Geophysics: The Slower Side of the Sciences

In geophysics, speed can be a major obstacle to interdisciplinary study. A cosmic ray passes in an instant; a mountain is seemingly unmoved in a millennium. At this spring's meeting of the American Geophysical Union in Baltimore, some topics of interest fell toward the slow end of the scale, where rocks can flow and the sun wax and wane.

A Layer Cake Continent Beneath the Midwest

The Midwest has been long been a geological terra incognita. Blanketed by several kilometers of sediment, the continental crust there is out of reach of the geologist's hammer unless an oil or water well happens to bring up a handful of deep rock.

That remoteness is slowly being overcome. The latest development is the return of the Consortium for Continental Reflection Profiling (COCORP) to the flat expanse of the central United States. As hinted in earlier studies, COCORP found that the rock beneath the veneer of sediment is layered somehow, the layering extending through 11 kilometers or more of the crust. What creates the layering and how that much rock got there in the first place remain mysteries of the Midwest.

Thomas Pratt and Douglas Nelson of Cornell University, where COCORP is headquartered, reported at the AGU meeting that along 170 kilometers of an east-west line across southern Illinois and Indiana, man-made seismic waves reflect from nearly horizontal layers that begin just beneath 3.5 kilometers of sediment and typically continue down to a depth of about 10 kilometers and sometimes almost 14 kilometers. The banded basement rock extends northward at least 100 kilometers in oil industry reflection profiles, thickening as it goes.

The few samples serendipitously recovered from wells show that at least the first few meters of this basement rock are part of a million-square-kilometer province about 1.5 billion years old that stretches from western Texas to Ohio. It is granite, which solidifies from great blobs of magma that remain below the surface, or rhyolite, which is magma of the same composition that flows on the surface as lava. Both probably formed by melting of older crust. Just how an estimated 5 to 6 kilometers of preexisting crust melted has always been a problem. Suggestions include insulating the mantle beneath it with a supercontinent, in order to raise the temperature, and pulling apart the continent the way Nevada is now being stretched. Generating the even thicker granite-rhyolite province implied by the COCORP observations will not make the explanation any easier to come by.

The layering itself presents another problem. In order to reflect seismic waves as strongly as these layers do, there must be considerable differences in their properties. The differences between one rhyolite lava flow and the next will not do. A bit of erosion-generated sediment between lava flows might suffice. Alternatively, Nelson pointed out, the layering may represent not volcanic rock but extensive sediments, the kind of deposits geologists crave for the ancient records they contain or, even more speculatively, the oil or gas that they might yield. The possibility of unsuspected hydrocarbon deposits at great depth "cannot be ignored," says Nelson. COCORP and other deep reflection profiling efforts have detected layering in unlikely places before, but where it has been drilled it has turned out to be non-sedimentary.

Relax, the Sun Is Brightening Again

For a while, the situation had some potential for disaster. The sun was fading in the early 1980s at a rate of 0.018% per year with no end in sight. Hardly large enough to threaten the summer tanning season, such a decline, if continued for a few decades, would undoubtedly have affected climate. A century-long decline would have plunged Earth into a little ice age.

Fear not, the decrease of solar irradiance has turned around, the sun is now brightening. At the AGU meeting two groups confirmed an earlier report that the downward trend in solar irradiance had bottomed out at about the time of the sunspot minimum in the fall of 1986 and that the trend is now upward.

Douglas Hoyt of Research and Data Systems Corporation in Lanham, Maryland, and his colleagues reported that they have seen a distinct increase in irradiance as measured by the radiometer monitoring the sun's output from the Nimbus-7 satellite. In another session, Robert Lee of the Langley Research Center in Hampton, Virginia, and his colleagues reported a similar change in data from the solar monitor aboard the Earth Radiation Budget satellite. These confirmations came just a week after Richard Willson of the Jet Propulsion Laboratory and Hugh Hudson of the University of California at San Diego published their detection of the upturn using the monitor aboard the Solar Maximum Mission satellite. Clearly, these three instruments record reliable, long-term trends.

