Precambrian Tectonics: Is the Present the Key to the Past?

The great 19th-century revolution in geology established a single pervasive concept known as the principle of uniformitarianism. It states that the forces seen shaping the earth's surface today acted in the same way and with the same results in the past. This precept has served geology well ever since, but some investigators are now suggesting that it may not strictly apply to large parts of the earth's history.

Few researchers doubt the central role of plate tectonics in shaping the earth's surface and determining the distribution of the major crustal blocks during the last several hundred million years (see box). The geologic evidence concerning the role of plate tectonics during the earliest 90 percent of the earth's history (the Precambrian era, prior to 570 million years ago) has been regarded as inconclusive. Now, however, some investigators are proposing, on the basis of paleomagnetic evidence from ancient continental rocks, that the operation of plate tectonics was restricted in the Precambrian. They are suggesting that many of the geological features supposedly resulting from the collision of widely separated continental plates may have been created by some other process, one not observed today. This viewpoint faces strong opposition from those who fault the sufficiency of the paleomagnetic data and cite contrary evidence from the geological record.

The range of likely types of long-term crustal behavior is bounded by two extreme positions. One assumes that the theory of plate tectonics as visualized for the last few hundred million years can be extended back toward the formation of the crust, perhaps about 3.8 billion years ago. Since the production of heat by radioactive decay was about three times higher at that time, the pace of the plate tectonic cycle must have been much greater in order to dissipate the additional heat. New sea floor would have been formed more rapidly at spreading centers, and it would have been more quickly consumed by sinking beneath continental crust in subduction zones. The same number of plates or perhaps many more would have formed in response to the vigorous convection within the mantle. Continental plates would have frequently collided and become welded together. The rifting of continental plates and the opening of new ocean basins would have occurred often as well.

At the other extreme, some have speculated that the higher heat production had a drastic effect on crustal behavior. In their view, thin plates, too hot and light to be subducted, may have jostled about like ice floes on a turbulent ocean. In the commotion, the plates could have buckled and sheared internally, producing zones of deformed rock encircling more stable blocks. Continental blocks would not have been driven into each other by the motion of the underlying crustal plates. Only as the crust cooled, perhaps as late as the end of the Precambrian, would plate tectonics as it is known today have begun operating.

The magnetic properties of crustal rocks can be used to discover how plates actually behaved in the past. By measuring the direction of the lingering magnetization originally imposed on a rock by the earth's magnetic field at the time of the rock's formation, paleomagnetists can determine the position of the earth's ancient magnetic pole relative to the rock. By linking together a number of pole positions of different ages from the same rock unit, they can plot the relative movement of the rock unit with respect to the geomagnetic pole. Although it is the pole that is assumed to remain stationary, the usual convention is to plot the apparent movement of the pole on a map having stationary land masses. Thus, the compilation of paleomagnetic data for a particular rock unit over a period of time results in an apparent polar wander (APW) path.

Paleomagnetic studies can in principle be used to determine whether a deformed zone separating more stable Precambrian blocks, or cratons, is a "mobile belt" resulting from internal stresses or a "suture" marking the collision between two different continental plates. Identical APW paths for two cratons would imply that they moved as a single unit during that time.

Results from these types of studies have led some paleomagnetists to suggest that Precambrian mobile belts did not result from the collision of widely separated plates, as thought by some, but must have originated within a single plate. In Australia, Brian Embleton of CSIRO's Minerals Research Laboratory believes that preliminary APW paths from the Pilbara and Yilgarn cratons in Western Australia are consistent with the idea that the cratons have maintained their present relative positions for the last 2.4 billion years. The mobile belt between them is thought to have been formed between 1.8 and 1.3 billion years ago. Michael McWilliams, now at Stanford University, has drawn the same conclusion in the case of the Kalahari and Congo cratons of Africa. The paleomagnetic data suggest that the mobile belt between them "almost certainly did not result from the collision of widely separated plates," he says.

