A Wizard of Middle Earth Under Fire

For 10 years Raymond Jeanloz has been shaking up mineral physics; now he is facing some major tests himself

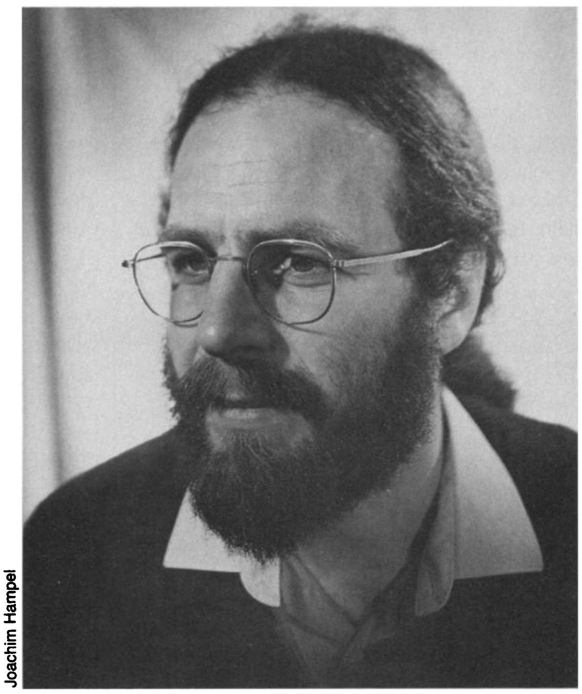
EVERYONE AGREES: RAYMOND JEANLOZ is an "outstanding young investigator." In the 10 years since he received his Ph.D from the California Institute of Technology, the American Geophysical Union, the Mineralogical Society of America, and the National Science Foundation have all affirmed his elevated status. The MacArthur Foundation even anointed him with one of its "genius" awards, worth $230,000 over a 5-year period.

Now a full professor at the University of California, Berkeley, Jeanloz himself shuns the genius label. But there is no denying that he has a special talent for stirring up his field. By mimicking deep-Earth conditions in his laboratory—and at times drawing provocative conclusions from these experiments—the Berkeley mineral physicist has unlocked entirely new, and fruitful, research directions. But in championing new ideas, Jeanloz has managed at times to rankle colleagues not only in his own field but in several others as well.

Take, for example, the argument Jeanloz has stirred up over Earth's magnetic field. He sees geomagneticians as misinterpreting much if not all of what they see in magnetic field variations. From laboratory experiments, he concludes that chemical reactions between the molten iron core and the overlying rocky mantle have been piling up a slag heap at the bottom of the mantle that distorts the magnetic field emanating from the core. With no clear view of the magnetic field, geophysicists would have no chance of figuring out exactly how the core generates it.

And Jeanloz has jumped into the fractious debate over Earth's slow internal circulation by supporting a compartmentalized mantle. If his side of the debate is right, most of Earth's crust has been drawn from the upper mantle, leaving the original stuff that dates from the time of the planet's creation largely sealed in the lower mantle.

How does a young researcher become embroiled in such controversy? In Jeanloz's case, it is partly his style of doing science. "We've been accused of speculating too much, and perhaps rightfully so," he observes, not using the royal we but referring to himself and his students at Berkeley. "But as long as we are making careful measurements and putting out hard numbers, I think there should be a combination of data and interpretation. It's a matter of style. Some groups will put out the numbers and that's it. We try to wave our hands a bit about how they apply to the Earth."



Raymond Jeanloz: *"He's very bright, but a lot of people are bright," says Thomas Ahrens of Caltech. "His most important attribute is that he picks very important problems and works on them very hard."*

But hand-waving, even the constructive sort, is not to everyone's taste. Asked his opinion, crystallographer Robert Hazen of the Carnegie Institution's Geophysical Laboratory in Washington, D.C., starts out with the up side: "Raymond's work is incredibly provocative and stimulating," Hazen told *Science*. "What he sometimes lacks in experimental rigor, he makes up for by stimulating the community to think about the big questions." Hazen then tosses in the caveat: "But you also have to learn the basic physics" of ultrahigh pressures.

Hazen's colleague at Carnegie, chemical physicist Russell Hemley, sees things a bit differently. "Raymond is doing novel experiments, which always provokes a lot of people. That's normal." Hemley also points out that Jeanloz has made major and less controversial contributions in areas ranging from the use of gold as a standard in high-temperature experiments to studies of the behavior of boron nitride.

