

Earth's Solid Iron Core May Skew Its Magnetic Field

The inner core is the most remote part of our planet: a 2500-kilometer ball of solid iron that sits at Earth's very center. It's also the most neglected.

Geophysicists have long assumed that the inner core is largely irrelevant to the planet's inner workings, in particular the magnetic field generated just outside the inner core by the churning molten iron of the outer core. But lately researchers have taken a second look at the inner core and its role in the life of the planet, and they find that it's not so irrelevant after all. The inner core's latest boost comes from two researchers who propose that it may leave its stamp on the magnetic field—even, at times, rivaling the main field with one of its own.

Building on seismic evidence that the iron in the inner core has a "grain" much like

the same two patches on Earth's surface during some reversals, and once a reversal is complete the new north and south poles don't seem to form a perfect mirror image of their predecessors.

The possibility of invoking the inner core to explain such mysteries intrigues other magnetic field specialists. "Thinking about the inner core as possibly important is attractive; it's been ignored for a long time," says paleomagnetist Kenneth Hoffman of California State Polytechnic University in San Luis Obispo. "The [Clement and Stixrude] model is rather remarkable in that it can explain some things like the [reversal] patches." The problem remaining for this attractive hypothesis, say Hoffman and others, will be to explain how any magnetic signal from the inner core manages to make

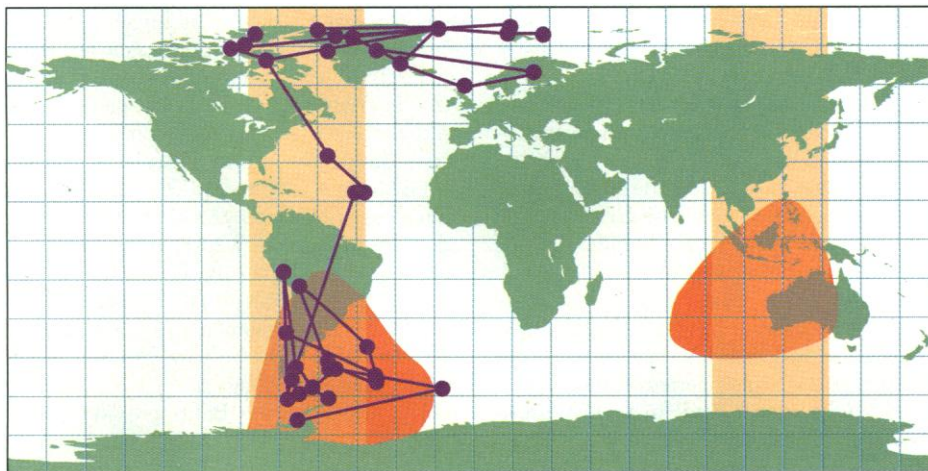
and Ronald Cohen of the Carnegie Institution of Washington's Geophysical Laboratory test that assumption with some theoretical calculations. They suggest that the particular form of crystalline iron thought most likely to form the inner core—the hexagonal close-packed phase—could produce the observed seismic anisotropy, at least if its crystals were almost perfectly aligned.

Just how the crystals could have become aligned in the first place, however, remains uncertain. Hans-Rudolf Wenk and Raymond Jeanloz of the University of California, Berkeley, have suggested that the inner core, although solid, might be churning much like the overlying outer core, albeit much more slowly. Kneaded by the flow, the crystals could line up in a preferred direction. Other researchers have proposed that the magnetic field of the outer core might have the same effect, aligning the crystals as they form from molten iron just as iron filings line up along the magnetic field lines of a bar magnet.

Whatever its cause, the alignment of the crystals could allow the inner core to influence the magnetic field generated by the outer core's dynamo, say Clement and Stixrude. The dynamo field would induce a field in the inner core, but the induced field would take its orientation from the grain of the crystals. Whenever the two fields diverged, the influence of the inner core's field might shine all the way through to the surface.