The number of paleomagnetic pole determinations is limited, but Precambrian paleomagnetists contend that there is historical support for the data's reliability. Only about 200 pole positions have been determined for rocks formed 600 to 2600 million years ago compared to about 1500 or more for rocks formed in the last 600 million years (the Phanerozoic era). But James Briden of the University of Leeds points out that this relative sparsity of data is very similar to the situation 20 years ago when divergent Phanerozoic APW paths were first claimed to be distinguishable. The early evidence failed to convince the rest of the scientific community. Acceptance of plate tectonics had to await the discovery of anomalies in the magnetic record in the sea floor. The general trends of the APW paths were eventually upheld as more poles were determined.

Michael McElhinny of the Australian National University, Canberra, and McWilliams have reviewed all paleomagnetic results from the Precambrian formations of Africa, Australia, and North America. They conclude that all Precambrian tectonic mechanisms could not have been the same as present-day plate tectonics. They compare the APW paths from different cratons both before and after six major mountain building events and find that they were the same within the error of the method. This error, they believe, would allow the opening of 500- to 1000-kilometer basins to go undetected. But the two plates would be required to return to their original positions. While this would be allowed by plate theory, it is generally regarded by plate theorists as being rather unlikely. They did find, as others have, that plates moved about during the Precambrian much as they do now, but adjacent cratons moved as a unit. McElhinny and McWilliams thus believe that the proba-

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bility of continental collisions being involved in all six cases is "exceedingly small".

A frequently voiced concern about such conclusions is that the interpretation of limited paleomagnetic data must be too subjective. Briden acknowledges that deformation within plates is consistent with some impressive paleomagnetic evidence, but observes that such deformation is still an open question in light of the impossibility of determining paleolongitude, the ancient longitude with respect to the magnetic pole. Only paleolatitude can be measured from

Skepticism Persists as Plate Tectonic Answers Come Harder

The theory of plate tectonics has, in the space of the last 25 years, made the transition from lunatic fringe to accepted dogma, the paradigm of the geological sciences. It has allowed geophysicists to include towering mountain belts, deep ocean trenches, ocean-circling volcanic systems, and entire island chains in a single coherent picture of crustal plate creation and destruction. But every revolution has its holdouts, its stragglers. The plate tectonics revolution is no exception. Many revolutions can also be carried to unreasonable extremes by the passionate, seemingly black-and-white nature of the issues at hand, only to fall back toward reason and tolerance as passion cools. So it seems to be with plate tectonics.

Opposition to plate tectonic theory continues in the greatest bastion of resistance, the Soviet Union, but even there plate tectonic theory is making considerable inroads. Reports of major Russian meetings in the geosciences are full of the head-to-head confrontations not seen in the West for 10 years. "Mobilists" talk about continental sutures and sea floor spreading while "fixists" speak only of deep faults and oceanization. Arthur Meyerhoff, now at the University of Calgary and one of the most vocal of the American skeptics, has traveled extensively in the Soviet Union. He estimates that no more than a few percent of Soviet scientists in applied geosciences strongly favor the theory of plate tectonics. Feelings within the academic community are more disposed toward it, but Meyerhoff contends that no more than half of the academic researchers strongly support it.

Warren Hamilton of the U.S. Geological Survey, Denver, agrees that Soviet scientists have yet to come around entirely to the western viewpoint. "Some marine geophysicists see it," he says, "but only in a more primitive form, circa 1960."

This is the same polarization observed in the West in the early days of plate tectonics. Younger marine geophysicists discovered and readily accepted the relatively straightforward evidence found beneath the ocean. Older, experienced continental geologists, faced with the muddled record of tectonic activity on land, were more reluctant. Some of these continental problem areas have still not been worked out to anyone's satisfaction.

