Probing the Deep Continental Crust

Seismic reflection profiling is creating a clearer picture of some unseen continental rock, but now there is much needed help from other techniques

To the untrained eye, most seismic reflection profiles resemble the blur of a pictureless television screen with the contrast turned way up. To geophysicists who have been using seismic reflection to look for oil during the past few decades, the subtle shadings in a profile produced by this echo-sounding technique may represent a dome of sedimentary rock where oil is trapped.

Increasingly, other geophysicists using seismic reflection are reaching tens of kilometers deeper, probing rock that will never yield oil or gas. Their goal is understanding the unseen structure of the continents and what it means for their origin. Those attending a recent meeting* on seismic reflection profiling and continental structure heard that the new application of this oil exploration technique has major achievements to its credit, that expansion of its use around the globe is under way, and that its strengths and limitations complement other geophysical techniques with which it is now being combined.

Many of the stunning successes of seismic reflection have come through the Consortium for Continental Reflection Profiling (COCORP), which operates through Cornell University, the site of the meeting. Early COCORP profiling detected the gentle sloping of a fault beneath the Wind River Mountains of Wyoming, proving that horizontal squeezing of the continents—not a vertical lifting—formed the mountains (*Science*, 10 February 1978, p. 672). In the southern Appalachians of Georgia and South Carolina, COCORP traced a nearly horizontal fault an improbable 200 kilometers or more, along which it separated a thin sheet of crystalline rock and the sediments over which a continental collision had shoved the sheet.

Such thrusting of an intact thin sheet of rock had seemed mechanically unlikely, but COCORP then showed that a thin skin of rock in the Basin and Range province of Utah had been pulled back down an inclined fault without falling apart, a feat presumed to be impossible (*Science*, 3 June 1983, p. 1030). COCORP's latest discovery, first presented at the Cornell meeting, is the tentatively identified suture formed during a collision of North America and Africa and left behind near the present Florida-Georgia border during the disruption of the supercontinent Pangaea.

As spokesmen for the 14 countries presently conducting seismic reflection programs began recounting their latest results, a more general discovery about continental crust became evident. To the "eye" of seismic reflection profiling, the earth's crust is often divided into an upper transparent layer of few or no reflection features and a lower layer cluttered with more or less horizontal reflectors 1 to 10 kilometers long. The subhorizontal reflectors disappear rather abruptly at about the presumed depth of the Mohorovičić discontinuity or simply the Moho, which is the boundary between the granitic crust and the ultramatic mantle that runs as deep as 55 kilometers beneath the surface.

Geophysicists are just beginning to learn what causes reflections in the deep crust.

Interestingly, the reflective lower crust seems to control the extent of deep faults. The gently dipping faults detected by COCORP and other programs often bend until almost horizontal and disappear into the clutter of subhorizontal reflections of the lower crust. From the other side, similar faults cut from the upper mantle, across the Moho, and into the lower crust, as first shown around Great Britain by the British Institutions Reflection Profiling Syndicate (BIRPS). The French ECORS Project found one fault that appears to have not only cut the Moho but offset it on either side of the fault as well.

The separation of a brittle upper crust and a brittle upper mantle, where rock can break and form faults, by a layer that does not readily fault has prompted the proposal of the jelly sandwich model of the outer parts of the earth. Actually, it is a jelly sandwich made with stale bread, the jelly representing ductile rock that flows rather than breaks and the stale bread rock brittle enough to break. In this model changing pressure, temperature, and chemical composition combine first to increase ductility with increasing depth and then reduce it once again in the upper mantle. Rock flow in the ductile lower crust would create the subhorizontal reflectors. The reflectionless upper crust is perhaps too complex to produce major reflections. Alternatively, the lamination of the deep crust in seismic reflection profiles might result from the presence of fluid, actual layering of differing rock compositions, the intrusion of molten rock, or crustal stretching.

The enigma of lower crust reflectors points up an underlying problem with seismic reflection profiling. Unless a deep reflection feature can be traced from the surface or penetrated by drilling (an expensive process impractical below 10 to 15 kilometers), positive identification by reflection methods of the responsible structure is exceedingly difficult or impossible. If the structure is too steeply inclined to the surface or not mirror-like in its reflection properties, it may not show up in a reflection profile at all. Indeed, all the revolutionary structures discovered by COCORP have been continuous, relatively planar, gently inclined features that could be positively identified where they outcropped at the surface.

