Time after time
Continents break apart and rejoin over hundreds of millions of years, resculpting Earth's ever-changing face.

Nuna
1.4 billion years ago

Rodinia
750 million years ago

ART: NICOLLE RAGER FULLER; SOURCES: D.A.D. EVANS, Z.-X. LI AND J.B. MURPHY (EDS.)/ *SUPERCONTINENT CYCLES THROUGH EARTH HISTORY 2016*; D.A.D. EVANS; R. MITCHELL

SUPERCONTINENT SUPERPUZZLE

Geologists trace the comings and goings of Earth's landmasses **By Alexandra Witze**

Look at any map of the Atlantic Ocean, and you might feel the urge to slide South America and Africa together. The two continents just beg to nestle next to each other, with Brazil's bulge locking into West Africa's dimple. That visible clue, along with several others, prompted Alfred Wegener to propose over a century ago that the continents had once been joined in a single enormous landmass. He called it Pangaea, or "all lands."

Today, geologists know that Pangaea was just the most recent in a series of mighty supercontinents. Over hundreds of millions of years, enormous plates of Earth's crust have drifted together and then apart. Pangaea ruled from about 400 million to 200 million years ago. But wind the clock further back, and other supercontinents emerge. Between 1.3 billion and 750 million years ago, all the continents amassed in a great land known as Rodinia. Go back even further, about 1.4 billion years or more, and the crustal shards had arranged themselves into a supercontinent called Nuna.

Using powerful computer programs and geologic clues from rocks around the world, researchers are painting a picture of these long-lost worlds. New studies of magnetic minerals in rock from Brazil, for instance, are helping pin the ancient Amazon to a spot it once occupied in Nuna's heart. Other recent research reveals the geologic stresses that finally pulled Rodinia apart, some 750 million years ago. Scientists have even predicted when and where the next supercontinent may form — an amalgam of North America and Asia, evocatively named Amasia — some 250 million years from now.

Reconstructing supercontinents is like trying to assemble a 1,000-piece jigsaw puzzle after you've lost a bunch of the pieces and your dog has chewed up others. Still, by figuring out which puzzle pieces went where, geologists have been able to illuminate some of Earth science's most fundamental questions.

For one thing, continental drift, that gradual movement of landmasses across Earth's surface, profoundly affected life by allowing species to move into different parts of the world depending on what particular landmasses happened to be joined. (The global distribution of dinosaur fossils is dictated by how continents were assembled when those great animals roamed.)

Supercontinents can also help geologists hunting for mineral deposits — imagine discovering gold ore of a certain age in the Amazon and using it to find another gold deposit in a distant landmass that was once joined to the Amazon. More broadly, shifting landmasses have reshaped the face of the planet — as they form, supercontinents push up mountains like the Appalachians, and as they break apart, they create oceans like the Atlantic.

"The assembly and breakup of these continents

Pangaea
200 million years ago

Amasia
250 million years from now

have profoundly influenced the evolution of the whole Earth," says Johanna Salminen, a geophysicist at the University of Helsinki in Finland.

Push or pull

For centuries, geologists, biogeographers and explorers have tried to explain various features of the natural world by invoking lost continents. Some of the wilder concepts included Lemuria, a sunken realm between Madagascar and India that offered an out-there rationale for the presence of lemurs and lemurlike fossils in both places, and Mu, an underwater land supposedly described in ancient Mayan manuscripts. While those fantastic notions have fallen out of favor, scientists are exploring the equally mind-bending story of the supercontinents that actually existed.

Earth's constantly shifting jigsaw puzzle of continents and oceans traces back to the fundamental forces of plate tectonics. The story begins in the centers of oceans, where hot molten rock wells up from deep inside the Earth along underwater mountain chains. The lava cools and solidifies into newborn ocean crust, which moves continually away from either side of the mountain ridge as if carried outward on a conveyor belt. Eventually, the moving ocean crust bumps into a continent, where it either stalls or begins diving beneath that continental crust in a process called subduction.

