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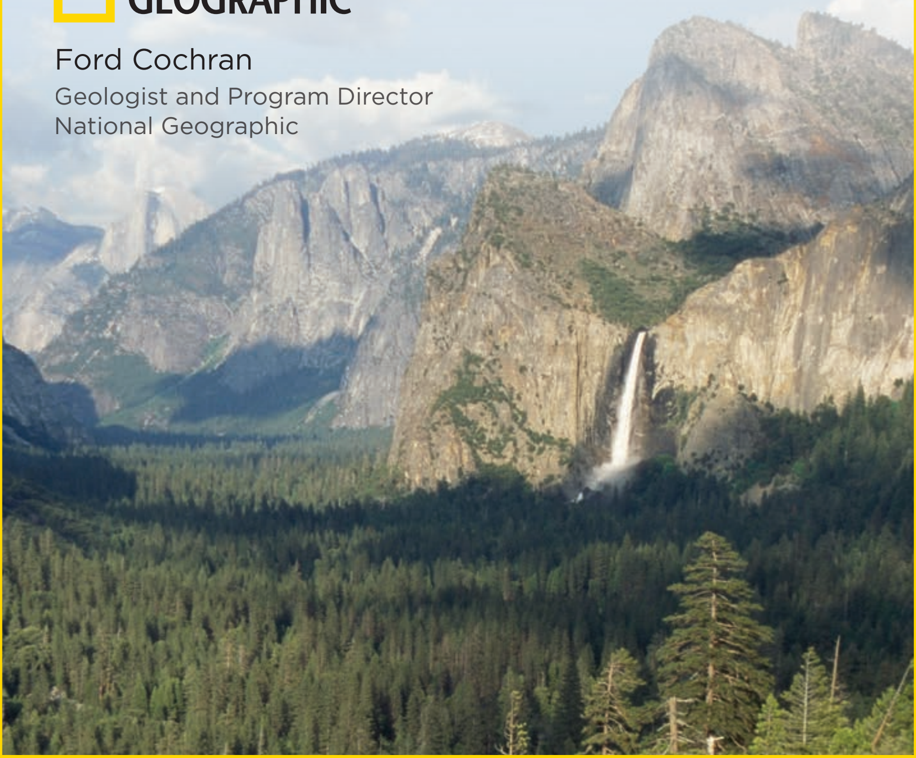
Wonders of the National Parks

A Geology of North America

Course Guidebook

NATIONAL GEOGRAPHIC™

Ford Cochran
Geologist and Program Director
National Geographic



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Geologist, journalist, and educator Ford Cochran is Director of Programming for National Geographic Expeditions. He selects and manages the expert scholars, writers, photographers, explorers, and staff sent by the National Geographic Society on expeditions for travelers to destinations around the world.

Mr. Cochran studied English literature as an undergraduate at the College of William & Mary, where he edited the century-old student newspaper, *The Flat Hat*, for two years. He did field research on Hawaii's volcanoes and Mount Saint Helens, with a focus on biogeochemistry and climate change, as a graduate student at Harvard and Yale Universities. Mr. Cochran earned a Master of Philosophy degree in Geology at Yale, where he was awarded competitive Global Change fellowships from both NASA and the Department of Energy. He was elected to represent Yale's graduate students across the natural and physical sciences on the policy-making Executive Committee of the Graduate School. Mr. Cochran earned Yale's Philip M. Orville Prize in recognition of outstanding research and scholarship in the earth sciences, along with the William Ebenezer Ford Prize for excellence in mineralogy, and he was invited to be the Honor Marshall of his Graduate School of Arts and Sciences class.

Mr. Cochran has taught a number of university courses and has given the invited keynote address at the Geochemical Society's international Goldschmidt Conference in Edinburgh, Scotland. He also has given numerous academic presentations, including invited talks at Caltech and the Massachusetts Institute of Technology. He was an Assistant Professor of Geology and Environmental Science at the University of Kentucky before leaving to join the National Geographic staff.

Over his 20-plus-year career with National Geographic, Mr. Cochran has written for *National Geographic* magazine, served as principal contributing writer for its *Historical Atlas of the United States*, helped launch Nationalgeographic.com and directed content development and programming for the website, and documented numerous Society-funded research expeditions in the field. Mr. Cochran blogs for National Geographic and has traveled as a Society expert on National Geographic Expeditions to Iceland, Hawaii, the Mediterranean, the Canadian Rockies and Pacific Northwest, and the national parks of the American West. He also has joined Society research and media teams on expeditions to Iceland, Costa Rica's Cocos Island, Chile's Easter Island and Sala y Gómez, Florida's Wakulla Springs, the Gulf of Mexico, and a number of U.S. national parks. Mr. Cochran led the development of National Geographic's first interactive online atlas and its first site for K–12 classrooms, plus dozens of applications and documentary features, including websites on Jamestown and the Chesapeake Bay, the Lewis and Clark expedition, Arctic exploration, Iceland, Yellowstone, Monterey Bay, the Florida Keys, biodiversity, and habitats. His work online has earned multiple Webby, CODiE, and People's Voice Awards, along with the American Association of Museums' Gold MUSE Award. ■

A trio of National Geographic's top creative talents—in charge of editorial content and storytelling, research and exploration, and mapmaking and visual design—appear in special vignettes to share additional insights into the parks.

Chris Johns

Chief Content Officer
National Geographic

Photojournalist Chris Johns grew up inspired by nearby Wizard Island at Crater Lake National Park in Oregon and Lassen Volcanic National Park in California, as well as family trips to Yosemite and Yellowstone National Parks. He was the first photojournalist into Mount Saint Helens six weeks after it erupted in 1980. In addition, he is the author of *Hawaii's Hidden Treasures*; *Valley of Life: Africa's Great Rift*; and *Wild at Heart: Man and Beast in Southern Africa*. He was editor in chief of *National Geographic* magazine from 2005 to 2014, after which he became chief content officer for National Geographic across all media platforms. He lives in Virginia adjacent to Shenandoah National Park, a park National Geographic helped establish in 1935.

John Francis

Vice President for Research, Conservation, and Exploration
National Geographic

Biologist John Francis conducted his Ph.D. research off the coast of southern California just beyond Channel Islands National Park at San Nicolas Island. He has been a producer of wildlife documentaries, including *Yellowstone: Realm of the Coyote*; served on the National Park System Advisory Board from 2004 to 2010; and helped reestablish the National Park Service's National Natural Landmarks program, where he has been active since its revival in 2006. As vice president for research, conservation, and exploration at National Geographic, he proposed and led a 10-year BioBlitz initiative to encourage citizen science and catalog biodiversity in national parks, which culminated with dozens of parks participating during the 2016 centennial of the U.S. national parks.

Kaitlin Yarnall

Executive Editor for Maps and Visual Design

National Geographic Magazine

Cartographer Kaitlin Yarnall grew up near Redwoods National Park in northern California, where family trips made it “her” national park. She has worked on several atlases, including the ninth edition of *National Geographic Atlas of the World* and the first edition of *National Geographic Collegiate Atlas of the World*. As executive editor for maps and visual design at *National Geographic* magazine, she oversees everything from the illustrative artwork and custom-made maps for which the magazine is traditionally famous to innovative information graphics using sophisticated databases and interactive tools for exploring thematic information online. ■

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Wonders of the National Parks: A Geology of North America

Scope:

The drama and sublime beauty of the natural wonders preserved in America's national parks reflects the astonishing drama of their creation. Titanic forces and earth-shattering events—earthquakes, volcanic eruptions, glaciations, floods, the collision of continents, and the disappearance of seas—have left their mark on the specific landforms and overall landscapes of the parks. Conversely, the national parks together tell a story of the origins, evolution, and present-day marvels of the North American continent.

How did a river carve a mile-deep canyon hundreds of miles long across northern Arizona? What triggered the largest volcanic eruption of the 20th century on the Alaska Peninsula southwest of Anchorage? Why does the longest cave on Earth lie beneath an unassuming plateau in central Kentucky? What created the majestic cliffs that encircle Yosemite Valley? How did desert dunes hundreds of feet high form at the foot of the Colorado Rockies, much less in northern Alaska? Why do rocks glide, untouched and unseen, across a barren mudflat in eastern California? What makes hot water flow from the ground in central Arkansas? What blew a hole dozens of miles across through northwestern Wyoming, and why do we think it will happen again?

In this unprecedented and comprehensive course, you'll visit and learn about every designated national park in the United States. You'll also explore national monuments, national seashores and lakeshores, national rivers, national marine sanctuaries, national historical trails, state parks, Canadian and Mexican parks, and even the remote, icebound island of Greenland—a breakaway slice of the North American continent.

You'll begin your journey in America's—as well as the world's—first national park, Yellowstone, where a hot spot deep beneath the surface supports Earth's largest collection of geysers, hot springs, mud pots, and more and where a series of massive volcanic eruptions over the last 2 million years has blasted away entire mountains. In neighboring Grand Teton National Park, you'll discover how motion along a nearly vertical fault gives rise to one of the youngest and most beautiful mountain ranges on the continent.

You'll travel to Hawaii, where another hot spot has created the largest mountains on Earth (measured from seafloor to mountain peak), along with a chain of exquisite islands that are ultimately doomed to weather away into the sea. Back on the mainland, you'll witness the magnificent devastation wrought by the explosive volcanoes of the Pacific Northwest and Alaska, including Mount Saint Helens, Mount Rainier, and the flooded caldera known as Crater Lake—America's deepest lake.

Turning from fire to ice, you'll trek across ice sheets and watch glaciers melt away in Alaska. Then, you'll explore Yosemite National Park, where vanished glaciers polished the soaring granite cliffs, leaving waterfalls in their wake. You'll discover what drew the '49ers to California and why towering redwoods and sequoias—relicts of a bygone era—survive and thrive where they do.

