the SV40 gene to the gene for atrial natriuretic factor, which is normally produced by both atria. Although Field still does not know why the tumor appeared only in the right atrium, he thinks that a gene in the host mice may play a role because one mouse strain developed tumors much more quickly than another. The tumor cells divided in an uncontrolled way but contracted spontaneously and were similar in other respects to normal myocytes, he says.

Working independently, Jacques Peshon, Richard Palmiter, and Stephen Hauschka of the University of Washington in Seattle and Richard Behringer and Ralph Brinster of the University of Pennsylvania in Philadelphia and their colleagues also produced transgenic mice with tumors of the right atrium—for them, a completely unexpected result. "We were not even thinking that we were going to study cardiac cells," says Hauschka. "This was just serendipitous." The group had expected to stimulate tumor growth in the testes, but instead got tumors in the right atrium of the heart and a section of bone near the ear. Over a 2- to 3-month period, the atrial tumors of the mice became larger than the entire heart.

Hauschka, like Field, does not know why the transgene stimulated asymmetrical tumors. But he and Cindy Gartside have capitalized on it by using the tumors to set up a permanent line of heart muscle cells. "We have been able to maintain cells from these tumors in culture for over a year," says Hauschka. "Some of them still contract." Now they can study cardiac-specific genes, gene regulation, and factors that alter myocyte growth in the cultures, he says.

The long-term goal is to develop new strategies for treating heart disease. "The whole concept is very exciting," says Isidore Rosenfeld of the Rosenfeld Heart Foundation in New York City. "The heart fails for a number of reasons—stress, bad valves, hypertension. But the most common cause is damage from myocardial infarction."

When a person has a heart attack, the muscle tissue disintegrates over a period of several days. "It lyses and is attacked by phagocytes [scavenger cells from the bloodstream]," says Ferrans of NHLBI. "Then after 3 to 4 days fibroblasts invade the muscle and make a fibrous tissue scar." The time delays in these responses may make it possible to intervene in several ways, he suggests—perhaps to prevent extensive muscle loss, retard the growth of the fibrous scar, and also to stimulate myocyte regeneration and differentiation.

Claycomb is about to submit a grant application along these lines that he describes as "kind of science and kind of science fiction." The first part is science. "If we can understand why cells stop dividing then we may be able to restimulate their division." Then comes the science fiction. If researchers learn how to trigger myocyte replication, they may be able to take a biopsy of heart cells from someone after a heart attack, stimulate them to grow in vitro, and place them back into the damaged heart where they could divide and differentiate in a controlled manner. Such a procedure, if successful, would avoid the problem of tissue rejection, which is the major complication with heart transplants.

Despite recent progress in the field, not many scientists are studying heart muscle cell replication or regeneration. "The funding is not good," says one researcher. NHLBI officials are quick to point out that the institute cannot fund a grant unless it gets a high rating during the peer review process. In 1983 the institute began soliciting grants on the development and cell biology of cardiac myocytes, and today funds 22 such grants. While none of them addresses the problem of regeneration specifically, perhaps some of the new information will change that.

■ **Deborah M. Barnes**

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Slices of Continental Crust Coming into View

The study of sections of deep crust exposed at the surface is supplementing expensive geophysical methods and deep drilling

Killarney, Ontario, Canada

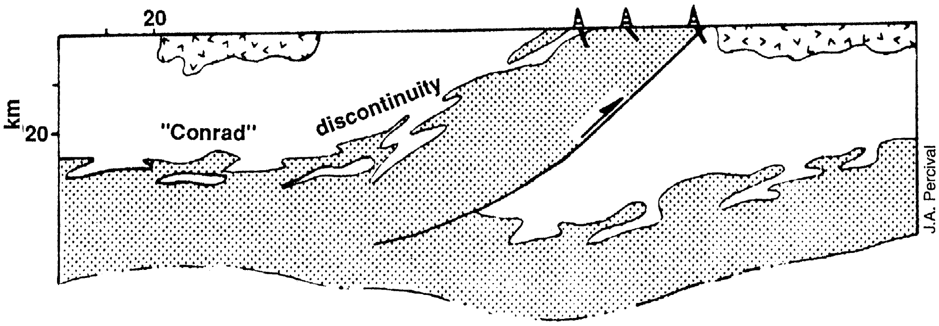
THE DEEP CRUST OF EARTH is as exotic as it is unreachable. Under the crushing weight of more than 20 kilometers of rock and temperatures of hundreds of degrees Celsius, rock sweats off its last vestiges of water, transforms its minerals, and, given time, can bend, twist, and tear like soft dough. It is under such conditions that much of the growth and modification of continents occurs. Geologists would love to take a great scoop out of the crust to expose these lower reaches, just as rivers or road engineers slice through mountain sides to reveal their geologic structure.

