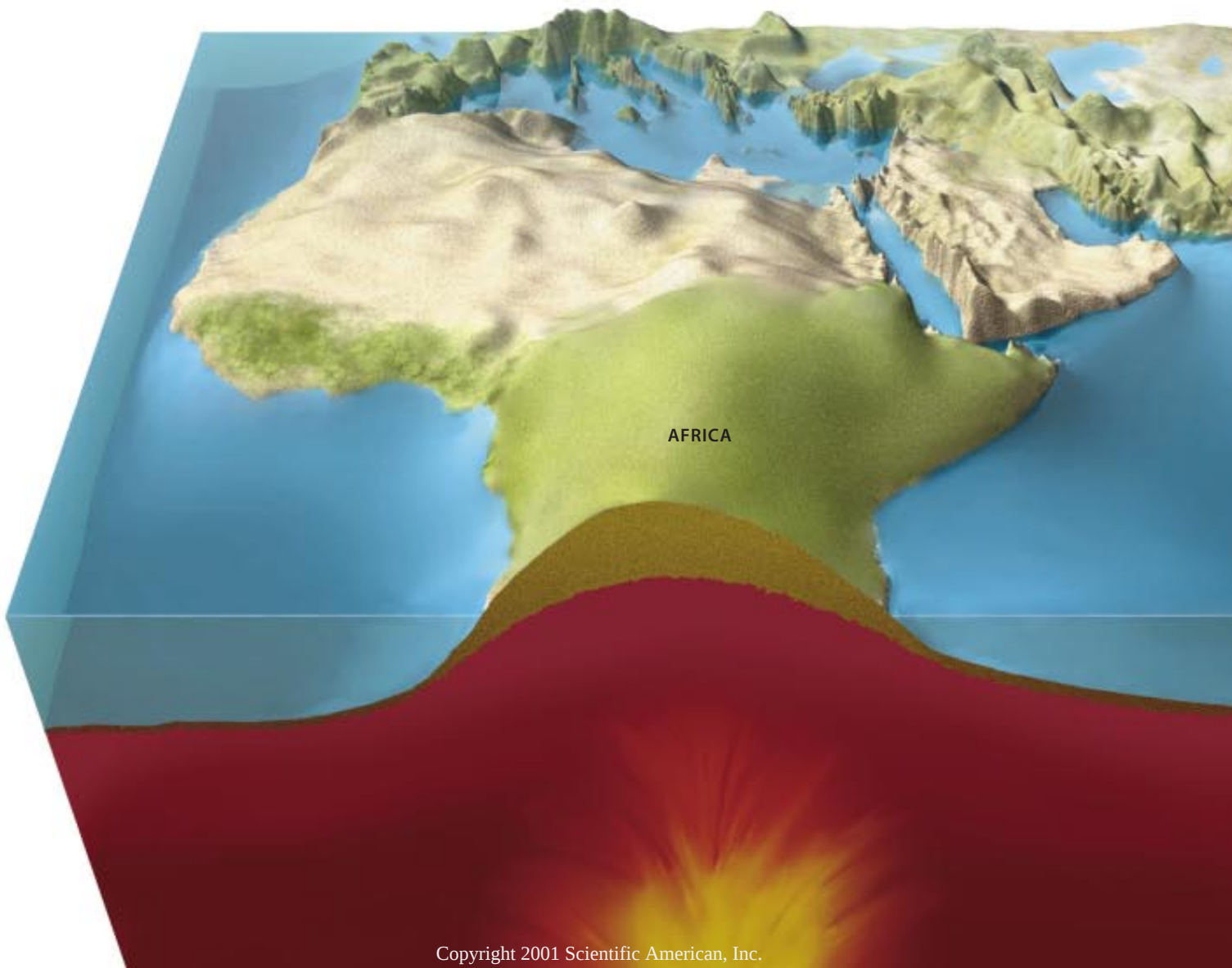


Sculpting the Earth from Inside Out

Powerful motions deep inside the planet do not merely shove fragments of the rocky shell horizontally around the globe—they also lift and lower entire continents

by Michael Gurnis



Credit for sculpting the earth's surface typically goes to violent collisions between tectonic plates, the mobile fragments of the planet's rocky outer shell. The mighty Himalayas shot up when India rammed into Asia, for instance, and the Andes grew as the Pacific Ocean floor plunged beneath South America. But even the awesome power of plate tectonics cannot fully explain some of the planet's most massive surface features.

Take southern Africa. This region boasts one of the world's most expansive plateaus, more than 1,000 miles across and almost a mile high. Geologic evidence shows that southern Africa, and the surrounding ocean floor, has been rising slowly for the past 100 million years, even though it has not experienced a tectonic collision for nearly 400 million years.

The African superswell, as this uplifted landmass is known, is just one example of dramatic vertical

movement by a broad chunk of the earth's surface. In other cases from the distant past, vast stretches of Australia and North America bowed down thousands of feet—and then popped up again.

