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GSA TODAY

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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.

Splitting *continued on p. 140*

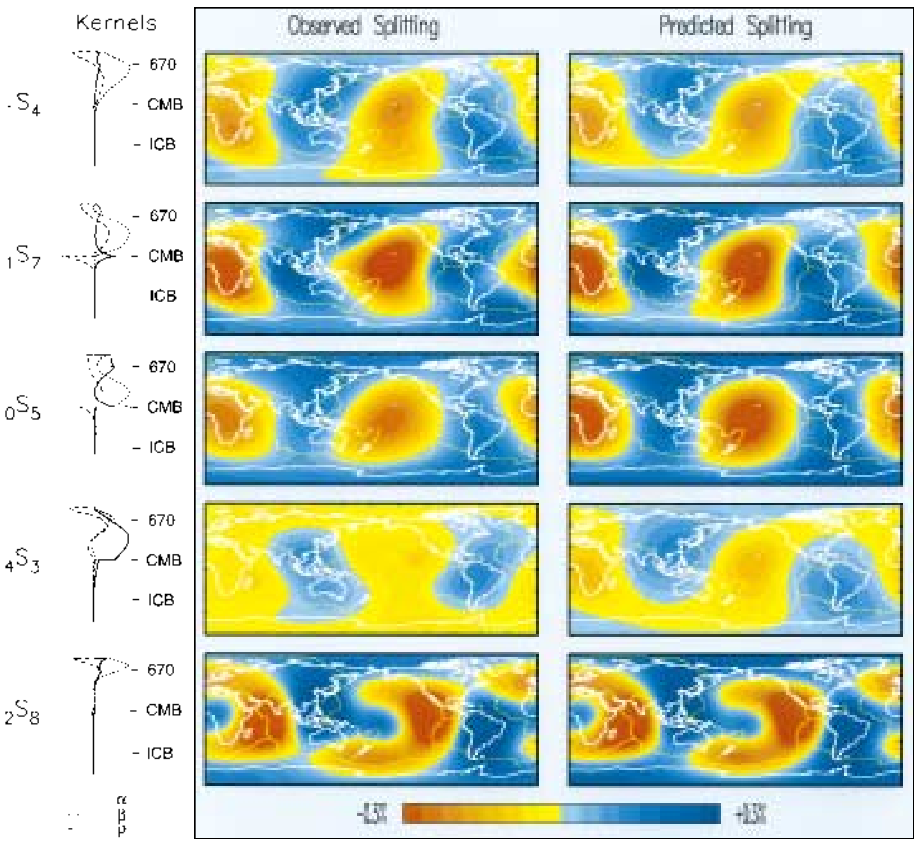

Figure 2. Splitting observations and predictions for mantle modes. In the left column the sensitivity of a normal mode to perturbations in compressional speed α, shear speed β, and density ρ is shown as a function of depth. Labels indicate the radii of the inner-core boundary (ICB), core-mantle boundary (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.

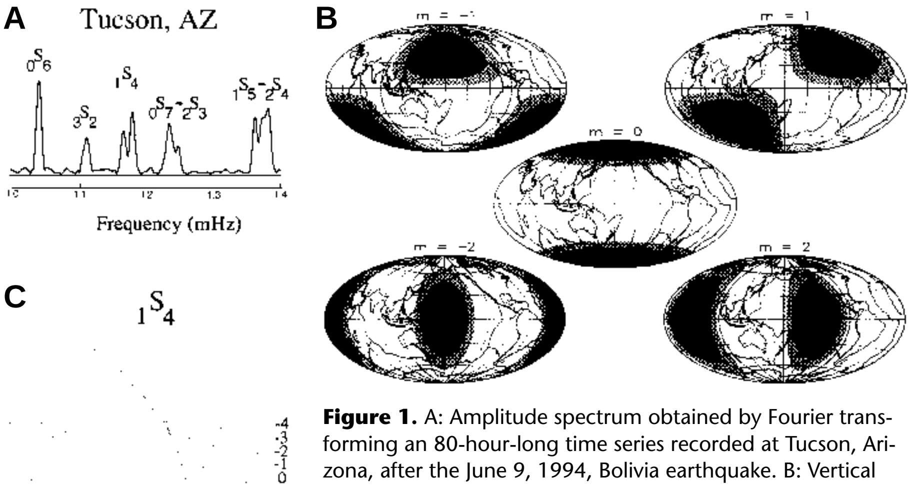

Figure 1. A: Amplitude spectrum obtained by Fourier transforming an 80-hour-long time series recorded at Tucson, Arizona, after the June 9, 1994, Bolivia earthquake. B: Vertical component of the surface displacement of the five spherical Earth singlets that compose an angular degree-two multiplet, such 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.)

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Each monthly issue posted on the WWW is a separate electronic file created in "Portable Document Format" (PDF), an electronic file format that combines high-quality graphics and electronically searchable text in the same document. The technology is called Acrobat, from Adobe Systems, Inc., whose well known and widely used PostScript page-description language is the foundation on which Acrobat was created. The file-name extension used for documents in the unique Acrobat format is "PDF."

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ANNOUNCEMENT

Travel Grant Program

30th IGC in Beijing, China • August 4–14, 1996

The Geological Society of America is accepting applications for the International Geological Congress (IGC) Travel Grant Program.

This program was established as a final act of the Organizing Committee for the U.S.-hosted 28th IGC held in Washington, D.C., in July 1989. Surplus funds available at the conclusion of the 28th IGC were transferred to the GSA Foundation with the stipulation that income from the fund be used to support the attendance of young geoscientists at future IGCs, until such time as the United States again hosts an IGC. Travel grants will consist of economy airfare to and from China.

To be eligible, an applicant must be a resident or citizen of the United States (includes students); must have a birth date after August 31, 1956; and must have an abstract for inclusion in the program of the 30th IGC.

Official application forms are available from the Grants Administrator, GSA Headquarters, 3300 Penrose Place, P.O. Box 9140, Boulder, CO 80301. Along with the form, applicants must include a copy of the abstract that was submitted to the 30th IGC. Applications must be supported by two letters from current or recent supervisors; students may use faculty members. **Qualifying applications and letters of support must be postmarked no later than September 15, 1995.** Applicants will be notified of results early in 1996. ■

In Memoriam

George G. Anderman
Denver, Colorado
February 23, 1995

John E. Armstrong
Vancouver, British Columbia
February 10, 1995

Roland Brinckman
Germany
April 3, 1995

Eleanor J. Crosby
Santa Fe, New Mexico

Albert E. J. Engel
Victor, Montana
March 31, 1995

Helen B. Hay
Richmond, Indiana

Huang Jiqing
China
March 22, 1995

Kalervo Rankama
Finland
March 10, 1995

Ialo Dewitt Stephens, Jr.
Roseburg, Oregon
April 11, 1995

Donald D. Utterback
Memphis, Tennessee

GSA Officer and Councilor Nominees for 1996

Council announces the following officer and councilor candidates. Biographical information on all candidates will be mailed with the ballot to all voting members in August.

For Councilor (1996–1997) and President (1996)
Eldridge M. Moores
Davis, California

For Councilor and Vice-President (1996)
George A. Thompson
Stanford, California

For Councilor and Treasurer (1996)
David E. Dunn
Richardson, Texas

For Councilor (1996–1998)—Position 1
Joanne Bourgeois
Seattle, Washington
Judith Totman Parrish
Tucson, Arizona

For Councilor (1996–1998)—Position 2
Eric J. Barron
University Park, Pennsylvania
John E. Costa
Vancouver, Washington

For Councilor (1996–1998)—Position 3
Charles G. Groat
El Paso, Texas
Craig M. Schiffries
Washington, D.C.

For Councilor (1996–1998)—Position 4
Warren B. Hamilton
Denver, Colorado
Walter D. Mooney
Menlo Park, California

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Macintoshes, and Unix machines. You need only the appropriate Adobe Acrobat reader for each platform. These reader programs can be downloaded at no cost from GSA and other online sources. Currently, DOS and Unix machines use Acrobat Reader 1.0. There are separate readers in version 2.0 for Macintosh and Windows. GSA will provide the latest versions.

The more powerful Adobe Acrobat Exchange program, available from commercial software suppliers, may also be used as a reader and offers additional tools, such as “sticky notes,” bookmark creation, and a more sophisticated text-search routine.

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At press time, the January through July 1995 issues of *GSA Today* and the Acrobat readers were available on the WWW. Use the Universal Resource Locator (URL): http://www.aescon.com/geosociety/pubs/index.html. From this menu, select GSA Today.

You may also access these from GSA’s home page, the address of which is shown in the “What’s New on the Web” box below.

Additional issues of *GSA Today* will be posted on the WWW monthly, as soon as they are sent to press. Other GSA documents will also be made available in this format in the future.

Acrobat technology is also being used in the production of *GSA Journals on Compact Disc* for 1995. Acrobat will greatly improve the quality of the printable graphics, as well as the screen views of graphics of the *GSA Bulletin, Geology,* and *GSA Today* in that medium. This year, for the first time, the first six issues of those publications will be released on CD in July. The full year’s edition will be shipped at the end of the year.

