Plate Tectonics Goes Back 2 Billion Years

In a 1.5-billion-year extension of plate tectonics, geologists are showing that North America is a collage of wandering fragments

The Proterozoic Eon had always seemed different to geologists. Back then before animals began forming hard, easily fossilized bodies about 600 million years ago, Earth seemed to follow different rules, to shape its surface in ways unseen since. Presumably, the great unifying concept of plate tectonics with its recycling ocean crust and drifting, colliding continents did not apply then.

After a long, close look, geologists studying the ancient rocks of North America have decided that its core was assembled about 1.8 billion years ago from several chunks of even older continent. The sutures joining the chunks look much like the one that once joined North America to Africa and Europe along the Appalachians. It formed when the Atlantic's predecessor was swallowed up between the two colliding continents. The conclusion that plate tectonics has been operating for at least 2 billion and not just 600 million years seems inescapable to North American geologists. The present is indeed the key to the past, or at least the most recent half of it.

Extending plate tectonics into the Proterozoic is not a new idea, but now there is a big picture of how North America came to be. Even Precambrian geologists sorting out the details of their favorite rocks in the central United States and Canada find the new model acceptable. Paul Hoffman of the Geological Survey of Canada in Ottawa and Samuel Bowring of Washington University at St. Louis, drawing on their own work and that of others, have constructed a widely accepted sequence of events cast in the plate tectonics mold that begins with odds and ends of continents. These pieces, called cratons, ranged from about a fifth the size of present-day North America to a lump smaller than the state of Texas and are older than 2.5 billion years. This places their creation in the 2 billion years of the Archean Eon that opened the history of Earth.

Long viewed as the oldest and most stable parts of the continent, cratons, according to the new view espoused by Hoffman and Bowring, were independent, free-wheeling minicontinents before about 1.9 billion years ago. Then, mainly within a period of 100 million years, four or five Archean cratons collided and became welded together to form what is now central Canada and north-central United States. Caught between the cratons in belts of now eroded mountains called orogens was all the miscellaneous debris typically swept up by drifting continents: sediments from continental shelves and deeper ocean floor, strings of volcanic rock like that of Japan, and tiny scraps of continents, all sliced up by faults.

Alan Green of the Earth Physics Branch in Ottawa and his colleagues recently described just such a plate tectonics jumble where the Superior craton and the Churchill craton (which was probably joined on the south to the Wyoming craton) collided just after 1.9 billion years ago north of the present-day U.S.-Canadian border in the vicinity of Lake Winnipeg. According to their extension of previous interpretations of the region's geology, the two cratons had been closing on each other as the ocean floor between them dove into the mantle near the Churchill-Wyoming craton, as happens today beneath Japan. In a further analogy with the modern island arc, as Japan is called, the subduction of wet ocean crust into the mantle generated magma that formed a line of volcanoes and thus new crustal rocks.

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Next, the cratons squeezed between them one end of the volcanic island arc and then slid by each other, slicing up the arc and trapping the pieces along with a wayward bit of craton in a pocket of oceanic material. Ten years ago, says Green, the location and orientation of this island arc assemblage helped mislabel it as an Archean greenstone belt, something thought too unusual to be a product of plate tectonics. More recent dating and geochemical and geophysical studies show that it more closely resembles a modern island arc.

Until the last few years, there was another obstacle to the plate tectonic interpretation of such island arc assemblages caught between once wandering cratons. Some paleomagnetists had argued that the cratons had never been so far apart that oceans, island arcs, and subducting ocean crust appeared between them. Just a bit of jiggling between the cratons had squeezed up the mountain belts, they said.

Geologists and many paleomagnetists now believe that the data on which that conclusion was based had two problems. The rocks studied retained more than one lingering magnetic field impressed upon them by Earth's magnetic field. Each field corresponded to the latitude of the rock at the time the field was recorded, but paleomagnetists could not always know which field the rock recorded at the date determined for its age. Rock ages were a problem too. Transient heating of the rocks often changed ages when it released the radiogenic isotopes of argon and strontium used in the dating methods. More reliable methods are now being used, but the acceptable paleomagnetic results gathered so far are still inconclusive.

Beyond the outside edge of the Superior craton, as collisions began suturing the cratons together, the same basic plate tectonic mechanism of subduction and collision began adding new crust to the edge of the continent. Hard against the Superior craton in northern Wisconsin are volcanic rocks studied recently by Paul Sims and Zell Peterman of the U.S. Geological Survey in Denver and Klaus Schulz of the USGS in Reston, Virginia. In the late 1970's Sims had suggested that these volcanic rocks had formed within the Archean craton, despite the earlier proposal by W. R. Van Schmus of the University of Kansas that they were the result of plate tectonics. But now, says Sims, "It's pretty hard to explain the features we see as anything but the collision of an island arc."