Scientists who specialize in studying the earth's interior have long suspected that activity deep inside the earth was behind such vertical changes at the surface. These geophysicists began searching for clues in the mantle—the middle layer of the planet. This region of scalding-hot rock lies just below the jigsaw configuration of tectonic plates and extends down more than 1,800 miles to the outer edge of the globe's iron core. Researchers learned that variations in the mantle's intense heat and pressure enable the solid rock to creep molasseslike over thousands of years. But they could not initially decipher how it could give rise to large vertical motions. Now, however, powerful computer models that combine snapshots of the mantle today with clues about how it might have behaved in the



ENIGMATIC DIPS AND SWELLS have occurred over continent-size swaths of the earth's surface several times in the past. Southern Africa has been lifted about 1,000 feet over the past 20 million years, for example, and a sunken continent's highest peaks today form the islands of Indonesia. Scientists are now finding that the causes of these baffling vertical motions lie deep within the planet's interior.

past are beginning to explain why parts of the earth's surface have undergone these astonishing ups and downs.

The mystery of the African superswell was among the easiest to decipher. Since the early half of the 20th century, geophysicists have understood that over the unceasing expanse of geologic time, the mantle not only creeps, it churns and roils like a pot of thick soup about to boil. The relatively low density of the hottest rock makes that material buoyant, so it ascends slowly; in contrast, colder, denser rock sinks until heat escaping the molten core warms it enough to make it rise again. These three-dimensional motions, called convection, are known to enable the horizontal movement of tectonic plates, but it seemed unlikely that the forces they created could lift and lower the planet's surface. That skepticism about the might of the mantle began to fade away when researchers created the first blurry images of the earth's interior.

About 20 years ago scientists came up with a way to make three-dimensional snapshots of the mantle by measuring vibrations that are set in motion by earthquakes originating in the planet's outer shell. The velocities of these vibrations, or seismic waves, are determined by the chemical composition, temperature and pressure of the rocks they travel through. Waves become sluggish in hot, low-density rock, and they speed up in colder, denser regions. By recording the time it takes for seismic waves to travel from an earthquake's epicenter to a particular recording station at the surface, scientists can infer the temperatures and densities in a given segment of the interior. And by compiling a map of seismic velocities from thousands of earthquakes around the globe they can begin to map temperatures and densities throughout the mantle.

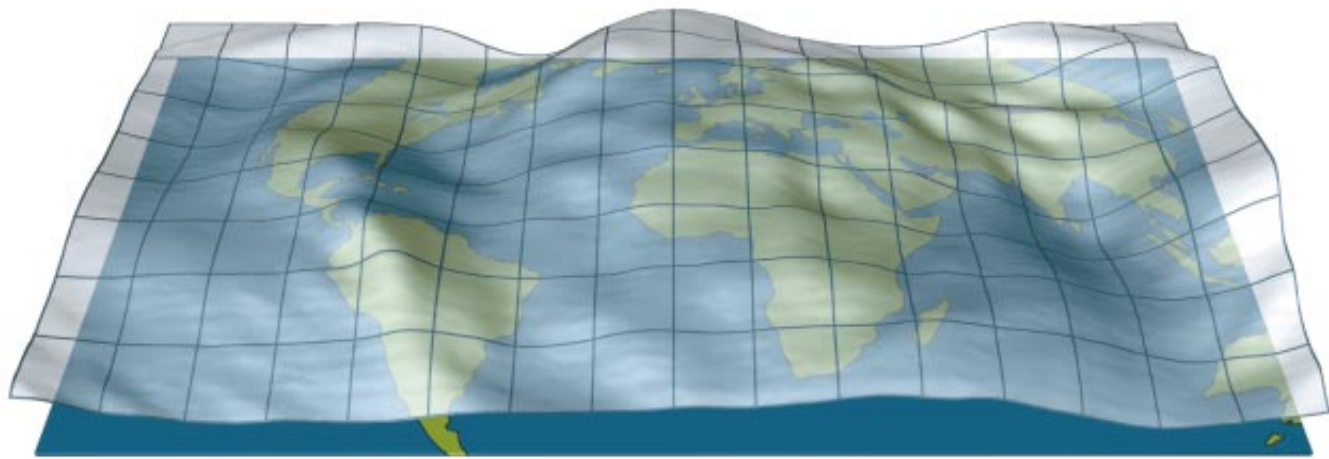
These seismic snapshots, which become increasingly more detailed as researchers find more accurate ways to compile their measurements, have recently revealed some unexpectedly immense formations in the deepest parts of the mantle. The largest single structure turns out to lie directly below Africa's southern tip. About two years ago seismologists Jeroen Ritsema and Hendrik-Jan van Heijst of the California Institute of Technology calculated that this mushroom-shaped mass stretches some 900 miles upward from the core and spreads across several thousand miles [see illustration on opposite page].

