Crustal Defor *and* Earthquakes

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A growing array of Global Positioning System (GPS) monitoring stations is continuously measuring crustal deformation in Southern California. These measurements are the beginning of an attempt to quantify the relationship between plate boundary deformation and the occurrence of earthquakes.

The theory of plate tectonics teaches us that Earth's surface is composed of about 10 large rigid plates. While the plates are rigid in their interiors, complex deformation is occurring along their boundaries. The deformation is cyclical because of the accumulation and release of strain on geologic faults. This process is often called the earthquake cycle. In the coseismic phase of the cycle, one or more faults break during an earthquake and release the accumulated elastic strain since the last earthquake. In the interseismic phase, the strain begins to accumulate again until the next earthquake. Two other distinct phases to the earthquake cycle have been identified. In the postseismic stage, which immediately follows an earthquake, inelastic effects cause crustal motion that is different from the motion that occurs during the interseismic period. Postseismic stage deformation gives insight into the rheology of the crust and the underlying mantle and may be crucial to understanding the physics of earthquakes. The fourth and most elusive stage in the earthquake cycle is the preseismic, which occurs near the end of the interseismic period and directly before an earthquake. The preseismic stage is manifested by anomalous variations in strain. These anomalies, if they exist, may be an important tool in predicting earthquakes.

Geodetic measurements of crustal deformation play an increasingly important role in earthquake research. The most common method is to repeatedly measure positions of geodetic monuments with GPS at 1-year to 2-year intervals or immediately after large earthquakes. A more recent development is the establishment of continuously operating GPS arrays in central Japan and in California to provide frequent measurements of crustal deformation. The Permanent Geodetic GPS Array (PGGA) in Southern California consists of 15 continuously tracking GPS monitoring stations. This project is funded primarily by the Dynamics of the Solid Earth Program at NASA, and by the U.S. Geological Survey and National Science Foundation through the Southern California Earthquake Center.

The Permanent Geodetic GPS Array uses geodetic receivers at each site to collect data from all visible GPS satellites every 30 seconds. Every evening, computers at central collection facilities invoke a series of programs that dial up the PGGA stations using high-baud-rate modems over commercial telephone lines. They download the previous 24 hours of data, uncompress and reformat it, and copy the data to a magnetic disk residing on a network of scientific workstations and to an optical storage device for archiving. The data are analyzed with data from a global network of stations called the International GPS Service for Geodynamics (IGS) to obtain accurate "snapshots" of the 3-D positions of the regional stations. Significant variations in these positions indicate deformation within the network with respect to a worldwide geodetic reference frame. The precision of each daily determination is about 2-3 millimeters horizontally and 5-10 millimeters vertically.

The first real test of the PGGA was the Landers earthquake sequence of June 28, 1992, which occurred in a remote, sparsely populated region in Southern California. The Landers earthquake (M 7.5), and the Big Bear earthquake (M 6.6), which occurred on the same day were typical strike-slip events on transform faults. Surface displacements of up to 6 meters were observed; the associated elastic deformation affected all the PGGA sites. The PGGA sites detected far-field coseismic horizontal displacements ranging between 4 to 46 millimeters, which were determined by analyzing the 24-hour PGGA solutions over a 10-week period that was centered on the day of the earthquakes. The coseismic displacement of each PGGA site was determined by the variation in the positions before and after the earthquakes. There was good agreement between the observed displacements and theoretical displacements computed from an earthquake dislocation model based on seismic and geologic observations. In addition, postseismic displacements of 1-2 millimeters a day were detected at the PGGA site at Pinyon Flat Observatory for several weeks following the earthquake. These displacements were confirmed by laser strainmeters at the site and field GPS measurements closer to the earthquake epicenter.

