Radioactive dating provides a powerful way to measure geologic time. It has revealed the overall pace of the earth's evolution and has enabled researchers to calculate that our planet is about four and a half billion years old. Yet the earliest stages of terrestrial history—during which the earth acquired its large iron core and light, mobile continents—have eluded easy investigation because of the many processes that act to reset the radioactive clock.

As continents drift across the surface, the ocean floor between them recycles into the hot interior. Where continents clash, they raise folded mountains. Hot underlying material invades the continental rocks and can break through, unleashing lava that covers the surface. Erosion planes off the mountains and sweeps sediments into ocean trenches where they, too, return to the mantle.

Earth scientists are now using increasingly sophisticated techniques to pry meaningful stories about the earliest events in the earth's history from previously taciturn rocks. Examinations of ancient minerals are revealing when the first continents appeared and how extensive they were. Workers are also uncovering evidence that plate tectonics has operated throughout most of the earth's history much the same as it does now, contrary to some theoretical expectations. The recent discoveries are filling in the long-mysterious details of the formative years when our planet acquired many of its most characteristic traits.

To search for clues about the earth's youthful nature, geophysicists make use of an assortment of radioactive dating methods. These methods vary in their strengths and weaknesses, but they all rely on determining the relative abundances of a radioactive isotope and the subsequent isotope, or daughter nucleus, into which it decays. Every radioactive isotope eventually produces a final, stable decay product. Knowing the rate at which the nuclear transformation occurs (which can be measured to high precision in the laboratory) allows one to infer how long the decay products have been collecting in a rock. That information, taken with other evidence, reveals much about geologic history.

In the ongoing search for the oldest continental remnants, researchers primarily examine isotopes of uranium. Uranium ultimately decays into lead, so the relevant dating technique is called the uranium-lead method. That approach greatly benefits from the fact that samples of uranium and lead large enough to analyze can usually be extracted from zircon crystals. Such crystals are very commonly found in granitic and metamorphic rocks, as well as in some volcanic rocks and in sedimentary material derived from any of those rocks. Zircons also resist heat and weathering strongly, so they may survive intact in rocks that have experienced one or more metamorphic episodes.

A potential problem with the uranium-lead dating method is that rocks exposed to tremendous heat and pressure may lose a significant amount of their...
lead, thereby resetting the radioactive clock. In 1956 George W. Wetherill of the Carnegie Institution of Washington showed a way to circumvent the difficulty. His procedure depends on the fact that there exist two radioactive isotopes of uranium, uranium 238 and uranium 235. Each form of uranium follows its own decay path: uranium 238 breaks down into lead 206, uranium 235 into lead 207. Therefore, for any uranium-bearing mineral, researchers can derive an age estimate from two sources.

Wetherill measured the two uranium-lead abundance ratios in a large number of samples and plotted them against each other. On such a plot, samples that have never been disturbed, and hence that are perfect clocks, would lie along a continuous curve that Wetherill called a concordia curve. (The curve simply reflects the fact that both uranium 235 and uranium 238 decay at a steady, predictable rate.)

Wetherill then made the remarkable discovery that by plotting abundance ratios he could determine the age of a group of rock samples (all of the same age), even if much of their lead had leaked out during a metamorphic episode. His method works because lead 206 and lead 207 are chemically identical, and equal fractions of the two isotopes would have escaped from the rocks. When the abundance ratios of uranium to lead in the rocks are measured and plotted, the data points associated with the various samples fall on a straight line lying below the concordia curve. The end points of that line intersect the concordia curve at locations corresponding to the time of crystallization and to the time of metamorphism [see box on next page].

