The Foggy Crystal Ball Of Mineral Physics

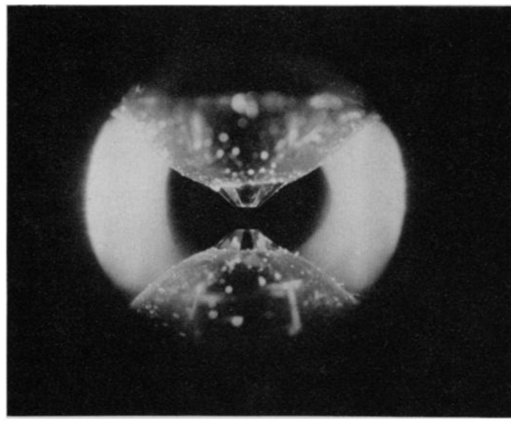
Researchers squeezing rocks under deep-Earth conditions are wondering what's going on inside their super presses

THE NATURE OF EARTH'S DEEP INTERIOR, all 1 trillion cubic kilometers of it, is being debated on the basis of the behavior of a few trillionths of a liter of rock caught between the finely honed tips of a pair of diamonds acting like opposed anvils. That vanishingly small chip of rock, once it is squeezed to more than a million times atmospheric pressure and laser-zapped to more than 2000°C, acts as a surrogate for the 2800-kilometer-thick layer of mantle rock between the familiar crust and the molten core.

This big squeeze has produced some important results. In 1987, for example, Elise Knittle of the University of California, Santa Cruz, and Raymond Jeanloz of the University of California, Berkeley, published a landmark paper showing that a mineral called perovskite is dominant in the mantle. But lately researchers relying on the technique to probe the workings of Earth's great heat engine, which extends from the fiery core to the surface and drives plate tectonics, have found themselves in a theoretical squeeze.

In recent years, some experiments have been yielding vastly different results in different labs—so different that they lead to conflicting conclusions on the central question of Earth dynamics: Is the mantle divided into two layers that never mix, or does the mantle churn from bottom to top so that even its deepest reaches contribute to the rock we see on the surface? Some mineral physicists, like Robert Hazen of the Carnegie Institution of Washington's Geophysical Laboratory, have begun to despair over whether the current crop of diamond-anvil experiments can shed any light at all on these deep-mantle processes. "The extent to which these experiments don't agree may tell us more about the experiments than about Earth," says Hazen. "These pioneering experiments have to be done, but I hesitate to support the interpretations made from them."

Not everyone is quite so pessimistic, but the abundance of conflicting studies is giving pause to many in the field. Perhaps the most confounding conflict in high-pressure studies surrounds attempts to measure the electrical conductivity of rock under deep mantle conditions, a property that could provide a clue to the precise composition of the deep mantle. One problem is that there



ANNE M. HOFMEISTER

The business ends of a diamond-anvil cell. *These opposed diamond "anvils," 0.6 millimeters across at the tips, can exert more than a million atmospheres of pressure on samples trapped between them and heated by a laser.*

are only eight or so groups in the world operating the diamond cell at deep mantle pressures, and only two have been trying to measure conductivity. And after several years of experimentation, the two groups have been unable to reconcile their results.

The gap between labs is considerable. J. Peyronneau and Jean-Paul Poirier of the Institute of Physics of the Globe in Paris have reported a conductivity for samples having a conventional mantle composition that dovetails nicely with the mantle conductivity inferred by geomagneticians, who monitor how the core's magnetic field leaks out to the surface. But graduate student Xiaoyuan Li (now at the University of Hawaii) and Jeanloz find one-thousandth the conductivity for the same composition.

