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National Park Service
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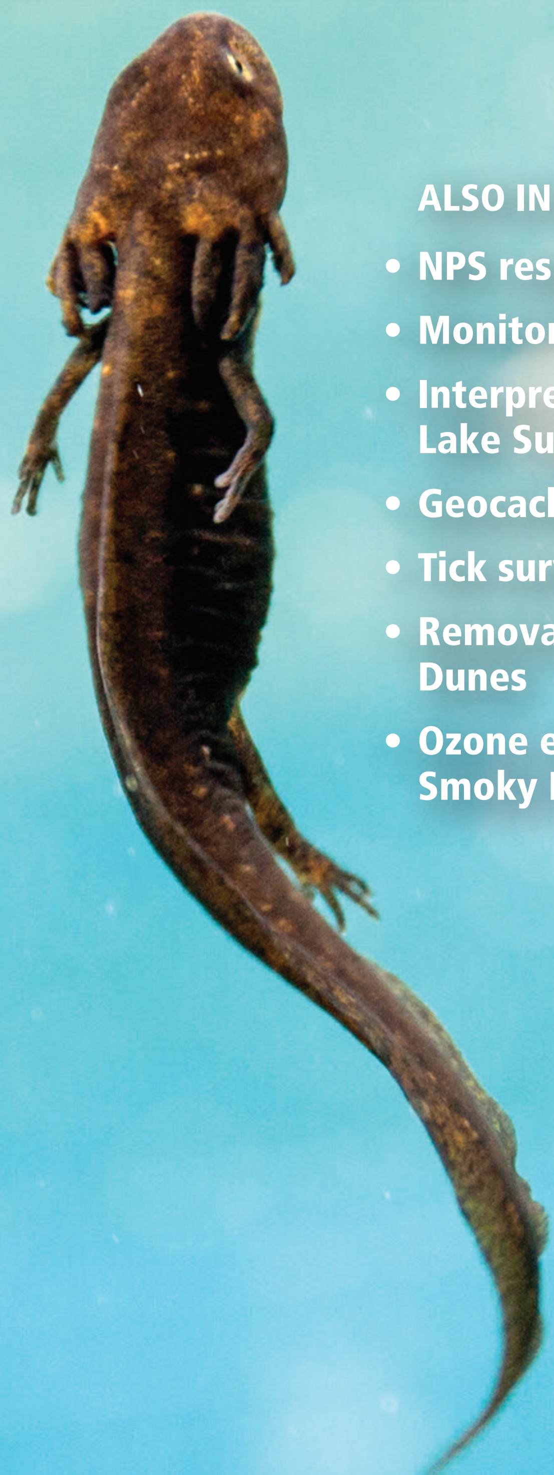
Natural Resource Stewardship and Science
Office of Education and Outreach

THE MAZAMA NEWT: CLASH WITH NONNATIVE CRAYFISH IN CRATER LAKE



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- Monitoring physiological stress in pikas
- Interpretive primer: The Midcontinent Rift and Lake Superior parks
- Geocaches as interpretation at Everglades
- Tick surveillance along the Appalachian Trail
- Removal of artesian wells from Great Sand Dunes
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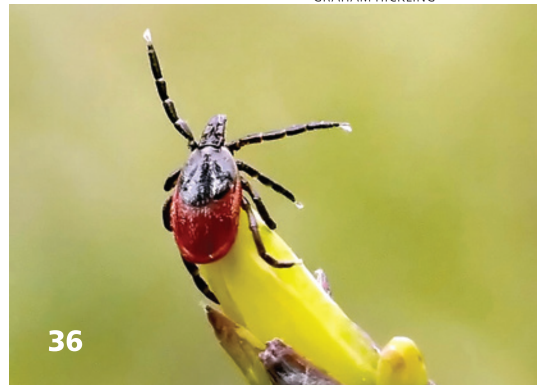
NPS PHOTO

GRAHAM HICKLING



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A Mazama newt swims toward the surface of Crater Lake, Oregon. This endemic species' liquid habitat is as clear and clean as nearly any on Earth, yet it faces increasing competition from a nonnative predator.

Interpretive Primer

SETH STEIN

Using Lake Superior parks to explain the Midcontinent Rift

By Seth Stein, Carol A. Stein, Eunice Blavascunas, and Jonas Kley

Kayakers paddle past sandstone rocks in Apostle Islands National Lakeshore. Geologists are trying to establish the age of these rocks, which would give insight into how and when the Midcontinent Rift System died.

Abstract

Few areas give interpreters and educators the opportunity to illustrate geoheritage—the role of geology in shaping an area's culture and growth—as well as the Lake Superior region. Lake Superior itself, and the spectacular scenery around it in national, state, and provincial parks, result from a huge geologic structure. Known as the Midcontinent Rift System (MCRS), this structure is a 1.1 billion–year–old, about 1,800-mile (3,000 km) long scar along which the North American continent started to tear apart, but for some reason failed to form a new ocean. The rift gave rise to Lake Superior, which is the basis of the area's water-based history and economy, the copper and building stone deposits that shaped the region's settlement and growth, and today's tourist industry.

Key words

Lake Superior parks, Midcontinent Rift System, mineral deposits, plate tectonics, regional history

