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Structure of the Earth: Mantle and Core

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Abstract. The deep interior structure of the earth has been extensively analyzed using a wide variety of seismic phases and techniques during the last four years. Most studies have emphasized quantitative three-dimensional mapping of the lateral velocity heterogeneity of the mantle and core. These aspherical velocity variations are believed to be direct manifestations of thermal and compositional heterogeneity associated with convective processes. A first generation of global models for the lateral velocity variations in the deep earth has been produced, providing tantalizing images of large scale structures suggestive of a non-steady state thermal convection system.

The upper 400 km of the mantle has the strongest lateral velocity variations, of up to ±10% for shear velocity. Surface-wave analyses that do not require *a priori* regionalizations have demonstrated that there is a strong association between surface tectonic provinces and the uppermost mantle velocity variations. Thus, the thermal and convective state of the upper 200 km of the mantle can be reliably interpreted in the context of plate tectonics. The upper mantle models support the contention that continents have deep roots, with differences in velocity structure from oceanic and active tectonic regions extending as deep as 400 km. Very long-wavelength lateral velocity variations of a few percent have been detected in the transition zone at depths from 400 to 670 km, as well as throughout the lower mantle. These deep-seated variations have little correspondence to surface tectonics, and efforts to interpret their nature are just beginning. The lowermost 200 km of the mantle (D″ region) has lateral velocity fluctuations comparable to those in the upper mantle, and evidence has been presented for the presence of a sizable velocity discontinuity at the top of the D″ layer. A combined thermal and compositional boundary layer, roughly mirroring the lithosphere, is a likely explanation for this anomalous zone. The core-mantle boundary appears to have significant (10 km) long-wavelength topography, presumably sustained by dynamic stresses from deep mantle convection. The inner core may have strong lateral heterogeneity or axially symmetric anisotropy, suggesting a complex thermal and compositional state.

Significant progress has been made in characterizing the frequency dependence of anelastic attenuation in the mantle in the short-period body-wave band. Models for teleseismic P-wave attenuation operators have converged, with t^* values of 0.7-1.0 s appropriate at 1 Hz, and t^* values of 0.4-0.6 s appropriate at 4 Hz. Regional variations of attenuation are slowly being mapped out as well.

MANTLE STRUCTURE

An unprecedented increase in our knowledge of mantle structure has been achieved in the last four years. A broad spectrum of seismological techniques, including body-waveform modeling, global travel-time inversion, surface-wave dispersion and waveform inversion, and normal-mode splitting analysis, have been brought to bear upon the problem of mapping the velocity deviations from radially symmetric earth structure in the deep interior. While this lateral velocity heterogeneity is relatively small, typically being only a few percent variation about the average earth model, its significance is profound. This is because the velocity variations are signatures of thermal, compositional, and crystal orientation differences, all of which are associated with mantle dynamics. Accurate three-dimensional imaging of the heterogeneity thereby provides the most direct means for determining the configuration of mantle convection systems. The seismological models also serve as critical constraints for geodynamic and geochemical modeling of the earth, and are resulting in increasing interdisciplinary interaction. Perhaps the most important inference to be drawn from the first generation of global models is that the rich complexity of the interior indicates a non-steady system, for which simplistic notions of steady-state flow may be inapplicable.

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Surface-Wave Tomography

The accumulation of a substantial data base of long-period digital recordings from Global Digital Seismic Network (GDSN) and International Deployment of Accelerometers (IDA) instruments has enabled, for the first time, systematic analyses of surface-wave dispersion on a global scale. Additional large data bases of body-wave travel-times collected by the ISC or from special readings of WWSSN recordings have enabled corresponding global and continental scale body-wave investigations. The process of inverting these large sets of path anomalies for a heterogeneous model has been called seismic tomography [Anderson and Dziewonski, 1984; Dziewonski and Anderson, 1984]. Several different procedures have been used to analyze the surface-wave observations. One procedure involves the standard analysis of isolated fundamental-mode wavetrains to extract phase and group velocities, which are subsequently inverted for upper mantle structure. Another procedure involves direct waveform modeling of the entire seismic trace, including overtones and amplitudes. The latter procedure directly results in a velocity structure, but must be performed iteratively, and has so far been implemented only with asymptotic approximations to the normal-mode theory of Woodhouse and Girnius [1982] that make it almost equivalent to the step by step dispersion analysis.

