Evidence for Inhomogeneities near the Core-Mantle Boundary [and Discussion]

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Evidence for inhomogeneities near the core–mantle boundary

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Detailed analysis of observed short-period precursors to the seismic phase PKIKP indicates that the precursors are generated by seismic wave scattering from structural inhomogeneities near, or bumps on, the core-mantle boundary. Analysis of PKIKP precursor wavetrains observed at the Norwegian seismic array, Norsar, shows that observed precursors generally arrive from only very limited parts of the full ranges of arrival directions theoretically possible. In some cases the observed arrival directions of precursors migrate systematically with time along the wavetrains. The detailed characteristics of the data can be modelled in particular cases by postulating distributions of structural inhomogeneities that have either strong regional variations or strongly directional character. Theoretical calculations indicate that observed amplitudes of precursors require lateral length scales for the inhomogeneities not exceeding a few tens of kilometres. There is a suggestion that in some cases the observed scattering may occur at lateral boundaries of regions of much larger extent.

1. INTRODUCTION

The boundary separating the Earth's solid mantle and liquid outer core (hereafter referred to as the c.m.b.) is by far the most extreme discontinuity inside the Earth. Evidence from the seismic phases P and PcP indicates that the main transition from solid to liquid at the c.m.b. occurs abruptly at a depth of about 2890 km. In addition to this major discontinuity, other seismic evidence indicates the existence of a gradual transition region about 100–200 km thick at the base of the mantle (designated as region D″) in which the physical properties of the mantle tend towards those of the core by as much as about 2 or 3 %.

Until about 10 years ago all commonly observed seismic body wave phases were interpreted in terms of spherically symmetrical layered Earth models. Subsequent detailed analyses have shown, however, that certain observed core phases previously interpreted in this way originate instead by seismic wave scattering from structural inhomogeneities in the vicinity of the c.m.b.

The scattered wave phases are associated with regular seismic phases that pass through or are reflected from the c.m.b. So far the most definitive evidence on both the existence and characteristics of inhomogeneities near the c.m.b. has come from detailed analysis of seismic array data on precursors associated with the seismic phase PKIKP. In this paper an account will be given of the principal characteristics of observational data on these precursors and their interpretation in terms of the characteristics of the inhomogeneities responsible.

Detailed information on the characteristics and distribution of inhomogeneities near the c.m.b. is likely to be of fundamental importance in theories concerning the geodynamical processes thought to occur inside the Earth.

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2. Precursors to PKIKP

(*a*) *Paths of observed seismic core waves*

The propagation of short period seismic body waves inside the Earth is most conveniently described in terms of geometric ray theory. Figure 1 shows a family of rays for PKP waves which have their lowest points in the outer core. The ray OA, which in the mantle is at just greater than grazing incidence on the c.m.b., emerges at an epicentral distance $\varDelta$ near 180°. With steepening angles of incidence on the c.m.b., the depth of penetration of the rays increases and the epicentral distance of emergence first decreases to a minimum of about 143°, whereupon it then increases back to about 153° (corresponding to the ray that grazes the inner core). Figure 2 shows the principal t–$\varDelta$ branches for core phases of P-wave type. The branches AB and BC (which together are designated as PKP) correspond to the rays forming the caustic shown in figure 1, while the branches CD (PKiKP) and DF (PKIKP) correspond, respectively, to rays that are reflected at and pass through the boundary of the inner core.

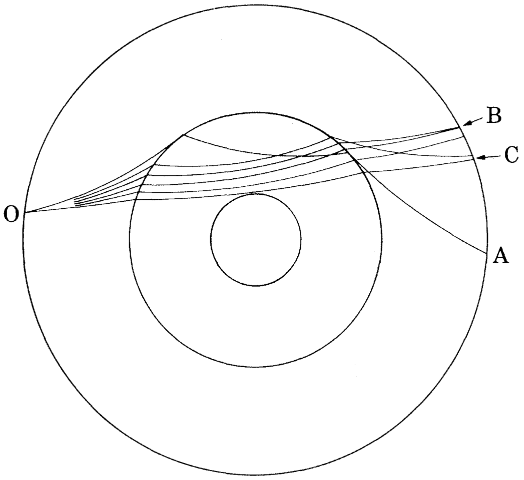

Figure 1. Rays for PKP waves in a spherically symmetrical Earth model.

