Seismic Reflection Profiling: A New Look at the Deep Crust

Descriptions of the deep continental crust have varied widely in the past, depending on how the observations were made. For example, field geologists have looked at outcrops of deep crustal rocks and found complex, folded structures—from millimeters to kilometers in size—that have been altered by heat and pressure. Geophysicists analyzed the passage of sound waves through long horizontal sections of the crust and deduced a simple, layered structure of rocks with compositions resembling the granite of the upper continental crust and the basalt of the oceanic crust.

Seismic reflection profiling, which is a vertical sounding technique that has been perfected by the oil industry, is now being used by the American academic community to reveal some of the structural detail that had been observed only in surface outcrops. As a result of this work and other recent investigations, the simple layered model of the crust appears to have been put aside for good. Preliminary analysis of data from several sites seems to indicate that the method is capable of resolving structural details only a few kilometers in size at a depth of up to 45 kilometers beneath the surface. Seismic refraction, a more extensively used complementary technique, can only detect crustal features that are tens or hundreds of kilometers in size.

The Consortium for Continental Reflection Profiling (COCORP) was formed in 1973 by a group of researchers* to foster reflection profiling of the lower crust and upper mantle. The large-scale cooperative American effort is unusual in solid earth geophysics in that it combines costly, sophisticated technology for reflection profiling with the data processing capabilities of powerful computer systems.

The Soviet crustal program centers around the technique of deep seismic sounding, a hybrid of reflection and refraction. This technique demands considerable manpower, but does not require computer processing. Cooperative European programs have involved lower cost seismic refraction. Europeans using conventional methods had studied reflections from the deep crust, but not in a concerted or exhaustive manner. American geophysicists came to believe that the possible rewards warranted adoption of the most sophisticated field technology available, that of the American oil industry. While reflection profiling is the primary oil prospecting technique, its use in the United States has been limited more or less to shallow, sedimentary basins where oil is likely to be found at drillable depths.

With only minor modifications, COCORP adopted the VIBROSEIS® system developed by Continental Oil Company. But COCORP has used it to explore the crust to depths several times greater than those studied by the oil companies. At these greater depths, the rocks are igneous or metamorphic rather than sedimentary.

Reflection Technology

Reflection studies involve sending an acoustic signal into the ground and listening near the same location for a return signal reflected from structural features within the crust. Most previous noncommercial studies have depended on cumbersome chemical explosives as sources of sound energy. The COCORP signal source is a truck-mounted, hydraulically vibrated pad that transmits a low frequency, controlled 20-second "chirp" into the ground. The receivers, or geophones, are buried a few inches below the soil surface. Five vibrators and more than 1500 geophones are arranged in a single line about 5 kilometers long with the vibrators at one end. Several sets of reflected signals are recorded to build up a single strong record. Then the vibrators are moved a few meters before another set of signals is generated. Sixteen sets of reflections are summed into a single record for the 100 meters of the profiling line that the vibrators traversed. At the next step, 100 meters of the geophone array is moved from the back end to the head of the line. The entire process is then repeated to produce a continuous profile for as long a distance as desired.

The major difference between the COCORP operation and that of oil exploration companies is that COCORP listens for the reflected signal longer, about 15 seconds after the end of the chirp. Since travel time is roughly proportional to depth, COCORP can detect features at greater depths, up to 45 kilometers, with only slightly modified equipment.

Reflected signals can be expected from most interfaces between two different kinds of rock. The rocks may be molten and solid, have different chemical compositions, or be chemically similar but have different crystal structures. Thus, among the likely candidates for profiling are bodies of molten rock, intrusions of once-molten rock, and the various patterns in metamorphic rocks wrought by high temperature and pressure.

Since a typical profile may be compiled from about 25 million individual reflection points, powerful data processing techniques play a central role in the COCORP approach to crustal studies. As in the case of oil exploration, the first step is compensation for the effects of the near surface layers through which the reflected signals have to pass. This processing must be unique for each site and is the most secretive aspect of geophysical prospecting. COCORP faces an additional problem, Robert Phinney of Princeton University points out, because its signals are returned from an entirely different part of the crust, forcing an all-new approach to data treatment. The major difference is that no simplifying assumptions can be made about the shape of deep crustal features, which are often lumpy and irregular, as is done with shallow sediments.

Preliminary data from several sites have generated considerable enthusiasm among COCORP researchers for the potential of the approach. Profiles of several major identifiable features have been obtained, but considerable data treatment is still required to extract the details recorded in the raw record of reflections.

The first profiles, at a site in northern Texas, substantiated the feasibility of receiving reflected signals from a depth of as much as 45 kilometers. Although this profile did not reveal any striking geologic features, COCORP researchers consider that the pattern of the deep reflections at the Texas site is suggestive of intrusions from the upper mantle and folding of the crust.

The second site selected by COCORP, near Socorro, New Mexico, and within the Rio Grande Rift, also yielded numerous reflections from the deep crust, but among them was a spectacularly strong reflection from a previously suspected

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magma chamber. In addition, the profile contained reflections from what may be the Mohorovičić discontinuity (the Moho), a feature found in refraction studies and commonly interpreted as the boundary between the crust and the upper mantle.

