MEETING

Looking Back to Early Mars, Deep Into Earth

SAN FRANCISCO—Last month, more than 8200 earth scientists gathered here for the fall meeting of the American Geophysical Union. The talks included signs of early martian plate tectonics and rocks from the deep mantle.

Traces of Martian Plate Tectonics

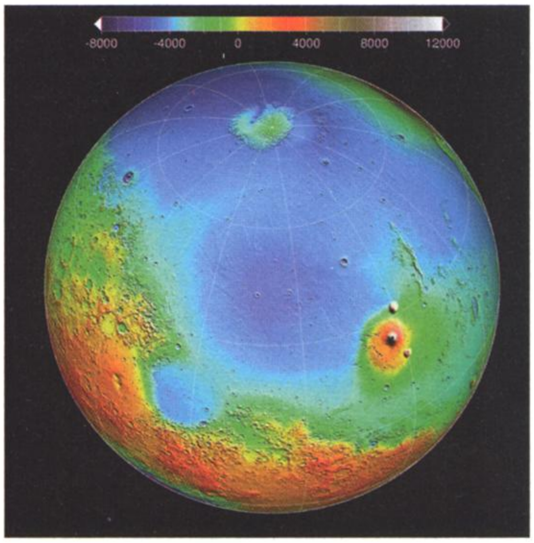
Phrenology may have little credibility for determining personality traits these days, but Mars Global Surveyor (MGS) scientists are using something like it to probe the deep-seated character of the Red Planet, with stunning results. By combining information about the bumps and basins of the martian surface with a subtle measure of the lumpiness of the planet's gravity field, MGS geophysicists have detected signs that the northern third of the planet may have been shaped by plate tectonics early in its history. That would be exciting news, because so far the only known example of plate tectonics is on Earth.

Specifically, members of the MGS team reported at the meeting that the area around the north pole has a remarkably thin and uniform crust. It could have been shaped, they argue, by tectonic processes like those that have given Earth's ocean basins their thin crust. The finding explains the mysterious "crustal dichotomy" of Mars—because thin crust is less buoyant, the northern region has sunk to create lowlands, while the thicker crust of the southern two-thirds of the planet has bobbed up to create highlands.

The MGS results are "provocatively similar to what you'd expect in a plate tectonics regime," says planetary physicist William McKinnon of Washington University in St. Louis. When plate tectonics was first suggested for the northern lowlands in 1994 on the basis of subtle geologic features alone, "it seemed like a wild idea," says McKinnon, because Mars looks tectonically dead—locked into a single, immobile, unchanging plate—and may have been that way for eons. But now, at least early on in the north, Mars appears to have been very much alive tectonically.

The new tectonic view of early Mars arises from two types of exquisitely sensitive MGS measurements. In orbit 400 kilometers above the surface, the spacecraft's laser altimeter has shot the planet with light pulses at more than 200 million spots and recorded the light's travel time, providing surface elevations accurate to 1.6 meters. And by measuring 50-micrometer-per-second Doppler shifts in the spacecraft's radio signal, MGS team members have recorded the subtle bobbing of the spacecraft as it passes over areas of greater or lesser gravitational pull. Then they used the altimeter-derived topography to subtract the varying gravitational effects of massive volcanoes and the missing mass of deep basins. The remaining variations in gravity revealed variations in rock density beneath the surface, including how much crust overlies the denser mantle.

Most strikingly, the combined topography-gravity data exposed a large range in the thickness of the martian crust. Beneath the south pole it is 75 kilometers thick, MGS team member Maria Zuber of the Massachusetts Institute of Technology told the meeting, but it thins gradually to a mere 35 kilometers in the region under the north pole.



Thin-skinned and sunken. Something akin to plate tectonics formed the thin crust of the lowlands of Mars (blue).

The relatively thin crust of the northern lowlands is "the kind of thickness you would expect to have in a plate tectonics regime," says David Stevenson of the California Institute of Technology. Crustal thickness is a sort of temperature gauge, notes Stevenson. Planetary tectonics is a geologic machine fueled by the flow of heat out of the planet. If a planet is "running hot" because its heat is held in by an encircling shell of immobile rock, the high temperatures of the interior will melt large amounts of mantle rock. The resulting abundant magma will rise here and there to form a thick, possibly lumpy crust, as happens, for example, on Venus.