Those competing forces — pushing newborn crust away from the mid-ocean mountains and pulling older crust down through subduction — are constantly rearranging Earth's crustal plates. That's why North America and Europe are getting farther away from each other by a few centimeters each year as the Atlantic widens, and why the Pacific Ocean is shrinking, its seafloor sucked down by subduction along the Ring of Fire — looping from New Zealand to Japan, Alaska and Chile.

By running the process backward in time, geologists can begin to see how oceans and continents have jockeyed for position over millions of years. Computers calculate how plate positions shifted over time, based on the movements of today's plates as well as geologic data that hint at their past locations.

Those geologic clues — such as magnetic minerals in ancient rocks — are few and far between. But enough remain for researchers to start to cobble together the story of which crustal piece went where.

"To solve a jigsaw puzzle, you don't necessarily need 100 percent of the pieces before you can look at it and say it's the Mona Lisa," says Brendan Murphy, a geophysicist at St. Francis Xavier University in Antigonish, Nova Scotia. "But you need some key pieces." He adds: "With the eyes and nose, you have a chance."

No place like Nuna

For ancient Nuna, scientists are starting to find the first of those key pieces. They may not reveal the Mona Lisa's enigmatic smile, but they are at least starting to fill in a portrait of a long-vanished supercontinent.

Nuna came together starting around 2 billion years ago, with its heart a mash-up of Baltica (the landmass that today contains Scandinavia), Laurentia (which is now much of North America) and Siberia. Geologists argue over many things involving this first supercontinent, starting with its name. "Nuna" is from the Inuktitut language of

2.1 billion years ago: Landmasses begin assembling toward the first true known supercontinent, Nuna (also known as Columbia).

1.5 billion years ago: Nuna reaches its maximum landmass.

1.3 billion years ago: Nuna begins to fragment and the parts reassemble as Rodinia.

1 billion years ago: Rodinia reaches maximum landmass.

750 million years ago: Rodinia begins to break apart, creating the Pacific Ocean.

400 million years ago: Subducting ocean crust once again shifts landmasses toward one another, in early steps toward Pangaea.

300 million years ago: Pangaea reaches maximum landmass.

200 million years ago: Pangaea begins to break apart, creating the Atlantic Ocean.

Next big event: About 250 million years from now: North America and Asia will smash together with other land fragments to create the supercontinent Amasia.

SOURCES: D. EVANS; J. MEERT; Z.-X. LI, D.A.D. EVANS, J.B. MURPHY/*SUPERCONTINENT CYCLES THROUGH EARTH HISTORY* 2016; M. YOSHIDA/*GEOLOGY* 2016 the Arctic. It means lands bordering the northern oceans, so dubbed for the supercontinent's Arctic-fringing components. But some researchers prefer to call it Columbia after the Columbia region of North America's Pacific Northwest.

Whatever its moniker, Nuna/Columbia is an exercise in trying to get all the puzzle pieces to fit. Because Nuna existed so long ago, subduction has recycled many rocks of that age back into the deep Earth, erasing any record of what they were doing at the time. Geologists travel to rocks that remain in places like India, South America and North China, analyzing them for clues to where they were at the time of Nuna.

> "As soon as you start asking why [Pangaea] formed, how it formed and what processes are involved ... you run into problems."
> BRENDAN MURPHY

One of the most promising techniques targets magnetic minerals. Paleomagnetic studies use the minerals as tiny, time capsule compasses, which recorded the direction of the magnetic field at the time the rocks formed. The minerals can reveal information about where those rocks used to be, including their latitude relative to where the Earth's north magnetic pole was at the time.

Salminen has been gathering paleomagnetic data from Nuna-age rocks in Brazil and western Africa. Not surprisingly, given their current lock-and-key configuration, these two chunks were once united as a single ancient continental block, known as the Congo/São Francisco craton. For millions of years, it shuffled around as a single geologic unit, occasionally merging with other blocks and then later splitting away.

