Living Rock: The Earth's Continental Crust
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Transcript

U.S. Geological Survey
Deep Continental Studies Program

Planet Earth is a living planet.

Even solid rock, unmoving as it seems, has an exciting life of its own. But rocks live in geologic time. Their lives span billions of years. We humans can barely glimpse the living Earth in action.

Ranger: “Seven-two-four-victor, four-three-oh. Yeah, can you give me an Old Faithful prediction, please?”

[“The next eruption is at one-twenty p.m”]

Ranger: “Copy, thank you.”

Ranger: “It’s one-twenty.”

Where geologic wonders rule the landscape, the power of the Earth is most intense. We’re drawn to these places. We make them the centerpieces of our world’s great parks. Here, our deep connection with planet Earth is restored.

The rocks we live on make up the Earth’s outermost layer. It’s continental crust.

In recent years, scientists have gained new insight into the nature of these rocks. This is their story. It is a new story to us, but it is really as ancient as the Earth itself.

The continental crust is the part of the Earth we walk on. It is so familiar we often take it for granted.

Jill McCarthy: “The Earth’s crust is intimately linked to the sustainability of all human life. It’s from the Earth’s crust that we get the mineral resources that we depend upon, as well as the oil resources. Our water supply is linked to the Earth’s crust. The minerals that plants require to grow and to feed on come from the Earth’s crust. So all of our ecosystems and all of living matter is dependent on the Earth’s crust.”

The Earth did not always have a hard crust. When the planet first formed about four and half billion years ago, its surface was a molten sea of fire.

Mary Lou Zoback: "The Earth formed as part of the big bang. The big explosion resulted in the formation of our solar system. Mass was strewn out all through space. It began to accumulate together, and probably the initial Earth was a pretty hot, pretty inhospitable place, and probably initially fairly homogeneous. Just think of it as a very hot material. Eventually, started to cool down, and probably an outer scum or cool layer formed. It wasn't until some form of plate tectonics began that we probably began to build continental crust. To get continental crust, some of the scum began to break off and fall down into the hotter interior part of the Earth. That probably began to melt. As it melted, the melt that came off was slightly different – a different kind of rock. It was probably lighter. It floated up to the scum, to the existing crust, and formed volcanoes."

Volcanic lava hardens to rock, forming the first continental crust. It is now 35 miles thick in places. The continental crust is much thicker than the crust under the ocean, which is less than 9 miles thick.

Overall, the crust is just a thin film on the planet, making up only one percent of the Earth's total size. Below the crust is the mantle, which is made of denser, hotter rock. At the center of the Earth is the core: a sphere of iron that is half the total size of the planet.

Mary Lou Zoback: "A real good way to think about the Earth's crust…. I think a real good analogy is to think about an egg, and if you think of it the shell of the egg is very thin in relationship to the size of the egg. And inside the egg there's a clear white of the egg. You can think about that in a sense like the Earth's mantle, the second layer down. And in the middle of the egg is the yolk, and that's a lot like the Earth's core, because it's about half the size of the egg is in the yolk, and our Earth's core takes about half the size. But the Earth's crust is where we live, and it's that thin outermost shell that we derive all that we need for life and to make life liveable."

Civilizations have been built with resources from the Earth's crust. Knowledge about the nature of the crust has been the keystone of this work.

Today, scientists are probing ever deeper into the mysteries of Earth. This is the KTB drill site in Bavaria, Germany. Using the largest on-shore drill rig in the world, scientists and engineers have drilled 30,000 feet into the Earth's crust. It is the second-deepest research drill hole in the world, after one that measures 40,000 feet in Russia.

These rock cores come from depths several miles below the surface. KTB scientists have begun to analyze them with the most advanced methods of rock analysis, for they come from a very special part of the Earth's crust.

Peter Kehrer: "Here we are on old crust, very old continental crust where usually we only drill very shallow holes for water or mineral deposits and in this old crust lies the key to the understanding of the evolution of the Earth. The oceans are quite young—200 million years, maximum—but the continents are up to 4.5 billion years old, and in order to understand how the Earth, everything, came about, we have to look into this deep, old crust, and this is why we choose this place here. We need a direct place of observation and this is our drill hole."

