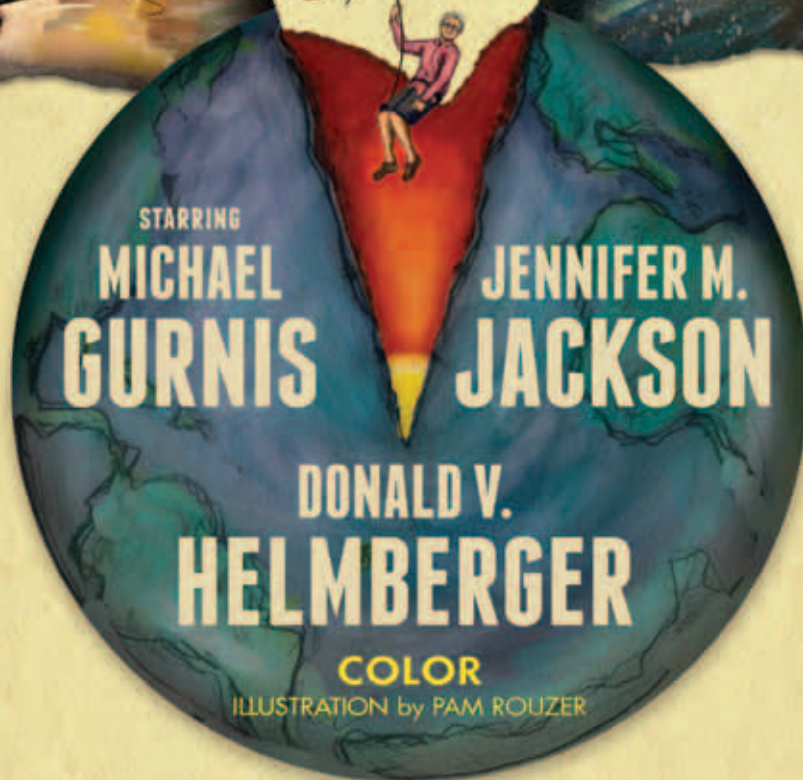


IT'S AN ASTONISHING WORLD UNDER THE WORLD!

EGS MAGAZINE
PRESENTS

CALTECH'S
JOURNEY
TO THE
CENTER
OF THE
EARTH



STORY BY
KATIE NEITH

In Jules Verne's 1864 sci-fi tale, *A Journey to the Center of the Earth*, a group of explorers access the deepest parts of our planet through a volcano to discover a world of giant mushrooms, huge geysers, and violent prehistoric creatures, among other oddities. The theory that people could travel miles below the earth has since been refuted, along with many of the other ideas that Verne posed in his book. And yet, we still don't know the exact composition and structure of the earth's interior. Which is why, like Verne's trio of adventurers, three researchers in the Seismological Laboratory in Caltech's Division of Geological and Planetary Sciences are combining their talents to build a better picture of what lies deep beneath the earth's surface.

Our planet can be roughly divided into five parts: the crust, the upper mantle, the lower mantle, the outer core, and the inner core. If it was humanly possible to take a trip to the core, one would first have to get through the lithosphere—which consists of the rigid, rocky crust and the uppermost part of the mantle, which is broken into tectonic plates. Under the lithosphere lies a weaker and hotter part of the upper mantle, which likely resembles an ocean of rocks in some places, particularly where it bubbles up to feed volcanoes. Next, our intrepid travelers would find the lower mantle, a layer of highly viscous rock—mostly solid, but with the ability to flow over long periods of time—that extends

down to a depth of nearly 2,900 kilometers. There they would hit the outer core, a layer of molten nickel-iron alloy over 2,200 kilometers thick. The final stop, the inner core, is thought to be a solid ball of similar material, with a temperature comparable to that of our sun's surface, at approximately 5,500 degrees Celsius.

