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INSIDE

Normal-Mode Splitting Observations from the Great 1994 Bolivia and Kuril Islands Earthquakes: Constraints on the Structure of the Mantle and Inner Core

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ABSTRACT

On June 9, 1994, a magnitude 8.3 earthquake struck ~650 km below Earth's surface in Bolivia. Four months later, on October 4, a second large earthquake of similar magnitude occurred >60 km below the Kuril Islands. Both events were recorded by more than 80 digital instruments distributed around the globe. For comparison, the last earthquake of comparable magnitude was the 1970 Colombia event, which was recorded by just one digital seismometer. Analog data from 60 additional stations had to be hand-digitized. The Colombia earthquake provided the basis for the first high-resolution radial Earth models; one can imagine the wealth of information contained in the numerous digital recordings of the Bolivia and Kuril Islands events.

An amplitude spectrum of a time series recorded after a big earthquake contains hundreds of easily identifiable resonance peaks. Each resonance peak corresponds to a particular normal mode or free oscillation of Earth and contains information about its density and its elastic and anelastic structure. The effect of Earth's rotation, ellipticity, and lateral heterogeneity is to distort the shapes of the resonance peaks; this phenomenon is referred to as splitting. The details of the splitting of a given resonance peak are determined by the mode's sensitivity as a function of depth. By analyzing the fine structure of a large number of resonance peaks, global seismologists attempt to improve our knowledge about Earth's three-dimensional structure.

Splitting observations for mantle-sensitive modes are generally quite well explained by current shear-speed models of the mantle. Observations of compressional modes should help constrain the scaling relation between shear and compressional speeds, which in turn will tell us about thermal vs. chemical heterogeneities in Earth's mantle.

A collection of core-sensitive normal modes is split much more than expected from Earth's rotation, ellipticity, and mantle heterogeneity. Body-wave seismologists who study the inner core have recognized for more than 10 years that compressional waves traversing the inner core along a trajectory parallel to Earth's rotation axis arrive faster than waves traveling in the equatorial plane. In 1986, Morelli et al. and Woodhouse et al. put forward the hypothesis that the inner-core compressional speed exhibits a directional dependence such that waves travel faster along the rotation axis than in the equatorial plane; such a directional dependence of wave speed is called anisotropy. I confirm that both inner-core travel-time anomalies and the splitting of most anomalous modes can be explained in terms of inner-core anisotropy.

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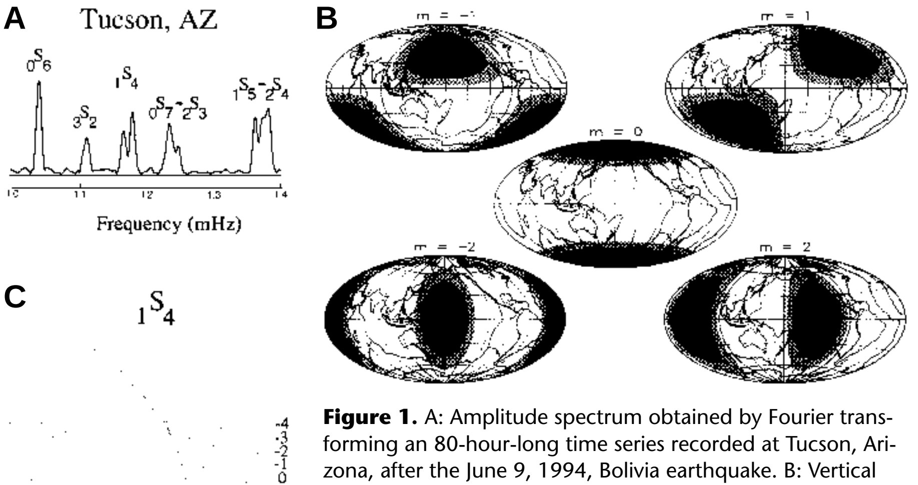

Figure 1. A: Amplitude spectrum obtained by Fourier transforming an 80-hour-long time series recorded at Tucson, Arizona, after the June 9, 1994, Bolivia earthquake. B: Vertical component of the surface displacement of the five spherical Earth singlets that compose an angular degree-two multiplet, such as $_3S_2$. In a spherically symmetric Earth model, all five singlets oscillate with the same frequency. In a laterally heterogeneous Earth model, the singlet eigenfrequencies are "split," such that each singlet oscillates with its own individual eigenfrequency. In that case, the $l = 2$ singlet displacements are a linear combination of the five spherical Earth singlet displacements shown. C: The spheroidal multiplet $_1S_4$ consists of $2 \times 4 + 1 = 9$ singlets with azimuthal orders $m = -4,-3,-2,-1,0,1,2,3,4$. In this figure, all nine singlets that constitute the spectral peak labeled $_1S_4$ in Figure 1A have been "stripped"; the values of the azimuthal order m for each strip are shown on the right. The linear splitting of this multiplet as a function of the azimuthal order m is characteristic of modes that are predominantly split by Earth's rotation. (Courtesy of Guy Masters.)