The reversal suggests, but does not prove, that solar irradiance is varying on an 11-year cycle. The latest 11-year sunspot cycle formally ended with the minimum in the number of sunspots in September 1986. The coincidence of the irradiance minimum and the sunspot minimum is consistent with an 11-year cycle. But 1986 might also be taken as the end of the 22-year solar magnetic cycle, during which the sunspot number peaks twice but the magnetic polarity of sunspots reverses only once. To judge by the shape of his irradiance curve, Willson sees a much better fit to the 11-year cycle than to the 22-year cycle, especially after the minimum.

An 11-year cycle also makes best sense in terms of the leading explanation for the irradiance decline. Judith Lean of Applied Research Corporation in Landover, Maryland, and Peter Foukal of Cambridge Research and Instrumentation in Cambridge, Massachusetts, proposed last year that the immediate cause of long-term irradiance changes is an imbalance between the irradiance decrease due to sunspots and the increase due to bright areas called faculae (*Science*, 26 June 1987, p. 1624). The areas covered by both sunspots and faculae, which occur where magnetic flux tubes pierce the visible surface, vary with the 11-year cycle. So, explains Foukal, as solar magnetic flux roughly triples through the cycle, the difference between the irradiance contributions of the two should also vary.

This model fits observed irradiance variations observed over periods of months as well as the long-term trend since 1980, says Lean. That is probably too short a time for significant climate effects, but the model also explains the chill of the Little Ice Age that gripped the world in the 17th century, a time when sunspots were rare. On an intermediate time scale, peaks of the sunspot cycle are known to be modulated on an 80- to 90-year cycle. That long a cycle might well allow a significant climate effect during a lifetime.

How Long Does It Take to Build a Mountain?

Vermont still preserves the roots of mountains shoved upward 390 million years ago as two continents collided. But how long did the squeezing, heating, and alteration of rock go on within the new mountains? No technique in the geologist's bag of tricks could measure that time, so John Christensen, John Rosenfeld, and Donald DePaolo of the University of California at Los Angeles developed a new method. It depends on measuring the growth of garnet minerals that grew by a few millionths of a millimeter per year as long as the rock was hot enough.

The UCLA group believes that it has just the tool, rubidium-strontium dating, to determine how long it took minerals to grow within the mountains and thus the duration of the heat- and pressure-induced metamorphism that marks mountain building. The radioactive decay of rubidium-87 acts as a clock, ticking away at a steady, known rate as its atoms disappear to produce new atoms of strontium-87. In this method, strontium-86, a stable isotope whose abundance is unaffected by decay, provides the benchmark for measuring the other changing isotopes. The increasing ratio of strontium-87 to strontium-86 is thus a measure of the passage of time.

Garnets turn out to be a good match with this dating technique. Most any mineral will continually incorporate strontium as it grows, each increment of growth recording the passage of time in the changing isotope ratio of surrounding rock. But garnets take up little rubidium-87 that would subsequently increase the ratio of interest. Hence the time record is easier to read because the contrast is enhanced between ratios sampled by sequential shells. And these time-sensitive ratios stay locked in, thanks to the highly retentive qualities of garnet.

The UCLA group took several Vermont garnets 3 centimeters in diameter, sliced them open, and measured the isotope ratios of samples from their cores toward their rims. Given the rubidium-87–strontium-86 ratios of the rocks that encased them, the garnets took about 8 million years to grow. In this case the method has a resolution of 2.5 million years, Christensen noted, but given higher concentrations of rubidium relative to strontium, the resolution could be pushed to 0.25 million years.

Clocking the growth of garnets allows an estimation of other rates of interest in mountain building. Garnets also rotate as they grow if the surrounding rock is being deformed. As they rotate, they engulf other minerals that have been aligned by the same deformation. The sequential preservation of aligned minerals creates a spiral trail of occluded grains that, combined with the measured duration of growth, yields a rate of deformation. In the Vermont case the measured strain rate was 3×10^{-14}, which is a physically reasonable rate. It implies that the crust, much of which is normally quite brittle, had the consistency of the deep mantle asthenosphere, the viscous layer on which the continental plates are rafted.