GSA ON THE WEB

What’s new on the GSA home page on the World Wide Web? If you haven’t yet connected to the Web, the Universal Resource Locator (URL) is **http://www.aescon.com/geosociety/index.html.**

For current information on the 1995 Annual Meeting in New Orleans, go to **Meetings** and choose **1995 Annual Meeting.** This area contains a listing of Symposia and Theme Sessions and has information about Field Trips, Continuing Education, Exhibits, Travel, and Lodging.

If you want to know more about the GSA Employment Service or about becoming a GSA Campus Representative, check the **Membership** section, which also has information on nominating a member to fellowship and on obtaining forms for applying to become a GSA Member or Student Associate.

See the **Geoscience Calendar** section for a listing of meetings of general geological interest.

The **Publications** section has a monthly table of contents and abstracts of articles for the *GSA Bulletin* and *Geology.* Also in this section is a guide for authors preparing manuscripts for submission to GSA publications. *GSA Today* issues are posted here for download and viewing.

For Congressional Contact Information, see the **Administration** section. ■

WASHINGTON REPORT

Bruce F. Molnia

Washington Report provides the GSA membership with a window on the activities of the federal agencies, Congress and the legislative process, and international interactions that could impact the geoscience community. In future issues, Washington Report will present summaries of agency and interagency programs, track legislation, and present insights into Washington, D.C., geopolitics as they pertain to the geosciences.

Declassified Intelligence Satellite Photographs—Extending the Baseline for Environmental Change Detection

The material in these imagery archives will open a gold mine of hitherto unavailable data. At a time when we are cutting back on unnecessary and duplicative government services, we have chosen to release this information. We are confident that these materials can provide an additional basis from which to develop a deeper understanding of conditions in the past and thus improve our ability to predict and perhaps mitigate environmental disasters in the future.

—Vice President Al Gore,
February 24, 1995, at ceremony announcing the signing of the executive order that directs the declassification of early satellite imagery.

Figure 1. Soviet strategic bomber base near Dolon, Kazakhstan, photographed on August 20, 1966. The source photograph is a 30× enlargement of the original negative.

Have you heard of CORONA, ARGON, or LANYARD? Prior to February 23, 1995, unless you were part of the intelligence community, most likely, you knew nothing about these three satellite reconnaissance systems. On that date, an executive order signed by President Clinton set in motion a process that will result in the declassification of more than 800,000 images collected by these space-based national intelligence reconnaissance systems for the U.S. Intelligence Community from 1960 to 1972. The 12 year period of coverage is significant in that it precedes, yet dovetails with, the launch of Landsat I in 1972. Temporally, these data fit in perfect sequence with the systematic, near global coverage of Earth features provided since 1972 by the Landsat multispectral scanner (MSS) on the Landsat I–V satellites, and more recently enhanced by space shuttle photography, Landsat thematic mapper (TM) imagery, SPOT imagery, large-format camera photographs, and similar, more recent, nonclassified views of Earth. With the newly identified imagery as its foundation, a 35-year-long record of sequential views of Earth's features will be available to document changes to glaciers, coastlines, coral reefs, and many other dynamic and environmentally sensitive features.

CORONA, ARGON, and LANYARD were developed during the peak of the Cold War in response to the successful launch of Sputnik by the Union of Soviet Socialist Republics on October 14, 1957. The U.S. program was endorsed by President Dwight Eisenhower in February 1958. The early imagery collections were driven, in part, by the need to confirm purported developments in Soviet strategic missile capabilities. Worldwide photographic coverage was also used to produce maps and charts for the Department of Defense and other U.S. Government mapping programs.

According to a Central Intelligence Agency (CIA) press release, distributed at the February 24 ceremony, "The recommendations to release the imagery were based on the findings of the Classification Review Task Force (CRTF) led by the Central Imagery Office. The CRTF consisted of intelligence community, military and civilian government officials, who examined imagery security policy and evaluated national security risks in the post–Cold War era as well as the potential utility of satellite photo reconnaissance imagery to the U.S. Government and the public." To date, only four "sample" images have been declassified. All four, collected as photographs, are included with this Washington Report. Available details are included in each figure caption.

From May 15 to 18, 1995, a very successful joint U.S.–Russian workshop was held at Chantilly, Virginia, to discuss opportunities for utilizing these space-based images and other remote-sensing databases held by civil, military, and intelligence organizations for investigation and monitoring of specific environmental problems. The workshop, titled the U.S.–Russian Joint Environmental Seminar, was held in accordance with a decision reached between Vice President Gore and Russian Prime Minister Victor Chernomyrdin. The workshop focused on the unclassified exchange of ideas and papers in plenary and technical sessions on four themes: (1) ecological monitoring and natural resource management, (2) ecological regulatory ideas, (3) radioactive pollution and clean-up, and (4) scientific methods and data compatibility.

One purpose of the workshop was to encourage a similar release of classified data by the Russians. Both sides left the meeting with a much fuller understanding of the many peaceful uses for the previously classified U.S. data. In his closing remarks, Russian Minister of Environmental Protection and Natural Resources Victor Danilov-Danilyan, head of the Russian delegation, commented that "if we haven't broken the ice" with respect to a parallel release of Russian classified information, "we have cracked a wider hole" in this proverbial ice. In geological terms, he was obviously speaking about the relict ice of secrecy remaining from the late Holocene Cold War.

Other Russian workshop participants represented the Ministry of Defense, the Russian Academy of Science, the Russian Space Agency, the Ministry of Fuel and Energy, the Ministry for Science, the Federal Cartography and Geodesy Service, the Russian State Committee for Land Reform, the Russian State Committee for Water Industry, and the Russian State Forestry Service.

The February executive order directed that "within 18 months of the date of this order" the images

Washington Report
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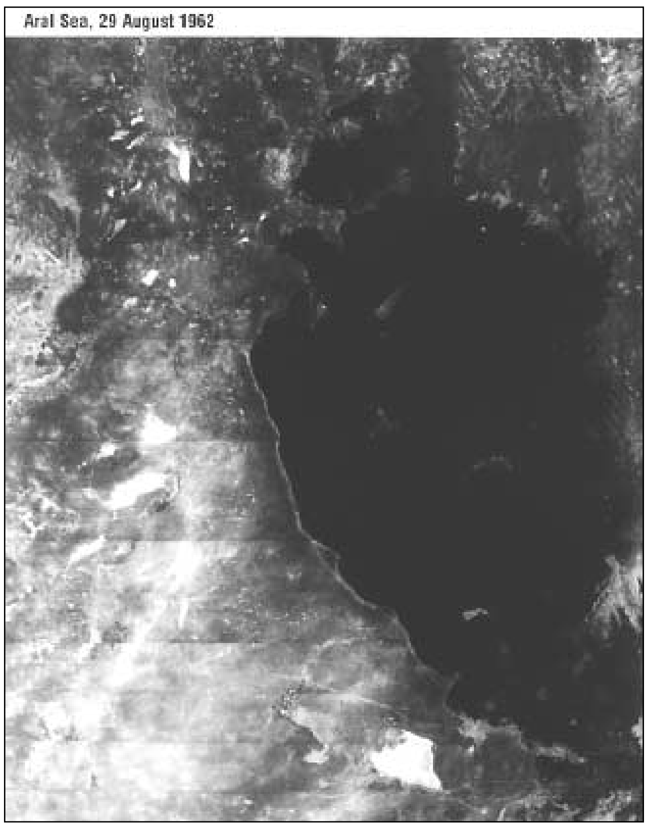

Figure 2. Mosaic made of 17 individual images showing the Aral Sea as it looked on August 29, 1962. Source photograph is a 30% reduction from the original composite negative. The area shown is about 240 × 260 mi (385 × 420 km).

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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*.

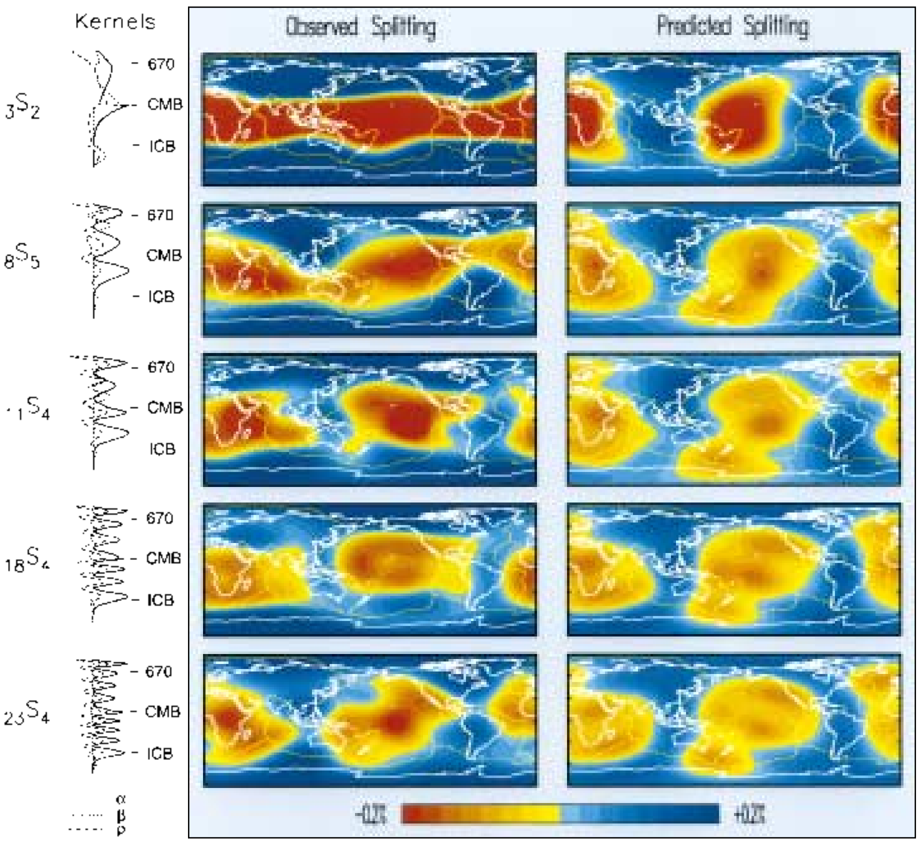


Figure 3. Observed and predicted splitting functions for several anomalously split normal modes. Notice that a large zonal degree-two contribution—i.e., a banded signal parallel to the equator—is missing in the predicted splitting functions, but that the remaining signal is reasonably well predicted 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.

