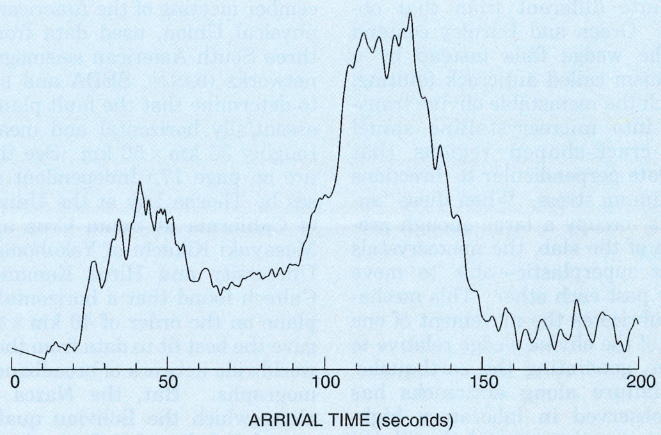
BOLIVIAN QUAKE GIVES A RARE GLIMPSE OF EARTH'S INTERIOR

The most challenging paradox of the magnitude-8.2 earthquake that struck the Bolivian Alteplano (literally, "high plane") on 9 June is not that it caused minimal damage while still being strong enough to be felt throughout most of the Western Hemisphere, to excite normal modes of vibration of the Earth never before seen and potentially to enable geophysicists to map the Earth's interior with 50 km resolution. Rather it is that the earthquake could occur at all. That is because the depth of the Bolivian quake (640 km) puts it in a rare class of earthquakes called "deep focus" quakes, whose foci lie between 75 km and 670 km beneath the Earth's surface. How such deep-focus quakes occur in the mantle, where high pressures and temperatures cause rock under stress to flow rather than fracture, has been a subject of intense interest and controversy ever since their existence was established in the late 1920s. The importance of the Bolivian quake is further increased because it is the first really large, very deep event to occur since the deployment of modern global networks of digital seismographs. Three networks of portable broadband seismographs recently deployed in South America promise to provide an unprecedented close-up view of the quake. (The color relief map on the cover of this issue shows the positions of the stations in these networks in relation to the quake's epicenter.) Researchers hope that data from the earthquake will yield a wealth of information on the Earth's interior as well as shed light on how deep-focus events occur.



Seismogram shows the arrival of compressional P waves from the Bolivian quake at a station 637 km south of the quake's epicenter, followed about 70 seconds later by the transverse S waves. Researchers compare arrival times at different stations of distinct features (such as the onset of motion) in the P- and S-wave envelopes to determine the quake's focus and fault plane. (Courtesy of Terry Wallace, University of Arizona.)

An alternative mechanism

The difficulty in understanding deep-focus earthquakes lies in the fact that although they occur at pressures and temperatures where the brittle-failure mechanism of shallow quakes (in which the rock along a fault fails structurally, allowing movement along the fault plane) cannot operate, the pattern of seismic energy they radiate looks very similar to that from shallow quakes. The vast majority of deep-focus quakes occur in areas where one section of the Earth's crust, or lithosphere, is being subducted, that is, forced under another section. For this reason geophysicists have sought a mechanism for these quakes that explains the observed seismic radiation pattern in terms of the behavior of common minerals of the earth's lithosphere as they descend into the hot, high-pressure mantle.

Experiments by Charles Meade of the Carnegie Institution of Washington and Raymond Jeanloz of the University of California at Berkeley have shown that, most probably, earthquakes between 75 and 300 km under the Earth's surface occur when minerals such as serpentine—$(Mg,Fe)_3Si_2O_5(OH)_4$—dehydrate, releasing liquid water.[1] The water expands the pores in the rock and allows movement along pre existing faults. However, this mechanism has not been observed at pressures corresponding to depths below 300 km. Another mechanism is needed to explain earthquakes at those depths. One possibility is a repetition of the hydration–dehydration cycle, with new, higher-pressure hydrous minerals forming in the mantle, then dehydrating and thereby lubricating motion along faults. However, the existence of high-pressure hydrothermal reactions was established only recently,[2] and little experimental work has so far been done to demonstrate the applicability of such a model to earthquakes below 300 km. Meanwhile some researchers have been looking for alternative explanations.