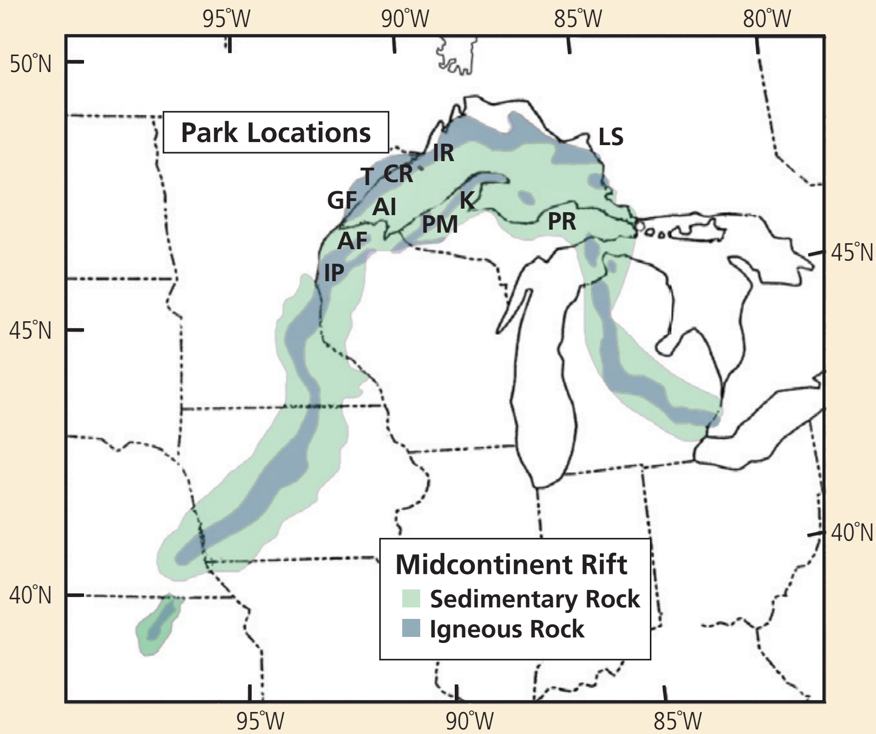
SOME OF THE MIDWEST'S MOST spectacular scenery occurs near Lake Superior, in places like Pictured Rocks and Apostle Islands National Lakeshores, Isle Royale National Park, Interstate Park, and Porcupine Mountains Wilderness State Park. These landscapes provide an enormous but underused opportunity for park interpreters and educators to explain some of the most important processes that shape our planet. A crucial aspect of doing this is recognizing that many of the rocks and landforms in the Lake Superior parks are pieces of a huge regional structure. Called the Midcontinent Rift System (MCRS), this structure is a 1.1 billion–year–old, 1,864-mile (3,000 km) long, mostly buried scar along which the North American continent started to tear apart. However, the rifting stopped for some reason and failed to form a new ocean. The MCRS also provided mineral deposits that shaped the region's settlement and growth. Drawing on our experience as researchers and teachers studying the MCRS (Steins and Jonas Kley) and as an interpreter at Isle Royale National Park (Eunice Blavascunas), we seek to give interpreters a brief introduction to MCRS to help them present information to visitors in nontechnical terms about what geologists know already and what they are learning from continuing research. Our goal is to help interpreters visualize and explain how what they see at a specific site fits into an exciting regional picture spanning much of the Midwest and more than a quarter of Earth's history.

Finding the Midcontinent Rift

Many of the rocks around Lake Superior are part of one of the Midwest's most impressive geological features, the long belt of igneous (mostly volcanic) and sedimentary rocks called the Midcontinent Rift System (MCRS) or the Keweenaw Rift (fig. 1, next page). The rift system has two major arms meeting in the Lake Superior region (Hinze et al. 1997; Ojakangas et al. 2001). One extends southwestward at least as far as Oklahoma, and the other extends southeastward through Michigan to Alabama.

Interpreters will find that despite the rift's size, most visitors do not know about it, because these rocks are mostly covered by sediments and sedimentary rocks younger than those of the rift. They appear at Earth's surface only near Lake Superior. One of the best exposures is along the St. Croix River on the Wisconsin-Minnesota border (fig. 2, next page), where the river has cut through a huge stack of lava flows from the rift. Similar flows can be seen in many places, including Isle Royale and the parks along Minnesota's north shore. These flows are billion-year-old versions of modern basalt lava flows that can be seen in Hawaii Volcanoes National Park, or the geologically young (few thousand years) flows at Craters of the Moon National Monument in Idaho. Basalt rock forms from dark, very fluid or "runny" (low-viscosity) lava that typically erupts from hot spot (Hawaii) or rift volcanoes

Figure 1. Location and general structure of the Midcontinent Rift, showing some of the parks where rift-related rocks can be seen. Igneous rocks in the rift can be seen at Interstate (IP), Isle Royale (IR), Amincon Falls (AF), Gooseberry Falls (GF), Tettegouche (T), Cascade River (CR), Lake Superior (LS), and Porcupine Mountains (PM) parks. Sediments deposited after the volcanism can be seen at Apostle Islands (AI) and Pictured Rocks (PR) National Lakeshores. The history of copper mining in the rift rocks is presented at Keweenaw National Historical Park (K).



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and flows out on Earth's surface before it solidifies.

Geologists combine what they learn from the exposed rocks with clever techniques that allow them to "see" the deeply buried parts of the rift. One technique uses very accurate measurements of gravity and magnetism (fig. 3). The buried volcanic rocks contain lots of iron, and so are denser and more magnetic than the surrounding rocks. These can be detected by gravity surveys that use equipment like a super-precise bathroom scale, and magnetic surveys that use equipment like a super-precise metal detector. Surveys have mapped a huge thickness—up to 15 miles or 25 km—of volcanic rocks, so the entire rift system has more than 240,000 cubic miles (a million cubic kilometers) of volcanic rocks. This is 44 times the volume of all the Great Lakes combined!

Other methods use seismic waves, vibrations traveling through rock, to visualize at depth. This method, which is also used to find oil and natural gas deposits, is like the way doctors use ultrasound to see inside patients. Surveys across Lake Superior (fig. 4) used seismic waves generated by a sound source towed behind a boat (Green et al. 1989). The seismic waves travel downward, reflect off interfaces at depth between different rocks, and return to the surface. The reflected waves are detected by seismometers at the surface, and computers generate graphics called "seismograms" that provide an image of deeply buried rock layers. A north-south cross section compiled from seismograms shows a deep depression under Lake Superior filled by layers of volcanic rocks and overlying

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Figure 2. Basalt flows form cliffs at Interstate Park along the St. Croix River, Wisconsin.