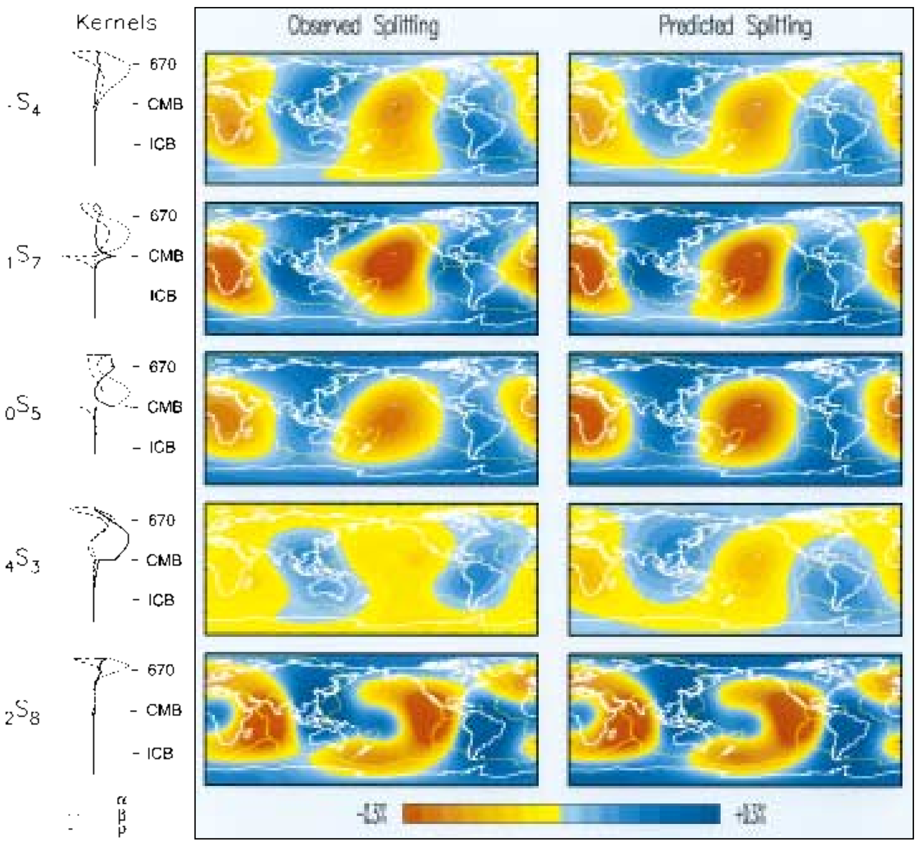

Figure 2. Splitting observations and predictions for mantle modes. In the left column the sensitivity of a normal mode to perturbations in compressional speed α, shear speed β, and density ρ is shown as a function of depth. Labels indicate the radii of the inner-core boundary (ICB), core-mantle boundary (CMB), and the 670 km discontinuity (670). The center column shows the observed splitting function, which is a function of latitude and longitude. The splitting function may be regarded as a local radial average of Earth's three-dimensional structure. The manner in which a mode averages Earth's structure is determined by its sensitivity kernels, shown in the left column. For example, spheroidal mode $_1S_4$ sees the entire mantle, whereas $_2S_8$ is predominantly sensitive to the upper mantle; this difference in sensitivity is reflected in the observed splitting functions. Blue shades correspond on average to fast velocities, whereas red colors reflect slow velocities. The pattern of lateral heterogeneity consists of all even spherical harmonics up to degree 6, corresponding to a total of 28 model parameters. Notice the distinct ring of fast velocities surrounding a relatively slow region beneath the Pacific Ocean. The splitting function predicted by mantle model SKS12WM13 (X. F. Liu and A. M. Dziewonski) is shown in the right column. Multiplets $_1S_4$, $_1S_7$, and $_2S_8$ are predominantly sensitive to shear-speed perturbations and are quite well predicted by shear velocity model SKS12WM13. Perturbations in compressional speed and density are obtained by scaling shear-speed model SKS12WM13. As shown by the sensitivity kernels in the left column, mode $_4S_3$ is predominantly sensitive to perturbations in compressional speed throughout the mantle, and mode $_0S_5$ is sensitive to perturbations in compressional speed in the upper mantle, which exhibits large lateral variations in speed. Nevertheless, SKS12WM13 predicts the observed splitting reasonably well, as shown in the right column.

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INTRODUCTION

From the point of view of a global seismologist, Earth is a large musical instrument that is played by earthquakes. What we can learn about Earth by listening to its music depends on what notes the earthquakes play. If I can make an analogy between Earth and a piano, the music of the Bolivia and Kuril Islands earthquakes is equivalent to that of sitting down on a piano's keyboard. These two large earthquakes were each recorded by more than 80 long-period seismometers all over the world. Every note of Earth manifests itself as a resonance peak in amplitude spectra obtained from the recordings of this event. Most notes that are readily detected have periods of five minutes or more and may be observed for as long as a week after the earthquake. In an amplitude spectrum obtained by Fourier transforming a time series of the Bolivia earthquake recorded in Tucson, Arizona (Fig. 1), several isolated resonance peaks are readily identified, and some, like the one labeled ${}_1S_4$, are visibly split. Splitting is a manifestation of Earth's rotation, ellipticity of figure, and lateral heterogeneity. By analyzing the splitting of a large number of resonance peaks, we can learn something about Earth's internal structure and dynamics.

Normal-Mode Nomenclature

Let us investigate the structure of a resonance peak in a bit more detail. A spherically symmetric Earth model such as PREM (Dziewonski and Anderson, 1981)—i.e., a model that is a function of radius only—supports two distinct classes of normal modes: toroidal and spheroidal modes. Toroidal modes can be observed only on the horizontal components of a seismometer, whereas spheroidal modes can be observed on all three components. Because of sensitivity to tilting, the horizontal components of a seismometer tend to be much noisier than the vertical component, which is why the analysis of toroidal splitting is still in its infancy. At high frequencies, toroidal modes correspond to horizontally polarized shear waves, whereas spheroidal modes correspond to a combination of compressional waves and transversely polarized shear waves. In the context of surface waves, toroidal modes correspond to Love waves, whereas spheroidal modes correspond to Rayleigh waves. For a good introduction to normal-mode seismology, see Lay and Wallace (1995).

To identify a particular free oscillation, each mode is labeled by three unique integers: an overtone number n, an angular degree l, and an azimuthal order m. For every value of l there are $2l + 1$ associated values of m: $m = -l, \dots, m = 0, \dots, m = l$. A multiplet ${}_nT_l$ (toroidal modes) or ${}_nS_l$ (spheroidal modes) is the collection of all $2l + 1$ free oscillations with the same quantum numbers n and l; the $2l + 1$ members of a multiplet are called singlets and are denoted by ${}_nT_l^m$ or ${}_nS_l^m$. In Figure 1B the vertical component of the surface displacement of the five spherical Earth singlets that compose an $l = 2$ multiplet, such as ${}_3S_2$, is displayed. On a spherically symmetric Earth model, all singlets within a given multiplet have the same eigenfrequency ${}_n\omega_l$; we say that the singlets are $2l + 1$ degenerate. This implies that the resonance peaks of all $2l + 1$ singlets within a multiplet ${}_nT_l$ or ${}_nS_l$ are centered on the same frequency ${}_n\omega_l$. As a result, we observe one single resonance peak for every multiplet of a spherically symmetric Earth. Any departure of Earth from sphericity removes the degeneracy and causes the singlets to split, such that each individual singlet has a resonance peak centered on its own distinct eigenfrequency ${}_n\omega_l^m$. As a result, one can often identify several peaks within the resonance peak of a particular multiplet. For example, in Figure 1A one can clearly see two peaks associated with spheroidal multiplet ${}_1S_4$. In Figure 1C all $2 \times 4 + 1 = 9$ singlet resonance peaks that compose the multiplet ${}_1S_4$ have been "stripped." This multiplet is predominantly split as a result of Earth's rotation, which causes linear splitting as a function of the azimuthal order m.

