EAVESDROPPING AT

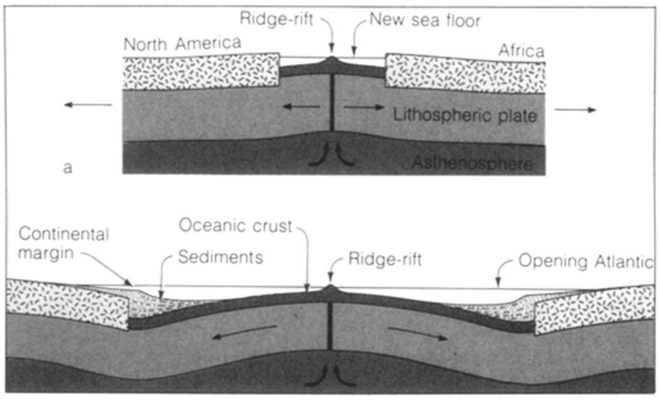
By STEFI WEISBURD

Scrolls of seismic records, looking to the uninitiated like TV screens full of static, were tacked everywhere around the conference room at Woods Hole (Mass.) Oceanographic Institution (WHOI). Forty-eight earth scientists from four countries gathered recently to compare these 3- to 18-foot-long records of the earth's response to probing with sound waves. The seismic profiling method that generated these records was first developed 60 years ago, but with technological advances has more recently been embraced by academic scientists as a powerful tool for mapping the underlying structure of the crust and upper mantle.

One purpose of the WHOI meeting was to discuss the strengths and weaknesses of the various profiling techniques that are currently available. But in a larger sense, these geologists and geophysicists had come to learn about the evolution of continents by hunting for common patterns in seismic sections of continental margins, the transition regions between the continents and the ocean floor.

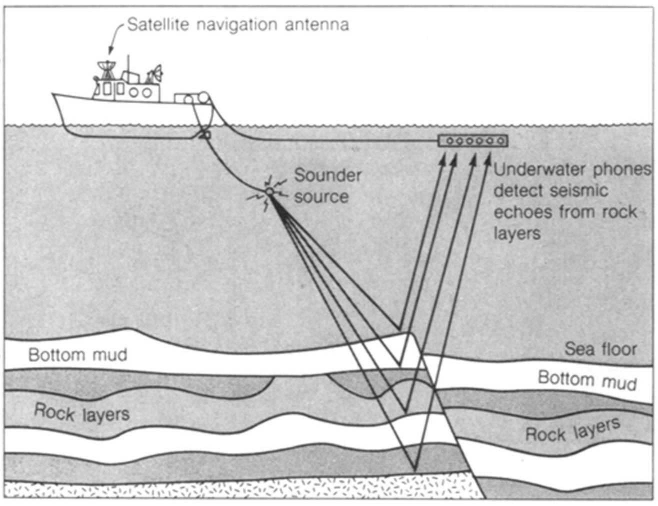
According to the theory of plate tectonics, continents are embedded (along with oceanic crust) in about a dozen plates that float, like rafts, on a viscous underlayer in the mantle. Propelled by the formation of new seafloor, the drifting plates periodically collide and grind together, creating mountain ranges and deep sea trenches. When plates separate, oceans are born and continents can be rifted and fragmented. Many scientists believe, for example, that the present Atlantic Ocean was created 150 million years ago when a large land mass split into the continents of Africa, America and Eurasia.

"Plate tectonics was a great event in the history of geology," says Jack Oliver of the Consortium for Continental Reflection Profiling (COCORP), which operates through Cornell University in Ithaca, N.Y., and has been instrumental in seismically charting the North American continent. "But at the same time, plate tectonics is based largely on data for the oceanic areas, and it tells us mostly about what's going on in the oceans. We're developing a story of continental tectonics that will mesh with plate tectonics, but it will tell us in more detail about the kinds of rocks we see in the continents."



Adapted from U.S. Dept. of Interior model

Continental margins, the transition regions between the continental crust and the ocean floor, are created after continents are torn or rifted apart. As the rift widens and new seafloor is born, thick wedges of sediment are deposited on the margins from inland erosional debris.



Offshore, seismic reflection profiles of the seafloor crust and mantle are made by towing a sounder source such as an air gun or explosive charges and a set of hydrophones to pick up the sonic signal after it bounces off the buried layers of rock and sediment.

Adapted from "Geosynclines, Mountains and Continent-Building," R. S. Dietz© 1972 Sci. Am., Inc.

A key to understanding the processes that shape continents may lie with the layers of rock buried deep in the crust and upper mantle at continental margins. Because these layers are well beyond the reach of drilling, geophysicists have turned to seismic profiling to probe the earth's architecture.