Salminen has now figured out where the Congo/São Francisco puzzle piece fit in the jigsaw that made up Nuna. In 1.5-billion-year-old rocks in Brazil, she unearthed magnetic clues that placed the Congo/São Francisco craton at the southeastern tip of Baltica all those years ago. She and her colleagues reported the findings in November in *Precambrian Research*.

It is the first time scientists have gotten paleomagnetic information about where the craton may have been as far back as Nuna. "This is quite remarkable — it was really needed," she says. "Now we can say Congo could have been there." Like building out a jigsaw puzzle from its center, the work essentially expands Nuna's core.

Rodinia's radioactive decay

By around 1.3 billion years ago, Nuna was breaking apart, the pieces of the Mona Lisa face shattering and drifting away from each other. It took another 200 million years before they rejoined in the configuration known as Rodinia.

Recent research suggests that Rodinia may not have looked much different than Nuna, though. The Mona Lisa in its second incarnation may still have looked like the portrait of a woman — just maybe with a set of earrings dangling from her lobes.

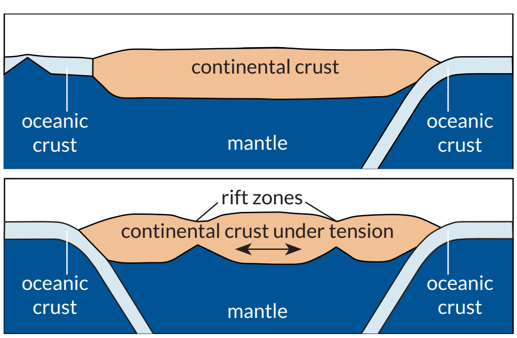
A team led by geologist Richard Ernst of Carleton University in Ottawa, Canada, recently explored the relative positions of Laurentia and Siberia between 1.9 billion and 720 million years ago, a period that spans both Nuna and Rodinia. Ernst's group specializes in studying "large igneous provinces" — the huge outpourings of lava that build up over millions of years. Often the molten rock flows along sheetlike structures known as dikes, which funnel magma from deep in the Earth upward.

By using the radioactive decay of elements in the dike rock, such as uranium decaying to lead, scientists can precisely date when a dike formed. With enough dates on a particular dike, researchers can produce a sort of bar code that is unique to each dike. Later, when the dikes are broken apart and shifted over time, geologists can pinpoint the bar codes that match and thus line up parts of the crust that used to be together.

Ernst's team found that dikes from Laurentia and Siberia matched during four periods between 1.87 billion and 720 million years ago — suggesting they were connected for that entire span, the team reported in June in *Nature Geoscience*. Such a long-term relationship suggests that Siberia and Laurentia may have stuck together through the Nuna-Rodinia transition, Ernst says.

Other parts of the puzzle tend to end up in the same relative locations as well, says Joseph Meert, a paleomagnetist at the University of Florida in Gainesville. In each supercontinent, Laurentia, Siberia and Baltica knit themselves together in roughly the same arrangement: Siberia and Baltica nestle like two opposing knobs on one end of Laurentia's elongated blob. Meert calls these three continental fragments "strange attractors," since they appear conjoined time after time.

It's the outer edges of the jigsaw puzzle that



Subduction's drag
Supercontinents assemble (top) as pieces of continental crust amass. Later they may break apart (bottom) when slabs of plunging oceanic crust (light blue) begin pulling the continent from either side, creating tensional forces that rift it apart.

P.A. CAWOOD ET AL/EARTH AND PLANETARY SCIENCE LETTERS 2016 change. Fragments like north China and southern Africa end up in different locations around the supercontinent core. "I call those bits the lonely wanderers," Meert says.

Getting to know Pangaea

While some puzzle-makers try to sort out the reconstructions of past supercontinents, other geologists are exploring deeper questions about why big landmasses come together in the first place. And one place to look is Pangaea.