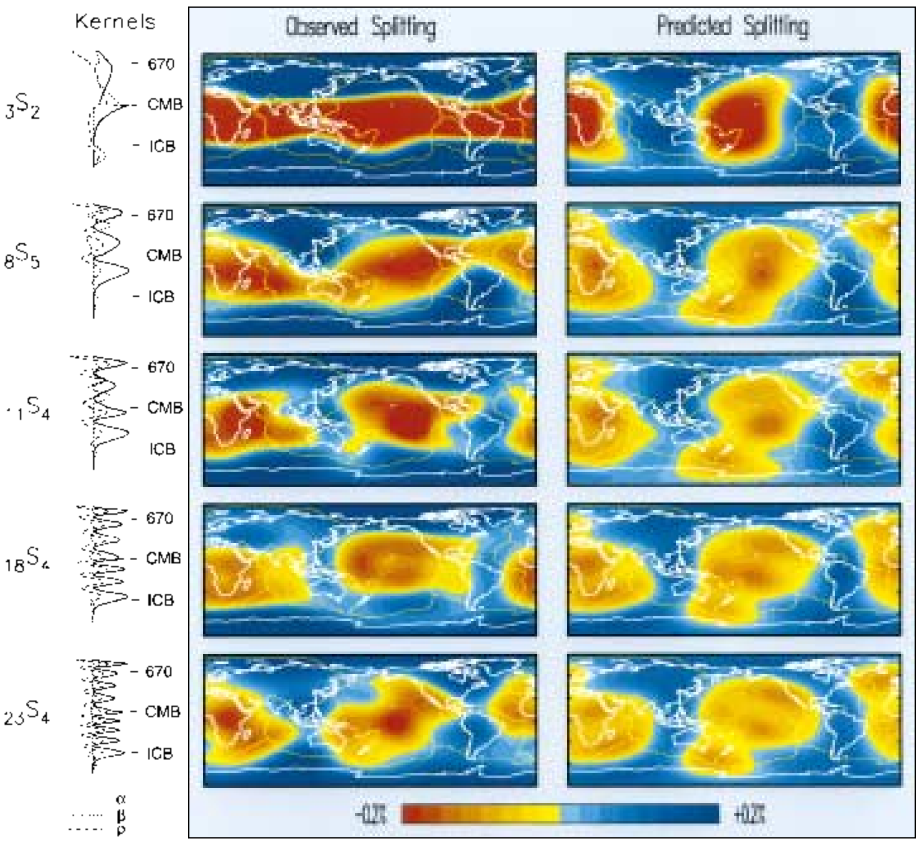

Figure 3. Observed and predicted splitting functions for several anomalously split normal modes. Notice that a large zonal degree-two contribution—i.e., a banded signal parallel to the equator—is missing in the predicted splitting functions, but that the remaining signal is reasonably well predicted by mantle model SKS12WM13. All anomalously split modes are sensitive to structure in Earth's inner core, which turns out to be the source of the anomalous signal. See the Figure 2 caption for further details.

The width of a resonance peak contains information about Earth's shear and bulk attenuation, which represent a measure of seismic energy dissipation due to shearing and compression, respectively. Bulk attenuation within Earth is poorly determined because seismic dissipation tends to be dominated by shear. However, a certain type of spheroidal free oscillation, called a radial mode, has a purely radial displacement and is uniquely sensitive to bulk attenuation. The Bolivia earthquake in particular excited several of these radial modes; analysis of their spectral peaks should help to determine a more detailed picture of Earth's bulk attenuation.

Splitting Function

Every normal mode "sees" the structure of Earth differently. Some modes are predominantly sensitive to the shear-speed structure of the mantle, and other modes see a combination of shear and compressional speeds. There are observable modes that see all the way into the inner core, whereas others are confined to the crust. How a given normal mode samples the structure of Earth is determined by kernels, which describe a mode's sensitivity to compressional speed, shear speed, and density as a function of depth (Fig. 2). By combining the information contained in all observable modes we can improve our knowledge about Earth's interior.

A convenient way to visualize normal-mode splitting is provided by the splitting function, which was first introduced by Giardini et al. (1987). Basically, at a given location on the surface, a mode's splitting function represents a local radial average of Earth's interior structure. By plotting the value of the splitting function everywhere on the surface, we can visualize how a certain mode averages Earth's three-dimensional speed and density structure (Fig. 2). Red colors are used to denote that the radial regions sampled by the normal mode are on average slow, whereas blue colors indicate an average fast speed.

One disadvantage of considering the splitting of isolated resonance peaks, such as those labeled ${}_0S_6$, ${}_3S_2$ and ${}_1S_4$ in Figure 1A, is that one can determine only even heterogeneity—i.e., heterogeneity that is symmetric upon reflection through Earth's center. To determine both odd and even heterogeneity, one must consider coupling between overlapping resonance peaks, such as those labeled ${}_0S_7$-${}_2S_3$ and ${}_1S_5$-${}_2S_4$ in Figure 1A. This year, the first coupled-mode inversions were performed by Rosovsky and Ritzwoller (1995).

In this paper I compare observations of splitting functions for isolated mantle- and inner-core sensitive spheroidal modes with predictions based upon current shear-speed models of Earth's mantle. I subsequently invert core-sensitive traveltime and splitting observations for inner-core anisotropy.