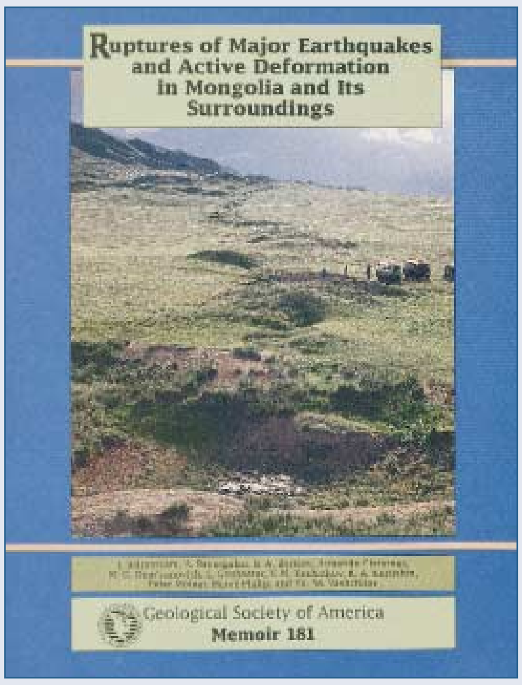
One disadvantage of considering the splitting of isolated resonance peaks, such as those labeled ${}_0S_6$, ${}_3S_2$ and ${}_1S_4$ in Figure 1A, is that one can determine only even heterogeneity—i.e., heterogeneity that is symmetric upon reflection through Earth's center. To determine both odd and even 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,

Splitting *continued on p. 141*



Splitting *continued from p. 140*

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;

Splitting *continued on p. 148*

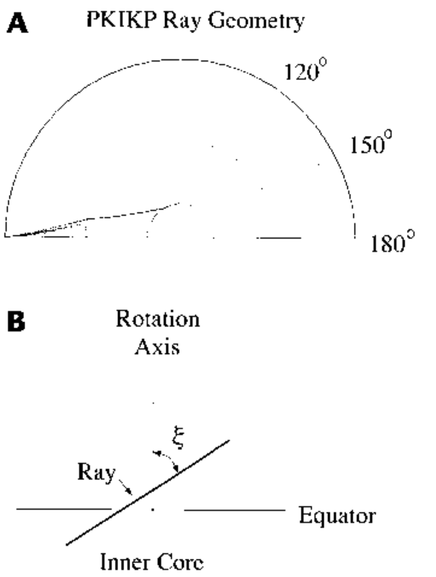


Figure 4. A: Ray geometry of a compressional inner-core (PKIKP) wave. B: The parameter ξ denotes the angle between the inner-core leg of the PKIKP wave and the symmetry axis of the cylindrical anisotropy; this axis more or less coincides with Earth's rotation axis. The inner-core ray segment of a PKIKP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

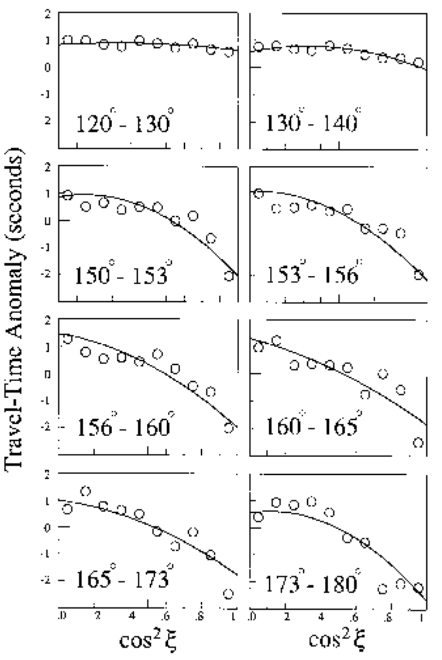


Figure 5. PKIKP traveltime observations and predictions in eight epicentral distance bins. The circles represent the average traveltime anomalies determined by Su and Dziewonski (1995). The solid line is the traveltime prediction based upon the anisotropic inner-core model displayed in Figure 7. The 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.

Granite, South Dakota, And FDR

Jill S. Schneiderman, GSA Congressional Science Fellow

March was a good month for geology in Senator Daschle's office. During the middle of that month, Senator Daschle became aware of the fact that granite from South Dakota was slated to be the building stone for the new memorial to President Franklin Delano Roosevelt in our nation's capitol. Senator Daschle's excitement about rock from his home state afforded me the opportunity to feed his curiosity about geology. Most important, it provided the occasion to explain to the senator and his constituents the relevance of earth science to environmental and natural resource issues in South Dakota. Earth scientists must look for such opportunities to engage fellow citizens and elected representatives; they need to recognize that geological knowledge forms the foundation for sound decisions concerning the wise use of our natural resources, the mitigation of natural hazards, and the stewardship of our environment.

Senate Democratic Leader Tom Daschle (D—SD) and GSA Congressional Science Fellow Jill Schneiderman discuss Dakota granite and other things geological at the FDR Memorial construction site, Washington, DC, March 30, 1995.

The FDR memorial is being constructed between the Jefferson and Lincoln memorials on a 27 acre site first considered in 1958 and later designated by President Johnson as the location for a monument to Roosevelt. The FDR memorial will consist of 7.5 acres of 2500-million-year-old granite from a quarry in Milbank, South Dakota. I found, much to my relief, that unlike the Vietnam Veterans Memorial, which is gabbro that everyone calls "black granite," the Dakota granite is truly granite: reddish brown, coarse-grained porphyritic rock consisting of subequal proportions of quartz, alkali feldspar, and biotite, with minor amounts of plagioclase and opaque minerals. The quarried rock's trade name is Mahogany granite because of its rich reddish color. It has been used to build monuments throughout the United States and in Canada.

FDR would have preferred nothing more than the simple block of white Vermont marble bearing his name and dates of his birth and death in a small park in front of the National Archives on Pennsylvania Avenue. Nonetheless, construction of the FDR memorial began in fall 1994 and will be completed in spring 1997. Designed by Lawrence Halprin, who was selected by the FDR Memorial Commission and the Commission of Fine Arts, the memorial will depict 12 pivotal years of American history through a series of four open-air galleries made of Dakota granite, each devoted to one of FDR's four terms in office.

The first gallery will contain a bronze sculpture of the presidential seal and a life-size bas-relief bronze of Roosevelt at his first inauguration, and it will have carved into the granite Roosevelt's first inaugural insight, "The only thing we have to fear is fear itself.…" In the second room three sculptures will symbolize the Great Depression: a weary rural couple, portraying despair; figures in a bread line, depicting hunger, and a man listening to a "fireside chat," representing hope. Roosevelt's New Deal legislation will be delineated in a wall-sized bas-relief in the second room. A 9-foot-tall sculpture of FDR, seated with his cape draped around him and his dog, Fala, at his feet will dominate the third room. The sculpture has aroused controversy because FDR's cape conceals his wheelchair. The room itself will be made of unpolished, rough Dakota granite and is meant to evince the horror of World War II. The fourth room will consist of a water garden and will emphasize world peace. It will showcase a 30-foot-long bas-relief of Roosevelt's funeral cortege, a sculpture of Eleanor Roosevelt as this country's first representative to the United Nations, and a last bas-relief of Roosevelt as Commander in Chief. What is in my opinion the devastation being wrought by the Republican "Contract on [sic] America" has been made more poignant by the history lesson I've had researching FDR and the memorial for Senator Daschle.