The researchers immediately began to wonder whether this enormous blob could be shoving Africa skyward. Because the blob is a region where seismic waves are sluggish, they assumed that it was hotter than the surrounding mantle. The basic physics of convection suggested that a hot blob was likely to be rising. But a seismic snapshot records only a single moment in time and thus only one position of a structure. If the blob were of a different composition than the surrounding rock, for instance, it could be hotter and still not rise. So another geophysicist, Jerry X. Mitrovica of the University of Toronto, and I decided to create a time-lapse picture of what might be happening. We plugged the blob's shape and estimated density, along with estimates of when southern Africa began rising, into a computer program that simulates mantle convection. By doing so, we found last year that the blob is indeed buoyant enough to rise slowly within the mantle—and strong enough to push Africa upward as it goes.

Seismic snapshots and computer models—the basic tools of geophysicists—were enough to solve the puzzle of the African superswell, but resolving the up-and-down movements of North America and Australia was more complicated and so was accomplished in a more circuitous way. Geophysicists who think only about what the mantle looks like today cannot fully explain how it sculpts the earth's surface. They must therefore borrow from the historical perspective of traditional geologists who think about the way the surface has changed over time.

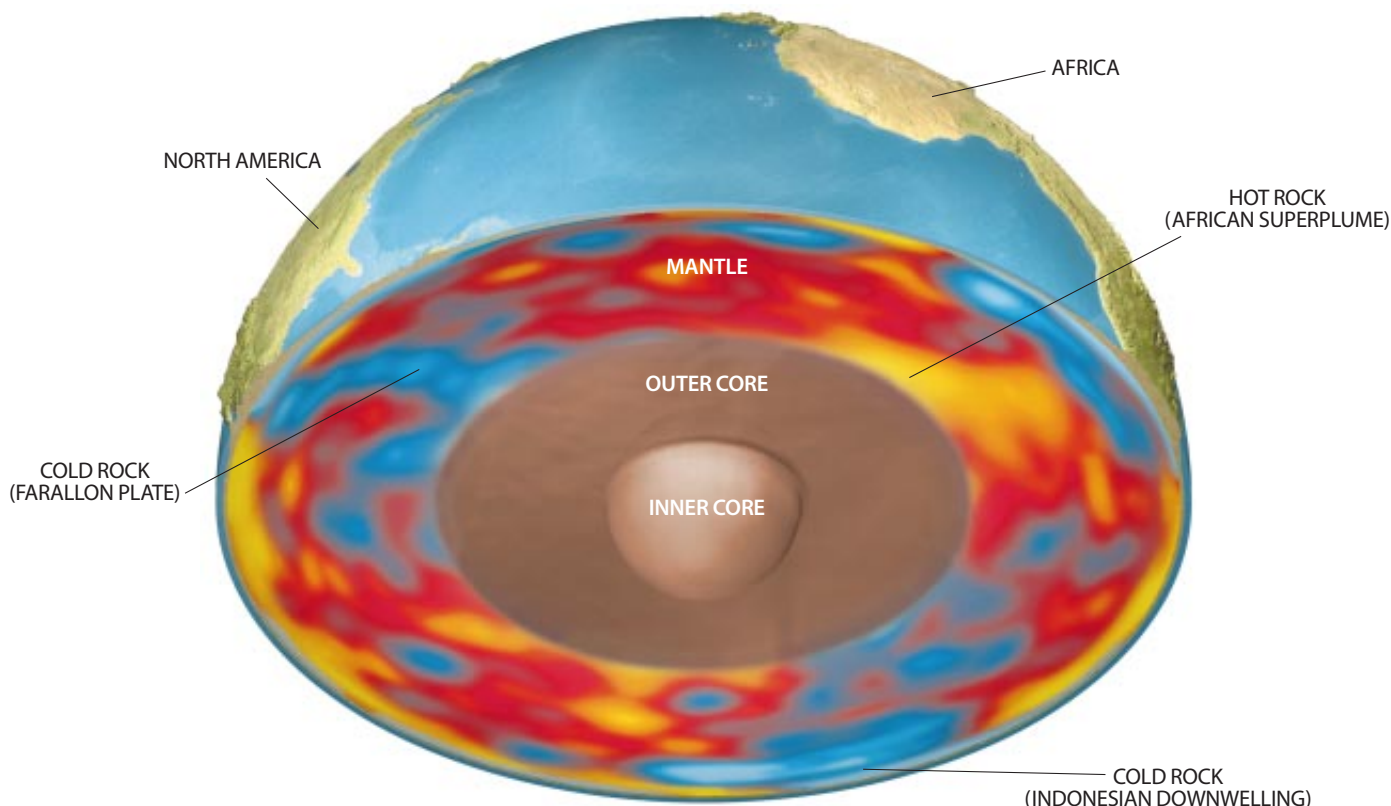
Ghosts from the Past

The insights that would help account for the bobbings of Australia and North America began to emerge with investigations of a seemingly unrelated topic: the influence of mantle density on the earth's gravitational field. The basic principles of physics led scientists in the 1960s to expect that gravity would be lowest above pockets of hot rock, which are less dense and thus have less mass. But when geophysicists first mapped the earth's gravitational variations, they found no evidence that gravity correlated with the cold and hot parts of the mantle—at least not in the expected fashion.