Allan Sanford of the New Mexico Institute of Mining and Technology at Socorro first detected, by means of microearthquake seismology, signs of a magma chamber 18 to 20 kilometers below the surface. This method was used to construct a relatively detailed map of the chamber, but the amount of detail discernible within any particular part of the chamber was largely determined by the distribution and frequency of the microearthquakes. Phinney observes that the COCORP data provide a continuous profile rather than a collection of scattered reflection points which may be several kilometers apart. He believes that preliminary COCORP data provide an indication of layering of the chamber edges.

While providing interesting new details, early results from COCORP have also pointed up the difficulty of correlating results from vertical reflection profiling with those from refraction studies. For example, as the result of refraction studies, the Moho has been defined as the depth at which the velocity of sound changes sharply.

On the basis of COCORP data, Jack Oliver of Cornell University believes that a

Speaking of Science

Neutron Scattering: A New National Facility at Oak Ridge

One experimental technique that blossomed in the 1970's is small-angle neutron scattering. It has proved to be extremely useful for exploring the structure of a wide variety of biological, chemical, and physical entities with characteristic dimensions ranging from about 10 to 1000 angstroms. For American researchers, however, access to the neutron technique has been severely limited because European countries have had far and away the most numerous and best equipped facilities for neutron scattering. It was welcome news for these researchers, then, when the National Science Foundation (NSF) recently announced that the Oak Ridge National Laboratory (ORNL) will receive $1.4 million to be spent over 3 years for the establishment of a National Research Facility for Small-Angle Neutron Scattering.

According to Lewis Nosanow of NSF, an important reason that the award was made to ORNL rather than to one of a half-dozen other competing university and government laboratories was the laboratory's development of elaborate computer programs. These programs will enable users unskilled in the arts of small-angle scattering to carry out experiments with only a few hours training on what will be a largely automated instrument. Some construction will be needed to put the new facility into operation; this is expected to be finished in late 1979. In the meantime, an existing neutron scattering system at ORNL will be available about half of the time to outside users. In addition, a small-angle x-ray scattering system at ORNL will be available about 30 percent of the time as part of the new national facility. Small-angle x-ray scattering is complementary to its neutron cousin because the two structural probes have compensating strengths and weaknesses.

Neutron scattering can be used as a spectroscopic tool (inelastic scattering) to obtain information such as the spectrum of lattice vibrations in a solid. For structural studies, however, the technique works much like x-ray diffraction (elastic scattering). Needed are a source of monochromatic neutrons (that is, neutrons all having the same energy or wavelength), a detector to measure the intensity of the scattered neutrons at different angles relative to the incident beam, and a computerized data system to analyze the scattering patterns.

ORNL will be using its High Flux Isotope Reactor, the most powerful U.S. research reactor, as a source of neutrons with wavelengths near 4.7 angstroms. A position-sensitive proportional wire counter (with an area 70 centimeters by 70 centimeters) designed by Casimir Borkowski and Manfred Kopp of ORNL will be the detector. This detector is regarded as one of the most important features of the facility because of its ability to collect data so rapidly. Among other equipment to be built are a multipurpose sample chamber equipped for low- and high-temperature experiments and for studies at elevated pressures, and a 20-meter long evacuated tube for the scattered neutrons to travel through. The long tube is necessary so that the detector can achieve an angular resolution of the order of 2×10^{-3} radian. Finally, offices and sample preparation rooms will be built in a currently unused area near the reactor.

As with most large facilities, there will be a policy and advisory committee to oversee operation of the laboratory and a program committee to review research proposals and judge them according to their scientific merit. Since NSF and ORNL conceive the neutron scattering facility as a national resource, proposals from biologists, chemists, materials scientists, and physicists from any institution are equally welcome. If demand for time exceeds that available, a likely development at ORNL in the near future, the policy committee may have to establish some system to ensure that all disciplines have an equal opportunity to run experiments, a job that will require some diplomacy. For example, the director of the ORNL facility will be Wallace Koehler, a solid-state physicist, and the assistant director will be Robert Hendricks, a metallurgist. Moreover, ORNL has no tradition of in-house research on biological structures. Thus, one can already guess that biologists, who have found neutron scattering to be a fruitful technique (*Science*, 4 November 1977, p. 481), will be watching the administration of the ORNL facility closely.

As for catching up with the Europeans, Nosanow notes that there are already a half-dozen small-angle neutron scattering centers in France, Germany, and the United Kingdom, with more planned throughout Europe. In the United States, there are small-angle neutron scattering laboratories at Brookhaven National Laboratory (devoted mostly to biological research) and at the National Bureau of Standards (used mainly for polymer research), but these are intended primarily for support of in-house researchers and their collaborators. Thus, for U.S. scientists, it seems to be a matter of matching quantity with quality for the foreseeable future.—ARTHUR L. ROBINSON

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reflective layer about 36 kilometers below the Socorro site is probably the Moho, although it is neither continuous nor located at a single depth. He suggests that, rather than being at a discrete depth, the Moho below the Rio Grande Rift is a series of laminations on a scale that is too small to be resolved by refraction.

