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Seismic Observations of Structure and Physical Properties of the Subcrustal Lithosphere as Evidence for Dynamical Processes in the Upper Mantle

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Observations of body waves from explosions and earthquakes have revealed recently some unexpected properties of the lower lithosphere: P-wave velocities definitely larger than 8.2 km/s and anisotropy with velocities dependent on the azimuth of propagation both under oceans and continents. A model of the subcrustal lithosphere with pieces of laminas of high velocities is proposed to explain the transmission of high-frequency P_n and S_n to teleseismic distances and the tunneling of low-frequency body waves through the subcrustal lithosphere. The preferred orientation of these laminas is probably achieved by the same mechanism which produces the anisotropy.

The observations of high velocities in the lower lithosphere is evidence in itself that anisotropy is present there. Since the direction of maximum velocity correlates in the ocean and on the continent with a number of tectonic features, a causal connection between anisotropy and dynamical processes related to plate motion must be suspected.

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Seismic Anisotropy – a Summary

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The matrix formulation of Crampin (1970), and the decomposition of the elastic tensor into three-by-three sub-matrices (Taylor and Crampin, 1977; Crampin, 1977), permit numerical calculation of both body and surface wave propagation in simple layered anisotropic structures (Keith and Crampin, 1977a, 1977b, 1977c; Crampin and Taylor, 1971; Crampin and King, 1977). The general principles of propagation in anisotropic structures are well understood from these studies, but the effects of the anisotropy on the behaviour of the waves are often subtly different from the corresponding isotropic propagation.

The best known of these differences is that, in the presence of anisotropy, there are azimuthal variations in the velocity of body waves and the dispersion of surface waves. These are difficult to observe in the earth except in particular uniform structures. Such velocity anisotropy in the upper mantle has now been observed many times in refraction experiments at sea, in West Germany (Bamford, 1977), and velocity anisotropy of the dispersion of the Fundamental Rayleigh mode has been observed in the NAZCA plate in the Pacific Ocean (Forsyth, 1975).

Refraction experiments are, perhaps, the most direct way of measuring the variation of velocity within the earth, but they can only give reliable measurements in relatively homogenous areas, and are expensive to perform. It can be shown (Crampin, 1977) that observations of P-wave velocity in a single plane of weakly anisotropic (less than 7% velocity anisotropy) have a relatively simple form:

$$\rho c^2 = A + B\cos 2\theta + C\cos 4\theta,$$

where c is the phase velocity, θ is the azimuth measured from a direction of sagittal symmetry, and A, B, and C are simple linear combinations of the elastic constants. Even when A, B, and C are well determined by the observations, they contain very little information about the elastic constants, or the constituent anisotropic structure (Crampin and Bamford, 1977), but do, of course, identify the symmetry direction.

The most distinctive characteristics, which distinguish propagation in anisotropic material from the corresponding isotropic propagation, are polarization anomalies, where the Rayleigh motion is coupled to the Love, and the P and SV motion is coupled to the SH. The coupling of Rayleigh and Love motion by anisotropy in the upper mantle is most clearly displayed by the Third Generalized mode; the equivalent of the Second Rayleigh mode in an isotropic earth (Crampin, 1975). Such polarizations have been observed along a network of paths covering a large part of Eurasia (Crampin and King, 1977), bounded by the Alpine and Himalayan mountains on land, and the 1000 m depth contour at sea. Such studies are limited by the homogenity of the structure necessary for higher mode propagation, and the difficulty of observing higher modes on conventional photographic seismograms.

Body wave polarization anomalies caused by anisotropy have only recently been recognised and synthesized (Keith and Crampin, 1977c), and have not yet been sought on seismic records. The P, SV, and SH coupling arises because there are 3 body waves propagating in any direction in anisotropic material (a quasi-P wave, and two quasi-shear waves) with orthogonal polarization. The polarizations are fixed by the alignment of the direction of propagation to the symmetry planes of the anisotropic structure, and not by the interface reactions, or the polarization of the incident wave. Synthetic seismograms show that the coupling produces small but significant P→SH and SH→P, and large SV→SH and SH→SV conversions at each isotropic/anisotropic interface, for all directions of propagation except those with sagittal symmetry. Along directions of sagittal symmetry the P and SV waves are decoupled from the SH waves as in isotropic material, although the individual equations of motion may be very much more complicated (Crampin, 1976). The polarization anomalies are very sensitive to the presence of even very weak anisotropy (Crampin, 1977), and it is suggested that analysis of polarization anomalies may be a powerful technique for examining earth structure.

Although the principles of propagation in anisotropic material are understood, the effects of anisotropy are varied and difficult to predict, and numerical calculation is necessary for the description of the behaviour of almost every anomaly. The solution of many problems, that can be solved in isotropic structures, can now be formulated in anisotropic structures, and solved, subject to the need for numerical calculation at an earlier stage in the manipulation. It is unfortunate that the seismologist's usual response is that the earth is largely isotropic, and that anisotropic studies are an unnecessary complication. Many anisotropic problems can now be solved exactly; it is only the effects that are complicated. P-wave arrival times are rather insensitive (except in refraction and reflection experiments) to the velocity variation within the earth, and the presence of an anisotropic layer in the lithosphere (a very plausible concept) may provide a simpler explanation of many arrival time anomalies than previous descriptions requiring scattering, heterogeneous, and discontinuous phenomena.

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Precise Continuous Monitoring of Seismic Velocity Variations

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Seismic velocities in the siting area of the Norwegian Seismic Array (NORSAR) have been monitored over a time period of one week using a hydroelectric power plant as a continuous wave generator. Propagational phase angle differences have been measured over travel distances ranging from 4.7–13.7 km, and group velocities of the order of 3.5 km/s are derived. This is close to the expected (phase) velocity for S-waves, and the particle motions derived at a distance of 4.7 km correspond also well with those for S-waves. The obtained precisions are 10^{-3} for a time period of about 2 h and 10^{-4} when one week of data are used. The phase difference data contain a semidiurnal spectral component with a peak-to-trough amplitude of around 10^{-3}.

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