Lacking godlike powers, earth scientists settle for what the vagaries of volcanoes, continental collisions, and erosion might bring to the surface. This has included plenty of once deep-seated rock from pebble-size on up, but the ideal—vertical cross sections through much of the crust that are still linked to similar rock at depth—have been hard to come by. At a recent workshop in Ontario on continental cross sections,* a group of about 60 geologists, geophysicists, petrologists, and geochemists traded professional tales of cross sections they have known. Thanks to more fieldwork, new techniques, and new perspectives, the selection of cross sections, especially those through a substantial part of the crust, has been considerably expanded.

A key to this improving outlook is the changing perspective of geologists. Perspective can be all important when interpreting rock strata. There is an old saying among geologists—"I wouldn't have seen it if I hadn't believed it"—that certainly applied to Grahame Oliver's experience in New Zealand. In the early 1970s Oliver, who is now at St. Andrews University in Scotland, was the first to make a geological map of the Doubtful Sound area of far southern New Zealand. As he told the meeting, the rocks revealed among the fjords, glaciers, and temperate rain forests of Fiordland (10 meters of rainfall annually) seemed familiar from his training in Europe.

Oliver presumed that, as in European examples, the so-called granulite group of rocks of Fiordland's lowest exposed strata, which had obviously suffered alteration at high temperatures and pressures, would be old, probably older than 500 million years. Those rocks above the granulites would be

*NATO international advanced course on Exposed Cross Sections of the Continental Crust, Killarney, Ontario, Canada, 17 to 27 September 1988.



One way to make a cross section. *The shove from a continent-continent collision off the left of the diagram apparently drove a layer of the lower crust (stippled) along a sloping fault to outcrop at the surface. The drill rigs show how middle and lower crust targets might be reached with shallow holes.*

younger and would have been shoved across the old basement rock along the intervening fault zone.

Reality turned out to be the exact opposite of a conventional reading of the rocks. Dating of the rocks a couple of years ago showed that the lower, granulitic rocks are younger, not older, than those above. Additional dating and a borrowing of some new ideas from studies in the American West recently allowed George Gibson of the Darling Downs Institute in Toowoomba, Australia, to show that instead of the upper rocks being thrust over the lower ones, Fiordland has been pulled apart, with the upper rocks sliding off the lower ones along the fault. The granulites now at the surface were once 45 kilometers down.

Explaining how this deep crust came to see the light of day requires a bit of speculation, but the general outline of its history can be seen. More than 100 million years ago, the sinking of an oceanic plate into the mantle injected magma into the upper crust and formed volcanic piles on the sea floor, creating a magmatic arc like the Aleutian Islands of today. The forerunner of Fiordland's once-deep granulites would have formed the base of this arc. Then the arc could have collided with a continent, jamming rock both upward and downward. Burial near the bottom of such a thickened crust would have formed the granulites from the deep arc rock.

Once buried, the granulites would need more than one push upward to reach the surface. The first would have come 80 million years ago as the opening of the Tasman Sea eased the squeeze on the collision zone, allowing the unnaturally thick crust to relax and extend. The deep crust, driven in part by hot, buoyant mantle drawn upward by the expansion, would rise to within 10 to 20 kilometers of the surface as erosion stripped off rock above. Then the Pacific plate was thrust up and over the adjacent Australian plate beginning 20 million years ago as the Alpine fault formed. Simultaneous erosion accomplished the present exposure.

The inevitable tilting involved in both of these kinds of motion has laid out three-quarters of the crust of the Pacific margin for inspection. Only another 10 kilometers or so of crust lies between the exposed section and the 3000 kilometers of mantle rock that extends to the molten core. It is this preserved connection to the rest of the crust as well as the breadth of its exposure that makes the Doubtful Sound cross section so interesting.