The Mantle's Structure—Having It Both Ways

Finally there is a middle ground in the earth sciences' long-running debate on the behavior of the mantle, the unseen but thickest of Earth's onion-like layers. The choices had been two. Either the heat flowing toward the surface stirs the mantle from top to bottom, leaving at best a few unmixed blobs, or an impenetrable barrier divides the mantle into upper and lower layers.

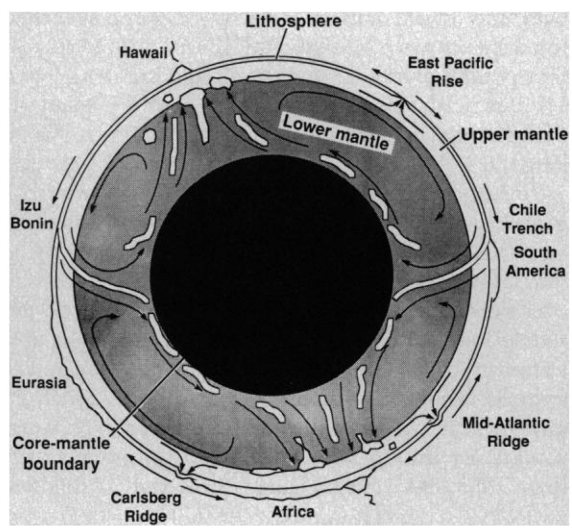
The choice seemed clear, but the evidence was not. Geochemists found that there must be at least two parts of the mantle, presumably upper and lower layers, and probably others that do not mix over billions of year. But recently seismologists using seismic waves like x-rays have imaged the rigid slabs of lithosphere, the outermost of Earth's layers, that sink into the mantle at deep-sea trenches (*Science*, 7 February 1986, p. 548). Contrary to earlier indications, the new seismic techniques showed some slabs sinking through the upper mantle, piercing the supposed barrier at a depth of 650 kilometers, and plunging on into the lower mantle. So, is there a barrier or not?

A collaborative group consisting of a geochemist, a seismologist, and a fluid dynamicist proposed at the AGU meeting that the mantle might be having it both ways. It could be passing a significant amount of rock through the barrier without much mixing of the two reservoirs.

Paul Silver and Richard Carlson of the Carnegie Institution of Washington's Department of Terrestrial Magnetism and Peter Olson of Johns Hopkins University suggested that a delicate balance in the density of the two layers could satisfy the seemingly contradictory constraints. It is the greater density of the slabs, due to their having cooled at the surface, that causes them to sink. In the proposed model, the difference in the density of the upper and lower mantle is about 2%, not enough to stop an onrushing slab but sufficient to separate the gently churning layers from one another. Once through the density barrier, a slab would continue sinking to the bottom of the mantle, where it would pile up at the boundary between the fluid core and the mantle.

Having reached the lower mantle by dint of their relative coldness, slabs could not stay there. Within 200 million years, they would be warmed up, buoyant, and heading back to the upper mantle. Most of these now blob-like masses would pop through the barrier and be at least partially mixed into the upper mantle. The most strongly heated blobs would sail through the upper mantle and melt their way through the lithosphere to form volcanic hot spots, such as Hawaii.

The key to this penetrative convection model, as its originators term it, is the exact amount of density contrast between the upper and lower mantle. It not only allows two-way passage of slabs, it also minimizes the amount of material from one layer that is entrained with a slab passing into the other layer. The 2% density contrast chosen for the model does have some support from a mathematical model of mantle convection and laboratory studies of rock.



"While all the dynamical and geophysical consequences of this model have yet to be established," write the authors, "its potential success argues for careful evaluation. If nothing else, this [model] may provide a fresh perspective from which to view the problem." That should be welcomed in a field where much effort has gone into explaining away evidence that contradicts one's favorite extreme view.

■ Richard A. Kerr