Nakanishi and Anderson [1982, 1983, 1984a,b] adopted the approach of inverting the dispersion measurements for spherical harmonic expansions of Love- and Rayleigh-wave phase and group velocity up to degree and order 6. By measuring both odd and even orbit arrivals at single stations, the odd harmonics of the expansion can be determined, albeit with greater uncertainty than for the even harmonics, which are constrained by more accurate great-circle measurements. The spherical harmonic expansions do not require an *a priori* tectonic regionalization. Nataf et al. [1984, 1986] inverted the dispersion measurements for transversely isotropic models that explicitly include shear-wave and compressional-wave anisotropy. Other inversions of the dispersion data were performed by Tanimoto [1985, 1986b] and Tanimoto and Anderson [1984, 1985]. The analyses by Tanimoto utilized Backus-Gilbert inverse theory to appraise the issue of error and resolution of the phase velocity models and associated shear velocity inversions. The error analysis illustrated the significance of the antipodal peak in the resolution kernel, which, in combination with statistical errors, seriously limits the resolvable anomalies. The resolution kernel for the data sets of 400 (Love) and 600 (Rayleigh) phase velocity measurements used in these studies is localized within an area of 2000 km radius. Limited azimuthal path coverage of most areas of the earth prevents inversions for global azimuthal anisotropy at present [Tanimoto and Anderson, 1985], and differences in the depth resolution of the Love (SH) and Rayleigh (P, SV) modes leaves open the question of how well transverse isotropy below 200 km can be resolved with the current data [Tanimoto, 1986b].

Woodhouse and Dziewonski [1984] and Woodhouse [1984] used a much larger data set of waveforms from 53 earthquakes and 870 paths in a complete waveform inversion procedure. The inversion resulted in a global shear-wave velocity model with a spherical harmonic expansion up to degree and order 8, and a cubic polynomial description with depth for the upper 670 km of the mantle. Their analysis was restricted to signals with periods longer than about 135 s, close to the 150 s cutoff of the dispersion analyses.

The very long-wavelength features in the models obtained from the dispersion and waveform procedures are remarkably similar, suggesting that first-order characteristics of the actual mantle structure have been resolved. All of the inversions have demonstrated that the strongest heterogeneities are in the upper 250 km of the mantle, and these have a strong correlation with surface tectonic features. Ocean ridges and west Pacific subduction zones are underlain by slow velocities, while all major shields have fast velocity roots, some of which extend to at least 350 km depth. The South Atlantic has relatively high velocities at shallow depths, and low velocities under the Red Sea and Gulf of California persist to 400 km depth. Below 250 km many portions of ridges are underlain by high velocity regions, notably the South East Indian Ridge. Many of these features would not have been anticipated in *a priori* regionalized models. The anisotropic inversions of Nataf et al. [1986] suggest a belt of SV>SH anisotropic velocities at depths of 200 to 400 km following the circum-Pacific ridge and subduction systems, suggesting vertical flow; however, similar features were not resolved by Tanimoto [1986b]. The procedure used by Woodhouse and Dziewonski [1984] appears to resolve mantle structure at somewhat greater depths due to the inclusion of overtone data, and their model shows a strong degree-2 component in the transition zone (400-670 km) with broad regions of high velocity under South America and the South Atlantic and under the western Pacific, and broad regions of low velocities under the central and eastern Pacific and under the Middle East. The velocity anomalies in these models are on the order of $\pm 8\%$ at 50 km depth, $\pm 2.5\%$ at 450 km, and $\pm 1\%$ at 650 km.

