in the outer core, was much used until recently. Others like Adams and Randall (1964) and Subiza and Båth (1964) favored the existence of two transition zones between the outer and inner core. Engdahl (1968) has investigated the range of existence of different core models and preferred a modification of Bolt's (1964) model, but several other possibilities could not be ruled out definitely by his data.

The essential difference between the proposed core models is due to the interpretation of the precursor phases, i.e., whether they are reflected (or refracted) waves associated with one or two velocity discontinuities in the outer-inner core transition zone or related to PKP caustic around 143 deg (Bullen and Burke-Gaffney, 1958). The investigations so far have been based mainly on single station observations using the travel time as the only quantitative parameter. In particular for the precursors the observed travel time data exhibit a considerable scatter which may be partly due to the fact that they are characterized by small amplitudes. In cases like these more parameters are required for sufficiently constraining the hypothesis and large array measurements will be advantageous as slowness ($dT/d\Delta$) measurements and more confident estimates of travel time and amplitude are possible.

In this paper results based on analysis of PKP and SKP phases recorded at the NORSAR array in Norway are presented and discussed. It is shown that the maximum energy in the precursors cannot be explained by ray theory in a nondispersive medium. Of the possibilities left, the hypothesis of diffraction at the caustic is considered to be the most tractable and such effects may play a more important role than generally assumed.

DATA AND METHOD OF ANALYSIS

The principal advantage of a seismic array is its ability to utilize the spatial characteristics of signal and noise as such a system may be regarded as a 3-dimensional filter in the frequency-wavenumber space. In practice we are concerned with the array response to transient signals, but at the same time we want to preserve the time resolution between different phases in a wave train. A method suitable for this purpose is the so-called Vespa process or velocity filtering as demonstrated by Davies et al, 1971. The main output of this type of processing is a 2-dimensional display or Vespagram of signal energy versus slowness $dT/d\Delta$ and travel time T as shown in Fig 1. Although the Vespa process is very useful in quickly locating signal energy in slowness and time, the accuracy in actually measuring these parameters may be surpassed by other methods like the iterative cross-correlation technique (Bungum and Husebye, 1971). Therefore we combined the Vespagram analysis with the above cross-correlation procedure to ensure the best estimate of $dT/d\Delta$ and travel time for different core phases.

A common problem encountered in seismic velocity measurements is the possibility of biased errors due to anomalous structures in the site and source regions. In the latter case it is preferable to restrict the analysis to deep focus events. Due to the

