MODELING A MAGNETIC MOON

By Pam Frost Gorder

DAVE STEGMAN IS LIVING THE GRADUATE STUDENT'S VERSION OF THE AMERICAN DREAM. ALTHOUGH HE HASN'T YET COMPLETED HIS DOCTORATE IN EARTH AND PLANETARY science, the University of California, Berkeley, student published a research paper in the January issue of *Nature*— as lead author.

Using an innovative computer model, he and his coauthors might have solved a decades-old mystery about the moon's geology. A giant plume of hot rock, they say, might have burst out from the lunar core four billion years ago, kicking off a series of events that endowed the moon with a temporary magnetic field.

Stegman's model is prompting scientists to re-examine the studies of magnetic lunar rocks collected during the early Apollo missions. The research has even caught the attention of the world media, who have dubbed his lunar hypothesis the "Big Burp Theory."

Notoriety aside, Stegman's work is advancing the application of a popular and versatile analysis method that's been around since the 1950s: finite-element analysis. With FEA, a computer breaks a complex problem into small pieces that are easier to process. In its early days, FEA modeled aircraft parts, but today it characterizes everything from the flow of atmospheric gases to the healing of broken bones.

Scientists who use FEA to study the Earth's interior face an immense challenge. Their work follows the theory of plate tectonics, which encompasses nearly every known geologic process. Were someone to construct a complete model of plate tectonics, the computer code would have to account for everything from the flow of liquid metal in the deepest regions of the Earth's core to geomagnetic fields that stretch well beyond the atmosphere's outer edges.

Such a task would be difficult enough, were all the variables known. But when it comes to what's going on deep inside the planet, many questions remain. To get answers, geophysicists are crossing disciplinary boundaries and pushing the limits of computing power.

Planetary Power Generators

Although the Earth and moon seem very different from each other today, scientists believe they share a common origin. When two planets of roughly equal size collided more than 4.5 billion years ago, Earth took on mass from the collision, and the moon condensed out of the resulting debris. Today, a key geologic difference between the Earth and the moon is the existence of a dynamo, or power generator, in the Earth's core.

As the Earth loses heat to space, cooling can be felt down to the planet's center, Stegman says. Earth's iron-rich core is slowly freezing, and a solid inner core is growing at the expense of a fluid outer one. Because iron is a good conductor, the roiling metallic fluid in the outer core acts like the armature of an electric motor, generating the Earth's magnetic field. To most people, the invisible field is noticeable only with the turn of a compass wheel or in the colorful glow of polar auroras.

At Texas A&M University, Mark Everett exploits the changes in Earth's magnetic field caused by solar storms to learn more about the planetary interior structure. An associate professor of geology and geophysics, he uses FEA modeling of geomagnetic induction to develop a surface map of oceans' and continents' electrical properties.

Everett faces a problem of geometry as well as physics, because he studies a thin layer of Earth's crust, much smaller than the planet's radius.

"The ocean–continent distribution is best modeled as a thin, heterogeneous conductive sheet," he says. "Coupling a thin sheet model to an underlying spherical model has not yet been accomplished. So there are really two problems to be solved—figuring out the sheet's conductance and wrapping the sheet around the Earth's sphere."

Ultimately, Everett's work might let scientists identify and interpret large-scale variations in mantle electrical conductivity. That's important, he says, because conductivity depends on the distribution of elements that affect mantle viscosity, mantle convection, and tectonic activity.

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The Need for Speed

While running Luna at NASA Goddard in 2002, Dave Stegman and his colleagues achieved a speed of 20 billion calculations, or gigaflops, per second. They continue to develop the Terra code, and benchmarked it at over one trillion calculations (one teraflop) last October, using only a fraction of the nodes available on Japan's Earth Simulator System. The Fortran program works on any operating system.

Another versatile FEA model is under development at NASA's Jet Propulsion Laboratory in Pasadena. The project, Numerical Simulations for Active Tectonic Processes, aims to unite several earthquake and plate tectonics codes into one high-performance parallel code.

Though the unified code, called QuakeSim, is only in the prototype stage, it will run on "everything from a Macintosh to a supercomputer," says principal investigator Andrea Donnellan.

That's important, because sometimes researchers don't need high-resolution simulations. "If you want to work out a simple model just to build up your intuition about something, you want to do that on a local machine—a supercomputer would be overkill," she says.

In recent tests, the QuakeSim team modeled earthquake faults by calculating some 15,000 finite elements though 500 time steps in eight hours real time. By June 2004, they hope to be able to calculate 400,000 elements through 50,000 time steps in 40 hours—sufficient speed and resolution to start to model and understand the earthquake process.

By Fall 2004, the QuakeSim software is to be available on the Web. Users wishing to test beta versions can do so by visiting http://quakesim.jpl.nasa.gov.

Everett says more cross-disciplinary collaboration would improve FEA modeling of geophysics. "I think that solid Earth people like myself need to interface much better with space physicists. We don't really understand what the other is doing, so we make oversimplified assumptions," he says.