STEIN ET AL. 2014

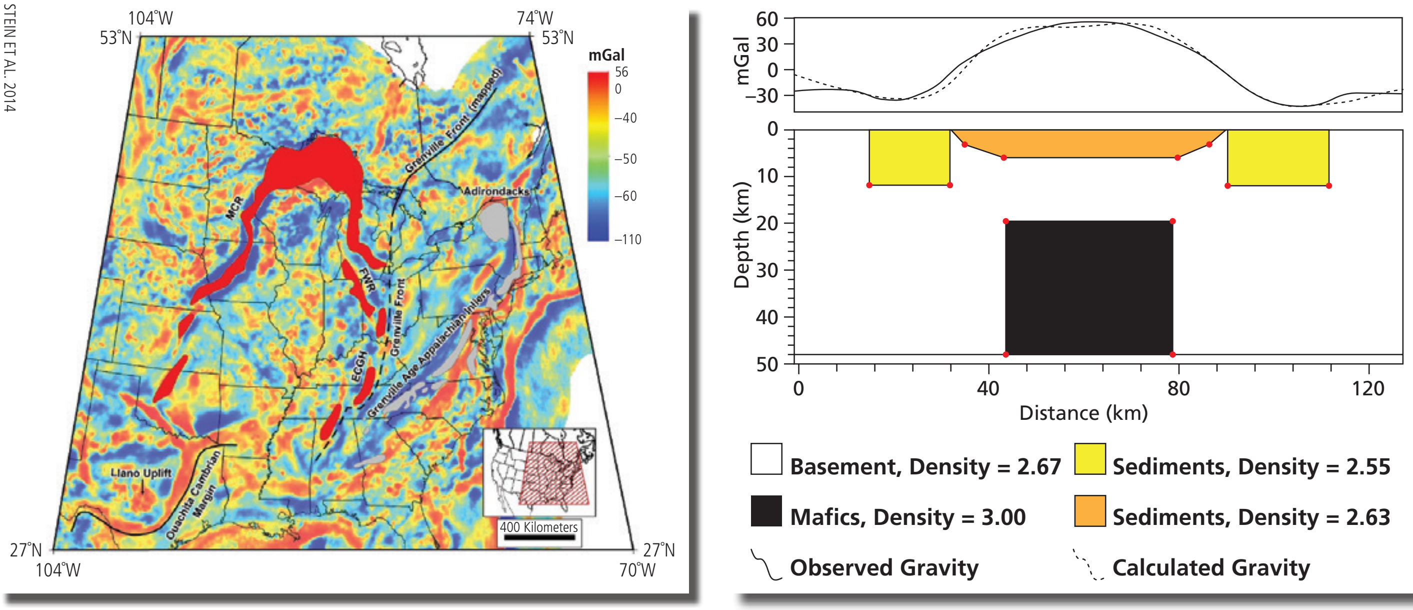

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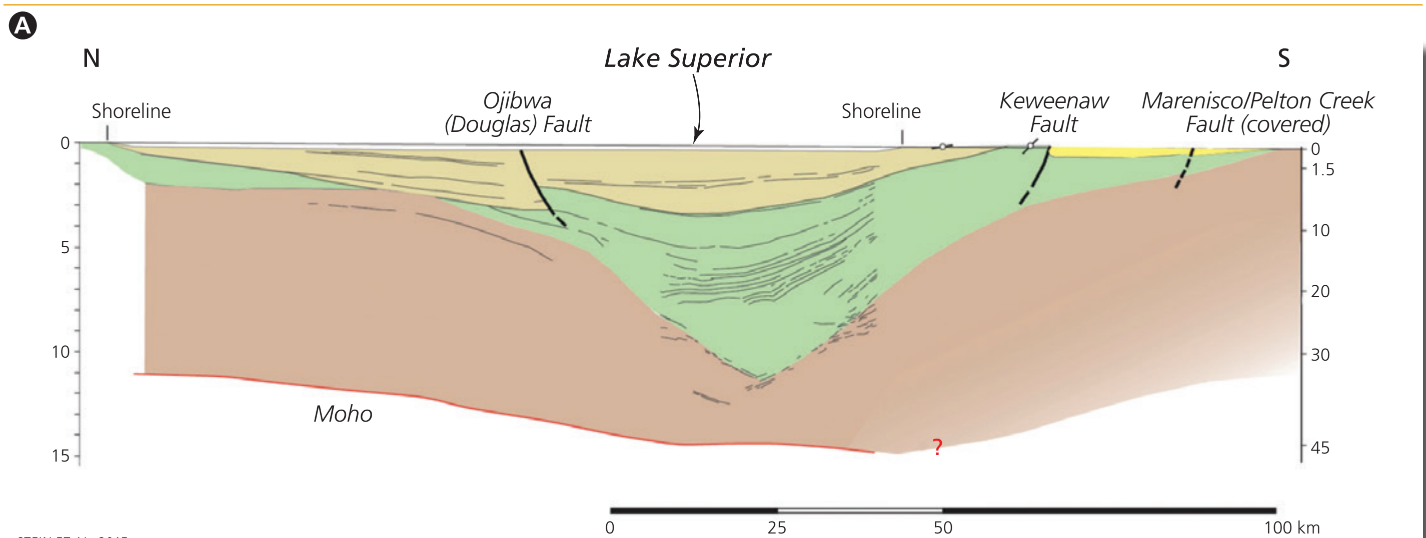
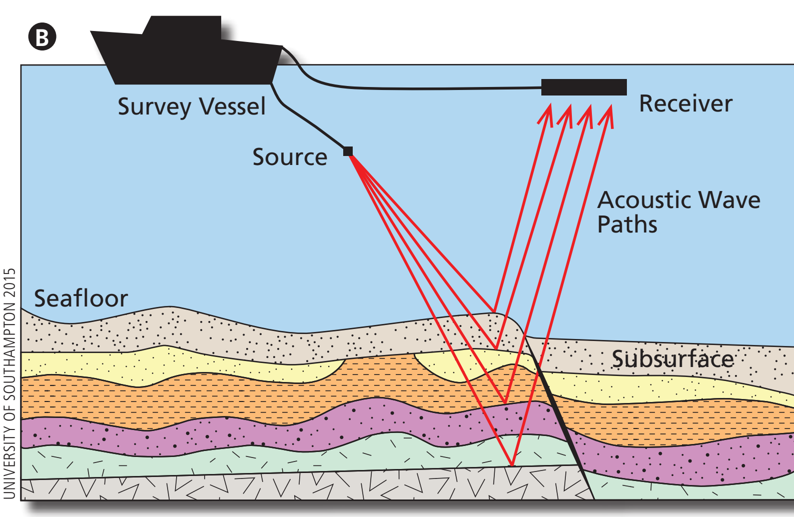
Figure 3. The gravity map on the left shows the Midcontinent Rift (MCR) and its continuations along the Fort Wayne Rift (FWR), and East Continent Gravity High (ECGH), indicated by high values (red). The conceptual model on the right shows a cross section of the MCR, illustrating how dense igneous rocks at depth (black rectangle) cause stronger gravity at the surface. The density of the rocks is given in g/cm^3 and the gravity effect of the rocks is measured in milligals (mGal), which are about a millionth of Earth's average surface gravity.