Applying the uranium-lead method to zircons can be difficult because zircon crystals frequently have a layered structure in which the original core is wrapped in subsequent mineral coatings. In the 1970s Thomas E. Krogh of the Royal Ontario Museum in Toronto demonstrated how to abrade zircons to isolate their cores; he also showed that

oldest known intact piece of the earth's surface. Radioactive dating indicates that the Acasta gneiss is nearly four billion years old, proving that some continental material existed only a few hundred million years after the earth's formation.
How Uranium-Lead Dating Works

Natural minerals such as zircons contain two isotopes of radioactive uranium: uranium 235, which decays into lead 207, and uranium 238, which decays into slightly lighter lead 206. In undisturbed zircons, plots comparing the two uranium-lead abundance ratios fall on a curve known as the concordia curve; their locations on the curve indicate the age of each sample. The uranium-lead data for zircons that underwent a metamorphic episode, thereby losing some of their lead, will fall along a line intersecting the concordia curve at two points (top). The upper point represents the original time when the rocks crystallized; the lower point indicates the time of metamorphism. Zircons from Mount Narryer in Australia all show some signs of disturbance (middle). Judging from how they fall on the concordia diagram, the oldest Mount Narryer zircons seem to be 4.1 to 4.2 billion years old; the others form three families 3.1, 3.3 and 3.75 billion years old. Based on similar reasoning, zircons from the Acasta gneiss appear to have crystallized about 3.96 billion years ago (bottom).

In 1983 SHRIMP began to supply noteworthy new information about the age of the earth's crust. Derek O. Froude of the Australian National University, working with Compston and others, began probing single crystals of zircon in quartzite, or metamorphosed sandstone, at Mount Narryer in Western Australia. Earlier work had shown that this region contains rocks about 3.6 billion years old. Froude's group performed detailed analysis on 20 zircon crystals from one rock specimen. Four of the crystals yielded lead-to-uranium data points indicative of an age of 4.1 to 4.2 billion years. Previously, the oldest known pieces of terrestrial material were rocks from southwest Greenland, which Stephen Moorbath of the University of Oxford and his co-workers had found to be 3.8 billion years old. The other 16 zircons furnished isotopic ratios that clustered around three lines that intersected the concordia curve at ages of about 3.75, 3.3 and 3.1 billion years, respectively.

Froude inferred that the 4.1- to 4.2-billion-year-old zircons and the 3.75-billion-year-old specimens formed long before they were incorporated into the surrounding sedimentary rocks. Somehow the zircons eroded from their parent rocks and found their way into sediments that later, under enormous heat and pressure, became the Mount Narryer quartzite. The younger, 3.3- and 3.1-billion-year-old zircons probably started growing during that period of metamorphism. Because zircons are found

the uranium-lead ratios of the cores frequently fall on Wetherill's concordia curve. Krogh concluded that the inner parts of the zircons had not been chemically altered and so still recorded the time when the mineral first crystallized.

During the 1980s, William Compston and Steven Clement of the Australian National University in Canberra took zircon dating one step further. Instead of analyzing the entire zircon core all at once, as researchers had previously done, Compston and Clement sought to study the composition—and hence the age—of the zircon at many spots. The researchers constructed a device that could blast a sample with a tightly focused (only 25 microns wide) beam of ionized, or electrically charged, oxygen atoms. Compston and Clement called their instrument SHRIMP, an acronym for Super High-Resolution Ion Micro-Probe. They trained SHRIMP at one spot on the inside of a zircon crystal that had been cut in half. The ions vaporize atoms of uranium and lead from that spot; the atoms then pass through a mass spectrometer that separates them by mass and counts them.

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overwhelmingly in continental rather than oceanic rocks, the Australians' finding strongly suggested that at least some continental material existed more than four billion years ago. Unfortunately, the zircons seem to be the only surviving relics of those ancient rocks.

In 1989, Samuel A. Bowring, then at Washington University, along with Ian S. Williams of the Australian National University and Compston, proved the existence of intact rocks nearly as old as the Australian zircons. The researchers trained SHRIMP on zircons from the Acasta gneiss, a small patch of metamorphic rock southeast of Great Bear Lake in the Northwest Territories. Bowring and his colleagues had earlier used Krogh's abrasion technique to determine that some zircons in the Acasta gneiss are at least 3.8 billion years old. Bowring suspected that buried inside the individual zircons lay evidence of even older ages; such information possibly could be extracted using SHRIMP. He therefore flew to Canberra carrying zircons from two Acasta rock samples.