One reason for Sims' initial reluctance was the apparent absence of some of the features found at other collision sites—slivers of ocean crust called ophiolites shoved up on the continent and rocks called blueschists that are metamorphosed at the unique high pressures and low temperatures of subducting ocean crust, for example. Most geologists no longer see this as an insurmountable problem. The resemblance of features common to both early Proterozoic and recent orogens is so strong that some differences are allowable, they say. In addition, notes Bowring, some features such as blueschists are so rarely preserved even in young orogens that their absence in older ones, subject far longer to erosion, might not be surprising. Careful searches by Precambrian geologists, keeping in mind how features would change with age, might reveal additional familiar features, he and others note.

Being familiar with modern examples that might turn up in the Proterozoic does seem to help. Gregory Harper of the State University of New York at Albany recently discovered an ophiolite in Wyoming that is at least 2.65 billion years old. It is metamorphosed, missing typical underlying mantle rocks, and is sliced up and severely stretched, but Harper's field experience on younger ophiolites let him recognize the mounded lava flows of underwater eruptions, the dikes feeding lava to the sea floor, the rock of frozen magma chambers, and other characteristic ophiolite features. Given a clear Archean example, says Harper, there is a strong possibility that ophiolites older than 1 billion years can be found in the rocks of the Proterozoic.

As further proof of the collisional nature of the Penokean orogen, as the Great Lakes crustal addition is called, Bruce Nelson and Donald DePaolo of the University of California at Los Angeles have determined the time at which its rock separated from the mantle as magma and became part of the crust. Using isotopes of the rare earth elements neodymium and samarium, they found that the average mantle separation age is 2.1 to 2.3 billion years, too young to be Archean crust but older than the 1.9-billion-year age of the collision. Either the collision mixed old Archean crust with newborn island arc magma, or island arc formation had been going on for hundreds of millions of years.

Farther outboard of the growing continent, the movement of continent and sea floor was about to add a far larger area of young crust to proto–North America, according to Hoffman and Bowring's story. M. E. Bickford of the University of Kansas, Van Schmus, and Isidore Zietz of the Phoenix Corporation in Falls Church, Virginia, have identified two orogens that appear to span the midsec-

New Sickle Cell Test

A new method has been developed for the prenatal diagnosis of sickle cell anemia that is faster and more sensitive than the ones currently in use. The method, which was devised by researchers at Cetus Corporation in Emeryville, California, works by combining two novel techniques for amplifying and analyzing specific DNA segments and may be generally useful for the diagnosis of genetic diseases. Moreover, the individual techniques have the potential for much wider application in molecular biology.

Sickle cell anemia is a hereditary disease caused by the alteration of a single nucleotide in the beta-chain gene, which encodes one of the two proteins of the adult hemoglobin molecule. Individuals who inherit two copies of the mutant gene get sickle cell disease. Persons who inherit just one copy do not have the full-blown disease but can pass the defective gene on to their children.

Current methods for diagnosing sickle cell anemia and other diseases that are caused by gene mutations often use restriction enzymes that cut DNA at very specific sites to detect changes either in the defective gene itself or in DNA that is closely linked to the gene. For example, the sickle cell mutation abolishes a site in the beta-chain gene that would ordinarily be cut by the enzyme designated *Dde*I. Consequently, digestion of the mutant and normal genes with the enzyme produces fragments of different sizes that can be separated and then detected by a method called Southern blotting.

The new method for diagnosing sickle cell anemia, which is published on p. 1350 of this issue of *Science*, also requires restriction enzymes. The improvements devised by the Cetus group include first the "polymerase chain reaction" protocol for amplifying the number of copies of the target DNA sequence and thus increasing the sensitivity of the analysis, and second, the "oligomer restriction" technique for determining whether the target DNA carries the mutation.

The polymerase chain reaction, which was conceived by Kary Mullis and Fred Faloona of Cetus, is a method for copying simultaneously both strands of a specific gene segment, in this case a 110–base pair sequence containing the sickle cell mutation site of the beta-chain gene. By repeating the reaction 20 times—each repetition requires only 5 minutes—the researchers obtain about a 220,000-fold amplification of the sequence.