STEIN ET AL. 2015

Figure 4. The illustration (A) is a cross section below Lake Superior drawn from seismic reflection profile data, showing the U-shaped rift filled by volcanic rocks (green) and overlying sediments (tan). At the right (B) the illustration shows how seismic reflection profiling works.



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sediments to a depth of 18 miles (30 km), which is much deeper than Lake Superior's average depth of about 500 feet (150 m). This structure is a "U-shaped" type of fold called a syncline. The volcanic rocks and associated sediments on the north side—as seen at Isle Royale—dip southward toward the center of the lake, whereas those on

SETH STEIN (2)

Figure 5. MCRS rocks on either side of the syncline are shown in the photos. (Left) North-dipping sediments near Copper Harbor, Michigan, on the Keweenaw Peninsula. (Right) South-dipping basalt flows near Rock Harbor, Isle Royale National Park.

the south side—as seen in the Keweenaw Peninsula—dip to the north (fig. 5).

More recent studies are using data from the National Science Foundation's EarthScope program (http://www.earthscope.org/). One component of EarthScope is the transportable array of 400 seismometers installed at sites about 45 miles (70 km) apart, extending across the United States from north to south. After two years at a site, each instrument is picked up and moved to the next location on the eastern edge of the array, so the array moves across the country. In addition, a network of seismometers called SPREE (Superior Province Rifting EarthScope Experiment), operated by Northwestern University, Washington University in St. Louis, the University of Minnesota, the University of Manitoba, and the University of Quebec at Montreal, recorded data for two years across and along parts of the rift (fig. 6). These studies' goal is to see how the rift area differs at depth from its surroundings (Shen et al. 2013) and thus how the deeply buried rocks record the events that formed the rift. Other ongoing research includes further gravity studies by researchers from the University of Oklahoma and studies of the electrical properties of the rift rocks by researchers from Oregon State University and the University of Utah.

SUZAN VAN DER LEE

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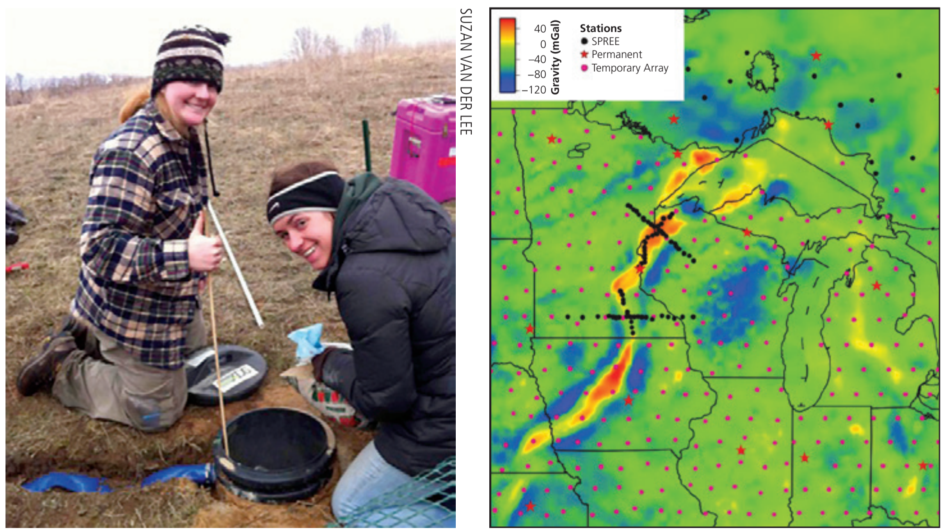

Figure 6. (Left) Northwestern University graduate students Emily Wolin and Jessica Lodewyk install a temporary SPREE seismic station in northern Wisconsin. (Right) The gravity anomaly map of the Midcontinent Rift region also shows the locations of permanent (stars), transportable array (red dots), and flexible array seismic stations (black dots) being used in SPREE.

How old is it?

The volcanic rocks in the rift are about 1,100 million, or 1.1 billion, years old (Davis and Green 1997). These dates come from measuring the concentration of isotopes of radioactive elements that decay into other isotopes. This method is like the carbon-14 dating used by archaeologists to study artifacts from ancient civilizations, but uses minerals containing uranium and lead isotopes that have much longer half-lives to date much older rocks. Their age, 1.1 billion years, is about a quarter of the age of Earth, 4.6 billion years. This time is during the Mesoproterozoic Era (1.6–1

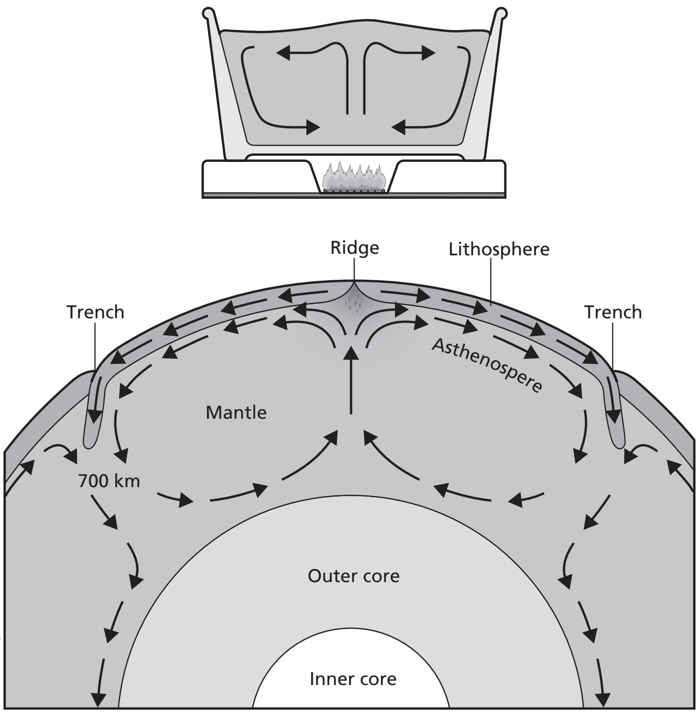

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Figure 7 (top). An ideal convection cell is illustrated by a pot of boiling water on a stove. (Bottom) Plate tectonics results from convection in Earth's mantle. The real pattern is more complicated than this ideal picture.