These layers are in constant motion. The earth's magnetic field originates in the outer core and is generated by convection, as the liquid metal roils like soup in a pot on a hot stove. Similarly, convection in the mantle carries heat from the interior to the surface, with the tectonic plates forming the upper part of the convection cells. "The earth is an incredible, dynamic system," says geophysicist Mike Gurnis, whose specialty is computational geodynamics. "But we cannot go deep inside the planet directly with a thermometer; nor can we sample the composition of the rocks directly. So we're working to take all the data we have—from a variety of sources—and integrate them into a comprehensive model. Some of this data is taken from the earth's surface, including informa-

tion about evolution deciphered from rocks, while remote-sensing data tells us about the physical state of the deep interior."

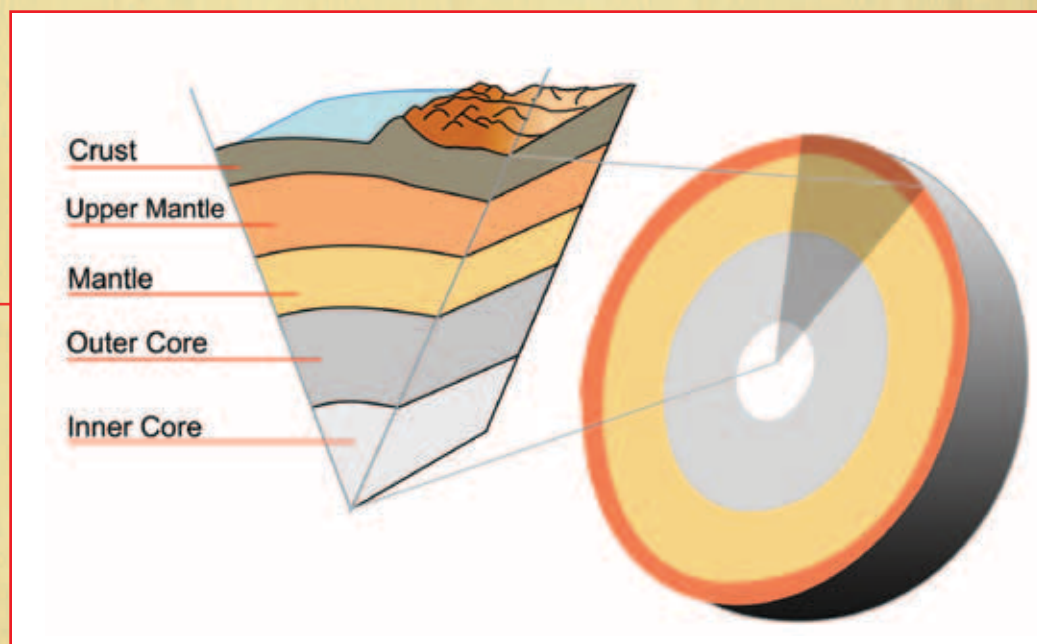
By *we*, he means himself, seismologist Don Helmberger, and mineral physicist Jennifer Jackson.

"We use different methods and different data, but we're trying to exploit their complementary nature," says Gurnis. "Between Don, Jennifer, and myself, we have a triangle of different methodologies, but seismology is the most direct way we're making observations."