The researchers probed a total of 82 spots on 53 of the zircons. When displayed on a Wetherill chart, the uranium-lead ratios from the two samples formed fan-shaped plots lying near the concordia curve. One plot fell between 3.6 and 3.96 billion years, the other between 3.8 and 3.96 billion years. Bowring and his co-workers concluded that the oldest zircons recorded the original crystallization age of the rocks. The spread in the data probably indicates that the zircons underwent at least two metamorphic episodes, one during the first few hundred million years after crystallization and another about two billion years ago.

If that interpretation is correct, then the Acasta gneiss is the metamorphosed remains of the oldest known intact, solid rock on the earth's surface. Geologists have identified other rocks nearly as old in Greenland, Labrador and Western Australia. Lance P. Black of the Bureau of Mineral Resources in Canberra and others, also using SHRIMP, recently reported finding 3.87-billion-year-old zircons in Antarctica as well.

These results leave little doubt that at least small patches of continental rock existed on the earth's surface during the first 700 million years of its history. They also underscore the incredible scarcity of crustal rocks more than four billion years old. Plate tectonics alone may not suffice to explain why such rocks are so rare. Perhaps the earth had an extensive primeval crust that was destroyed and remixed into the interior by the impact of giant meteorites, the leftovers from planetary formation. Vigorous convection, driven by the great internal heat of the newborn planet, might have aided that disruption by tearing apart blocks of continental rocks and by pulling continental sediments into the hot depths.

On the other hand, evidence is mounting, based on geochemical arguments, that the total amount of continental crust before about four billion years ago was minuscule. Studies of the relative abundances of isotopes of neodymium, strontium and lead in continental and oceanic crust imply that no more than trivial quantities of continental crust existed before then. About 3.8 billion years ago the earth's mantle began to separate into lighter and denser components, releasing the raw material from which continental blocks formed. The continents seem to have continued growing rapidly until roughly 2.5 billion years ago.

What were the earth's internal dynamics like during that era of swiftly expanding continents? My group in Toronto, in collaboration with Alfred Kröner of Gutenberg University in Mainz and Michael O. McWilliams of Stanford University, has been trying to address that question. We do so by assessing the extent of early continental drift. Geophysicists can trace recent continental motions by means of the magnetic record preserved in the ocean floor. Ocean floors survive only about 200 million years before they sink back into the earth's mantle at oceanic margins, such as along the Pacific trench off Asia.

Determining the motions of the continents more than two billion years ago demands extending the tools of geochronology to include measurements their inner structure. The researchers then measured the lead-to-uranium ratios at various spots in the zircons to find the oldest parts. The shallow pits were produced by beams of ions used to vaporize bits of the zircon crystals for analysis.
of a rock’s internal magnetism. When lavas erupt or when granites form in the outer layers of the earth, iron oxides in the rock become magnetized in the direction of the earth’s magnetic field at that site (the iron oxides act as tiny bar magnets that point toward the north pole). Measuring the direction of the field frozen into the rock reveals how far it was from the magnetic pole when it cooled. By studying the magnetism of rocks of varying ages, all from the same general site, one can, in principle, learn how much the continent has moved toward or away from the pole over time.

Unfortunately, if a rock is heated above a critical temperature, it loses its original magnetic direction and becomes remagnetized the next time it cools. The new direction may be totally different from the original if the continent has drifted significantly in latitude during the intervening years. If the rock was not severely reheated, however, some of the original magnetic orientation remains. In that case, geophysicists can extract from the rock a record of two ancient pole positions; one at the time of crystallization or initial cooling, the other at the time of metamorphic heating. Because all known Precambrian rocks have suffered some heating episode, it is critical to uncover a rock’s thermal history to decode its true magnetic record.

A valuable radioactive dating method known as the potassium-argon technique can sometimes permit researchers both to determine the age of magnetized rocks and to assess whether (and how much) they have been heated during their lifetime. Potassium 40, a rare isotope of potassium, decays to produce argon 40, a heavy version of the unreactive gas argon; the half-life of potassium 40 is 1.3 billion years. From the accumulation of argon 40 in potassium-bearing minerals, one can determine how long ago the mineral solidified.

Potassium-argon dating has assisted geochronologists in outlining the time scale of biological evolution over the past 500 million years. It has proved less appropriate for probing the earth’s more distant history because argon tends to leak from minerals during times of metamorphic heating. The uranium-lead method, along with a somewhat less widely used approach involving isotopes of rubidium and strontium, is more effective for revealing crystallization ages of the oldest rocks.