BULGES AND TROUGHS in the transparent surface above the world map represent natural variations in the earth's gravitational field. High points indicate stronger-than-normal gravity caused by a pocket of excess mass with-

in the planet's interior; low areas occur above regions where a deficiency of mass produces a band of low gravity. Such differences in gravity hint at the location of oddities in the structure of the earth's mantle.



MANTLE MAP integrates measurements of thousands of earthquake vibrations, or seismic waves, that have traveled through the planet. Regions where waves moved quickly (*blue*) usually denote cold, dense rock. Regions where waves slowed down (*yellow*) de-

note hot, less compact rock. Under southern Africa and the South Atlantic lies a pocket of sluggish velocities—a buoyant blob of hot rock called the African superplume. The map also reveals cold, sinking material that is tugging on North America and Indonesia.

Indeed, in the late 1970s and early 1980s Clement G. Chase uncovered the opposite pattern. When Chase, now at the University of Arizona, considered geographic scales of more than 1,000 miles, he found that the pull of gravity is strongest not over cold mantle but over isolated volcanic regions called hot spots. Perhaps even more surprising was what Chase noticed about the position of a long band of low gravity that passes from Hudson Bay in Canada northward over the North Pole, across Siberia and India, and down into Antarctica. Relying on estimates of the ancient configuration of tectonic plates, he showed that this band of low gravity marked the location of a series of subduction zones—that is, the zones where tectonic plates carrying fragments of the seafloor plunge back into the mantle—from 125 million years ago. The ghosts of ancient subduction zones seemed to be diminishing the pull of gravity. But if cold, dense chunks of seafloor were still sinking through the mantle, it seemed that gravity would be high above these spots, not low, as Chase observed.

In the mid-1980s geophysicist Bradford H. Hager, now at the Massachusetts Institute of Technology, resolved this apparent paradox by proposing that factors other than temperature might create pockets of extra or deficient mass within the mantle. Hager developed his theory from the physics that describe moving fluids, whose behavior the mantle imitates over the long term. When a low-density fluid rises upward, as do the hottest parts of the mantle, the force of the flow pushes up the higher-density fluid above it. This gentle rise atop the upwelling itself creates an excess of mass (and hence stronger gravity) near the planet's surface. By the same token, gravity can be lower over cold, dense material: as this heavy matter

sinks, it drags down mass that was once near the surface. This conception explained why the ghosts of subduction zones could generate a band of low gravity: some of that cold, subducted seafloor must still be sinking within the mantle—and towing the planet's surface downward in the process. If Hager's explanation was correct, it meant that the mantle did not merely creep horizontally near the planet's surface; whole segments of its up-and-down movements also reached the surface. Areas that surged upward would push the land above it skyward, and areas that sank would drag down the overlying continents as they descended.

Bobbing Continents

At the same time that Chase and Hager were discovering a mechanism that could dramatically lift and lower the earth's surface, geologists were beginning to see evidence that continents might actually have experienced such dips and swells in the past. Geologic formations worldwide contain evidence that sea level fluctuates over time. Many geologists suspected that this fluctuation would affect all continents in the same way, but a few of them advanced convincing evidence that the most momentous changes in sea level stemmed from vertical motions of continents. As one continent moved, say, upward relative to other landmasses, the ocean surface around that continent would become lower while sea level around other landmasses would stay the same.

Most geologists, though, doubted the controversial notion that continents could move vertically—even when the first indications of the bizarre bobbing of Australia turned up

