PALEOCEANOGRAPHY

Inconstant Ancient Seas and Life's Path

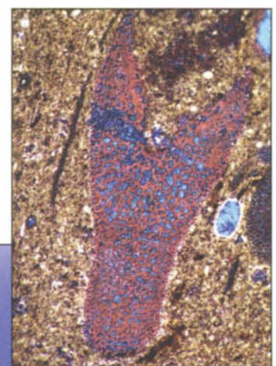
Seawater composition has changed over geological time, geochemists now realize. Has biological evolution changed along with it?

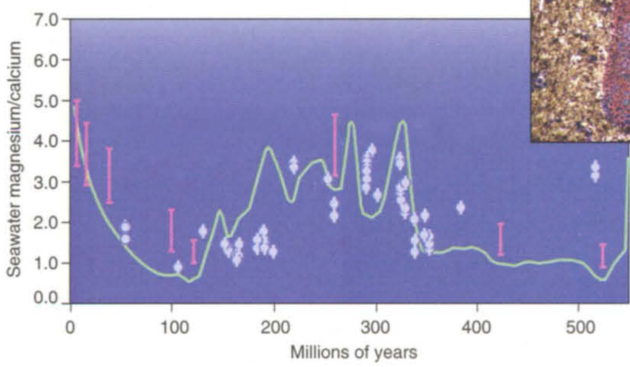
What could the geophysics of Earth's deep interior have to say about the evolution of life? The two disciplines might seem to be a world apart, but a paper in this issue of *Science* (p. 1222) could help link them together. The new work confirms that the chemical composition of the world ocean has swung back and forth during the past half-billion years. Those oscillations, likely driven by the varying tempo of plate tectonics, might have helped trigger a number of important evolutionary events. Among them: the explosion of shell-bearing animals in the Cambrian period, the outpouring of chalk that created the White Cliffs of Dover, and the resurgence of massive coral reefs of recent geologic times.

Geochemist Heinrich Holland of Harvard University, who has long been skeptical that the oceans were so variable, is now convinced. "There have been very significant changes in seawater" during the past 500 million years, he says. The details remain to be worked out, but several researchers are now sketching out a picture of how rock and life might have interacted through seawater chemistry in a sort of global-scale "geobiology."

The new evidence for inconstant seawater comes from the skeletons of fossil sea urchins. Previous signs of compositional changes came from analyses of concentrated seawater that was trapped in microscopic pockets in salts deposited in ancient evaporating seas. Geochemist Tim K. Lowenstein of the State University of New York, Binghamton, and his colleagues analyzed the brine of fluid inclusions from nine evaporites of various ages. Last year they reported the results: two broad oscillations during the past 550 million years in the relative proportions of magnesium and calcium, both major constituents of animal shells and skeletons. The seawater ratio of magnesium to calcium (Mg/Ca) was high 550 million years ago, just before the Cambrian explosion of shelled animals. It dropped precipitously into the Paleozoic era, rose to another peak in the Permian period 275 million years ago, fell again into the hothouse Cretaceous of 120 million years ago, and rose to modern high values—a cycle of roughly 275 million years.

Nine samples covering a half-billion years left some room for doubt, however. So sedimentologist Tony Dickson of the University of Cambridge, U.K., turned to another sort of chemical record. When echinoderms—such as sea urchins—build their calcium carbonate skeletons, they take up magnesium in proportion to its abundance in seawater. Dickson sorted through 103 fossils using scanning electron microscopy, looking for ones whose ornate, finely preserved microscopic skeletal structure suggested that nothing had altered the fossil's chemical composition. Twenty-eight samples from 18 different time intervals, stretching back 525 million years, fit the bill.





Oceanic ups and downs. Analyses of mineral-trapped ancient seawater (vertical bars) and marine fossils (blue dots, from red-stained fossil, above) show seawater composition swings in time with seafloor hot-spring effects on seawater (green line).

CREDITS: J. A. D. DICKSON

Dickson's resulting seawater Mg/Ca changes broadly match those derived from Lowenstein's fluid inclusions. And, helping clinch the case, geochemists Juske Horita of Oak Ridge National Laboratory in Tennessee, Heide Zimmermann of Harvard, and Holland report in the 1 November issue of *Geochimica et Cosmochimica Acta* that they see the same "double oscillation" in fluid inclusion analyses of their own and those in the literature.