Soviet reluctance to accept plate tectonic theory is often attributed to isolation from western research results, national pride (they obviously were not first), a lack of oceanic data of their own, and the entrenched hierarchy of Soviet science. Vladimir Beloussov, the dominant fixist and author of the Soviet geology textbook on the subject, headed that hierarchy until his retirement 3 years ago. According to James Heirtzler of Woods Hole Oceanographic Institution, though, the situation is changing rapidly. "Even Beloussov's group has largely accepted the basic tenets of plate tectonics."

Although far less numerous, there are still embattled holdouts in the West. Within this small community, there is still little unanimity. Concerns about the validity of plate tectonic evidence vary depending on the researcher's specialty. Some dissenters offer alternate hypotheses, such as an expanding earth (sea floor spreading but no subduction), while others find no support for any one hypothesis. They all share the experience of belonging to a dwindling but obstinate minority. The reaction of the majority to this heresy has at times been rather vehement, but tolerance is becoming a more common response.

"People on both coasts used to get very emotional about the whole thing," says Meyerhoff. "Some welcomed the intellectual stimulation, but otherwise I took a tremendous amount of flak. But in the last few years, I can talk anywhere, invitations are on the increase. Things seem to have opened up considerably."

Part of this change can probably be attributed to the subsidence of the early euphoria that greeted the unprecedented unification of so many geologic phenomena under a single principle. Now that the big picture of sea floor spreading, moving plates, and subduction has been largely filled in, the smaller scale details are proving more difficult to fit with the theory. As Heirtzler says, "We skimmed the cream off the top right away as plate tectonics. Now we're going back to the more complicated messy details."

Some of these "details" are among the points that the skeptics have been emphasizing for years. These problem areas are widey recognized as presenting fundamental research problems in the field of crustal dynamics, but not as threatening the theory itself. They include the mechanism of sea floor spreading, generally thought to involve some sort of mantle convection, and the driving force responsible for broad vertical uplift of the crust, a phenomenon that has not yet been fit into plate tectonics.

By most reasonable measures, support for the fundamentals of plate tectonics is widespread both among researchers and exploration geologists. The number of closet skeptics is difficult to determine. Meyerhoff claims that widespread indifference exists among exploration geologists. The indifference is sometimes real enough, but its impact is debatable. For example, traditional approaches to deciphering the complicated series of events required to form an oil field are, experts report, as useful as the plate concept, even on the geologically simpler continental shelf. The result has apparently been indifference but not hostility among many petroleum geologists toward plate tectonics.

Such indifference does not threaten the plate tectonic theory, but the vocal opposition of the few dedicated skeptics is likely to continue, at least until a convincing case is made for the mechanism that makes it all go around.

—R.A.K.

the direction of the remnant magnetism of a rock. Paleolongitude is not recorded. Anyone attempting to reconstruct the true APW path is faced with the task of assembling a number of polar positions based only on latitude and age.

The isotopic dating methods for Precambrian rocks, furthermore, commonly have an error of plus or minus 10 percent. Thus, the true age of a 2 billion-year-old rock might fall anywhere within a period of 400 million years, or the time needed for the opening and closing of an ocean the size of the Atlantic. Henry Spall of the U.S. Geological Survey in Reston asserts that, in the light of these uncertainties, the interpretation of limited paleomagnetic data tends to be somewhat subjective rather than objective. For example, essentially the same data used by McElhinny and McWilliams to support a modified form of plate tectonics have been interpreted by Kevin Burke, John Dewey, and W. F. S. Kidd of the State University of New York, Albany, to be consistent with the wandering and collision of a number of different plates.

Keith O'Nions of Lamont-Doherty Geological Observatory and his colleagues have recently applied a new dating technique to early Precambrian rocks which they believe will eventually allow more precise resolution of plate movement. They dated a 3.8 billion-year-old rock with an accuracy of 1 percent using a samarium-neodymium isotopic technique. The absolute accuracy of such an age would thus be comparable to that currently available for the Phanerozoic.