In a very few places, scientists can get to ancient rocks without the aid of special equipment. In the Beartooth Mountains of Montana, the rocks are right at the surface.

David Mogk: "Here in the Beartooths, we have some of the oldest rocks in the world. We have remnants of rocks that formed as old as 4 billion years ago, and these are mixed with somewhat younger rocks of magmatic origin that have a range in ages of about 2.8 to 2.75 billion years."

Many of these ancient rocks are made of granite. Granite contains the radioactive element uranium, which decays to lead. This allows it to be dated with a machine called a mass spectrometer. By measuring these elements in rocks from the Beartooths, scientists confirm that they were among the oldest known rocks on Earth.

The rocks in the Beartooths are 4 billion years old, but the Earth is 4.5 billion years of age. Why is the first half-billion years of the Earth's history missing from the rock record?

David Mogk: "The Earth is a dynamic planet, and we have competing processes in the form of plate tectonics driving the rock cycle, and we have processes at the surface of the Earth—the hydrologic cycle. And those two cycles conspire to wipe out the early history of the Earth. And so it's very rare to actually find pieces of rock that are actually as old."

The Beartooths are part of an ancient belt of mountains that includes the Grand Teton Range in Wyoming. Studies of the rocks in these old ranges reveal that the face of the Earth has changed dramatically over time. This is key evidence in support of geology's most important theory – plate tectonics.

Plate tectonics theory holds that the Earth's crust is broken into huge slabs called plates. The face of the Earth changes because the plates float like rafts on semi-molten rocks below. The force that moves the plates is heat, which emanates from the very heart of the Earth.

Mary Lou Zoback: "Ultimately, the energy that goes into driving the plates around is derived from the interior of the Earth, and it's just a result of the radioactive decay of the initial elements that were involved in the formation of the mass that became the Earth."

To understand how heat drives the plates, scientists simulate the extreme conditions that exist at the center of the Earth, where temperatures reach 7,000 degrees Fahrenheit. They achieve these conditions with the help of tiny bits of diamond.

Robin Reichlin: "We can recreate conditions of the Earth's core by using a diamond anvil cell. We can actually squeeze materials between the tips of two diamond anvils, and we can achieve pressures on the order of three or four million times the pressure at the Earth's surface. We can also achieve high temperatures in the diamond anvil cells by heating with an infrared laser."

["Okay, so you want to turn the laser on?"]

Scientists have learned that intense heat from the Earth's core and mantle rises up toward the crust. This causes the mantle to circulate along the bottom of the crust. It is this circulation that moves continents around and profoundly changes their shape and size.

Heat circulating deep in the Earth can cause the crust to fall apart, or rift. In North America, a rift dissects the homeland of Native American people in New Mexico. The Pueblo people have lived in the Rio Grande rift zone for thousands of years. They have retained ancient traditions, and many still live in communities called "pueblos".

The Rio Grande rift is named after the great Rio Grande River, which cuts a deep gorge down the middle of the rift zone. The river follows a broad valley in the rift, which is flanked on both sides by lofty mountain ranges. This topography is common in rift zones. As the Earth's crust pulls apart, it stretches and becomes thin. Magma swells up from the mantle below, causing the crust to bulge upward and break apart. Broken crustal blocks rise, fall, and tilt sideways, creating valleys and mountains at the surface.

When the crust falls apart for millions of years, valleys and ranges stretch to the horizon. This is the case of the Basin and Range province of North America. After spreading apart for 17 million years, sections of the Basin and Range have grown wider by 100 percent. The Basin and Range spans dry desert country, but the spreading, bulging crust has been warped up so high that it invites snow during the winter.

Most valleys in the Basin and Range province are enclosed by mountains. Rain and melted snow drain into these closed basins and form lakes, like Mono Lake in California. On the shores of Mono Lake stand odd rock formations called tufa towers. Tufas are made of calcium deposited by underwater springs. The towers were once submerged, but siphoning of lake water for human use has left the tufas high and dry. The presence of calcium-rich springs reveals another feature of crustal spreading: volcanic activity.