The Jan. 17, 1994, Northridge earthquake (M 6.6) was very different from the Landers earthquake. It was a thrust earthquake, there was no evidence for primary surface rupture, and it struck in the Los Angeles metropolitan area, causing extensive damage. The causative fault was a previously unknown south-southwest dipping thrust fault; the depth of faulting extended from 5 to 8 kilometers down to about

In other regions, the slab may poke several hundred kilometers into the lower mantle. Massive volumes of slab material have sunk into the mantle, and some of the larger scale features in tomographic models may represent the accumulation of cold relics of oceanic lithosphere. This material is concentrated near the 660-kilometer boundary, and the thickened accumulation of slab appears to be sinking into the lower mantle in some places. Geodynamic models that include the effects of the olivine phase transition producing the 660-kilometer discontinuity show that this transition is expected to impede downwellings. The transition may cause the cold material to pile up before eventually flushing out of the upper mantle. Calculations that include the strong viscosity variations of subducting slabs are being made to test these models.

Cold slab material sinking to the base of the mantle is one way to explain strong reflections observed from a seismic discontinuity about 250 kilometers above the core. This structure, which I discovered using S-wave reflections more than 10 years ago, has been the subject of extensive investigation. The investigations have resulted in many observations of P- and S-wave reflections from an intermittent boundary. The depth and strength of the discontinuity vary laterally, and the expanding global seismic network is providing the data needed to fully assess this major feature of the lower mantle.

Relating seismic observations to mantle dynamics is a challenging effort, so seismologists are striving to obtain measurements that are directly sensitive to the flow. One promising approach enabled by the new broadband data involves seismic anisotropy: the splitting of S waves that traverse regions with anisotropic properties. Shear flow-induced alignment of anisotropic minerals and the presence of shear fabrics in the mantle are possible causes of seismic anisotropy. Studies of S-wave splitting from portable and permanent seismic stations reveal that the upper 300 kilometers of the mantle has variable anisotropy, some of which must be locked into the stable lithosphere, and some of which must be dynamically maintained in the asthenosphere. S-wave splitting is revealing the flow of mantle material near slabs, under major faults, and in regions of continental collisions. While the lower mantle appears to be largely devoid of anisotropy (except possibly right near the core-mantle boundary), the inner core has an anisotropic structure largely aligned with the spin axis.

A final example of recent exciting developments in deep Earth seismology is a new hypothesis for the cause of deep earthquakes. Earthquakes that occur deeper than a few tens of kilometers are enigmatic, because the large confining pressures should preclude frictional sliding. Yet earthquakes as deep as 700 kilometers exist, with properties that are virtually indistinguishable from shallow faulting events. The presence of fluids, which are released from dehydrating minerals, is largely thought to be responsible for earthquakes as deep as 300 kilometers, since pore water pressures can reduce the effective normal stress on the fault plane. Although deeper events may involve similar dehydration of mineral phases that are stable to greater depths, phase transformations in olivine may explain the deep events. Slab material will transform to high-pressure phases as it descends because of increasing temperature and pressure. Phase transformations, however, are inhibited by kinetic effects, so untransformed material may penetrate to depths below the equilibrium phase transition. Experimental mineral physics has shown that transformation of metastable material under deviatoric stress conditions can involve "transformational faulting," with strain release similar to frictional faulting. Seismologists are studying deep earthquake signals to test this intriguing hypothesis.

These diverse advances in deep Earth seismology involve collaborations between seismologists and other earth scientists. Fostering such collaborations is the intent of a new National Science Foundation program called Cooperative Studies of the Earth's Deep Interior (CSEDI), organized by researchers in the United States. In the next decade, global seismologists will have to broaden their geophysical knowledge and interactions to solve the challenging problems of understanding the Earth's deep interior.

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Additional Reading

"Global mapping of topography on the 660-km discontinuity" by P.M. Shearer and T.G. Masters. *Nature*, v. 355, p. 791-796, 1992

"Long-term controls on eustatic and epeirogenic motions by mantle convection" by M. Gurnis. *USA Today*, v. 2, p. 142-157, 1992

"Mantle phase changes and deep earthquake faulting in subducting lithosphere" by S.H. Kirby and others. *Science*, v. 252, p. 216-225, 1991

"Tomographic inversion of P and pP data for aspherical mantle structure below the northwest Pacific region" by R.D. van der Hilst and others. *Geophysical Journal International*, v. 115, p. 264-302, 1993

The GeoRef database contains many references on the author's topic. The following strategy was used to search GeoRef on CD-ROM through December 1993.