Because Senator Daschle was interested in the fact that Dakota granite would memorialize FDR, I investigated connections between the former president and South Dakota. I learned that the West and things "western" were special to Roosevelt, especially during the drought and New Deal years. Roosevelt said, "We think of our land and water … not as a static and sterile possession but as life-giving assets to be directed by wise provision for future days. We seek to use our natural resources not as a thing apart but as something that is interwoven with … labor, agriculture, recreation, good citizenship." When FDR came to Mount Rushmore in 1936 to preside at the dedication of Jefferson's likeness, he said, "We can meditate and wonder what our descendants will think about us 10,000 years from now when they see this mountain." His appreciation for the solace provided by the wide open spaces of South Dakota must have led to his suggestion in 1944 that the United Nations be located in the Black Hills of South Dakota so that diplomats could ponder weighty questions with some degree of quietude.

These pieces of history prompted Senator Daschle to proclaim on the Senate floor, 50 years after FDR's death on April 12, 1945, "South Dakota is a land of awe-inspiring geological resources: the Black Hills, the Badlands, vast caves and glacial deposits, and, of course, the two-and-a-half-billion-year-old Milbank granite. Among the oldest rocks in the world, the South Dakota granite will produce a tribute of geological, almost infinite, duration to an extraordinary president.… We in South Dakota are proud that future generations will gaze upon the rock of South Dakota when they reflect on the lasting contributions to American society of Franklin Delano Roosevelt."

Senator Daschle's enthusiasm for the FDR memorial project led to our "field trip" to the construction site at the peak of cherry tree bloom. While we drove to the site, an analogy made clear the distinction between minerals and rocks: as a sentence is composed of words, a rock is made of minerals. Equipped with a hand lens and sample of Dakota granite at the site, we examined the sample, talked about rocks, minerals, geologic time, earth system science, and the USGS, and Senator Daschle ultimately asked to examine a geologic map of his state. Surprised by the senator's engagement on the topic of geology, the AP reporter who accompanied us later asked why Senator Daschle should know anything about geology. In an article headlined "Professor takes Daschle to school," he reported on the relevance of geology to natural resource issues in South Dakota. He made the connection between agriculture issues and earth science writing that "federal grazing leases … would seem to have more connection with biology than geology. [But] Grazing can lead to soil erosion, which leads to sedimentation in rivers and streams." This article, along with one about the granite and the FDR memorial ("South Dakota chips in granite") appeared in all the major newspapers in the state. Those South Dakotans who read these newspaper articles increased their awareness about geology.

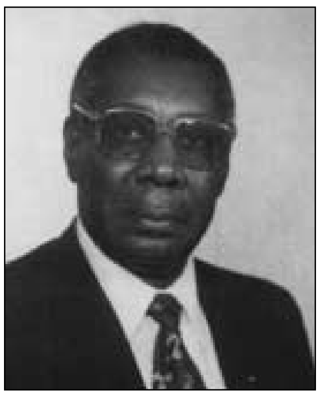
The 21st century will see an Earth that is resource-poor but population-rich. We earth scientists have a unique perspective on the upcoming century that is afforded by our understanding of geologic time and our knowledge of earth system processes. Therefore, we have a responsibility to other less informed members of our society to communicate our particular view. We must get the attention of policy makers and voters. We must speak loudly and frequently about the relevance of our science to society.

Jill S. Schneiderman, 1994–1995 GSA Congressional Science Fellow, is serving on the staff of Senator Thomas Daschle (D—SD). Schneiderman may be contacted at (202) 224-2321. The one-year fellowship is supported by GSA and by the U.S. Geological Survey, Department of the Interior, under Assistance Award No. 1434-94-G-2509. The views and conclusions contained in this document are those of the author and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

GSAF UPDATE

Robert L. Fuchs

Mack Gipson, Jr. Honored in Boulder



Mack Gipson

At a ceremony held in conjunction with the early May GSA Council and committee meetings in Boulder, the life and career of GSA Fellow Mack Gipson, Jr. received special recognition. An additional Second Century Fund gift from Bill and Cecile Bromery has been designated for the headquarters building, and the Bromerys specifically requested that the executive-administrative offices of the Society be named in honor of Gipson, who died on March 10, 1995, during hip replacement surgery.

Mack Gipson was one of the first black American geologists to be awarded a Ph.D. degree. Born in 1931 in Trenton, South Carolina, he received an undergraduate education at Paine College. After a brief period teaching high school math, followed by U.S. Army service, Gipson enrolled in the University of Chicago, where he earned master's and doctoral degrees. He worked briefly for a Chicago engineering firm and then joined the staff of Virginia State College in Petersburg, where he built up the department of geological sciences into an effective educational entity. He then worked in industry for a number of years, including the Exxon Corporation.

Gipson was very active in both teaching and minority organizations and activities. He was a member of the Clay Minerals Society, Sigma Xi, AGU, and NAGT. He was active in the GSA and AGI minorities committees. At the time of his election to GSA Fellowship, it was noted by his sponsors John Maxwell, Clyde Wahrhaftig, and Julian Goldsmith that he was a pioneer in the geological education of black students at a black college. Gipson was successful in placing his students in top universities for graduate work, and also in good jobs in industry.

At a time when there was little opportunity for and attention paid to blacks and other minorities in sciences, particularly in earth science, Gipson was an activist. Moreover, he was an activist who was successful in bringing about change, and this change has impacted many careers and lives. The dedication of GSA's executive offices to honor Mack Gipson by his colleague Bill Bromery, an eminent black geologist, educator, and businessman, permanently testifies to the achievements of this persevering and dedicated geologist.

Upon his death, Mack Gipson was a tenured Professor of geology at the university of South Carolina, in Columbia, South Carolina. He is survived by his wife, Alma Gadison Gipson; four children; two grandchildren; and his mother, Artie Watson. ■

Trustees Set Endowment Gift Policy

Meeting in Boulder on May 5, the Foundation's trustees addressed the matter of gifts that are undesignated as to endowment or current program expenditure. Often contributions that are received do not state the donor's preference. While donations to special restricted funds such as the Dillon Fund and GeoSTAR establish intent by the nature of the fund (both are endowment funds from which only income is spent), monies to other categories such as unrestricted are not so categorized. Accordingly, the trustees agreed that the Foundation's general policy would be to consider undesignated funds as endowment gifts, in the absence of specific instructions from the donor.

Other matters occupying the meeting included the possible combination of GSA and Foundation accounting functions for reasons of efficiency and economy, and a review of Second Century Fund and other fund-raising progress. GSA managers made presentations on the Society's programs and operations. ■

GEO STAR

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☐ Enclosed is my contribution in the amount of $__________.
☐ Foundation—Unrestricted ☐ GSA—Unrestricted

☐ Please add my name to the Century Plus Roster (gifts of $150 or more).

☐ Please designate my contribution to the Minority Fund.

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Second Century Fund Donors Feted at Boulder Reception

Some of the major Second Century Fund donors to date were recognized by GSA at a reception at Boulder headquarters on May 5, prior to the spring meeting of GSA Council. Those present or acknowledged by GSA President Dave Stephenson were Phil and Bunnie LaMoreaux, Bill and Cecile Bromery, Don and Mary Davidson, Newmont Gold, Unocal, and the Gates, El Pomar, and Boettcher foundations. Don and Carmen Deere were represented by their son Don, Jr., president of Rocky Mountain Consultants, an environmental firm, and his wife Claudia.

The Gates Foundation provided a capital grant in support of SAGE and the GSA Education Department. The funds have been applied to the Education offices in the new wing. The Boettcher and El Pomar Foundation grants were directed to equipment purchases—computer network hardware and software for the entire facility, and a major upgrade to Publications Department pre-press production capability. Later funding from these foundations will be spent on the SAGE technology training facility, a state-of-the-art center for classroom training of K–16 teachers, earth science educators, scientists, and consultants. ■

Ed Geary and Barbara Mieras of GSA's education staff at the Gates Foundation Education offices marker.

Publications Department pre-press production equipment. Standing from left: Bill Douglas, Boettcher Foundation, David Palenchar, El Pomar Foundation, Jim Clark, GSA Production Manager, Don Davidson, GSA Executive Director. Seated: Kim Thomas, Graphics Production Coordinator.

Donors to the Foundation, March and April 1995

Claude C. Albritton, Jr. Fund
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*Second Century Fund—gifts of $150 or more.

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DATE AVAILABLE __________ **TELEPHONE (** area code **)** __________ Business / __________ Home **VISA** __________ If not U.S. citizen, list visa

EXPERIENCE Must use specialty codes listed below.
Choose three that best describe your expertise in order of importance.
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PRESENT SPECIALTY
Choose one from codes listed below __________
YEARS EXPERIENCE IN THIS SPECIALTY __________

PRESENT EMPLOYER ____________________

TYPE OF POSITION DESIRED (Check as many boxes as apply.)
Interested in: ☐ Academic ☐ Government ☐ Industry ☐ Other
Specific interest: ☐ Administration ☐ Exploration/Production ☐ Field ☐ Research ☐ Teaching
Will accept employment in: ☐ U.S. only ☐ U.S. with foreign assignments ☐ Either

GIVE NUMBER OF YEARS EXPERIENCE FOR ANY OF THE FOLLOWING THAT ARE APPLICABLE
Administrative_____ Exploration/Production_____ Field_____ Research_____ Teaching_____ Total geological experience______

KNOWLEDGE OF FOREIGN LANGUAGES: ☐ French ☐ German ☐ Russian ☐ Spanish ☐ Other __________

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Postgraduate work beyond highest degree in (field) ____________________ **Number of years** __________

SPECIALTY CODES Select those that best describe your ability. Use codes in boldface only when other breakdowns are inadequate.

