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A Comparison of PKP Precursor Data From Several Seismic Arrays

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Abstract. Data from the four UKAEA arrays have been analyzed, using methods similar to those applied previously to NORSAR data. This allows a comparison of the different data sets, and such a comparison has been made for PKP phases and their precursors: The precursors are characterized by direction of approach and relative arrival time and spectral content; computational values, based on the interpretation of scattering in the lower mantle or at the core-mantle boundary (CMB), are used as a reference. Precursors at the different arrays have sampled different regions of the lower mantle and CMB. Significant differences between the various data sets, in characteristics like spectral ratio and azimuth deviation from the great circle, suggest large scale lateral variations in the properties of heterogeneous structure sampled by the data. It leads to the mapping of relatively "smooth" regions (beneath the S. Sandwich Islands and Central North America, from YKA data), and "rough" regions (beneath the Fiji Islands and Fennoscandia, from NORSAR data).

Key words: Scattering – Core-mantle boundary – Lower mantle – Lateral variations – Arrays.

1. Introduction

During the last 5 years or so, seismic array data have been used in exploring lateral variations in the lower mantle. The array evidence of large scale variations as inferred mainly from slowness vector anomalies (e.g., Davies and Sheppard, 1972; Kanasewich et al., 1973; Wright and Lyons, 1975), is still subject to debate (Green, 1975; Berteussen, 1976; Vermeulen and Doornbos, 1977). More conclusive has been the evidence of small scale variations as inferred from the characteristics of certain types of precursors to core phases, following their interpretation in terms of scattered waves (Cleary and Haddon, 1972); see, e.g., Doornbos (1976) and Husebye et al. (1976) for precursors to PKP,

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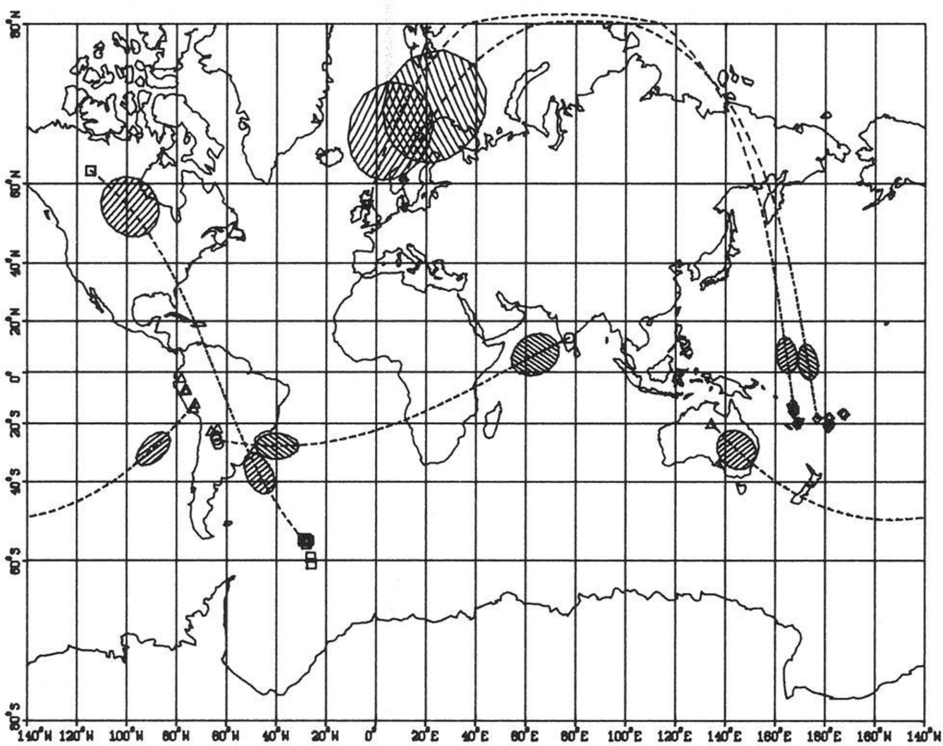