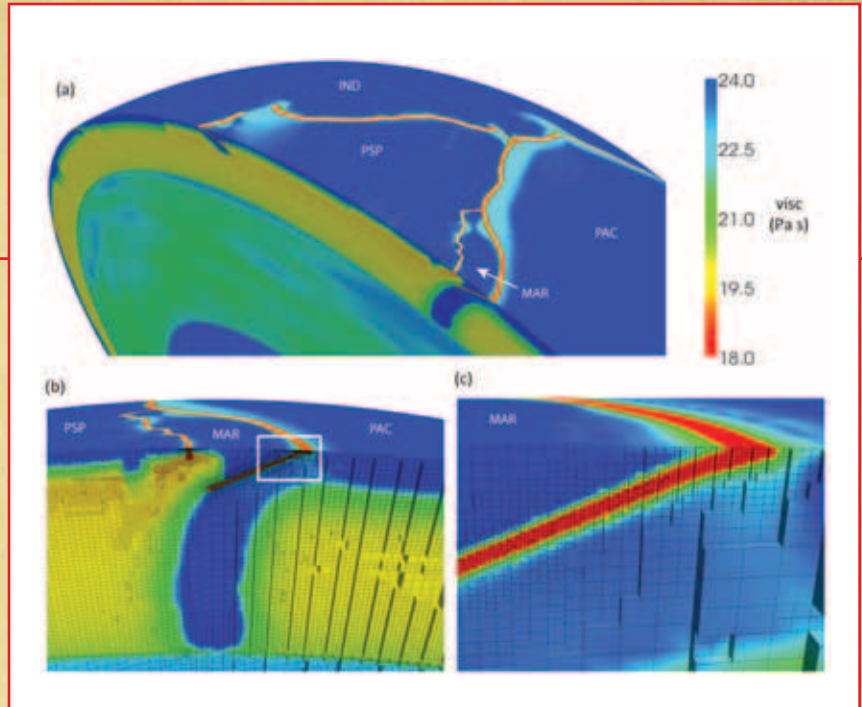
Seismology is a good place to start, partly because it's been around a bit longer than the other disciplines, says Helmberger, who has been a faculty member at Caltech since 1970, and who devised the first synthetic seismogram three years before his arrival, during his grad studies at UC San Diego.

Synthetic seismograms are models that use wave-propagation data to help model the earth's structure and movement. Helmberger first used the method to investigate the crust-mantle transition in the Bering Sea for his

This diagram shows the five basic layers of the earth, from the outer crust—on which we live—to the innermost layer of the core. The distance from our planet's surface to the middle of its inner core has been determined to be approximately 6,300 kilometers at the equator.



(a) A multiscale global model from Mike Gurnis's lab shows an area of the western Pacific. By "zooming in" on the subducted slab south of Japan in the Marianas Islands (b), the model shows the dynamic weakening of the Pacific Plate. A further zoom in on the fault between the two plates (c) shows the system of grids used to apply computer algorithms in order to learn more about individual fault zones.



PhD thesis in 1967. When he started working in seismology, researchers in the field were using small explosions to measure seismic waves. The advantage of this, of course, was that they could control when and where the explosives went off. A network of sensors called geophones would monitor the resulting seismic waves, which could then be analyzed mathematically to build up a picture of how the shock waves traveled through the layers below.

"The trouble is that explosions are expensive and disruptive, and you can't put them in many places," Helmberger notes. "So we started treating earthquakes as explosions, in the sense that you could determine all their properties."

It's been 40 years since he made his first model of an earthquake, a research move inspired by the 6.6 Sylmar quake that shook Southern California in February 1971. Since then, seismological modeling has become an integral part of geophysics research well beyond temblor studies. Helmberger in particular has used seismic modeling to map the core-mantle boundary and define some characteristics of superplumes, giant upwellings of the mantle that rise all the way up to the lithosphere to feed volcanoes. Since 1997, he and Gurnis have combined their different methods of modeling in the hopes of creating a clearer picture of the earth's interior.

Gurnis, for his part, uses computational geodynamics to interpret seismological observations made on local, regional, and global scales. In fact, he was part of a breakthrough study published in 2010 that modeled, simultaneously, the earth's mantle flow, large-scale tectonic motions, and the behavior of individual fault zones using computer algorithms.

"This was the first time that

researchers were able to get the physics of the plate motions into the models correctly," says Gurnis of the research, done in collaboration with scientists at the University of Texas at Austin and published in the journal *Science*. "We were able to resolve the structure around the giant faults while zooming in to areas where the forces driving and resisting plate motions are balanced. This allows us to predict the large-scale motions of the planet, as well as some of the details."

He says his research has a dual focus of trying to understand the physics of the interior by including the history of the earth in the discussion, while at the same time attempting to provide a deeper physical understanding of why the earth's surface evolved the way it did.