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102 geothermal, etc.
103 metallic deposits
104 nonmetallic deposits
105 mining geology
120 Engineering Geology
150 Environmental Geology
160 Public Education & Communication
200 General Geology
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221 organic
222 high temperature
223 low temperature
224 stable isotopes
225 geochronology
250 Geomorphology
300 Geophysics
301 seismic
302 gravity/magnetics
303 seismicity
304 paleomagnetism
320 Hydrogeology
321 hydrochemistry
322 ground water
323 surface water
330 Library
350 Mathematical Geology
351 computer science
352 statistical geology
400 Mineralogy
401 crystallography
402 clay mineralogy
410 Museum (curator)
420 Oceanography
421 marine geology
422 coastal geology
450 Paleontology
451 invertebrate
452 vertebrate
453 micropaleontology
454 paleobotany
455 paleoecology
500 Petroleum Geology
501 exploration
502 subsurface strat.
520 Petrology
521 igneous
522 metamorphic
523 sedimentary (clastic)
524 sedimentary (carb.)
525 experimental
550 Planetology
575 Quaternary Geology
600 Regional Geology
620 Remote Sensing
621 photogeology
622 photogrammetry
630 Science Editing
650 Sedimentology
651 sed. processes
652 sed. environments
720 Stratigraphy
750 Structural Geology
751 tectonics
752 tectonophysics
753 rock mechanics
800 Volcanology

Résumé must be attached, ***limited to two pages,*** typewritten on one side only, to be acceptable for reproduction to employers. Include your name, address, and phone number; concise details of work experience; and majors/minors on degrees. Fee: $30 if you are a Member or Student Associate of GSA in good standing (Member #__________), $60 if you are not a member of GSA. Payment in U.S. funds (check, money order, or charge information ***must accompany form***).

Make check payable to the Geological Society of America. ≈ This application will be active for one year.

☐ Check/Money Order ☐ MasterCard ☐ VISA ☐ American Express or Optima

Card Expires Mo/Yr ☐☐☐ Card Number ☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐

Signature ____________________
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Date

I agree to release GSA or their representatives from responsibility for errors that may occur in processing or distributing these data. I understand that GSA makes ***no guarantee*** of contact by an employer in this service. I agree to notify GSA Employment Service immediately of (1) change of address, (2) acceptance of a position.

Signature *(required)* ____________________ I will/will not attend the 19_____ GSA Annual Meeting in __________

GSA Employment Service

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Are you looking for a new position in the field of geology? The GSA Employment Service offers an economical way to find one. Potential employers use the service to find the qualified individuals they need.

You may register any time throughout the year. Your name will be provided to all participating employers who seek individuals with your qualifications. If possible, take advantage of GSA's Employment Interview Service, which is conducted each fall in conjunction with the Society's Annual Meeting. The service brings potential employers and employees together for face-to-face interviews. Mark your calendar for November 6–9 for the 1995 GSA Annual Meeting in New Orleans, Louisiana.

To register, complete the application form on this page, prepare a one- to two-page résumé, and mail it with your payment to GSA headquarters. One-year listing for GSA Members and Student Associates in good standing: $30, nonmembers: $60.

NOTE TO APPLICANTS: If you plan to interview at the GSA Annual Meeting, GSA must receive your material no later than September 1, 1995. If we receive your materials by September 1, your record will be included in the information employers receive prior to the meeting. Submit your forms early to receive maximum exposure! Don't forget to indicate on your application form that you would like to interview in November. Good luck with your job search!

For additional information or submission of forms, please contact T. Michael Moreland, Manager, Membership Services, Geological Society of America, P.O. Box 9140, Boulder, CO 80301, (303) 447-2020, or E-mail: member@geosociety.org.

◀ APPLICANT FORM

GSA Names 1995 Medal and Award Recipients

Society awards for 1995 will be presented to the following individuals at the New Orleans Annual Meeting.

Penrose Medal
John C. Crowell
Institute for Crustal Studies
University of California at Santa Barbara
Santa Barbara, CA 93106-1100

Day Medal
Thomas J. Ahrens
Division of Geological and Planetary Sciences
Seismological Lab 252-21
California Institute of Technology
Pasadena, CA 91125

Donath Medal
(Young Scientist Award)
Ward E. Sanford
U.S. Geological Survey
12201 Sunrise Valley Drive
National Center, Mail Stop 430
Reston, VA 22092

GSA Distinguished Service Award
John E. Costa
U.S. Geological Survey
Cascades Volcano Observatory
5400 MacArthur Boulevard
Vancouver, WA 98661
and
Henry T. Mullins
Department of Geology
204 Heroy Geology Laboratory
Syracuse University
Syracuse, NY 13244-1070
and
Arthur G. Sylvester
Department of Geological Sciences
University of California
Santa Barbara, CA 93106-9630

Rip Rapp Archaeological Geology Award
(Archaeological Geology Division)
John P. Albanese
3511 Carmel Drive
Casper, WY 82604

Gilbert H. Cady Award
(Coal Geology Division)
Richard R. Thompson
Bethlehem Steel Corporation
2621 Nottingham Road
Bethlehem, PA 18017
and

Medals/Awards *continued on p. 145*

Looking for a New Employee?

When was the last time you hired a new employee? Did you waste time and effort in your search for a qualified geoscientist? Let the GSA computerized search file make your job easier.

How does it work? Complete the Employer's Request for Earth Science Applicants form on this page. Remember to specify educational and professional experience requirements as well as the specialty area or areas of expertise your applicant should have. The GSA computer will take it from there.

You will receive a printout that includes the applicants' names, addresses, phone numbers, areas of specialty, type of employment desired, degrees held, years of professional experience, and current employment status. Résumés for each applicant are sent with each printout at no additional charge. For 1995, the cost of a printout of one or two specialty codes is $150. (For example, in a recent job search for an analyst of inorganic materials, the employer requested the specialty codes of geochemistry and petrology.) Each additional specialty is $50. A printout of the applicant listing in all specialties is available for $350. (Specialty codes printed in boldface type are considered major headings. If you request a listing of one of the subspecialties, applicants coded under the major category will be included but not those coded under the other related subspecialties.) If you have any questions about your personalized computer search, GSA Membership Services will assist you.

The GSA Employment Service is available year round. However, GSA also conducts the Employment Interview Service each fall in conjunction with the Society's Annual Meeting (this year in New Orleans, Louisiana, November 6–9). You may rent interview space in half-day increments from GSA. Our staff will schedule all interviews with applicants for you, the recruiter. In addition, GSA offers a message service, complete listing of applicants, copies of résumés at no additional charge, and a posting of all job openings.

EMPLOYER FORM ▶

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ORGANIZATION ______________________________

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area code Number

FAX ( ) __________

SPECIALTY CODES (see list below)
List the specialty code numbers that you wish to order, or ☐ check here if you want the entire file of applicants in *ALL* specialties.

1. ________ 2. ________ 3. ________ 4. ________ 5. ________ 6. ________

POSITION DATA: What position(s) do you expect to fill? ______________________________

In what area(s)? ______________________________

Degree requirements ______________________________ Number of positions available _______

SPECIALTY CODES

100 Economic Geology
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102 geothermal, etc.
103 metallic deposits
104 nonmetallic deposits
105 mining geology
120 Engineering Geology
150 Environmental Geology
160 Public Education & Communication
200 General Geology
220 Geochemistry
221 organic
222 high temperature
223 low temperature
224 stable isotopes
225 geochronology
250 Geomorphology
300 Geophysics
301 seismic
302 gravity/magnetics
303 seismicity
304 paleomagnetism
320 Hydrogeology
321 hydrochemistry
322 ground water
323 surface water
330 Library
350 Mathematical Geology
351 computer science
352 statistical geology
400 Mineralogy
401 crystallography
402 clay mineralogy
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422 coastal geology
450 Paleontology
451 invertebrate
452 vertebrate
453 micropaleontology
454 paleobotany
455 paleoecology
500 Petroleum Geology
501 exploration
502 subsurface strat.
520 Petrology
521 igneous
522 metamorphic
523 sedimentary (clastic)
524 sedimentary (carb.)
525 experimental
550 Planetology
575 Quaternary Geology
600 Regional Geology
620 Remote Sensing
621 photogeology
622 photogrammetry
630 Science Editing
650 Sedimentology
651 sed. processes
652 sed. environments
720 Stratigraphy
750 Structural Geology
751 tectonics
752 tectonophysics
753 rock mechanics
800 Volcanology

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***Minimum* degree required:**
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***Minimum* professional experience:**
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Experience desired (years):

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Administrative	☐	☐	☐
Exploration/Production	☐	☐	☐
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Research	☐	☐	☐
Teaching	☐	☐	☐

Employment in: ☐ U.S. only ☐ U.S. with foreign assignments ☐ Either

Foreign Languages: ☐ French ☐ German ☐ Russian ☐ Spanish ☐ Other __________ ☐ Not required

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Medals/Awards *continued from p. 144*