Because olivine—$(Mg,Fe)_2SiO_4$, a major constituent of the lithosphere—becomes unstable with respect to a transition to the denser mineral spinel at a depth between 300 and

400 km, Stephen Kirby of the United States Geological Survey,[3] among others, has looked to this transition for a mechanism for earthquakes below 300 km. Based on results of subsequent laboratory investigations into such a mechanism, Harry Green of the University of California, Riverside, and Pamela Burnley, now of the University of Colorado,[4] proposed that as a cold slab descends into the hotter mantle, a wedge up to several kilometers thick composed mainly of metastable olivine may persist within the slab well below 400 km. The catastrophic collapse of such a wedge would yield a seismic energy distribution quite different from that observed. Green and Burnley contend that the wedge fails instead by a mechanism called anticrack faulting, in which the metastable olivine transforms into microcrystalline spinel along crack-shaped regions that propagate perpendicular to directions of maximum stress. When these "anticracks" occupy a large enough proportion of the slab, the microcrystals become superplastic—able to move readily past each other. This mechanism lubricates the movement of one region of the olivine wedge relative to another, generating the earthquake. Such failure along anticracks has been observed in laboratory high-pressure experiments with the related germanate mineral $(Mg,Fe)_2GeO_4$, which transforms at much lower pressures, and anticrack faults have also been observed in natural olivine at very high pressures.[5] However, it remains to be seen whether this mechanism can be shown to be the cause of earthquakes below 300 km.

Testing models

Distinguishing between models of deep-focus earthquakes is difficult, because the fault zone is not observable and because the seismic signals for deep earthquakes provide few clues as to their mechanism. The large magnitude of the Bolivian quake and the presence of a network of state-of-the-art seismometers just above its focus make it the best opportunity yet for gaining insight into the mechanism of such earthquakes. One hope for testing the anticrack faulting mechanism lies in detecting the metastable olivine wedge within a subducting slab. Because olivine is less dense than spinel of a similar temperature, the speed of sound would drop as it passed through olivine. Takashi Iidaka and Daisuke Suetsugu of the University of Tokyo claim to have found evidence for such a drop by analyzing travel times of seismic waves from deep quakes near Japan.[6] However, to draw any conclusion at all, Iidaka and Suetsugu had to assume specific models for the Earth under the seismic stations; this renders their results less than certain.

Recent work by Meade, Paul Silver, and David James at the Carnegie Institution along with Susan Beck, Terry Wallace and Stephen Myers at the University of Arizona may pose a serious challenge to the anticrack theory. Their findings cast doubt on whether the postulated olivine wedge could in fact be large enough to contain the fault plane of the Bolivian quake. This work, an abstract of which has been submitted for the December meeting of the American Geophysical Union, used data from the three South American seismographic networks (BANJO, SEDA and BLSP92) to determine that the fault plane was essentially horizontal and measured roughly 35 km × 50 km. (See the figure on page 17.) Independent analyses by Thorne Lay at the University of California at Santa Cruz and by Masayuki Kikuchi of Yokahoma City University and Hiroo Kanamori of Caltech found that a horizontal fault plane on the order of 40 km × 40 km gave the best fit to data from the IRIS worldwide network of broadband seismographs. But, the Nazca plate, along which the Bolivian quake occurred, is believed to descend into the mantle at an angle of about 45°, and most models have the thickness of the olivine wedge going to zero as it reaches the 670-km seismic discontinuity, below which there are no earthquakes. Hence it is difficult to see how the slab could contain the fault plane of the quake unless the slab makes a sharp bend to become horizontal near the depth of the discontinuity. Silver contends that, "The rupture properties of this earthquake provide a particularly stringent test for transformational faulting. It may require that this model be modified or abandoned. If so, then it shows that we have truly learned from this earthquake."