Once the beta-chain gene segment is amplified, it is analyzed for the presence or absence of the *Dde*I restriction site by the oligomer restriction technique that was devised by Randall Saiki and Henry Erlich of Cetus and Norman Arnheim of the University of Southern California. In this procedure, a short, radioactively labeled DNA segment (the oligomer) is used as a probe for the restriction site. Ultimately it is restriction fragments released from the probe that are detected, and not fragments of the gene itself. An eight-nucleotide fragment is produced if the beta-chain gene is normal; if the gene carries the sickle cell mutation, there is a three-nucleotide fragment.

The Cetus workers have shown that the new method can readily determine whether an individual carries two copies of the sickle cell gene, one copy, or none at all. According to Erlich, the analysis takes only 1 day to complete once they have isolated the DNA from the test cells, compared to 5 to 6 days for current methods. Basically each step of the analysis is faster than similar steps in the current procedure.

Moreover, 20 nanograms of DNA—about one-fiftieth of the one microgram or so that is now required—is sufficient for analysis by the new method, although more time may be needed with such small samples. Finally, all the steps of the procedure except the final separation of the restriction fragments are test-tube operations and amenable to automation.

Small sample size can be a problem, especially when DNA must be obtained from fetal cells for prenatal diagnosis. The virtue of the polymerase chain reaction is that it can amplify the beta-chain DNA and potentially any DNA that might be in short supply. In addition to being used for genetic diagnosis, the method might aid in diagnosing infectious diseases or in forensic medicine, Erlich suggests. As he points out, "If there isn't enough specific target available, you can just make more of it."—**Jean L. Marx** tion of the United States. One developed between 1.78 and 1.72 billion years ago and extends from Arizona and Colorado, where it is exposed at the surface, out under the thick sedimentary rock of the central United States as far as eastern Kansas and Nebraska. To follow it there, they used rock samples retrieved from the bottom of oil, gas, water, and other kinds of wells as well as magnetic and gravity surveys that reveal patterns in the basement rock beneath the sedimentary cover. The second orogen, formed between 1.67 and 1.63 billion years ago, is exposed in southern Arizona and New Mexico and extends east to central Missouri and perhaps as far as central Michigan.

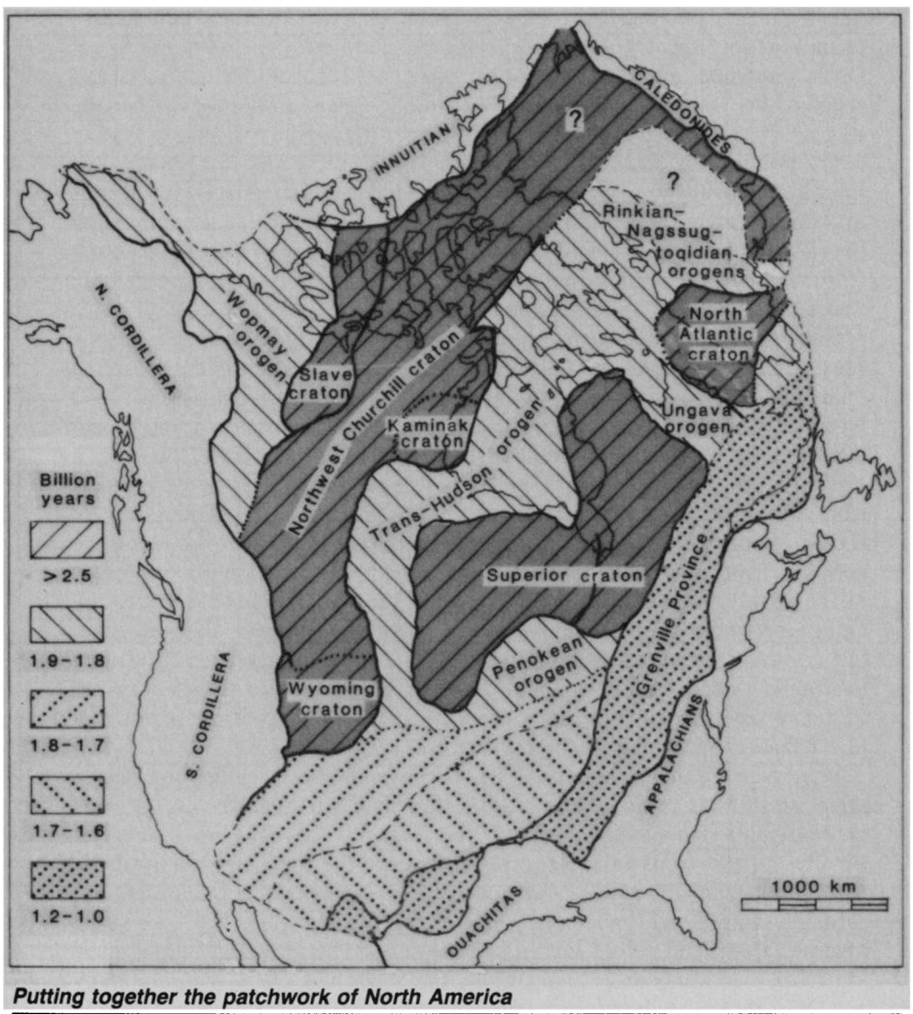
Collisions between the continent and island arcs appear to have created both of these orogens too. Where the rocks are exposed in the west, geologists have recognized the remnants of island arcs, and most of the rocks of both orogens rose from the mantle as magma at about the time of the collisions, as would be reasonable if they formed at island arcs. Sims and Peterman take their own interpretation a bit farther. They trace a single 500-kilometer-wide Central Plains orogen from Colorado and Wyoming northeast and then southeast to Missouri, where the recently recognized Missouri gravity low marks its eastern extension. Either way, collisions added a big hunk of the growing continent about 1.7 billion years ago.

