

ANCIENT CONTINENT OPENS WINDOW ON THE EARLY EARTH

by Carl Zimmer

ACASTA RIVER, NORTHWEST TERRITORIES--On the banks of the Acasta River, deep in the barrens of Canada's Northwest Territories, stands a lonely shed. There's no sign of humanity for many miles--just low hills, a few black spruce, a thick cover of reindeer moss, and an endless succession of lakes and rivers. The only way to get here is by canoe or by float plane. But this shed, filled with geologists' hammers, boats, and camping gear, marks a special place. Over the door is a plank on which someone has painted, "Acasta City Hall. Founded 4 Ga." It commemorates the surrounding rocks, some of which are over 4 billion years old--the oldest rocks on Earth.



Acasta River.

Geologists first recognized the antiquity of the Acasta region in the early 1980s, but at the time it wasn't clear whether its oldest rocks could say much about Earth's early history. Most of the ancient landmass to which the rocks belonged had been remelted, buried in the mantle, or eroded down to sand. What little remains has been deformed and shot through with intrusions of younger rocks. As a result, geologists had no clear idea how the oldest rocks were related to the surrounding formation (known as the Slave Province). It was as if most of the pieces to the ancient puzzle had been thrown out and the few remaining ones were tattered and torn.

But that is now changing. For the past 5 years, geologists led by Wouter Bleeker and Richard Stern of the Geological Survey of Canada (GSC) have been studying this remote territory intensively. Systematically traversing the region, they have mapped the Acasta area and adjacent parts of the Slave Province, and they have collected samples for precise dating based on uranium and lead isotopes to help them piece the jigsaw puzzle back together. "This is the oldest terrestrial crust known on Earth, so we need to understand it in as much detail as we can," says Bleeker.

Now the researchers have started to publish their results in several journals, including special issues of the Canadian Journal of Earth Sciences (July 1999) and Geoscience Canada (March 1998). They report that they have placed the Acasta rocks within a relatively large protocontinent. What's more, they can trace the history of that continental nucleus for 1.5 billion years after its beginnings 4 billion years ago. "The incredible longevity of history in this area is mind-boggling even for a geochronologist," says Stern.

In the process they are shedding light on some of the most important questions about the early Earth. When did the cores of the continents first become stable? Was this early crust created and destroyed by plate tectonics, as crustal rock is today? Or did some other process dominate the younger planet, as the new research hints? In the past, geologists have debated these questions fiercely but have had little evidence to draw on. Now they have a window on the planet's formative years. "[Bleeker] is doing it right," says Warren Hamilton, a geologist at the Colorado School of Mines in Golden. "He's going where the rocks and the dates take him. He's not working backward from a model and ignoring the data that don't fit."

Old rock, young Earth

By the 1980s geologists working in the region knew that the Slave Province represented an ancient core of a continent, known as a craton. The rocks dated back into the Archean eon, before 2.5 billion years ago, but beyond that their age was unclear--and given that the Archean takes up almost the first half of Earth's history, that was a lot of ambiguity. So Sam Bowring, now at the Massachusetts Institute of Technology, set out to determine the age of an Acasta rock by analyzing crystals known as zircons that had formed as the rock cooled and crystallized.

Zircons can act as timekeepers because they trap uranium in their lattice when they form, and the uranium then steadily decays into lead. Although zircons are remarkably durable, even they can get damaged over 4 billion years. New zircon crystals can grow on top of old ones, and old crystals can suffer radiation damage--all of which can throw off the uranium dating method. So researchers use a device called a Sensitive High-Resolution Ion Microprobe (otherwise known as a SHRIMP) to home in on undamaged parts of a zircon crystal. The SHRIMP fires a narrow beam of oxygen ions to blast atoms off a patch of the zircon's surface a few micrometers across, then analyzes the atoms' isotopic composition.

Bowring teamed up with researchers at Australian National University (ANU, the birthplace of SHRIMP technology) in Canberra to analyze the Acasta rock. In 1989 they reported that zircons in a few samples were at least 3.96 billion years old, edging out other ancient rocks elsewhere in the world by a few hundred million years. (Geologists have found individual zircons in Western Australia that date back further, to 4.28 billion years, but they had eroded out of their original rock and were incorporated into much younger sedimentary rocks.)



About 4.0-billion-years-old orthogneisses and older enclaves of mafic rock.