A notorious example of the difficulties of interpreting seismic reflection profiles is the Phillips Arizona State A-1 well drilled in 1980. The Phillips well tested the hypothesis that crystalline rock had been shoved over sedimentary rock in southeast Arizona, as had happened to the north. If the hypothesis were true, the well would enter sedimentary rock and, with luck, strike oil 3 kilometers beneath the barren crystalline rock. Seismic surveys seemed to support the controversial hypothesis. Beneath a transparent zone of crystalline rock, they revealed strong, laminated reflections that certainly looked as if they could come from typical layered sediments. The hole proved that they did not. It found a fault zone but only more crystalline rock beneath that.

Even after drilling, no one is quite sure what caused those deceptively laminated reflections. The mineral composition of rocks did not change enough down the well to produce the abrupt changes in

*International Symposium on Deep Structure of the Continental Crust: Results from Reflection Seismology, held 26 to 28 June; Muawia Barazangi, Cornell University, coordinator.

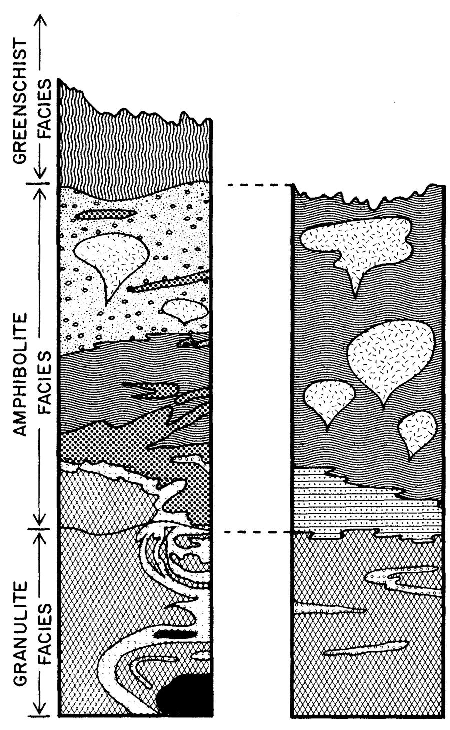
seismic velocities required for reflections. Thus, the layering does not seem to be compositional. Jamie Robinson of Cornell University, while at Phillips Petroleum, suggested that the earlier strain on the rock in the fault zone might have fractured or deformed parallel zones of the adjacent rock. The resulting variations in the texture of the rock could then produce reflections. But, despite study of the seismic properties of rock down the well and extensive reprocessing of the reflection profile, Robinson reported little success in distinguishing between crystalline and sedimentary reflectors.

In fact, geophysicists are just beginning to learn what causes reflections in the deep crust. A strong contrast in seismic velocities between adjacent rock types, such as sandstones and carbonates, will produce reflections. Less clear has been the cause of reflections from deep faults. Scott Smithson and his colleagues at the University of Wyoming reported that a type of deformed rock called mylonite, which can form in deep fault zones, can produce strong reflections. To prove it, they traced a 2- to 3-kilometer thick mylonite zone at Kettle Dome on the Columbia River down from the surface, using reflection profiling. Still, the pulled-taffy texture of the mylonite alone could not slow seismic waves enough to produce the observed reflections, which resembled sedimentary layering. Smithson suggested that such reflections require a thick zone of mylonite layering that amplifies reflections through constructive interference of waves.

Given strong reflectors, interpretation of reflection profiles still depends on the reliable determination of the shape of those reflectors. That is no easy task, as David Fountain of the University of Wyoming and Matthew Salisbury of Scripps Institution of Oceanography suggested. To illustrate how much more complicated than the relatively flat-lying sediment beds of oil prospects the lower crust is liable to be, Fountain and Salisbury created a likely crustal cross section from a study of the deep rocks exposed in the Ivrea Zone of the southern Italian Alps. Since 500 million years ago, when they were part of an Atlantic-type continental margin, these rocks have been slivered, injected with magma, torn apart during ocean basin formation, altered by high heat and pressure, and shoved to form mountains. The result is more of a marble cake than a layer cake.