Rufus Catchings: "When there's rifting, there's typically a break in the crust so the crust itself is broken apart, and prior to breaking apart it stretches and thins, and so as molten materials make their way up, it's very easy for them to get through the crust, and as they come through the crust, we see them as volcanoes."

In the past, mammoth volcanic eruptions have blanketed the rift zones of North America with thick layers of lava and ash, now hardened to colorful rock. Volcanic rock was a building material for the ancient pueblo people of the Rio Grande rift. In some places, cliffs of volcanic rock form the back wall of dwellings. A volcanic rock called tuff was soft enough that cave dwellers could carve into it with simple hand tools.

If crustal spreading persists, it could split a continent in half. Ocean waters move in. This happened in Africa, where the famous African Rift opened a gap between the continent and Saudi Arabia. The Red Sea was born.

In North America, the Rio Grande rift and Basin and Range province may or may not progress to the ocean stage. But the crust is spreading apart today, creating a lively, rugged landscape. One of the liveliest places associated with crustal spreading lies just north of the Basin and Range province, at a place called “Yellowstone”.

Yellowstone National Park is world famous for its bizarre volcanic landscape. There are no active volcanoes here today, but past eruptions are among the largest ever produced on Earth. Below Yellowstone, a column of hot magma rises from the mantle to with a few miles of the Earth’s surface. The subterranean magma fuels hundreds of geysers in the park. Thousands of other thermal features are found here. In fact, Yellowstone Park contains the greatest concentration of magma-driven features in the world.

At any time, magma may once again rise to the surface at Yellowstone. Geysers will be replaced by volcanoes and mammoth eruptions of lava and ash. Past eruptions at Yellowstone have thickened the Earth’s crust with thousands of feet of volcanic ash and lava. The entire depth of the colorful Yellowstone River Canyon is made of volcanic rocks. Where lava flows pile up in the canyon, the river cascades hundreds of feet over waterfalls.

Yellowstone dramatically shows how volcanism thickens the continental crust at the surface. Recently, geologists have discovered that volcanism also thickens the crust in a different way – from the bottom, down.

This is the Cima Volcanic Field, part of the Basin and Range province in California’s Mojave Desert. Here, geologists comb the flanks of Cima’s dormant volcanoes looking for special rocks called “xenoliths”.

Howard Wilshire: “Very special localities like the Cima Volcanic Field have a great abundance of xenoliths—tens of thousands of them—so they’re very important localities to try to piece together what’s happened in the upper mantle and lower crust. The word “xenolith”, the roots of the word “xenolith,” indicate foreign rock fragment. “Xeno-” means foreign and “-lith” is rock. These are rocks that did not belong to the lava that brought them to the surface.”

Xenoliths were once part of the bottom of the Earth’s crust and even part of the mantle. They form the deep, inner lining of volcanic conduits. When volcanoes come to life, rising magma rips chunks of rock from the lining and carries them to the surface.

Jane Nielson: “When you see the lava at the surface, you’ll notice different-looking rocks in it, maybe little white and black rocks that come from deep in the crust, or those fascinating little green beauties, little granular green clusters which are pieces of the mantle.”

Xenoliths are important because they give us a direct look at the bottom side of the continent. With the help of machines like the electron microprobe, xenoliths reveal a fascinating new picture of the bottom of the Earth’s crust. Traditional theories hold that the crust ends abruptly where it meets the denser rocks of the mantle. This neat, sharp boundary is nicknamed “the MOHO.” But xenoliths show that the MOHO was a bit messier in volcanic regions.

Magma from the mantle often rises to the bottom of the crust but then goes no further. The MOHO is obscured. Scientists recently learned that this was the start of an important process of crustal thickening called “underplating”.