Jeanloz's novel views of Earth's interior arise out of his work with a device called the diamond-anvil cell (also see box). His group and a Carnegie group are two of only a half dozen in the United States, eight or so in the world, that are using the hand-size cell to squeeze bits of rock between gem-quality diamonds until the rock fragments experience the tremendous pressures—more than 1 million atmospheres—found in Earth's lower mantle.

"We're driven by an engineering breakthrough," says Jeanloz, one that allows him and others to transform one material into another simply by using ultrahigh pressures to bend, shorten, and rearrange the chemical bonds that hold atoms together. And because deep rock is also heated to several thousand degrees, researchers shoot beams of laser light through their diamond anvils, heating the sample to deep-Earth temperatures. The Berkeley group did not invent this approach, but Jeanloz points out that they "quantified this technique for heating the samples and measuring the temperature." And this, he says, has given his group an inside track in the efforts to reproduce deep-Earth conditions in the laboratory.

All this technological innovation gives the field in general, and Jeanloz's group in particular, an inherent distinctiveness. "Almost everything you do, no one has done it before," says Elise Knittle, who with her husband Quentin Williams (both ex-students of Jeanloz's), is setting up a high-pressure lab at the University of California, Santa Cruz. Once the right touch with the diamond-anvil cell is achieved, "even a simple project can be interesting. Almost everything you do is publishable," says Knittle, who had 20 publications out of her dissertation work. Jeanloz's students typically have a half dozen or more papers to their credit on finishing their degrees.

With all this novelty and only so many workers capable of reproducing a given experiment, it is inevitable that controversy, once it arises, is going to simmer for a while. "On almost every question, we know what has to be done," Hemley notes. "It's just going to take a little time" before we can get around to them all.

Controversy is indeed still simmering around one experiment Knittle performed while still a graduate student with Jeanloz. She sought to simulate in the diamond-anvil cell the boundary between Earth's 7000-kilometer-wide core of molten iron and the overlying rocky mantle. To do this, she scaled down the Mars-size core-mantle boundary to a fleck of iron foil embedded in grains of mantle rock, all about 150 micrometers across. Then she squeezed it to 0.7 million bars in the diamond-anvil cell and zapped the iron with a laser to melt it at more than 3700 K.

When the pressure is high enough, Knittle found, the iron and the mantle rock react chemically. All well and good. But in the paper that Knittle and Jeanloz subsequently published, they suggested that "similar chemical reactions occur at the Earth's core-mantle boundary," forming a layer of crud at the bottom of the mantle. That, they concluded, could explain the abruptly varying rock properties inferred for the lowermost mantle by seismologists.

At this point, Knittle and Jeanloz were bordering on the provocative. Demonstrating a chemical reaction at high pressures in the diamond-anvil cell is new and intriguing. But, some colleagues have cautioned that gauging exactly what the products of the reaction might be in the Earth itself is far trickier. A minutes-long laser shot might only produce what, at the eons-old boundary, would be intermediate products on their way to an entirely different fate.

Jeanloz remains undeterred by such criticisms. While recognizing limitations in the diamond-anvil cell work, he goes a step or two farther in his talks and review papers, speculating on the possible implications of the reactions in the core-mantle boundary experiment for Earth's magnetic field.

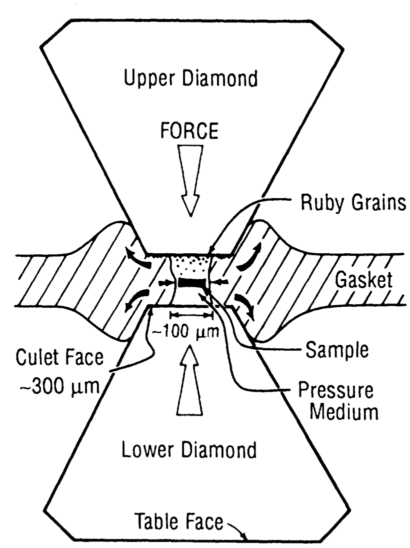
Recipe for a Bit of Deep Earth

First take a tiny sliver of rock. Then add pressure, the equivalent of the weight of a small herd of elephants concentrated on an area no wider than the head of a match. Now put in the heat, enough to melt any rock if not for the pressure. And you've done it—reproduced the conditions in Earth's lower mantle, the layer just above the molten iron core. Now all you have to do is measure what the pressure and heat are doing to the rock sample in order to understand Earth's deep interior.