Fig. 1. Mercator projection of the world, with epicentra and array receiver locations, and surface projections of great circle paths and areas sampled on and above CMB; the hatched areas are for one typical source in each source region only. Array symbols: ◇ (NORSAR at 60.82° N, 10.83° E), □ (YKA at 62.49° N, 114.61° W), ○ (GBA at 13.60° N, 77.44° E), ▽ (EKA at 55.33° N, 3.16° W), △ (WRA at 19.95° S, 134.35° E). Event symbols according to the receiver array

Doornbos (1974a) for precursors to PKKP, Haddon et al. (1977) for precursors to P′P′. Yet, there are some significant differences in the models of small scale heterogeneity proposed or inferred by different authors. For example, some workers explain the PKP precursor data by a uniform scattering layer of thickness 200 km or less at the base of the mantle (Haddon and Cleary, 1974; Wright, 1975; Husebye et al., 1976); Doornbos (1977) concluded that both a slightly rough coremantle boundary (hereafter referred to as "CMB") and a slightly heterogeneous lower mantle would explain the observed energy level in most of the PKP precursors, but as was pointed out, the simultaneous explanation of other characteristics like travel time and slowness vector, by scattering in an otherwise standard Earth model, may require scattering regions well above CMB, and/or large scale lateral variations in these regions (c.f., Doornbos, 1976).

Besides differences in source-receiver geometry, thereby smapling different regions of the lower mantle or CMB, some differences in the proposed scattering models may be due to the different array systems and data analysis techniques used. This paper reports on an experiment where we try to avoid introducing subjective differences by analyzing data from the 4 UKAEA arrays, in comparison with the existing NORSAR data set. The UKAEA analog data were converted to the same digital form as NORSAR data. Thus, although several of these arrays have been employed separately for similar purposes, our aim here is to test the idea of large scale variations in the lower mantle or CMB structure (besides the small scale variations inherent in the scattering interpretation), by a similar analysis of data from different source-receiver combinations. Figure 1 illustrates the source-receiver geometry and the areas thus sampled (these areas are shown for one typical source in each source region only).

In the next section we give a brief summary of the arrays and data processing techniques used. The observational results are parameterized in the form of arrival time, slowness vector and spectral ratio (relative to PKP). The results are presented and discussed along with theoretical results for scattering from a rough CMB and a heterogeneous lower mantle.

2. The Arrays and Data Analysis Techniques

The arrays we use have been extensively documented. Moreover, NORSAR and three of the four UKAEA arrays have been used for similar purposes as in this paper. For discussions of the arrays, their response, etc., we therefore refer to the literature. (For general discussions, see, e.g., Birtill and Whiteway (1965) and Bungum et al. (1971); for discussions in the context of core phase analysis, see, e.g., Doornbos and Husebye (1972), Ram Datt and Varghese (1972), King et al. (1974), Wright (1975). We use the NORSAR data from Doornbos and Vlaar (1973). UKAEA analog data records from events with $m_b > 5.5$ during a period of about 2.5 years from 1-1-1971, have been converted to a 20 Hz sampling rate digital form, in analogy to the NORSAR short period data. Similar processing techniques could thus be employed, and we have adopted those applied previously by, e.g., Doornbos and Husebye (1972) and Doornbos (1974b). Briefly, a rough estimate of the direction of approach of incident wave energy was obtained by Vespa analysis at a number of azimuths at and around the event azimuth; maximum coherent power peaks in slowness and time were then relocated in an iterative beamforming program. The procedure yields the direction of approach and arrival time of relatively coherent energy in a wave train, similar to the BEAMAN analysis described by King et al. (1975). Spectral analysis of the energy maxima was subsequently performed on the final array beams; the analysis involved the concept of so called instantaneous spectra (Dziewonski et al., 1969; Doornbos, 1974b). The procedures were applied to both precursors and PKP, thus allowing the results to be presented in a relative, rather than absolute form (e.g., spectral ratios).