KEY WORDS	TOTAL REFERENCES
(seismology OR velocity structure OR discontinuities) AND ((earth AND interior) OR mantle OR core OR asthenosphere)	8,630

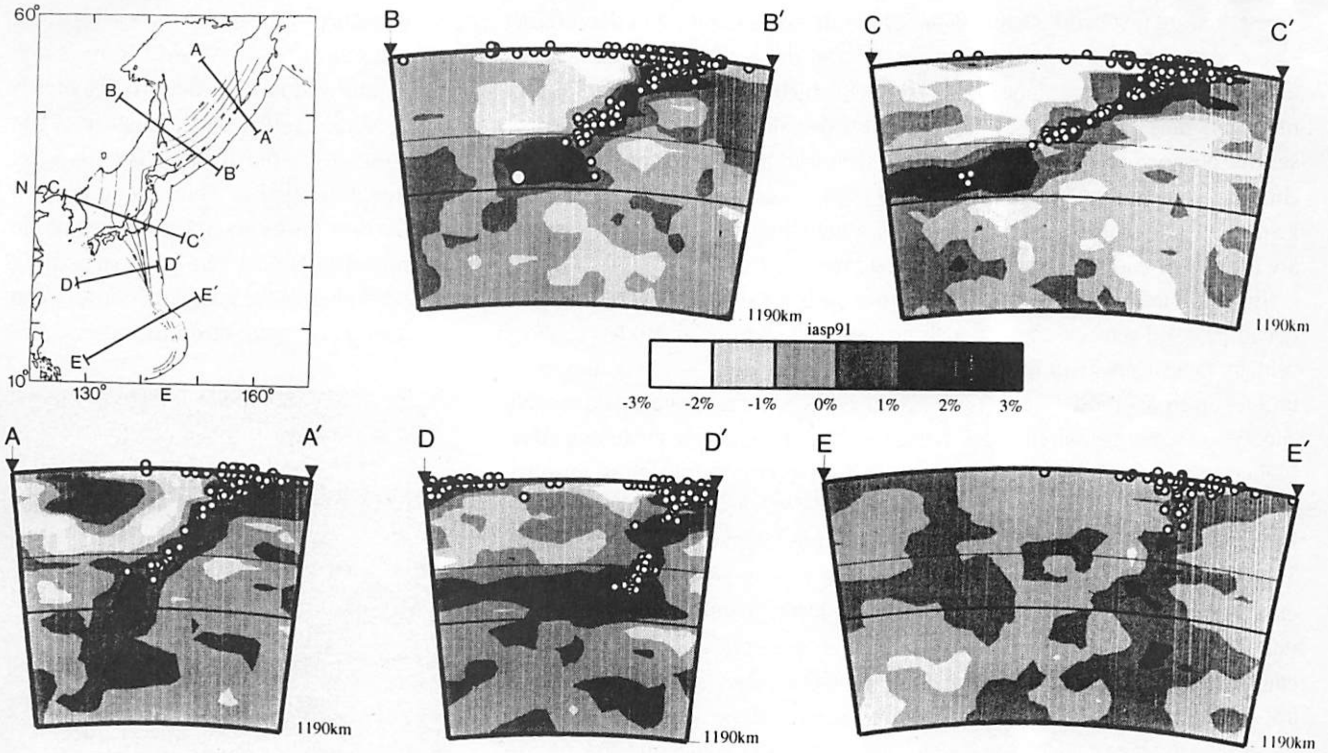

Illustration shows cross sections through subduction zones in a high-resolution tomographic model for the western Pacific. The map shows the positions of the vertical sections. The darker regions are faster than average velocities, and the circles are earthquake locations. Note that the subducting slabs are well defined by the seismicity and the fast velocity zones.

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on the continents. Induced motions of the continents, however, are associated with epeirogenic sea-level fluctuations, as underthrusting of oceanic lithosphere produces stresses that locally pull down the continental margins.