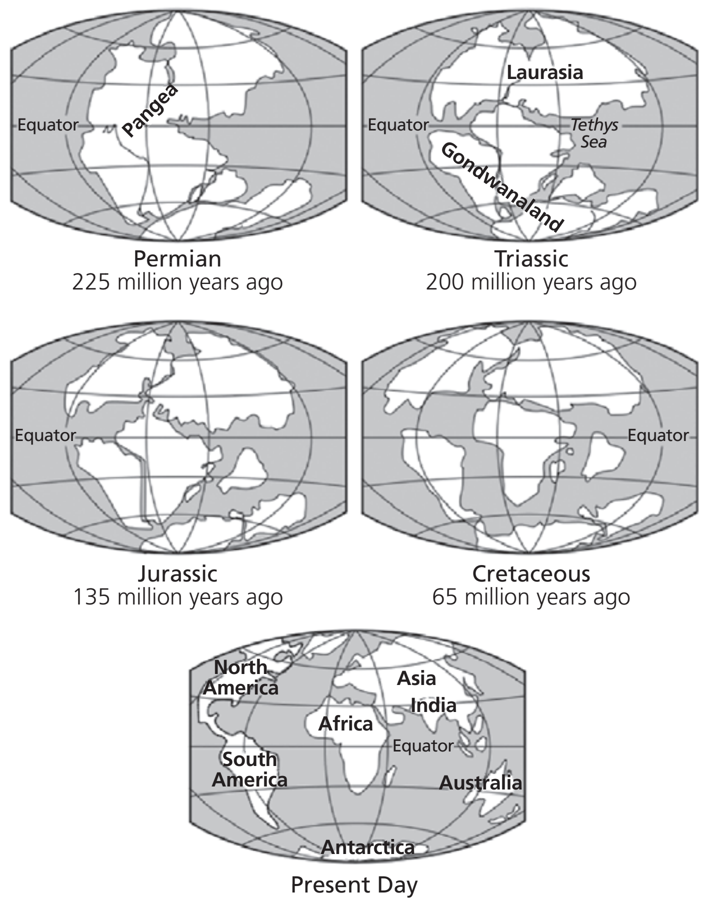

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Figure 8 (right). Reconstruction of Pangaea and the motions of the continents since its breakup.

billion years ago), during which the most complex organisms included multicellular algae. It is long before dinosaurs appeared, about 230 million years ago.

Rifts and plate tectonics

The Midcontinent Rift demonstrates important aspects of the fundamental concept of modern geology, plate tectonics, which explains how Earth works and why it differs from our neighboring planets. The key aspect of plate tectonics is that Earth's outer shell consists of continent- and ocean-sized moving plates of relatively cold, strong rock, about 60 miles (100 km) thick, that move relative to one another at speeds of a few inches per year—about the speed fingernails grow (fig. 7). This shell is called the lithosphere. The strong plates slide over warmer and weaker rocks below called the asthenosphere.

Plates are pretty rigid, which means that their insides do not deform much. Instead, almost all the geological action happens at the boundaries between plates, like the San Andreas Fault. These are where most earthquakes and volcanic eruptions occur and where mountains are constructed. Plates are like ice chunks floating around on water, sliding by and banging into one another.

What happens at the boundary between two plates depends on the motion between them. At divergent boundaries, such as a mid-ocean ridge or continental rift, plates move away from each other, whereas at convergent boundaries they move toward each other. At the third type, transform fault boundaries, plates slide by each other. For example, earthquakes happen on California's San Andreas Fault because it is part of the transform boundary between the Pacific and North American plates.

To see how plate tectonics works, think of heating a pot of water on a stove. As the water on the bottom gets hotter, it expands, becomes less dense, and rises to the top. Once it gets there, it cools, becomes denser, and sinks. This process of hot fluid rising and cold fluid sinking is called convection. Plate tectonics is a more complicated version of this simple convection system. Mid-ocean ridges are upwelling areas where hot material rises from the deep mantle and cools to form cold, strong plates. Subduction zones are downwelling areas where plates are consumed as their cold material sinks, heats up, and is mixed back into the mantle.

The heat causing convection is partly left over from when the planet accreted from a dust cloud and partly from the decay of radioactive elements. Earth still has enough heat for active convection, but Mars—which is much smaller, about the size of Earth's core—has cooled too much for active plate tectonics.

Because plates move relative to each other, their geometry changes with time. Continents come together to form supercontinents—such as Pangaea 225 million years ago (fig. 8, previous page)—that later split apart in a process called rifting. A successful rift evolves into a new mid-ocean ridge that creates a new ocean basin between the pieces of continent. However, some rifts fail, because rifting stops before a new ocean basin forms. The MCRS is a very old rift that failed to split North America 1.1 billion years ago.

Figure 9. Samples of basalt (left) and granite (right).

CAROL STEIN

The creation of ocean basins between continents occurs because rocks of Earth's crust under continents are different from those under the oceans. Crust under the continents is pretty much like granite, the light-colored rock in figure 9. Granite is exposed in places like Yosemite National Park in California, Mount Rushmore National Memorial in South Dakota, and Missouri's Saint Francis Mountains. When these rocks are eroded by rain, wind, and ice, the sediments that result are carried by rivers and end up in places like beaches, giving us the beautiful white sand along the Great Lakes' shores. Some of this sand turns into the sandstone rock that appears in many places in the Midwest.

In contrast, the crust under the oceans is mostly basalt, the darker rock in the picture. Basalt is the volcanic rock that forms plates at mid-ocean ridges. It is not as common on the continents as granite, but there is some. Basalt lava flows fill the Midcontinent Rift, as shown by the cliffs along the St. Croix River (see fig. 2), on Isle Royale (see fig. 5), and along the shores of Lake Superior.

Granite and basalt have different colors because they have different chemistry. Granite contains mostly the elements silicon and oxygen, while basalt has less of these and more iron and magnesium. That difference makes granite about 15% less dense than basalt, which means that a chunk of granite weighs about 15% less than a chunk of basalt of the same size.

This density difference has a huge consequence for how Earth works. Because the continents are made up of less dense granite, they "float" higher than the denser basalt under the oceans, just the way wood floats in denser water. For the same reason, the rocks forming the continents do not sink into the denser mantle at subduction zones, so continental rocks stay at the surface much longer than oceanic rocks. That is why oceanic lithosphere is never more than 200 million years old, but billion-year-old continental rocks are found in the Midwest.