The global models indicate, but have limited resolution of fine features such as the evolution of velocity structure of oceanic lithosphere with age. Greater resolution of oceanic structure, particularly for the Pacific Ocean, has been obtained in the regionalized dispersion studies of Anderson and Regan [1983], Regan and Anderson [1984], Chao et al. [1983], Dziewonski and Steim [1982], Knopoff [1982], Nishimura and Forsyth [1985, 1986], and Rosa and Aki [1986]. Detailed continental dispersion analysis of the crust and upper mantle under Eurasia was performed by Feng and Teng [1983]. Improving the spatial resolution of both the global and smaller scale inversions requires the use of shorter period data, but the great-circle path assumption employed in the dispersion and waveform modeling procedures has dubious validity for periods less than 150 s. Several studies have addressed the great-circle assumption using surface-wave raytracing [Lay and Kanamori, 1985; Schwartz and Lay, 1985; Tajima and Garmany, 1986; Wong and Woodhouse, 1983], and by appraising the effects of heterogeneity on moment tensor inversions [Nakanishi and Kanamori, 1982; Tanimoto and Kanamori, 1986]. The recognition that strong amplitude and phase effects due to departure from great-circle paths can occur for periods as long as 300 s has led to efforts to directly utilize the focussing and defocussing information in inversions for the heterogeneous models [Wong and Woodhouse, 1986; Yomogida, 1985; Yomogida and Aki, 1985, 1986]. In a parallel development, Tanimoto [1984] obtained degree-2 Love-wave models using a Born approximation in a waveform inversion procedure that explicitly utilized long-period amplitude information.

Other surface-wave procedures for improving the resolution of the upper mantle models have involved detailed analysis of overtones, which sample the transition zone more completely than the fundamental-modes. Lerner-Lam and Jordan [1983] extracted the higher-mode information using branch cross-correlation functions between single-mode branch synthetics and the observed seismograms. This procedure was used to develop upper mantle shear velocity structures across Eurasia and the eastern Pacific. The resolution capability of this procedure was analyzed by Gee and Jordan [1986], and an extension to anisotropic inversion was considered by Lerner-Lam [1986]. Okal and Jo [1983, 1985] have analyzed dispersion characteristics of longer period spheroidal overtones. One of the most promising procedures appears to be inclusion of body-wave and early overtone signals in the global surface-wave inversions, as shown by Woodhouse and Dziewonski [1986]. Further progress will be possible as instruments which remain linear for the first surface-wave arrivals from large earthquakes are deployed.

Free-Oscillations

The surface-wave investigations described above have proven most fruitful in leading to models of upper mantle heterogeneity because of asymptotic approximations for the traveling waves which lead to straightforward data analysis and inversion. Analysis of the splitting of normal-mode spectra due to ellipticity, rotation and lateral heterogeneity is also beginning to yield aspherical earth structure models, and formalisms are being developed that should eventually lead to non-asymptotic inversions.

Masters et al. [1982] inverted multiplet locations for the degree-2 spherical harmonic component of the earth's heterogeneity. Their preferred model localized the heterogeneity in the transition zone, with shear velocity variations on the order of 1.7%. This interpretation was questioned by Kawakatsu [1983], who showed that some regionalized models of shallow heterogeneity have a correspondingly strong degree-2 component, but the transition zone feature was also obtained in the surface-wave inversion by Woodhouse and Dziewonski [1984]. Giardini et al. [1986] have recently inverted split-mode data for mantle heterogeneity models, finding that small perturbations about the surface-wave derived models can explain the mode data that are sensitive to the upper mantle.

Other free-oscillation research has concentrated on mode-coupling considerations, which have proved more significant than was previously recognized, and on procedures for calculating the normal-modes for an aspherical earth model. Tanimoto and Bolt [1983] analyzed coupling of toroidal-modes, and Masters et al. [1983] presented observations of coupling between spheroidal- and toroidal-modes at very low frequencies. Theoretical treatments of the aspherical earth calculations have been presented by Dahlen and Henson [1985], Morris and Geller [1982], Park [1986], Park and Gilbert [1986], Tanimoto [1984], and Tsuboi et al. [1985]. Davis [1985] has considered variations in apparent attenuation resulting from lateral heterogeneity, and Davis and Henson [1986] addressed the validity of the great-circle assumption for normal-mode measurements.

Efforts to refine radially symmetric mantle models and mode measurement procedures have been presented by Davis [1986], Henson [1982] and Masters and Gilbert [1985]. The effects of anisotropy on the normal-modes has been considered by Anderson and Dziewonski [1982] and Tanimoto [1986a]. The development of normal-mode partial derivatives for general anisotropy will be important for the next generation of upper mantle surface-wave and normal-mode inversions for anisotropic velocity structure.

