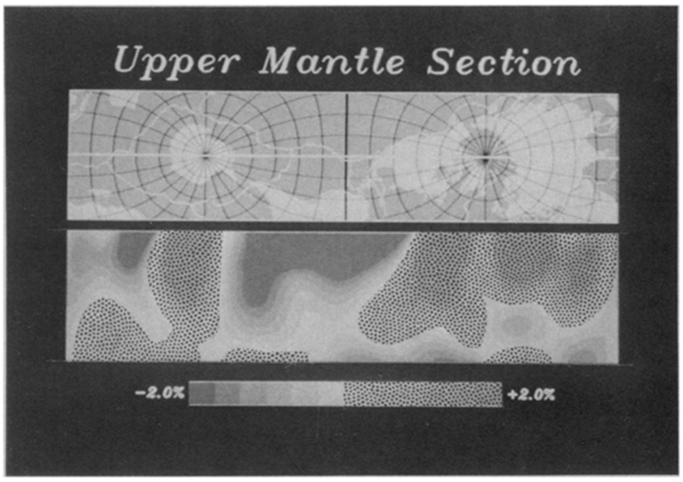
Rooting for Continental Roots

The discovery that the old cores of continents are unusually thick is rifting traditional notions about continental drift

By STEFI WEISBURD



Woodhouse/Dziewonski

Using seismic waves to probe the earth, researchers generated this vertical cross section (bottom) of the upper mantle lying under the horizontal line in the map (top). Stippled continental roots, denoting regions where seismic waves travel faster than in surrounding areas, extend to depths of 300 kilometers or greater.

At one time, scientists thought that mountains and valleys arise because the earth is shrinking; all the wrinkles, folds, faults and other deformations in the planet's crust were likened to the crinkly skin of a drying apple. Then came the theory of plate tectonics, which revolutionized the earth sciences and gave researchers a more tenable framework for understanding a remarkable variety of geologic processes. According to this theory, the continents and oceans are embedded in a dozen or so thin plates that make up the earth's mechanically strong "lithosphere" and that float like rafts over the weak, partly molten "athenosphere." Mountains are created when two continental plates collide; the Himalayas, for example, have been built over the last 50 million years by the Indian plate's relentless drive into Asia.

But plate tectonics, too, has its faults. While the theory is very successful at explaining how oceans and oceanic crust form, in many ways it leaves the continents high and dry. In the case of the India-Asia collision, for instance, it doesn't explain why the oldest part of the Indian plate has survived the collision intact while sections of Asia have been violently deformed.

Plate tectonics also assumes that plates are no thicker than about 100 kilometers and that the structure of the lithosphere and athenosphere beneath the continents is essentially the same as that underlying oceanic crust. Over the last several years, however, many scientists have come to think that the plates under cratons — the oldest continental cores, which have remained undeformed for more than a billion years — are much thicker than 100 km and may indeed have temperature and chemical profiles that differ from plates under oceans.

While researchers are still debating exactly how deep these "continental roots" extend, the evidence for thick continental plates is challenging traditional models of how the continents evolved. And recent studies suggest that to understand continents' surface behavior, such as the India-Asia collision, one must look at the deep structure of cratons, which billions of years ago somehow shepherded and stabilized the normally mobile mantle material beneath them.

Scientists got their first inklings that cratonic plates differ from plates under oceans and the younger, deformed parts of continents, called orogenic zones, in the 1960s. Using the seismic waves generated by earthquakes to probe the inner earth, they found regions, lying about 100 km under the oceans and orogenic zones, in which sound waves travel more slowly than in surrounding areas. Because the speed of the seismic waves tends to decrease with increasing temperature, researchers reasoned that these low-seismic-velocity zones correspond to the warm, partially molten athenosphere. Under cratons, however, such zones either did not exist or lay much deeper; the mantle directly under cratons was colder and had a high seismic velocity to depths greater than 200 km.

This presented problems for the newly emerging plate tectonics theory. If the plates were constantly moving, then there should be no reason to expect that cold regions in the athenosphere would always be found under continents and never under oceans. Moreover, if there really were thick, cold roots under cratons, how would scientists explain their formation? They might have formed as the continents cooled and thickened in the last billion years or so; oceanic plates are thought to thicken by this process. But cooling oceanic plates also grow denser and sink — so that the oldest regions of oceans are covered by the most water. Not only are cratons not covered by water or low-density sediments, but these regions are often being lifted in relation to other parts of the continents.