MANTLE STRUCTURE

The splitting predictions in Figure 2 are based upon the most recent Harvard model SKS12WM13 produced by X. P. Liu and A. M. Dziewonski; the long-wavelength structure of this model is similar to that of the latest Scripps model (Johnson et al., 1994). SKS12WM13 is based upon an inversion of traveltimes and waveforms, but it contains no normal-mode information. It is remarkable how well this model predicts the observed splitting. As far as these modes are concerned,

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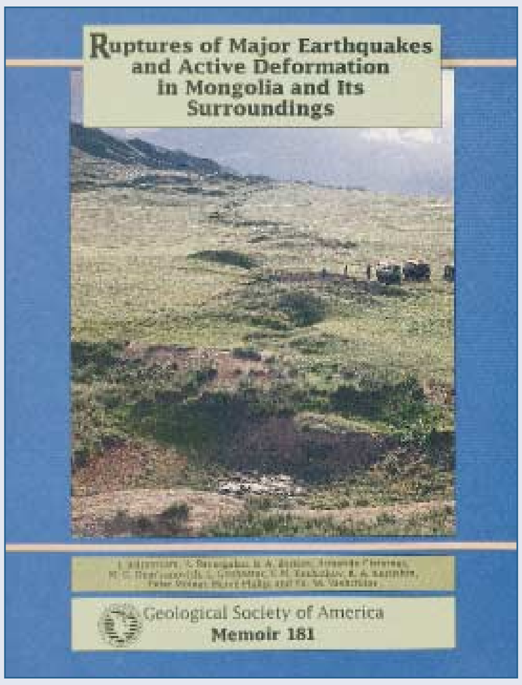

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the long-wavelength heterogeneity in the mantle is quite accurately represented by current tomographic shear-speed models.

Compressional-speed and density perturbations throughout the mantle are commonly obtained by scaling shear-speed perturbations. Compressional-speed perturbations are roughly half and density perturbations roughly one-third the size of shear-speed perturbations. The splitting calculations presented in this paper are based upon such scaling relations. Most of the modes shown in Figure 2 are predominantly sensitive to perturbations in shear speed, except for ${}_0S_5$ and in particular ${}_4S_3$, which are also sensitive to perturbations in compressional speed. The splitting predictions for such compressional modes are generally not quite as good as for shear modes. Splitting observations from the Bolivia and Kuril Islands earthquakes, such as those shown in Figure 2, should help determine better scaling relations among shear speed, compressional speed, and density throughout the mantle. If Earth's lateral heterogeneity is a manifestation of purely thermal phenomena associated with convection, we may expect a relatively uniform scaling relation throughout the mantle. Nonuniform scaling as a function of depth would indicate potential chemical heterogeneities. It is likely that such chemical heterogeneities exist not only in the shallowest regions of Earth's mantle, but also in its deepest part, *D''*.

INNER-CORE STRUCTURE

Earth's inner core was discovered 50 years ago by Inge Lehmann (1936). It has an approximate radius of 1221 km and represents less than 1% of Earth's volume. Notwithstanding its small size, it appears to be one of the more intriguing and unusual regions within Earth.

In a depiction (Fig. 3) of several splitting functions for inner-core sensitive normal mode, although some of the splitting pattern is reasonably well predicted by SKS12WM13, a large zonal degree-two contribution—i.e., a banded signal parallel to the equator—is missing. This type of anomalous splitting is characteristic of most normal modes that are sensitive to Earth's inner core. The first observations of anomalous splitting were reported in 1981 by Masters and Gilbert. By the time of the Bolivia earthquake, a collection of about 20 such anomalously split modes had been identified (Ritzwoller et al., 1986, 1988; Giardini et al., 1988; Li et al., 1991; Widmer et al., 1992). The Bolivia and Kuril Islands earthquakes have more than doubled the number of available spectra, and the quality of the splitting measurements is much improved. The number of anomalously split modes will undoubtedly continue to grow.

Compressional waves traveling through Earth's inner core are called PKIKP waves (Fig. 4). In 1983, Poupinet et al. reported that PKIKP waves travel several seconds faster along a trajectory parallel to Earth's rotation axis than in the equatorial plane. Three years later, Morelli et al. (1986) and Woodhouse et al. (1986) introduced the concept of inner-core anisotropy as an explanation for both inner-core traveltime and normal-mode anomalies. In an anisotropic medium, seismic wave speeds exhibit a directional dependence. In the case of the inner core, waves travel faster in a direction parallel to the rotation axis than perpendicular to it. Although this concept appears to have been generally accepted as an explanation for the directional dependence of PKIKP traveltimes (Shearer et al., 1988; Shearer and Toy, 1991; Creager, 1992; Song and Helmberger, 1993, 1994; Vinnik et al., 1994; Shearer, 1994; Su and Dziewonski, 1995), there has been considerable debate about the level and radial distribution of anisotropy, and doubts have been raised as to whether inner-core anisotropy can explain the anomalous splitting of all currently identified core-sensitive modes (Widmer et al., 1992).

In 1993 I demonstrated that the anomalous splitting of most inner-core sensitive normal modes may be explained in terms of cylindrical anisotropy (Tromp, 1993, 1995). Even though my analysis did not include PKIKP traveltime observations, my anisotropic inner-core model makes reasonable traveltime predictions (Tromp, 1993;

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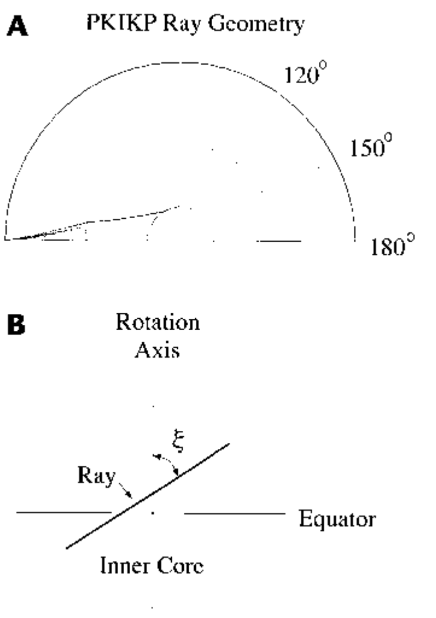

Figure 4. A: Ray geometry of a compressional inner-core (PKIKP) wave. B: The parameter ξ denotes the angle between the inner-core leg of the PKIKP wave and the symmetry axis of the cylindrical anisotropy; this axis more or less coincides with Earth's rotation axis. The inner-core ray segment of a PKIKP wave is nearly a straight line because the speed in the inner core is relatively uniform.