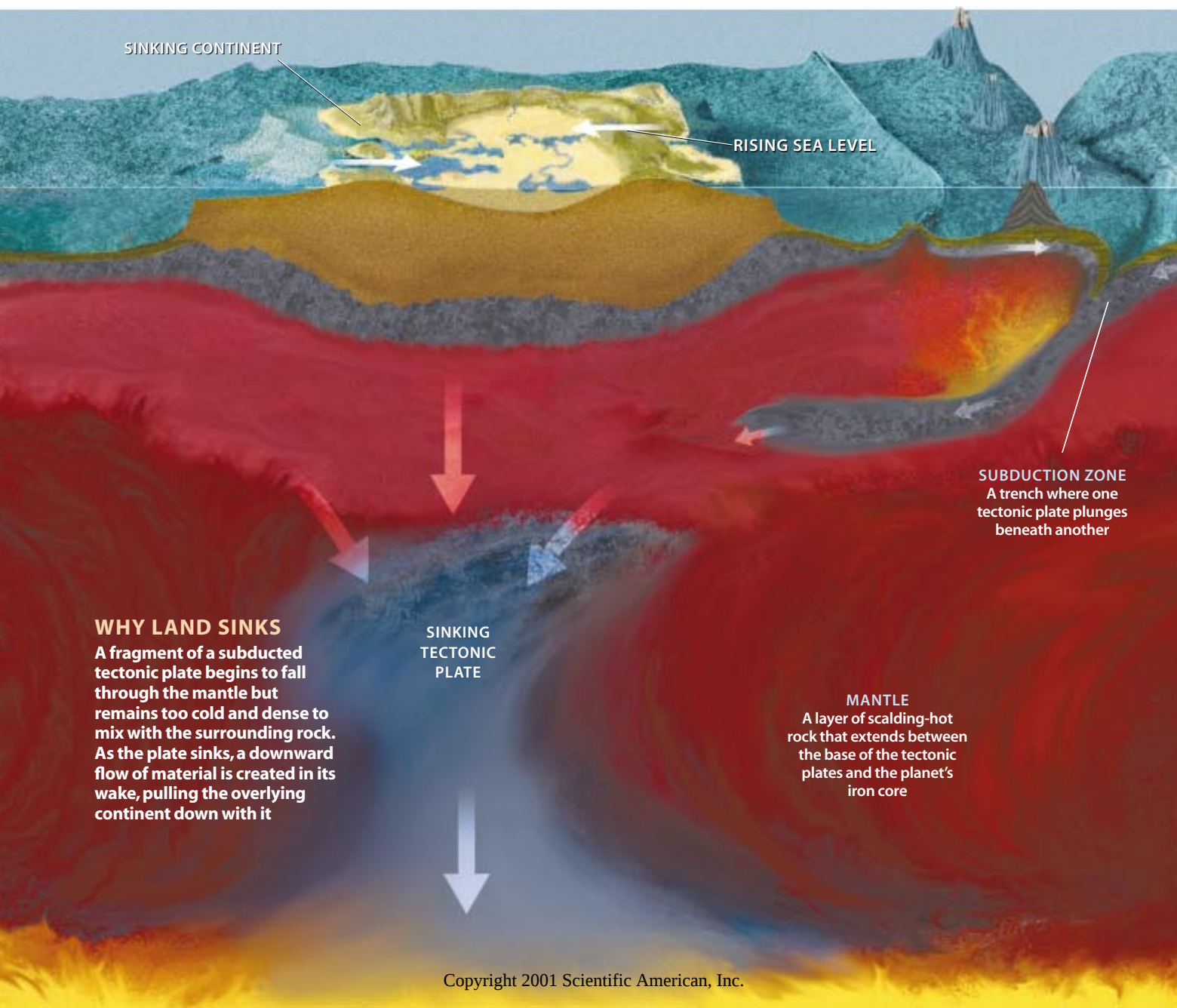
in the early 1970s. Geologist John J. Veevers of Macquarie University in Sydney examined outcrops of ancient rock in eastern Australia and discovered that sometime in the early Cretaceous period (about 130 million years ago), a shallow sea rapidly covered that half of Australia while other continents flooded at a much more leisurely pace. Sea level climaxed around those landmasses by the late Cretaceous (about 70 million years ago), but by then the oceans were already retreating from Australia's shores. The eastern half of the continent must have sunk several thousand feet relative to other landmasses and then popped back up before global sea level began to fall.

Veevers's view of a bobbing continent turned out to be only part of Australia's enigmatic story. In 1978 geologist Gerard C. Bond, now at Columbia University's Lamont-Doherty Earth Observatory, discovered an even stranger turn of

events while he was searching global history for examples of vertical continental motion. After Australia's dip and rise during the Cretaceous, it sank again, this time by 600 feet, between then and the present day. No reasonable interpretation based on plate tectonics alone could explain the widespread vertical motions that Bond and Veevers uncovered. Finding a satisfactory explanation would require scientists to link this information with another important clue: Hager's theory about how the mantle can change the shape of the planet's surface.

The first significant step in bringing these clues together was the close examination of another up-and-down example from Bond's global survey. In the late 1980s this work inspired Christopher Beaumont, a geologist at Dalhousie University in Nova Scotia, to tackle a baffling observation about Denver, Colo. Although the city's elevation is more than a