Many Precambrian geologists welcome the new paloeomagnetic data as further support for their long-held contention that the deformation and mountain building of mobile belts did not result from the collision of continents. They have always found it difficult to accommodate the patchwork of cratons and mobile belts of Africa, Australia, and Canada within the framework of plate tectonics. Most geologists recognize that the ramming of the Asian continent by the Indian landmass formed the Himalayas about 45 million years ago.

Speaking of Science

The Oldest Fossil Bird: A Rival for Archaeopteryx?

Although Archaeopteryx is generally considered the earliest bird on record, a recent find suggests that the creature, which lived some 130 million years ago, may not have been the only bird alive then. A new fossil found by James Jensen of Brigham Young University dates back to the same period—the Late Jurassic—and appears to be the femur (thighbone) of a bird. If this proves to be the case, then a reexamination of the postulated role of Archaeopteryx as the evolutionary link between reptiles and birds may be in order.

Jensen unearthed the bone last summer in the Dry Mesa quarry of Eastern Colorado, a dig where he has excavated many other fossils, including those of dinosaurs and flying reptiles. The specimen is now being examined by John Ostrom of Yale University's Peabody Museum of Natural History, who is trying to verify its identity. Ostrom says it looks more like a bird bone than anything else. While he has some reservations about the identification, he asserts, "If it's not a bird bone, I don't know what else it is."

The fossil resembles the thighbone of modern birds more closely than the comparable Archaeopteryx bone does. Archaeopteryx had feathered wings but did not fly well and in many respects was more of a running dinosaur than a bird. In particular, its skeleton was reptilian and characteristic of animals whose survival depends on their ability to maneuver on the ground. For example, the Archaeopteryx femur, which has a large, well-developed knob for a head (the portion that fits into the hip socket), was like that of a ground animal. But birds that are good flyers have femurs with small heads. And the head of the newly found fossil femur also appears small.

Jensen suggests that similar fossils may not have been located previously because a good flyer is not likely to perish in a site where it will be preserved. In contrast, Archaeopteryx, which was at best a glider and not capable of sustained, powered flight, probably had trouble staying in the air. The chances of its plummeting from the sky into a sea where it would be preserved were thus greater.

The hypothesis that Archaeopteryx represents a direct link from reptiles to birds has been generally accepted. The existence of another bird—one that was an adept flyer and thus more advanced on the evolutionary scale—would present a challenge to that hypothesis.

The situation also presents Ostrom with something of a delicate dilemma, for he is one of the principal developers of the evidence regarding the evolutionary role of Archaeopteryx. Although the paleontologist says that the identification of the new fossil is about 90 percent certain, he points out that it is not exactly like any of the numerous bones of modern birds with which he has compared it. This is not especially surprising. More disturbing to him is the fact that the fossil is not perfectly preserved and a portion of the head may be missing. In other words, the femur head may be more reptilian in character than it appears. And Jensen has taken a number of fossilized bones of flying reptiles from Dry Mesa quarry. But Ostrom is not sure that the head is not intact; it might just be different from that of other kinds of femurs.

There is also the question of the exact age of the fossil. It was found in a type of rock that geologists date as having formed some 130 million years ago and therefore comes from the same period as Archaeopteryx. But it could be a few million years older or younger. Since the five Archaeopteryx fossils were found in Europe, direct comparisons of their age with that of the new fossil are impossible. All in all, Ostrom thinks that it would be premature to knock Archaeopteryx off its perch as the oldest form of bird without additional evidence.

Jensen thinks that he may have found such confirmatory evidence in the form of another, more complete fossil femur excavated just a few feet away from the one in question. According to the Brigham Young investigator, this second femur is very similar to that of modern birds. Ostrom has not yet examined this latest find, however. Until he does, the situation will remain very much up in the air.—J.L.M.