You'll trace the San Andreas Fault along the California coast, head to Alaska and northwestern Canada to summit North America's tallest peaks, and then plummet to the lowest, hottest, and driest place on the continent at Death Valley. You'll hike the Appalachian Trail and witness the aftermath of collisions that built the supercontinent Pangaea at Acadia, Shenandoah, and Great Smoky Mountains National Parks.

You'll dive reefs in Florida, the Virgin Islands, and American Samoa; cross dune fields like a latter-day Lawrence of Arabia; surf the coast from Hatteras north to Cape Cod and south to the Florida Keys; and follow rivers downstream—even if it takes you over Niagara. You'll reach the bottom of the national marine sanctuaries, America's network of submerged parks.

You'll learn how nature sculpted the Dakota Badlands and contemplate how a passion for the badlands might have influenced Theodore Roosevelt, the most conservation-minded U.S. President, to create and protect new parks. Then, you'll venture up the Colorado Plateau, where nature has carved stupendous canyons, such as Zion, the Grand Canyon, and the Black Canyon of the Gunnison, and sculpted wonderlands, such as Bryce, Arches, and Canyonlands. You'll unearth more than one petrified forest as you explore some of America's most fossil-rich parks, and then take an archaeological turn at Mesa Verde and other early human settlements.

You'll examine the rise of the Rockies at Rocky Mountain and Glacier National Parks, as well as parks of the Canadian Rockies; float the Rio Grande, where green "sky islands" float above a parched desert at Big Bend on the U.S.-Mexico border; and then cool off in caverns, from Mammoth Cave to Carlsbad. You'll wade the "river of grass" that is the Florida Everglades, and then find the continent's scoured and ancient core at Voyageurs and Isle Royale. Finally, the pieces will come together to assemble a geological story of the North American continent.

Along the way, you'll learn about essential rocks and minerals, important plate tectonic processes, and geomorphology—the science of landforms. You'll come to understand the deep geological histories of many of the most interesting and spectacular places on Earth. And you'll leave with a better appreciation for why novelist and historian Wallace Stegner called the national parks America's "best idea." ■

Lecture 1

Yellowstone: Microcosm of the National Parks

A magma chamber beneath Yellowstone "cooks" the rocks above, and the water circulating through these hot rocks has created a multitude of geothermal features: travertine terraces, hot springs, steam vents, mud pots, and geysers. These dynamic features are ever changing. Yellowstone's breathtaking array of geological wonders led not merely to its preservation by people who recognized the land's unique beauty and value, but to the invention of a brand new idea—the idea of a national park.

Yellowstone National Park

- Yellowstone National Park is one of the most extraordinary and dynamic places on our planet. Geologically, so much has happened here that this one park on a plateau high in the Central Rockies is like a microcosm of the entire national park system. In 1872, President Ulysses S. Grant signed legislation that declared this land of marvels as the world's first national park.

- Native Americans who lived in and near what is today northwestern Wyoming certainly knew of the region that would become Yellowstone National Park and its wonders. Some tribes regarded the Yellowstone Plateau—with its steaming geyser basins, boiling springs, and roaring steam vents—as sacred.

- Like a kettle of water on a hot stove, much of Yellowstone sits atop a huge heat source. That heat source is a gigantic magma chamber several miles beneath much of the park. Magma is molten rock, the stuff that feeds volcanoes. Magma becomes lava when it's erupted at the surface of the planet.

- The magma chamber beneath Yellowstone resembles an oblong balloon filled with a spongy mixture of viscous liquid, thick and sticky, plus crystalline solids. Evidence suggests that this magma

Yellowstone National Park geyser.

chamber might be more than 50 miles long and nearly 20 miles wide.

- Material within Yellowstone's magma chamber is much, much hotter than the rocks typically found at this depth beneath most of the continents. It radiates heat upward through adjacent rocks, and as portions of the magma continue to crystallize—that is, to convert from liquid to ordered, solid, mineral forms—the process releases yet more heat.

- The immense heat from Yellowstone's magma chamber warms water that's percolating underground. Derived mostly from rain and spring snowmelts, this groundwater fills tiny pores within rocks beneath the park as well as fractures created by earthquakes and the dome-like swelling of the land.

- As hot groundwater beneath Yellowstone interacts with the surrounding rock over, in some cases, centuries underground, it dissolves substances it will later precipitate as it cools and evaporates at the surface. As it heats up, this groundwater also expands slightly, becomes less dense—more buoyant—and begins to migrate upward toward the surface.

- This process resembles what you see in a pot of water on a hot stove, where warm water over the burners rises and pushes water to the edges of the pot, where it cools, becomes more dense, sinks, warms at the bottom of the pot, and rises again.

- This circulation of heated fluid is called convection, and it's the engine that drives the flow of hot water to Yellowstone's geothermal features. Because it's more efficient than conduction of heat directly through rocks, convection also brings a lot of heat to the surface.

- What kinds of features Yellowstone's hot water ultimately creates depends in part on the composition of the rocks it passes through as it travels underground, in part on the volume of water and its flow rate, and in part on the geometry of the subterranean plumbing system.

Travertine Terraces

- Five major types of geothermal features occur at Yellowstone: travertine terraces (formed by hot springs whose waters pass through limestone), hot springs, mud pots, steam vents (also called fumaroles), and geysers. These features are constantly evolving. Events such as torrential rains or an earthquake swarm can transform one of Yellowstone's steam vents into a hot spring, or a hot spring into a geyser.

- The exquisite cascading travertine terraces at Mammoth Hot Springs near the park's northern entrance cover nearly a square mile, making this the largest set of springs of their kind anywhere on Earth.

- Where the water's flowing, the spring terraces can advance horizontally and grow vertically at an astonishing rate. The growth of some of Mammoth's terraces happens so relatively quickly that they've encroached on historic buildings near the Mammoth Hot Springs Hotel and the park's headquarters.

- At Mammoth, the hot groundwater feeding the springs passes first through limestone, formed from the shells of tiny creatures that lived in shallow seas that covered much of the continent's interior many millions of years ago.

- As water flows from Mammoth's springs at the surface, the water quickly cools, and some of it evaporates. The water becomes oversaturated with dissolved calcium and bicarbonate, so they precipitate to form a mix of calcium carbonate minerals: aragonite and calcite. Both have the composition $CaCO_3$, with crystals that differ slightly, and both can form travertine.

- Cooling and evaporation happen preferentially where water flows over bumps, ridges, and terrace edges, accelerating deposition of travertine at these sites.

- Like the stalactites, stalagmites, flowstone, and terraced pools found in Mammoth's terraces, limestone caves also form because evaporating water is saturated with calcium and bicarbonate. They're also made of travertine.

- However, at Mammoth Hot Springs, growth happens much faster than it typically does in caves. This is because heat and the sizeable flow rate allow Mammoth's waters to bring so much dissolved calcium and bicarbonate to the surface. The warmth of the water as it emerges, and its rapid cooling at the surface, also accelerate evaporation—and therefore the precipitation of more travertine.

Mammoth Hot Springs.

- The same precipitation that builds the Mammoth terraces sometimes chokes the flow of water to the springs. When this happens, water pressure quickly builds until it finds or makes a new outlet, one portion of the Mammoth terraces is abandoned, and a new terrace starts to grow. Dormant springs become active and active springs become dormant. Tremors can cause this to happen, as well.

- Hot and active springs at Mammoth tend to produce brilliant white terraces, while older dry and abandoned ones turn a dull gray. The bright oranges, yellows, greens, and browns you see here—and surrounding other geothermal features at Yellowstone—are due to the presence of microorganisms, both algae and bacteria, that have adapted to survive in the extreme temperatures of the springs and the streams that drain them.

- These creatures, collectively called thermophiles because they thrive in extreme heat, number among the planet's most primordial life-forms. The thermophiles play an important role in concentrating and depositing the minerals that form Yellowstone's terraces and other features.

Hot Springs

- Nowhere are Yellowstone's rainbow hues more famously on display than at the sprawling Grand Prismatic Spring in Midway Geyser Basin. It's the largest hot spring in the United States.

- Processes similar to those that created the Mammoth terraces are at work here as well, but with one critical difference: Before arriving at the surface, the spring water passes not through limestone, but through silica-rich volcanic rocks, such as one formed from hot volcanic ash that is called rhyolite.

- The many connected pore spaces within a rhyolite make it easier for water to dissolve some of rhyolite's minerals as it passes through the rock.

- Silica that began in grains of loosely consolidated ash in a rhyolite can precipitate to form solid walls of impermeable sinter. This is called siliceous sinter, and it is this, not travertine, that precipitates to form the rims, bowls, and basins containing and surrounding Grand Prismatic and other hot springs in Yellowstone's geyser basins.

Steam Vents and Mud Pots

- What happens when the ground is so hot that water approaches the surface at temperatures above about 200 degrees Fahrenheit—the average boiling temperature for water at the high elevations found in the park? That is, what happens if all the water turns to steam below ground? This produces a hissing, simmering feature called a steam vent, also known as a fumarole. You can find thousands of steam vents in and around Yellowstone's geothermal basins.

- Yellowstone's mud pots plop, burble, and sometimes croak like frogs. Some wetter mud pots roil and churn like soup nearing a boil on a hot stove. Other, dryer ones—thick and gooey—resemble brownie batter.

- Yellowstone's playful mud pots result when hydrogen sulfide rises from deep underground and mixes with groundwater. Thermophilic microorganisms in the water convert the hydrogen sulfide to sulfuric acid, making the water extremely acidic.

- This acidic water then converts minerals in surrounding rock to clays. Unless the flow of water is strong enough to carry away all the clays suspended in the water, they accumulate, and the spring becomes a mud pot.