Fountain and Salisbury then created a reflection profile from scratch based solely on the theoretical effect of this structure on seismic waves and the seismic properties of the rocks. As observed in the real crust, upper levels were transparent to seismic waves. At greater depths, the complex, nonplanar structure produced upward pointing, hyperbola-shaped reflections. As expected, complex structures need not produce reflections with mirror-like fidelity. If noise obscured their weaker tails, Fountain suggested, these reflections would closely resemble the observed subhorizontal reflections. Indeed, Carl Wentworth and his colleagues at the U.S. Geological Survey (USGS) in Menlo Park noted that even the Franciscan rocks of California, a mélange of contorted rock, seem to produce a texture of subhorizontal reflectors.

This daunting complexity contributes to considerable controversy where reflectors cannot be traced to the surface. For example, everyone agrees now that the hidden sediment layer in the southern Appalachians extends at least 200 kilometers toward the present coast, but where it stops and where the underlying 500-million-year-old ocean-continent boundary lies remains uncertain. A lack of constraints on the nature of dipping reflectors beneath the outer piedmont region limits interpretations of the location and history of the old continental edge. Are these reflectors volcanic rock erupted at the old edge, ocean sediments shoved across the edge, or faults slicing down into the upper mantle?



Reflection profiling's target

These two cross sections of the earth's crust and upper mantle were constructed from study of rock exposed in the Italian Alps (left) and western Australia. Interpreting seismic waves reflected from such complex structures is a major challenge. [Reprinted from D. M. Fountain and M. H. Salisbury, Earth Planet. Sci. Lett. *56, 263 (1981) by permission of Elsevier Scientific Publishing Company.*]

In order to combat such difficulties of interpretation, many of the countries that are following the COCORP lead in reflection profiling and the USGS are using that technique in combination with detailed geological surveys and other geophysical techniques, especially that of seismic refraction. Unlike seismic waves reflected from the deep crust, which follow almost vertical paths, those refracted through the crust follow more nearly horizontal paths.

A major advantage of recording refracted waves is the ability to determine precise seismic velocities, which can help to identify rock type. Recently refined techniques for processing refracted waves allow construction of two dimensional crustal velocity models. These in turn can be interpreted in terms of rock type and redrawn as an interpretive geological cross section of the crust and upper mantle. Once reflection profiles are calibrated with precise refraction-determined velocities, reflections can be more accurately used to mark the boundaries between different rock types.

Several speakers presented examples of the fruitful combination of the reflection and refraction techniques. Wentworth noted that, without refraction studies, a reasonable interpretation of rock outcrops and reflection profiles in the Coast Range of California would have led to a misidentification of a wedge of Franciscan mélange as the sediments of the Great Valley. Penny Barton of the University of Cambridge combined the reflection and refraction techniques as practiced by BIRPS in the North Sea to demonstrate that the bottom of the reflective layer of the crust really does coincide with the Moho. Its location is defined by refraction-determined velocities and has only been tentatively inferred in reflection profiles.

In the Vancouver Island Seismic Project, reflection profiling is being used to verify and refine a new refraction model of the oceanic crust diving beneath the edge of North America, where such subduction has plastered scraps of new crust called terranes against the continent. According to Ron Clowes, George Spence, and Robert Ellis of the University of British Columbia, the refraction model includes the accreted terrane Wrangellia underlain by bits of several other terranes whose larger fragments sit jammed together on Wrangellia's ocean side, all overlying the gently inclined subducting ocean crust. A section of ocean crust apparently broke off and underlies the accreted terranes. Prominent reflectors in recently acquired data coincide with the upper-lower crust boundary, the bottom of the detached oceanic plate, and either the continental Moho or the top of the subducting ocean plate.