Evidently, identical analysis procedures do not prevent the differences introduced by different array geometry and geological structure. Array geometry determines the array response. At a large array like NORSAR it limits wave interference, and interference tests as described by Doornbos and Vlaar (1973) may be quite useful. The response of the medium aperture UKAEA arrays is much smoother and the possibility of more interference must be admitted, although slowness measurements with these arrays usually suffice to discriminate between scattering at the source and receiver side of the core (King et al., 1974; Wright, 1975). The effect of structure beneath the arrays should ideally be compensated for, and correction tables for slowness measurements have been used on a routine basis at NORSAR (Berteussen, 1974). Again, for the medium aperture arrays the situation is more difficult. Although consistent slowness measurements may be made for events in the same region (as we have verified by measuring PKP; YKA anomalies were consistently about 0.3 s/deg), it is also known that, in particular for medium and small arrays, the effect of local structure may change rapidly with small changes in the incident wave direction (Berteussen, 1975). Indeed, slowness anomalies at the UKAEA arrays of PKP and those of nearby *P* in the slowness plane from data of Corbishley (1970), were sometimes very different, so it is not clear whether a correction based on interpolation between calibrated points in the slowness plane is justified. Since also the geological structure itself is not known in sufficient detail, we decided to leave the slowness data from the UKAEA arrays uncorrected; such a correction was also omitted by Ram Datt and Varghese (1972) at GBA, by King et al. (1974) at WRA and by Wright (1975) at YKA.

3. Model Calculations

We will present observational along with theoretical results, since it facilitates interpreting trends in the data (e.g., with epicentral distance), and it indicates which observations should be considered anomalous. The choice of a scattering model is somewhat arbitrary. Following the formulation of Doornbos (1976; 1977), we give results for scattering by a rough CMB with average radial variations of 200 m, and by a heterogeneous 400 km thick layer at the base of the mantle, with an average relative density variation of 1%. Similar variations in the elastic properties could have been included, but the resultant amplitude-distance curves would not be much different. The results represent scattering at one side of the core only (either the source or the receiver side, which is consistent with precursor observations at arrays). Scale lengths of variation of 10 and 20 km will be considered in both cases. It has been shown by Doornbos (1977) that both of the above models produce the energy level that is observed in most of the PKP precursors, and that scale lengths of 10–20 km should be considered relevant, except at relatively long epicentral distances where larger scale lengths may become important. The 400 km layer model is akin to the 200 km layer model of Haddon and Cleary (1974).

We emphasize that the computational curves are not intended to fit all observed precursor characteristics. For example, the models are laterally uniform whereas we will present evidence of lateral variations in scattering regions. Relative to the above models, scattering from laterally limited regions will decrease the precursor energy or alternatively, the heterogeneity in this region would have to be increased to maintain the same energy level of the precursors. The array response has a similar effect since it restricts interference to a limited region in the slowness plane. The latter effect is important for NORSAR, whose response reduces the energy level produced by a laterally uniform scattering model with roughly 3 to 6 dB at 1 Hz (Doornbos, 1977), but for the UKAEA arrays with their much wider response, the effect is unimportant. Ideally, the characteristics of groups of precursor data should be inverted to obtain scattering regions consistent with these data. This strategy has been applied to some groups of precursor data at NORSAR (Doornbos, 1976). However, for data from the UKAEA arrays, such an inversion is not warranted due to the limited resolving power of these arrays, so only the forward approach will be followed here.

4. Results and Discussion

The precursor data from the different arrays were also associated with different source regions (Fig. 1). NORSAR data are from the Solomon and Fiji Islands region, the bulk of the YKA data (around an epicentral distance of 136°) is from the S. Sandwich Islands region, most EKA data are from the New Hebrides, WRA data are from several regions in S. America, whereas GBA gave only two data from Argentina events at relatively long distances (142°–143°). Typical records with PKP and precursors from each of these arrays are shown in Figure 2. For purposes of comparison, the NORSAR central subarray, rather than the arraybeam, has been used here (not in the remainder of this paper). UKAEA data are given in Table 1; for NORSAR data tabulation we refer to previous work (e.g., Doornbos, 1976). In the Figures to follow, the data will be distinguished according to array type, no further distinction will be made.