Jill McCarthy: “Underplating is the process by which magma that’s generated in the Earth’s mantle is added to the Earth’s crust, but at the base of the crust. Normally, we think of magma as rising all the way through the crust and coming out at the surface at volcanoes. But with underplating, instead of it making it all the way to the surface, it actually stops and ponds right at the base of the crust where it contacts the upper mantle.”

Eventually, the magma from the mantle hardens to rock and becomes new continental crust. In this way, underplating makes the crust grow thicker, from the bottom down.

It turns out that underplating has added new crust to the bottom of continents all over the planet. Here in the Alps of northern Italy, geologists can actually see where this happened millions of years ago. This is the Ivrea-Verbano Zone, a rugged place where geologists must also be expert rock climbers. The Ivrea Zone is near the boundary where two crustal plates meet—the European and African plates.

Millions of years ago, Italy, a part of the African plate, was an island in the ancient Mediterranean Sea. The African plate then moved north, causing Italy to dock with the continent. During the collision, rocks of the ancient seafloor had nowhere to go but up. They now rise more than 12,000 feet above sea level in the Dolomite Range of northern Italy. Geologists once thought that the entire thickness of the crust rose out of the ground here, exposing the MOHO. The Ivrea-Verbano Zone was a place where the MOHO could be seen. The MOHO was thought to be so sharp a line that one could put a finger on it. It appeared that crust rocks were on one side, mantle rocks on the other. But the more geologists studied the area, the less this theory seemed true. It began to look as though all the rocks here were crustal rocks. Perhaps this was one of those places where mantle rocks had been transformed into crustal rocks by underplating. To find out for sure, geologists took hundreds of rock samples back to the lab for analysis.

[“Okay, Ben, I think we’re ready for the pressure vessel.”]

In lab experiments, the Ivrea rocks were subjected to the extreme conditions that exist at the bottom of the Earth’s crust. Temperatures down there reach 1,200 degrees Fahrenheit, and pressures are 10,000 times greater than at the surface. These experiments confirm that underplating did, indeed, take place in the Ivrea-Verbano Zone. Scientists have also learned that underplating and other processes happening in the lower crust can have major effects at the Earth’s surface.

Steven Bohlen: “Well, we know that there’s lots of things that go on down in the lower crust of the Earth and many of these things have a profound influence on us as humans on the surface of the Earth. Rocks and minerals change when they are subjected to heat and pressure. Rocks can melt, the minerals in the rocks can change themselves into denser minerals so the rocks themselves become heavier, and all of these things manifest themselves on the surface of the Earth. Rocks melting give rise to magmas which are implicated in explosive volcanism. Minerals and rocks can be hydrate, giving rise to water and CO2, which are implicated in formation of gold and silver and copper deposits. All of these processes which have their origins deep in the crust manifest themselves on the surface of the Earth in ways that are very important to our survival as human beings or to the longevity of our civilizations."

In the San Francisco Bay Area, the crust-mantle boundary plays a role in a destructive scenario. In the Loma Prieta earthquake of 1989, damage was heavy in and around San Francisco, but the quake's epicenter was more than 60 miles away. In between, relatively minor damage occurred. It turns out that loose soils were a factor in the severity of ground shaking in San Francisco, but scientists think there may have been another factor.

Some seismic waves generated during the quake went down, struck the MOHO at an angle, and then bounced back under San Francisco. Apparently, these bouncing waves were more destructive than waves travelling straight through the Earth's crust.

A large quake is predicted to strike the heavily populated east side of San Francisco Bay, which lies above the Hayward fault. Because so many people are at risk, earthquake scientists conducted an experiment to predict what might happen when that quake finally strikes.

Rufus Catchings: "From the 1989 Loma Prieta earthquake, we noticed that, indeed, seismic energy does go down, strike the MOHO, and come back underneath San Francisco. We wanted to see in the east bay, along the Hayward fault, if a similar type phenomenon would occur. And since we can't wait for the next earthquake, one of the things we did is went out and generated our own. We put explosive sources in high-probability areas, areas that we know are very likely to generate a large earthquake in the near future, and we wanted to see how the energy would travel from those locations to the north in Berkeley, Oakland, and the populated areas, and also to the south and the San Jose area."