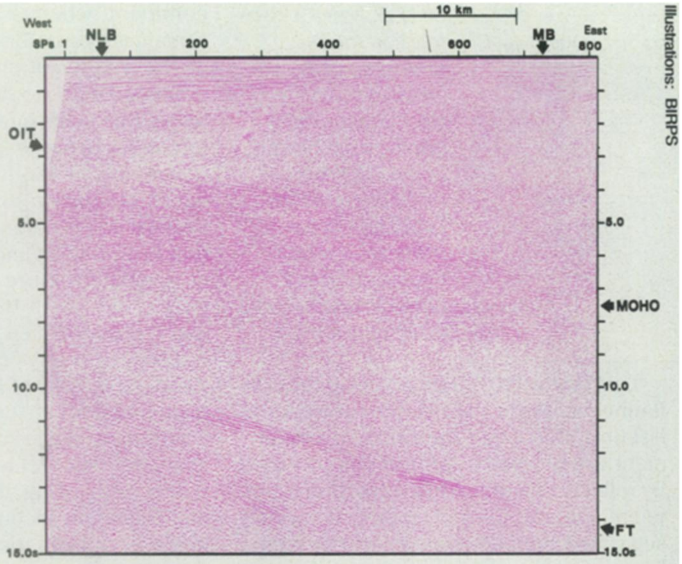
Seismic reflection profiling was first developed by oil companies in the 1920s to map the unseen layers of sediment and rocks in the upper crust. Sound waves are generated at the surface — either with large truck-mounted vibrators on land or with air guns or explosive charges at sea. These sonic signals, propagating through the crust, are reflected back whenever they encounter an interface between different kinds of rock — sandstone and carbonates, for example. By collecting, sorting and adding up all the reflected sound waves, a picture, or seismic section, of the earth's vertical structure is constructed in much the same way medical ultrasonic scanning is used to depict the interior of the human body.

The petroleum industry — which is, of course, interested in looking for oil only at depths to which it can drill — tends to take seismic data of relatively shallow layers, down to only about 10 kilometers. By the 1960s, however, geophysicists began to notice reflections from much deeper layers, around 30 km. These signals were written off at first as being artifacts of the seismic technique, but gradually scientists began to realize that the deep reflectors in the lower crust and upper mantle were real.

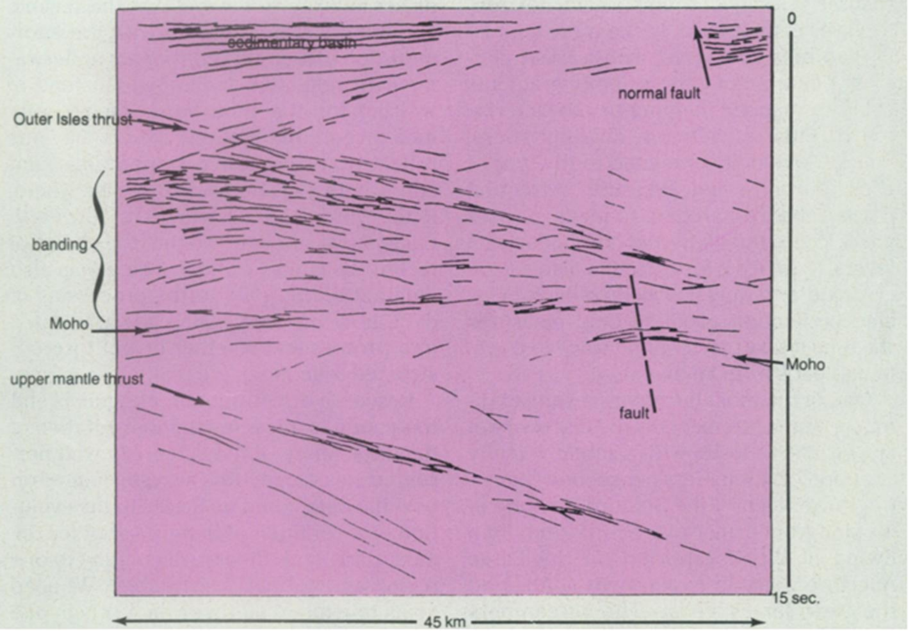
"It's become clear that observations of

CONTINENTAL EDGES

The seismic reflection profile at right was obtained in 1982 by BIRPS along an east-west line running just north of Scotland. The line-drawing below highlights the main features of the data, including Moho and two thrust faults. The vertical axis denotes the time it takes for a sound wave to travel to and from a rock layer; here, 15 seconds corresponds to 45 to 50 kilometers in depth.