To the south and east of the Central Plains orogen or orogens, the basement rocks, which except at rare exposures are reached only by drilling, are younger and do not resemble the rocks of an island arc–continent collision. Instead, they are the rocks of volcanic calderas like those at Yellowstone and Long Valley, formed from the ash that they spewed and the magma chambers that fed them. Bickford and Van Schmus have divided these anorogenic rocks into two provinces on the basis of their ages, one formed 1.34 to 1.40 billion years ago over Oklahoma, northern Texas, and parts of surrounding states, and another formed 1.42 to 1.50 billion years ago from the edge of the Penokean province of the Great Lakes south to northern Mississippi and Alabama and northeast Missouri.

Despite its more recent noncollisional history, this expanse of continental crust probably did derive initially from island arcs accreted to the continent. Bickford, Van Schmus, and Zietz suggest that these rocks are only a veneer a few kilometers thick overlying accreted volcanic arc rocks that remelted to produce a second round of volcanism. In support of that conclusion, Nelson and DePaolo found that these anorogenic rocks may have formed about 1.4 billion years ago, but the material in them separated from the mantle to first become part of the crust about 1.8 billion years ago. That means that the better part of the continental crust underlying the United States, from Arizona to the Great Lakes to Alabama, formed in one great surge of crustal generation 1.7 to 1.9 billion years ago, an event unequaled in North America since. Whether plate tectonics and thus crustal generation operated at a faster rate during the Proterozoic because the Earth's interior was warmer at the time remains to be seen.

Hoffman and Bowring suggest that the great volcanic outpouring of the anorogenic provinces occurred because they were well within a continent that had grown far larger than the present North America. The heat required to melt the crust and produce that volcanism could have accumulated in the mantle beneath the middle of a large supercontinent before part of it broke away, as suggested in 1982 for continents in general by Don Anderson of the California Institute of Technology.

Anderson pointed out that a supercontinent would allow heat to accumulate beneath its center by keeping cold subducting ocean crust at a great distance at its margins. Once sufficiently heated, the central continent could erupt with volcanism and the warm, weakened crust could break apart. Such rifting is a possible source of the anorogenic provinces of North America. Set free by rifting, the fragments of the supercontinent would have dispersed, according to Anderson's hypothesis, leaving behind a warm, uplifted part of the mantle that generates hot spots and exceptionally active volcanism. Hoffman and Bowring suggest that the presence of the expected type of midsupercontinent volcanic rock near the edge of North America implies that North America was part of a supercontinent itself in the early Proterozoic.



Putting together the patchwork of North America

North America was assembled from blocks and scraps of various sizes by the crustal motion inherent in plate tectonics, which now appears to have operated as early as 2 billion years ago. The pieces shown here include a core of ancient continental blocks or cratons (gray), the collision-induced mountains or orogens between the cratons, and accreted volcanic island arcs (central U.S. provinces). [Redrawn from a map by P. Hoffmann and S. Bowring]

That would not have been the last time that proto-North America served as the core of a larger assemblage. Gerard Bond, Peter Nickeson, and Michelle Kominz of Lamont-Doherty Geological Observatory have pinned down the breakup of another supercontinent having North America at its core, this time in the late Proterozoic. By determining the cooling rate of continental margins formed during the rifting of the supercontinent, they estimate that the breakup occurred between 625 and 555 million years ago, a far narrower range than previously available. The apparent coincidence of this breakup, which created and then dispersed 18,500 kilometers of new continental margin, and the explosion of new life forms at the end of the Proterozoic suggests some causal link.