Geysers

- Old Faithful is certainly the best-known geyser in the United States—possibly the best-known geyser anywhere on Earth. Its spectacular white plume of water, with each eruption rising 90 to more than 180 feet above the Upper Geyser Basin, is the iconic image of Yellowstone. It conjures and symbolizes the national parks for a majority of Americans.

- Although the frequency of Old Faithful's eruptions has slowed a bit over the years since the park's founding, it still erupts about every 60 to 110 minutes.

- Old Faithful is usually not the most reliable geyser in the park. A smaller geyser, such as Bead Geyser, might erupt on a more regular schedule and for roughly the same length of time every eruption.

- And Old Faithful is definitely not the largest geyser in the park. Steamboat, in Yellowstone's Norris Geyser Basin, is far less reliable than Old Faithful, but hurling water up to 380 feet in the air, as it sometimes does, makes Steamboat the world's tallest geyser.

- When water is under pressure, its boiling point goes up, so it can get hotter as a liquid without becoming steam. In the network of cavities beneath a geyser, the weight of all the water above exerts pressure on the water below.

- Hot rocks deep underground—on the order of a mile, in many cases—"superheat" circulating water to temperatures above its boiling point at the surface, and this superheated water, now buoyant, begins to rise.

- As long as the water stays under high enough pressure—or cools enough, for example, by mixing with cooler waters from above—it remains a liquid. If pressure decreases gradually, the hot water might also form steam bubbles that burble up gently through the cooler water above.

- But if superheated water rises suddenly enough, or if the water pressure suddenly decreases because, for example, water at the surface sloshes out of a pool, a whole lot of water can transform abruptly into steam. This steam blasts water above it out of the geyser and into the air, reducing the pressure below, causing more superheated water to burst into steam, blasting more water from the geyser—and so on.

- Many geysers spray until they've nearly emptied the network of reservoirs near the surface that feed them. Over minutes, days, months, or years, these reservoirs refill until a threshold is reached or some other triggering event takes place, and the geyser erupts again.

- Just as at Mammoth Hot Springs—whether due to gradual deposition of precipitating minerals or earthquake tremors—geothermal features in Yellowstone's geyser basins sometimes become dormant, dormant ones become active, and new ones appear. Pools drain away, and peaceful hot springs turn into geysers.

Suggested Reading

Achenbach, "When Yellowstone Explodes."

Alley, *Geosciences 10*.

Burns, *The National Parks*.

Dickas, *101 American Geo-Sites You've Gotta See.*

Fritz and Thomas, *Roadside Geology of Yellowstone Country*.

Good and Pierce, *Interpreting the Landscape*.

Harris, Tuttle, and Tuttle, *Geology of National Parks*.

Heacox, *The Making of the National Parks*.

Hendrix, *Geology Underfoot in Yellowstone Country*.

Kiver and Harris, *Geology of U.S. Parklands*.

Lillie, *Parks and Plates*.

National Geographic, *Guide to National Parks of the United States*.

———, *Guide to the National Parks of Canada*.

———, *Secrets of the National Parks*.

———, *The Ten Best of Everything*.

National Park Service, *National Park Service*.

Parks Canada, http://www.pc.gc.ca/eng.

Quinn and Woodward, eds., *Earth's Landscape*.

Smith and Siegel, *Windows into the Earth*.

U.S. Geological Survey, *USGS Geology in the Parks*.

Questions to Consider

1. Yellowstone became the world's first national park because of the exceptional mix of geological wonders it contains. Have you visited a place that isn't a national park but that you'd like to see become one? If so, why?

2. Have you visited a cave and seen features resembling the travertine terraces at Mammoth Hot Springs? If so, how were they similar to and/or different from the terraces at Yellowstone?

Lecture 2

Yellowstone's Cataclysmic Origins and Future

Yellowstone's story involves the massive volcanic eruptions that created Yellowstone and will one day destroy it, the glaciers that shaped and sculpted the park, and the meltwater floods that carved the spectacular Grand Canyon of the Yellowstone. The hot spot deep beneath Yellowstone today has blazed a trail across the northwestern United States. In so doing, it has obliterated mountains and created geothermal wonders. In its wake, it has flooded the landscape with dark basalt, leaving a high, broad, fertile plain. The magnificent havoc wrought by the hot spot draws visitors from every nation to the world's first national park.

Volcanic Eruptions

- Much of what we encounter in Yellowstone resulted from a trio of caldera eruptions, staggering in scale, and a multitude of minor ones. They left their indelible signature on the landscape in and around Yellowstone.

- A caldera eruption is one in which a large magma chamber empties itself in one big volcanic event, and its ceiling—which happens to double as the ground above it—gets blasted away or caves in.

- The first and largest of the caldera eruptions at or near Yellowstone occurred about 2.1 million years ago. This first eruption produced the vast Huckleberry Ridge caldera that encircled much of the park and regions west of it, along with an associated layer of welded ash and other debris called the Huckleberry Ridge tuff.

- A smaller but still enormous eruption about 1.3 million years ago formed the Island Park caldera and created the Mesa Falls tuff.

- The third major eruption produced the Yellowstone caldera—larger than the second but smaller than the first. Also known as the Lava Creek caldera, the ash bed it scattered across much of the continent was the widest ranging of the three, reaching as far as southern

California, Louisiana, and beyond North Dakota. This caldera encompasses much of central Yellowstone National Park.

- Subsequent lava flows that filled in much of the caldera and glaciation have obscured the sharp outline of the third big caldera. But that high ridge along the Madison River is a surviving portion of its rim.

- All three of these caldera eruptions were tremendously larger than any sort that has taken place during historical times. Wind carried ash from each around the globe, and it piled in drifts across most of what is now the western United States. Dust and other aerosols pumped into the stratosphere during the eruptions would have cooled the planet dramatically for years.

- What sequence of events led to these colossal eruptions, and could it happen again? Today, swelling and deflation of the gigantic magma chamber beneath Yellowstone as magma shifts about or is added from below causes the land above to rise and fall by up to about an inch per year over a number of years.

- Land in the park bulges upward at two large domes that were eruptive centers during the last caldera eruption, one called Mallard Lake near Old Faithful and one called Sour Creek north of Fishing Bridge near Yellowstone Lake. These two rise and fall, not concurrently, but on their own timetables.

- It seems likely that the magma chamber beneath Yellowstone has been similarly dynamic for much of its history. As the magma chamber below Yellowstone fills, swelling stretches the brittle land above it.

- This swelling produces fractures (breaks in the rock) and faults (surfaces across which relative motion occurs). These fractures and faults form in concentric bands. Shaking from earthquakes associated with motion in the magma chamber and on the faults helps create even more fractures in the stressed rocks.

- Occasionally in the past, pockets of magma reached up to the surface, or a fault from the surface reached down to the magma, resulting in an eruption on more modest, familiar scales. But when, for example, a rupture occurred on one or several of the concentric faults, reducing pressure across a large lobe of the magma chamber and causing gas bubbles to form within it, this would have triggered a catastrophic eruption.

Yellowstone National Park.

- As it blows up and apart, the magma transforms into hot gases, dust, ash, and chunks of pumice. Pumice forms when lot of gas gets trapped inside to form a type of soft rock and is so full of low-density ash and air pockets that it floats on water. The mixture of pumice, hot gas, dust, and ash is called tephra.

- The trio of huge magma chambers at Yellowstone emptied themselves in and around what would become the park, deflating like balloons. What land remained above collapsed into the calderas, falling as much as 2,000 feet by the time the eruption ended. Whole mountains vanished into these chasms or were ripped apart and scattered around them.

- Then, ash and other hot ejected material inundated the surrounding land, leveling the landscape by filling some valleys. Other ejected material fused into so-called welded tuffs hundreds of feet thick all around the calderas. These are the Huckleberry Ridge, Mesa Falls, and Lava Creek tuffs we find today.

- After each of the major caldera eruptions in and near Yellowstone, a succession of additional, smaller eruptions released more material, backfilling much of the deep calderas and obscuring their outlines. The most recent of these occurred at Yellowstone about 70,000 years ago, when a large lava flow buried cliffs and gullies to form the park's Pitchstone Plateau.

- Another, more violent eruption blasted the West Thumb of Yellowstone Lake into existence about 174,000 years ago. The Upper Geyser Basin, including Old Faithful, is nestled between several lava flows that passed it by.

- All this subsequent volcanism, less titanic in scale, is why it might be difficult for a park visitor to grasp the sheer immensity of the caldera surrounding the Yellowstone Plateau and of the profound havoc it wreaked for dozens of miles in every direction.

The Hot Spot

- Why did this trio of severe eruptions occur in and near Yellowstone, and why does this huge magma chamber lurk, not so quietly, beneath the park today?

- The answer lies with something called a hot spot in Earth's mantle that blazed a trail across the northwestern United States over most of the last 20 million years. It is this hot spot that feeds the magma chamber beneath the park and is the furnace of the Yellowstone supervolcano.

- Earth has three main layers, from the standpoint of the strata where different elements predominate: a dense core comprised mostly of iron and nickel; a less-dense mantle surrounding the core and comprised primarily of silica, magnesium, and iron oxides; and an even less-dense, relatively thin crust with an even higher abundance of silica, less magnesium and iron than the mantle, and more aluminum, potassium, and other lightweight elements.

- A cross section of the Earth deep beneath Yellowstone reveals a hot spot below. This is a massive heat source or conduit in the mantle that provides both warmth and partially molten rock to inflate the magma chamber in the crust just below the park.