["Seven, six, five, four, three, two, one"]

Rufus Catchings: "From the southern Hayward, if we were to have a large earthquake, seismic energy from that earthquake would travel down, strike the MOHO, and surface underneath the Oakland/Berkeley area, and from our indications, shaking would be very intense, much more so than was observed from the 1989 Loma Prieta earthquake coming under San Francisco."

To scientists, earthquakes are a source of invaluable information. When a big quake occurs anywhere on Earth, scientists get a glimpse of the entire inner structure of the planet.

Mary Lou Zoback: "Most of what we know about the Earth's deep interior has been derived from studies of earthquakes. Some of the deepest earthquakes occur quite deep, 700 kilometers deep, and the waves—just like throwing a rock into a pond of water—the earthquakes release energy, create waves. These waves travel all the way through the Earth. Through the center of the Earth, they're recorded on the other side of the world. And by studying these waves that travel—this is the job of seismologists, studying them around the world—we've learned that the interior of the Earth is layered, is not just one single homogeneous mass, but is comprised of layers of different compositions."

While earthquakes reveal a rough picture of the planet's interior, scientists often need more detailed information about the Earth's crust. One of their methods of getting it is through aeromagnetic surveys.

The instruments in this specially designed plane detect the magnetic fields in crustal rocks. Many rocks in the crust contain magnetic minerals such as magnetite. By analyzing the magnetic variations of these rocks, scientists can detect unseen geologic features buried deep within the Earth's crust.

The plane flies low and slow over the terrain to collect data. Recently, an aeromagnetic survey was flown over North America's west coast. The objective: to explore the differences between continental and oceanic crust. As flight lines of data are pieced together on a map, an incredibly complex picture of the Earth's crust unfolds. Yet there is no hint of this complexity in the subdued terrain around Seattle, Washington, a major west coast city. It is only through magnetic surveys and other geologic studies that the startling subterranean scene beneath the west coast is revealed.

Two crustal plates overlap each other below Seattle. One plate makes up the ocean floor, and where it meets the continent, it bends and dives underneath it. This is called a subduction zone. Sometimes, the two plates lurch toward each other, unleashing a tremendous jolt at the surface.

Good Friday, 1964, North America's strongest quake on record struck near Anchorage, Alaska, leveling the seaside city. So tremendous was the shock that it was felt in Florida some 5,000 miles away. The Alaska quake was a subduction zone earthquake. Beneath the mountainous terrain around Anchorage, the Earth is restless. Here, the Pacific Ocean floor is subducting below the continent. The most powerful earthquakes on Earth are triggered by subduction of the Earth's crust. A subduction zone runs along North America's west coast, from Alaska, along the coast of Canada, all the way to Cape Mendocino in California. Subduction sculpts a beautiful, rugged coastline when it occurs at a continent's edge.

This is because, over time, the subducting plate grinds forcefully on the plate above as it slides underneath. The top plate is shoved upward in response. Mountain ranges are built along the coast, like the Olympic range in Washington. After millions of years, the subducting plate sinks deep into the hot mantle, where it begins to melt. Magma forms and sometimes rises through ruptures in the plate above. This creates another powerful force caused by subduction.

Mount St. Helens in Washington erupted in May of 1980. Subduction triggered the eruption, which devastated the landscape for miles in all directions. A dense forest was blown over by the blast, and buried under thick layers of volcanic ash. Mount St. Helens is one of many powerful volcanoes that were built by subduction along North America's west coast. Majestic Mount Rainier stands 50 miles from Seattle. Mount Baker, Washington, rises near the U.S.-Canadian border. To the south, Crater Lake in Oregon was a huge volcanic peak before an eruption blew its top off 7,000 years ago. Many times in the geologic past these volcanoes have erupted far more powerfully than Mount St. Helens. As long as subduction drives the crustal plates below, these sleeping giants will surely awaken again and again.