While the USGS and non-U.S. programs emphasize the use of multiple techniques at the same sites, COCORP speakers placed a new emphasis on the reconnaissance nature of most of their program. Refraction will help, but the ultimate test of seismic methods—deep drilling—is only now being proposed. A 10-kilometer hole in the southern Appalachians (*Science*, 29 June, p. 1418) would help determine what some reflectors really are.—**RICHARD A. KERR**

Esoteric Math Has Practical Result

A new method of computer graphics relies on math results that seemed so abstruse that they were never published

The problem with natural objects is that they are so irregular. When programmers try to tell a computer how to draw a cloud or a leaf or a forest, they run into difficulties. If they attempt to specify each and every detail, they will come up against a monumental computing task. It can take thousands or millions of bits of stored data to draw a realistic scene and computers quickly run out of space. It also takes computers a long time—18 hours in some cases—to put all this stored data together to make a picture. If programmers try to provide general rules for drawing scenery, the computer pictures will look a little too smooth and regular. It is even more difficult to solve what computer scientists call the encoding problem. Take a scene, digitize it, and compress the information substantially so it can be easily stored. Then ask the computer to recreate that exact scene any time you want to see it.

But Mehrdad Shahshahani, a mathematician at Boeing Aerospace in Seattle has an extremely promising approach to solving both of these problems. He has found a way to make computer pictures of natural objects and to encode pictures of scenery with very little effort. He can generate a realistic picture of a leaf, for example, with only 21 numbers and three simple equations. Boeing Aerospace wants to use Shahshahani's results in its flight simulators, which are computerized systems used to train pilots by giving them the exact sensations of flying, complete to the scenery outside the window, without ever leaving the ground.

Shahshahani's work relies on some very esoteric abstract mathematics, which seems so unrelated to the real world that when Persi Diaconis, a statistician at Stanford University, studied this math 10 years ago, he decided not even to publish his results. But the mathematics results turned out to be just what is needed to determine which numbers and simple equations will make which pictures of natural objects. The story of how this mathematics came to light is the sort of story that is dearest to mathematicians' hearts. It is a story of mathematics pursued for its own ends that eventually finds an unexpected and significant use.

In 1974, as a graduate student in the statistics department of Harvard University, Diaconis at first had difficulty finding a research problem that interested him. Then, by chance, he came upon the "first digit problem," a problem first described around the turn of the century by Simon Newcomb, an astronomer. Newcomb was led to a curious result about the distribution of the first digits of numbers when he noticed that the beginning pages of books of logarithms were the most worn, indicating that people were looking up more logarithms of numbers starting with 1 than any other number.

If you look at the lead digit in any source of numbers, such as the pages of *Science* or the numbers in the almanac, you might expect that the number 1 would turn up about one-ninth of the time. After all, there are nine possible first digits and there is no reason to believe that any one digit would be favored over any other. But, surprisingly, the number 1 is the first digit about three times out of ten because the numbers that begin with 1 are irregularly spread among all the numbers. So, for example, one-ninth of the numbers from 1 to 9 begin with 1. One-half of the numbers from 1 to 20 begin with 1. One-ninth of the numbers from 1 to 100 start with 1. One-half of the numbers from 1 to 200 start with 1. As you look at larger and larger sets of numbers, the proportion of numbers in the sets with lead digits that are 1 oscillates between one-half and one-ninth. Diaconis asked whether there was some other natural way to take an average so that the average number of lead digits that are 1 will settle down rather than oscillate.

A way to do this, Diaconis found, is to use the Riemann zeta function, which has been the object of intense study for the past century because if more were known about it, more would be known about where prime numbers lie. The zeta function is an infinite sum, and Diaconis found that if he used the terms of that sum as weighting factors, he could get a way of averaging that would avoid the oscillations in the first digit problem. At the same time, this averaging method would give the usual sort of average in cases where the average does not oscillate. For example, both it and the ordinary way of taking an average say that one-half of all whole numbers are even. His method of "zeta averages" says that the density of the set of numbers that begin with 1—the chance that if you pick a number at random it will begin with 1—is $\log_{10} 2$, or .301.

"This was very esoteric math," Diaconis says. "It was the sort of math that made people say, 'Gee, that's funny, but why would anyone care?' " In fact, when Diaconis went to the University of California at Berkeley in 1973 to give a talk on his thesis as part of a job interview, he recalls the Berkeley statisticians saying, "We assume you'll find something else to work on."

Diaconis accepted a job at Stanford rather than at Berkeley and he did find many other things to work on. He all but forgot the first digit problem. In the meantime, Shahshahani was investigating a highly innovative way of producing computer graphics. He got his inspiration from some work done 3 years ago by John Hutchinson of the Australian National University in Canberra. Hutchinson was interested in generating fractals, which are mathematical entities with fractional dimensions. "There was no