Body-Waves

A variety of body-wave phases have been analyzed to determine both radial and lateral velocity structure in the upper mantle. WWSSN recordings of long-period transverse component S and SS phases have been particularly fruitful. A series of waveform modeling studies of these phases by Given [1983], Grand and Helmberger [1984a,b, 1985], Graves et al. [1985], Helmberger et al. [1985a,b], and Rial et al. [1984] has led to detailed shear velocity models for tectonic regions, shield regions, young and old oceanic provinces, and the transitional zones connecting tectonic provinces. These studies have not only refined our knowledge of the size of upper mantle discontinuities and of the velocity gradients between them but have also established that continental roots persist to 400 km depth and that 10% lateral variations in shear velocity exist near 200 km depth. Travel-time anomalies for the SS reverberations have been used to develop continental scale images of the upper mantle heterogeneity beneath North America [Grand, 1986a,b] the Atlantic [Kuo et al., 1986], and the Indian Ocean [Stark and Forsyth, 1983], with a resolution that is not viable with the global surface-wave inversions. Corresponding PP-wave analysis has just begun [Lefevre and Helmberger, 1984].

Analysis of short-period P-waves recorded by the large Southern California array has resulted in models of the lateral heterogeneity under California, as well as radial P-wave models for the upper mantle structure of a tectonically active region. Humphreys et al. [1984] used tomographic inversion to refine the image of a high velocity anomaly in the upper 300 km beneath the Transverse Ranges. Walck [1984, 1985] and Walck and Clayton [1984] analyzed a dense array of data from the upper mantle triplication range to develop radial P-wave velocity models, placing tight constraints on the upper mantle velocity gradients and size of the discontinuities at 400 and 650 km depth. These models, together with the S-wave structures from the SS analyses have been used to bound petrological models for the upper mantle by Anderson and Bass [1984], Bass and Anderson [1984], and Jeanloz and Thompson [1983]. Underside reflections of P'dP' have also been analyzed to appraise the sharpness of the discontinuities [Lees et al. 1983; Murtha and Tanimoto, 1982], as have long period ScS-type reverberations [Revenaugh and Jordan, 1985].

An increasing number of studies are attempting to extract upper mantle structure from SV component recordings, which have always been more difficult to interpret than the SH signals. Baag and Langston [1985a,b,1986], Baumgardt and Alexander [1984], Langston and Baag [1985], and Zandt and Randall [1985] have performed modeling calculations for Sp and SPL phases that are particularly sensitive to uppermost mantle structure. Propagation of S-waves in heterogeneous media has been considered by Cormier [1984, 1986], who appraised the effects on the S-wave polarization. Observations of S-wave splitting attributed to anisotropy were presented by Ando et al. [1984].

Body-wave travel-time and amplitude station anomalies have been used to investigate upper mantle heterogeneity on a variety of scales. Taylor [1983], Lynnes and Lay [1984], and Priestley and Chavez [1985] have considered the travel-time and focussing effects of upper mantle heterogeneity beneath the Nevada Test Site, which appears to be related to deep roots of the caldera system in the region. Michaelson and Weaver [1986] analyzed upper mantle structure under the Pacific Northwest using travel-time delays. Variations of P-wave amplitudes and travel-times across the North American continent have been considered by Butler [1983, 1984a,b, 1985] and Lay and Helmberger [1983a], while global P-wave [Dziewonski and Anderson, 1983] and S-wave [Souriau and Woodhouse, 1985] travel-time anomalies have been presented and related to temperature and compositional variations.

Slab Structure

Subducted oceanic lithosphere constitutes the strongest localized velocity heterogeneity in the upper mantle. Numerous seismicity and body-wave travel-time studies have addressed subducting slab geometry and velocity structure. Complexity of the stress state in subducted slabs has been revealed by studies of the multiple Benioff zones found in some slabs [Kawakatsu, 1985, 1986a,b; Kawakatsu and Seno, 1983; Cahill and Isacks, 1986; Taber and Hudnut, 1984], as well as by studies of focal mechanisms and seismicity levels [Giardini and Woodhouse, 1984; Vassiliou, 1984; Vassiliou et al., 1984]. The configuration of various subducted slabs, as indicated by seismicity and velocity heterogeneity, has been analyzed by Boyd et al. [1984], Chiu et al. [1985], Cockerham [1984], Grange et al. [1984], Hauksson [1985], Roecker [1985], and Rohay [1982]. Several studies have addressed the effects of slab heterogeneities on propagating waves as well [Bolt and Drake, 1986; Langston and Arnold, 1982].