The difficulty of relating the two approaches arises because signal travel times from source to reflector and back vary depending on the velocity of the signal in each different part of the crust through which the signal passes. If only nearly vertically reflected signals are used, it is very difficult to measure the transmission velocity of a particular part of the deep crust. Thus, the conversion from travel time to depth is necessarily an approximation based on estimated velocities.

Accurate velocities within deep crustal layers have most often been determined by seismic refraction studies. Unlike the vertically reflected signals used so far by COCORP, refracted signals travel considerable horizontal distances from their source before being recorded. The refracted signals first penetrate the crust at some angle from the vertical and are bent into a more or less horizontal path by the refractive effects of passing from one crustal layer to another. Eventually, the signal is bent back toward the surface where its arrival time, which is determined by its velocity through the crust, can be recorded.

Seismic refraction is not a true imaging method like reflection profiling, which produces an optical image directly. The end result of a refraction study is only the broad variation of velocity with depth. Because the varied effects of many kilometers of crust are averaged to give a single value at a particular depth, refraction studies cannot resolve small detail the way reflection profiling can.

Refraction studies are already supplementing COCORP data at several sites. Ronald Ward of the University of Texas at Dallas has conducted a series of limited "piggy-back" studies with COCORP signals refracted through the crust as well as those reflected at a wide angle. They are being used to determine shallow crustal velocities, to remove interfering signals from the COCORP data, and to map three-dimensional subsurface features, such as the roots of the Los Pinos Mountains near the Socorro site. Oliver is optimistic that future piggyback studies will improve depth determinations by the use of wider angle reflections.

Independent refraction work by Dan McCullar and Scott Smithson of the University of Wyoming and by Kenneth Olsen and his colleagues at Los Alamos Scientific Laboratory tends to confirm the location of the Moho near Socorro at a depth of about 33 to 35 kilometers. This depth is slightly shallower than the depth outside the rift. Their work also suggests the presence of anomalous, and perhaps molten, rock beyond the limits set by the work of Sanford and COCORP.

Thinning of the crust and upwelling of magma are typical of areas such as the Great Rift Valley in East Africa which are generally regarded as geologically active zones of incipient ocean basin formation. COCORP researchers expect to return to the Rio Grande Rift to investigate further this conveniently located example of crustal alteration.

COCORP approached another basic geologic problem, the mechanism of midcontinent mountain formation, in its study of a deep fault near the Wind River Mountains of Wyoming. Reflection profiling is particularly well suited to tracing faults since they can be distinguished by the differences in the fine detail of the crustal blocks on either side of the fault, as well as by diffraction of the signal by features associated with the fault itself.

The fault straddled by the COCORP profile appears from surface indications to descend at a shallow angle, suggesting that one section of the crust slid over another as compression of the crust raised the mountains. But some geologists have raised the possibility that the angle of the fault might steepen with depth. If so, a block of crust might have been uplifted vertically instead of having slid horizontally to form the mountains.

Smithson, in a cooperative effort with COCORP, has done a preliminary analysis of the data from the Wyoming site. He believes that the fault can be traced to a depth of at least 30 kilometers. It appears to maintain its shallow angle throughout its descent, supporting the compressional theory.

COCORP seems well on its way to achieving its initial goal of demonstrating the utility of reflection profiling for studying the little known rocks of the deep crust. It is also making another point. Before COCORP, Phinney notes, solid earth research had not been included in "big science" as had such fields as oceanography and meteorology. He believes that the "old-fashioned, pickup truck" operation of the past had become a hindrance and that COCORP should serve as a model of cooperative, high quality data collection from the continental portion of the solid earth.

—RICHARD A. KERR

AAAS–Newcomb Cleveland Prize

The AAAS–Newcomb Cleveland Prize for 1976–1977 has been awarded collectively to all the participants in the Viking mission. The first results from this project, describing the Viking mission and the environment of Mars, were published in 47 reports in *Science* on 27 August, 1 October, and 17 December 1976. According to Bentley Glass, chairman of the award committee, it was the committee's opinion "not only that the scientific reports collectively represent a unique achievement in the exploration of a neighbor planet, but also that the observations made and the scientific data reported so depend upon the technological development of the Viking Lander and its instrumentation that the prize should go to the entire group of persons who have made the Viking mission such an extraordinary achievement in the annals of modern science." At least 60 scientists and 10,000 supporting personnel were involved in the Viking mission.

The AAAS–Newcomb Cleveland Prize formerly was awarded to the best paper presented at the annual AAAS meeting. The format was changed last year because of the declining number of reports of original research presented at the meeting and the increasing emphasis of the meeting on public policy aspects of science. The prize is now awarded to the author of the outstanding paper published from September through August in the Reports section of *Science*. To be eligible, a paper must be the first publication of the author's own research. The award to the Viking mission is the first presentation made under the new format.

The award, which consists of $5000 and a bronze medal, will be accepted by Thomas Mutch of Brown University at the 1978 AAAS meeting in Washington. Mutch is leader of the Lander imaging team.—T.H.M.

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