The granite domes of Yosemite National Park in California mimic the shapes of the volcanic peaks in the Pacific Northwest. Subduction created both, but the domes of Yosemite formed in a different way. Granite is a rock that owes its existence to subduction. It forms when a subducting plate melts, and magma rises up through the overlying plate. But the magma often fails to make it to the surface in a volcanic eruption. Instead, it cools and hardens deep within the crust, forming granite. This is called a granite batholith. This is the process that formed Yosemite's granite. We see these rocks today because erosion stripped thousands of feet of earth off the top of the Sierra Nevada batholith.

Another granite batholith was exposed by erosion in the state of Idaho. But geologists working in the area were puzzled to find rocks that were formed by subduction. Subduction generally occurs at the edge of a continent, but these rocks are 350 miles away from the nearest coastline to the west. How did they end up so far inland? Clues came from the rugged Hells Canyon area, just to the west of the Idaho batholith. On the banks of the Snake River, geologists found huge piles of volcanic rocks called pillow lavas. These rocks formed where molten lava poured into the ocean.

Pillow lavas are forming today on the island of Hawaii. Lava is erupting from a small vent on the volcano, Kilauea. From this fiery cauldron, molten fingers of lava flow in underground tunnels to the Pacific Ocean shoreline. Underwater, the lava seems to be fighting to stay molten, but it cools quickly, hardening into pillow-shaped rock. When they found these same kinds of rocks in Hells Canyon, geologists had a problem. A crucial ingredient in the rocks formation—the ocean—was missing. These rocks seemed wildly out of place. Further work in Hells Canyon yielded more rock that had formed in the ocean.

["There may be a fossil there, hang on to that one. Here's another one."]

Fossils of creatures that live on tropical coral reefs were found alongside the volcanic rocks. Coral reefs only form near the equator, but Hells Canyon is thousands of miles north of the equator. Geologists were now certain that the rocks of Hells Canyon were formed in a far-off, exotic location.

Tracy Vallier: "At that time, the landscape looked much different than it does now. In fact, we think that there were probably chains of islands out in the north, ancient Pacific. We don't even know exactly where they were. But so different from what we see today in Hells Canyon. And you can probably think about a string of islands, maybe twenty or thirty of them, out in the ocean, maybe for several hundred miles, some of which had volcanoes on them. Once in a while, those volcanoes would erupt, and when they erupted, they were powerful. They threw things into the air probably eight, ten, twenty miles. Probably blotted out the sun for a while, they were so explosive. But the debris that we see from those volcanoes are mostly what I've been mapping in Hells Canyon."

For the ancient Hells Canyon islands to move from the tropics all the way to their present location in Idaho, there must have been profound movements of the Earth's crustal plates. About 130 million years ago, the west coast of North America was located in western Idaho. The volcanic islands of Hells Canyon were a group of islands offshore from the mainland. A subduction zone existed along the coast. As the ocean plate subducted below the continent, the ancient islands that were attached to the moving plate moved closer and closer to the coast. Finally, the islands collided with the continent.

Tracy Vallier: "When the islands joined the continent, it took a long time. It may have taken 100 million years for the process to occur. It's slow. And if we'd lived, we wouldn't even know it was occurring. And even during the time of the dinosaurs—probably about as long as the dinosaurs lived—is how long it took for these islands to join to North America."

Subduction has been active ever since, bringing in more islands and parts of the seafloor. The west coast of North America grew larger, bit by bit. These new pieces of continental crust are called “exotic terranes”.

In Alaska, at the edge of the original continental landmass, sits Mount Denali, North America’s highest mountain. To the south and west, all of the land is exotic, added to the continent by subduction. Anchorage is built on the Chugach terrain; a beautiful, exotic land that was once part of the ocean floor. Farther south along the Canadian coast, a huge island will become a new exotic terrane of North America. Subduction is pushing Vancouver Island closer and closer to the mainland, and eventually they will collide. Vancouver Island might be renamed “the Vancouver Peninsula”.