The most significant advances in our knowledge of slab structure concern the depth of penetration and sharpness of the velocity gradients of the slab. Creager [1984] and Creager and Jordan [1984, 1986a] analyzed travel-time residual patterns from intermediate and deep focus earthquakes in western Pacific subduction zones, finding systematic patterns that can be well explained by thermal models of subducting slabs that penetrate into the lower mantle to depths of at least 1000 km, well below the depth of the deepest earthquakes [Stark and Frohlich, 1985]. Similar analyses of travel-time residual patterns for events in Tonga [Fischer et al., 1986] and the Aleutians [Spencer and Engdahl, 1983; Boyd and Creager, 1986] also indicate aseismic extensions of the slab velocity anomaly below the maximum depth of seismicity. Other investigations of the sharpness of the velocity gradients in the slab [Stefani et al., 1982]; the velocity structure in the mantle surrounding the slab [Suyehiro and Sacks, 1985]; and anisotropy of the slab itself [Anderson, 1986], have not refuted the lower mantle slab penetration hypothesis. Silver and Chan [1986] and Beck and Lay [1986] have analyzed waveform complexity in broadband S waves that appears to arise from interaction of the waves with strong velocity heterogeneity in the lower mantle. Azimuthal patterns and travel-time correlations in these data are consistent with multipathing in a lower mantle slab extension. Although further work on the slab penetration hypothesis is clearly needed, it presently appears that a strong case has been made for mass flux across the 650 km discontinuity, which has profound consequences on the issue of whole mantle versus layered convection.

Lower Mantle Structure

In addition to the slab structures that appear to extend into the lower mantle, velocity heterogeneity at a variety of scales has been detected below the 670-km discontinuity. Surface-wave analysis cannot be used to determine the structure in the lower mantle, but body-wave travel-times reveal both small and large scale variations. Localized velocity heterogeneities with scale lengths of about 1000 km and 2% velocity heterogeneity were detected beneath the Caribbean and South America by Lay [1983], using S and ScS travel times from WWSSN recordings. A high velocity anomaly beneath the Caribbean at depths of 800 to 1900 km was found to extend northward, with a systematic offset to the east with increasing depth, in the tomographic inversion by Grand [1986a]. A similar, elongate high velocity ridge beneath Alaska is apparent in the recent inversions of Woodhouse and Dziewonski [1986], which incorporated body-wave data in the global inversion. The geodynamic significance of these structures is not yet established.

Several studies have used the vast travel-time data base accumulated by the ISC to investigate lower mantle structure. Lee and Johnson [1984a,b] established extremal bounds on radial velocity models for the lower mantle using Tau-p measurements from the ISC travel times. Dziewonski [1984] used a time-term approach to analyze about 500,000 travel-time residuals from 5000 earthquakes in deriving an aspherical P velocity model for the lower mantle. The model was represented by spherical harmonics up to degree 6 and radial order number 4. The earthquakes were relocated in each iteration for the structure, and weighting schemes were used to suppress the aliasing due to non-uniform coverage of the interior. The model has strong velocity perturbations of 1-1.5% just below the 670-km discontinuity and just above the core-mantle boundary. At a depth of 2000 km the perturbations in velocity are about 3 to 4 times smaller than at the two boundaries. Qualitatively similar results were obtained in the ISC travel-time inversions of Clayton and Comer [1983] and Comer and Clayton [1986], who used a tomographic procedure with blocks rather than an analytic representation. This procedure provides higher spatial resolution, and can easily be extended to include travel-times from phases other than P [Zhou and Clayton, 1985]. The low order variations of the two approaches are quite similar, and have been shown to successfully predict long-wavelength components of the geoid under the assumption of a dynamic, viscous earth by Hager et al. [1985], who applied the theory of Hager [1984] and Richards and Hager [1984]. The large-scale velocity variations apparent in these models do not have any simple relation to surface tectonics, and appear to have much greater complexity than anticipated for a simple, steady-state convection system. Two possible interpretations are that there are significant compositional heterogeneities entrained in the flow [Davies, 1984], or alternatively, the flow is not steady-state at all.