The information on arrival time and slowness vector is summarized in Figures 3–5. The theoretical curves in these figures do not bring out the difference between 10 and 20 km scale length, as this difference was not important in these cases. Arrival times of energy maxima in precursors and PKP were measured from the instantaneous spectral envelopes in the frequency range 0.8–1.2 Hz.

The precursor times are plotted in Figure 3, relative to PKIKP. Since measured PKP energy does not only involve PKIKP but also, e.g., PKiKP, we have assumed that, when the energy maxima did not separate (which was always the case for surface focus distances below 138°), the observed maximum is halfway between PKIKP and PKiKP, and applied a time correction accordingly. It should be realized that the CMB curve in Figure 3 lags the minimum time curve (see, e.g., Cleary and Haddon, 1972) by several seconds. Whereas the model curves in Figures 3 indicate the general trend in the data, the relatively poor fit of any of the individual curves to the data may reflect deviations from a uniform scattering model. Indeed, from previous experience with NORSAR data alone it has become clear that large scale lateral variations in scattering properties must be invoked to account for the characteristics of these data.

In plotting $dT/d\Delta$ and azimuth deviations from the great circle (Figs. 4 and 5), it was realized that for the UKAEA arrays, large biases may be introduced by wave interference and by uncorrected effects of near array structure

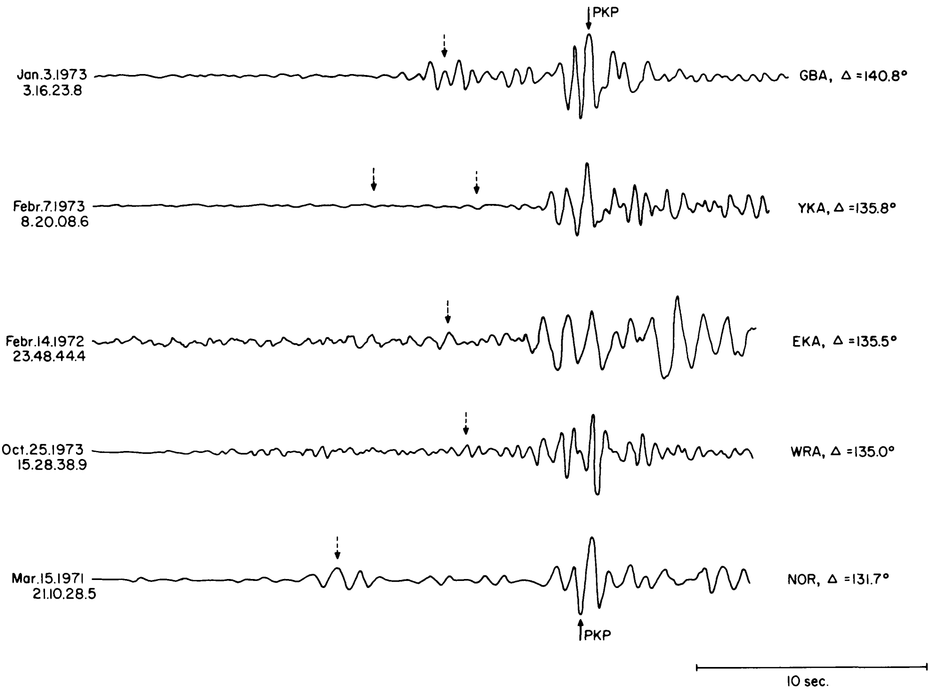

Fig. 2. PKP with precursors at UKAEA arrays (array beams) and at NORSAR (central subarray beam); filtered traces. Dashed arrows indicate precursor detections