In fact, it was an interdisciplinary foray into an astronomy lecture at Berkeley that inspired Stegman to study the moon. He learned that magnetic rocks brought back by the Apollo astronauts had ignited a mystery: if the moon has no magnetic field, then how did magnetic rocks form there? Did the moon once have a magnetic field—and, by extension, a dynamo?

To find out, Stegman developed a model called Luna.

Modeling a Planet's Interior

Luna is based on another 3D FEA model, called Terra, developed by John Baumgardner at Los Alamos National Laboratory. Terra models convection in the Earth's mantle region, the rocky portion above the metallic core. Like the interior of a soft-cooked egg, the mantle is solid, but may flow like a fluid. Cooler sections of it sink toward the core, where they eventually heat up and expand, floating back toward the surface. There the rock cools, and the cycle (known as convection) continues.

Stegman took Terra, which models basic variables such as velocity, pressure, and temperature of mantle rock, and added more complex analysis of material layers in the mantle. Because different chemicals heat and cool differently and have different densities, a chemically diverse mantle might separate into stratified layers over time, he reasoned. He added new algorithms to Terra to model the separation.

He did this work at the suggestion of his thesis advisor, Mark Richards, professor of Earth and planetary science. At first, Stegman intended to develop a more complex model of the Earth's interior, but that fateful astronomy lecture,

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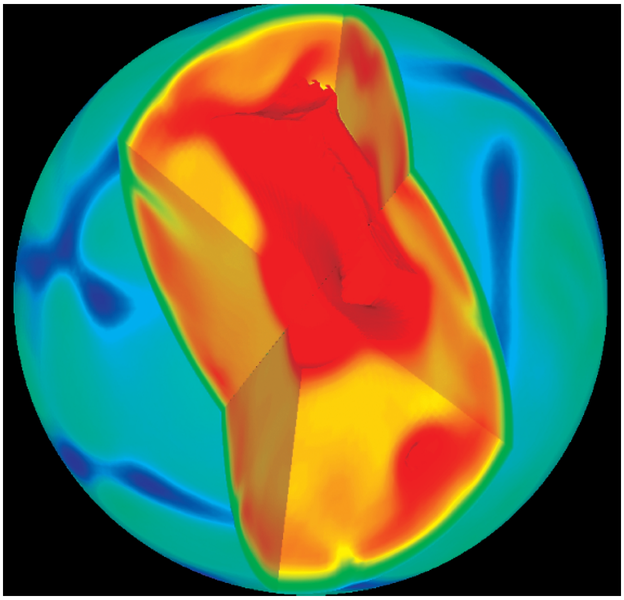

Figure 1. A model of the moon showing an enormous superplume of hot rock (red) bobbing to the surface—a lunar burp—about 500 million years after the moon's formation. The colors indicate temperature throughout the lunar mantle, with red the hottest and blue the coolest. The small lunar core can be seen in the middle, also red. (Figure courtesy of David Stegman, UC Berkeley.)

coupled with conversations with Berkeley colleagues, sparked his interest in how a layered mantle would play out on the moon.

Fine-grain, high-resolution FEA models require thousands of elements. But even today's massively parallel computers can only handle so much resolution, and Luna is complex enough to challenge the most elite computing machines.

Measured in lines of code, convection modeling programs such as Luna are second in size only to global climate models, which trace chemical elements in the atmosphere. While the most detailed climate models have achieved roughly 50-km resolution, Stegman attained a resolution of 10 km at the inner surface of the moon's mantle and 30 km at the outer surface, the variation a result of the core being so small relative to the moon's overall size. The smallest core radius allowed by his analysis was 450 km, close to the largest possible radius predicted by NASA's Lunar Prospector spacecraft.

A Mini Epiphany

Stegman and his colleagues had already secured time to run Luna on a Cray T3-E 1200 supercomputer at NASA Goddard Space Flight Center in Greenbelt, Maryland, when serendipity struck. A mistake in the input file, Stegman says, gave him a "mini epiphany."

The model included estimates of radioactivity, in the form of thorium and other radioactive elements that exist in trace amounts in mantle rock, and Stegman had inadvertently left the moon's total amount of radioactive elements at a level appropriate for the Earth. He discovered his mistake, but not before he could be surprised by the result—that the super-enriched radioactive layer heated the moon's core.

"This idea of a core heating up over time instead of cooling off makes perfect sense, yet it never occurred to me such a thing could happen in a planet or moon. This effect was so exaggerated by the mistake, it really jumped out of the model output," he says. "In our published models, we of course used a more plausible amount of radioactive elements in the layer."

But the result remained the same. Luna showed that the layer would have sealed the core in a "thermal blanket." According to the model, the blanket would have fed heat into the core, while blocking heat from dissipating into the mantle. With no way to cool off, the blanket would eventually become buoyant and thrust up through the mantle in a great superplume of radioactive rock.