And, even if cold cratonic roots were somehow to form, how would they remain stable? One would think that the vigorous convection of material in the mantle would destroy thick roots, and that the cool roots, being denser than the surrounding mantle, would sink away from the plate.

Because the seismic data in the 1960s could be interpreted in a number of ways, however, some scientists argued away these difficulties by choosing a model that kept the lithosphere thickness to less than 200 km.

With the help of Stuart A. Sipkin, now at the U.S. Geological Survey in Golden, Colo., and Thomas H. Jordan, now at the Massachusetts Institute of Technology, the continental root idea was put on a slow comeback trail about 10 years ago. These researchers used a different set of seismic waves to measure differences between the mantle under cratons and the mantle under oceans. With both sets of data in hand, they concluded that craton roots most certainly extend below 200 km and probably exceed depths of 400 km.

To geoscientists these are remarkable numbers, because they imply that where roots form, the plates contain not only lithosphere but a little athenosphere as well. Jordan thinks the athenosphere part is able to move with the root because it is more viscous than athenosphere under the oceans. Because the word "plate" has become synonymous with the lithosphere in plate tectonics, he prefers to use the term "tectosphere" to define the upper part of the earth that moves as a single entity.

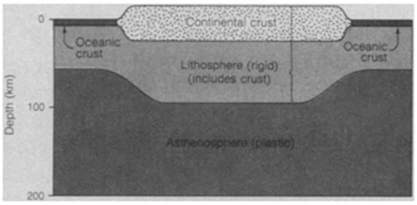


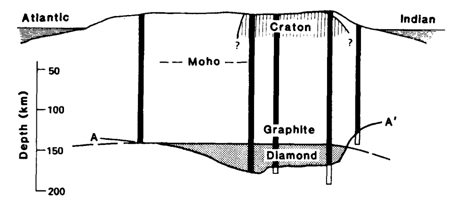
Fig. 1-14, *Earth* 2nd ed., Press/Siever, © 1978 W.H. Freeman

According to conventional plate tectonics, the crust and upper mantle of the earth make up the rigid lithosphere, which rides on a weak, partially molten athenosphere and is never thicker than about 100 kilometers. Some scientists are now finding, however, that the plates — the layer that moves as a single entity — extend much deeper under continents, perhaps to 400 kilometers, including part of the athenosphere.

Since his early work, Jordan says, he and his co-workers have been able to show with more seismic studies that there is no possible model that has continental roots going down to only 220 km while still satisfying the data. "Since we see variations in the seismic signature of the root zone that correlate with the surface pattern of geology — and with surface tectonics that occurred long ago — we infer that the structure at the surface has got an expression at great depth that's essentially frozen in the plate [or tectosphere]," he adds.

Support for continental roots has come from other seismologists as well. Harvard University's John Woodhouse and Adam Dziewonski, using a technique similar to the computerized axial tomography (CAT scans) developed for medicine, have produced maps of the mantle that show high-seismic-velocity zones beneath continents (SN: 4/30/83, p.280). "We can't say whether these roots extend to 250 km or 400 km," says Woodhouse, "but it's clear that continents do have roots, . . . and roots that are deeper than what would have been expected by most people."

Using a different seismic technique, Stephen Grand at the University of Illinois at Champaign-Urbana, Donald Helmberger at Caltech in Pasadena and their colleagues have also discovered high-velocity areas, which they think extend to depths of 400 km, beneath the Canadian shield in North America, the Russian plateau in Eurasia and the northwest African shield. "These three [cratonic] areas are tectonically similar in that they've been very stable for a very long time," says Grand. "All other areas that have had folding episodes, mountains or any kind of tectonic activity are found to [have slower seismic speeds] to 400 km depth than the stable regions."