A new way of looking at familiar rock was also needed to recognize that the Kapuskasing structure of Ontario is another broad crustal cross section still rooted in the crust. The granulite rocks of the north-south trending wedge of the Kapuskasing structure had always been recognized as having once been deeply buried. One suggestion was that they had popped up between blocks of shallow crust as the continent was briefly pulled apart.

That picture of the Kapuskasing did not hold up in the field studies of John Percival of the Geological Survey of Canada in Ottawa. Beginning as a student, Percival searched for the two faults along which the block of deep crust was supposed to have risen, but he found only one that could account for the uplift. He did find that rock alteration due to high temperatures and pressures graded continuously over a distance of 100 kilometers from the most severe metamorphism in the east, where the rock had been buried at a depth of 25 kilometers, to the least severe metamorphism in the west. These and other identifying signs of deep cross sections were just the sort that David Fountain of the University of Wyoming and Matthew Salisbury of Dalhousie University in Halifax gave in a 1981 paper.

Percival hypothesized that a sheet of crust had been shoved eastward, perhaps by the collision of the Churchill continental plate about 2 billion years ago at what is now Manitoba. Instead of simply crumpling the crust at the point of impact, some of the collision's stress was transmitted 1500 kilometers to the east. There it shoved a layer of crust upward along an inclined fault that rose to the surface on the eastern edge of the present Kapuskasing zone. As crust swung up along the fault, erosion took off shallower rock to reveal the crust across 20 to 25 kilometers of its depth, or perhaps half of its depth there. This picture has since been largely confirmed.

Although not a complete cross section, Kapuskasing has considerable merit. Like Doubtful Sound, it can be traced back to where it originally belonged in the crust. It is the oldest crust revealed in cross section. And it provides a sample of the crust in the middle of a continent. So far all other cross sections of significant depth were near relatively young continental margins.

The Ivrea zone of the southern Alps in western Italy is a chunk of crust that has always been near a plate margin, but it has the considerable merit of being an essentially complete cross section. Formed and modified during a mountain-building, continent-continent collision about 450 million years ago, the Ivrea zone was stretched by the crustal extension that eventually split Africa away from Eurasia, only to be thrust to the surface during the collision that raised the present Alps.

After all that, at least 90% of the original crust is still there and, like Doubtful Sound and Kapuskasing, is traceable to the crustal layer in which it was formed. Debate continues, but there are rocks at the bottom of the cross section that could have formed the Moho, the lower boundary of the crust.

There is another group of cross sections, far larger than that of Doubtful Sound, Kapuskasing, and Ivrea, that Fountain designated as the geological type, as opposed to the geophysical type. The three geophysical types can be traced back down into the contemporary crust using geophysical techniques such as seismic reflection profiling. Geological types have not yet been linked to similar rock now at great depth. Among the latter type is the magmatic arc of the Kohistan region of the Himalayas, up to 40 kilometers of section shoved to the surface during the collision of India and Asia. The collision of Europe and North America 400 million years ago converted dry granulites to hydrated eclogites at a depth of 50 kilometers. How they reached the surface along the west coast of Norway is a mystery.

Another sort of geologic cross section that has drawn a lot of attention in the American West is the metamorphic core complex. These windows on the deep crust were Gibson's guide to deciphering the true nature of the Doubtful Sound area. They too were once taken by geologists to be old, compressed crust exposed by a bit of erosion. That seemed to fit nicely with geologists' understanding of western North America. But by the late 1970s contrary evidence began changing minds. The chain of metamorphic core complexes running from British Columbia to Mexico turned out to have been compressed more than 100 million years ago but was stretched as recently as 20 million years ago, exposing cross sections penetrating as deep as 25 kilometers into the crust.

Given the increasing selection of continental cross sections, how typical of the rest of the crust are they? Almost all sections have been compressed, extended, and perhaps compressed again as they were raised to the surface, not to mention injected by hot magmas from below. All this kneading of the crust has led to interleaving of continental and oceanic slabs, thrusting of one rock layer over another, the addition of magma-derived layers at the base of the crust, the melting of existing rock by intruding magma, and the flooding of the lower crust by mantle-derived, rock-altering fluids.