"When you look at structures inside the planet, there is a clear pattern that's related to present-day plate tectonics on the surface and the evolution of plate tectonics," explains Gurnis. "So we create models of the earth that are intimately connected to the geological evolution of the surface. I'm filling in this gap between Don and Jennifer and creating structural models based upon the history of the earth itself."

The seismic waves passing through Gurnis's models change course or velocity as they pass through regions of different temperatures, densities, and chemical compositions. Figuring out how those properties change the speed of seismic waves is mineral physicist Jennifer Jackson's province.

"We focus on trying to understand what minerals are found deep inside the earth," says Jackson, who joined Caltech in 2007. "Those minerals—or iron alloys if we're talking about the earth's core—dictate how the whole earth behaves."

Her research group looks at how earth materials behave under the extreme temperatures and pressures of the earth's interior by recreating those conditions in a diamond anvil cell. These compact devices—some are small enough to carry in your pocket—squeeze sand-grain-sized samples between two diamonds to create pressures up to 3.6 million times what we feel at the surface. That's a lot of work for a tiny, precious gem.

The group prepares its cells at Caltech and takes them to an X-ray source at the Argonne National Laboratory in Chicago—one of only three X-ray facilities in the world powerful enough to do this kind of study. While the

diamonds squeeze the sample and a laser heats it up, the X-rays interact with lattice vibrations in the materials—essentially creating ripples of distortion in the crystal structure that pass through the sample.

“By measuring these vibrational properties, we can understand what these minerals and iron alloys look like to seismic waves that pass through them,” says Jackson. “And by recreating the conditions we expect them to be at, we arrive at a closer understanding of what’s really down there.”

Similar measurements have been done at surface conditions, but Jackson notes that once you compress a material, it’s very difficult to predict its behavior. The only way to really know how a mineral will behave inside our planet is to measure it under deep-earth conditions.