Structure near the Core-Mantle Boundary

While the global tomographic inversions can resolve the presence of large-scale heterogeneity near the base of the mantle, other procedures are required to model the detailed structure. Accurate velocity models are needed in order to assess recent thermal calculations that predict a major, unstable thermal boundary layer at the base of the mantle that serves as a source of thermal plumes [Boss and Sacks, 1985; Loper, 1984; Loper and Stacey, 1983; Stacey and Loper, 1983]. Short-period P-waves near the onset of the core shadow zone indicate substantial lateral variation in average radial structure of the lowermost 200 km of the mantle (D″ region) [Ruff and Lettvin, 1986]. Model experiments have been conducted by Menke [1986a,b] to assess the behavior of short period PcP phases. PKP phases have also been analyzed, and appear to require short scale length heterogeneities in D″ [Snoke and Sacks, 1986]. Strong heterogeneity in the S-wave velocities of D″ are indicated by the diffracted S-wave study of Bolt and Niazi [1984] and the ScS travel time study of Lavely et al. [1986].

A series of modeling studies of long period SH and SV signals traversing D″ by Lay [1985, 1986a,b], Lay and Helmberger [1983b,c,d], Lay and Young [1986], Young and Lay [1986a], and Zhang and Lay [1984] indicate the presence of waveform complexities that can be well-modeled by shear velocity models with a 2.75% shear discontinuity about 280 km above the core-mantle boundary. A reflection from this velocity increase is apparent in transverse component seismogram profiles at distances greater than 70°, with data sampling four different regions of D″ having consistent waveform characteristics. Waveform modeling of long-period ScSH and ScSV indicates the presence of either fine structure just above the core or possibly anisotropy in D″ [Lay and Helmberger, 1983d; Cormier, 1985]. At this time the seismic models for D″ are not consistent enough to resolve the nature of the thermal boundary layer, as is discussed in the review by Young and Lay [1986b], and it appears that the presence of both a thermal and a chemical boundary layer at the base of the mantle is the best way to explain the radial and lateral structure of the region [Jordan and Creager, 1986].

Core Structure

The radial and lateral velocity structure of the core has received increasing attention, particularly with the availability of models of the mantle heterogeneity that allow the shallow travel-time effects to be removed from data that sample the core. Large ISC travel-time data sets have been used to determine extremal bounds on the radial velocity models for the core

[Johnson and Lee, 1985; Stark et al., 1986]. Detailed analysis of SKS travel-times at distances less than 95° provide control on the velocity gradient in the outermost core [Murtha, 1984; Lay and Helmberger, 1983d], which appears not to have an anomalously steep value. Waveform modeling studies of broadband PKIKP phases indicate a simple inner core-outer core discontinuity [Choy and Cormier, 1983; Cormier and Choy, 1986], consistent with the radial travel time inversions.

However, the first generation of three-dimensional core models indicate greater complexity of core structure. Jordan and Creager [1986] and Morelli et al. [1986] have used large data sets of PKP and PKIKP travel times from the ISC bulletins to image the low-order heterogeneity of the core. Both studies indicate long-wavelength heterogeneity that appears to reside in both the inner core and near the core-mantle boundary. Topography on the core-mantle boundary of ±8 km or so with very long wavelengths can account for much of the anomaly in PKP times. Some of the heterogeneity may actually be in the outer core, but dynamic considerations prevent any density heterogeneity from persisting in this region. Anomalously large splitting of normal-modes sensitive to the core structure also indicates very long-wavelength aspherical structure. Ritzwoller et al. [1986] concluded that an axisymmetric structural anomaly in the outer core is required to explain these observations. Giardini et al. [1986] developed an inversion procedure utilizing the anomalously split modes and derived core structures with 8 km undulations of the core-mantle boundary, 25 km undulations of the inner core-outer core boundary, and several percent velocity variations within the inner core, dominated by zonal harmonics. Morelli et al. [1986] and Woodhouse et al. [1986] have proposed an alternate model in which the inner core has a strong axially symmetric anisotropy, which produces systematic PKIKP anomalies and anomalous mode splitting. The complexity of the inner core appears compatible with the models for this boundary proposed by Loper and Fearn [1983] based on geodynamic and geochemical arguments.