The device that makes all this possible is the high-pressure diamond-anvil cell, an example of the maxim that smaller is better. Researchers pursuing the Holy Grail of deep-Earth studies had at first resorted to room-size presses capable of squeezing a cubic centimeter of sample to pressures of 0.3 million bars. But good as the big presses were, they could not duplicate the million bars of pressure occurring in the lowermost mantle. That required a new approach. And so researchers reasoned that if they could not obtain their goal by increasing the force applied, then they could get there by just reducing the area to which they applied it.

And thus was born the diamond-anvil cell, a model of simplicity, especially by big science standards. In operation, two opposing anvils are squeezed together by a modest force that is applied by hand and multiplied by a nutcracker-like device. The trick is that the faces of the anvils are only about 350 micrometers across, so the resulting pressures can reach 4 million bars, as high as the pressure at Earth's very center.

To stand up under this strain, the anvils of the minipress are made from a pair of diamonds, a third of a carat each and cut like a gem. Each diamond has one extra face. These faces are aligned parallel to each other within a fraction of a micrometer with the sample caught between the diamonds and confined by a gasket. Once cranked up to megabar pressures, the cell can be hand-carried across the lab or across the continent.



The diamond-anvil cell *allows the attainment of a million or more bars of pressure. [In* Mantle Connection, *W. R. Peltier, ed. (Gordon & Breach, New York, 1989)]*

Conveniently enough, diamonds are not only hard, they are also transparent. That lets an experimentalist focus a near-infrared laser, which puts out less power than it takes to light an ordinary household light bulb, through the diamond and onto a 30-micrometer spot of sample. Within a fraction of a second, the temperature of the sample can soar thousands of degrees, reproducing the temperatures of the lower mantle and core. By monitoring the emissions of the now incandescent sample, its temperature can be determined, much as astronomers measure the temperatures of stars.

Diamond's transparency provides another crucial advantage when researchers are trying to figure out what is going on at high pressures and temperatures. They can and do release the pressure on a cell, remove the sample, and analyze it. But they can never be sure that the sample has retained the changes induced by mantle conditions. Better to probe it while in the cell, and passing electromagnetic radiation through the diamonds is a highly productive way of doing this. X-rays are a favorite probe, but conventional x-ray sources are so weak and diamond cell samples so small that gathering data can take days or weeks per sample, if it is practical at all.

More and more, diamond-anvil cell workers are solving this problem by using x-rays generated by synchrotrons, which produce x-rays a million times more brilliant than those generated by conventional sources. With synchrotron x-rays, the time it takes to do a wide variety of sample analyses, including scattering, diffraction, spectroscopy, and fluorescence studies, can be reduced from days to minutes or seconds. Synchrotron x-rays can also make studies possible at higher precision and at higher temperatures. And the improvements are not over. The next generation of synchrotron sources will zap diamond anvils with x-rays 1,000 to 10,000 times more brilliant than now available.

But some technical challenges remain. The number of analytical tools that can be used on samples held in diamond-anvil cells at deep-Earth temperatures and pressures is still limited. If researchers are to understand how the mantle works, they will have to develop more capable instruments, which they expect to do in the next few years. Then they can continue their journey to the center of Earth. ■ **R.A.K.**

One of the products Knittle detected, for example, is iron (II) oxide. Under high pressure, this compound acts like a metallic alloy with an electrical conductivity a billion times greater than plain rock. Some of the irregularities that seismologists see in the lowermost mantle could be 100-kilometer blobs of iron oxide, Jeanloz suggests. If so, then the blobs would play havoc with the core-generated magnetic field—and therefore with geophysicists' ability to see into the core. Field lines would snag on the blobs near the core-mantle boundary, producing the swirling variations in the field at the surface that researchers have always assumed reflected the swirling of the fluid core itself.

Researchers in the magnetics of Earth routinely take exception to this whole idea. But, Jeanloz explains, "I'm promoting this to encourage the magnetics people to coordinate with the seismologists on the discrimination of what they see at the core-mantle boundary. Not that it's the only reasonable answer. We're just asking how much of the variation can be attributed to these reactions. Either the idea will survive or not. I find it difficult to get emotional about science; it's always changing." This laid-back attitude may be in tune with Jeanloz's equally laid-back, 70s look, but it tends to belie the self-assurance sometimes seen in his papers and talks.

But that does not mean Jeanloz relentlessly promotes himself. In fact, he frequently promotes his students. "All I do really is collaborate with my students," he says. "I've been very lucky in having students willing to work hard and take the initiative and tell me if I'm dead wrong. I'm not a smart person, so I have to work pretty hard to catch up. If I'm putting in a lot of work, I expect everyone else to as well."