If Anderson is right about supercontinents inevitably breaking up and eventually reforming from the dispersed fragments, over and over again, then this late Proterozoic and the possible early Proterozoic breakups would simply be two in a series of such episodes that most recently included the breakup of the patchwork continent Pangaea supercontinent 180 million years ago. Hoffman and Bowring have another to propose. They suggest that the Archean Superior craton is itself a composite of two continental fragments sutured by a continent-continent collision. They appear to have caught the usual island arc debris between them about 2.7 billion years ago, just as in the case of younger orogens. Instead of being the ultimate building blocks of continents, Archean cratons could be just more fragments of larger assemblages that suffered disruption and dispersal.

This would explain why many Archean cratons now found around the world were assembled at about that same time, during an orogeny called the Kenoran. In fact, the 1.9-billion-year Trans-Hudson orogen not only binds the cratons of North America together but is found in southeast Asia, Siberia, Australia, South America, and Scandinavia. Instead of some deep-seated mechanism in the mantle triggering a burst of mountain building around the globe, as previously suggested, "global orogenies" would result from motion of the shallow parts of Earth, like ice floes drifting together and freezing into a single mass, only to be broken apart, perhaps in new combinations, and shuffled once again.

The North America finally assembled during the Proterozoic has stabilized enough to resist a billion years of jostling, and rifting. In fact, it has continued to grow through the plastering of bits and pieces of continents and arcs to its edges. Using the present as a key to the ever more distant past, geologists want to find just how long Earth has been behaving this way.—**Richard A. Kerr**

Additional Reading

1. A. G. Green, W. Weber, Z. Hajnal, *Geology* **13**, 624 (1985).
2. P. K. Sims, Z. E. Peterman, K. J. Schulz, *Geol. Soc. Am. Bull.* **96**, 1101 (1985).
3. M. E. Bickford and W. R. Van Schmus, submitted to *Geology*; P. K. Sims and Z. E. Peterman, submitted to *Geology*.

Burst of Publicity Follows Cancer Report

The results are still preliminary, but suggest that the patients' own immune cells can be bolstered to fight a wide variety of solid cancers

A preliminary clinical trial of an experimental cancer therapy suggests that the treatment may limit the growth of a broad spectrum of cancers. The therapy, which is being developed by Steven Rosenberg and his colleagues at the National Cancer Institute, seeks to destroy cancerous tumors by mobilizing an immune attack on them. Although the results of the first tests of the treatment in patients with a variety of advanced cancers appear promising, Rosenberg sounds a note of caution. "This is just the first step," he points out. "It is not a cure for cancer in 1985."

The treatment being studied at NCI is part of a growing effort aimed at exploiting the tumor-fighting capabilities of naturally occurring, biologically active substances, especially those that act through the immune system. The Rosenberg group uses interleukin-2, a protein that is produced by the T cells of the immune system and is required for normal immune responses, to stimulate tumor-killing by the patients' own cells.

The investigators first withdraw lymphocytes from the patients' blood and activate the cells by growing them in culture with interleukin-2. The cells are then injected back into the patients, who are also given large doses of interleukin-2 to maintain the killer activity of the lymphocytes. Rosenberg and his colleagues had previously shown that this treatment could produce the regression of several different types of cancerous tumors in mice.

The results of the first clinical trial of this therapy in human patients, which have been published in the 5 December issue of the *New England Journal of Medicine*, showed that 10 of 25 patients experienced partial tumor shrinkages of at least 50 percent. An 11th patient, who had melanoma, had a complete remission that has now lasted 1 year. All of the individuals had very advanced disease that had not responded to previous treatments. "Given the clinical state of the patients he has treated, getting responses in that fraction is very encouraging," says NCI's Daniel Longo.

The treatment can have serious side effects, however. In particular, the patients may experience fluid retention that causes them to gain 10 percent or more of their body weight and may result in fluid accumulation in the lungs. One patient, who was treated after the original group of 25, apparently died as a result of the therapy, although the individual had widely disseminated melanoma.

The death was not mentioned either in the *New England Journal* report or in a press "update" sent out by NCI's Office of Cancer Communications. According to Rosenberg, this was because he did not wish to discuss unpublished results, although he did mention the death on the CBS News program "Face the Nation." An occasional treatment-related death is not unusual in the very ill patients who participate in the early trials of cancer therapies.

Other side effects of the interleukin-2 treatment include malaise, fever and chills, nausea, diarrhea, and anemia, although these resemble the effects of many chemotherapeutic drugs. The fluid retention and other side effects were reversible when the treatment was stopped.

In earlier studies the NCI workers had