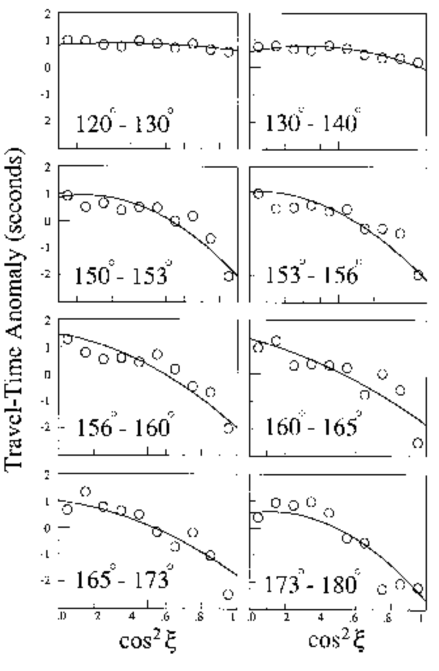

Figure 5. PKIKP traveltime observations and predictions in eight epicentral distance bins. The circles represent the average traveltime anomalies determined by Su and Dziewonski (1995). The solid line is the traveltime prediction based upon the anisotropic inner-core model displayed in Figure 7. The parameter ξ represents the angle between the direction of the inner-core leg of the PKIKP wave and the symmetry axis of the anisotropy, as shown in Figure 5B. This symmetry axis nearly coincides with Earth's rotation axis. When $\cos^2\xi = 0$, PKIKP waves travel in the equatorial plane, and when $\cos^2\xi = 1$, they travel parallel to the symmetry axis.

The Active Tectonics Planning Initiative

George H. Davis, University of Arizona

A National Science Foundation–supported planning initiative in active tectonics has now been completed. Recommendations are presented in "Active Tectonics and Society: A Plan for Integrative Science" (1995). This report is available through the World Wide Web at http://www.muohio.edu/tectonics/activetectonics.html.

ORIGIN OF THE INITIATIVE

The planning effort in active tectonics grew from two major studies, Active Tectonics (1986) and Solid-Earth Sciences and Society (1993), both supported by the National Research Council. Active Tectonics advocated the need to build a national basic science initiative in active tectonics, emphasizing both the scientific and strategic value of this research. Mitigation of hazards related to great earthquakes, explosive volcanism, and major landslides were recurrent themes. Solid-Earth Sciences and Society identified active tectonics as one of eight priority themes representing critical opportunities for research in the coming decades, especially as related to important societal issues involving such matters as the global environment, natural resources, and natural hazards. In April 1993, NSF's Advisory Committee for Earth Sciences (ACES) recommended active tectonics as one of five high-priority initiatives. The ACES report said, "We recommend an increased emphasis on interdisciplinary research on active crustal deformation. The overall scientific objective of better understanding how and why crustal stresses ultimately result in faulting, seismicity, and rapid geomorphic change contributes directly to the national goal of mitigating geologic hazards. [Another] objective … is to foster and facilitate interdisciplinary collaborations among subdisciplines such as experimental and theoretical rock mechanics, field studies of active and Neogene faults and the rock products of faulting, geodynamic modeling in areas of active deformation, seismology and earthquake mechanics, quantitative geomorphology and paleoseismology."

RESPONSE

A 20-person planning team (see list) met in September 1993, and began drafting an active tectonics science plan in response to the call from ACES. Their long-range objective was to produce an active tectonics science plan for concerted, integrated efforts to understand the fundamental processes underlying the full range of deformational processes that currently shape Earth's lithosphere and that threaten life and property. A major emphasis emerged: To understand how single tectonic processes work, and how these processes link together through time as parts of larger systems that ultimately lead to the formation of mountain systems and the evolution of the solid Earth.

Strategic applications are clear. For example, as the past decade of earthquakes in California has so dramatically demonstrated to the public, cities and towns in tectonically active regions are built not on single faults, but on complex systems with hundreds of potential "moving parts," any one of which might reveal itself through a sudden shift. Understanding why one part moves, or why one part might move, requires systems knowledge. The 1994 Northridge earthquake, a case in point, occurred along a fault that does not even breach the surface, and yet the natural disaster created by movement along this fault was the most expensive in our nation's history.

THE PLAN

Draft versions of the active tectonics science plan evolved between September 1993 and April 1995, with input from the national geoscientific community. The draft versions were made available for inspection and comment on Mosaic. The plan was presented in poster sessions at national and regional meetings of the Geological Society of America and of the American Geophysical Union. Special symposia highlighted opportunities in active tectonics research, including an AGU session convened by Robert B. Smith in December 1993 and a GSA symposium convened by J.-Bernard Minster and me in October 1994. The plan elaborates on five basic themes: Integration of geology and geophysics, relevance to mitigation of tectonic hazards, capturing tectonic processes in action, exploiting the geologic record, and harnessing new technologies.

PROPOSED DIRECTION

Active Tectonics and Society (1995) places a high premium on planning and on collaborative team efforts. Current collective scientific approaches to understanding active tectonic processes fail to fill one important niche: the formation of fully integrated partnerships among independent teams of individuals from disparate though complementary fields. The proposed concept lies somewhere between that of an individual principal investigator and a consortium. Its compelling difference acknowledges that, with some exceptions, individual investigators make greater scientific contributions if they enlarge their range of expertise by collaborating with a few other experts from complementary fields in both formulating and executing research plans. Small teams of investigators can work especially effectively on integrated active tectonics science, addressing understanding of the inner workings of interconnected active tectonic processes. Those of us involved in this planning process hope that Active Tectonics and Society (1995) can be used to gain broader and deeper support from federal and state agencies whose scientific and public policy mission objectives can be supported effectively by active tectonics research. For example, the NSF Division of Earth Sciences has now established Active Tectonics as a special emphasis area. The planning document provides strong scientific and societal justification for enhanced national funding of active tectonics research. Research grant funding drawn from sources nationwide would enable the community to investigate the fundamental processes underlying the development and evolution of tectonic systems, including individual deformational mechanisms.

Regardless of funding source, active tectonics research proposals might profitably share some distinctive elements: high potential for meaningful integration of multiple disciplines; demonstrated capability of measuring dynamic-earth properties that are directly relevant to elucidation of specific tectonic processes; harnessing of new technologies (such as GPS, GIS,

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Shearer, 1994; Su and Dziewonski, 1995).