In addition to mapping volumetric heterogeneity in the mantle, seismologists are also mapping lateral variations of impedance contrasts at depth. Some seismic velocity discontinuities are observed globally, such as those near depths of 410 kilometers and 660 kilometers, while others are observed intermittently, at depths near 60, 80, 220, 330, 710, and 2,640 kilometers. Characteristics of these mantle discontinuities are being studied using large digital seismic data sets from both global stations and seismic arrays used for earthquake monitoring. The 410-kilometer and 660-kilometer discontinuities are attributed to phase transformations in the upper-mantle mineral olivine, caused by increasing pressure and temperature with depth. Mapping the lateral variations in depth of the discontinuity provides a means for inferring absolute temperature variations deep in the Earth, with calibration from experimental mineral physics. The first global map of the topography of these internal boundaries was produced by Peter Shearer of the University of California, San Diego.

Models of topographic undulations of the mantle discontinuities can also be used to investigate one of the fundamental questions of global geophysics — the extent of mass flux between the upper and lower mantles. It appears that the 660-kilometer discontinuity is not caused by a major change in composition, which could produce a stratified mantle convection system. The boundary, however, does influence the flow. This influence is indicated by high-resolution tomographic models of velocity structure near subducting slabs. Earthquakes delineate slabs to maximum depths near 700 kilometers, but no deeper, while seismic velocity heterogeneity can reveal aseismic extensions of the slabs. In some places, slabs deflect horizontally above the 660-kilometer boundary.

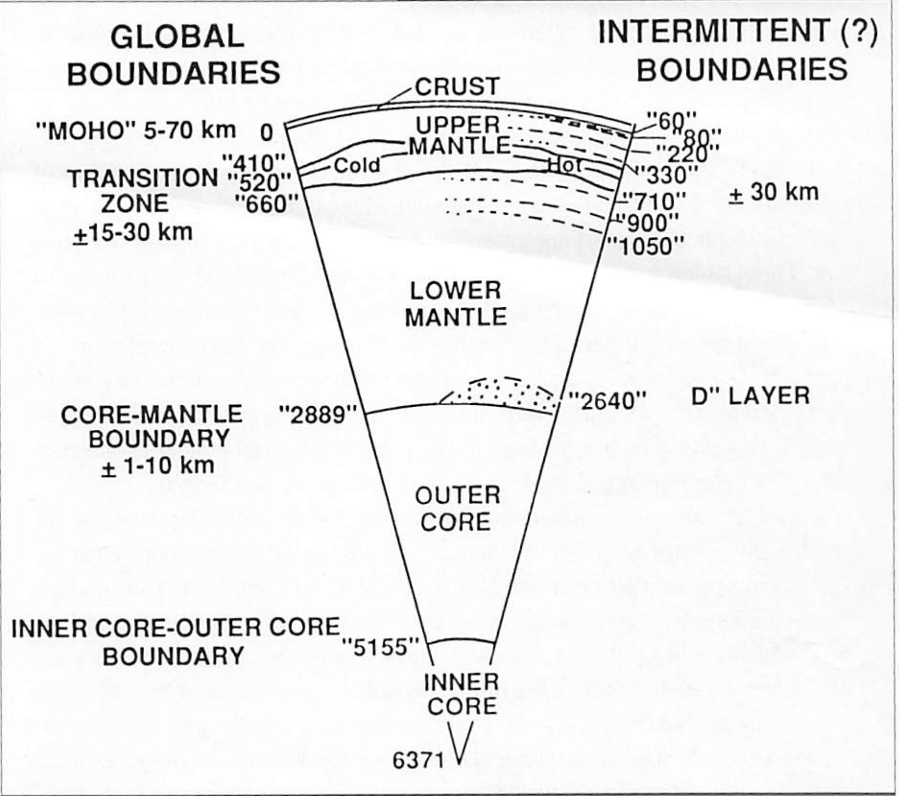
Exciting discoveries and advances in our understanding of deep Earth structure continue to occur. As always, the key to progress is high-quality seismic data. A generation of broadband, high dynamic range digital seismometers developed in the 1980s is being widely deployed to upgrade global seismic observatories by the Incorporated Research Institutions for Seismology (IRIS) and the international Federation of Digital Seismic Networks. While the instrument deployment will continue at least until the year 2000, these systems are already providing remarkable seismograms.