HOW THE MANTLE SHAPES THE EARTH'S SURFACE

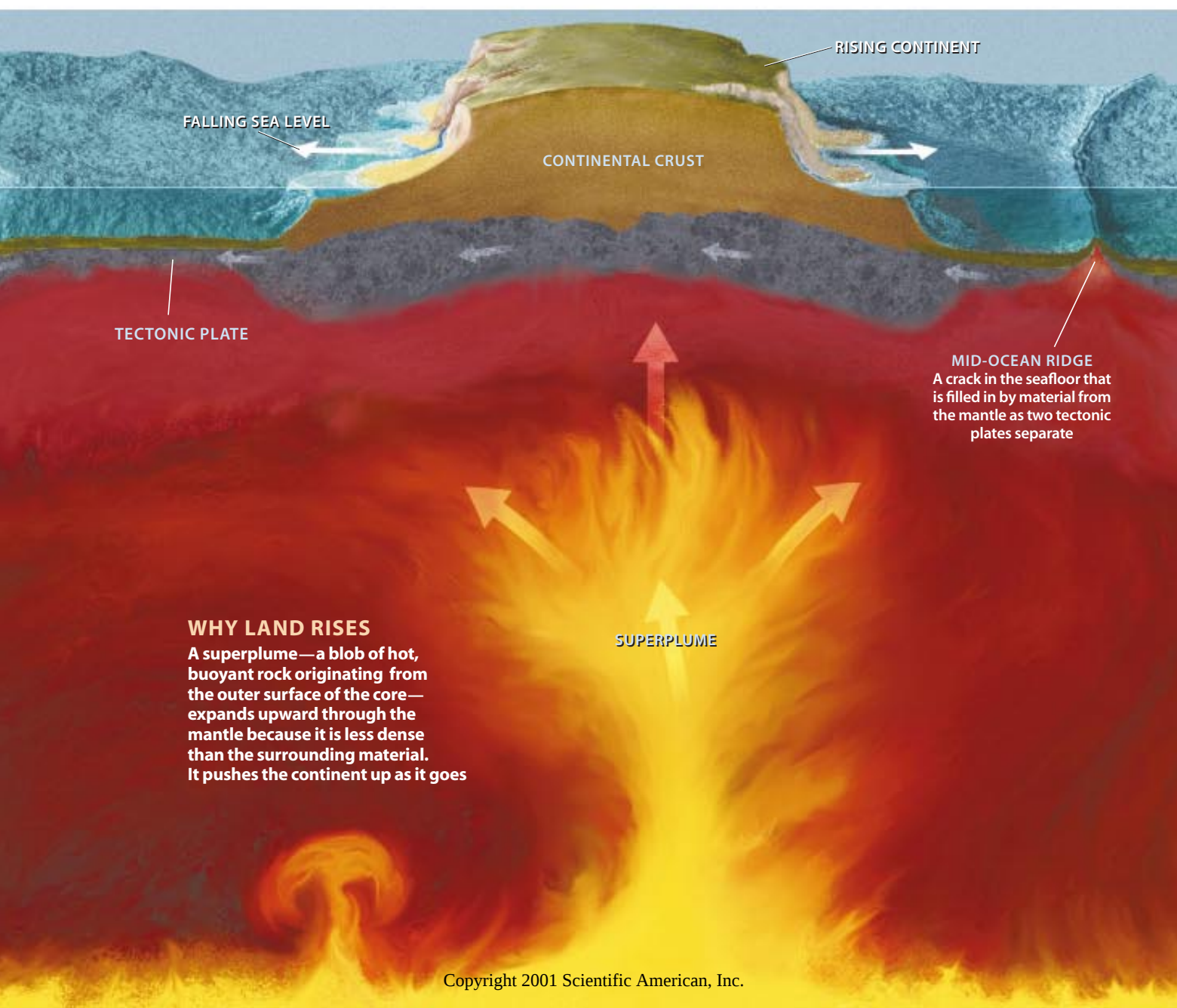


mile above sea level, it sits atop flat, undeformed marine rocks created from sediments deposited on the floor of a shallow sea during the Cretaceous period. Vast seas covered much of the continents during that time, but sea level was no more than about 400 feet higher than it is today. This means that the ocean could never have reached as far inland as Denver's current position—unless this land was first pulled down several thousand feet to allow waters to flood inland.

Based on the position of North America's coastlines during the Cretaceous, Beaumont estimated that this bowing downward and subsequent uplift to today's elevation must have affected an area more than 600 miles across. This geographic scale was problematic for the prevailing view that plate tectonics alone molded the surface. The mechanism of plate tectonics permits vertical motions within only 100 miles or so of plate edges, which are thin enough to bend like a stiff

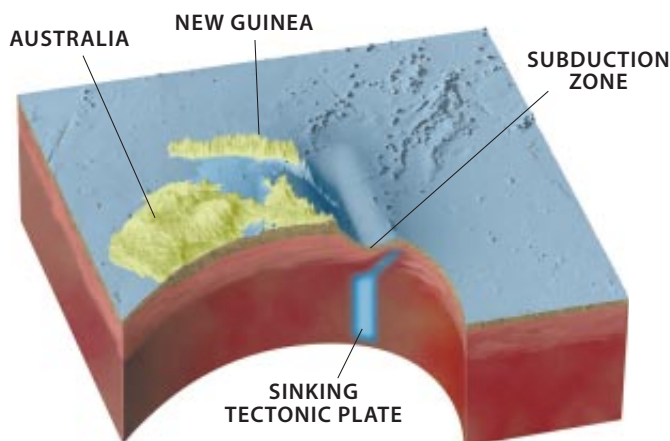
fishing pole, when forces act on them. But the motion of North America's interior happened several hundred miles inland—far from the influence of plate collisions. An entirely different mechanism had to be at fault.