(section 2). Some control on the reliability of (dT/$d\Delta$, azimuth) data may be exercised by applying the scattering interpretation and requiring that, within specified limits, measured arrival time, dT/$d\Delta$ and azimuth be consistent with a scattering source on or above CMB. By applying this test we had to reject some of the (dT/$d\Delta$, azimuth) solutions, and these are not reproduced in Figures 4 and 5. Figure 4 clearly shows the separation of dT/$d\Delta$ in precursors due to scattering at the source and receiver side of the core, respectively. Besides, we remark that the dT/$d\Delta$ data in Figure 4 are not necessarily at the same position relative to the model curves, as their corresponding arrival times in Figure 3. The YKA data in Figures 3–5 are generally in agreement with those of Wright (1975). The correspondence of WRA data with those of King et al. (1974) is less clear; this may be partly due to our limited number of good data for this array, which was characterized by many (partial) breaks during our observation period. Most striking in Figure 5 are the large azimuth deviations for NORSAR data groups corresponding to scattering at the receiver side of the core, whereas for the other arrays (in particular YKA) no consistently large deviations are observed.

Spectral information is summarized in Figures 6 and 7. Peak frequencies of PKP and its precursors are generally around 1 Hz (for UKAEA data slightly higher).

Table 1. Events and precursor data at UKAEA arrays

Array	Date	Source region	Depth (km)	Dis-tance (°)	Resid-ual time (s)	$dT/d\Delta$ (s/°)	Azi-muth devia-tion (°)	Spectral ratio peak frequency (Hz)	Spectral ratio at 1 Hz (dB)
YKA	1972, Jan 8	South Sandwich Isl.	60	135.5	7.10			0.9	32.05
	1973, Feb 2	South Sandwich Isl.	33	136.0	8.05	3.65	4.2	1.5	24.61
					4.25	2.30	0.	1.6	24.80
	1973, Feb 7	South Sandwich Isl.	33	135.8	10.50	3.50	0.	1.7	27.71
					4.60	2.30	0.	1.7	23.13
	1973, Feb 18	South Atlantic Ridge	33	125.1	5.70			1.3	19.13
	1972, Feb 25	South Sandwich Isl.	33	140.1	8.05			1.6	16.01
	1973, Feb 25	Scotia Sea	33	136.2	9.25	3.44	−9.9	1.8	23.02
					3.95			2.1	20.77
	1972, Mar 31	South Sandwich Isl.	33	135.4	9.80	3.86	−8.1	1.1	14.75
	1973, Apr 25	South Sandwich Isl.	67	138.9	8.55	2.75	−0.1	1.1	25.14
					5.55	3.46	−6.6	1.1	14.00
	1973, Nov 25	South Sandwich Isl.	33	135.5	2.05			1.2	24.40
	1972, Dec 22	South Sandwich Isl.	33	135.4	8.50	2.90	3.6	1.5	26.68
					3.40	2.00	3.6	1.5	29.51
	1972, Dec 22	South Sandwich Isl.	33	135.4	7.95	3.71	2.1	1.5	23.11
	1972, Dec 28	South Sandwich Isl.	33	135.5	8.65			1.9	30.83
GBA	1973, Jan 3	Santiago del Estero prov. Argentina	563	140.8	5.40	3.28	0.	1.6	14.89
	1973, Nov 19	Salta prov. Argentina	40	142.6	3.60			1.5	10.76
EKA	1972, Feb 14	Santa Cruz Isl.	102	135.5	8.25			1.3	14.35
					5.75	2.66	5.5	1.4	14.46
	1972, May 4	New Hebrides Isl.	45	140.9	7.25			1.7	10.45
	1971, Sep 14	New Britain	33	127.2	3.80	0.72	−11.5	1.8	16.97
	1971, Oct 27	New Hebrides Isl.	40	139.5	7.45			1.6	9.66
	1973, Nov 30	New Hebrides Isl.	124	139.3	7.50			1.6	7.41
	1973, Dec 9	New Hebrides Isl.	39	142.9	2.65	3.31	15.4	0.7	4.78
	1973, Dec 28	New Hebrides Isl.	26	138.5	8.70			1.6	11.51
WRA	1973, Feb 1	Jujuy Prov. Argentina	229	133.1	11.80			1.0	11.18
	1972, Mar 20	Northern Peru	64	139.4	9.10			1.7	16.29
	1973, Sep 18	Northern Peru	133	139.8	4.90	2.15	−19.7	2.0	17.10
	1971, Oct 15	Peru	54	136.1	10.40				
					3.10	1.50	0.2	0.6	19.22
	1973, Oct 25	Southern Bolivia	548	136.0	12.40				
					5.60	1.81	35.6	1.7	10.72