Louis G. Benedict
Bethlehem Steel Corporation
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Bethlehem, Pennsylvania 18016

E. B. Burwell, Jr., Award (Engineering Geology Division)
Charles G. Higgins
P.O. Box 1727
Carmel Valley, CA 93924
and
Donald R. Coates
18 Savery Lane
Falmouth, MA 02540-3106

George P. Woollard Award (Geophysics Division)
Walter D. Mooney
U.S. Geological Survey, Mail Stop 977
345 Middlefield Road
Menlo Park, CA 94025

History of Geology Award
Robert H. Dott, Jr.
Department of Geology and Geophysics
University of Wisconsin
1215 West Dayton Street
Madison, WI 53706-1692

O. E. Meinzer Award (Hydrogeology Division)
Grant Garven
Department of Earth and Planetary Sciences
The Johns Hopkins University
Baltimore, MD 21218

G. K. Gilbert Award (Planetary Geology Division)
Baerbel K. Lucchitta
U.S. Geological Survey
Branch of Astrogeologic Studies
2255 North Gemini Drive
Flagstaff, AZ 86001

Kirk Bryan Award (Quaternary Geology and Geomorphology Division)
Jim E. O'Connor
U.S. Forest Service
3055 NE Everett Street
Portland, OR 97232

Structural Geology and Tectonics Division Career Contribution Award
Burrell C. (Clark) Burchfiel
Department of Earth, Atmospheric, and Planetary Sciences
Room 54-1010
Massachusetts Institute of Technology
Cambridge, MA 02139 ■

GSA Announces New Honorary Fellows

P. G. Cooray
426 Mahakanda Road
Hinddagala
Sri Lanka

Ferenc Horvath
2045 Torobalint
Arany Janos u.35
Hungary

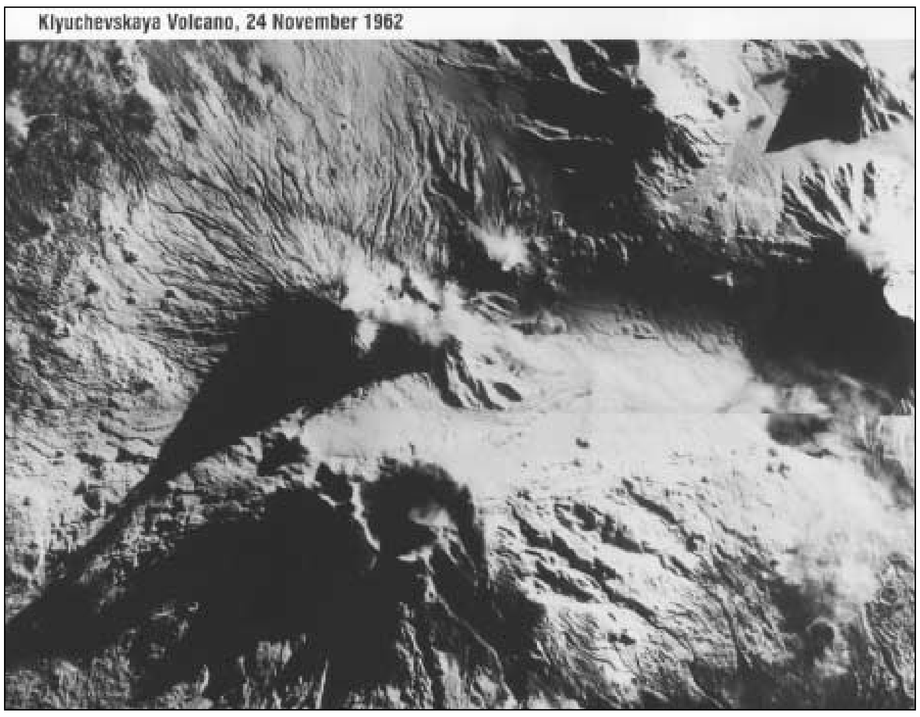

Figure 3. Cluster of small volcanoes around Klyuchevskaya Volcano on the Kamchatka Peninsula. Klyuchevskaya Volcano erupted as recently as November 1994. The source photograph is a 2× enlargement of the original two-image composite.

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"be declassified and transferred to the National Archives and Records Administration (NARA) with a copy sent to the United States Geological Survey (USGS) of the Department of the Interior consistent with procedures approved by the Director of the Central Intelligence Agency and the Archivist of the United States. Upon transfer, such imagery shall be deemed declassified and shall be made available to the public." The Order defines "imagery" as "the product acquired by space-based national intelligence reconnaissance systems that provides a likeness or representation of any natural or man-made feature or related object or activities and satellite positional data acquired at the same time the likeness or representation was acquired." As described, the imagery resides on 2.1 million feet of film (more than 395 miles), currently stored in 39,000 cans.

The CORONA program operated from August 1960 to May 1972, collecting both intelligence and mapping information. CORONA, the world's first reconnaissance satellite, achieved the first mapping of Earth from space and the first stereo-optical data collected from space. The first test launch took place on February 28, 1959, and the first successful test recovery from space on August 12, 1960. The first CORONA image, a photograph of a military airfield near Mys Schmidta on the Chukchi Sea (Fig. 4) was obtained on August 18, 1960, on the fourteenth CORONA mission. The last images of the series were taken by CORONA 145 on May 31, 1972. CORONA involved multiple reentry vehicles with mid-air capture of these vehicles as they returned from space. Image resolution was originally 25 ft (8 m), but was improved to 6 ft (2 m). Individual images covered an area approximately 10 mi (16 km) by 120 mi (192 km). ARGON, a mapping system, had seven successful missions between May 1962 and August 1964. LANYARD, an attempt to gain higher resolution imagery, had one successful mission in 1963.

The USGS at its Earth Resources Observation System (EROS) Data Center (EDC) in Sioux Falls, South Dakota, will create a duplicate film negative for each photograph. These "masters" will then be used to produce black-and-white duplicate film negatives, positive film transparencies, and black-and-white paper prints. These will be made available for purchase by the public at the cost of reproduction. By August 1996, customers will be able to order photographs from the USGS EDC and the NARA through their existing product ordering and distribution systems.

Figure 4. Soviet Airfield along the coast of the Chukchi Sea, photographed on August 18, 1960. Source photograph is a 30× enlargement from the original negative. This is the first image produced by the Corona mission. Evidence of sediment transport and ocean surface dynamics is clearly visible.

An Internet catalog and image browse capability will be available for the entire collection, available at no charge, on the USGS Global Land Information System (GLIS). The GLIS on-line catalog and browse capability is already operational and can be used for satellite image data collected by the Landsat MSS, Landsat TM, and the NOAA advanced very high resolution radiometer (AVHRR). The text-only Internet GLIS interface is: telnet glis.cr.usgs.gov. The X windows GLIS interface is: telnet xglis.cr.usgs.gov.

An on-line description of this potentially very useful photographic collection, including sample GIF and raster images, is available on the USGS World Wide Web server using public domain browse tools such as Mosaic or Netscape. The USGS Universal Resource Locator (URL) address for the USGS Declassified Intelligence Satellite Photographs home page is: http://edcwww.cr.usgs.gov/dclass/dclass.htm.

An information packet for the Declassified Intelligence Satellite Photographs is available for $25. It contains the four black-and-white declassified sample prints shown in this Washington Report and, for comparison purposes, a Landsat MSS color image of the Aral Sea. For information, contact the Customer Service Center at the EDC. The address is USGS, EDC, Sioux Falls, SD 57198, (605) 594-6151, fax 605-594-6589, E-mail: custserv@edcserver1.cr.usgs.gov.

Upon release, imagery will be available for hands-on inspection by the public at the National Archives facility located at College Park, Maryland. The phone number is (301) 713-7030. ■

GSA Section Officers, 1995–1996

GSA has six regional North American sections, generally including GSA members who live within the geographical limits of each section. (Members who live in one section but have professional interest in another section can declare membership in the section of interest rather than their geographical section.) Each section holds annual technical and business meetings. The number of voting members shown for each section is as of December 31, 1994.

CORDILLERAN Voting members: 3738
Geographic area: Alaska, Arizona south of lat 35°N, California, Hawaii, Nevada, Oregon, Washington, British Columbia, Yukon and Northwest Territories.
Officers: Catherine J. Hickson, chair; J. Casey Moore, vice-chair; Bruce A. Blackerby, secretary; Eldridge M. Moores, past chair.

ROCKY MOUNTAIN Voting members: 1814
Geographic area: Arizona north of lat 35°N, Colorado, Idaho, Montana, New Mexico, North Dakota, South Dakota, Utah, Wyoming, Alberta, Saskatchewan.
Officers: Colin J. Paterson, chair; Perry H. Rahn, vice-chair; Kenneth E. Kolm, secretary; Stephan G. Custer, past chair; David R. Lageson, past vice-chair.

NORTH-CENTRAL Voting members: 1272
Geographic area: Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, Nebraska, Ohio, Wisconsin, Manitoba, Ontario west of 89th meridian.
Officers: Carl F. Vondra, chair; Paul G. Spry, vice-chair; George R. Hallberg, secretary; Robert F. Diffendal, Jr., past chair; James B. Swinehart, past vice-chair.