In this paper I simultaneously invert inner-core traveltime observations and anomalous splitting observations from the Bolivia and Kuril Islands earthquakes for inner-core anisotropy. The simplest type of anisotropy that exhibits cylindrical symmetry about Earth's rotation axis is transverse isotropy. Let ξ denote the angle between the inner-core ray segment of a body-wave trajectory and Earth's rotation axis, as shown in Figure 4B. The directional dependence of the compressional speed v in a transversely isotropic inner core may be expressed as (Su and Dziewonski, 1995)

$$v = v_0\,(1 + \varepsilon\cos^2\xi + \gamma\sin^2 2\xi), \qquad (1)$$

where v_0 is the unperturbed isotropic compressional wave speed in spherical Earth model PREM. I seek to determine the behavior of the two parameters ε and γ as a function of radius in the inner core. Although PKIKP traveltime anomalies are solely determined by the compressional-speed distribution in the inner core, and hence by the radial dependence of the two parameters ε and γ, some normal modes have sensitivity to the shear-speed structure of the inner core; this shear-speed sensitivity will be represented by the radial dependence of a third parameter, which I will call σ. Theoretically, there exists a body wave that travels through the mantle and outer core as a compressional wave, and through the inner core as a shear wave. This body-wave arrival, named PKJKP, would put valuable additional constraints on the third model parameter σ, but it has never been unambiguously observed because the transmission coefficient at the inner-core boundary is very small. Peter Shearer recently pointed out to me that PKJKP has become the Holy Grail of body-wave seismology.

The normal-mode data used in the inversion consist of splitting functions for 16 anomalous modes similar to the ones shown in Figure 3. These splitting functions are corrected for mantle contributions based upon shear-speed model SKS12WM13 produced by X. F. Liu and A. M. Dziewonski. The remaining signal, which consists mainly of a large degree-two zonal pattern, is inverted simultaneously with PKIKP traveltime measurements obtained by Su and Dziewonski (1995) for inner-core anisotropy. Su and Dziewonski collected more than 310,000 PKIKP arrival times reported by the International Seismological Centre in eight epicentral distance bins that correspond to all regions within the inner core. The longer the distance between the epicenter and the station, the deeper the PKIKP waves penetrate into the inner core, as shown in Figure 4A. For example, from 120° to 130° PKIKP waves sample the upper few kilometers of the inner core, whereas from 175° to 180° they travel close to Earth's center. From their analysis, Su and Dziewonski determined that the symmetry axis of the anisotropy is tilted relative to Earth's rotation axis such that the pole of the symmetry axis is located at 80°N, 160°E. Because of the relatively inaccurate splitting corrections for mantle structure, normal-mode data do not reliably constrain a tilting of the symmetry axis. Therefore, for the purposes of this analysis, I will take Su and Dziewonski's orientation of the symmetry axis for granted and correct the normal-mode observations for this tilt. Their averaged traveltime anomalies are represented by the circles in Figure 5. In each epicentral distance bin the traveltime anomaly relative to PREM plus SH12WM13 (Su and Dziewonski, 1994) is plotted as a function of the angle ξ between the ray direction and the symmetry axis; when $\cos^2\xi = 0$, PKIKP waves travel in the equatorial plane, whereas when $\cos^2\xi = 1$, they travel parallel to the symmetry axis. The fact that the traveltime anomalies are negligible in the epicentral distance range 120°–130° indicates that the source of the signal in subsequent bins is located in the inner core, rather than the outer core or mantle. The 1 s (second) offset is an artifact due to the spherical reference model that was used in the analysis. The small anomalies in the epicentral distance range 120°–140° are in agreement with

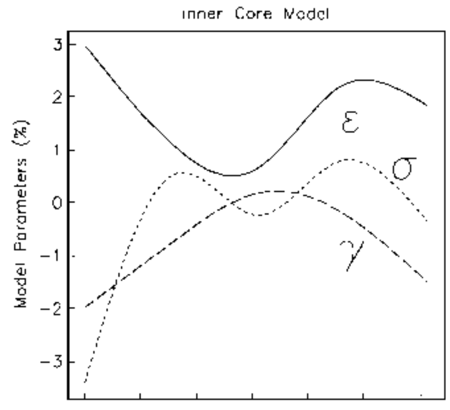

Figure 6. Anisotropic inner-core model obtained by the joint inversion of anomalous splitting functions and PKIKP traveltime anomalies. The elastic response of an isotropic medium is determined by two elastic parameters: the shear modulus μ and the bulk modulus κ. A transversely isotropic medium, on the other hand, has an elastic response that is governed by five elastic parameters: A, C, F, L, and N (Love, 1927). The parameters A and C govern the compressional speed of seismic waves, whereas the parameters L and N govern the shear speed. The fifth parameter F influences the speed of both compressional and shear waves. PKIKP traveltimes constrain just two combinations of the five elastic parameters: $\varepsilon = \tfrac{1}{2}(C - A)/A_0$, and $\gamma = -\tfrac{1}{4}(\tfrac{1}{2}A + \tfrac{1}{2}C - 2L - F)/A_0$, where $A_0 = \kappa + \tfrac{4}{3}\mu$, is determined by the bulk and shear moduli at the center of spherical Earth model PREM. Normal modes constrain one additional combination of the five elastic parameters: $\sigma = \tfrac{1}{2}(L - N)/A_0$. This third combination corresponds to shear anisotropy in the inner core. The behavior of the three parameters ε, γ, and σ is shown as a function of inner-core radius.

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Tectonics *continued from p. 148*

remote sensing, innovative dating techniques, radar interferometry); designation of an actively deforming region or subregion where dynamic activities can be observed or measured; ability to integrate models of tectonic processes; and potential for transfer to proactive societal outreach in such arenas as hazards and environmental and global change.

COORDINATION OF THE INITIATIVE

An Active Tectonics Coordinating Committee has been established to foster and enhance communication, coordination, and integration among scientists engaged in active tectonics research, education, and service to society. Members are Kerry Sieh (California Institute of Technology), chair; Susan Beck (University of Arizona), vice-chair in charge of highlighting key scientific issues; Mark Brandon (Yale University), coordinator of annual planning workshops; Mike Bevis (University of Hawaii), coordinator of training workshops; Rick Allmendinger (Cornell University), coordinator of international relations; Roy Dokka (Louisiana State University), coordinator of societal relations; and Larry Mayer (Miami University), coordinator of the Mosaic hub.