- The heat and magma rise toward the surface in what's called a mantle plume. Seismic waves generated by earthquakes pass more slowly through partially fluid rock than through solid rock, and scientists have used this fact to create three-dimensional images of the plume rising from the Yellowstone hot spot as well as the magma chamber.

- For millions of years, the Atlantic Ocean has grown along a rift in its basin called the Mid-Atlantic Ridge, becoming wider as the Pacific Ocean shrinks and contracts. To accommodate the Atlantic's growth, the North American Plate has crept southwestward at a rate of about 1.8 inches per year relative to the mantle below—including the Yellowstone hot spot.

- It began about 18 million years ago near what is today the border between Nevada and Oregon. Multiple caldera eruptions burst through the land, scorching it, scarring it, and creating the McDermitt volcanic field.

- The process repeated itself again and again, across northern Nevada and then into and across southern Idaho, tracing a path of devastation and creating a sequence of Yellowstone-like calderas across the northwest before reaching northwestern Wyoming a few million years ago.

- One final signature of the Yellowstone hot spot's passage was the release of vast quantities of basaltic lava. As North America continued its long, slow slide to the southwest and these blasted landscapes moved away from the hot spot, they typically would have descended more than a thousand feet in elevation, because the hot spot lifts up the land above it.

- As this occurred, fracturing and faulting provided conduits up which a new sort of magma made its way to the surface. This lava had a lower concentration of silica and was therefore more fluid and less viscous, so less explosive, than most of the lavas released during the caldera eruptions. The fluid lava flooded and paved much of the hot spot's trail, burying it beneath basalts.

- In its wake, the Yellowstone hot spot left the central and eastern portions of the Snake River Plain, a trail that leads straight to Yellowstone. Today, this plain, cleared of big mountains, acts as a conduit for moisture-laden air blowing in from the Pacific Ocean. This helps give both the Yellowstone Plateau and Grand Teton National Park just to the south of it more rain and snow than they would receive otherwise.

Glaciers and Meltwater Floods

- About 22,000 years ago, at the height of the most recent glacial advance—called the Pinedale glaciation in the Rocky Mountains—the Yellowstone Plateau lay buried beneath about 4,000 feet of ice.

- This ice sheet completely covered not just the park's lowlands, but also the summits of Mount Washburn and Mount Sheridan. Only the highest, jagged peaks of the Absarokas pierced the surface of the ice to peek out above it. What would become Yellowstone Lake lay buried beneath nearly a mile of ice. This ice scoured out the land below and depressed it as well, as some of the soft asthenosphere flowed out from under the ice-burdened, down-bowing lithosphere.

- Glaciers are Earth's great leveler. They might appear static, but they're always on the move, just at a glacially slow rate: As snow and ice pile thicker and thicker, the weight transforms snowflakes into a compact form called firn and then firn into denser forms of ice. The tremendous pressure of all the ice above causes some at the bottom of a glacier to melt and flow.

- This is why glaciers flow outward and downward toward places where the ice can melt or calve off into water and get carried away. Glaciers are massive conveyer belts for whatever they can pluck from the rocks they override, and as they drag rocks and grit across what lies below, they scratch, gouge, and grind them.

- Ice has plowed and smoothed the Yellowstone landscape. In addition, glaciers have lifted and carried car-sized boulders from far-off locations and deposited them as so-called glacial erratics around the park.

- As the ice cap over Yellowstone advanced and retreated, it created dams of both ice and earth that made large, temporary lakes. When these dams failed, they produced catastrophic floods. Geologists conjecture that such floods helped the Yellowstone River carve the spectacular Grand Canyon of the Yellowstone through soft, colorful, geothermally altered volcanic deposits. It's the geothermally heated groundwater that altered these rocks and transformed them via reactions, called chemical weathering, into so many pastel hues.

Suggested Reading

Achenbach, "When Yellowstone Explodes."

Fritz and Thomas, *Roadside Geology of Yellowstone Country*.

Good and Pierce, *Interpreting the Landscape*.

Hendrix, *Geology Underfoot in Yellowstone Country*.

Smith and Siegel, *Windows into the Earth*.

Questions to Consider

1. The caldera left by the most recent major eruption at Yellowstone measures about 30 miles wide by 45 miles long. Draw or simply imagine a caldera this size on a map with your home at the center of it. What cities or towns would the caldera enclose?

2. What do you imagine Yellowstone would look like today if it hadn't been set aside as a national park?

Lecture 3

Grand Teton and Jackson Hole

A short drive south of Yellowstone National Park is a 10-mile-long lake, Jackson Lake, that mirrors a 40-mile-long range of sheer gray mountains that rises more than 7,000 feet above the water's surface and the adjacent valley floor. Deep canyons divide the mountains. Atop the summits of these imposing sentinels sit some of North America's oldest rocks. Yet this is the youngest range in the Rocky Mountains, one of the youngest on the continent. This is Grand Teton National Park.

Grand Teton National Park

- Despite being only 27 miles apart, the soaring granite peaks of Grand Teton look remarkably different from the lava beds, travertine terraces, geyser basins, and rainbow canyon of Yellowstone. This is because the Yellowstone hot spot that's making its way across North America never crossed paths with the Tetons.

- The broad valley that runs the length of the Teton Range is called Jackson Hole. The Snake River meanders along the floor of Jackson Hole, with the Tetons to the west. The Continental Divide is to the east. Unlike Yellowstone, Grand Teton National Park is entirely west of the Continental Divide, and unlike the Yellowstone River, the Snake River flows west.

- Teton Park Road, the main western road through Grand Teton National Park, takes you from Jackson Lake to Jenny Lake at the foot of the mountains. Directly across the lake, Cascade Canyon tumbles down from the highlands between Mount Saint John, Mount Owen, and Teewinot Mountain, while the 13,770-foot summit of Grand Teton looms to the southwest. Just beyond the southern end of the park lie Moose Junction, the National Elk Refuge, and the town of Jackson.

- The Tetons are the youngest mountain range in the American Rockies. They have been rising for only about 9 or 10 million years. Compared to the Tetons, Signal Mountain is relatively short, topping out at an elevation of 7,720 feet. This more modest mountain shows the influence of a few processes quite different from those that elevated the Teton Range.

- Tephra from the first big Yellowstone caldera eruption, Huckleberry Ridge, covered the small fault-bound block of rock that would become Signal Mountain about 2.1 million years ago. The Yellowstone Ice Cap helped it along, carrying and dumping mountains—or at least much of this mountain—of debris called glacial till in conveyor-belt fashion, building Signal Mountain at its melting edge.

- The Huckleberry Ridge Tuff, a layer of welded ash from the caldera eruption, forms a straight, dark band more than 100 feet thick that's visible across the face of Signal Mountain. This band isn't horizontal; it tilts down toward the big mountains to the west at an angle of about 10 degrees.

- There is no reason that the floor of Jackson Hole would have sloped like this 2 million years ago when tephra came spewing forth from the caldera to the north. There is no reason that ash should have formed with a sloping upper surface, either. At first, the tuff would have formed as a relatively flat, horizontal layer as it inundated the landscape.

- The continent is stretching and thinning in Grand Teton National Park, perhaps on its way to ripping itself in two. Across a great fracture in the crust called a fault, one edge rises as the adjacent edge falls. Motion along the fault has caused the mountains to rise to the west as the adjacent edge of the valley sinks to the east.

- As the valley's western edge subsides, underlying rocks and sediments pivot. From large to small, boulders, cobbles, pebbles, sand, silt, and mud all eroded from the mountain heights and transported down into Jackson Hole. They were carried by streams,

Grand Teton National Park.

glaciers, and landslides and have helped weigh down the edge of the valley and help it along.

- But despite the large cumulative downward pivot of the western edge of Jackson Hole over the last few million years, the valley floor looks, and has remained, more or less horizontal. What filled the void left by the descending bedrock below?
  - The prodigious volume of sediment shed from the slopes and summits of the Tetons has filled much of the void.

  - Loads more sediment carried into the valley from the north by the Snake River and deposited here have made a contribution.

  - Sediment transported by glaciers from the north when Yellowstone was glaciated topped the valley off.

- Today, nearly a mile of sediment sits above the Huckleberry Ridge Tuff where it abuts the fault across which the Tetons have risen.

- The Teton fault is a normal fault. In general, faults are surfaces in solid rock, or sometimes in unconsolidated sediment, across which relative motion has taken place. A normal fault is an angled fault, typically steeply angled, in which rocks of the block above the fault have moved down and away relative to rocks of the block below the fault.

Earthquakes

- Motion on active faults can occur gradually through an ongoing succession of small movements that generate comparably small earthquakes, or stresses can build up on a locked fault over many years before getting released all at once in much more powerful and dangerous earthquakes.

- A big one happened just north of the Tetons and west of Yellowstone on the night of August 17, 1959, when the magnitude 7.3-plus Hebgen Lake earthquake produced a landslide and flood that killed more than two dozen people.

- Displacement of land during the earthquake occurred on a normal fault. This produced a rise of broken earth called a fault scarp. Normal faults often occur where Earth's lithosphere, the ridged rocks of the crust and uppermost mantle, have thinned and stretched because they're being pulled apart. They're characteristic of regions of crustal extension.

- The extension that's occurring in Grand Teton National Park reflects a large-scale trend of crustal extension that continues to the south and west across the so-called Basin and Range Province of the United States. The Basin and Range is a large expanse of parallel ranges with deep intervening valleys, bounded by normal faults.

- National Parks at Death Valley and Great Basin show this pattern. Both comprise deeply down-dropped, fault-bound blocks (the basins) bordered on both sides by tall, steep mountains (the ranges).

- The dip of the Huckleberry Ridge Tuff tells us how far the western edge of Jackson Hole has descended as it slides down the Teton fault. But it hasn't answered a related and interesting question: How quickly are the mountains of the Teton Range rising?