SOUTH-CENTRAL Voting members: 1231
Geographic area: Arkansas, Kansas, Oklahoma, Texas.
Officers: Page C. Twiss, chair; Mark Cloos, vice-chair; Rena M. Bonem, secretary-treasurer; Philip L. Kehler, past chair.

NORTHEASTERN Voting members: 2179
Geographic area: Connecticut, Delaware, District of Columbia, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, New Brunswick, Newfoundland, Nova Scotia, Prince Edward Island, Quebec, Ontario east of the 89th meridian.
Officers: Barry L. Doolan, chair; Susan D. Halsey, vice-chair; Kenneth N. Weaver, secretary-treasurer; Stephen G. Pollock, past chair.

SOUTHEASTERN Voting members: 1535
Geographic area: Alabama, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, Virginia, West Virginia.
Officers: P. Geoffrey Feiss, chair; David R. Bazard, vice-chair; Harold H. Stowell, secretary-treasurer; Donald C. Haney, past chair; Harry Y. McSween, Jr., past vice-chair.

CALENDAR

Only new or changed information is now being published in *GSA Today*. A complete listing can be found in the **Geoscience Calendar** section on the Internet: **http://www.aescon.com/geosociety/index.html.**

1995 GSA Penrose Conferences

August

August 22–27, **Fault-related Folding,** Banff, Alberta, Canada. Information: David Anastasio, Department of Earth and Environmental Sciences, Lehigh University, Bethlehem, PA 18015-3188, (610) 758-5117, fax 610-758-3677, E-mail: dja2@lehigh.edu.

August 31–September 4, **Fine-grained Fault Rocks,** Leavenworth, Washington. Information: Jerry F. Magloughlin, Department of Geological Sciences, 1006 C.C. Little Building, University of Michigan, Ann Arbor, MI 48109-1063, (313) 747-0664, fax 313-763-4690, E-mail: jerry.magloughlin@um.cc.umich.edu.

September

September 28–October 3, **Tectonic Development of the Canada Basin and Surrounding Regions,** Banff, Alberta, Canada. Information: Lawrence A. Lawver, Institute for Geophysics, University of Texas at Austin, 8701 N. MoPac Expressway, Austin, TX 78759-8397, (512) 471-0433, fax 512-471-0433, E-mail: larry@utig.ig.utexas.edu.

October

October 6–11, **Mesozoic Evolution of the Cordilleran Continental Margin in Central and Southern California,** Tehachapi, California. Information: Andrew Barth, Department of Geology, Indiana/Purdue University, Indianapolis, IN 46202-5132, (317) 274-1243, E-mail: ibsz100@indyvax.iupui.edu.

October 14–20, **The Argentine Precordillera: A Laurentian Terrane?,** San Juan, Argentina. Information: Ian W. D. Dalziel, Institute for Geophysics, University of Texas at Austin, 8701 N. Mopac Expy., Austin, TX 78759-8397, (512) 471-0341, fax 512-471-8844, E-mail: ian@utig.ig.utexas.edu.

1995 Meetings

August

August 13–18, **Rock Deformation** (Gordon Conference), Tilton, New Hampshire. Information: World Wide Web on Rock Net at http://sair019.energylan.sandia.gov:70 or Terry E. Tullis, Brown University, Providence, RI 02912-1846, (401) 863-3829, fax 401-863-2058, E-mail: terry_tullis@brown.edu.

September

September 25–28, **Land Satellite Information in the Next Decade,** Vienna, Virginia. Information: American Society for Photogrammetry and Remote Sensing, 5410 Grosvenor Lane, Suite 210, Bethesda, Maryland 20814-2160, (301) 493-0290, fax 301-493-0208, E-mail: asprs@asprs.org.

September 29–October 3, **Comparative Evolution of Peri-Tethyan Rift Basins** (IGCP Project 369 Annual Meeting and Field Trip), Mamaia, Romania. Information: William Cavazza, Dept. of Mineralogical Sciences, University of Bologna, Piazza Porta San Donato 1, 40126 Bologna, Italy; phone 39-51-243-556, fax 39-51-243-336, E-mail: cavazza@geomin.unibo.it. See also the IGCP 369 home page on the Internet at http://geode.geomin.unibo.it/min/igcp/igcp.htm.

October

October 1–7, **Association of Engineering Geologists Annual Meeting,** Sacramento California. Information: AEG, 323 Boston Post Rd., Suite 2D, Sudbury, MA 01776, (508) 443-4639.

October 10–14, **5th International Conference on Paleoceanography,** Halifax, Nova Scotia, Canada. Information: Trudy D. Lewis, Lewis International Inc., ICP-V, Richmond Terminal, Pier 9, 3295 Barrington St., Halifax, NS, B3K 5X8, Canada, (902) 492-4988, fax 902-492-478?, E-mail: icpv@predator.ocean.dal.ca; Mosaic: agc.bio.ns.ca. ###***

October 17–19, **Industrial Minerals '95,** Vancouver, British Columbia, Canada. Information: D. Hora, British Columbia Geological Survey, Ministry of Energy, Mines & Petroleum Resources, 5th Floor, 1810 Blanshard St., Victoria, BC V8V 1X4, Canada, (604) 952-0414, fax 604-952-0381.

October 22–25, **Minerals and Geotechnical Logging Society Sixth International Symposium on Borehole Geophysics for Minerals, Geotechnical, and Groundwater Applications,** Santa Fe, New Mexico. Information: Carol LaDelfe, EES-1, MS D462, Los Alamos National Laboratory, Los Alamos, NM 87545, (505) 667-8474, fax 505-665-3285, E-mail: cladelfe@lanl.gov. See also Internet Web home page at http://xrfmac.lanl.gov/cml.mgls/mgls_symposium.html.

November

November 6–9, **Geological Society of America Annual Meeting,** New Orleans, Louisiana. Information: GSA Meetings Dept., P.O. Box 9140, Boulder, CO 80301, (303) 447-2020, fax 303-447-6028.

1996 Meetings

January

January 16–19, **Tailings and Mine Waste '96,** Fort Collins, Colorado. Information: Linda Hinshaw, Dept. of Civil Engineering, Colorado State University, Fort Collins, CO 80523, (970) 491-6081, fax 303-491-7727.

March

March 26–27, **Platform Carbonates in the Southern Midcontinent,** Norman, Oklahoma. Information: Kenneth Johnson, Energy Center, 100 E. Boyd, Rm. N-131, Norman, OK 73019-0628, (405) 325-3031, fax 405-325-7069. *(Abstract deadline: November 1, 1995.)*

May

May 13–16, **Tidalites '96,** International Tidal Sedimentology Conference, Savannah, Georgia. Information: V. J. Henry, Jr., Coastal Research Laboratory, Georgia Southern University, 10 Ocean Science Circle, Savannah, GA 31411, fax 912-598-22366, E-mail: henry@skio. peachnet.edu. ###***

June

June 23–27, **Carbonates and Global Change: A Multidisciplinary Approach** (SEPM/IAS Research Conference), Switzerland. Information: Maria Mutti, Geological Institute, ETH-Z, Sonneggstrasse 5, CH-8092 Zurich, Switzerland, phone 41-1-632-3673, fax 41-1-632-1080, E-mail: maria@erdw.ethz.ch.

July

July 15–17, **Cephalopods—Present and Past,** IV International Symposium, Granada, Spain. Information: Federico Olóriz Sáez or Francisco J. Rodríguez-Tovar, Dept. Estratigrafía y Paleontología, Univ. Granada, Avd. Fuente Nueva s/n, 18002 Granada, Spain, fax 34-58-243345, E-mail: fjrtovar@goliat.ugr.es.

September

September 15–20, **Deep Seismic Profiling of the Continents,** 7th International Symposium, Asilomar, California. Information: Simon Klemperer, Dept. of Geophysics, Mitchell Building, Stanford University, Stanford, CA 94305-2215, (415) 723-8214, fax 415-725-7344, E-mail: klemp@pangea.stanford.edu.

October

October 28–31, **Geological Society of America Annual Meeting,** Denver, Colorado. Information: GSA Meetings Dept., P.O. Box 9140, Boulder, CO 80301, (303) 447-2020, fax 303-447-6028.

Send notices of meetings of general interest, in format above, to Editor, *GSA Today*, P.O. Box 9140, Boulder, CO 80301.

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,

Tectonics *continued on p. 149*

Splitting *continued from p. 141*

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)

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

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

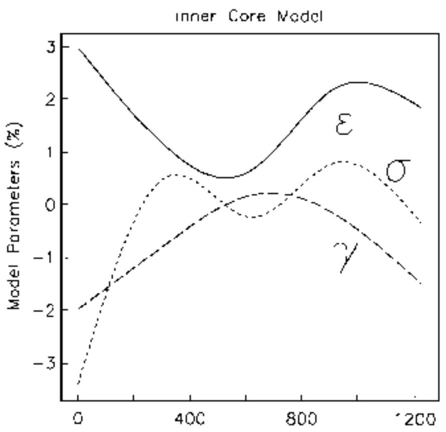


Figure 6. Anisotropic inner-core model obtained by the joint inversion of anomalous splitting functions and PKIKP traveltime anomalies. The elastic response of an isotropic medium is determined by two elastic parameters: the shear modulus μ and the bulk modulus κ. A transversely isotropic medium, on 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: $\varepsilon = \frac{1}{2}(C - A)/A_0$, and $\gamma = -\frac{1}{4}(\frac{1}{2}A + \frac{1}{2}C - 2L - F)/A_0$, where $A_0 = \kappa + \frac{4}{3}\mu$, 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: $\sigma = \frac{1}{2}(L - N)/A_0$. 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.