In Figure 6, peak frequencies of the precursor/PKP spectral ratio are plotted. The PKP spectrum used is representative of PKiKP. Because source and receiver effects are largely eliminated, the spectral ratio is thought to be more representative of the scattering mechanism itself. However, two points must be made. First, for low energy precursors (e.g., YKA data around 136°) the signal to noise ratio is low in particular at the higher frequencies (say above 1.4 Hz), and spectral ratio peaks in this frequency range may become unreliable. Second, if the incident precursor energy is not well concentrated in slowness space

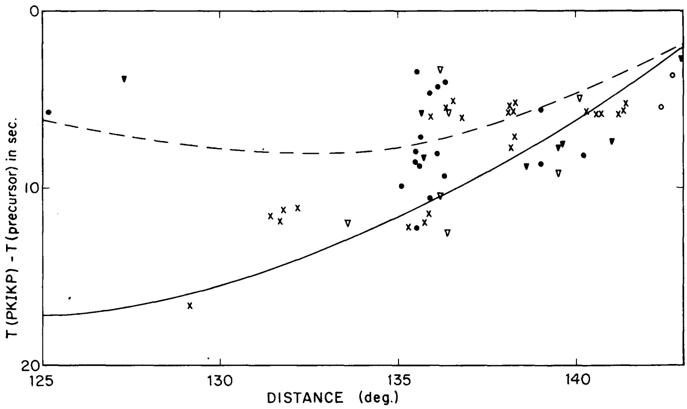

Fig. 3. Residual travel times of precursors, relative to PKIKP. Data and theoretical curves represent energy maxima. Data symbols: × (NORSAR), ● (YKA), ○ (GBA), ▼ (EKA), ▽ (WRA). Model curves: —— (rough CMB), --- (density heterogeneity in 400 km thick layer at the base of the mantle)