- Geologists have determined that rocks of the central Teton Range have risen nearly six miles, about 30,000 feet, relative to rocks across the fault beneath the western edge of Jackson Hole. As the Grand Tetons have ascended above the valley over the last several million years, miles of rock must have eroded off the top of them, filling the valley floor and being carried off downstream by the Snake River or valley-filling glaciers, or else shedding off the rising mountains to the west.

Glaciers

- Just as at Yellowstone, glaciers have played a critical role in shaping the landscapes of Grand Teton National Park. During the greatest extent of ice over the last few million years, glaciers filled Jackson Hole to a depth of a few thousand feet.

- The most recent glaciers didn't cover the highest peaks of the Tetons but scoured portions of them smooth midway up their flanks. In addition to helping build Signal Mountain, material dropped by a glacier on the valley floor as it receded north up Jackson Hole toward Yellowstone left a series of ridges and rises that ring and dam Jackson Lake. We can thank this glacier for the presence of the beautiful lake.

The city of Jackson Hole.

- Glaciers also have excavated the canyons between the mountains in the Teton Range. Snow and ice accumulated on the slopes of the mountains themselves and in the highlands of the mountain backcountry.

- As gravity caused it to flow eastward downslope into Jackson Hole, these glaciers cleaned sediment from the canyons and plucked rocks from the walls and the base of the canyons. Water on canyon floors under intense pressure beneath the weight of overlying ice penetrated even the tiniest cracks in rocks.

- Water has the unusual property of expanding rather than contracting as it freezes. Ice lenses form in narrow fractures, wedging the rocks apart as they freeze and expand. The expanding ice sometimes forces trapped liquid water nearby deeper into cracks, increasing pressure on the water until those cracks begin to wedge open as well.

- The glaciers carry broken rock fragments away and renew the process on newly exposed rock. Glaciers strip soils from bedrock and drag large rocks across other rocks, gouging, grinding, and breaking bedrock. They abrade and sculpt the landscape, broadening and deepening the canyons through which they flow.

- All this ice-driven action gave canyons such as Cascade and Avalanche in Grand Teton National Park their pronounced U-shaped profiles, with steep walls and broad floors. Where the glaciers encountered harder or less fractured rocks in the valley floors, they left them and plucked out rocks downslope, leaving sharp ridges that waterfalls spill over today.

- Where the glaciers filling these canyons spilled out onto the floor of Jackson Hole and melted, they also dropped the sediment they were carrying. Over time, this process created ridges of debris called moraines. The moraines at the mouths of glacier-filled canyons below the Tetons account for the spectacular series of lakes along the western margin of Jackson Hole at the foot of the Teton Range.

- Near the summits of the Tetons, smaller so-called alpine glaciers formed. Over time, alpine glaciers tend to produce the steep, concave slopes and sharp ridges that characterize peaks such as the pyramid summits of Grand Teton.

Landslides

- As is true of so many of the most geologically compelling and unforgettable landscapes, the forces that make the Tetons so inviting sometimes cause trouble. In addition to the powerful and deadly Hebgen Lake earthquake, another example is the Gros Ventre landslide of 1925, which is still visible from many places in and around the park.

- While the actual slide didn't injure anyone, it dammed the Gros Ventre River, creating a new lake that grew to become more than 200 feet deep and five miles long. A heavy spring snowmelt caused the debris dam produced by the landslide to break two years later, flooding the town of Kelly downstream and killing six people.

- The prominent bare swath of hillside left by the Gros Ventre slide is a healthy reminder—not just that rocks will give way occasionally anywhere there's steeply sloping ground, but also that dams sometimes fail.

John D. Rockefeller Jr.

- Grand Teton National Park as we know it today exists due to the largesse of a single motivated patron, John D. Rockefeller Jr., for whom the road between Yellowstone and the Tetons was named.

- Rockefeller bought thousands of acres of private land in Jackson Hole beginning in 1927 for addition to a future national park. Congress designated the mountains and a few small lakes Grand Teton National Park in 1929. But it took Rockefeller more than 20 years to persuade the federal government to accept the land he had purchased over the objections of local cattlemen, who wanted to keep the valley open for grazing.

- In the meantime, President Franklin Roosevelt's Interior Secretary, Harold Ickes, commissioned Ansel Adams to create photographic murals of current and possible future parks. As with painter Thomas Moran's paintings and William Henry Jackson's photographs of Yellowstone in the 19th century, Adams's iconic photography played a critical role in building support for setting aside remarkable landscapes in national parks.

- Rockefeller's gift to the nation was finally accepted in 1949, when it was added to Jackson Hole National Monument. In 1950, Congress finally transformed the monument into an expanded Grand Teton National Park and the National Elk Refuge.

Suggested Reading

Alt and Hyndman, *Roadside Geology of Montana.*

Good and Pierce, *Interpreting the Landscape*.

Smith and Siegel, *Windows into the Earth*.

Questions to Consider

1. The summits of Grand Teton and the Matterhorn in the Alps both resemble horns. Why? By searching online, can you locate other glaciated mountains with horn-shaped summits?

2. John D. Rockefeller Jr. was instrumental in the creation or expansion of many of the U.S. national parks. Read about his commitment to conservation and public service and discover how he supported such parks as Acadia, Great Smoky Mountains, Shenandoah, Yosemite, and more.

Lecture 4

Hawaii Volcanoes: Earth's Largest Mountains

Hawaii (Hawai'i in Hawaiian) exists because a hot spot feeds the volcanoes of Hawaii Volcanoes National Park. Volcanoes have grown the Big Island, and they continue to do so. Volcanoes also give rise to exotic landscapes and constantly reshape the land as they build it. Five volcanoes—Kilauea, Mauna Loa, Mauna Kea, Hualalai, and Kohala—together comprise the Big Island of Hawaii, the largest and youngest island in this most recent addition to the 50 United States.

Hawaii Volcanoes National Park

- Why do Hawaii and its volcanoes exist, so far from any continent? If we consider Earth's tectonic plates, Hawaii is near the center of the Pacific Plate, which is overwhelmingly under water.

- The answer is that even an oceanic plate can give rise to land. Flow by flow over about the last 700,000 years, geologists estimate, successive eruptions of lava beneath the ocean, and then lava flows and ashfalls above it, have built Mauna Loa and created the landscapes that define Hawaii Volcanoes National Park. That's a long time by human standards but not by geological ones.

- Perched against the southern shoulder of Mauna Loa, Kilauea is younger still. Even the Big Island's oldest volcano, Kohala, might have started forming a little more than a million years ago.

- Just to the south of the island and not far from shore, a submerged volcano called Loihi rises thousands of feet above the surrounding seafloor. In another 60,000 years or so, geologists predict, Loihi will emerge at the surface to add its bulk and a sixth volcano to the Big Island, making it bigger still.

- Far below Hawaii Volcanoes National Park, the entire Big Island hides another secret: Hundreds of miles deep in the rocks of the mantle, a hot spot of upwelling rock and magma similar to the one that created Yellowstone stokes Hawaii's fires.

- Unlike the Yellowstone hot spot, however, the one below Hawaii currently resides beneath the dense oceanic crust that underlies the Pacific Ocean rather than below the thicker, more buoyant, silica-enriched rocks of the North American continent. And that has made all the difference.

- Hawaii Volcanoes National Park contrasts in striking ways with what's on display at Yellowstone, whether in eruptive style, mineralogy, landforms and landscape, or volcanic threat. But there are plenty of similarities, too.

Hawaii Volcanoes National Park.

  - Yellowstone sits at the end of a string of buried volcanic calderas stretching away to the southwest beneath the Snake River Plain. Similarly, Hawaii's Big Island sits at the end of a string of volcanic islands and seamounts that stretch away to the west-northwest to the Midway Islands and beyond.

  - The buried calderas that form a connect-the-dots line to Yellowstone become progressively older as you get farther away from Yellowstone. The volcanic islands and seamounts of the Hawaiian-Ridge chain also become progressively older as you get farther away from the Big Island.

  - Ancient calderas formed by the Yellowstone hot spot have sunken or subsided as they moved away from the hot spot. The Hawaiian Islands also have sunken or subsided—and also eroded—as they moved away from the Hawaiian hot spot.

  - Frequent minor earthquakes and earthquake swarms, punctuated by occasional large quakes, signal the motion of magma beneath the ground at Yellowstone and the response of the stressed, brittle land above. The Big Island also experiences frequent minor earthquakes, earthquake swarms, and occasional major quakes.

- For tens of millions of years, the Pacific plate has drifted across the Hawaiian hot spot in the mantle below, and as it does so, magma generated by the hot spot has repeatedly punctured the seafloor and built the islands and seamounts of the chain.

- Hawaii Volcanoes National Park and the Big Island around it are a work in progress, constantly under construction. They are home to some of the newest land on Earth, as nearly constant lava eruptions on the flanks and at the summits of Kilauea and Mauna Loa continue to thicken the volcanoes and extend the island's coast into the sea.

- But the similarities between Yellowstone and Hawaii do not tell the entire story. After all, unlike Yellowstone, geysers do not erupt in the calderas on Kilauea and Mauna Loa, and their calderas are not 30 miles wide. If Hawaii were like Yellowstone, entire islands might blow themselves to bits once in awhile.

Hawaiian Magma and Lava

- The Yellowstone hot spot sits beneath continental crust, which is enriched in silicon, aluminum, and potassium and is less dense than oceanic crust. Partial melting of continental crust by heat and magma rising through it enriches the magma further in these elements. The magma that results is viscous and highly explosive and creates mostly light-colored, lightweight rocks called rhyolites that are rich in silica and ash.

