Another Movement in the Dance of the Plates

A history of North America's first billion years supports repeated episodes of tectonic plate aggregation and dispersal

For 20 years, Paul Hoffman spent 3 or 4 months a year in far northwestern Canada, fighting off the swarms of bugs that thrive in the 24-hour-a-day sunshine there. His annual pilgrimage was driven by the need to understand some of the ancient rocks that make up the core of the continent. "You learn to live with the bugs," recalls the researcher for the Geological Survey of Canada in Ottawa. "It was worth it for the geology you could see there."

While most of his colleagues were still searching elsewhere for some sort of pattern, Hoffman saw that tectonic plates were drifting and colliding then much as they do now. They had hardly missed a beat for at least the past 2 billion years (*Science*, 20 December 1985, p. 1364). With that insight from his far corner of the continent, he came to see the geology of the rest of North America as the aftermath of a kind of rambunctious dance of the continents—a tarantella on a time scale of eons in which the collisions, rupturing, and reshuffling of tectonic plates shaped the world of today.

To flesh out his theory of the United Plates of America, as he calls it, Hoffman abandoned that fieldwork 5 years ago and began synthesizing the geology of North America throughout Precambrian time, the 4 billion years of geologic time prior to 0.6 billion years ago. "It's a very important, a remarkable synthesis," says Precambrian geologist Nicholas Christie-Blick of Lamont-Doherty Geological Observatory. "He's taken the understanding of North America a quantum leap forward."

Hoffman sees the centerpiece of his synthesis as a dance set to a symphony in four movements. In the first movement, seven microcontinents quickly merge, never to part again. Then new dancers slowly gather round the original seven; a supercontinent is born with North America within it. No new players appear but much commotion comes from within. In the final movement, some dancers are torn from the pack just before more collide from either side. Eventually, many dancers break away, but they will all be reunited in another supercontinent in the next episode of the dance of the plates.

For almost 2 billion years, the product of this dance has remained intact through two and perhaps three cycles of continent aggregation and dispersal. The history of North America developed by Hoffman lends further support to the idea that continents follow cycles of aggregation and dispersal and that supercontinents renew this cycle by sowing the seeds of their own destruction. In the process, seas come and go, climate is altered, Earth's poles wander, and biological evolution may be abruptly redirected.

Hoffman's symphonic dance begins with aggregation. The first movement includes the rapid welding together of seven previously formed microcontinents and the addition of new crust around them, all between 2.0 and 1.8 billion years ago. "The most remarkable thing about North America,"

"We cannot understand North America without knowing what was going on globally," says Hoffman.

says Hoffman, "is this rapid-fire aggregation." He speculates that the microcontinents were swept together 2 billion years ago over a spot where colder than average mantle rock was sinking, the way floating leaves bunch together over a drain. The best analog for the peripheral addition of new crust is the western Pacific, where volcanic island arcs such as Japan are being plastered against Asia.

This formation of a continental core may be the first movement in the North American symphony, Hoffman notes, but it was not the first time these small tectonic plates had been part of a larger continent. The Superior province just north of the Great Lakes, for example, seems to consist of bands of island arcs and sediments sandwiched together and then broken around the edges. It is only a fragment. But much of the island arc rock in the seven fragments had welled up as magma from the mantle during the relatively short interval between 2.8 and 2.6 billion years ago, suggesting to Hoffman that the fragments were once part of a single continent that broke apart.

The tempo of the second movement, running from 1.8 to 1.6 billion years ago, was more moderate, as additions to the perimeter continued to be swept in. In addition, magma whose production was unrelated to any collisions and attendant mountain building began to ooze into the crust and break through to the surface. This so-called anorogenic magmatism dominated the interior during the third movement 1.6 to 1.3 billion years ago as mountain building due to peripheral collisions slowed to insignificance.

Just how large the continent was at this point is not certain, but Hoffman believes that it was probably a supercontinent, one perhaps including most of the continents of the time. Several other continents record collisions and anorogenic activity at about the same time, suggesting they all might have been part of the same continent then.