The raising of the Appalachians about 375 million years ago by a collision with the European plate has gained wide acceptance. But geologists have not arrived at a generally acceptable explanation for Precambrian mobile belts.

Alfred Kröner of the University of Mainz, among others, maintains that many of the mobile belts of central and southern Africa do not appear to have resulted from continental collision, but rather from a reworking of rocks which lay between the cratons all along. For example, he does not find in these mobile belts the distinct demarcation that should occur between two different plates. Instead he finds a band of rocks increasingly altered by heat and pressure (metamorphosed) with increasing distance from the band's edges. Nor can he locate other features normally present at sites of ocean closure: a geosyncline, the thick deposit of sediment that accumulates along the trailing margin of a plate, as on the present-day Atlantic coast; ophiolites, the remnants of the ancient ocean floor which had sunk beneath the oncoming continental plate; and the severe compression and crustal thickening resulting from a continental collision.

In contrast, strong proponents of plate theory such as Burke, Dewey, and Kidd deny that there is a need for nonplate tectonic mechanisms to explain the formation of mobile belts. They argue that, while plate tectonics is based on very simple principles, the end results observed in the field can be very complex. This complexity of plate tectonic mechanics, combined with the greater erosion and metamorphism of older formations, makes the interpretation of mobile belts as sutures difficult, they maintain, but not impossible.

Physical and chemical evidence has survived from the Precambrian which some researchers suggest indicate that plate tectonics in that era were the same as the Phanerozoic, but here again the data are limited. For example, Paul Hoffman of the Geological Survey of Canada, Ottawa, believes that he has identified an exceptionally well preserved 2 billion-year-old continental margin which has remnants of an initial rifting event. The structure of this margin also may contain the geologic record of the closing of an ocean basin. The Coronation Geosyncline of northwest Canada apparently developed as a repository of sediment along the western margin of an ancient continental plate which is more than 2.5 billion years old. This geosyncline is associated with a similar feature, the Athapuscow aulacogen, a filled trough that enters the proposed continental plate at an angle to its margin. The trough contains less sediment but includes volcanic rocks as well.

Hoffman draws a parallel between these two Precambrian features and the generally recognized incipient rifting observed today in the Afar region of Ethiopia. There, the Gulf of Aden and the Red Sea are opening into ocean basins, but the Ethiopian Rift, angled into the African continent like the third spoke of a wheel, has thus far not gone beyond a trough stage. The Afar region may thus be considered a model, Hoffman suggests, for the formation of the Coronation Geosyncline and Athapuscow aulacogen. The results of recent geologic mapping in the area have led Hoffman to speculate that a younger rock deformation, previously unrecognized, may have resulted from the closing of the same ocean that was initially formed from the rifting.

Isotopic Evidence

Another piece of evidence supporting the similarity of tectonic processes in the two eras is to be found in the strontium isotope ratios of Precambrian rocks. The present-day ratio of strontium-87 to strontium-86 in a rock depends upon its age and the amount of rubidium-87, the radioactive precursor of strontium-87, incorporated in the rock when it was chemically differentiated from its parent rock. Simple metamorphism cannot alter the ratio. Stephen Moorbath of the University of Oxford has found that the strontium ratio of the Nûk gneiss (metamorphic granite), which makes up a large part of western Greenland, is significantly different from that of the neighboring 3.75-billion-year-old Amîtsoq gneiss. Moorbath concludes that the 2.85-billion-year-old Nûk gneiss is not simply reworked Amîtsoq gneiss but was derived from the mantle. He suggests that, perhaps along with other processes, oceanic crust was being subducted, partially melted, and chemically differentiated to form new continental crust, as is now happening along the Andes of South America.

John Tarney of the University of Birmingham and Ian Dalziel and M. J. de Wit of Columbia University have suggested that another similarity in tectonic processes may be found between greenstone belt associations, which are always greater than 2.5 billion years old, and marginal basin complexes, which are common in the Phanerozoic. Greenstone belts consist of volcanic and sedimentary rocks that have suffered varying degrees of alteration by heat and pressure. These metamorphosed rocks were originally laid down on dry land as well as under water and are now surrounded by gneiss and dissected by other granites.