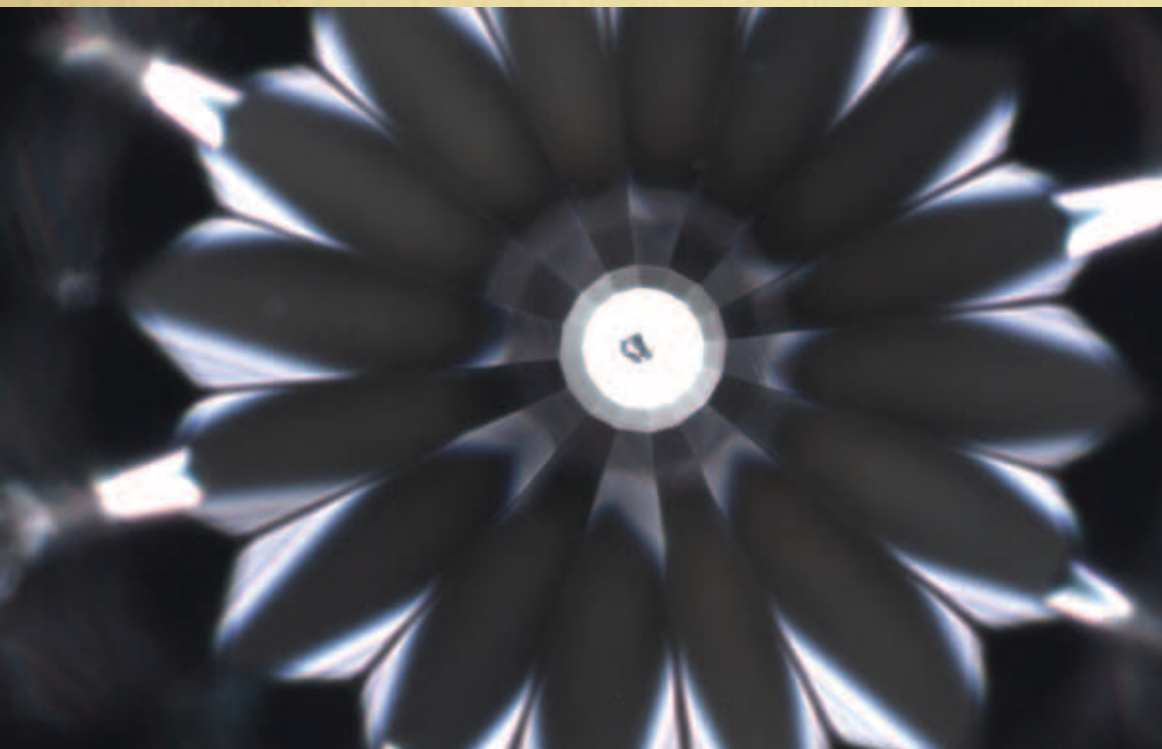
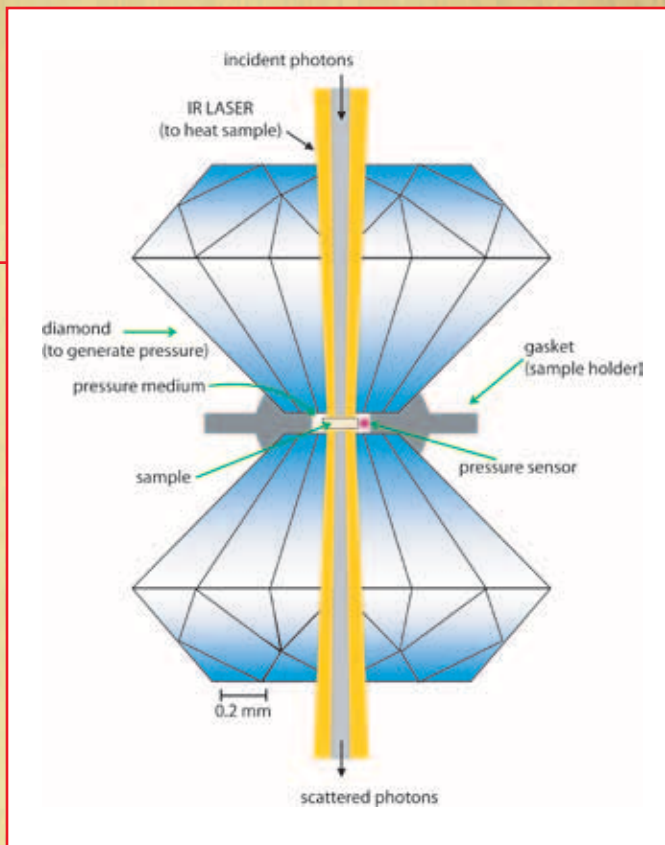
“When we do high-pressure,

high-temperature experiments, we discover properties we would not have imagined,” says Jackson. “It’s not as if we are finding unphysical behaviors—like defying the law of gravity or anything—but our experiments allow us to open our minds up to different models of the earth’s interior. By different models, I mean what types of landscapes are possible down there, which can indicate how the earth’s interior has evolved.”

Recently, she, Gurnis, and HelMBERGER have been focusing on the core-mantle boundary, home to ultralow velocity zones, or ULVZs. Discovered by HelMBERGER’s group in the mid-’90s, ULVZs are areas where seismic waves travel very, very slowly.