A large aggregation of continents would also best explain the outpourings of anorogenic magmatism, Hoffman says. A supercontinent would act as an insulating blanket, trapping some of the heat rising from the deep mantle. It would also keep at a distance the cold ocean crust that was sinking beneath island arcs. Given 100 million years or so, the mantle beneath the supercontinent would warm, choking off the cold downwelling that brought it together in the first place and starting the upwelling of hot mantle. That could produce the melting needed for the anorogenic magmatism, Hoffman suggests.

Don L. Anderson of the California Institute of Technology, seismologist and all-around theorist, had proposed that such mantle insulation beneath the supercontinent of Pangea led to volcanism, broad crustal bulging, and Pangea's eventual breakup 180 million years ago. As evidence, he pointed to a lingering bulge and a clustering of volcanic hot spots centered on the eastern Atlantic–Africa region where Pangea sat before its breakup. Ironically, notes Hoffman, mantle insulation as the cause of supercontinent breakup and dispersal was also proposed in a 1931 paper by prominent geologist Arthur Holmes. He was attempting to provide a viable mechanism for the moribund theory of continental drift developed by Alfred Wegener, who first proposed Pangea.

Holmes' idea was ignored, but, prompted by Anderson's thoroughly documented version, geophysical modeler Michael Gurnis of Caltech recently used a supercomputer to simulate how a continental plate and the circulation of the mantle might interact. In the model, large continents induce upwelling beneath them that breaks them apart, the pieces gravitating toward areas of downwelling where they once again merge and begin insulating the mantle.

Hoffman's fourth movement, in which the supercontinent should rip itself apart in a closing-scene act of self-destruction, is a bit muddled in terms of a cycle of aggregation and dispersal. There are signs of tension and breakup. Fields of magma-filled cracks thousands of kilometers across opened up about 1.3 billion years ago. This could have been when the mantle upwelling weakened the plate and tore away the margins of the supercontinent, says Hoffman, but any proof of it was lost when the next continents slammed into North America.

Shortly after this possible dispersal, about 1.1 billion years ago, a great volcano-filled crack split the continent from what is now Kansas to Lake Superior . This too might be taken as a sign of upwelling, except that at the same time a large continent struck from present-day Texas to Sweden. If the supercontinent had been sitting over hot, rising mantle, what was the other continent doing there without downwelling mantle to pull it in? Whether this was a complete dispersal or one aborted by an untimely collision, Hoffman is not sure. According to geologist Gerard Bond of Lamont-Doherty Geological Observatory, however, there is clearer evidence that a supercontinent including North America, the one preceding Pangea, did break apart about 0.6 billion years ago. As in the earlier case, the identity of the departed continents is unknown. Siberia, Australia, and Africa, among others, have been suggested.

"How do we test this notion, and I wouldn't call it any more than that, of supercontinent episodicity?" asks Hoffman. Primarily, he says, geologists have to look more closely at continents besides North America and Australia, where all the laboratories capable of high-precision dating are located. If the same types of activity could be shown to have occurred at the same time on different continents, the reasoning goes, perhaps they were part of a single supercontinent. This will be a messy business, observes Hoffman, since "the dance of the continents is not a minuet."

The cycle might also be followed through analysis of the magnetic fields locked in continental rocks when they formed. Hoffman cautions that paleomagnetic data are not very good in Precambrian rocks, something that took more than a decade for paleomagneticians to realize.