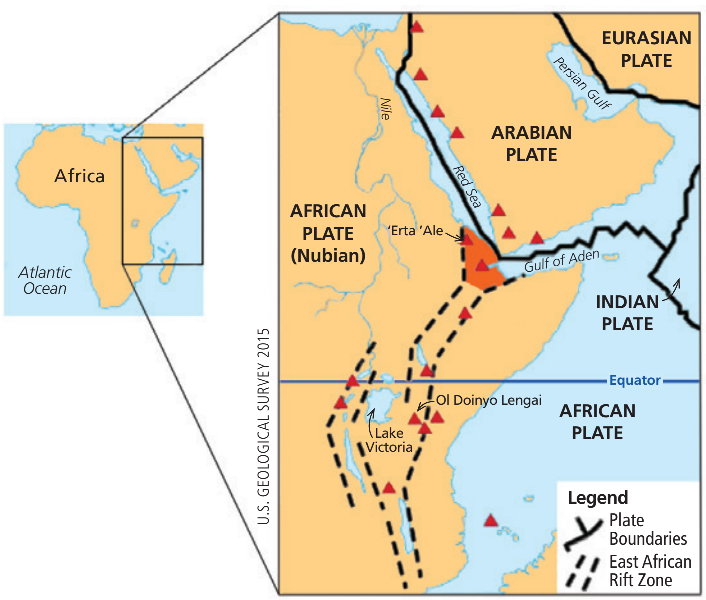

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Figure 10. (Left) Geometry of the East African Rift. Triangles indicate active volcanoes. (Right) The East African Rift in Kenya. The MCRS looked similar before it was filled by sediment, but its volcanic rocks can be seen in some places today (see figs. 1, 2, and 5).

Continental rifting

To understand how plate tectonics operates, geologists use one of their most powerful methods: visualizing how features formed in the past by looking at places where similar features are forming today. Geologists often say "the present is the key to the past." That is nice because it is a lot easier to see the present. For example, if we did not know how people grew up, we could get a good idea by looking around and seeing babies, toddlers, children, teenagers, young adults, and older adults.

To study how the Midcontinent Rift formed more than a billion years ago, we can look at a similar feature that is active today. For example, the East African Rift is splitting up Africa, forming the huge rift valley and causing volcanoes like Mount Kilimanjaro. The rift system is dividing Africa into two plates and rifting Arabia away from it, forming new ocean basins in the Red Sea and Gulf of Aden between the landmasses (fig. 10). That is how the Midcontinent Rift looked 1.1 billion years ago. Of course, there were no lions, giraffes, trees, or even grass—because they had not evolved yet.

The East African Rift is in the early stages of the life cycle that continents and oceans go through, called the Wilson cycle (fig. 11). It begins when part of the continent starts to be pulled apart. The process involves heating from below, but geologists still do not know exactly why and how. The granite crust stretches like taffy and starts to break along newly formed faults, and a rift valley forms as earthquakes move blocks of crust downward, while the material below flows sideways. It is like what happens if you pull both ends of a candy bar that has an outer chocolate shell and a nougat interior: the chocolate layer breaks and the inside stretches and bends downward (fig. 12).

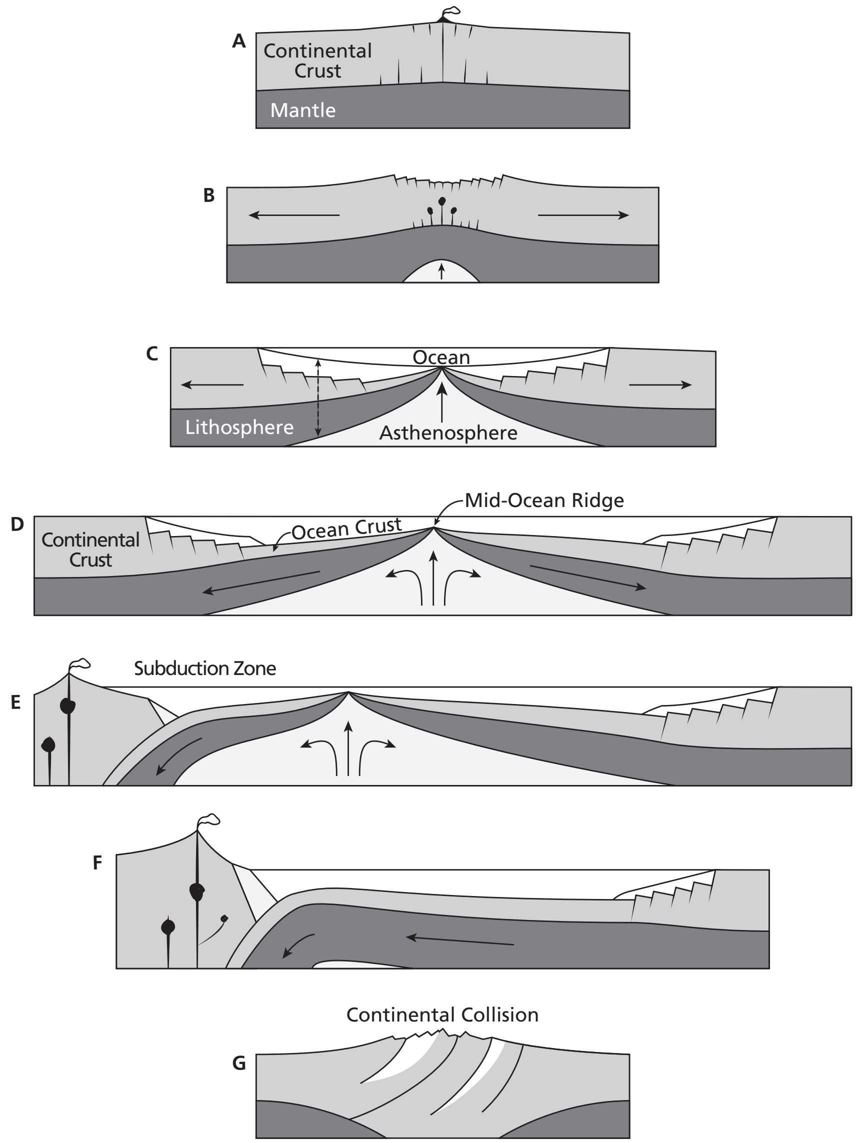

Figure 11. The Wilson cycle shows the stages through which the continents and oceans evolve. (A and B) Continental stretching and rifting; (C) seafloor spreading begins, forming a new ocean basin; (D) the ocean widens and is flanked by sedimented passive margins; (E) subduction of oceanic lithosphere begins on one of the passive margins, (F) so the ocean basin gets smaller. Eventually, the ocean basin is all subducted away and the continents collide, building a mountain range (G).