Illustrations: BIRPS



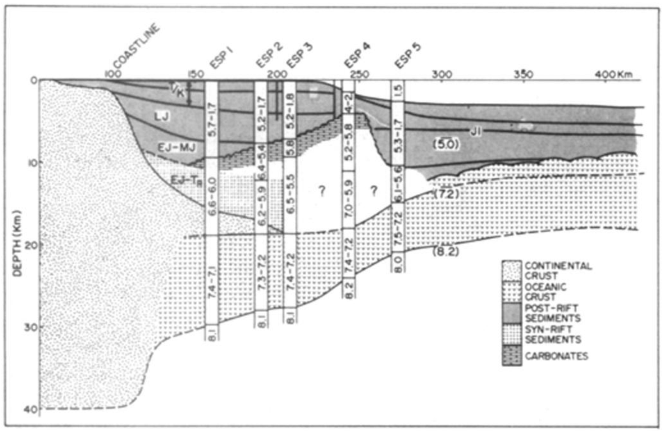
very deep reflectors ... are extremely common now. It's almost routine," says Michael Purdy of WHOI. "But in terms of organizing an interpretation of these reflectors, I'm not sure that we've made the progress that we should have." Now the job of the geophysicist is to unearth the composition and structure of the rock layers that create deep reflections, and then to read from that geologic mosaic the history of the continents.

For the most part, however, the research is still in its early stages. One geophysicist likened the WHOI meeting to a game of poker: "We're all here to show our cards."

From the seismic sections scattered about the WHOI conference room, a fairly consistent picture of the continental crust emerges. In almost every profile, reflections from the youngest and most shallow layers, typically sediments, lie like icing on top of the upper crust, which is remarkably barren of seismic reflections. This is followed, in many of the records, by a region in the lower crust that is busy with horizontal reflectors, clustered together in bands. On each section, a geophysicist has noted the Mohorovičić discontinuity, or Moho, named after the Yugoslavian seismologist who discovered it in 1909. Moho denotes the boundary between the crust and upper mantle located around 35 km under the continental surface and about 10 km beneath the ocean floor. While Moho is often used as a reference line with which to get one's bearings when looking at a seismic section, its origin, thickness and continuity are subject to considerable debate.

Some of the most striking data illustrating this crustal structure were presented by Michael R. Warner of the British Institutions Reflection Profiling Syndicate (BIRPS). In addition to the features already mentioned, the BIRPS seismic section (shown here) contains two diagonal reflectors. Warner and others believe that the topmost dipping reflector in the crust above Moho is a thrust fault, the Outer Isles thrust, formed 500 million years ago when the predecessor to the Atlantic Ocean closed up as the plates collided. The horizontal lines at the top of the profile are reflections from a sedimentary basin that Warner thinks may have formed later in the Mesozoic era when the Outer Isles thrust was reactivated as a normal fault. BIRPS researchers can only guess what the lower dipping reflector in the upper mantle is, but because it parallels the upper thrust, the group has proposed that it is a thrust as well. By revealing structures all the way down into the upper mantle, these kinds of recent profiles mark a significant advancement in seismic technology.

While the Outer Isle thrust can be traced to the surface to verify its nature and composition, the interpretation of dipping reflectors that do not outcrop through the surface is much more difficult and often controversial. Jim Leven of the Bureau of Mineral Resources in Australia presented profiles of the Adavale basin in eastern Australia, in which two dipping reflectors appear in the upper mantle. Leven thinks these reflectors could be pieces of old oceanic crust that were subducted, or pulled down into the upper mantle, during the Cambrian or Precambrian time. In his scenario, the eastern part of the continent was accreted from sediments that were scraped off the ocean crust as it was subducted. If the profiles really do show two successive subductions — and not everyone supports the idea — they raise an intriguing question as to what caused the first subduction to stop.



LASE

Cross section of a continental margin off N.J., based on refraction measurements of the velocity of sound in each layer. The geology and extent of the 7.2 km/s velocity layer, which LASE here interprets as one continuous piece of oceanic crust, is still open to question.

One way to learn about ancient subduction processes is to study those currently taking place, such as that in Alaska. Michael A. Fisher of the U.S. Geological Survey in Menlo Park, Calif., showed a seismic record taken near Cook Inlet in the Gulf of Alaska that contains a broad dipping reflector extending for 60 km to a depth of about 20 km. Unfortunately, without more data to follow the reflector further toward the surface, it is difficult to draw conclusions about what causes this reflection. Fisher says the reflector could be a piece of past oceanic crust, sedimentary rocks riding on the Pacific plate as it is subducted, or a major thrust fault.