With its thermal insulation removed, the core would have been able to release its pent-up heat, generating enough convection to spawn a magnetic field of one-tenth of a Gauss—roughly one-fifth of Earth's field today (see Figure 1).

The model could explain the lunar maria's existence, darkened areas of thorium-rich volcanic rock, on the lunar surface's Earth-facing side. Popularly known as "the man in the moon," the maria might be the result of radioactive blanket material flooding ancient impact craters on the moon's surface.

The moon's small core could only sustain convection for some 300 million years, but that's long enough to preserve its existence in lunar rocks, Stegman says. Previous studies showed that metal atoms contained within were aligned as if the rock had solidified in the presence of a magnetic field.

Earth Burps, Too

If the moon's long-ago discharge of molten rock constitutes a burp, then the Earth has a case of chronic (albeit mild) gas. Burps rising up from the mantle's deepest part might be the source of volcanic island chains like Hawaii, Stegman says.

He contrasts this "burping" behavior with the planet's constant ejection of magma along cracks in the sea floor. As older sea floor sinks underneath Earth's coastlines and moves back into the mantle, new sea floor is created at the mid-oceanic ridges, where crustal plates pull apart and fresh magma bubbles up to fill the void.

Studies of how convection began or ended on the moon

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or other planets could help scientists better understand Earth's geologic past, but they can't be used to answer provocative questions about the future. For instance, could the Earth issue a superplume of hot rock, as the moon did?

Maybe it already has.

"The Earth is a much more dynamic and complex system than the early moon," Stegman cautions, and Luna results can't be applied so easily to the Earth's interior. "Also, we can't predict Earth's future like climate models can, since our prediction would be for hundreds of millions of years in the future—well past when anyone could prove us wrong. Untestable, unfalsifiable hypotheses are not science."

Seismologists have, however, detected a dense layer of rock just above Earth's core that may resemble Luna's thermal blanket, he says. There is also evidence of two large piles of dense material in the deepest part the mantle; one resides underneath the Pacific Ocean, and the other under Africa.

"There is a great deal of debate about what these features are, where they came from, and if they are responsible for some of the volcanism we see at the surface," Stegman says.

He hopes that his group's current work on the Earth Simulator System (ESS) in Japan will help guide this debate and increase understanding of geophysical dynamics. "It takes our sophisticated computer model and the fastest computer to make progress, however," he says.

Pam Frost Gorder is a freelance science writer living in Columbus, Ohio.

BRIEFS

TOMORROW'S QUANTUM COMPUTING WITH TODAY'S SEMICONDUCTOR TECHNOLOGY

By Anne Jacobson

A big leap toward quantum computing has arrived in a tiny package: a 30- x 50-micron solid-state device that controls electron spin with electrical rather than magnetic fields. Developed by two physics professors, the device shows that quantum computing is possible with today's charge-based semiconductor technologies.

Electron spin forms the theoretical basis of quantum computing. The orientation of electron spin—either up or down—can be used to store one bit, or *qubit*, of information. If electron spin can be easily manipulated, quantum logic gates could be constructed to perform quantum calculations. And because the quirky rules of quantum mechanics let an electron be in both spin states simultaneously, quantum computing has the potential to be richer and more powerful than in current computers in which the bits must always be either "0" or "1."

The idea of controlling 100 million magnets each independently on a chip has boggled the imaginations of researchers, most of whom have assumed that electron spin must be controlled by magnetic fields, says Jeremy Levy, associate professor of physics at the University of Pittsburgh and codeveloper of the device. Yet controlling 100 million devices with electrical gates is what computers sitting on desks throughout the world already do, he says.

"We have shown that it is possible to build a scalable array of quantum gates using semiconductors in a relatively straightforward manner," says collaborator David Awschalom, professor of physics and electrical and computer engineering at the University of California, Santa Barbara.

Awschalom is also director of the Center for Spintronics and Quantum Computation, part of the California Nanosystems Institute; Levy directs the Center for Oxide-Semiconductor Materials for Quantum Computation at the University of Pittsburgh. The team recently published details of their work in *Science*.

Described as a semiconductor sandwich—composed of an inner layer of aluminum-gallium arsenide flanked by layers of gallium arsenide, which are in turn lined by metal plates—the device uses very small voltages and rapidly alternating current to manipulate electron spin. In the innermost layer, varying concentrations of aluminum provide an environment in which electron spin changes when an electrical field is applied.

Now that this proof of concept has been demonstrated, Levy says, the challenge is to scale down the device to the point where it can control the spin of a single electron. "In this device, we are still talking about something on the order of 10^8 electrons. But it shouldn't be too difficult to scale things down. This approach is suited to working on an extremely small scale," he says.

"For the industrial sector looking at quantum information processing and asking whether there is a future, there is a trillion dollars of semiconductor technology for leveraging, and electrical control of spin makes the leveraging far more feasible and cost-effective than control with magnets," Awschalom says. "The only thing new here is the concept; the technology is today's technology. Our hope is that people will do this much better in the next generation."

Anne Jacobson is a freelance writer based in Washington, D.C.