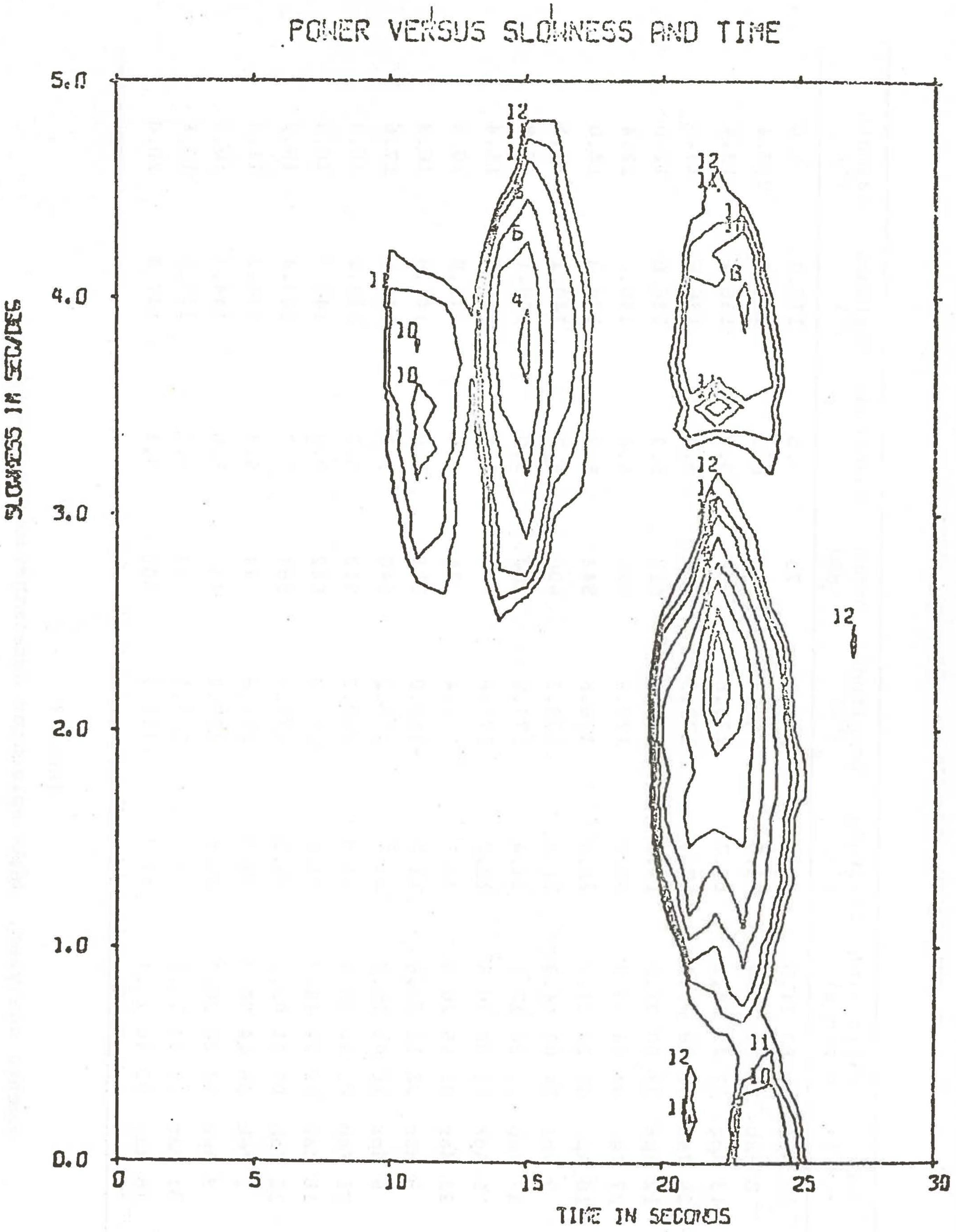

Fig 1. Event no. 5 (Table 1), $\Delta = 136.6^{o}$, depth = 612 km. The Vespagram start time is 1971, 12 April, 21h 18m 32s.

Event no.	Date (1971)	Origin time (h min s)	Latitude (°S)	Longitude (°W)	Depth (km)	Magnitude	Distance (°)	Azimuth (°)
1	13 Apr	05 57 34.5	15.9	174.0	73	5.5	135.0	6.6
2	8 Feb	21 04 21.8	63.5	61.2	33	6.3	135.3	217.4
3	13 Apr	17 47 24.2	17.7	178.8	559	5.3	136.4	13.4
4	28 Jan	06 29 01.0	17.9	178.5	616	5.0	136.6	13.0
5	12 Apr	21 00 37.3	17.9	178.2	612	5.3	136.6	12.6
6	27 Feb	04 44 35.0	20.2	177.8	524	5.0	139.0	12.4
7	10 Apr	01 22 17.2	21.3	178.8	542	5.7	139.9	14.0
8	3 Jul	04 07 44.3	21.5	179.1	600	5.3	140.1	14.5
9	27 Feb	13 26 27.1	21.4	177.9	390	5.0	140.1	12.8
10	6 Apr	11 06 30.6	22.2	179.6	603	5.6	140.7	15.4
11	23 Mar	02 15 26.9	22.9	176.4	76	6.0	141.8	10.8
12	9 Mar	08 11 52.8	23.4	-180.0	511	5.0	141.9	16.2
13	6 Apr	16 01 25.2	23.8	-179.2	540	5.3	142.1	17.6
14	21 Feb	03 20 20.0	23.8	180.0	512	5.2	142.2	16.3
15	18 Mar	02 34 48.7	23.8	-180.0	542	5.0	142.2	16.3
16	15 Feb	07 51 02.6	25.2	-178.3	584	5.7	143.4	19.2
17	1 Feb	06 14 50.2	25.5	176.8	44	5.4	144.3	11.9
18	5 Apr	14 26 30.7	25.9	179.8	432	5.0	144.3	16.5
19	31 Mar	11 33 14.1	29.1	177.5	67	5.2	147.8	13.8
20	18 May	00 46 20.1	29.7	-178.7	600	5.4	147.8	20.0