Global models of the mantle's aspherical velocity structure were first produced 10 years ago, and these models are now quite advanced. Models of shear velocity heterogeneity in the entire mantle, with spherical harmonic representations up to degree 12, have been produced by several groups. The models show good agreement in the basic patterns of heterogeneity at all depths. Also, higher resolution models of lower mantle P-wave velocity structure have recently been obtained, using millions of accumulated arrival time observations. But more stable investigations of broadband P-waveform data are just starting. These seismic tomography models reveal large-scale regions of faster-than-average or slower-than-average velocity in the lower mantle, which appear to dominate smaller scale variations. While heterogeneities in the upper mantle can largely be related to surface tectonic processes, deep structures have less apparent relationships with surface features. Lower mantle regions, which show faster than average velocities and which are presumably colder and sinking, are found below many current subduction zones. This finding suggests that descending oceanic slabs penetrate deep into the mantle. Lower-than-average velocity regions, presumably hot and upwelling, correlate with surface volcanic hot spots. Efforts continue to relate the seismic heterogeneity to mantle dynamics over the past few hundred million years.

Upper mantle shear velocity heterogeneity is particularly well mapped, with models now having lateral resolution of 1,000 kilometers (degree 36 spherical harmonics). Such a high resolution allows investigations of tectonic processes such as the deep structure of oceanic ridges and upwellings under hot spots. New research efforts attempt to relate high-resolution seismic models to geochemical heterogeneity to infer the degree of melting and depth of the deep magma reservoirs. Mapping the thermal structure of the mantle was a prime motivation for developing the first generation of global aspherical models of seismic wave attenuation, which provides an additional measure of thermally activated processes in the upper mantle.

Quantifying the heterogeneous structure of the upper mantle provides critical constraints on the dynamic mantle system. The importance of this dynamic system on the history of the continents, particularly for sea-level fluctuations, has been recognized in the past few years. Increases in mantle upwellings and sea-floor spreading rates change the geometry of the ocean basins and cause eustatic sea-level rise

Schematic cross section through Earth identifies the major boundaries inside the planet that are observed globally (left side) or only intermittently (right side). The 410-kilometer and 660-kilometer boundaries appear to have deflections of a few tens of kilometers.



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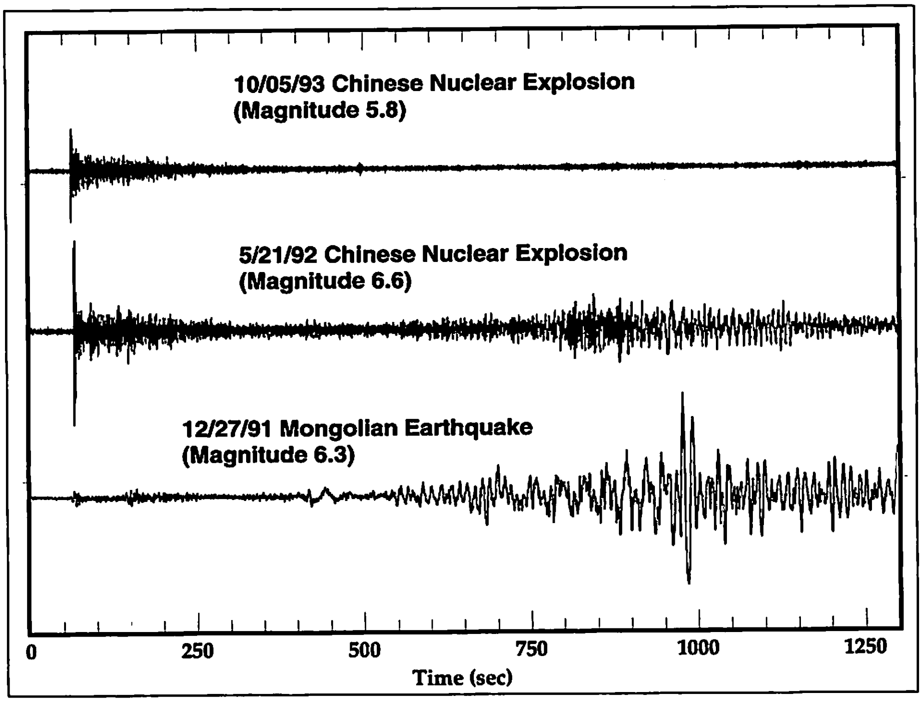
were 99 percent accurate, many events will still not be positively identified by seismic means alone. Furthermore, at this level, one must distinguish possible small nuclear tests not only from earthquakes but also from chemical explosions used for legitimate industrial purposes. In the United States, for example, hundreds of chemical explosions of 10 or more tons occur each month.