The origin of greenstone belts has been much debated, but Tarney and his colleagues argue that the formation and destruction of marginal basins, as recorded from about 130 million years ago in the "rocas verdes" of Chile, is a reasonable model for the more ancient greenstone belts. Marginal basins, such as the Japan Sea, apparently form by extension and fracturing of the crust on the continental side of a subduction zone, leaving a line of volcanic activity to its ocean side. When, for still obscure reasons, the basin begins to close, the volcanic lavas overlaid by collected sediments are compressed. Tarney's group suggests that the differences between today's marginal basins and ancient greenstone belts are not as great as had been thought. They reason that the chemistry of the rocks in greenstone belts and the behavior of the Precambrian crust may have been strongly affected by the higher radiogenic heat production known to have occurred then.

The importance of the earth's thermal evolution to the question of whether tectonics has evolved or remained uniform has been given varying weight by those involved in the debate. It is generally recognized that the production of heat in the earth's crust has decreased by a factor of about 3 in the last 4 billion years. Whether this decrease could have triggered a drastic change in the behavior of the crust, merely slowed plate tectonics to the pace seen today, or had no substantial effect is a matter of some debate.

David Chapman of the University of Utah and Henry Pollack of the University of Michigan believe that the higher heat production probably led to thinner and more numerous crustal plates whose motions were more active than those seen today. They base their conclusions on a map they constructed of the present-day thickness of the lithosphere, the cooler, rigid upper part of the earth's crust. The map was not drawn from direct measurements of lithospheric thickness. Rather, using several assumptions, they converted a large number of heat flow measurements to lithospheric thicknesses.

According to plate tectonic theory, lithospheric plates are able to move relative to one another because they are separated from the mantle by the athe-

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nosphere, a relatively plastic layer. Chapman and Pollack's map generally agrees with more direct but limited measurements and seems to indicate that the lithosphere thickens with age, older crust being thicker than younger crust. As the lithosphere thickens, the athenosphere becomes thinner and more viscous; that is, Chapman and Pollack suggest that the plate transporting machinery is slowly grinding to a halt.

Many geologists regard peridotitic komatiite, a unique type of lava which is always found to be at least 2.5 billion years old, as evidence of increased thermal effects early in the history of the earth. O'Nions notes that the tectonic implications of this high temperature, mantle-like rock are not unequivocal. He believes, however, that its very existence tends to support the idea of shallower high temperature regions, thinner plates, and rapid transport of mantle melting products to the surface. Burke, on the other hand, infers that while mantle convection was indeed faster, continental plate thickness and rigidity were essentially the same as now. He cites the apparent occurrence of deep, but relatively low-temperature, 2.5 billion-year-old metamorphism in the Superior Province of Canada.

Recent theoretical studies have emphasized the possible relation between the thermal structure of the crust and oceanic plate subduction. For example, A. J. Baer of the University of Ottawa has suggested that the warmer plates of the Precambrian might actually have been incapable of sinking into the mantle because of their higher buoyancy. If the buoyancy of a plate plays a role in determining its ability to be subducted, then its temperature could set its size. Baer argues that early plates were always too hot to allow a mineralogical phase transition to a denser form, thus preventing any subduction.

The final word concerning the behavior of the earth's crust during most of geologic time is not in. There does seem to be an apparent openness among a large number of researchers to the possibility of another tectonic mechanism, perhaps operating simultaneously with plate tectonics. This mechanism may have been a significant or even the dominant one very early in the Precambrian, only to be supplanted by plate tectonics. Confirmation of this possibility must, in all likelihood, await the accumulation of conclusive paleomagnetic and isotopic data.—RICHARD A. KERR

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