Other researchers counter that the direction and size of the fault plane do not seriously threaten the anticrack theory. Heidi Houston of the University of California at Santa Cruz points out that although several researchers favor a horizontal fault plane for the Bolivian quake, some suggest a more complex arrangement of multiple vertical or horizontal faults. Houston and Green also cite evidence that the subducting slab thickens and becomes contorted as it descends into the mantle, especially near the 670-km seismic discontinuity, where spinel and olivine transform into still denser perovskites.[7] They claim that the olivine wedge could remain quite thick even down to the 670-km discontinuity because it would be insulated from the hot mantle by the thicker slab. In this interpretation earthquakes would cease below 670 km not because the olivine wedge disappears but rather because the endothermic transition from spinel or olivine to perovskite quenches the formation of anticracks. Green points out that experiments with $CdTiO_3$, whose transition to a spinel-like phase is endothermic, do not produce anticrack faults. Fortunately, since both temperature and density affect the velocities of seismic waves, seismologists should be able to resolve the question of whether a cold, thick wedge of olivine continues to exist at the level of the Bolivian quake. Several groups are currently trying to use the seismic waves of the main quake and its aftershocks to better map out the geometries of the slab and the fault plane.

A window on Earth's interior

Perhaps most significant for geophysicists is the unprecedented window this earthquake provides into the Earth's interior. Like all solids, the earth oscillates in normal modes when excited. The frequencies of these modes and their attenuation contain a great deal of information about the Earth's structure and composition.

Information from large deep-focus earthquakes is important for modeling the Earth for several reasons. Because the zone of faulting tends to be more localized than in the much more common shallow-focus events, deep-focus quakes can be viewed as easily modeled point sources of long-wavelength seismic waves. Unlike shallow quakes, deep quakes efficiently excite the higher modes of the Earth that sample the core and the deep mantle without exciting surface waves that tend to mask these higher modes.

By looking at how inhomogeneities and other distortions of the Earth's spherical symmetry split normal modes of the Earth that would otherwise be degenerate, geophysicists hope to be able to model those features. According to Guy Masters of the University of California at San Diego, if researchers can determine enough of these splittings, they should be able to clarify such problems as the nature of inhomogeneities in the mantle and the postulated anisotropy of the Earth's core. Resolving the features that split degenerate modes will in turn allow a better determination of the degenerate frequencies of the normal modes and thereby provide a better understanding of the Earth's average density and composition as a function of depth, perhaps with a depth resolution of 50 km through the mantle and most of the core. Among the important questions to be resolved are whether the upper and lower mantle have significantly different chemistries and whether the composition of the outer core varies with depth.

Masters characterizes the Bolivian quake's importance as somewhere between "very helpful" and "revolutionary," depending on how many degenerate modes can be decomposed. He and most other researchers analyzing the quake are optimistic that they can turn the data from hundreds of recording stations in the global and regional seismic networks into an improved model of the Earth's interior in time for the December meeting of the American Geophysical Union, an entire day of which has been devoted to research related to the Bolivian quake. Given the quality of the data from the quake and the excitement in the geophysics community over it, that may be a day to mark on your calendars.

—Ray Ladbury

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TABLETOP CAPILLARY-DISCHARGE SOFT-X-RAY LASER DEMONSTRATED

Optical-wavelength lasers are ubiquitous, from the checkout scanner at the supermarket to the CD player in your Discman. They come in all sizes, all the way down to microelectronic scales. Lasers operating at wavelengths shorter than 100 nanometers, however, have been rare and expensive behemoths ever since their first demonstration a decade ago; they rely on bulky, high-powered optical lasers to produce the plasma conditions needed for x-ray lasing.