"Most people would accept what Pangaea looks like," Murphy says. "But as soon as you start asking why it formed, how it formed and what processes are involved — then all of a sudden you run into problems."

Around 550 million years ago, subduction zones around the edges of an ancient ocean began dragging that oceanic crust under continental crust. But around 400 million years ago, that subduction suddenly stopped. In a major shift, a different, much younger seafloor began to subduct instead beneath the continents. That young ocean crust kept getting sucked up until it all disappeared, and the continents were left merged together in the giant mass of Pangaea.

Imagine in today's world, if the Pacific stopped shrinking and all of a sudden the Atlantic started shrinking instead. "That's quite a significant problem," Murphy says. In unpublished work, he has been exploring the physics of how plates of oceanic and continental crust — which have different densities, buoyancies and other physical characteristics — could have interacted with one another in the run-up to Pangaea.

Supercontinent breakups are similarly complicated. Once all the land amasses in a single big chunk, it cannot stay together forever. In one scenario, its sheer bulk acts as an electric blanket, allowing heat from the deep Earth to pond up beneath it until things get too hot and the supercontinent splinters (*SN 1/21/17, p. 14*). In another, physical stressors pull the supercontinent apart.

Peter Cawood, a geologist at the University of St. Andrews in Fife, Scotland, likes the second option. He has been studying mountain ranges that arose when the crustal plates that made up Rodinia collided, pushing up soaring peaks where they met. These include the Grenville mountain-building event of about 1 billion years ago, traces of which linger today in the eroded peaks of the Appalachians. Cawood and his colleagues analyzed the times at which such mountains appeared and put together a detailed timeline of what happened as Rodinia began to break apart.

They note that crustal plates began subducting around the edges of Rodinia right around the time of its breakup. That sucking down of crust caused the supercontinent to be pulled from all directions and eventually break apart, Cawood and his colleagues wrote in *Earth and Planetary Science Letters* in September. "The timing of major breakup corresponds with this timing of opposing subduction zones," he says.

The future is Amasia

That stressful situation is similar to what the Pacific Ocean finds itself in today. Because it is flanked by subduction zones around the Ring of Fire, the Pacific Plate is shrinking over time. Some geologists predict that it will vanish entirely in the future, leaving North America and Asia to merge into the next supercontinent, Amasia. Others have devised different possible paths to Amasia, such as closing the Arctic Ocean rather than the Pacific.

"Speculation about the future supercontinent Amasia is exactly that, speculation," says geologist Ross Mitchell of Curtin University in Perth, Australia, who in 2012 helped describe the mechanics of how Amasia might arise. "But there's hard science behind the conjecture."

For instance, Masaki Yoshida of the Japan Agency for Marine-Earth Science and Technology in Yokosuka, recently used sophisticated computer models to analyze how today's continents would continue to move atop the flowing heat of the deep Earth. He combined modern-day plate motions with information on how that internal planetary heat churns in three dimensions, then ran the whole scenario into the future. In a paper in the September *Geology*, Yoshida describes how North America, Eurasia, Australia and Africa will end up merged in the Northern Hemisphere.

No matter where the continents are headed, they are destined to reassemble. Plate tectonics says it will happen — and a new supercontinent will shape the face of the Earth. It might not look like the Mona Lisa, but it might just be another masterpiece. ■

Explore more

- Z.-X. Li, D.A.D. Evans and J.B. Murphy (eds). *Supercontinent Cycles through Earth History*. Geological Society of London Special Publication, Vol. 424, 2016.
- UNESCO International Geoscience Programme. Supercontinent Cycles & Global Geodynamics. http://bit.ly/supercontinents

Volcanic features called dikes form when molten rock squirts into a crack and cools to form a long linear feature. Matching dikes of the same age and chemical composition across continents can help geologists reconstruct maps of long-lost supercontinents. The dike above, at Singhbhum craton near Keonjhar, India, is about 1.7 billion years old.