TABLE 1

Events analyzed. NOAA epicenter determinations are used.

intricacy of the above problem, we shall base our conclusions mainly on relative rather than absolute dT/dΔ values. (For a more detailed discussion, see Doornbos and Husebye, 1972.)

Altogether, we analyzed 20 earthquakes, which are listed in Table 1, in the distance range 135-149 deg. The main results obtained are summarized in Fig 2-5, while further details are given in another paper by the authors (Doornbos and Husebye, 1972).

INTERPRETATION AND DISCUSSION

The discrepancies between current core models are mainly due to the interpretation of the precursors to the PKIKP phase as pointed out previously. An interpretation of these precursors, in particular if made in terms of branches, may have observational consequences on standard PKP waves, as well as other core phases like SKP. In turn, this may be used as an additional check on a proposed core velocity model.

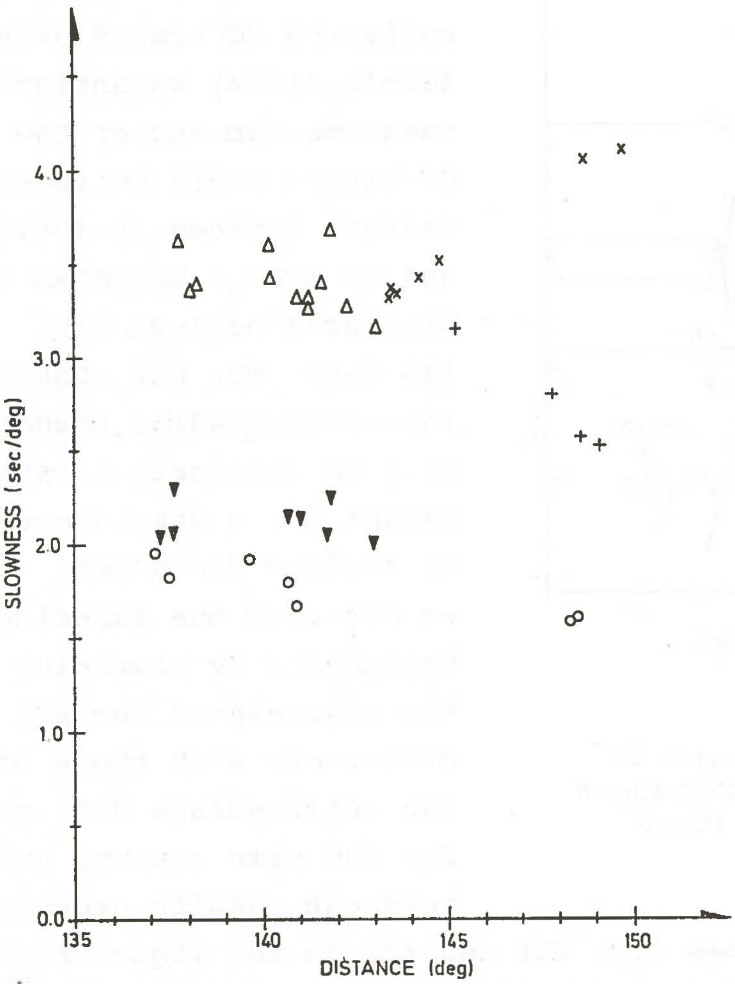

Fig 2. Corrected slownesses of PKP phases. The distances adjusted to a focal depth of 33 km. Phase identifiers: o - PKIKP, ▼ - PKiKP, Δ - precursors, + - PKP1, × - PKP2.