Splitting *continued on p. 149*

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

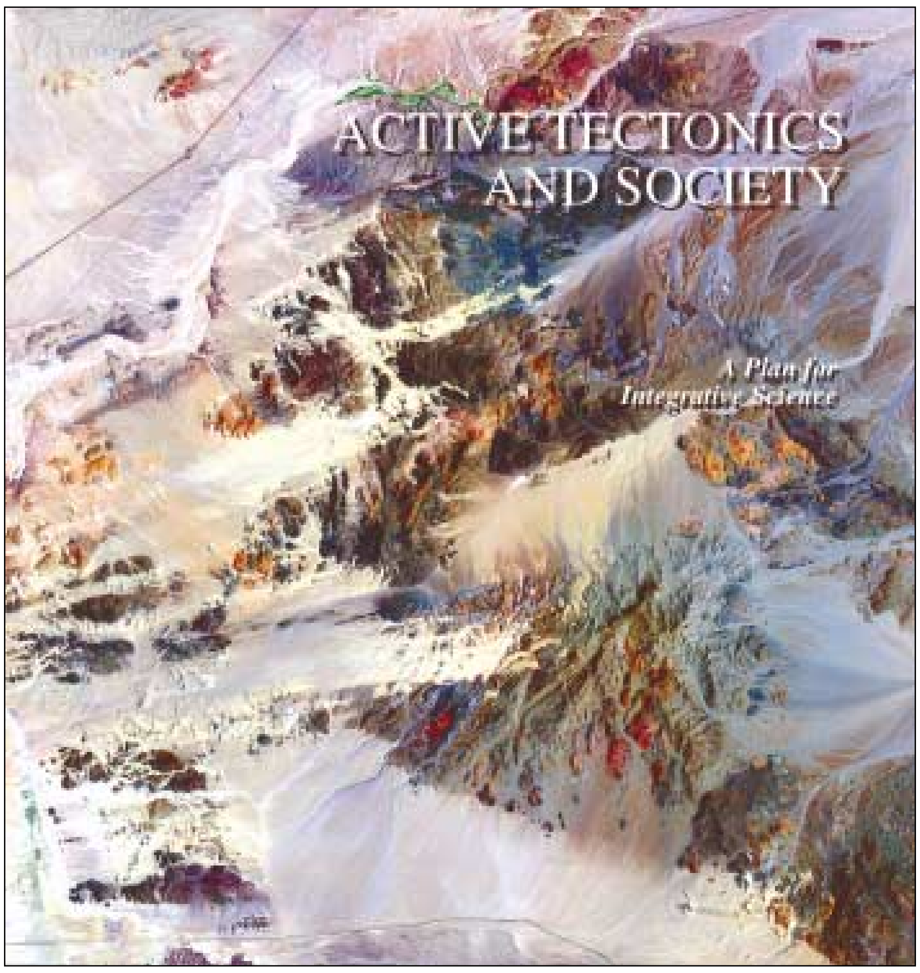
If you are interested in becoming involved in some aspect of working on the initiative, please contact Kerry Sieh at sieh@seismo.gps.caltech.edu. There is a lot of work to go around, especially during the launch year of this cooperative initiative. The coordinating committee seeks to establish a core 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

I thank the members of the Active Tectonics Planning Committee for the wisdom, energy, and integrity with which they carried out their work; Roy Dokka for joining me in the final writing efforts and for taking chief responsibility for illustrations, design work, and layout of Active Tectonics and Society; Larry Mayer for, especially, establishing Active Tectonics on Mosaic; and Lori Stiles, University of Arizona science reporter, for help in the preparation of this article. ■



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U.S. Geological Survey, Menlo Park

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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.

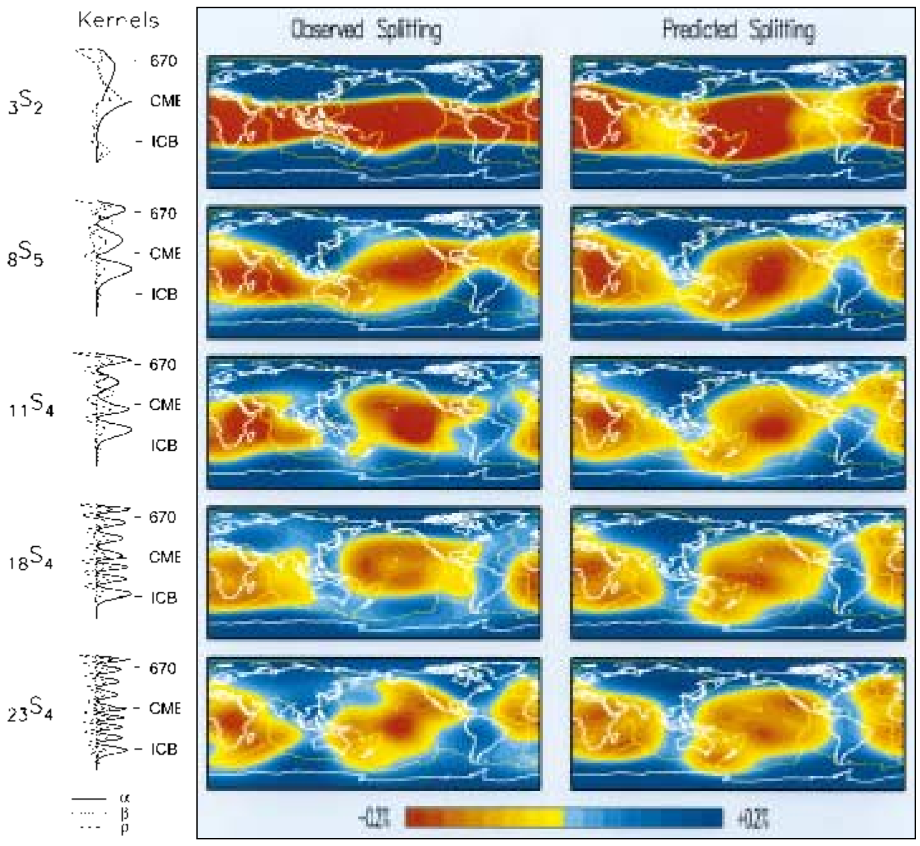

Figure 7. Observed and predicted splitting functions of several anomalously split normal modes. The splitting predictions are based upon mantle model SKS12WM13 (X. F. Liu and A. M. Dziewonski) and the anisotropic inner-core model shown in Figure 6. See the caption of Figure 2 for further details.

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-

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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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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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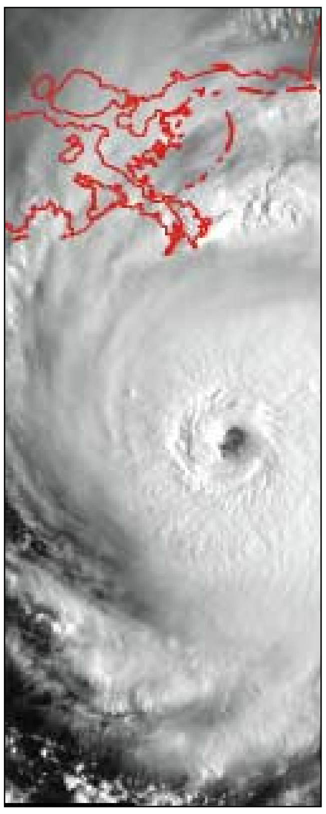

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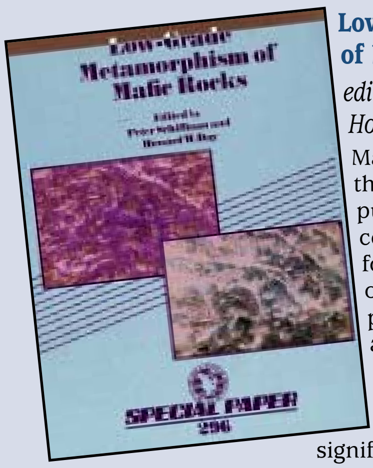

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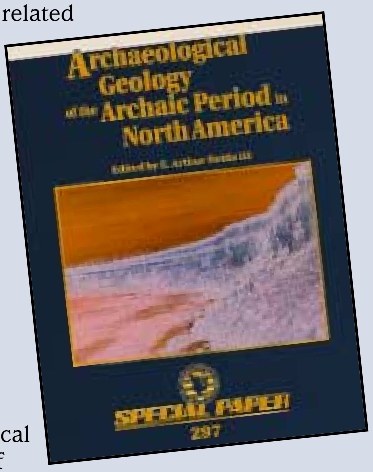

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