Conveniently enough, these are the processes that seem to have been involved in the formation and modification of new continental crust, at least during the past few billion years. In many cases, the same events that add new crust to continents can expose snippets of it as cross sections. The mechanisms that provide cross sections of oceanic crust, on the other hand, seem to select only certain types of crust and give them a good battering in the process (*Science*, 18 March 1983, p. 1307).

In addition to the opportunity to dissect deep crust from the kilometer to the micrometer scale, cross sections offer researchers a chance to generalize from these tiny scraps of exposed deep crust to the structure of continents themselves. A key approach will be calibrating the remote sensing techniques of geophysics against the known rock structures of deep cross sections. For example, the seismic waves used to probe the deep crust for the past 10 years have been reflecting back to form sometimes striking images, but in many cases researchers have had no idea what was causing the reflections (*Science*, 3 August 1984, p. 492). Especially intriguing have been widespread, more or less horizontal reflections from the lower crust, particularly in extended crust.

Possible seismic reflectors include any juxtaposition of materials having sufficiently different physical properties: fluids in cracks, new rock intruded as magma, differing types of rock brought in contact by fault movement, and faults themselves due to the orientation of their minerals. Even repetitive layering of rocks with little contrast could amplify reflections through constructive interference if the spacing of the layers were just right.

In one case, at least, particular seismic reflections have been matched up with deep reflectors in a cross section. As part of the Canadian LITHOPROBE project, a set of reflections curving up from a depth of 15 kilometers was linked to rocks outcropping in the Kapuskasing zone. Allowing for erosion, these rocks were once 25 kilometers below the surface in the lower crust. In this case, the reflections are from the juxtaposition of rocks emplaced by repeated intrusion and solidification of magma. The differing chemical compositions of the intruded rocks and their varied histories of temperature and pressure lead to varying seismic velocities.

Margaret Burke of Dalhousie University and Fountain reported a less direct link between reflections and rock. In the laboratory they measured seismic velocities in rocks from the Ivrea zone and calculated what reflections would look like when those velocities were assigned to the appropriate Ivrea formations, when they are realigned in their original configuration in the deep crust. The resulting reflections were similar to those from extended crust—a largely unreflective upper crust and a highly reflective lower crust. The strong lower crust reflections were from contrasts between juxtaposed rock and from constructive interference among reflections from layers less than a kilometer thick.

Salisbury and Fountain have suggested that rocks exhibiting another interesting variation of seismic velocity may outcrop in the Kapuskasing zone. Seismic velocities tend to increase more or less smoothly with increasing depth, but for more than half a century geophysicists have observed that seismic velocity takes a moderate jump at mid-crustal depths, at least in some regions. This so-called Conrad discontinuity has proved elusive, but Salisbury and Fountain see signs of it in the measured seismic velocities beneath the Kapuskasing zone and in rocks from the surface.

The Kapuskasing's apparent Conrad discontinuity and other parts of cross sections are tempting targets for another approach to study of the crust, deep scientific drilling. Holes a few kilometers deep through igneous rock are technically attainable at modest cost. A superdeep hole of 10 or 12 kilometers, as achieved on the Soviet Kola Peninsula and planned in West Germany, runs to many tens of millions of dollars.

In the Kapuskasing zone, 25 kilometers of crust has already been removed. A hole a few kilometers deep, as Salisbury has pointed out, could provide a continuous record through the unreflective middle crust, the Conrad discontinuity, and into the reflective lower crust. Geologists working in the Kapuskasing zone must content themselves with the few percent of rock that is exposed among sediment, soil, and vegetation.

Crustal cross sections are not perfect. The question of how typical they are remains. Problems of limited exposure are unavoidable. Their rocks long ago left the conditions of temperature, pressure, and fluid content that cause the lower crust to behave as it does. And there is the nagging dearth of lowermost crust among available cross sections. But they clearly offer a broader view of the deep crust than any drill hole and more readily identifiable crustal structure than geophysical techniques.

■ RICHARD A. KERR

D. M. Fountain

The beauty of deep crust *is evident where erosion has cut through the Ivrea zone of the Alps in northern Italy.*

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