In addition to these major phases there is also commonly observed a relatively small amplitude phase arriving as a first arrival by as much as about 20 s earlier than the phase PKIKP at epicentral distances between about 125° and 143°. Early interpretations of the origin of this precursor phase (as it is commonly called) have included frequency-dependent refraction in the outermost part of the inner core (Gutenberg 1957), diffraction associated with the PKP caustic (see, for example, Bullen & Burke-Gaffney 1957), refraction by one or more postulated transition layers surrounding the inner core (see, for example, Bolt 1962, 1964; Adams & Randall 1964) and reflexion from the boundaries of one or more of such transition layers (Sacks & Saa 1970; Buchbinder 1971). With the availability of high-quality array data during the last decade it has transpired that none of these proposed interpretations is tenable. The detailed characteristics of the data indicate, rather, that the precursors are generated by seismic wave scattering of the AB and BC phases by structural inhomogeneities in the vicinity of the c.m.b. (see, for example, Haddon 1972; Cleary & Haddon 1972; Doornbos & Vlaar 1973; King *et al.* 1973*a*, *b*; Haddon & Cleary 1974; Wright 1975).

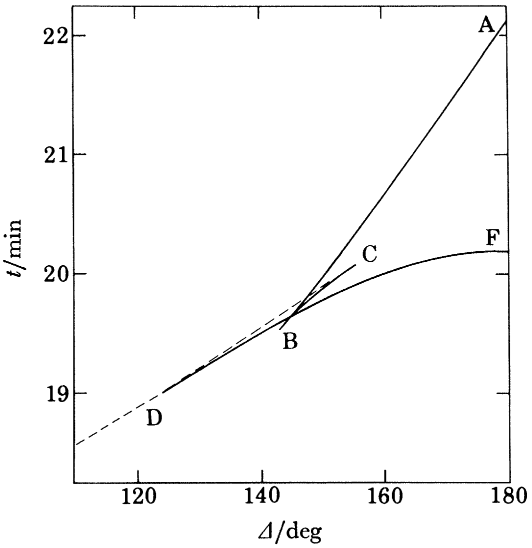

FIGURE 2. Travel time branches for core phases in a two-layer core model. The branch DF corresponds to the phase PKIKP. Observed precursors to PKIKP arrive up to 20 s before PKIKP in the distance range 125°–143°.

(*b*) *Scattering interpretation of precursors to PKIKP*

The existence of suitable structural inhomogeneities in the vicinity of the c.m.b. could evidently cause seismic wave energy to be scattered, with the result that energy could propagate from a seismic source near the Earth's surface to receivers on the Earth's surface along paths that differ from ray paths for a spherically symmetrical Earth model. Two such possible paths for scattered wave energy are shown schematically in figure 3. In the paths shown it is assumed that the energy propagates along ordinary PKP rays from the source to scattering points P and Q in the postulated inhomogeneous region and that the scattered waves generated then propagate along ordinary rays from P and Q to receivers on the Earth's surface. It is generally sufficient to restrict attention to scattered waves that result from single scattering events on either the source or the receiver sides of the c.m.b. (but not both). (On theoretical grounds amplitudes of multiply scattered waves would generally be much smaller than for singly scattered waves.)

The paths of the scattered waves arriving at a given receiver would not generally be confined to the diametral plane of the source and receiver. Figure 4 shows, for example, the theoretical ranges of arrival direction for waves scattered at the level of the c.m.b. for a receiver on the Earth's surface at an epicentral distance of 136°. Assuming a source pulse of short duration, each curve in the figure corresponds to a particular arrival time for scattered waves at the receiver. Each point on each curve corresponds to a pair of slowness and azimuth values that uniquely characterize the arrival direction of an 'elementary' scattered wave contribution originating by scattering at a single point on the c.m.b. The resulting signal arriving at the receiver may be regarded as the superposition of all such elementary scattered waves.