Later, some of the rocks at Acasta sneaked past the 4-billion-year mark. The Geological Survey of Canada purchased a SHRIMP from ANU in 1995 and within a few months was using it for a systematic survey of the rocks around Acasta. "Nobody would want to go digging around in a place like that without such a tool. You couldn't solve anything without it," says Stern. In 1997 the Canadians announced that they had dated the rocks to 4.03 billion years ago. Meanwhile, Bowring and Ian Williams of ANU dated more samples from Acasta and got essentially the same age. Since then the Canadian team has pushed back the date even further--to 4.055 billion years ago. The rocks formed when Earth itself was a little over 500 million years old, its interior still seething hot from its formation and its surface pummeled by asteroids and comets.

Now the mapping project led by the GSC's Bleeker is beginning to work out how these oldest rocks--found to date in only a few square kilometers of the Slave--are related to the formations that surround them. In many parts of the Slave Province, a recurring geological pattern can be seen exposed on riverbanks and hillsides. The lowermost, oldest layers of rock--which include the 4-billion-year-old specimens--are made of gneiss, a metamorphic rock created under high temperatures and pressures. The top of the gneiss is weathered and uneven, suggesting that the rock was exposed for a long period, eons ago. Above lie much younger layers of rock--quartzite, banded iron formations, and volcanic rocks--creating a time gap called an unconformity. Previous researchers had noticed this succession of layers here and there in the Slave Province, but Bleeker has now traced the stratigraphy across hundreds of kilometers. John Ketchum, another geochronologist on the team, has dated two volcanic layers above the unconformity, and they consistently date to just over 2.8 billion years. "Correlations over such large distances are tricky," says Bleeker. "But we feel we've got it worked out."

The researchers conclude that these Archean gneisses were not scattered, unrelated bits of crust but were united, at least 2.9 billion years ago, in a protocontinent. It then experienced uplift, possibly as a hot mantle plume pushed it up from below. As the

continent rose, its surface eroded, creating the unconformity. Then it began to subside (perhaps as the plume dissipated) and sank far below the surface of an ancient ocean, where sediments could cover it: first quartz-rich sandstone, and then other sediments that formed the banded iron formations. Finally volcanic rocks spread over its surface as the Slave protocontinent was rifted apart about 2.8 billion to 2.7 billion years ago.

Nested in the heart of this continental nucleus are the 4-billion-year-old Acasta gneisses, as the researchers will report in *Current Research 2000*, Geological Survey of Canada. Their position below the unconformity indicates that these ancient rocks don't represent some exotic tectonic sliver driven into the Slave hundreds of millions of years after it formed. "This work places the Acasta gneisses firmly in this larger geological entity," says Stern, implying that they mark the very core of the continent. "Perhaps it was a piece of crust that survived [impacts of giant] meteorites and avoided getting stuffed down into the mantle, and it acted like a seed for further crust formation. At this stage of the game, we don't really know why this place is so special."

A protosupercontinent?

The new maps of the region around the Acasta will help geologists search for more rocks over 4 billion years old. But researchers are less interested in breaking records than in decoding the 1.5-billion-year history of this protocontinent. One pressing question is whether it was actually part of an even bigger landmass. In more recent Earth history, continents seem to have evolved in a cyclical pattern, colliding to form a supercontinent, which later rifts apart and then joins back together in a different arrangement. The last supercontinent was Pangaea, which started splitting up about 200 million years ago; its predecessor was Rodinia, which aggregated about 1 billion years ago.

Before Rodinia, the record is shadowy, but some researchers have speculated that a supercontinent existed as early as 3 billion years ago. Bleeker thinks the protocontinent he and his colleagues have mapped may have been part of it. Along the eastern edge of the territory they mapped, for example, the old gneisses, the distinctive unconformity, and overlying quartzite and banded iron formations are all missing. That suggests that the eastern part must have rifted off at some point and drifted away. "If you see the head of an elephant cut off at the neck," says Bleeker, "you know there must be a body lying around somewhere." Bleeker suggests that parts of the body may already have been identified: Archean cratons of the same age in Zimbabwe, Wyoming, and elsewhere have been reported to have quartzite layers and banded iron overlaying gneisses as well. "These may be several pieces of a larger continent of which the Slave nucleus is just one remnant," he says.