That has now changed, with the demonstration by Jorge Rocca and coworkers at Colorado State University of a 46.9-nm laser that can fit handily on an optical table.[1,2] (Strictly speaking, that wavelength is in the extreme ultraviolet, but the laser community calls this class of devices "soft-x-ray lasers" even at the longer wavelengths.) In Rocca's design, the lasing occurs within a cavity about half the size of a milk-shake straw. A fast electrical discharge through argon in this capillary produces a plasma with the necessary population inversion. (See figures on pages 20 and 21.) Rocca's device has three important advantages over present-day laser-pumped systems: smaller size, improved efficiency and less expense.

William Silfvast (Center for Research in Electo-Optics and Lasers, University of Central Florida), an expert in short-wavelength lasers, considers Rocca's result to be the most significant development in the field since x-ray lasers were first demonstrated by Dennis Matthews and coworkers at Lawrence Livermore National Laboratory and by Szymon Suckewer and coworkers at the Princeton Plasma Physics Laboratory.[3]

Matthews concurs, calling it the most exciting advance he has seen in recent years. "Many other groups have tried to use pulsed-power technology to pump x-ray lasers, but none had succeeded in achieving such incontrovertible results," he told us. "Rocca has demonstrated an alternative technology that is simple, compact and relatively inexpensive."

Silfvast points out that devices based on Rocca's design will allow much more refined experiments in many fields. "Having a compact x-ray laser in your lab that you work with all the time will be a lot different from getting one or two shots a day on a huge, expensive laser." Possible applications include photolithography of microcircuits, holography of biological materials, diagnostic studies of conditions in plasmas (such as those of interest for the fusion program) and studies of interactions between materials and high-intensity coherent x rays. Extending the capillary-discharge technique to even shorter wavelengths will greatly facilitate these and other applications.

Ray Elton (University of Maryland), who wrote the book on x-ray lasers,[4] points out that the typical efficiency in going from the output of a visible-laser pump to an x-ray laser is a disappointingly low 10^{-6}–10^{-5}. "Rocca's achievement, getting away from the big laser drivers, is a giant step," he says. "In the next few years many groups—probably mostly overseas—are going to be milking this advance."

Two other groups working on capillary-discharge designs are those of Tong-Nyong Lee[5] (Pohang University of Science and Technology, South Korea) and Hans-Joachim Kunze[6] (Ruhr University in Bochum, Germany). In Rocca's experiment Ar is injected into the capillary and a very fast current pulse pumps it to an excited neon-like state (Ar^{8+}). Lee's and Kunze's groups both use discharges in somewhat shorter and narrower capillaries to eject carbon from the walls of the capillary itself, creating a plasma with population inversions in C^{5+}. (This capillary-discharge carbon scheme was proposed by Rocca and coworkers[7] in 1988.) Both groups have achieved amplification of the hydrogen-like Balmer α line at 18.2 nm, but neither has matched Rocca's dramatic gain–length product of 7.2, corresponding to more than two orders of magnitude of amplification. (For a plasma showing a gain of g, the intensity increases with the length l of the plasma as e^{gl}, and the gain–length product is gl.)

On the Colorado State team with Rocca are Vyacheslav N. Shlyaptsev (P. N. Lebedev Physical Institute, Moscow), Osvaldo D. Cortázar (Mar del Plata University, Argentina), Mario C. Marconi (Buenos Aires University, Argentina), Fernando G. Tomasel, Dana Hartshorn, Juan L. A. Chilla, Gustavo Giudice and Benito Szapiro (all at Colorado State).

Hot, dense, uniform plasma

In traditional, laser-pumped x-ray lasers, high-power optical lasers blast a strip of foil or a solid target to produce a plasma with a suitable population inversion. A handful of laboratories in the US and abroad have demonstrated amplifications comparable to or in excess of Rocca's using this technique, but only with very large facilities. Livermore,[8] for example, pumping with its 10^{13}-W, multikilojoule, two-beam Nova laser, has achieved gain–length products of up to 30 at about 20 nm with Ne-like states of selenium.