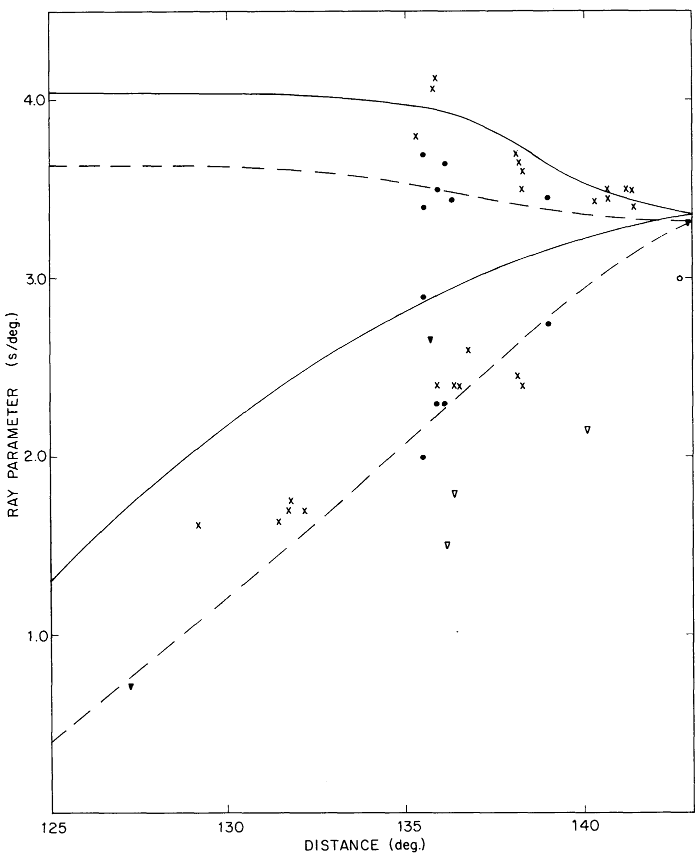

Fig. 4. Ray parameters of precursors. Data symbols and models as in Fig. 3

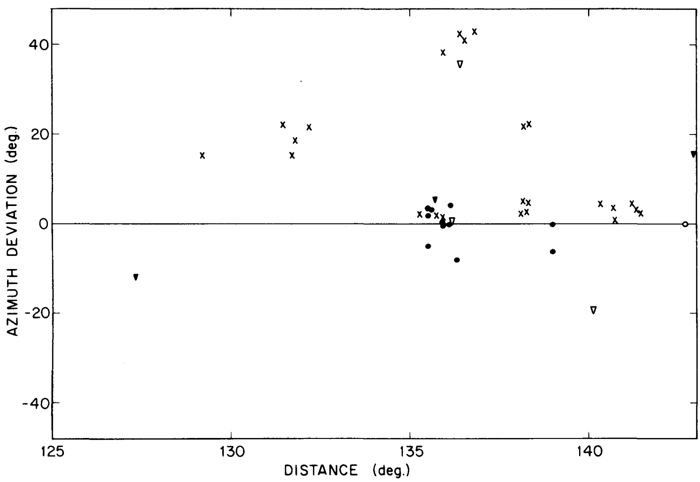

Fig. 5. Azimuth deviation from great circle of precursor direction of approach. Data symbols as in Figure 3

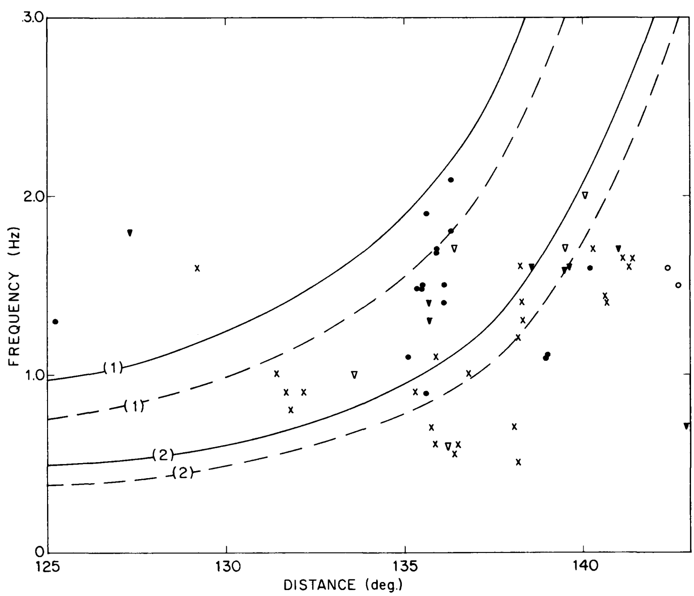

Fig. 6. Dominant frequencies of (precursor/PKiKP) spectral ratios. Data symbols and model curves as in Figure 3. (1): 10 km scale length of variation in radius CMB or in lower mantle structure (for details see text; (2): 20 km scale length

(e.g., if one of the laterally uniform scattering models were valid), the reduction of interfering precursor energy by large array beamforming increases with frequency; as a result the measured peak frequency of spectral ratio may be biased to lower frequencies. These points may explain at least part of the differences in Figure 5 between NORSAR and YKA data around 136°.