The first of the puzzles to which Clement and Stixrude apply this new model is a peculiar distortion in the magnetic field recorded in lavas and ocean sediments during the past 5 million years. At Earth's magnetic equator, the field—a two-poled field like that of a bar magnet—should be horizontal before curving downward into either pole. But the paleomagnetic record instead shows a persistent 4-degree tilt at the equator. If the inner core's texture is the result of convection, as Jeanloz and Wenk propose, its induced field could be most effective at altering the surface field near the inner core's equator. There, Clement and Stixrude calculate, the inner core field might be oriented so as to tilt the main dipole field away from the horizontal, as observed.

An inner core field might help explain why reversals don't seem to produce mirror-image poles, say Clement and Stixrude. In the paleomagnetic record, the magnetic poles of normal fields—fields oriented like today's—are offset from the poles of reverse fields by a few degrees. Clement and Stixrude think the offset is an illusion—the product of a spotty paleomagnetic record and the influence of the inner core. A modest tilt of the inner core's grain away from Earth's spin axis would be enough to produce anomalous field inclinations at some longitudes, they note. Add to that the incomplete paleomagnetic



Signature of the inner core? During magnetic reversals, the wandering poles tend to follow preferred north-south paths (yellow) across Earth's surface or linger in one of two patches (orange). The zigzag path traces one magnetic reversal, which was recorded in rock from Fiji.

a piece of wood, paleomagnetist Bradford Clement of Florida International University in Miami and mineral physicist Lars Stixrude of the Georgia Institute of Technology argue that it should have a magnetic grain as well—one that could shape the field generated above it in the outer core. In the latest *Earth and Planetary Science Letters*, Clement and Stixrude propose that this "anisotropy" could explain three puzzles of the ancient magnetic field as recorded in rock and mud: an unexplained tilt of past fields and two aspects of the field's behavior when the north and south poles switch places, as they do every few hundred thousand years. The wandering poles seem to linger for thousands of years in

its way through the turbulent outer core. "We have to wait for calculations from theoreticians to see if it's in the ballpark," says Hoffman.

The one solid underpinning of what Clement and Stixrude concede is a "highly speculative" model of magnetic field behavior is seismologists' observation that seismic waves passing through the inner core in the direction of Earth's axis of rotation move about 3% faster than those passing through its equatorial plane. To explain this disparity, researchers have assumed that the inner core's iron crystals are oriented so that the axes along which seismic waves travel fastest somehow get lined up with Earth's spin axis. In this issue of *Science* (p. 1972), Stixrude

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SOURCE: VAN HOOF ET AL (REVERSAL PATH) AND BROWN ET AL

record, which leans more heavily on data from some longitudes than others, and offset poles would appear when none existed.

The inner core's influence would show through most clearly, however, when the field is reversing. Just how the field behaves during reversals is controversial; Hoffman argues that some wandering poles spent much of their time in one of two patches centered south of South America and around western Australia, while other researchers say those "preferred patches" are segments of larger "preferred paths" within which the wandering poles tend to be confined. Still other researchers doubt the reality of either pattern, but Clement and Stixrude see increasing support for such behavior in some, although not all, reversals.

Hoffman had suggested that enrichments of electrically conductive iron at the bottom of the mantle might be guiding the reversing poles into preferred patches (*Science*, 21 June 1991, p. 1617), but Clement and Stixrude propose that the observed pattern is the work of the inner core. During the 8000 years or so of a reversal, the main field weakens and becomes distorted as the rapid convective currents of the dynamo reorganize. The slow-responding field of the inner core, however, could remain unaffected for thousands of years—able to capture the wandering main field poles at its own poles, creating preferred patches, or guide them along preferred paths.

Clement and Stixrude's colleagues aren't ready to believe that some of their knottiest problems can be solved so neatly. "I would like to see some hard numbers before I believe anything," says geomagnetist Jeremy Bloxham of Harvard University. "There's also the problem that you still have to get any inner-core magnetic field through the 2200 kilometers of the outer core, which is convecting and distorting and twisting the field. I think that is going to be the hard part."