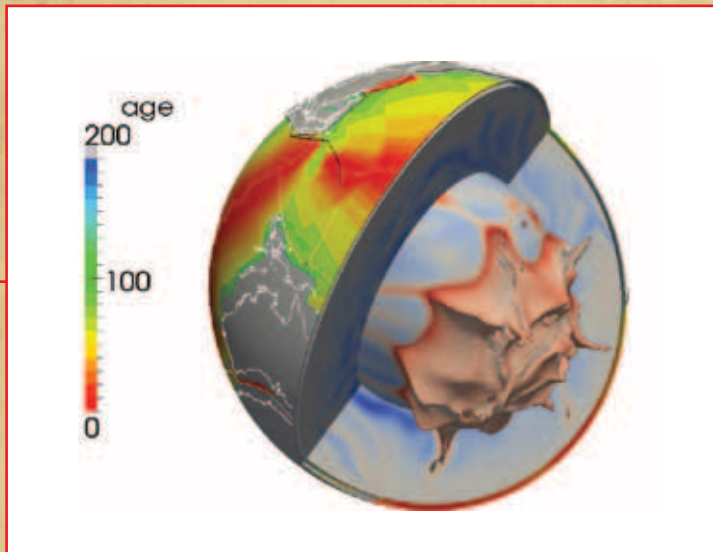
At the core-mantle boundary, which

is roughly halfway to the center of the earth, the churning liquid-iron alloy that is carrying heat away from the earth’s outer core meets the insulating silicate



Top: A schematic cross section of the diamond anvil cell used by Jennifer Jackson. Two diamonds (in blue) squeeze a tiny, deep-earth sample while an infrared (IR) laser heats it and X-rays probe the atomic vibrations. By learning more about the vibrational properties of compressed samples, the team can study how seismic waves will behave when passing through.

Left: An overhead image of a beveled diamond anvil with a single crystal of olivine in the center. This tiny piece of the earth’s mantle is ready to be outfitted with a sample chamber so that it can be pressurized in the diamond anvil cell, as shown above.



A dynamic earth model reveals both the tectonic plates at the surface, and the structure of the deep mantle. This snapshot is of the late Cretaceous period (about 77 million years ago), when Australia was still connected to Antarctica. The large pink surface seen at the core-mantle boundary is a mass of dense material responsible for the plumes of mantle that appear in the Pacific Ocean.

rocks of the mantle. The ULVZs lie just above this boundary, at the bottom of the mantle, and the traditional idea was that they were regions of molten rock in an otherwise solid zone.

“We’re finding that the core-mantle boundary is complicated, like the surface of the earth, and these patches of ULVZs—which we’ve been able to image seismically with Don Helmberger’s group and model dynamically with Mike Gurnis’s group—appear to have a more solid-like behavior,” Jackson says.

“This was a beautiful example where we combined our dynamic models, we created a theory, and we used our laboratory results to predict the seismic characteristics of the ULVZs,” says Gurnis.

Based on these models, theories, and lab results, the researchers now believe that many ULVZs are solid, heavy layers of iron-rich material, but also that those layers can bulge up into the lower mantle, thanks to the hotter outer core material lying beneath them.

“We have all this energy coming out of the core, so the ULVZs are going to get hot. As they heat up, it’s likely that their density will drop, causing them to bulge,” says Helmberger. “We believe these bulges look like big rolling hills, and think that we have detected these things at the core-mantle boundary. Unfortunately, it’s kind of hard for us to drill a hole down there and say ‘here it is—look at it!’ But we’re pursuing this idea with a lot of enthusiasm.”

and the Pacific Ocean that are full of materials hotter than their surroundings. Learning how this material convects and how these deep structures behave can help in the understanding of large-volume eruptions that have happened in the past, such as the Deccan Traps event that occurred in India approximately 65 million years ago and likely covered an area of 1.5 million square kilometers with lava.

“Looking at the geologic record, many scientists agree that the Deccan Traps eruption event caused a large stress on many living creatures,” says Jackson. “A future eruption of comparable magnitude would probably cause similar stress levels to life on the planet.”

A lot of researchers have speculated that this historical eruption began as a smaller plume, and the only way that a volume of material that large could have built up on its way to the surface is if its roots were near the core-mantle boundary. There are similar plumes in the earth today that seismologists have detected.

“If we can model them more carefully and track them, it lets us place more constraints on the predictions of large-volume eruptions,” says Jackson.