The curves shown in figure 4 are seen to belong to two sets. Those in the upper part of the figure correspond to scattering at points on the source and those in the lower part to scattering at points on the receiver sides of the c.m.b. The first elementary scattered wave arrivals from

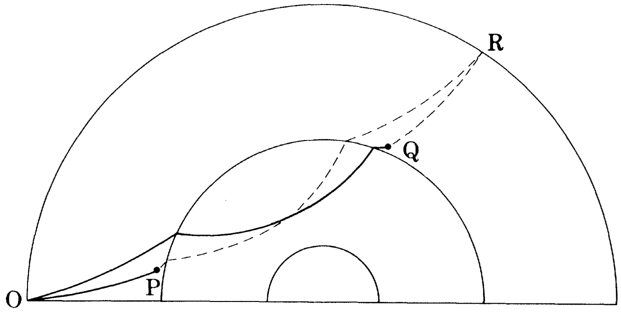

FIGURE 3. Schematic diagram showing paths for waves scattered before entry to and after exit from the core. The full lines show ordinary PKP rays from the source O to scattering points P and Q and the broken lines rays for scattered waves from P and Q to receiver R.

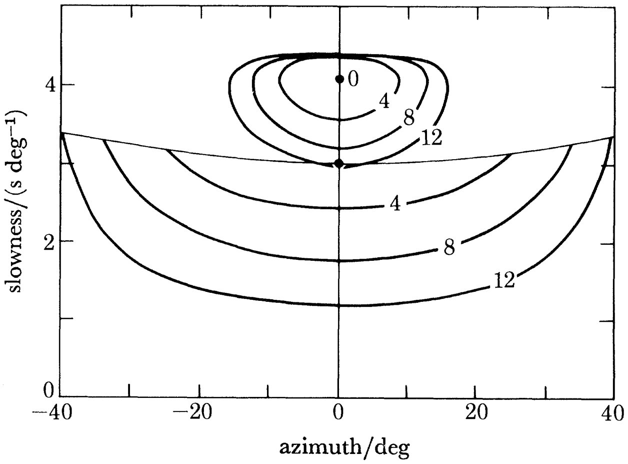

FIGURE 4. Ranges of slowness and azimuthal deviation of waves scattered at the c.m.b. arriving at a receiver at distance 136° from the source. The upper and lower fields correspond to scattering on the source and receiver sides of the c.m.b. The curves represent slownesses and azimuths of scattered waves arriving at the receiver at times 4, 8 and 12 s after the earliest scattered waves.

the source and receiver sides of the c.m.b. arrive simultaneously, both from true azimuth (i.e. in the diametral plane of the source and receiver) but with different slownesses – in this case about 4.0 and 3.0 s deg^{-1}, respectively. With increasing time the arrival directions of the elementary scattered waves change continuously: the curves in the figure indicate the instantaneous sets of arrival directions possible for simultaneously arriving sets of elementary scattered waves at 4 s intervals along the PKIKP precursor wavetrain.

For a uniformly random distribution of inhomogeneities on the c.m.b. the individual elementary scattered waves would generally differ in amplitude and phase as well as in arrival direction: in such circumstances the resulting signal consisting of the superposition of such waves might therefore be expected to exhibit fluctuations in amplitude and arrival direction as well as other interference effects. Systematic regional variations in the distribution or orientations of inhomogeneities, on the other hand, would be expected to exhibit more systematic effects. In the following section examples will be given of observational data exhibiting each of these kinds of behaviour.

(*c*) *Observational evidence on precursors to PKIKP*

High-quality recordings from medium and large aperture seismic arrays are a prerequisite for reliable interpretation of precursor phases. Up to now, recordings of suitably high quality have been obtained from arrays in Norway (Norsar), the U.S.A. (L.A.S.A.), Australia (Warramunga) and Canada (Yellowknife). In all reported cases the recordings obtained have discriminated decisively in favour of the scattering as against any of the earlier proposed interpretations of precursors to PKIKP. Although all the array data on scattered wave phases relate only to a tiny sampling of the entire c.m.b., the ubiquitous observation of precursors with similar characteristics at single seismic stations indicates that the existence of structural inhomogeneities near the c.m.b. is a geographically widespread phenomenon. Array observations of precursors are indispensible, however, in that they alone can provide sufficiently detailed information to enable detailed characteristics of the inhomogeneities to be inferred.