Oceanographers are sure to debate the reasons behind the cyclical changes in seawater composition, but most agree that the answer will involve a link between plate tectonics and the percolation of seawater through the hot rocks of the midocean ridges. Ever since the 1977 discovery of hot springs along the crest of the volcanic midocean ridges, oceanographers have presumed that chemical reactions between seawater and hot ridge rock would influence seawater composition. The rock removes magnesium from seawater, for example, and releases calcium.

The flux of midocean ridge brine into the world ocean should wax and wane along with the midocean ridges: The more ridges there are and the faster they produce hot, new ocean crust, the reasoning goes, the more chemically altered brine will be produced. Plates drifting on the deep churnings of the mantle have repeatedly merged into a single supercontinent that eventually breaks up. When supercontinents rule, the total length of midocean ridges in the world is at a minimum; when the continents are dispersed, with midocean ridges separating them, total ridge length peaks. Researchers can trace the ebb and flow of the midocean ridges in the rise and fall of sea level: The more extensive the ridges, the higher sea level will rise, like the bottom of a bathtub being pushed up.

In 1996, geochemist Lawrence Hardie of Johns Hopkins University in Baltimore, Maryland, who has worked with Lowenstein, put all this together in a model in which the hot, mineral-laden brine of midocean hot springs controls seawater composition. Using past sea level variations as a proxy for hot-spring fluxes, Hardie's model showed the Mg/Ca ratio rising and falling through the past half-billion years (the Phanerozoic eon), much as the evidence from fluid inclusions and fossils now suggests. "Everything fits together so beautifully in this story," says geochemical modeler Robert Berner of Yale University. "I would like it to be right; it makes sense." Berner and others caution, however, that there might be a bit more to changes in seawater than changing hot-spring fluxes. Changes in the input of river-borne minerals, for example, look significant, says geochemist Fred T. Mackenzie of the University of Hawaii, Manoa. And estimates of the magnitude of past sea level changes are shrinking.

Although most researchers might be willing to accept that the vagaries of plate tectonics may in large part drive oceanic chemistry variations, the suggestion that chemistry variations have influenced the path of evolution is more controversial. Twenty years ago,

P. A. Sandberg of the University of Illinois, Urbana-Champaign, pointed out that the carbonates precipitated from seawater without the assistance of living organisms had alternated between two crystalline forms. The observed variations in seawater Mg/Ca now explain that alternation, because abundant magnesium favors one form over the other. In 1999 Hardie and Johns Hopkins paleontologist Steven Stanley took the next step, proposing that the swings in the Mg/Ca ratio had acted as evolutionary gatekeepers. Corals and mollusks that build massive reefs came and went through the Phanerozoic, they said, depending on whether particular taxa were equipped to deal with a new Mg/Ca ratio.

Likewise, carbonate-producing nanoplankton that have been prevalent in the seas since 140 million years ago produced massive deposits of chalk—like the White Cliffs of Dover—only when the low Mg/Ca ratio favored them, 60 million to 100 million years ago. Hardie and Stanley also see signs of "evolutionary osteoporosis" setting in following the nanoplankton's heyday: Smaller, thinner, spindly carbonate encased the nanoplankton as the Mg/Ca ratio rose and calcium concentrations declined. High calcium might have had the reverse effect 545 million years ago, geochemist Sean Brennan of the U.S. Geological Survey in Reston, Virginia, Lowenstein, and Horita suggested last week at the Geological Society of America annual meeting in Denver. They reported a tripling of calcium as measured in fluid inclusions from the late Precambrian into the Cambrian, just when animals first began forming calcareous shells in the Cambrian explosion of life.

"It's a really interesting idea," says paleontologist David Jablonski of the University of Chicago, "that ocean changes could drive these major turnovers" of marine animals or even facilitate shelled animals' bursting on the scene. The trick, he says, will be refining the patterns of evolutionary and ocean change so that cause and effect can be firmly linked. Then geophysics and life might be joined for good.