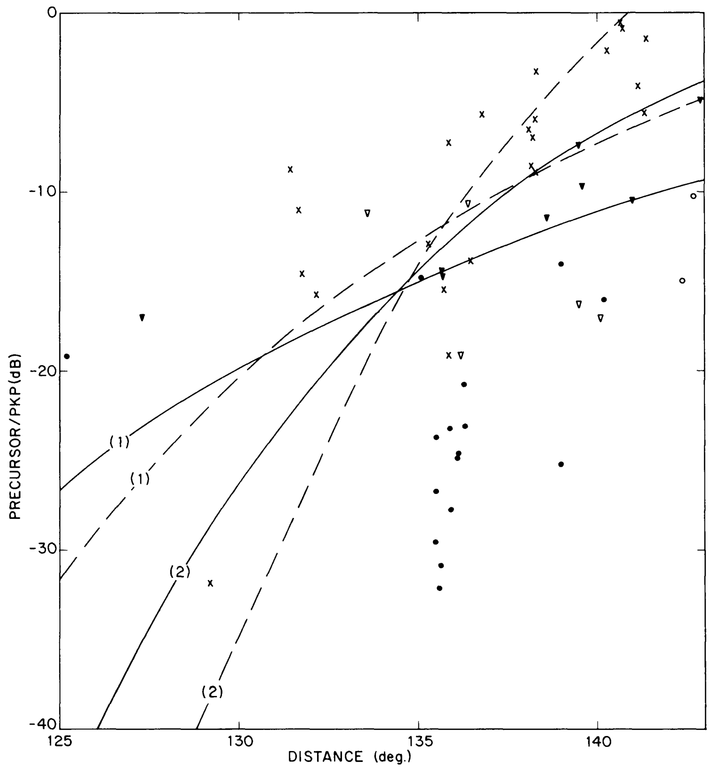

Fig. 7. Maximum precursor energy at 1 Hz, in dB relative to PKiKP. Data symbols and models as in Figures 3 and 6

Figure 7 gives spectral ratios at 1 Hz. As mentioned before, frequencies at or slightly above 1 Hz are representative of our data set. We have also computed the spectral ratios at 1.2 Hz and the results were similar to those in Figure 7. The figure clearly demonstrates the difference in energy level between the NORSAR and YKA data, which we estimate to be of the order of 10–15 dB. The energy level of the NORSAR data is higher than most of the other data and if the afore-mentioned correction for large array beamforming were applied, most NORSAR data would also fall clearly above the theoretical curves. On the other hand, the YKA data fall far below these curves. Data from the other arrays are generally in between those of NORSAR und YKA. NORSAR data have sampled lower mantle and CMB regions beneath the Fiji Islands and beneath Fennoscandia (c.f., Doornbos, 1976); YKA data (around 136°) have sampled regions beneath the S. Sandwich Islands and beneath Central North America. The observed differences may be a manifestation of large scale variations involving these regions. In this respect we also mention that UKAEA precursor wave trains appear to be more complex than many of the NORSAR data, although this difference is difficult to evaluate and may be partly due to different array geometry. Another argument would involve so called negative evidence, e.g., Ram Datt and Varghese (1972) report on an unsuccessful search for PKP precursors from Nevada explosions recorded at GBA (at a distance of nearly 128°). More quantitative evidence of lateral variations is given by the large azimuth deviations of some groups of precursors at NORSAR whereas for YKA, no consistently large deviations have been observed.

In summary, the characteristics of the YKA data may be well explained by any of the models involving slight lower mantle heterogeneity and/or a slightly rough CMB, whereas some groups of NORSAR data require laterally limited regions of stronger heterogeneity. The implied large scale lateral variations in the amount of heterogeneity seems to be confirmed in this comparison of different array data, sampling different regions of the lower mantle and CMB. The difference in relative energy between YKA and NORSAR precursors is particularly pronounced (10–15 dB) and leads to the mapping of relatively "smooth" regions (beneath the S. Sandwich Islands and Central N. America, from YKA data), and "rough" regions (beneath the Fiji Islands and Fennoscandia, from NORSAR data).

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