The most detailed analyses on precursors to PKIKP yet carried out have been performed on data recorded at Norsar by using a technique called Beam Analysis or BEAMAN (King *et al.* 1976). In this technique distributions of 'power' as functions of travel-time, slowness and azimuth in recorded wavetrains are obtained by forming a large number of full array beams corresponding to the nodal points of a rectangular grid at spacings of approximately 0.4 s deg^{-1} in slowness and 3° in azimuth. Beam powers (energy per second) are estimated by summing the squared beam amplitudes over each second of beam for each nodal point and the results are displayed as contour power plots in slowness–azimuth planes.

Such BEAMAN analyses have been performed on a total of more than 50 PKIKP precursor wavetrains observed at Norsar. All of the wavetrains analysed provide clear evidence of scattered waves arriving from widely different directions. Some of the wavetrains also contain highly coherent arrivals, indicating that simultaneously contributing elementary waves arrive from relatively limited ranges of arrival direction. Selected BEAMAN results for an example in which precursor waves arrive from widely different directions are shown in figure 5. The power peak in frame *h* in figure 5 corresponds to the maximum power for the (unresolved) phases PKIKP and PKiKP. The power distribution in this frame is typical of any normal (i.e. non-scattered) reflected or refracted phase. In particular, it may be noted that there is a single power peak that is compact and symmetrical about its centre, which is located near a slowness of 2.0 s deg^{-1} and azimuth 31° (in good agreement with the theoretical values for the event). In sharp contrast, the power distributions for the precursor wavetrain (frames *a*–*g*) are complicated and change markedly from frame to frame. Such erratic behaviour is clearly indicative of waves arriving simultaneously from widely different directions with associated interference effects.

Examples of precursor wavetrains that exhibit dominant arrivals from limited ranges of arrival direction have been published by Husebye *et al.* (1976). In such cases there is generally a single dominant power peak in each BEAMAN frame. Of particular importance is the fact that the single dominant peaks do not usually have the same locations in successive BEAMAN frames but shift systematically from frame to frame as shown, for example, in figure 6. In this figure the locations of the centres of the dominant power peaks in successive 2 s BEAMAN frames are compared with corresponding sets of theoretical arrival directions for scattering at the c.m.b. for one of the examples given by Husebye *et al.* The results show that the 'instantaneous' arrival directions for successive 2 s intervals of the observed precursor wavetrain are fully