Beaumont knew that subducted slabs of ancient seafloor might sit in the mantle below North America and that such slabs could theoretically drag down the center of a continent. To determine whether downward flow of the mantle could have caused the dip near Denver, Beaumont teamed up with Jerry Mitrovica, then a graduate student at the University of Toronto, and Gary T. Jarvis of York University in Toronto. They found that the sinking of North America during the Cretaceous could have been caused by a plate called the Farallon as it plunged into the mantle beneath the western coast of North America. Basing their conclusion on a computer model, the research team argued that the ancient plate thrust into



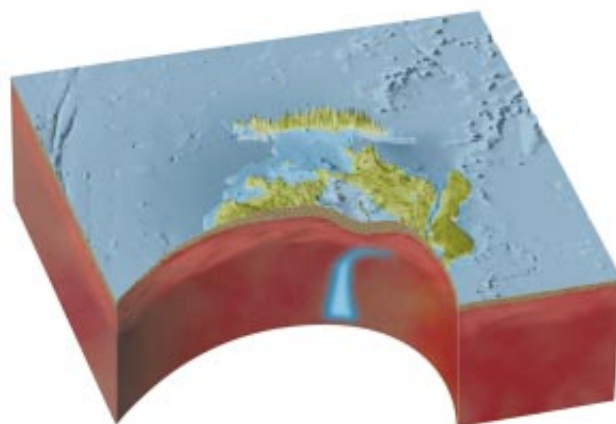
AUSTRALIA'S UPS AND DOWNS

A computer model reveals how the ghost of an ancient subduction zone dragged down a continent



130 Million Years Ago

Australia is bordered by a subduction zone, a deep trench where the tectonic plate to the east plunges into the mantle. The sinking plate (blue) pulls the surrounding mantle and the eastern edge of Australia down with it. Later, subduction ceases and the continent begins to drift eastward.



90 Million Years Ago

The entire eastern half of Australia sinks about 1,000 feet below sea level as the continent passes eastward over the sinking tectonic plate. About 20 million years later the plate's downward pull diminishes as it descends into the deeper mantle. As a result, the continent then pops up again.

the mantle nearly horizontally. As it began sinking, it created a downward flow in its wake that tugged North America low enough to allow the ocean to rush in. As the Farallon plate sank deeper, the power of its trailing wake decreased. The continent's tendency to float eventually won out, and North America resurfaced.

When the Canadian researchers advanced their theory in 1989, the Farallon plate had long since vanished into the mantle, so its existence had only been inferred from geologic indications on the bottom of the Pacific Ocean. At that time, no seismic images were of high enough resolution to delineate a structure as small as a sinking fragment of the seafloor. Then, in 1996, new images of the mantle changed everything. Stephen P. Grand of the University of Texas at Austin and Robert D. van der Hilst of M.I.T., seismologists from separate research groups, presented two images based on entirely different sets of seismic measurements. Both pictures showed virtually identical structures, especially the cold-mantle downwellings associated with sinking slabs of seafloor. The long-lost Farallon plate was prominent in the images as an arching slab 1,000 miles below the eastern coast of the U.S.

Moving Down Under

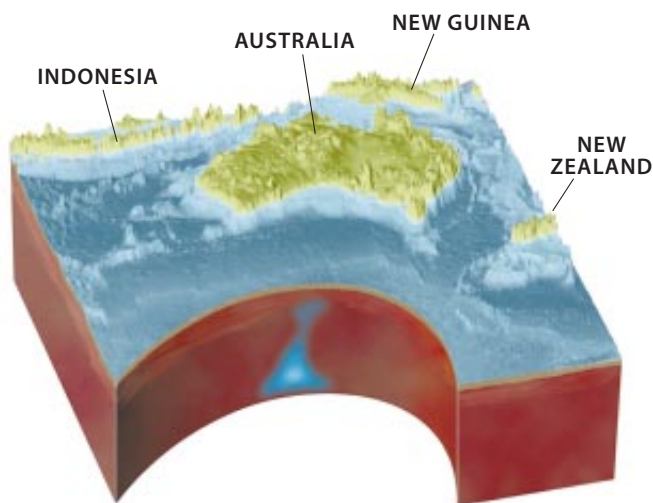
Connecting the bobbing motion of North America to the subduction of the seafloor forged a convincing link between ancient sea-level change and goings-on in the mantle. It also became clear that the ancient Farallon slab sits within the band of low gravity that Chase had observed two decades earlier. I suspected that these ideas could also be applied to the most enigmatic of the continental bobbings, that of Australia during and since the Cretaceous. I had been simulating mantle convection with computer models for 15 years, and many of my results showed that the mantle was in fact able to lift the surface by thousands of feet—a difference easily great enough

to cause an apparent drop in sea level. Like Chase, Veevers and other researchers before me, I looked at the known history of plate tectonics for clues about whether something in the mantle could have accounted for Australia's bouncing. During the Cretaceous period, Australia, South America, Africa, India, Antarctica and New Zealand were assembled into a vast supercontinent called Gondwana, which had existed for more than 400 million years before it fragmented into today's familiar landmasses. Surrounding Gondwana for most of this time was a huge subduction zone where cold oceanic plates plunged into the mantle.