Dipping reflectors are not the only seismic features that have drawn debate. A number of theories have been proposed to explain the banding of reflectors in the lower crust. Some geophysicists think the banding is due to water or other liquids. Others believe the lower crust is made up of cells of igneous rocks that were plastered to the bottom of the crust. Another theory holds that these laminations are caused by shearing of the ductile rock layers in the lower crust.

According to Warner, the banding is brightest where there has been crustal stretching that orients the fabric of the rocks. Around Britain, where banding appears in over 80 percent of the BIRPS data, the continent was stretched prior to the opening of the Atlantic. Similarly, COCORP profiles show very bright banding in the actively extending Basin and Range province in the western United States. Warner says the stretching not only aligns the layer material but also could enhance the other proposed processes by creating more cracks to let in more liquid or by causing higher temperatures that would result in more igneous rocks.

There is also much confusion about the location and interpretation of Moho. While the BIRPS data show a distinct reflector as Moho, separate and below the banding, other scientists at the meeting presented profiles where Moho was labeled above or even as completely comprising the banding section. "It's more than a question of semantics," says Purdy. What and where Moho is has a lot to do with the geophysical process that formed the crust.

That is why Purdy and others at the conference stressed the need for seismic refraction studies of the crust to complement the geometric information provided by reflection profiles. In a refraction experiment, the sounder and receiver are widely separated. Sound waves are sent through a layer of rock, parallel to the surface, so that the velocity of sound in each horizontal layer is measured. In the more sophisticated measurements, with a great density of data points, the velocity gradients are also mapped, helping to characterize the boundaries between different rocks. Since the velocity is related to the type of rock, porosity and pressure, refraction data enable researchers to make guesses about the composition of the underlying layers. Velocity information is also essential in determining how deep reflectors lie, since reflection profiling only measures the time it takes for a sound wave to travel to and back from an object.

One of the most intriguing results of refraction measurements is the discovery of a layer above Moho with a sound velocity of about 7.2 kilometers per second (km/s). Charlotte Keen of the Bedford Institute of Oceanography in Nova Scotia and John Ewing of WHOI reported on the Large Aperture Seismic Experiment (LASE) off the New Jersey coast. The researchers found that the 7.2 km/s layer is crowned by a sharp upper boundary, enabling them to trace the layer continuously from the oceanic crust through the margin and under the continent. The LASE group based its conclusions on five Expanding Spread Profiles (ESPs), a refraction technique in which the receiving and blasting ships steam away from one another.

Jean Barrus of the Institut Française du Petrole in France presented a schematic cross section of the velocity structure in the Gulf of Lions in the Mediterranean that was derived from 10 times that number of ESPs. His sketch showed a number of different velocity layers pinching together toward the 7.2 km/s layer in the ocean crust. But Barrus argued that there is no reason to suppose that the 7.2 km/s layer on the ocean side is actually made of the same material that is found under the continent, because the composition of continental crust is quite different from that in the ocean; the fact that both sides have the same velocity could be purely coincidental. So the nature of the 7.2 layer under the continent, whether oceanic crust or not, remains to be determined.

These kinds of profiles are going to be examined with great interest because they help address the question of how the crust thinned when the continents rifted and where new ocean floor began to be produced in relation to the present-day continental edges. Keen noted in the meeting that both LASE's and Barrus's schematics of crustal structure show a marked thinning of layers as they near the margins, and she questioned whether it is realistic to expect, on physical grounds, that such slender sections of brittle rock would remain intact for so long.

For many of the scientists at the conference, the most relevant discussions were those contrasting the various refraction and reflection techniques in terms of the kinds of information they provide and their costs. It seems that everyone has his or her favorite. Some feel that the seismic community should get on with the enormous job of mapping continents underwater with reflection techniques instead of waiting for the final word on velocity measurements. Others stress various reflection/refraction combinations, and still others suggest choosing sites where, in the words of one participant, "the earth really speaks to you," so that the choice of technique is less critical. There was also much attention paid to the processing of data, how the raw signals are translated into profiles and whether or not the constructed reflections are real.

Research at continental margins is still too young to allow much interpretation of the data. Many of the scientists who presented seismic records also speculated on how the data could be linked to the evolution of a continental margin — but for the most part, each theory was unique to one region and not easily verifiable. "We need ideas to explain all those data sets in one fell swoop," says Warner. "If the world's full of unique explanations, it makes it awfully difficult to study."

In order to interpret the seismic information in terms of the formation of continents, geophysicists must have a firmer grasp of what causes the reflections. And as John Ewing, one of the conference's organizers at WHOI, said, "We still don't know what's down there." □