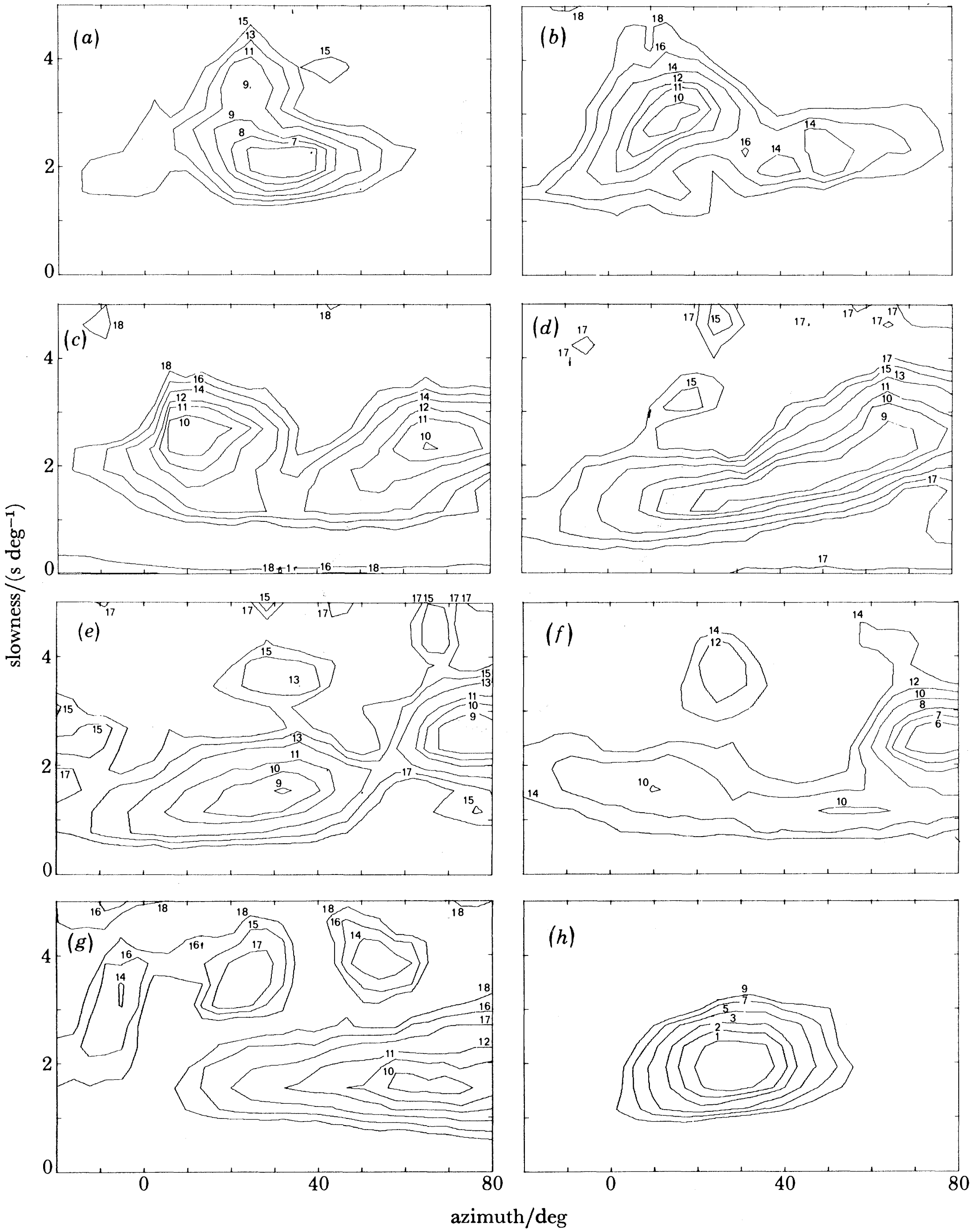

FIGURE 5. BEAMAN power distributions for 1 s intervals of a precursor wavetrain observed at Norsar. The contours represent power levels in decibels down from maximum observed power, which in this case corresponds to the arrival of PKIKP and PKiKP (*h*). Power peaks indicate the arrival of coherent energy and the locations of the peaks the directions from which the energy comes. Frames (*a*) to (*g*) correspond, respectively, to mean arrival times of 10, 9, 7, 6, 5, 4 and 3 s before that of (PKIKP+PKiKP) (i.e. frame (*h*)). Note the rapid changes in arrival direction of energy with time in the precursor wavetrain.

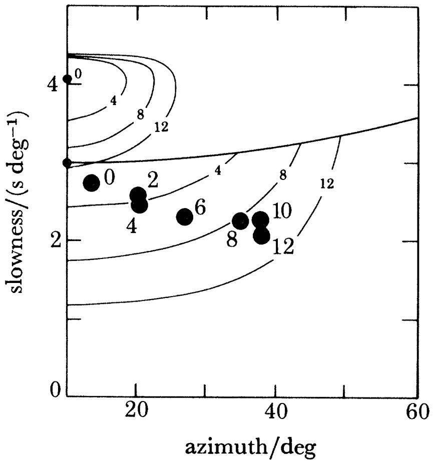

Figure 6. The black circles show the locations of the centres of dominant power peaks in successive 2 s BEAMAN frames for an example given by Husebye *et al.* (1976) in their Figure 6. The data refer to a PKIKP precursor wavetrain for an event at a distance of 136° from Norsar. The numbers 0, 2, 4, . . . represent time in seconds from the earliest theoretical arrival time for waves singly scattered at the c.m.b. Note the systematic migration of observed arrival direction with time and the extent of agreement between observed and theoretical arrival directions.

consistent with theoretical arrival directions for scattering at the c.m.b. The same is found to hold generally true for all reported array analyses of PKIKP precursor wavetrains at Norsar as well as at other arrays.