- By contrast, the Hawaiian hot spot sits beneath oceanic crust, which is much thinner than continental crust but also denser. Compared with continental crust, it has less silica and more closely resembles the chemistry of rocks in the upper mantle.

- Yellowstone's silica-rich magmas are sticky and viscous. Hawaii's volcanoes, by contrast, have magma that is more fluid and less viscous than that rising beneath Yellowstone. When it erupts as lava, it typically forms a dark, fine-grained igneous rock called basalt. Basalts are found everywhere in Hawaii Volcanoes National Park and on the larger Big Island.

- New lava on both Mauna Loa and Kilauea has vented primarily at one of two locations: in and near the calderas at the summits of the volcanoes, and in long, linear rift zones where the volcanic mountains are opening up, allowing magma to flow upward toward the surface in great sheets. These rifts extend for dozens of miles from the calderas down the flanks of the volcanoes.

- At Hawaii Volcanoes National Park, both summit eruptions and rift eruptions can sometimes result in dramatic fountaining, when brilliant orange lava spouts hundreds to a thousand or more feet into the air. These fountains can build cones of splattered lava and hot scoria cinders hundreds of feet tall, called cinder cones. Hawaiian

Big Island.

lavas also often erupt along long, narrow vents, not as a single, central fountain but in spectacular blazing curtains of fire.

- Whether erupted as fountains or sheets, Hawaiian lava can fall back to the ground in several forms. There can be liquid splatter or chunky cinders. It can freeze in the air as oblong volcanic bombs. It can disperse on the wind as ash, or even form gossamer golden strands called Pele's hair that float and finally settle downwind of an eruption. Eruptions on Mauna Loa and Kilauea also send lava in flows downhill, overrunning or incinerating much of what's in its path.

- Once lava drains away and the surrounding rock cools, many subterranean conduits remain as lava-tube caves. Some have "lavacicles," resembling the stalactites found in limestone caves, hanging from their ceilings, and spatter from splashing lava adorns their walls. The Thurston Lava Tube on Kilauea is one readily accessible lava-tube cave.

Weather Zones

- As with large mountains anywhere around the globe, Hawaii's volcanoes create distinct zones of weather. The temperature decreases as you climb toward their summits. At these elevations, air becomes about 3.5 degrees Fahrenheit cooler for every thousand feet gained above sea level.

- While it's warm and balmy on the coast of the Big Island, it's often sweater weather 4,000 feet up on the summit of Kilauea. Ascend nearly 14,000 feet to the summit of Mauna Loa or Mauna Kea, and you'll wish you'd brought a jacket.

- There's also a significant difference in rainfall between the windward side of the Big Island and its leeward side. Hilo, on the Big Island's eastern coast, is a lush garden with many overcast and rainy days. Rain forest covers much of the eastern slopes of the island.

- On the island's leeward side is a sprawling savannah, a grassland, home to a quarter-million-acre cattle ranch—the Parker Ranch—

one of the largest in the United States. And while they still get some rain, the beach resorts of the Kona Coast get just a fraction of what falls on Hilo.

- The Ka'u Desert, sparsely vegetated, stretches to the southwest just downwind of the Kilauea caldera. But a paucity of rainfall isn't what keeps this particular desert a desert: Sulfur dioxide gas emerging from the caldera reacts with oxygen and moisture in the atmosphere to create tiny suspended droplets of sulfuric acid. The result is a sort of volcanic smog or fog that is dangerous to breathe and discourages plant growth as well.

- Hundreds of lava flows of different ages, from days to thousands of years, form a mosaic across the landscape of Hawaii Volcanoes National Park. Geologists at the U.S. Geological Survey's Hawaiian Volcano Observatory have led a decades-long effort to map and determine the ages of all these flows.

- Dense rain forest full of tree ferns covers older flows on the lower slopes of the windward, rainy side of Hawaii. Where more recent flows surrounded portions of these older ones, they've left islands of forest surrounded by stark, black lava fields.

A Natural Laboratory

- The extraordinary variety and continuum of conditions on the Big Island and across the Hawaiian chain make this one of the world's great natural laboratories. To understand complex processes and interactions, field scientists need a means to isolate variables. Here, scientists can study the effects of isolated changes in flow age and type, temperature, or rainfall. They can look at differences in, for example, ecosystems or weathering rates as temperature or precipitation change while holding the age, the composition of underlying rocks, and other factors constant.

- Hawaii is also incredibly remote, and endemic species have emerged and evolved to fill numerous niches on each of the islands. For all these reasons—and of course because of its dynamic, ongoing volcanism—geologists and biologists constantly visit, study, and monitor Hawaii Volcanoes National Park.

- The clear air of the Mauna Kea summit, far above the clouds and remote from continental dust and industrial pollution sources, has lured astronomers to the Big Island from around the world. On the northern slope of Mauna Loa, adjacent to the national park, air samples from the National Oceanic and Atmospheric Administration's Mauna Loa Observatory have provided an astonishing data set that documents important, ongoing changes on our planet.

Suggested Reading

Hazlett and Hyndman, *Roadside Geology of Hawaii*.

Holland, "Red Hot."

Questions to Consider

1. Compare and contrast eruptions on Hawaii's Big Island with those at Yellowstone and Mount Saint Helens.

2. Eruption activity on the Big Island changes frequently. Check the Hawaii Volcano Observatory website and read about the latest conditions on the island.

Lecture 5

The Hawaiian Islands and Maui's Haleakala

Above a hot spot deep within the Earth, volcanoes rise from the Pacific Ocean's abyssal depths to form the incredibly broad, tall mountains of Hawaiian Volcanoes and Haleakala (Haleakalā in Hawaiian) National Parks, along with the islands of American Samoa. From the moment they're born in fountains of liquid fire, natural forces begin to reshape these volcanic islands—and ultimately destroy them. But along the way to their own demise, for a time at least, they resemble, as much as any place on Earth, historical notions of a garden paradise.

The Big Island

- The Hawaiian Islands are born of fire as mid-ocean hot spot volcanic islands, yet no sooner are they formed than other natural forces—gravity, life, and the elements—begin to tear them down. Along the path to their inevitable destruction, these forces conspire to green the land and sculpt cliffs and chasms from the fresh, broad shields found at Mauna Loa, Mauna Kea, and Kilauea.

- Life makes soils and digests the volcanic bedrock and ash below. Streams carve canyons and cascade as ribbonlike waterfalls. New islands subside—the ocean floor sags beneath them—as they move off the hot spot and adjust to the weight of all the lava piled on top.

- Landslides of epic magnitude take huge bites out of the islands, undoing in minutes the work of hundreds of millennia. This process, known as mass wasting, strews island material for miles across the ocean floor and plays an outsized role in the wearing away of the Hawaiian Islands.

- Working together, these fundamentally destructive processes have transformed mere mounds of basalt—albeit huge ones—into some of the most intensely beautiful, intricately sculpted places on the planet.

- The Big Island continues to grow at Mauna Loa and Kilauea, replenished by plumes of hot, partially melted rock from the Hawaiian hot spot far beneath the southeastern corner of this island. Yet, even here where everything's still getting built, we encounter early signs of the island's undoing in Hawaii Volcanoes National Park.

- Brittle, glassy volcanic crusts fragment even as they cool. Surf pounds fresh lava deltas, undercutting them, causing some to tumble into the sea and slide down the long, steep, submerged flanks of the island. It's a perennial battle between fire and water, one that in time the water will surely win.

Big Island.

- The disassembling of the Big Island is even more evident to the north on the oldest of its volcanoes, Kohala, beyond the borders of the park, where landslides and slumps have claimed huge chunks of the mountain, steepening slopes. Thick vegetation has covered the rocks, and below, plant roots secrete organic acids designed to digest them.

- We see the work of time already in full flower on Maui—the second-youngest island in the chain—in the dissected slopes of Haleakala National Park and in more advanced stages on well-worn older islands, such as Kauai.

- Beyond Kauai, remnants of older volcanic islands disappear beneath the waves, sometimes leaving behind a fringing reef that outlives the island it fringed to become an atoll, a halo of life near the surface of the dark blue water.

- Nature carves the Hawaiian chain via the processes of weathering, erosion, and transport, with local deposition thrown in to round out the toolset before everything vanishes below the sea.
  - Weathering, the breakdown of material such as rock and ash, occurs by both chemical and physical means.

  - Erosion is simply the removal of material. Bits of rock and ash can dissolve or become suspended in water and carried off, blown off on the wind if they're fine enough, or simply slide downhill. That journey—from a place of origin to somewhere else—we call transport.

  - Deposition occurs when material that originated somewhere else gets transported to a location and left there.

- One of the most dynamic, effective, and colorful weathering agents we encounter in Hawaii's national parks is vegetation.

- The Hawaiian Islands are one of the most isolated archipelagos on the planet. Their extreme remoteness combined with their separation from one another have made the islands hotbeds of speciation.

- Plants and animals rafted or blown to Hawaii by chance across hundreds and hundreds of miles of open water have proliferated here and differentiated from one another and their ancestors, even cousins on other islands in the chain, creating numerous unique endemic species—that is, species found here and only here.

- Unfortunately, many of the islands' unique species have perished since human settlement, out-competed by nonnative plants and animals brought from elsewhere. At least a dozen known species of birds went extinct on the Hawaiian Islands after Polynesian settlement but before the arrival of the first Europeans in 1778.

- More than 25 more bird species have vanished from the islands since. A number of insects, mollusks, and plants have met the same fate. But many endemic species persist—including the Hawaiian or nene goose, the Hawaiian petrel, and the Mauna Kea silversword—some of them only in Hawaii's national parks.

- The unique geological forces that created these islands in the middle of the Pacific Ocean, and that wear them away, make possible all of this biodiversity. And the organisms that have adapted to live on the islands transform them in turn.