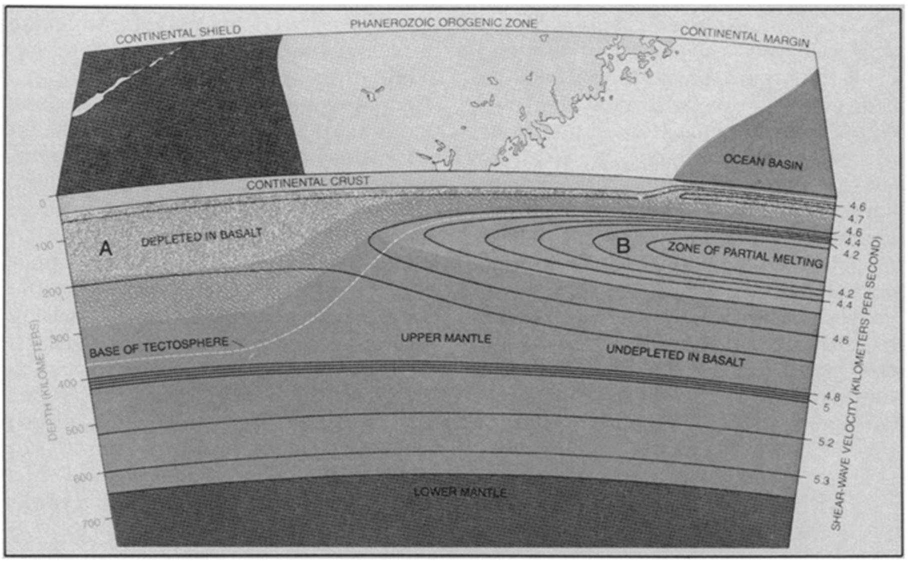
This cross section of the Kaapvaal craton in southern Africa is based on petrologic studies of kimberlite rocks brought up from the crust and mantle by the vertical volcanic pipes shown in the picture. Only kimberlites in the craton contain diamonds, which form at depths of 150 kilometers or greater. The line A-A' marks the transition between the lithosphere and athenosphere.

Boyd and Gurney/SCIENCE

Recently the craton root idea has been given a fresh infusion of support from petrologists, who study the origins and chemistry of rocks. In a paper published in SCIENCE earlier this year, Francis R. Boyd of the Geophysical Laboratory at the Carnegie Institution of Washington (D.C.) and John J. Gurney at the University of Cape Town in Rondebosch, South Africa, summarize the petrologic lines of evidence favoring a root that lies beneath the 3.5-billion-year-old Kaapvaal craton in southern Africa.

Most of the evidence comes from their own and others' studies of mineral grains, mantle rocks and mineral inclusions in diamonds, all of which were brought to the surface millions of years ago by kimberlite eruptions. Kimberlite is a type of rock that is found in long, narrow volcanic pipes. Because these pipes originate in the mantle and because kimberlite eruptions occur very quickly, kimberlites offer scientists some of the deepest rock samples on earth.

One clue to the existence of the craton root is the fact that while kimberlites are found throughout southern Africa, only the ones that had been erupted within the craton boundary bear diamonds. Boyd and Gurney have argued that these diamonds could have crystallized only at depths of 150 km or greater in the mantle because it takes very high pressures for diamonds to form. Mineralogic studies of the Kaapvaal kimberlite samples reveal that the diamonds formed as deep as 200 km. Isotopic analysis by Stephen Richardson at the Institute of Physics of the Globe in Paris and his colleagues has



Jordan/SCIENTIFIC AMERICAN Vol. 240, No. 1, Page 102 © 1979 W.H. Freeman

Many scientists now believe that the plates (or the tectosphere, denoted by the white line extending from left) are much thicker and colder under continents than under oceans. Jordan thinks these continental roots are formed when the upper mantle is depleted of its basaltic components. This depletion lowers the density of the mantle material, so that a chunk of material from B would weigh more than a chunk from A if both were at the same temperature. But since the mantle under the continent is also about 400° C cooler (which increases the density) than the mantle at B, the two chunks have the same density.

also shown that the mineral inclusions in diamonds are about as old as the surface rocks.

"The fact that the diamonds are very ancient means that they must have been locked in the craton all that time," says Boyd. In their SCIENCE article, Boyd and Gurney liken the craton structure to that of an iceberg with a deep diamond-containing root.

Boyd, Gurney and others also have determined that the diamonds crystallized at temperatures of 900° to 1,200° C. This is much cooler than scientists believe rocks at the same depth were billions of years ago, when there were more radioactive elements in the earth's mantle to warm the planet. In fact, some scientists have argued that the hotter and more vigorously convecting mantle would have kept the plates thinner at that time than they are today and would have certainly prevented a root from forming. The petrologic results suggest otherwise, however, showing that a cold root had somehow formed despite the higher temperatures of the mantle.