In Fig 2 we have displayed the results of the dT/dΔ measurements for various types of PKP phases. It is noteworthy that the Vespa process gives evidence of relatively strong reflections, PKiKP phases, from the inner core boundary. However, the most interesting feature is that the slownesses of the precursors, although somewhat scattered, have an average value about the same as for the phases near Δ~144 deg. This may indicate that the precursor waves originate from the same region where the seismic rays forming the PKP caustic have their turning points. It thus suggests that the precursors represent diffracted waves which is consistent with the observed increase in the energy ratio between these waves and PKIKP phases with increasing distances (see Fig 3 and also Fig 4). Other precursor hypotheses in terms of reflections and/or refractions at a discontinuity in the outer core cannot be ruled out by these considerations only.

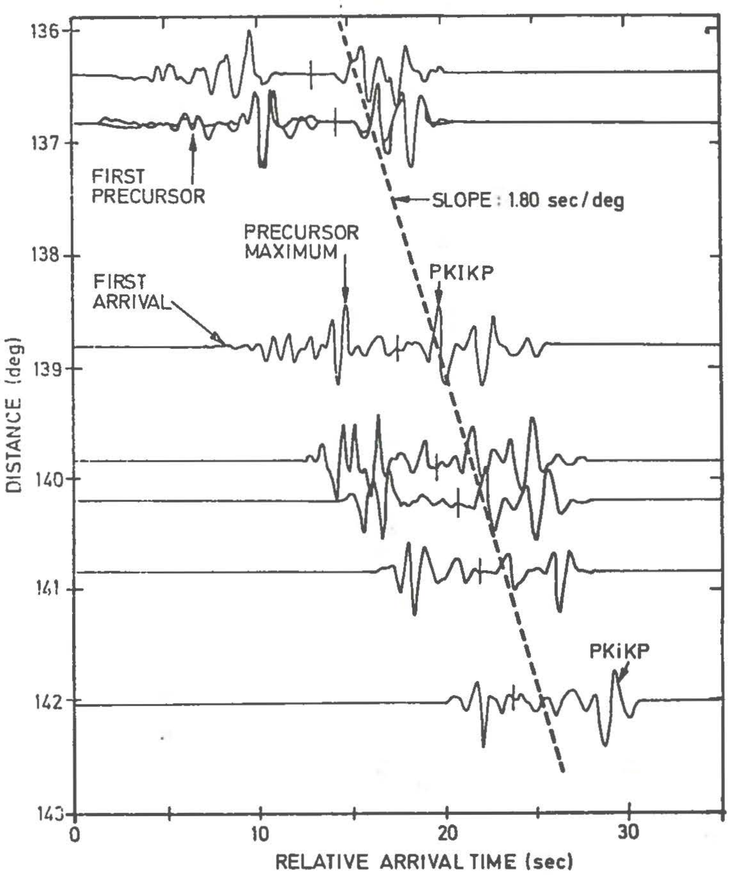

Fig 3. Composite seismograms of PKP phases. The distances are adjusted to a focal depth of 570 km.

Further constraints on current core models may be provided by taking SKP phases into account. If the precursor waves represent a refracted GH or a reflected CG branch using Bolt's (1964) nomenclature, then the far end of the GH branch would be intermediate between DF (PKIKP) and AB (PKP_2) branches at distances beyond, say 145 deg. For SKP phases, the corresponding branch will be similarly located except for a displacement to smaller distances. Thus, we may test the layering hypothesis by comparing the slowness of the PKP precursors with those of the intermediate SKP_1 phases for the same events, and relevant results are presented in Fig 5. The curves (1), (2) and (3) in the figure represent differences predicted from the model of Bolt and its revisions, A and B respectively as given by Engdahl (1968). Similar curves, namely, (4a) and (4b) for the revised Adams-Randall model (Engdahl 1968) are also included. The immediate objections against the latter model arise since it requires two different PKP precursors and two 'intermediate' SKP branches. The curve (5) is based on the revised Jeffreys' model (Engdahl 1968), if the precursors