The maximum power intensity observed in each BEAMAN frame changes only gradually from frame to frame along the entire precursor wavetrain in each of the examples given above. In other observed cases, however, large sudden power intensity variations corresponding to large impulsive-like arrivals are observed (see, for example, Doornbos 1976; Husebye *et al.* 1976). Possible implications of the above observed precursor characteristics will be considered in the next section.

3. CHARACTERISTICS OF STRUCTURAL INHOMOGENEITIES NEAR THE C.M.B.

While seismic scattering by inhomogeneities in Earth structure near the c.m.b. is now well established as the generating mechanism for precursors to PKIKP, inferences on the nature of the irregularities responsible involve considerable uncertainties. The distinction arises because, on the one hand, the conclusion as to the scattering origin of precursors is firmly based on travel time and slowness–azimuth considerations. Inferences on the characteristics of the inhomogeneities responsible, on the other hand, are subject to questions of uniqueness as well as on our capability to compute seismic scattering reliably for particular postulated scattering structures.

On the question of uniqueness, while geometrical considerations indicate that observed precursors originate by scattering at or near the c.m.b., it remains uncertain as to whether the structural inhomogeneities responsible are primarily geometrical bumps on the c.m.b. or inhomogeneities inside the transition layer D'', or both. Wave theory calculations show that either of these kinds of irregularity could produce scattered waves of the kind observed (Doornbos 1978). It is very probable that both kinds of irregularity occur.

One conclusion that appears to be firmly established is that to account for observed precursor amplitudes, at least one of the lateral scales of the structural inhomogeneities must not be greater than a few tens of kilometres. Most previous attempts to model precursor wave generation have been based on the random medium scattering theory of Chernov (1960), which yields estimates of correlation distances for the random inhomogeneities in the range 10–30 km and variations in physical properties of 1–2% (Haddon & Cleary 1974; Aleshin & Vinnik 1975) and more (Doornbos 1976). Similar correlation distances are obtained for models involving random geometrical bumps on the c.m.b., with bump elevations of a few hundred metres (Doornbos 1978).

Although Chernov-type models usefully indicate characteristic scales and strengths of inhomogeneities required to account for observed precursor amplitudes, such models are essentially statistical in nature and they are not applicable for modelling structural inhomogeneities that give rise to transient precursor behaviour in particular cases. A problem of particular interest in this regard is to determine characteristics of particular inhomogeneous structures that can account for observed precursors whose instantaneous arrival directions migrate systematically with time along the precursor wavetrains in the manner described in §2*c*. A useful approach for this purpose has recently been developed by Haddon & Buchen (1981) based on Kirchhoff theory. The method enables precursor wavetrains to be synthesized in the time domain for certain simple kinds of specified irregular structure near the c.m.b. including, in particular, the case of bumps or corrugations on the c.m.b.

Preliminary results that I have obtained by this method have indicated that observed migrations in arrival direction of the kind described in §2*c* may be explained either (i) by models having distributions of inhomogeneities concentrated along lines (or in bands) on the c.m.b. or (ii) by models having distributions that are strongly directional in character (such as one-dimensional corrugations on parallel ridges on the c.m.b.). Various combinations of these characteristics would also, of course, be possible. In either case more than one lateral characteristic scale of inhomogeneity appears necessary. Finally, the observed large-amplitude impulsive precursors referred to in §2*c* can be explained by models of the second kind when a prominent one-dimensional structure is present. Impulsive-like arrivals are generated by such structures when the travel times of the elementary scattered waves originating at points along the one-dimensional structure have stationary values at a surface receiver. The results so far obtained indicate that many of the observed characteristics of precursors can be modelled by using the Kirchhoff method. A great deal more work will be needed, however, before any more definite conclusions can be drawn.