"This was a great surprise," says Boyd. It suggests "that most of the extra heat that was being generated must have escaped through increased volcanic activity in the ocean basins."

Boyd says there is some evidence for a root under the North American craton as well as under southern Africa. But because diamond deposits in North America and other parts of the world are not nearly as rich as those in the Kaapvaal craton, mining activities in these regions are not extensive. So scientists are unlikely to get much more mineralogic data on the deep structure of other cratons.

According to Jordan, most geoscientists now accept that the continents are thicker than the 100-km or so limit set by traditional thin-plate tectonics. But the question of how much thicker is still controversial. While Jordan and others maintain that there is abundant seismologic evidence for roots extending to 300 or 400 km, Don L. Anderson at Caltech interprets the seismic data much differently.

"Seismic studies show that continents certainly extend down to 150 km, and then there's a drop in the seismic velocity where some of us think the continents are decoupled from the mantle," Anderson says.

Unlike Jordan, Anderson doesn't think of the high-velocity regions below 150 km as roots permanently attached to the cratons. Instead he believes that these fast regions correspond to cold oceanic plate pieces that have been overridden by continents. Unfortunately, the petrologic data don't settle this dispute because the available rock and diamond samples don't originate at depths greater than 200 km. Boyd says the petrologic results would be consistent with either view.

The question of the thickness of continental roots is not the only issue about which Jordan and Anderson disagree. Their different interpretations of seismic data put them on opposite sides of a related controversy about mantle flow patterns and the subduction of plates (SN: 8/16/86, p.106). Jordan believes that oceanic plates plunge into the lower mantle, and that belief supports a model in which material circulates between the upper and lower mantle. Anderson, on the other hand, thinks that the plates never reach the lower mantle and that the circulation of mantle material in the upper mantle is separate from that in the lower mantle.

If Anderson is correct about thin continental roots, then he may also be right about mantle flow, since thin roots are consistent with the idea of separate upper-mantle circulation. But if Jordan is correct about thick roots, then the roots would make it difficult for mantle material to stay confined to the upper mantle.

If one supposes that thick cratonic roots are real, then the most interesting question is how they formed, says Boyd. "The processes [that created roots] must have been different from the process that are operating today," he says.

One piece of the puzzle comes from thinking about the stability of the roots. Jordan reasons that the root probably stays afloat because its increased density, brought on by low temperatures, is balanced by chemical changes that lower the density of the root. A good candidate for a chemical change is the depletion of the mantle's basalts, since basalts are the rocks most commonly erupted by volcanoes and because mantle material does indeed become less dense when the basalts are taken out, according to Jordan.

With this in mind, Jordan has devised one scenario, based to some extent on current-day tectonics theory, for the formation of cratonic roots. Scientists think continents begin to form when oceanic plates are subducted, or plunge into the mantle. These plates carry along sediments and water, which escape once the plates reach a certain depth. The rising water induces the melting of rocks, which eventually results in volcanoes called island arcs. Jordan thinks the rising basalts, which may undergo additional chemical changes, are the beginnings of continental crust, and the mantle they leave behind is the beginning of a continental root.

The next step is that plate motions sweep up the island arcs and the underlying depleted mantle material into larger pieces that get stuck onto continents. Jordan suggests that the still-hot, depleted mantle regions are molded into roots through repeated collisions between continents. Collisions such as that between India and Asia thicken both the crust and mantle, but only the root part remains thick, according to Jordan, because the top layers of the continents are eroded.

Jordan says this scenario is the most speculative part of his thinking about cratonic roots. "I've never gotten into a big debate about how they form," he says, because people have not believed roots exist. But many scientists are beginning to take the idea more seriously — as reflected by a number of papers on deep continental structure presented this week at the meeting of the American Geophysical Union in San Francisco.

Continental roots may not represent another geosciences revolution in the making, but they certainly demonstrate that the conventional plate tectonics theory is not gospel. "People have had a hard time believing that continental drift is anything more than just a passive reaction to plate tectonics," says Jordan. "They think of these continents as being some flotsam and jetsam that sit on top of these plates and don't affect the fundamental plate structure. The [continental root] model attacks that. It says there's something really different about the continents, and even though they may share the same plate . . . they behave much differently. They grow and evolve by different mechanisms. Geologists, who study the surface of continents, are comfortable with that. But the geophysicists have been trying to make things simpler than they are." □