I thought that somehow the subduction zone that surrounded Gondwana for hundreds of millions of years might have caused Australia's ups and downs. I became more convinced when I sketched the old subduction zones on maps of ancient plate configurations constructed by R. Dietmar Müller, a seagoing geophysicist at Sydney University. The sketches seemed to explain the Australian oddities. Australia would have passed directly over Gondwana's old subduction zone at the time it sank.

To understand how the cold slab would behave in the mantle as Gondwana broke apart over millions of years, Müller and I joined Louis Moresi of the Commonwealth Scientific and Industrial Research Organization in Perth to run a computer simulation depicting the mantle's influence on Australia over time. We knew the original position of the ancient subduction zone, the history of horizontal plate motions in the region and the estimated properties—such as viscosity—of the mantle below. Operating under these constraints, the computer played out a scenario for Australia that fit our hypotheses nearly perfectly [*see box above*].

The computer model started 130 million years ago with ocean floor thrusting beneath eastern Australia. As Australia broke away from Gondwana, it passed over the cold, sinking slab, which sucked the Australian plate downward. The con-



Today

Australia lies north of its former site, having been pushed there by activity in adjacent tectonic plates beginning about 45 million years ago. The entire continent has dropped relative to its greatest elevation as the result of a downward tug in the mantle under Indonesia—a landmass that is also sinking.

continent rose up again as it continued its eastward migration away from the slab.

Our model resolved the enigma of Australia's motion during the Cretaceous, originally observed by Veevers, but we were still puzzled by the later continentwide sinking of Australia that Bond discovered. With the help of another geophysicist, Carolina Lithgow-Bertelloni, now at the University of Michigan, we confirmed Bond's observation that as Australia moved northward toward Indonesia after the Cretaceous, it subsided by about 600 feet. Lithgow-Bertelloni's global model of the mantle, which incorporated the history of subduction, suggested that Indonesia is sucked down more than any other region in the world because it lies at the intersection of enormous, present-day subduction systems in the Pacific and Indian oceans. And as Indonesia sinks, it pulls Australia down with it. Today Indonesia is a vast submerged continent—only its highest mountain peaks protrude above sea level.

Which brings us back to Africa. In a sense, Indonesia and

Africa are opposites: Indonesia is being pulled down while Africa is being pushed up. These and other changes in the mantle that have unfolded over the past few hundred million years are intimately related to Gondwana. The huge band of low gravity that Chase discovered 30 years ago is created by the still-sinking plates of a giant subduction zone that once encircled the vast southern landmass. At the center of Gondwana was southern Africa, which means that the mantle below this region was isolated from the chilling effects of sinking tectonic plates at that time—and for the millions of years since. This long-term lack of cold, downward motion below southern Africa explains why a hot superplume is now erupting in the deep mantle there.

With all these discoveries, a vivid, dynamic picture of the motions of the mantle has come into focus. Researchers are beginning to see that these motions sculpt the surface in more ways than one. They help to drive the horizontal movement of tectonic plates, but they also lift and lower the continents. Perhaps the most intriguing discovery is that motion in the deep mantle lags behind the horizontal movement of tectonic plates. Positions of ancient plate boundaries can still have an effect on the way the surface is shaped many millions of years later.

Our ability to view the dynamics of mantle convection and plate tectonics will rapidly expand as new ways of observing the mantle and techniques for simulating its motion are introduced. When mantle convection changes, the gravitational field changes. Tracking variations in the earth's gravitational field is part of a joint U.S. and German space mission called GRACE, which is set for launch in June. Two spacecraft, one chasing the other in earth orbit, will map variations in gravity every two weeks and perhaps make it possible to infer the slow, vertical flow associated with convection in the mantle. Higher-resolution seismic images will also play a pivotal role in revealing what the mantle looks like today. Over the five- to 10-year duration of a project called USArray, 400 roving seismometers will provide a 50-mile-resolution view into the upper 800 miles of the mantle below the U.S.

Plans to make unprecedented images and measurements of the mantle in the coming decade, together with the use of ever more powerful supercomputers, foretell an exceptionally bright future for deciphering the dynamics of the earth's interior. Already, by considering the largest region of the planet—the mantle—as a chunk of rock with a geologic history, earth scientists have made extraordinary leaps in understanding the ultimate causes of geologic changes at the surface. SA

The Author

MICHAEL GURNIS is a geophysicist who is interested in the dynamics of plate tectonics and the earth's interior. These physical processes, which govern the history of the planet, have intrigued him since he began studying geology as an undergraduate 20 years ago. With his research group at the California Institute of Technology, Gurnis now develops computer programs that simulate the evolving motions of the mantle and reveal how those motions have shaped the planet over time. Gurnis's research highlights over the past three years have been deciphering the mysteries of the present-day African superswell and the bobbings of Australia during the Cretaceous period.

Further Information

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