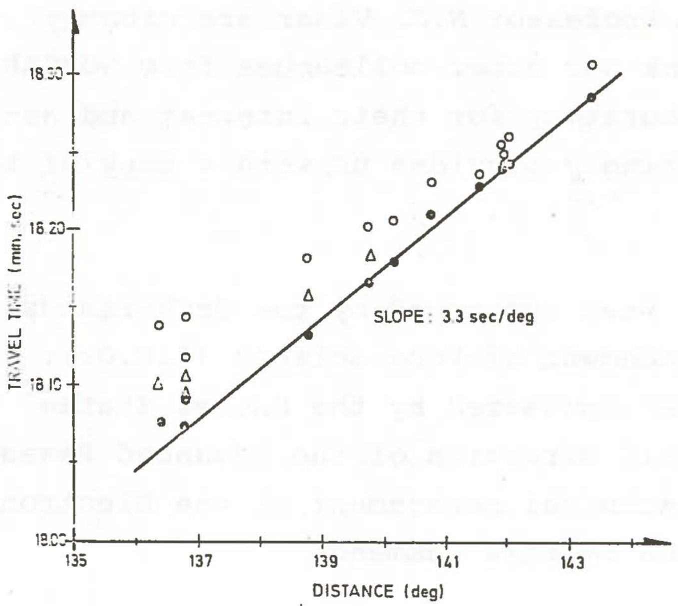

Fig 4. Travel times of precursors. Times and distances are adjusted to a focal depth of 570 km. ● - first onsets, o - energy maxima, Δ - secondary energy maxima at Δ<140°.

represent diffracted waves having the same slowness as the phase at the caustic. It is seen from Fig 5 that of the hypotheses considered, the diffraction hypothesis best accounts for our observational data. This point is discussed in more detail in the paper by Doornbos and Husebye (1972).

Finally we want to remark that at least part of our precursor observations cannot be explained by ray theory in a nondispersive medium. On the other hand, the diffraction hypothesis has intuitive appeal because of the observed slownesses, but it requires a phase spectrum of waves near the caustic which has not yet been theoretically established.

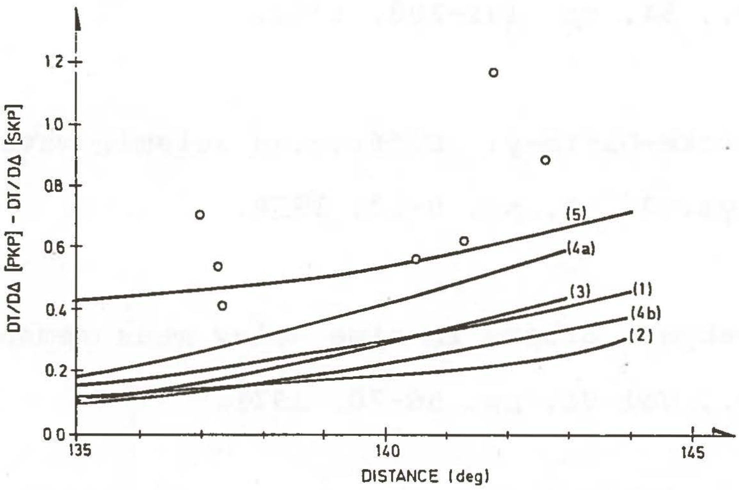

Fig 5. Observed slowness differences between PKP precursors and SKP1 phases.

ACKNOWLEDGEMENTS

Valuable discussions with Professor N.J. Vlaar are greatly appreciated. We also thank our other colleagues from NORSAR and the Vening Meinesz Laboratory for their interest and assistance. Dr. J. Filson kindly provided us with a copy of the original Vespa program.

Part of this research has been supported by the Netherlands Organisation for the Advancement of Pure Science (Z.W.O.). The NORSAR project has been sponsored by the United States of America under the overall direction of the Advanced Research Projects Agency and the technical management of the Electronic Systems Division, Air Force Systems Command.

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