In addition to following mantle plumes and, of course, providing answers to important scientific questions, knowing more about what is happening miles underneath our feet helps us comprehend more about the physical world that surrounds us.

For example, another aspect of

The three research groups are also working together to build better models of superplumes, which they believe are giant structures in the deep interior beneath Africa

Gurnis’s work is focused on long-term sea-level changes. “Imagine we have the earth today and we have our oceans, which are like water in a bathtub,” he explains. “One can imagine that the shape of the bathtub changes with time and your watermark in the tub changes. What we do is create a synthetic planet based upon our geophysical understanding, but one that evolves with known plate motion and is part of a big four-dimensional system.”

In the models, low areas are filled with water to see where sea level was high at different points in the earth’s history, and where it was low. “The models are then refined using our vast knowledge of the geologic evolution of oceans and continents,” Gurnis says.

“Because the earth is a dynamic planet, it turns out that the sea level doesn’t just uniformly go up and down everywhere on the planet in a simple way, which is something geologists have been debating for years,” he adds. “Rather, what we see is that some continents will move up and others will move down because of the dynamics in the earth’s interior. Knowing more about this process will help us predict how that might happen.”

For Helmberger, the most practical part of his research is connected with studying earthquakes. “If you model seismograms, you need to know the sources,” says Helmberger, who is proud to have 25 past students who are now professors in the field. “Furthermore, if you understand wave propagation, you can just change the frequency and the wavelength and move from studying big structures, like faults, to little bitty ones, like oil traps.”

All this knowledge about earthquake processes translates to a better understanding and prediction of earthquake hazards—including shaking and

flooding, which can have an impact across the globe.

"When you read a lot of modern geology books, they talk about understanding the nonlinear properties of nature," says Helmberger. "Knowing what's going on in the deep interior of the earth not only helps us better understand more surface events, like earthquakes and volcanoes, but also environmental changes and other things that may not seem related at first."

Jackson says the broad nature of studies involving the earth's interior may lead to advances in our knowledge about other planets and help improve our technologies.

"If we can understand the chemistry, dynamics, and structure of our planet's interior, then perhaps we may begin to home in on the nature of other planetary interiors in our solar system," she says.

"In addition, there is significant materials science overlap with mineral physics that can allow researchers to make better, stronger materials by understanding their basic properties under extreme conditions," she notes. (See "Big Small Things Happening Here," page 18.) "It may sound like a far stretch from the interior of the earth, but training the next generation of scientists will help us tackle future problems that need a scientific mind."

At the beginning of Verne's book, the lead character, a professor, must use his scientific mind to crack a code that reveals the exact path into the center of the earth. With the modern methods being pioneered at Caltech, that path is now clear, but the earth is still holding onto some deep secrets. Gazing out his office window, looking toward the San Gabriel Mountains, Gurnis is clearly excited about the journeys ahead.

"Looking at this mountain range, people can't even comprehend the fact

that they are moving," he says. "We're on the Pacific Plate, here in Pasadena—part of the same plate that is plunging underneath Japan. It's incredible to imagine ourselves here, in this office, and nearly 10,000 kilometers away from here—we're all moving together! Over hundreds of millions of years, the whole face of the planet changes. All of it rearranges over time—the continents combine into supercontinents and then they break apart. How does the earth do this? How does it work? That's what keeps me going. We're just one planet, but from a human perspective, it's pretty extraordinary that we're part of this incredible bubbling, convecting system that we call home." **ess**

Michael Gurnis is the John E. and Hazel S. Smits Professor of Geophysics, and director of Caltech's Seismological Laboratory. His research is supported by the National Science Foundation, the Gordon and Betty Moore Foundation (through the Caltech Tectonics Laboratory), and Statoil, a Norwegian oil company.

Donald V. Helmberger is a professor of geophysics and served as director of the Seismo Lab from 1998 to 2003.

Jennifer M. Jackson is an assistant professor of mineral physics. The National Science Foundation and the Keck Institute for Space Studies at Caltech sponsor her studies.