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Discussion

R. Hide, F.R.S. (*Meteorological Office, Bracknell, U.K.*) Professor Runcorn has suggested that I should give my present views on the production of bumps on the core–mantle interface and related matters. I am still of the opinion that the evidence supports the idea that viscous stresses associated with deep convection in the mantle are largely responsible for the production and maintenance of the bumps. I first advanced the hypothesis that there are bumps (i.e. departures from axial symmetry) on the core–mantle boundary of about a kilometre in vertical dimensions, and therefore beyond the limit of easy resolution by seismological methods, when I realized that the hypothesis can provide a basis not only for interpreting the highly variable frequency of geomagnetic polarity reversals if mantle convection is deep and intermittent, but also for accounting for the magnitude of the torques at the core–mantle interface that are implied by the so-called 'decade variations' in the length of the day without having to depend entirely on the electromagnetic torques first proposed by Bullard but later shown to be not quite strong enough.

Owing to the large density contrast between the core and mantle, bumps on the core–mantle interface would distort the gravitational field at the core–mantle interface, but only on horizontal scales that are comparable with or greater than the depth of the mantle. If the bumps are produced by mantle convection, their gravitational effects at the Earth's surface would be well correlated with gravitational effects associated with density variations distributed throughout the mantle.

Bumps would also affect the magnetic field of the Earth through their influence on core motions. Owing to the rapid rotation of the Earth, this influence could be considerable even with geometrically very shallow bumps. Thus it was argued that large-scale features of the Earth's gravitational and magnetic fields might be expected to show some degree of spatial correlation. This was subsequently demonstrated to be so (in work reviewed by Malin and myself in our joint contribution to this meeting). My original hypothesis gains further support from more recent work on theoretical models of magnetohydrodynamic flow over bumpy boundaries in a rotating fluid.

The seismological methods described in Dr Haddon's important contribution to this meeting are best suited to examining structure in the deep mantle on horizontal scales of about 10–30 km, which would have no perceptible direct influence on the surface gravitational field. His results do not rule out shallow bumps on much larger scales.

R. A. Haddon. I agree. The bumps proposed by Professor Hide are not in conflict with any available seismic evidence.

M. F. Osmaston (*The White Cottage, Sendmarsh, Woking, Surrey, U.K.*). I wonder if these multiple precursor paths could be due to irregular solid deposits of differentiates from the convecting core fluid that have been frozen or precipitated at the core boundary. If so, their density and seismic velocity could well be intermediate between those of the core and of the lower mantle proper. Thus from a seismological viewpoint they would probably lie outside the core–mantle boundary and so would give rise to precursors of PKP. On a timescale of years rather than seconds, however, drift of the core flow temperature pattern might make such deposits susceptible to thermal erosion by and redeposition from the core fluid flowing past them; so, functionally, they might have to be regarded as still part of the core.

On this model, what velocity contrast between lower mantle proper and these deposits can be inferred from the precursor energies? Hence can Dr Haddon estimate the thickness differences and thickness gradients of the deposits that might fit his observations?

R. A. Haddon. Any kind of structural irregularity near the core–mantle boundary, including those of the kind suggested by Dr Osmaston above, could theoretically account for observed PKP precursor amplitudes if the velocity contrast, depth range and scales of the irregularities are suitable. It is not possible to estimate both the velocity contrast and depth range simultaneously from precursor amplitude data, because thin layers with large velocity contrasts and thicker layers with smaller velocity contrasts can have similar far-field wave scattering effects. To obtain an estimate of the least thickness variation of solid differentiates required in Dr Osmaston's proposed model, however, it would be reasonable to assume as an extreme case that the properties of the differentiates are identical to those of the mantle. On this assumption the differentiates would be effectively bumps on the core–mantle boundary, in which case results referred to in the paper indicate that the thickness differences required would need to be of the order of at least several hundreds of metres.