The ease with which the potassium-argon clock can be disturbed offers a compensating advantage: it enables researchers to unravel a rock’s thermal history. That information in turn makes it possible to make sense of the rock’s magnetic history. Geochronologists have studied many different kinds of minerals to determine how readily they release entrapped argon when heated. The common mineral hornblende has been shown to be quite resistant to loss of argon. Usually, only severe heating (above about 500 degrees Celsius) suffices to let some of the argon escape. The minerals muscovite and biotite, two forms of mica, are somewhat less resistant to heat; they can be disturbed by temperatures in the range of 250 to 350 degrees C. At the other extreme, the mineral feldspar shows signs of argon loss below 200 degrees C.

Workers searching for evidence of continental drift during the first half of the earth’s history have concentrated much of their attention on a series of remarkably well preserved rocks in the Barberton Mountain Land greenstone belt, located on the border between South Africa and Swaziland. The rocks are part of the Kaapvaal Craton, a section of stable, extremely old continental crust. The greenstone belt consists of numerous volcanic rocks buried underneath later sediments. Younger, granitic rocks have forced their way into the older greenstone layers.

My co-workers and I have looked for signs of tectonic drift more than two billion years ago by carrying out detailed magnetic analyses and by conducting both potassium-argon and uranium-lead zircon dating of two samples of granite from the Kaapvaal Craton. In Mainz, Kröner applied the uranium-lead method to single crystals of zircon from lavas in the craton and showed that they crystallized about 3.5 billion years ago, in broad agreement with earlier measurements made at the University of Cambridge. He also found that granites from the Nesbeet ge region of the Kaapvaal Craton crystallized about 3.2 billion years ago; granites from the nearby Mbabane region first cooled 2.69 billion years ago.

Paul W. Layer, Margarita Lopez-Martinez and I performed potassium-argon dating in my laboratory at the Universi-
forced out (steps 1–4, center); at each step, an age is derived from the ratio of argon 40 to argon 39. Low ages at cool temperatures indicate that some argon leaked out during the sample’s history; the plateau age at hotter temperatures should reflect the sample’s true age. At the right, laser step-heating of four hornblende grains from the Mbabane granite in Swaziland shows they are 2.7 billion years old, in close agreement with the age derived from uranium-lead measurements. Analysis of komatiite lavas from the same region reveals that they first cooled about 3.5 billion years ago.

![Graph of MBABANE GRANITE](image)

![Graph of KOMATITE LAVAS](image)

By modifying Megruie’s technique, my colleagues and I succeeded in using a continuously beamed laser to produce a precise age spectrum from a single grain of rock. We begin by bathing a bit of mineral in a low-power laser beam for 30 seconds and analyzing the released argon by means of a mass spectrometer. Then we increase the power of the laser beam in a series of increments and derive an age at each step. When the mineral fuses, it has reached its crystallization temperature, and the age spectrum is complete [see box above].

The combination of laser heating and argon-argon analysis is supplying impressively accurate information about the age and the thermal histories of ancient rocks. That information has enabled us to reconstruct an unprecedentedly well-documented account of continental drift as it occurred billions of years ago. We began by considering the history of the Mbabane granite. Layer and McWilliams had discovered that this rock contains a magnetic image of the pole, indicating that the rock solidified somewhere near the earth’s equator. Further analysis showed that the Mbabane granite acquired its magnetic orientation when the rock cooled from around 600 to 500 degrees C.

Laser argon-argon dating of four hornblende crystals in the granite, conducted by my group at Toronto, yielded an age spectrum displaying a broad plateau of 2.69 billion years, essentially identical with the uranium-lead age of the surrounding zircons derived by Kröner. The close agreement of the two dating techniques implies that the hornblendes, and hence the whole granite, had never been heated to temperatures above 500 degrees C after they first cooled. We concluded that the magnetic pole position detected in the granite was recorded when the rocks initially cooled and solidified some 2.69 billion years ago, at which time the Mbabane granite lay at the equator.