Anelastic Properties of the Deep Earth

With the exceptions of the normal-mode attenuation study by Masters and Gilbert [1983], the overtone attenuation study of Okal [1986] and the surface-wave attenuation study of Patton and Taylor [1984], most seismological research on attenuation in the last four years has involved the body-wave frequency band. Progress in this area has been substantial, largely due to the absorption band model concepts that were developed several years ago [see review by Cormier, 1982]. The frequency dependence of short-period P-wave attenuation and its regional variations have been studied using spectral shape measurements by Bache [1985], Bache et al. [1985, 1986], Der and Lees [1985], Der et al. [1982a,b, 1985, 1986] and Shore [1984]. Broadband P and S data have been analyzed to infer regional variations across North America by Taylor et al. [1986]. These studies have clearly demonstrated the decrease in attenuation for frequencies greater than 1 Hz. Additional studies have reliably established the absolute attenuation levels by comparing near-field source models with teleseismic observations [Burdick et al., 1984; Burger et al., 1986], or by source cancelation experiments using phases such as ScS-ScP [Burdick, 1985], sS-sP [Burdick and Grand, 1984] and multiple ScS phases [Lay and Wallace, 1983]. Consistent frequency dependent models for short-period P-waves have resulted from the different studies, with t^* values of 0.7 to 1.0 s for 1 Hz signals and 0.4 to 0.6 s for 4 Hz signals.

Deep mantle attenuation studies using PcP phases [Bolt and Canas, 1985] and ScS phases [Choy and Cormier, 1986] do not appear to support early models with a very low Q zone at the base of the mantle, although the recent model of Shore [1984] has such a feature in it. The effects of diffraction and the increased velocity heterogeneity in D″ need to be accounted for when producing Q models for the lowermost mantle. The apparent attenuation effects of scattering have received some attention [Menke, 1983; Richards and Menke, 1983], though it has proven difficult to separate intrinsic attenuation from scattering losses in actual data.

Conclusions

The large number of deep earth structure studies reviewed above reflects a recent emphasis on quantitative mapping of the three-dimensional velocity structure of the earth's interior. This has long been a principal goal of seismology, but it is only recently that high quality seismic data bases have been available for global analysis. The excitement generated by the first three-dimensional models of the aspherical heterogeneity has breeched disciplinary boundaries and has given strong impetus to the recent efforts to upgrade the global network of seismometers [IRIS, 1984]. The rapid progress in imaging the interior using both digital and WWSSN data is a testimonial to the benefits to be reaped from high quality global network data.

It appears that the earth is heterogeneous at all depths and at all scales; thus it will be a difficult task to accurately determine the detailed structure of the interior. Error and resolution analysis will be increasingly important for appraising the results of large inversion procedures, which are often subject to subtle biases and instabilities. An open mind with regard to the nature of the earth's structure, particularly regarding general anisotropy, boundary layer structure, and whole mantle convection is important in these modeling efforts. The development of aspherical earth models has been paralleled by development of techniques for modeling wave propagation in heterogeneous media, and inverse procedures will have to be developed to exploit these.

Studies of the core-mantle boundary and core structure have begun to reveal unexpected complexity that has important geodynamic and geochemical consequences. It will be particularly important to integrate body-wave and free-oscillation data bases to better constrain the heterogeneity of this region. Establishing the role of the core-mantle boundary as either a thermal or a chemical boundary layer is particularly important for the geothermal models of the interior.

The question of lower mantle slab penetration has not been completely resolved, and quantitative three-dimensional wave-field modeling is needed to further test the travel-time models. Additional studies of the 670-km discontinuity, especially in the vicinity of subducted slabs are needed to establish the nature of this major boundary. Similarly, additional studies of the nature of upper mantle transitions between shield and tectonic provinces are needed to better resolve whether thermal, chemical, or anisotropic variations are responsible for the strong contrasts.

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