True to his collaborative philosophy, Jeanloz was second author on the paper describing the core-mantle boundary experiment, which was the 110th or so of his career. And he is second author on almost all of his papers involving his students. "I've viewed the first author as having a primary responsibility. It's not only credit, it's also who's going to take responsibility."

Who is going to take lead responsibility on a paper also depends, however, on how much flak it is liable to draw. If it is a matter of describing an experimental result, then the student takes the lead. A bit of interpretation and extrapolation is fine, too, as long as the student is comfortable with it. But Jeanloz saves his boldest speculations—the blurring of the view of the core, for example—for talks and review papers on which he is the first author.

Direct tests of some of Jeanloz's bolder speculations must await further technological developments. Among them will probably be the analysis of samples in diamond-anvil cells with synchrotron x-ray radiation.

At a cost of several million dollars to buy into just a part of a synchrotron x-ray source, this evolving field is big science indeed. But it is one innovation Jeanloz has yet to capitalize on to any great extent. "If a synchrotron were critical in an experiment, we would do it, but my style is more oriented to the small scale of the diamond-anvil cell and the small group. I've always had just two to four students at a time because I couldn't handle more than that."

Some choices between style and the greater use of synchrotron sources are probably not that far off, but Jeanloz is in no hurry. He is still having fun. "I find it intellectually challenging becoming familiar with what's going on over broad areas of science, identifying a significant problem, and ultimately solving it. I think a lot of the slowness of our science is a psychological barrier, people convincing themselves that it can't be done." The expensive, multi-investigator work required by a synchrotron source would surely put a crimp in that style.

But there are other options, Jeanloz says. "It's something of a fluke that I'm in the sciences," he notes. Perhaps there are other endeavors that could absorb his energies just as well. In his youth, he was quite serious about playing the violin and had no interest in science until a stint at an isolated California junior college brought him face to face with geology. "Now I have some ideas about what would be useful to do. In 10 years, I may not." As he is fond of saying about the controversy he provokes, "it will work itself out." ■ RICHARD A. KERR

Faith in Fifth Force Fades

The case for the "fifth force" seems to be falling apart fast. Not only has a new experiment failed to find any evidence for it, but two earlier confirmations have now been withdrawn. "We're now saying that the evidence does not support the fifth force," declares Donald H. Eckhardt, who is a physicist at the Air Force Geophysics Laboratory in Bedford, Massachusetts, and a principal investigator on one of the experiments being retracted. "The case has not been established," agree the principal investigators on the other experiment, geophysicists Robert L. Parker and Mark A. Zumberge of the Scripps Institute of Oceanography in La Jolla.

The fifth force is supposed to be a new type of fundamental interaction beyond the four forces—strong, weak, electromagnetic, and gravitational—now known. Empirically, it is expected to show up as a tiny deviation from the inverse-square law of Newtonian gravity. If real, it would require major revisions in current theories.

The fifth force hit the headlines in January 1986, when Purdue University physicist Ephraim Fischbach and his colleagues found apparent anomalies in a 1922 measurement of the gravitational constant by the late Hungarian physicist Roland Eötvös. More direct evidence came from experiments such as Eckhardt's, which was conducted last year on a 600-meter television tower near Raleigh, North Carolina, and Parker's and Zumberge's, performed in 1987 in a 2-kilometer-deep borehole in Greenland. In each case, the scientists took gravity measurements at several different levels and found fifth-force type deviations from predicted Newtonian values.

Only one problem: the deviations disagreed in both magnitude and sign, raising suspicions about their significance. And, as Parker and Zumberge point out in the 2 November issue of *Nature*, those suspicions are well founded. The researchers show that the results of any such experiment are extremely sensitive to the corrections made for the gravitational effects of local geology. Indeed, they claim that equally plausible corrections can account for all the results *without* a fifth force.

Eckhardt, although skeptical of Parker and Zumberge's analysis, says he now concedes that his original conclusions are wrong for another reason. Subtracting out geological effects requires having ground-level gravity measurements for miles in every direction. But in eastern North Carolina, the survey teams tend to take their measurements by the roadsides instead of out in the swamps. "So you find that the gravity measurements are biased to high ground," he says.

And finally, there is a third nail in the coffin. In the 30 October issue of *Physical Review Letters*, James Thomas and his colleagues at the Lawrence Livermore Laboratory report on an experiment performed on a 465-meter tower at the Nevada Test Site, where the geological data are extremely complete. Their conclusion: no fifth force with an accuracy of better than one part in 10 million.

■ M. MITCHELL WALDROP