Scientists now believe that much of western North America is exotic. In general, most of the land west of the American and Canadian Rocky Mountains is made of exotic continental crust. The Rockies themselves were created when subduction first began millions of years ago. At that time, the continent ended here and it had a relatively flat coastline. But when the oceanic plate began to dive below the continent, coastal lands were shoved upward to create this majestic range of mountains. Western North America is perhaps the world’s best example of a continent pieced together by tectonic forces. Subduction, rifting, and underplating have all played a part in this drama of continental growth.

Plate tectonic forces create the continental crust. But where the crust shows itself at the surface, a different set of forces are active—sculpting, carving, and even destroying this tectonic handiwork. These are the forces of erosion. The boldest erosional artist is water. It works on the crust in the form of waterfalls, rivers, and rain.

One of the Earth’s most dramatic water-sculpted terrains is found in the southwestern United States. This is Bryce Canyon in southern Utah. It is part of the Colorado Plateau—a great block of the Earth’s crust that was arched upward by plate tectonic forces. Water carved this fairyland scene in the soft red rocks of Bryce.

In some areas of the Colorado Plateau, running water cut steep canyons through solid sandstone. At Canyon de Chelly, geology students get a powerful lesson in the processes of canyon formation.

Collette Brown: “This land here was all horizontal and flat. There were streams running through it, and there was this Colorado uplift of the Colorado Plateau, and when this uplift was happening, the streams were still running through, creating this Canyon de Chelly. So the canyons are still here today, and this took quite a long time, millions of years.”

As students explore the geology of Canyon de Chelly, they discover something unusual in the cliffs above. Centuries ago, Native American people built their dwellings in the nooks of sandstone cliffs. Arched caves are carved out by the combined forces of surface water and groundwater.

The grandparent of all canyons is the Grand Canyon in Arizona. It is almost too much to believe that this mile-deep spectacle was sculpted by water. But in geologic time, the years are many, and the Colorado River has worked without rest through the ages.

When water freezes to ice, another powerful erosive force is created. Glaciers sculpt the Earth's surface with a stronger hand than flowing water. Glaciers covered vast parts of the Earth during the ice ages, which ended about 10,000 years ago. When they retreated, they left a distinctive mark on the landscape. Nowhere is the signature of glaciers so striking as in Yosemite National Park. Yosemite Valley gets its smooth, u-shaped profile from the action of glaciers. Thousands of years ago, a glacier filled the entire valley. Eventually, the glacier retreated, revealing the bold handiwork of moving ice. When the glaciers retreated from Yosemite at the close of the last ice age, their melting ice filled deep pockets in the ground to form beautiful, alpine lakes. The cliffs mirrored in their waters seem as permanent as the sky above, but that is just an illusion. For this gentle substance called water will reduce these rocky cathedrals to nothing.

Flatness is the goal of erosion. Were plate tectonic forces to stop suddenly building mountains, water erosion would reduce the land to a level plain. Only sand dunes would rise above the plain, piled up by the blowing winds.

There is another force that is greatly modifying the Earth's surface. The Earth's human population is increasing at alarming rates, and with it, our huge appetite for resources from the Earth's crust. Are we damaging the crust beyond repair?

Steven Bohlen: "If we damage the crust, there are lots of active geologic processes that can undo the damage. I think the critical issue is: are we extracting resources from the crust at a sustainable rate? And the answer to that is, of course, no, we're not. We're extracting resources at a much greater rate than they can possibly be replenished. And this gets back to the issue of the geologic versus human time scales. We perceive the Earth as being here forever, on the human time scale, and yet the geologic processes that are required to replenish resources that we're using at a very rapid pace require millions and millions and millions of years. So we are, in fact, damaging the crust of the Earth in the ways that relate to the sustainability of our civilizations and us as humankind."

We may very well deplete the resources that the crust has provided. We may even have used the Earth's crust in ways that lead to our own extinction. But the processes that regenerate the crust originate many miles below the surface. It is unlikely that humans will be able to influence those processes.

Plate tectonics will carry on. New continental crust will be created at subduction zones. Offshore islands will be welded onto continents to become exotic terranes. Continents will be split and stretched wider along rift zones. The Earth will live on, forever changing the expressive features of its rocky face.

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