Figure 12. A candy bar shows how rifts work: when the bar is pulled apart, the top layer breaks and the lower layer stretches.

Scenery around Lake Superior records the geologic events 1.1 billion years ago that shaped the area and influenced the region's settlement and growth.

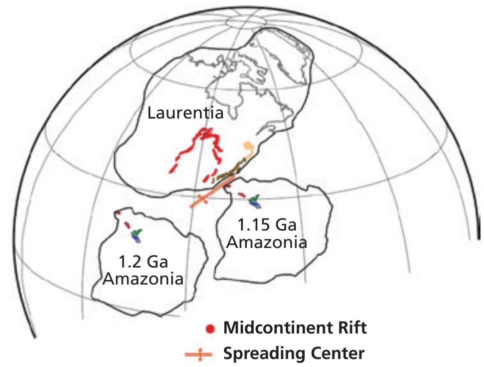

Figure 13. Reconstruction of plate positions 1.2 and 1.15 billion years ago showing the history of Amazonia rifting away from Laurentia. "Ga" denotes a billion years before the present. Although most rocks that old are buried beneath younger ones, some that record these events, marked by colored symbols at locations shown on either side of the opening ocean that are now thousands of miles apart, have been found. These matching rocks were used to reconstruct this history.

If the rift keeps opening, hot material from the mantle rises under the rift and causes volcanoes where basalt magma erupts, as is happening today along the East African Rift—and as happened a billion years ago along the MCRS. Eventually the rift valley is filled by enough basalt that it becomes an oceanic spreading center. Spreading at the new ridge forms a new ocean that separates the continental rock on both sides. With time, the ocean widens and looks like the Atlantic does today. Because the ocean cannot keep getting wider forever, eventually a new subduction zone forms, the entire ocean basin becomes closed, the continents on either side collide, and the cycle ends. Some time later, it starts again, so Earth's history has many cycles of continents rifting to form new oceans that eventually close.

However, sometimes rifting goes on for a while and then stops, failing to split the continent, and leaving behind a "failed rift," a long valley of stretched and faulted rock that eventually gets filled up with sediments and buried. That is what we see today in the Midcontinent Rift.

Ongoing research

Although geologists know a reasonable amount about the MCRS, there is a lot more to be learned. Current research addresses three major questions: how did it form, how did it evolve, and how did it fail? None of these are fully answered yet, but new data and ideas are giving additional insight.

Detailed mapping of the underground Midcontinent Rift using gravity data shows that the rift extends much farther than had been previously thought (Stein et al. 2014). Thus, although the MCRS is now in the middle of the continent, it formed at the edge of a larger continent. As continents form and break up, different pieces of the continents are grouped in different ways. Their positions can be figured out because, when volcanic rocks solidify, they record Earth's magnetic field, which depends on latitude (Swanson-Hysell et al. 2014).

The MCRS probably formed as part of the rifting of a continental piece called Amazonia (now in northeastern South America) from the continent of Laurentia (now central North America) (fig. 13). Once the seafloor was spreading and a new ocean began forming, the MCRS—the remaining piece of the rift system—shut down, leaving a failed rift. We do not know how this happened, where the hot material came from, or why this process ended. One possibility is that the rocks came from a hot spot, a volcanic region in the middle of a plate like that now under Hawaii (Hutchinson et al. 1990; Nicholson et al. 1997; Miller 2007). We hope that ongoing research will help answer these questions. Although the present Lake Superior was sculpted by much more recent glaciers—most recently about 10,000 years ago—its location reflects the geometry of the ancient rift below it (see fig. 3), because the soft sediment filling the rift was easier to erode than basalt.

How all this happened is an active research area. Figure 14 shows a schematic view of our current idea of the sequence of events. The rift formed by extension, with rocks above the major faults moving downward. Geologists call this "normal" faulting (fig. 15). Volcanic rocks filled the resulting depression. After the rifting stopped and the faults became inactive, huge additional thicknesses of volcanic rocks were deposited, and the cooling crust subsided. Once the volcanism ended, thick sediments filled the valley above the lava flows. After subsidence ended, beautiful flat-lying sediments seen in places like Apostle Islands National Lakeshore (page 19) were deposited. Eventually the area was compressed, and the faults that formed during extension and along which the central rift subsided moved the other way. The faults thus went from having "normal" motion during extension to having "reverse" motion during compression