The Berkeley group resolves the apparent conflict between their diamond cell results and geomagnetically inferred conductivities by postulating that the lower mantle has a much higher iron content than generally assumed. That would bring the Berkeley measurements in line with the geomagnetically inferred conductivity, but it leads to an inescapable conclusion about the way the mantle behaves: Weighted down with the additional iron, the lower mantle would be too dense to mix with the upper mantle, sealing the two layers off from one another. Jeanloz sees evidence for mantle layering in other diamond cell results (*Science*, 25 January, p. 382), but Poirier's conductivity measurements require no extra iron and therefore no layering.

Why the difference between two highly regarded groups using the same high-pressure tool? "I don't know," says Jeanloz, "it is very mysterious." The persistence of the mystery isn't for lack of effort or a spirit of cooperation. An obvious possible source of the different results might have been the use of different starting materials. Properties such as the oxidation state of the sample's iron could have a considerable effect on conductivity, so Jeanloz and Poirier recently exchanged samples. But the sample that yielded high conductivity in Paris produced a low conductivity in Berkeley and vice versa. "The discrepancy is not in the sample," says Poirier, "it's in the way it's measured."

Measurement techniques have been a fertile but so far unproductive field for speculation. Hazen and others worry in general about the limited control experimenters have over conditions in the diamond cell. Only temperature and pressure are actively controlled, he notes, leaving such critical properties as oxidation state without specific controls. And even temperature and pressure vary tremendously across a sample. Over a distance of a few micrometers, pressure can drop by a million atmospheres and temperature by more than 1000°C.

A more specific concern centers on the curious observation that the two labs cannot agree on the conductivity of samples containing 10% iron, the canonical composition for the lower mantle, but they do agree in the case of samples containing 20% iron. Poirier notes that the lower the iron content, the less readily the starting materials will absorb the laser light that is supposed to turn them into mantle minerals. Perhaps, he speculates, in the low-iron case the Berkeley group is not converting every bit of starting material into the two main mantle minerals, perovskite and magnesiowüstite. That could leave behind some starting material, which is more insulating than mantle minerals.

Bernard Wood of the University of Bristol takes a slightly different tack. The Berkeley group uses platinum electrodes to measure conductivity, but "platinum loves iron," says Wood. "It soaks it up like a sponge." He suspects the platinum electrode sucks iron from the low-iron sample around it, forming a micrometer or two of insulating material. The Paris group, notes Wood, uses tungsten electrodes, which should not take up iron. In high-iron samples, perhaps the platinum electrodes leave enough iron behind to allow agreement between the labs, he says.

Jeanloz sees no signs of such problems. As best as he and Li can tell by inspecting the lasered sample before conductivity measurements are made, the starting material is converted to mantle minerals right up to the electrode, but the electrode has not reacted with it. If asked what the problem might be, Jeanloz speculates that perhaps the Paris group's low-iron samples have some sort of contamination that increases conductivity.

Conductivity work by others has begun at lower temperatures and pressures that can be extrapolated to deep-Earth conditions, but results from these tests haven't changed the minds of either the Paris or Berkeley researchers. Wood and Johann Nell of Bristol have measured the conductivity of magnesiowüstite (which probably controls mantle conductivity) and find "excellent agreement with Poirier's data," according to Wood. Jeanloz, however, cites early work by Ho Kwang Mao and Peter Bell of the Geophysical Laboratory using an external furnace for final heating, as the French group does, that shows "good agreement" with his results. The decisive experiment, it would seem, has yet to be performed.

While the question of mantle conductivity persists, other disputes over results from the diamond cell rage on. The melting point of iron under lower mantle conditions ranges over 1000°C depending on who is doing the experiment, muddling estimates of the heat coming from the core and the temperature of the lower mantle. That in turn bears on whether the lower mantle is particularly hot, as required by a layered mantle, or is mixed with the colder upper mantle.

Removing mantle samples synthesized in diamond cells for further analysis has led to divergent results as well. Measurements of the expansion of perovskite with increasing temperature are central to the question of whether the lower mantle is dense enough to resist mixing with the rest of the mantle, but results have yet to converge (*Science*, 25 January, p. 382). The problem may be the instability of perovskite at pressures below those of the diamond cell. Even the location of iron atoms added to the crystal structure of perovskite—whether they substitute for silicon or magnesium—is in dispute. The culprit here may be samples containing something other than perovskite.