OPPORTUNITIES TO GET INVOLVED

If you are interested in becoming involved in some aspect of working on the initiative, please contact Kerry Sieh at sieh@seismo.gps.caltech.edu. There is a lot of work to go around, especially during the launch year of this cooperative initiative. The coordinating committee seeks to establish a core group of 50 or more people distributed among several working committees, both to further develop the initiative and to increase its impact.

ACTIVE TECTONICS: SCIENCE AND SOCIETY

A comprehensive understanding of the process of Earth's deformation, and effective transfer of this understanding to society, will help mitigate the human and economic costs associated with the inevitable tectonic events that mark our planet. The active tectonics planning effort is designed to foster the formulation of basic research proposals that help explain the fundamental origins of tectonic deformation. The geological and geophysical communities represent the nation's strategic intellectual resource in explaining the origins of tectonic hazards. Active tectonics science is an arena in which geologists and geophysicists can simultaneously carry out basic science and serve society's needs. We expect that enhanced communication and integration among active tectonics scientists will result in breakthrough-quality basic science, more effective transfer of knowledge, and exceptional opportunities for professional growth. A likely byproduct is accelerated integration of geology and geophysics within college and university curricula, thus preparing the way for more effective earth science education for the next generation.

ACKNOWLEDGMENTS

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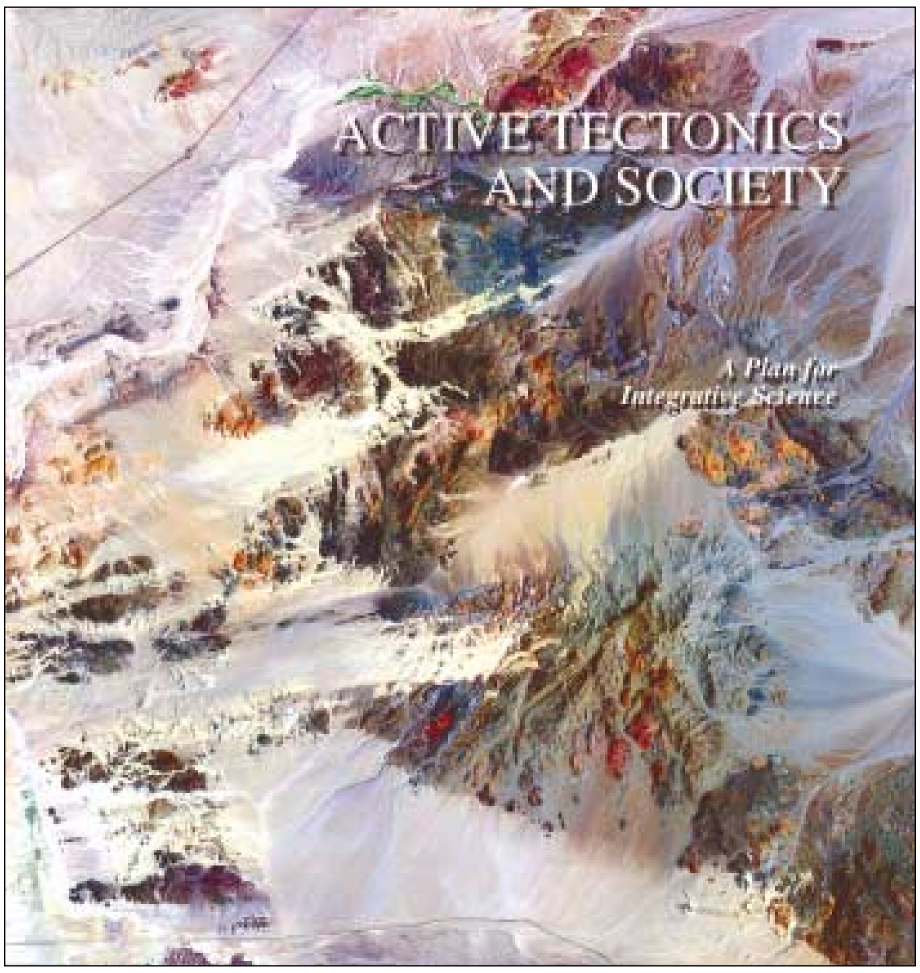

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Splitting *continued from p. 148*

the observations of Shearer (1994) and Song and Helmberger (1994) and suggest relatively small anisotropy near the ICB. Notice that traveltime anomalies in the epicentral distance range 175°–180° can be as large as 4 s. Such large traveltime anomalies were also observed by Vinnik et al. (1994) and suggest strong anisotropy near Earth's center. The anisotropic inner-core model that fits both the traveltime data and the anomalously split modes reasonably well (Fig. 6) is quite similar to the model obtained by Su and Dziewonski (1995) by an inversion of PKIKP traveltimes. The fit to the traveltime data is represented by the solid line in Figure 5. The inner-core model slightly overpredicts the traveltime anomalies in the epicentral distance range 130°–140°, and it slightly underpredicts the traveltime anomalies for the near polar paths in the epicentral distance range 160°–173°. The observed and predicted traveltime anomalies in the epicentral distance range 150°–153° are in general agreement with differential traveltimes between rays turning in the liquid outer core, PKP(BC), and rays turning in the solid inner core, PKIKP or PKP(DF) (Creager, 1992; Song and Helmberger, 1993). Normal modes have very little sensitivity to structure near Earth's center. Therefore, the large anisotropy in the center of the inner core is entirely constrained by the traveltime data in the epicentral distance bins 165°–173° and 173°–180°. Predicted splitting functions of several anomalously split modes (Fig. 7) are based upon mantle model SKS12WM13, and the anisotropic inner-core model shown in Figure 6. Inner-core anisotropy provides the large zonal degree-two signal that is missing in the predicted splitting in Figure 3. Clearly not all the remaining signal is explained. This unexplained signal may reflect errors in the mantle model (the mantle model is a shear-speed model, whereas the anomalously split modes are PKIKP-equivalent—i.e., compressional—modes), but it may also indicate that the inner-core anisotropy does not exhibit pure cylindrical symmetry. The traveltime variance reduction relative to PREM plus SH12WM13 is 92%, and the normal-mode variance reduction compared to a model incorporating only the effects of rotation and ellipticity is 70%. It should be noted that one anomalously split mode, $_{13}S_2$, is poorly fit by the inner core model displayed in Figure 6; thus far, the splitting of this mode has never been explained satisfactorily in terms of inner-core anisotropy.