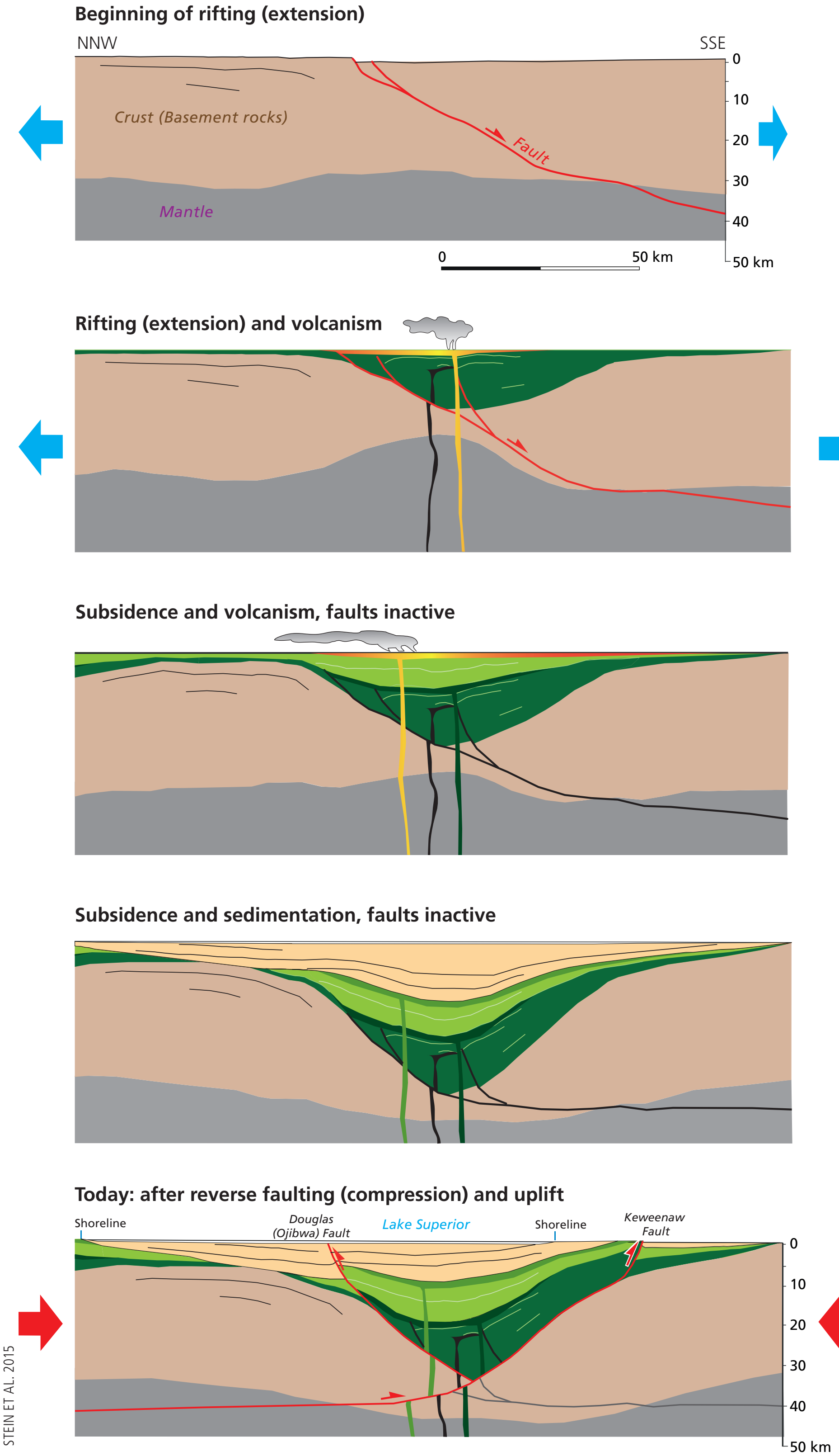

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Figure 14. Schematic view of the sequence of events that formed the Midcontinent Rift, leading to the structure seen today (fig. 4A). Extension is shown by blue arrows, and compression by red arrows.

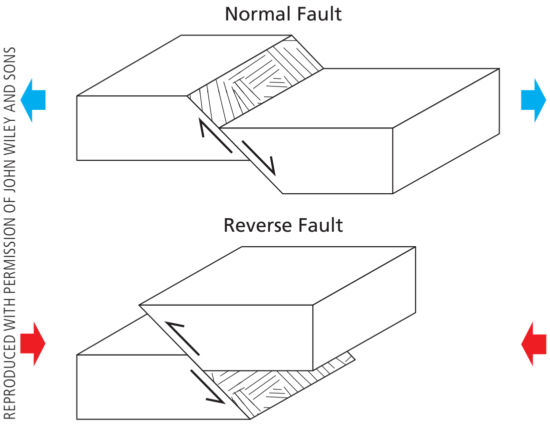

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Figure 15. Comparison of the normal sense of motion on faults that occurs during extension, shown by blue arrows, with the reverse motion that occurs during compression, shown by red arrows.

(fig. 15). The reverse motion on faults like those on either side of Lake Superior (see fig. 14) uplifted the volcanic rock, which is why we see it at Earth's surface today.

How the MCRS shaped the area's growth

Lake Superior is located above the Midcontinent Rift, so the rift provided the region's first transportation system, which is still crucial today. European settlers and traders used the lake to import and export trade goods, lake fisheries were significant first commercially and now recreationally, and the lake remains an economic engine today. The Port of Duluth-Superior, by far the largest and busiest on the Great Lakes, handles an average of 38 million tons (34 million metric tons) of cargo and nearly 1,000 vessel visits each year, connecting the heartland of the United States and Canada to the rest of the world. The lake also generates water-oriented tourism.

The MCRS also provided mineral deposits that shaped the region's settlement and growth. Hot water rising through the rift's volcanic rocks dissolved copper and deposited it in concentrations that became sources of valuable ore in many places around Lake Superior. For at least the past 7,000 years (Martin 1999; Pompeani et al. 2014) American Indians mined copper and traded it as far south as Illinois, as shown by archaeological studies in Cahokia, Illinois. The discovery of commercially viable copper deposits in the Upper Peninsula of Michigan during the 1840s led to a mining boom that shaped the area's economy (Bornhorst and Barron 2011). In the late 1800s, MCRS sandstone was quarried along the lakeshore and exported as building stone throughout the upper Midwest, primarily via Lake Superior shipping (Eckert 2000).

See the Midcontinent Rift

Rocks around the Lake Superior region record different aspects of this story. For example (fig. 1):

- Lake Superior fills the deep basin left over from the rifting and is the best place to seismically "see" the rocks at depth (see fig. 4).
- Interstate Park, Saint Croix National Scenic Riverway, Isle Royale National Park, Porcupine Mountains State Park, and parks along Minnesota's north shore show the volcanic flows that tell geologists when and how they erupted.
- Apostle Islands and Pictured Rocks National Lakeshores show sediments deposited after the rifting that scientists are trying to use to learn when and how the volcanism ended.
- Keweenaw National Historical Park presents the history of copper mining from the rift rocks and its effects on the area's development, and Michigan Tech's A. E. Seaman Mineral Museum shows spectacular examples of the copper.

Acknowledgments

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General references

A digital presentation and HTML version closely related to this article, together with other information, are available online at http://www.earth.northwestern.edu/people/seth/research/mcr.html. In addition to many scientific articles, sources including those listed below present more detailed and site-specific information. Keweenaw National Historical Park, the Keweenaw geoheritage program (http://www.geo.mtu.edu/KeweenawGeoheritage/KeweenawGeoheritage/Welcome.html) and the proposed upper peninsula Geopark (http://www.geo.mtu.edu/~raman/Geopark/Welcome.html), and the NSF EarthScope program provide additional resources.

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