Plate tectonics, on the other hand, helps a planet run cool and produce a much different crust. On Earth, new crust forms at midocean ridges, cools, and soon sinks back into the mantle to be replaced by new, hot crust. This efficient heat loss keeps the interior cool and the amount of mantle melting low. The resulting crust is therefore thin. Formation at midocean ridges also produces a uniform, smooth-topped crust. Indeed, the thin, uniform crust found by MGS coincides "really well," says Zuber, with the area that geophysicist Norman Sleep of Stanford University outlined in 1994 as geologically resembling crust formed by plate tectonics. Sleep proposed that about a third of Mars had been resurfaced with thin crust the way three-quarters of Earth has been.

Given the uniformly thin, smooth crust of the northern plains, "I'm inclined toward a plate tectonic explanation," says Stevenson. Sleep sees plate tectonics as the simplest, most familiar way to cool early Mars enough to produce any thin crust. "It's the one mechanism we know on Earth" that can do it, he notes. "Someone may come up with an imaginative idea that works better, but they haven't yet."

Although attractive, the plate tectonics interpretation is not being universally adopted. Zuber, for one, remains noncommittal while she and her colleagues sort through other ways the planet might conceivably have formed such thin, smooth, and uniform crust in the north. These possibilities include a giant plume rising from the deep interior beneath the north pole and sinking in the south and a one-time foundering of stationary plates in the north as they became too dense and began sinking in place, as suggested for all of Venus half a billion years ago.

Whatever was pumping the heat out of the north of Mars was operating in what "must have been interesting times," says planetary geophysicist and MGS team member Sean Solomon of the Carnegie Institution of Washington's Department of Terrestrial Magnetism. Because MGS gravity and topographic observations have revealed the faintly preserved remains of a huge impact crater on the northern lowlands, says Solomon, that crust must have formed in the first half-billion years of the solar system, when such giant impacts were common. Mars's first half-billion years or so was the only time that the planet managed to power up its own mag-

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netic field. Stevenson and geophysicist Francis Nimmo of Cambridge University in the United Kingdom now see a connection between the demise of that field and the end of plate tectonics. Generation of a magnetic field requires a churning molten iron core that acts as a geodynamo. The churning is driven by heat flowing out of the core, much as tectonics at the surface is driven by heat flowing out of the planet.

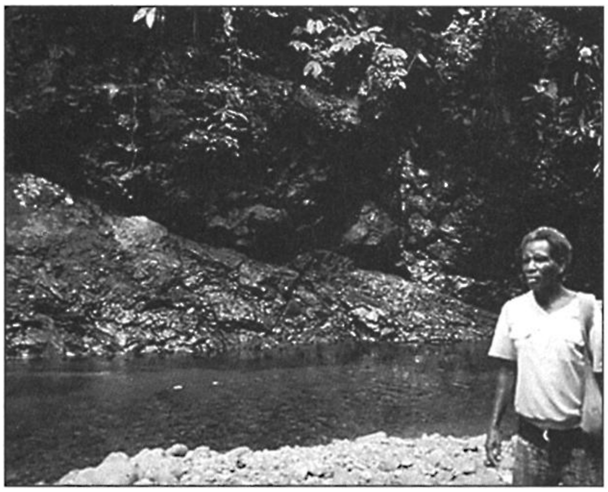
In fact, the core's heat flow and thus the magnetic field depend on a vigorous flow of heat at the surface, calculations by Stevenson and Nimmo suggest. If plate tectonics or something like it isn't pumping heat out at the surface, the interior warms until it's nearly as hot as the core. At that point, heat can no longer escape the core, its churning slows, and the magnetic field dies. That fits the MGS observation that crustal formation in the north ended about the time the magnetic field died, as recorded in magnetic stripes of the southern hemisphere crust. Some researchers initially considered those stripes to be signs of plate tectonics in the south (*Science*, 30 April 1999, p. 719), but a growing variety of alternative explanations, some related to plate tectonics in the north, have since been offered. Sorting out how the tectonic commotion in the north affected the rest of the planet's surface as well as the interior will take some more fingering of the martian noggin.

Ever Deeper Into Earth's Nether World

Researchers probing Earth's deep interior are celebrating what could be a startling new find: fresh, seemingly unaltered minerals from as deep as 770 kilometers, hundreds of kilometers deeper than any previously found. The newly analyzed rocks, from the island of Malaita in the Solomon Islands, are "potentially the most important rocks ever," says petrologist Harry Green of the University of California, Riverside. "[They] touch on many, many important aspects of geophysics."