But neatness is just what delights Clement about this proposed role for the inner core. "You've got three very complicated aspects of field behavior that might be explained by one simple mechanism," says Clement. "That's why I'm really excited." And he thinks that if the inner core's role in the magnetic field is widely accepted, the insights may eventually flow the other way. "The magnetic field could help us figure out the properties of the inner core," he says, finally bringing it a little closer to home.

—Richard A. Kerr

Additional Reading

B. M. Clement and L. Stixrude, "Inner core anisotropy, anomalies in the time-averaged paleomagnetic field, and polarity transition paths," *Earth and Planet. Sci. Letts.* **130**, 75 (1995).

R. Hollerbach and C. A. Jones, "Influence of the Earth's inner core on geomagnetic fluctuations and reversals," *Nature* **365**, 541 (1993).

ECOLOGY

Pacific Warming Unsettles Ecosystems

California surfers, used to shivering in bone-chilling breakers that average 13°C, might rejoice at news that the cold current washing their coastline seems to be warming up. From San Diego north to about San Francisco, ocean temperature records show a gradual upward trend beginning in the early 1950s—a trend that has accelerated since about 1976 as an unusual parade of El Niño warmings in the tropical Pacific pumped warm water northward. But the permanent residents of the California Current may be finding the 1.2 to 1.6°C warming less agreeable.

Earlier this month, researchers from the Scripps Institution of Oceanography in La Jolla announced that populations of zooplankton—tiny shrimp, larvae, and other drifting animals—in the California Current have declined 80% over the past 40 years, apparently because of the warming (*Science*, 3 March, p. 1324). Other ecologists say repercussions of this plankton loss seem to be rippling up the food chain and may help explain recent declines in fish and seabird populations. "There are tantalizing indicators out there," says Thomas Powell, an oceanographer at the University of California, Berkeley, "of food-web changes caused by changes in the ocean's physical environment."

Now Powell and other scientists are trying to decide whether the warming is a natural, decades-long fluctuation or a longer term trend toward warmer oceans, perhaps driven by greenhouse warming. For the moment, both possibilities seem plausible. "If it's part of a natural cycle, then it'll reverse itself," says Scripps' John McGowan, who with his colleague Dean Roemmich reported the plankton loss. "If this is man-caused ... then we're in serious trouble." Either way, he and his colleagues think the California Current could offer an early look at the changes that might be in store elsewhere in the oceans if global warming takes hold.

The California Current, which flows from Oregon southward down the coast, is particularly sensitive to temperature changes because of the upwelling that takes place along its path. The prevailing winds that drive the current also sweep surface water offshore, dragging up cold, nutrient-rich water from the depths. The upwelling supports dense plankton blooms that in turn feed other marine life. But when surface waters warm, explains McGowan, "the increased temperature ... puts a density cap on the upper layers," preventing cold, deep water from reaching the surface. As a result, the upwelling comes from shallower depths and carries less nutrients, and biological productivity decreases.

That is just what has happened over the

last 4 decades off southern California, according to McGowan and Roemmich's plankton studies. And there are hints, they say, that the plankton crash is taking a toll farther up the food web. For example, McGowan says, total commercial landings of fish in the California Current, including anchovy, sardine, mackerel, and squid, have gone down by some 35% since the 1950s.

Commercial catches are only a rough measure of fish populations, however, and many other factors besides a plankton shortage can drive them down. But Stephen Ralston, a fisheries biologist at the Tiburon Laboratory of the National Marine Fisheries Service, has evidence that populations of at



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In hot water. Three plankton-eating species—the sooty shearwater, the Cassin's auklet, and the rockfish (top to bottom)—have all declined in the last decade as a warming of the California Current reduced zooplankton numbers.