A CTBT will be considered verifiable as long as it is judged that the benefits of the treaty outweigh the costs of any potential small undetected violations. Through a similar cost-benefit analysis, the United States and other concerned countries will have to determine the level of effort they wish to apply to monitoring small seismic events around the world. Because the number of seismic events increases exponentially with decreasing magnitude, there will probably be about a tenfold increase in cost and number of ambiguous events for each magnitude unit that the detection-identification threshold is lowered. Inevitably, because funding and personnel are limited, the overall monitoring capability will largely be determined by the extent to which all available seismic data can be used.



Despite a multinational moratorium on the testing of nuclear weapons, China exploded a nuclear device Oct. 5, 1993, at their Central Asian test site at Lop Nor. The seismograms, comparing the 1993 test with a larger Chinese test conducted in 1992 and a Mongolian earthquake of intermediate size, illustrate how technological advances and geopolitical change assist the global monitoring of seismicity. They were recorded at the IRIS station outside Moscow; sent over an open computer communications network in near-real time to a data collection center in California; accessed and analyzed by seismologists in Colorado; and received by researchers nationwide within hours of the explosion. It is now the relatively slow speed with which seismic waves travel through Earth (a few kilometers per second) that limits how fast seismic data can be retrieved from around the world.

Global seismic monitoring has direct application not only for treaty verification but also for the recording of earthquake activity, the assessment of seismic risk, and the scientific exploration of Earth's interior. Major distinctions between an earthquake station and a nuclear-monitoring station are not needed, thus opening opportunities for collaboration and considerable cost savings.

Many high-quality seismic stations for earthquake monitoring and research are being installed by Australia, Canada, China, France, Germany, Italy, Japan, and the United States. The U.S. seismological community, under the aegis of the Incorporated Research Institutions for Seismology (IRIS), is deploying a global network of digital broadband seismic observatories. More than 50 stations have been installed, with roughly 100 more planned for completion within the next five years. Data exchange from these and other open stations is flourishing under bilateral agreements and informal arrangements. Technical developments in communication networks allow data from many (and soon nearly all) of these stations to be accessed in near-real time.

Recent schemes for monitoring a proposed CTBT have argued for a limited number of stations to trigger the collection of data from a larger global network. Such a tiered approach is now used for earthquake monitoring and is an appropriate framework for monitoring a CTBT. At present, however, many available seismological resources may be neglected. The open global networks are a cost-effective source of regional distance data to complement teleseismic data obtained from a handful of specialized seismic sensor arrays. By incorporating the networks in their entirety in the CTBT verification system, any redundancy of coverage would provide data validation and high reliability to the overall monitoring effort.

As computer communication systems continue to grow, such networks can expand into geophysical observatories, with different types of sensors that contribute data to treaty monitoring and to a range of scientific and environmental problems. The multiple applications of such stations will contribute to sustaining the interest and support of the host country more than specialized seismic stations, whose sole purpose is for treaty monitoring. Additionally, many geoscientists will indirectly aid the treaty monitoring effort through their use of geophysical data in related fields of research.