Layer and his colleagues had already deduced that another group of igneous rocks now located 12 kilometers from the Mbabane granite sat a little more than 30 degrees from the equator 2.875 billion years ago. If those two formations have always been close neighbors, then that area of the Kaapvaal Craton must have drifted through 30 degrees of latitude between 2.875 and 2.69 billion years ago. Such movement implies a drift rate of about 1.5 centimeters a year, comparable to the speed at which North America has drifted away from the Mid-Atlantic Ridge during the past 100 million years. We naturally wondered if plate tectonics occurred at the same pace during even earlier times.

Kröner had shown that the Nelshoogte granite is 3.21 billion years old. Laser analysis of individual hornblende crystals in the granite suggested that the rock acquired the magnetization early in its history, at least 3.18 billion years ago. When we examined the orientation of the magnetic field in the granite, we found that it, too, seemed to have formed 90 degrees away from the pole, that is, on the equator. But the direction of the North Pole recorded in the Nelshoogte granite lay many degrees away from the pole position frozen into the Mbabane granite, so the Kaapvaal
Craton must have rotated considerably during the intervening years.

Finally, we moved on to examine the oldest Barberton rock in our collection, fragments of magnesium-rich lavas known as komatiites. Zircons in volcanic rocks related to those lavas date from almost 3.5 billion years ago. David J. Dunlop and Chris J. Hale of the University of Toronto recovered a weak magnetic field frozen into the komatiites, indicating that when they first cooled, the lavas were only about 18 degrees from the pole—nowhere near the equator. The significance of this finding was unclear, however. The lavas evidently have been exposed to intense heat and pressure subsequent to their formation; they preserve few if any of their original minerals, so the magnetization observed by Dunlop and Hale could be much younger than 3.5 billion years.

To clarify the matter, Lopez-Martinez, then a graduate student in my laboratory, carried out an argon-argon measurement to determine the age of the komatiite samples. Much to her surprise—and to mine—her measured ages were indistinguishable from those that Kröner had found by studying zircons in the lavas. Zircons date the initial crystallization of the lavas, whereas argon-argon analysis measures the age of tremolite, a mineral that forms during metamorphism. The only way to make sense of Lopez-Martinez’s result is to conclude that the metamorphic event that created the tremolite must have occurred almost immediately after the lavas first erupted. If so, the pole location in the Barberton komatiites is a genuine recording of the location of the rock nearly 3.5 billion years ago.

Pulling together the above evidence yields an 800-million-year history of the drift of the Kaapvaal Craton, beginning 3.5 billion years ago. At that time, the craton was near the pole. By about 3.18 billion years ago it had wandered to the equator. The craton then moved more than 3,000 kilometers poleward, so that 2.875 billion years ago it lay at least 30 degrees from the equator. By 2.69 billion years ago the craton had drifted back to the equator, but its orientation was significantly different than it had been 490 million years earlier.

Our work implies that the Kaapvaal Craton was drifting about as fast as do modern continents since at least 3.5 billion years ago. Presumably, other continental fragments were behaving the same way. I should emphasize that despite the many advances in methodology and instrumentation, studies of magnetic traces still leave considerable room for error. Nevertheless, uranium-lead and argon-argon dating, when combined with paleomagnetic studies, have very much bolstered understanding of the earth’s dynamic early history.

The success of our investigation of the Barberton komatiites led us to wonder if the very oldest known rocks, the Acasta gneiss, carry a snapshot of their position relative to the magnetic pole 3.96 billion years ago. Much to our regret, they seem not to. In my laboratory, Hall performed preliminary argon-argon dating of hornblende crystals from one of Bowring’s samples. His results show that the rocks’ argon-argon clocks were reset by a pulse of tectonic activity 1.8 billion years ago. Any 3.96-billion-year-old magnetic traces evidently would have been completely erased.

Yet hope persists. Perhaps further measurements of rocks from the same region in northern Canada may yield a small fragment that escaped severe reheating during mountain-building events. The magnetic record in such a rock would be invaluable for decoding the earth’s evolution. Evidence that the earth possessed a significant magnetic field at that early date would be a telling sign that it had already developed a sizable metallic core—a key step in the transformation of an infant planet into a well-ordered, complex world.

**Further Reading**