No matter what side researchers may be on in any given dispute, there is general agreement that the "macho technology" of the diamond cell, as one scientist calls it, needs to be operated under more controlled, reproducible conditions in a number of labs. Jeanloz's solution is simple enough. "What we need are more people doing these experiments." Any takers? ■ RICHARD A. KERR

Is Nitric Oxide the "Retrograde Messenger"?

New data suggest this gas may provide the key synapse-strengthening element in the brain that allows us to learn

NITRIC OXIDE, A SHORT-LIVED, HIGHLY REACTIVE gas, is one of the more bizarre messenger molecules used by cells. Dissolved in the aqueous cellular fluids, it slips right through membranes that would contain other molecules and is so reactive that it disappears within moments of its production. Yet it seems to play an important role in many parts of the body, including the brain. Four years ago it was shown to trigger blood vessel relaxation, and its discovery in the brain the following year left neuroscientists speculating about a number of roles it may play there. Now, in a collection of data that provided some of the hottest news at the neuroscience meeting in New Orleans earlier this month, comes evidence for a particularly exciting role: Nitric oxide may be a key chemical player in the storage of memories in the brain.

> ***"If there is a presynaptic component of learning "then there has got to be a retrograde messenger."***
> —Charles Stevens

The idea that nitric oxide might be linked to memory storage arose because the molecule seemed perfectly suited to fill a long-vacant role: that of the "retrograde messenger." This messenger is an essential component of a hypothetical feedback loop that is required in one model of how learning may work. In the proposed scheme, a nerve cell on the receiving end of a message would send a "retrograde" messenger back to the sending cell, strengthening the connection between them and contributing to the formation of a long-term memory.

Among the properties that make nitric oxide appealing for such a job are the same ones that make it peculiar. An ability to slip right through cell membranes is a must, since there seems to be no other means of escape from the receiving cell, and a half-life measured in seconds ensures that the messenger's sphere of influence will be small—and precise. Nitric oxide seemed such a natural for the role, says Charles Stevens of the Salk Institute, that some insiders "were accepting that [it] was the retrograde messenger before there was even any evidence for it." Now the evidence is not only coming in, but it's showing up en masse from no fewer than four separate groups. But even this rich confluence of work hasn't removed all doubts, and fans of the hypothesis note that it remains far from established.

The concept of the retrograde messenger grew out of more than two decades of study of a phenomenon called long-term potentiation, or LTP, which seems to be one of the chief means by which memories are stored. LTP is triggered when a neuron receives several simultaneous signals. The signals trigger a class of glutamate receptors, called NMDA receptors, to let calcium into the cell. The calcium causes the synapses that delivered the simultaneous signals to be strengthened. That leads to "potentiation"—a bigger response in the receiving cell the next time signals are sent.

This intriguing feedback is central to some types of learning: Blocking the process, for example, erases spatial memory in rats. And that's why researchers are so eager to understand exactly how it works. Their findings have split the field and fueled a long and lively debate. One camp argues that the potentiation is due to an increase in the sensitivity of the receiving cell. But that view has been slipping out of favor in the last year, since data from both Stevens' lab and Richard Tsien's lab at Stanford suggested that at least some of the strengthening is due to an increase in the amount of neurotransmitter released by the sending cell (see *Science*, 29 June 1990, p. 1603).

If that view is right, it follows that something must carry a message from the postsynaptic (receiving) cell back to the presynaptic (sending) cell, telling the sender to increase its output. "As soon as you believe there is a component of LTP that is presynaptic, then there has got to be a retrograde messenger," says Stevens.

But nitric oxide wasn't the only candidate for this key brain molecule. Another early contender was arachidonic acid, chosen be-