–RICHARD A. KERR

THEORETICAL PHYSICS

Constructing Spacetime—No Strings Attached

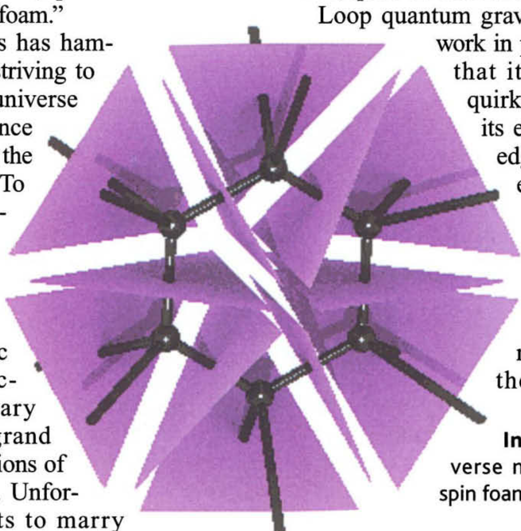
Move over, string theory. In the ongoing quest to meld quantum mechanics and gravity, an alternative theory aims to steal the stage

Space isn't smooth, and time doesn't flow. Regardless of what the rest of the world might think, physicists shed those illusions decades ago. To them, space and time are really two aspects of a single, stretchy thing called spacetime, which, thanks to the Uncertainty Principle of quantum mechanics, roils with tiny fluctuations measuring a few billion billion billion billionths of a meter. So when seen up close, spacetime resembles a frothy "quantum foam."

This foaminess has hamstrung physicists striving to explain how the universe sprang into existence and why it appears the way it does today. To tackle these questions, researchers need a single theory that accounts for everything from the frenetic quantum interactions of elementary particles to the grand gravity-driven motions of stars and galaxies. Unfortunately, attempts to marry quantum mechanics and the theory of gravity bog down in the foam, and even the leading candidate for a "theory of everything"—string theory—sidesteps the sticky froth.

Over the past 15 years, however, a few physicists have plowed headlong into the quantum foam. They've concocted a theory that precisely describes spacetime on the smallest length and time scales. Loop quantum gravity, as it is called, is the first theory that directly reconciles the minutiae of quantum mechanics with Einstein's general theory of relativity, which describes gravity as the warping of the very fabric of spacetime. It also predicts that space comes in discrete chunks, so that there is a smallest possible area and smallest possible volume. Just as matter is made of atoms and elementary particles, space consists of tiny indivisible bits.

Loop quantum gravity is very much a work in progress. Critics say that it sometimes gives quirky results, and even its enthusiasts acknowledge that many rough edges still need to be sanded down. But it's worth the effort, they say, because it takes them places where the more popular string theory doesn't go.



In a lather. Our universe may be a collage of spin foams like this one.

Whereas string theory begins by assuming how spacetime stretches and twists, loop quantum gravity builds the "geometry of spacetime" from scratch. That's a crucial feature of any fundamental theory of quantum gravity, says Lee Smolin of the Perimeter Institute for Theoretical Physics in Waterloo, Ontario. Come what may, he says, "it's hard to imagine that there could be a consistent formulation of quantum gravity that doesn't include these results."

Making a connection

Since the 1950s physicists have struggled to develop a quantum-mechanical theory of gravity. In the quantum theories of all the other forces—electromagnetism, the strong force that binds the atomic nucleus, and the weak force that causes radioactive decay—physicists assume that infinitely smooth spacetime is filled with quantum fields that describe particles, such as photons or electrons. They imagine small ripples in these fields, calculate the interactions between them, and add up the results for ripples of all lengths. For gravity, however, the ripples are in spacetime itself, and when their length sinks below the size of the "bubbles" in the quantum foam, the standard approach starts churning out mathematical gibberish in the form of nonsensical infinities.

String theory provides a way around such blowups. First formulated in the 1980s, the theory assumes that every fundamental particle is really a tiny loop known as a superstring. Because the strings are long enough to stretch over the fluctuations in the spacetime foam, awkward infinities do not arise. To the strings, spacetime looks relatively smooth.

Yet string theory still suffers from a fundamental weakness. In the theory, the strings move in a spacetime whose shape has been chosen from the beginning, as if they were actors on a previously constructed stage. A truly fundamental theory of gravity, everyone agrees, would build the stage itself. In the vernacular, the theory should be "background independent," and string theory is not.

Loop quantum gravity, in contrast, takes dead aim at background independence. The theory got its start in 1986, when Abhay Ashtekar of Pennsylvania State University, University Park, found a novel way to write

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