- Trees and shrubs might look innocuous, but given enough time, they can shatter rock, suck nutrients from it, and transform some of the hard minerals rocks contains into soft clays and dissolved ions, ripe for transport. Plants have been fine-tuned by evolution to alter rock, to break it down. After all, they need to get nutrients somewhere.

Haleakala National Park

- From the northernmost tip of Kohala on the Big Island, a 26-mile trek brings us to Maui, the next oldest island in the Hawaiian chain and home to Haleakala National Park. Haleakala—"House of the

Sun"—is the largest of the island's two shield volcanoes and the most recent to form.

- Geologists estimate that eruptions began to create it about 1.2 million years ago, and the most recent eruption occurred in 1790. Although these are late-stage eruptions, with the Hawaiian hot spot now located below the far side of the Big Island, it's a good bet that lava will flow again on Haleakala.

- The older, more heavily eroded West Maui Volcano forms a lobe of land to the northwest. While it tops out just below 5,800 feet today, geologists estimate that it once rose to a height of 13,000 feet or more, nearly the height of the Big Island's titans, Mauna Kea and Mauna Loa.

- The island of Maui has several close neighbors, separated from it by shallow straits: Kahoolawe, Lanai, and Molokai. At the greatest extent of continental glaciation during the last ice age roughly 20,000 to 26,000 years ago—when glaciers reached their maximum volumes—sea level would have been as much as 400 feet lower than today.

- At that time, these islands and Maui were joined by now-submerged lowlands into a larger island, Maui Nui. This enlarged Maui was composed—like Hawaii's Big Island—of several shield volcanoes that abutted and buttressed one another as they formed.

- Haleakala National Park on the island of Maui encompasses two quite distinct areas that are accessible to visitors: the mountain summit, with its spectacular erosional basin and rim rising to an elevation of more than 10,000 feet, and the coastal Kīpahulu District to the southeast.

- Between these entrances stretches the Kīpahulu Valley Biological Reserve, a part of the national park that shelters so many endangered endemic species—the most in any U.S. national park—that the park service prohibits entry. Streams draining the wet, windward, eastern

Haleakala National Park, Maui, Hawaii.

flanks of the volcano have incised this valley and other adjacent ones, rapidly transporting away large volumes of igneous rock and ash.

- Such moisture-driven erosion from the windward flanks of the volcano has helped carry away the mountaintop, leaving the large basin that many incorrectly call a caldera or crater as Haleakala's crown. Streams might in fact have exploited rifts and fractures surrounding an ancient caldera, but the basin today is not technically a caldera.

- From the Kīpahulu entrance down on the coast, it's possible to hike the Pīpīwai Trail up the lower reaches of the valley to view spectacular Makahiku and Waimoku Falls, along with other cascades. These falls form where streams tumble over more resistant basalt ridges as they make their way down to the sea. In nearby 'Ohe'o Gulch, Palikea Stream has carved dozens of pools that double as swimming holes for visitors and homes for native freshwater fish.

- Contrasted with the dense forest and bamboo stands at Kipahulu, Haleakala's summit is another world of sweeping open vistas. The landscape of brown and black volcanic ridges and amphitheaters is dotted with cinder cones.

- Here, landslides and stream erosion have carved a large, tilted basin seven miles long, two miles wide, and about half a mile deep into the older volcanic flows. A subsequent renewal of volcanic activity due to a late pulse of magma from below the island added the cinder cones, which follow the line of a rift that continues across both flanks of Haleakala. Some of the cones rise as high as 600 feet, and some recent lava flows have covered portions of the floor of the basin.

The National Park of American Samoa

- Although part of a different chain thousands of miles south of Hawaii in the South Pacific, the islands of Samoa—including both American Samoa and the country of Samoa—are also the product of a sub-Pacific hot spot.

- They show all the geological hallmarks of sub-oceanic hot spot volcanism found in Hawaii's national parks: shield volcanoes composed primarily of basaltic igneous rocks, weathering and erosion processes, and subsidence that steepen and sculpt the islands as they age.

- Voyagers from across the Pacific first arrived in Samoa about 3,000 years ago, and the islands would ultimately become a nexus for dispersal of settlers to islands throughout the Polynesian triangle—from Hawaii to the north, to New Zealand to the south, and Easter Island to the east.

- The national park here encompasses distinct units on three large islands: Tutuila (the most populous of the islands), Ofu, and Tau. The small island of Aunuu just off Tutuila also has been designated a National Natural Landmark.

- At Tutuila, the park sits just north of Pago Pago, American Samoa's largest city. The harbor at Pago Pago is in fact the collapsed caldera of a shield volcano whose remnants now occupy much of the park. This is just one of four shield volcanoes dating back about 1.4 million years that together built the island of Tutuila.

- At Ofu, the national park includes coral reefs and a coral-sand beach fringing an eroded shield volcano with lava flows, ash-tuff layers, and cinder cones.

- At Tau, enormous landslides driven in part by ocean surf erosion have created some of the tallest sea cliffs anywhere in the world. From their crests, these cliffs plummet more than 3,000 feet to the Pacific far below. More than three-fifths of the area included in the Tau portion of the national park lies underwater in protected coral reefs. And just as in Hawaii, with time, the islands of Samoa will continue to weather, erode, and evolve until they sink forever beneath the waves.

Suggested Reading

Hazlett and Hyndman, *Roadside Geology of Hawaii*.

Holland, "Red Hot."

Questions to Consider

1. The Hawaiian hot spot isn't the only undersea volcanic hot spot. Try to discover others.

2. Islands of the Hawaiian chain become progressively older to the northwest. Compare landscapes of the Big Island, Maui, Oahu, and Kauai to see what erosion does over time to the islands' shield volcanoes.

Lecture 6

Mount Saint Helens, Lassen Volcanic, Rainier

In the Pacific Northwest, the disappearance of ocean floor beneath the North American continent has created a line of ticking time bombs called the Cascade Volcanoes. The volcanoes of the Pacific Northwest are aligned along a Transverse Axis running from north to south, while the volcanoes of Mexico are aligned along a Transverse Axis running from west to east. But what they have in common is the action of an offshore ocean plate that is colliding with North America, pushing up the volcanoes and providing them with new sources of fuel below the surface.

The Cascade Range

- The Cascade Range of the Pacific Northwest traces a north-south line from British Columbia in Canada to northern California. In addition to what is now the Mount Saint Helens National Monument, the chain encompasses a number of U.S. national parks that share a common tectonic heritage, though each has a unique history and personality: Lassen Volcanic, Mount Rainier, Crater Lake, and North Cascades National Parks.

- Katmai and Lake Clark National Parks in Alaska also derive from similar geological processes—processes that define a Ring of Fire surrounding much of the Pacific Rim. Think of such volcanoes as Krakatoa, Pinatubo, and Fuji. Geologically, they're all siblings, but each is different, unique, and capable of astonishing us in different ways, despite their similarities.

- About 300 miles offshore the Cascades, the Pacific plate on one side and the Juan de Fuca and Gorda plates on the other are spreading in opposite directions along mid-ocean ridges. Closer to the coast, the Juan de Fuca and Gorda plates descend beneath the North American continent. About 100 miles inland sit the Cascade volcanoes.

- Why are the volcanoes here? The descending plate first crumples material scraped off by the overriding edge of the North American plate to form an accretionary wedge. By the time the slab has arrived beneath the Cascade volcanoes, it's reached a depth of about 50 miles.

- At this depth, the pressure is roughly 20,000 times as great as the single atmosphere of pressure we typically experience at sea level on Earth's surface due to the weight of the air above us. This is where metamorphic transformation begins in earnest. Fluids released by the plate rise through overlying continental crust and burst forth at the surface in majestic volcanoes.

Mount Saint Helens

- On May 18, 1980, a magnitude 5.1 earthquake signaled the start of the largest landslide anywhere during the span of recorded human history. Within moments, the abrupt reduction of pressure on magma inside the volcano caused gases within it to expand, and the magma exploded. The explosion blasted a mix of lava, rock, and hot gases horizontally from the throat of the volcano at a velocity of more than 300 miles per hour.

- A horizontal blast hugged the landscape, cresting over hills before plunging into valleys, leveling whole forests along the way. The eruption also propelled a roiling dark column of ash vertically, 80,000 feet into the stratosphere above the mountain.

- It melted glaciers near the volcano's summit, and the resulting floodwaters swept down Mount Saint Helens' flanks as devastating mudslides called lahars. They surged down stream and river valleys away from the mountain, following the topographic lows, ultimately traveling as far as the Columbia River 50 miles away. Clouds darkened the sky above and downwind of the volcano.

- The clouds rained abrasive ash that inundated the landscape, burying communities across central and eastern Washington an inch or more deep in heavy destructive grit. In total, 57 people lost their lives in this latest of many eruptions of Mount Saint Helens.

Mount Saint Helens.

- Although eruptions of various sizes and kinds have taken place near where Mount Saint Helens stands for about 275,000 years, geologists believe that most of the mountain as it existed just before the 1980 eruption had been built in the last 3,900 years.

- In addition to the new 1,000-foot dome that was present in the caldera in the decade after the eruption, an even newer dome arose beginning in 2004. So-called lava spines—rising slabs of largely degassed and solidified lava—built the second dome. The newer dome within the caldera has risen more than 1,500 feet.

- Conditions around the volcano, including the overall risk level for people walking the trails, change all the time. And the U.S. Geological Survey has declared Mount Saint Helens the most likely volcano in the Cascade Range to erupt again in the near future. But the next one probably won't be as catastrophic as 1980, with so much of the summit already having slid and been blasted away.