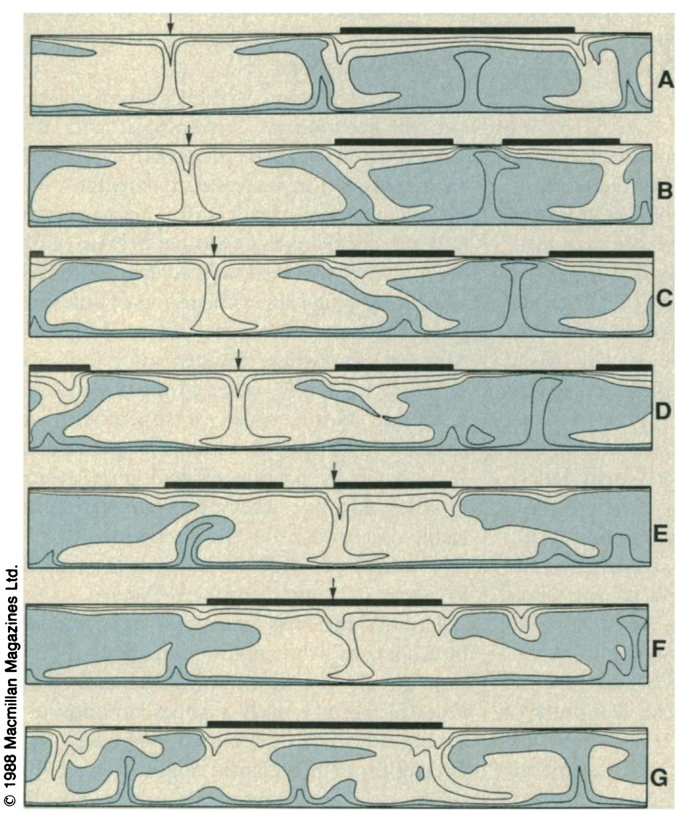
Another approach could be the correlation of the rise and fall of sea level with the aggregation and dispersal of supercontinents. Episodicity would affect sea level in two ways—the bobbing up and down of the continents over changing mantle convection would change the height of the sea on a given continent, and the creation of new mid-ocean ridges after supercontinent breakup would decrease the volume of the ocean basins. The net effect should be low sea levels just before supercontinent breakup and a surge to high levels shortly after breakup. The emergence of a supercontinent from the sea and the subsequent continental flooding should also show up in the geochemical cycling of such elements as strontium, sulfur, and carbon, as pointed out by Damian Nance and Thomas Worsley of Ohio University and Judith Moody of J. B. Moody and Associates in Columbus, Ohio, a motley group consisting of a tectonicist, oceanographer, and geochemist, respectively.

Sorting out the players in supercontinent episodicity would have myriad payoffs. The plate tectonic revolution established that plate motions raised mountains and induced volcanic activity, a revelation to geologists. Now they want to know which drifting continents were responsible. "We cannot understand North America," notes Hoffman, "without knowing what was going on globally."

But the benefits would extend beyond understanding the behavior of the crust to understanding more about Earth's ocean, atmosphere, and life as well. When the seas rise and spill onto the continents, climate can be ameliorated, ocean circulation shifted, the speed of geochemical cycles changed, and new ecological niches opened up. The high stand of the sea following the 0.6-billion-year breakup, as well as the 18,500 kilometers of new continental margin created and dispersed then, may have been crucial to the unprecedented explosion of new life forms that occurred at the time. The sea level fall after the Pangea breakup high stand may have contributed to the decline and eventual disappearance of the dinosaurs.

Supercontinent episodicity might even move Earth itself. Anderson has pointed out that the concentration of mass caused by mantle insulation and heating is most stable if it is at the equator. If it is created elsewhere, Earth will tip until the mass concentration and its supercontinent are on the equator and enjoying a tropical climate (*Science*, 10 April 1987, p. 147). The effect of this true polar wander is like that of continental drift without the chance of continental collision.

If the concept of supercontinent episodicity holds up, earth scientists will have identified a fundamental cause of Earth behavior: an inevitable modulation of the seepage of heat from the interior produces a terrestrial heartbeat, albeit an irregular one, that reverberates through every system of the planet. ■ RICHARD A. KERR



Two plates dancing. *In this computer simulation by Michael Gurnis of Caltech, the upwelling of hot mantle (in blue) and the downwelling of cold mantle interacts with a supercontinent (the horizontal slab at the top of each box). The upwelling breaks it apart (B), the two fragments drift toward the downwelling marked by the arrow (the left fragment is held stationary here) at up to 10.5 centimeters per year, and they collide after 150 million years (F). After 450 million years the new supercontinent has created its own hot upwelling (G).* [*By permission from* Nature *332, 695 (1988)*]

ADDITIONAL READING

P. F. Hoffman, "Speculations on Laurentia's first gigayear (2.0 to 1.0 Ga)," *Geology* 17, 135 (1989).
R. D. Nance, T. R. Worsley, J. Moody, "The supercontinental cycle," *Sci. Am.* 259, 72 (July 1988).