If the discovery holds up, the rocks could tell researchers about the nature and origin of a part of the planet once accessible only remotely, through seismic imaging. According to petrologist Kenneth Collerson of the University of Queensland in Brisbane, who announced the rocks' discovery at the meeting, he and his colleagues "are finding heaps of new minerals" that can form only at pressures prevailing between 300 and 770 kilometers, where the upper mantle gives way to the lower mantle. "We're finding the first real rocks from this region," he says. "It's an Earth-shattering discovery." Everyone who has heard the news is excited, although some remain cautious. "I desperately want them to be right, but they haven't convinced me," says Green. Completely persuading colleagues will take a year or two of crystal structure analysis to complement Collerson's chemical analysis.

The new rocks come as a surprise even to those who have tramped the jungle-covered Malaita, which lies just northeast of Guadalcanal of World War II fame and farther east of Papua New Guinea. For a couple of decades, researchers have known that 34 million years ago deep-seated volcanic eruptions blasted through a massive pile of 120-million-year-old submarine lavas called the Ontong Java Plateau. Carried by the Pacific Plate, the plateau eventually collided with the Australian Plate about 23 million years ago, pushing up Malaita and exposing the tops of the volcanic pipes. Such pipes are related to the classic kimberlite pipes of South Africa, which carried bits of rock—and the diamonds South Africa is famous for—to the surface from more than 150 kilometers down. But no one was finding any diamonds in Malaita, and none of the minerals came from deeper than 135 kilometers.



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A jungle story. At rare sites on Malaita, Solomon Islands, rock blasted from hundreds of kilometers down is exposed.

Then a mining exploration company sent the Queensland group some "funny-looking garnets" from Malaita unlike any seen before. Collerson and his colleagues found 10- to 20-micrometer crystals of diamond, majorite, and other minerals embedded in relatively huge 10- to 20-centimeter chunks of deep rock lifted by the eruption. These inclusions indicated decidedly higher pressures than previously reported for Malaita rocks. Pressures at 150 kilometers or deeper would have been required to squeeze carbon into microdiamonds. To create majorite—by squeezing enough silicon into crystals of garnet—would have taken pressures between those at 260 and 570 kilometers, near the traditional upper mantle–lower mantle boundary at 660 kilometers. And the team also found some crystals with the composition of silicate perovskite—a mineral that would be produced from the basalt of ocean crust once it has sunk to 770 kilometers, as seismic imaging shows it sometimes does (*Science*, 31 January 1997, p. 613).

The Queensland group's initial chemical analyses have the deep-mineral community abuzz. Minerals have been reported before from such depths (*Science*, 10 September 1993, p. 1391), but they had either returned to their low-pressure crystal forms or been too tiny for complete analysis. "The prospect of having natural samples [of the deep mantle] that appear so unaltered is very exciting," says Catherine McCammon of the University of Bayreuth in Germany. Without actual samples from such depths, petrologists seeking the composition and origins of the planet's largest rock reservoir must depend on theoretical calculations, laboratory experiments, and inferences from magmas derived from the mantle.

The detection of compositions indicative of high pressures convinces McCammon that the Malaita rocks have a deep source. "I don't know how you could [find those compositions] unless they're from the transition zone" at as deep as 660 kilometers, she says. Clive Neal of the University of Notre Dame in Indiana, who helped establish the 135-kilometer depth of other Malaita rocks, agrees. "It certainly looks like majorite, and you certainly need a high pressure to generate majorite."

But further analysis will be required to prove that any of these minerals came from the lower mantle, below 660 kilometers. Collerson's claim, based on chemical analyses, of crystals in the perovskite crystal structure that can form only below 660 kilometers will require confirmation by crystallographic analysis, says McCammon.

If Collerson is right, researchers will have samples from a new part of the mantle. The compositions of some of the minerals argue that the Malaita pipes blasted through mantle laden with old slabs of tectonic plate that had sunk from the surface, as slabs now sink into deep-sea trenches off Japan and South America. Seismic imaging of the mantle has shown that, contrary to the long-standing concept that the upper and lower mantle layers never mix, slabs can penetrate into the lower mantle, but many either fail to do so or pile up in the transition zone before falling deeper. Collerson believes he now has bits of such slabs in hand, confirming the seismic images.

–RICHARD A. KERR