By connecting these continental nuclei, geologists may also gain insight into how the early Earth behaved. On the modern Earth, plate tectonics assembles and destroys continents. They float atop rigid plates, which are pushed around the planet by the mantle's roiling heat. Where the plates rift apart, continents are divided and new oceans form; where they collide, mountains are pushed up, or one plate often dives beneath the other in a subduction zone, fueling volcanoes that build new crust on the overlying plate. But Bleeker thinks several features of the ancient rocks indicate that plate tectonics may not have shaped the Slave protocontinent during its first billion years. "I'm not sure plate tectonics will be the best explanation," he says, at least for the growth of the oldest crust.

Many geologists have envisioned an early start for plate tectonics, with small tectonic plates crashing into each other as much as 4 billion years ago. They point out that the

earliest kinds of rocks, such as gneisses, have a chemistry similar to rocks formed today by plate tectonics. They've also pointed to places, including parts of the Slave, that seem to show signs of plate-tectonic activity such as sea-floor spreading or accretionary prisms--the piles of sediments scraped off a plate as it descends into the mantle.

But others have argued that plate tectonics would have been impossible on the early Earth. They point out that 3 billion to 4 billion years ago the planet was much hotter than it is today--too hot, they say, for rigid continental plates to form. They also argue that the hot surface layer would have been too buoyant to sink in subduction zones, and without sinking plates, the whole plate-tectonic cycle grinds to a halt. And they've questioned whether geochemistry alone can say anything certain about how rocks were formed. "It's groupthink, with a bunch of people who don't know what they're comparing [Archean geology] to," says Hamilton of the Colorado School of Mines, who helped formulate the theory of plate tectonics in the 1960s and 1970s but has become an outspoken opponent of the idea that it operated in the Archean.

Believers in ancient plate tectonics will find little comfort in the new results. Bleeker says the oldest parts of the Slave province seem to lack key signatures of plate tectonics, such as the long, narrow belts of accreted and deformed rocks. The mapping has even eliminated some supposed relics of ancient plate tectonics. Bleeker and his co-workers say, however, that they aren't coming down against plate tectonics, only calling it into question. "Plate tectonics is an attractive paradigm, because we understand it well," says Bleeker. "But that doesn't necessarily mean it is the best model for the early Archean."

Exactly what process might have been at work to build the ancient continent remains a matter of speculation. "That's where things get much more tenuous," admits Hamilton. In the nucleus of the old continent, rocks differing in age by a billion years or more are sometimes juxtaposed. That's not what geologists expect from the gradual accretion of crust at plate boundaries, but it could be the handiwork of episodic volcanic outbursts, fed by broad plumes of rock that rose periodically from deep in the mantle. "We need some stretching or cracking, and then it comes bubbling up," says Hamilton. These lava flows would have gradually built up the continental nuclei. Eventually the planet cooled enough for plate tectonics to take over. Bleeker speculates that the breakup of the continental nucleus his team has documented at 2.8 billion to 2.7 billion years ago might represent the dawn of plate tectonics.

Paul Hoffman of Harvard University cautions that looking only at a small area like the Slave won't be able to resolve the debate. "I hate to be negative, but ... a fragment of crust the size of the Slave Province is simply too small to ever work out the governing tectonic boundary conditions." Hoffman accepts the ancient geography that Bleeker and his colleagues have mapped, but he says that geologists will need to compare its distinctive stratigraphy with what they find on other fragments of ancient crust to conclude anything about ancient tectonic processes. Bleeker agrees: "It's critical to try and find matching pieces scattered around the globe." But he adds that Earth's oldest crust is a good place to start. "The Slave Province is a wonderful laboratory for all these questions."

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Midnight rainbow from camp site at Acasta River

3. The ~4.0 Ga Acasta Gneiss Complex, Slave craton, Canada

Ancient crustal rocks provide the only direct evidence for surface tectonics, and the processes and products of differentiation in early Earth. However, the oldest recognized terrestrial rocks (~3600 Ma) are rare, and only nine terrains are preserved. The Acasta Gneiss Complex contains the 4.03 Ga orthogneisses (Bowring & Williams, 1999), which are the oldest rocks in the world so far.

We have reinvestigated geology and geochronology of the Acasta Gneiss Complex in Slave Province, Northwest Territories of Canada. Based on detailed 1:5000 scale geological mapping and petrographic investigation of about 1000 specimen, we have documented six distinct lithofacies, and at least eight tectonothermal events (Komiya et al., 2003). My research has focused on searching for information of the earliest surface environment through the study of multiple sulfur isotopes.

Photos from article by Yuichiro Ueno