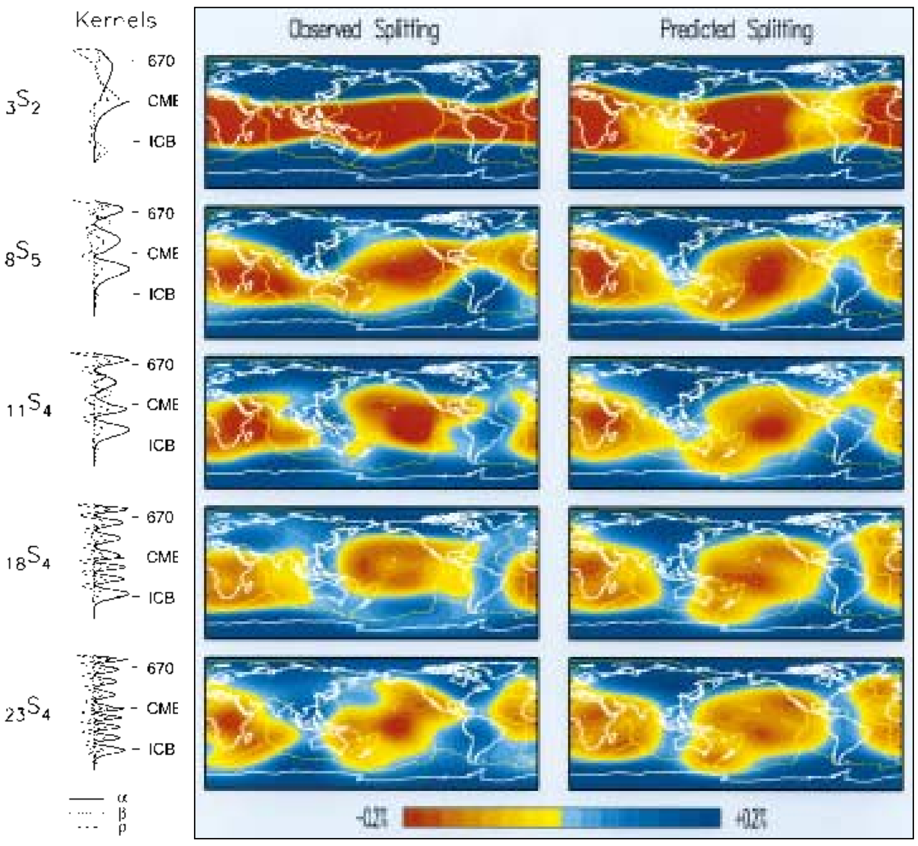

Figure 7. Observed and predicted splitting functions of several anomalously split normal modes. The splitting predictions are based upon mantle model SKS12WM13 (X. F. Liu and A. M. Dziewonski) and the anisotropic inner-core model shown in Figure 6. See the caption of Figure 2 for further details.

CONCLUSIONS

The 1994 Bolivia and Kuril Islands earthquakes have provided the seismological community with a large number of high-quality splitting observations. An analysis of some of Earth's mantle-sensitive spheroidal free oscillations indicates that especially the splitting of shear-sensitive modes is very well explained by current tomographic models of the mantle. The first toroidal-mode splitting observations were reported by Tromp and Zanzerkia (1995), and the first coupled-mode inversions for odd structure were performed by Rosovsky and Ritzwoller (1995).

Both the anomalous splitting of inner-core sensitive modes and anoma-

Splitting *continued on p. 150*

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Splitting *continued from p. 149*

lous PKIKP traveltime observations may be explained in terms of cylindrical anisotropy of Earth's inner core. This robust observation has important implications for the composition, growth, and internal dynamics of the inner core. First of all, we need to determine the mineralogy of Earth's core. Recent theoretical calculations by Stixrude et al. (1994) and Stixrude and Cohen (1995) confirm earlier calculations by Brown and McQueen (1985) which suggest that the inner core consists of hexagonally close-packed (hcp) iron. Under inner-core conditions, this phase of iron exhibits anisotropy on a level that is in accordance with the seismological observations. If we are willing to accept that the predominant mineral in the inner core is hcp iron, this raises questions about the mechanism for the preferential alignment of these minerals. Only if most of the minerals are more-or-less aligned does the aggregate behave as an anisotropic body; a random orientation would result in a seismically isotropic inner core. Jeanloz and Wenk (1988) and Wenk et al. (1988) suggested that this preferred orientation is a result of degree-one convection in the solid inner core. Much as in the mantle, this convection would be a manifestation of thermal effects, and we would be seeing a snapshot of the internal dynamics of the inner core. Karato (1993) proposed that the hcp iron minerals are oriented by Earth's magnetic field. The feasibility of this mechanism critically depends on the magnetic susceptibility of iron under core conditions. In this case, the three-dimensional distribution of anisotropy would reflect the history of the geometry of the magnetic field at or near the inner-core boundary. A third possibility is the preferred orientation of iron minerals due to rotation and self-gravitation during the solidification and growth of the inner core. At the moment, it is not at all unlikely that the inner core is one giant single crystal. During the next several years close collaboration between mineral physicists, geodynamicists, and seismologists will, one hopes, uncover more of the mysteries of this fascinating region of Earth's interior.

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Splitting *continued on p. 151*

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Splitting *continued from p. 150*

eltime anomalies, and Xiang-Feng Liu and Adam Dziewonski provided their latest mantle model. Göran Ekström developed the initial software for editing the data and answered many questions about time-series analysis. John He assisted in editing the data and making splitting measurements. I thank Adam Dziewonski, Wei-Jia Su, and Göran Ekström for numerous discussions; IRIS, the USGS, and Geoscope for providing the data used in this study; and two anonymous reviewers for their helpful suggestions and comments.

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