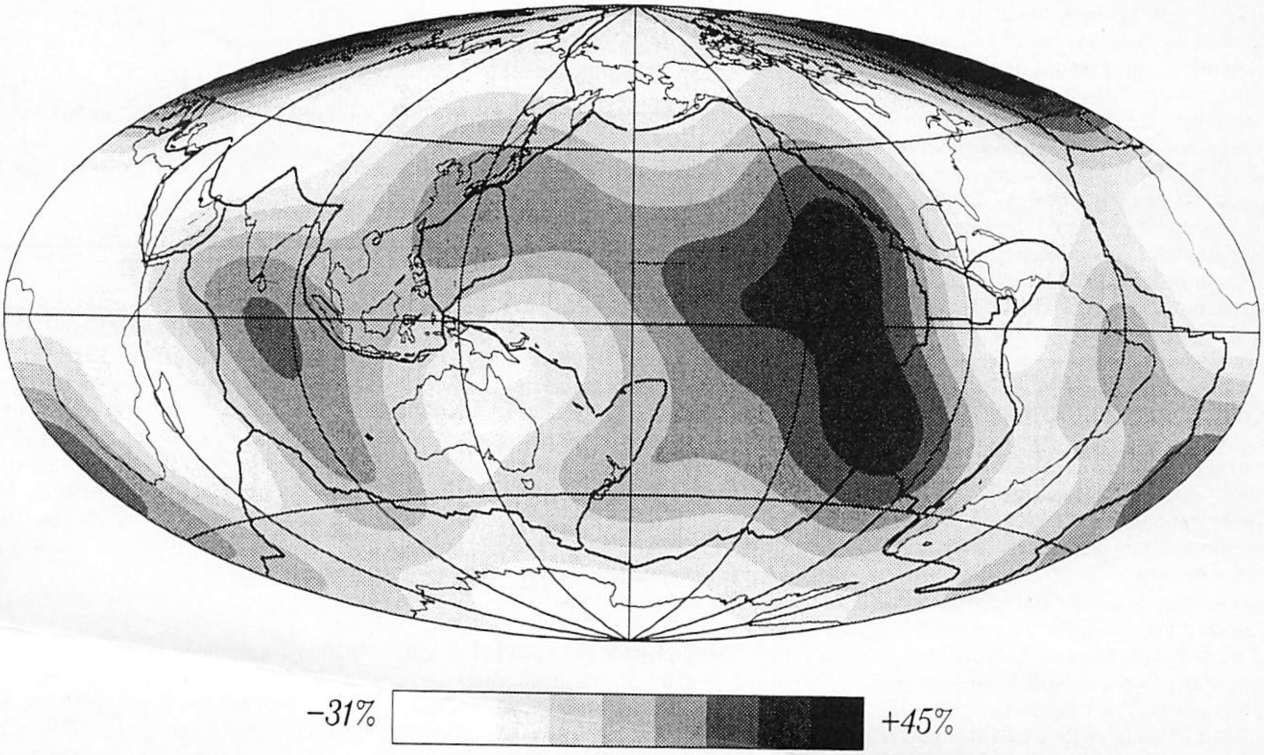
Although the new requirements are more extensive, new resources, combined with geopolitical changes, may now allow for improvements in treaty verification beyond what was thought possible. Although testing is not necessarily critical to the development of a simple-design, first-generation nuclear weapon, a CTBT will impede the development of advanced weapons and provide an unambiguous context in which other more direct nonproliferation efforts can be enforced. Such a CTBT, verified in part with data drawn from open seismic networks, may thus be able to deter horizontal proliferation more effectively than international agreements were able to deter vertical proliferation during the Cold War.

(Contributed by Gregory E. van der Vink, Incorporated Research Institutions for Seismology, Arlington, Va., and Jeffrey Park, Department of Geology and Geophysics, Yale University, New Haven, Ct., reprinted with permission from Science, *v. 263, p. 634-635)*

(Part of this work was done while van der Vink was an International Affairs Fellow of the Council on Foreign Relations.)

DEEP EARTH

SEISMOLOGY



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Above: **Lateral variations of attenuation of seismic waves at a depth of 160 kilometers in the mantle are shown. Such variations are presumably related to lateral temperature variations and presence of small amounts of partial melts.**

Global seismological investigations are systematically revealing the structure of the deep interior of Earth, providing insight into its composition and dynamics. Major recent advances include global mapping of topography on internal mantle discontinuities; the first generation of aspherical models of seismic anelasticity; three-dimensional, high-resolution images of subducting slabs; and mapping of complex structures near the core-mantle boundary.