Lassen Peak

- Lassen Peak, located at the southern end of the Cascade Range and nearby Cinder Cone, hosted hot springs and other geothermal features akin to Yellowstone's but was considered volcanically extinct. But in May of 1914, a new crater opened on Lassen Peak and began venting both lava and ash. Mudflows ensued. Hundreds of eruptions continued intermittently until 1921, filling in some of the 1914 crater and creating two new ones.

- At about one cubic mile in volume, Lassen Peak is a large example of a landform called a volcanic dome. Domes form when lava is simply too viscous to flow far across the landscape, so instead builds upward rapidly. A rock called dacite predominates at Lassen. Between more and less silica-rich rhyolite and andesite, dacite tends to extrude like thick toothpaste from vents or to swell domes from within.

- Lassen Peak sits on the northern flank of what had once been a much larger Cascade stratovolcano, called Brokeoff Volcano or

Mount Tehama. Topping out at more than 9,200 feet, the summit of Brokeoff Mountain in Lassen Volcanic National Park's southwestern corner is merely a remnant of the eroded rim of Tehama's caldera.

- The same goes for Pilot Pinnacle, Mount Diller, and Mount Conard. Geologists believe that Tehama rose to more than 11,000 feet before the series of eruptions and subsequent Pleistocene glaciation that reduced it to the vestiges we see today.

- The caldera defines a portion of the park that has something in common with Yellowstone: Heat generated by a near-surface magma chamber just below, an extensive fracture system, a silica-rich ash and rock substrate, and ample rain and snowmelt have given rise to this park's hot springs, mud pots, sulfur vents, and fumaroles.

- Lassen Volcanic National Park straddles two geologic provinces; the Cascade Volcanoes and the Basin and Range. The park's eastern reaches cross over into the western margin of the Basin and Range.

- Here, just as far to the northeast at Grand Teton National Park, the continental crust has stretched and thinned. This has produced normal faults that double as highways to the surface for less silica-rich magmas that formed some of the basalt and fluid andesite flows found here.

- The magma unleashed by these normal faults more closely resembles the composition of magmas that formed Hawaii's volcanic islands, a product of partial melting of mantle rocks with less of a contribution from the rocks of the continental crust.

- These flows built a broad lava plain on which Tehama and Lassen were later built. In the east, four shield volcanoes—more reminiscent of Hawaii-style volcanism than the explosive sort that created Mount Lassen and Mount Saint Helens—have grown above the flows.

- In the last few centuries, Cinder Cone formed in the northeast of the park through cinder and ash eruptions, capped by a basaltic lava flow through one wall of the cone that produced the so-called Fantastic Lava Beds.

Mount Rainier

- About 500 miles to the north up the Cascade Range, Mount Rainier looms—beautiful, ethereal, and ominous—over Tacoma, Seattle, and Puget Sound. The massive composite volcano rises above the surrounding landscape of jumbled hills and ridges, a landscape that records a multitude of lava flows and ashfalls. These include layers of ash not just from Rainier's own eruptions, but also from those of other Cascade volcanoes—including the 1980 Mount Saint Helens eruption.

Mount Rainier.

- As tall as Mount Rainier stands today, ancestors of the Northwest Indians saw it more than 1,000 feet taller. Volcanic activity between 6,600 and 5,700 years ago, including cataclysmic eruptions at the end of that span, brought down much of the mountain, produced enormous ash and mudflows, and left a summit caldera. Over the last 2,500 years, lava and ash have built a new cone in Rainier's caldera, and a new, smaller crater has opened to the east of it.

- More than 35 square miles of ice and snow blanket the mountain. Glaciers radiate from the mountaintop toward every point of the compass. Rainier is the most glaciated mountain in the United States south of Alaska.

- At more than four square miles, Rainier's Emmons Glacier has the largest surface area of any glacier in the United States south of Alaska. Rainier's Carbon Glacier is both the longest—at more than five miles—and the thickest. Six rivers find their sources in glaciers within the national park.

- Just as with Hawaii's volcanoes, gravity and other weathering and erosion agents are pulling Rainier down even as it's getting built. Heavy rains or the failure of ice dams on small lakes on the mountain's flanks initiate large and dangerous debris flows and floods.

- Despite the dangers, the powerful beauty of Rainier beckons. Below the glaciers, on the volcano's lower slopes, lakes left behind as glaciers retreated have filled with fine sediment and transformed into exquisite mountain meadows.

- As with every landscape dominated by active volcanoes, this particular one will be lost someday. Although Rainier hasn't erupted since the 19th century, the ongoing subduction of the Juan de Fuca plate, gliding beneath the mountain from the west, pretty much ensures that it will again.

- Geologists have identified Rainier as one of the most dangerous volcanoes on Earth—not so much because of the imminent likelihood of a Mount Saint Helens–style eruption, but because so much ice sits atop the mountain and so many people live near it.

- Rainier, Lassen, and Saint Helens aren't the only Cascade volcanoes that could erupt again in our lifetimes. Mount Hood—which towers to an elevation of more than 11,000 feet near Portland, Oregon—last erupted in the mid-19th century and has been assigned at least a single-digit probability of erupting again in the next several decades.

The Volcanoes of Mexico

- Some of the volcanoes of Mexico are both taller and, in recent decades, more active than the volcanoes of the Pacific Northwest. Mexico's volcanoes are gathered not along the Pacific Coast, but instead in a so-called Transverse Volcanic Axis stretching from west to east, right across central Mexico.

- This line roughly parallels, and appears to be caused by, the Cocos tectonic plate to the south of North America. The Cocos Plate is a relatively small oceanic plate of about 1 million square miles that is colliding with, and sliding under, the North American continent at what is called the Acapulco or Middle American trench.

- Closest to the Pacific Ocean of Mexico's major volcanoes is the Colima Volcano, also known as the Volcano of Fire. It's 12,533 feet tall and had a huge eruption in 1913 and a pretty big one in 2005. Five miles away is a neighboring volcano that's even taller but dormant, Nevado de Colima. Both have been part of a national park since 1936.

- Moving east, we pass Paricutin, the newest volcano in North America. This is a cinder cone volcano that erupted for the first time in 1943, stopped in 1952, and has been dormant ever since. Continuing east, just past Mexico City, we come to a national park nicknamed "Izta-Popo," with a much taller pair of volcanoes, where this time the active one (Popo) is even taller than the dormant one (Izta). These are Mexico's second- and third-tallest mountains.

- Traveling even farther east across the Transverse Volcanic Axis, we reach what is Mexico's tallest mountain: Pico de Orizaba. This is a dormant volcano that last erupted in 1846. It's a conical stratovolcano—that is, built up from many strata—and it's so tall that its peak is covered year-round with glaciers and snow. It is North America's tallest volcano and a worthy counterpart to the most famous stratovolcanoes of other continents, such as Mount Kilimanjaro in Africa or Mount Fuji in Asia.

Suggested Reading

Alt and Hyndman, *Roadside Geology of Northern and Central California*.

———, *Roadside Geology of Washington.*

Tucker, *Geology Underfoot in Western Washington*.

Questions to Consider

1. Big geological events make big news. What recollections do you have of the Mount Saint Helens eruption, if you're old enough to recall it? What other geological events—tsunamis, earthquakes, eruptions, avalanches, and so on—have made news during your lifetime?

2. Look at a map of areas directly affected by the 1980 Mount Saint Helens eruption, excluding ashfall. You'll find one example here: https://upload.wikimedia.org/wikipedia/commons/e/e6/St_helens_map_showing_1980_eruption_deposits.png. Then, look at a map of the region surrounding Mount Rainier and make a prediction of which areas would be most affected by a major eruption of Rainier.

Lecture 7

Crater Lake, Olympic, North Cascades

More than 100 million years of tectonic action along North America's western coast has built and destroyed a multitude of lofty landscapes. Seafloor subduction raised fiery Mount Mazama, only to obliterate it in a colossal eruption that left its dust settling on Crater Lake. Debris scraped from the seafloor by the prow of the continent upended into the imposing mountains of the Olympic Peninsula. Not far inland, the North Cascade Range reflects the complex legacy of past collisions.

Crater Lake National Park

- Crater Lake was once an enormous mountain—a mountain that melted away, leaving just a wizard's-cap-shaped island and a very large pool of water behind. In its prior incarnation, the lake was Mount Mazama, which obliterated itself during an enormous eruption roughly 7,700 years ago, leaving the lake for its legacy in the Cascade Range.

- Just as at Saint Helens, Rainier, and Lassen, what we see now was caused by the descent and partial melting of oceanic crust beneath the western edge of North America into the so-called Cascadia subduction zone. This is what first created, and then destroyed, Mount Mazama to give us Crater Lake.

- The Mazama eruption was huge by almost any standard, smaller only than supervolcanoes such as those associated with the Yellowstone hot spot. The ash from the eruption surrounds Crater Lake to depths as great as 300 feet. It's visible at numerous places surrounding the lake and blanketed much of the Pacific Northwest and western Canada.

- Extrapolating from the angles of beds leading away from the crater's rim, the depth of the caldera, and the volume of material ejected during Mazama's eruption, geologists estimate that the mountain rose to a summit height of more than 12,000 feet above sea level.

Crater Lake National Park.

- From projected peak to caldera floor, the eruption removed a good mile of the mountain. Some of Mazama erupted skyward or slid down the flanks of the volcano. Some might have collapsed into the magma chamber as it rapidly emptied itself.

- To the north of Crater Lake lies the Pumice Desert, a broad expanse of pumice and ash hundreds of feet thick that was ejected during Mazama's eruption. The substrate here is so porous, and therefore dry, that all these thousands of years later, plants still struggle to gain a foothold.

- Also north of the lake, Red Cone is another now-familiar feature from other volcanic parks, a cinder cone of scoria. This is the largest of several such cones in the park that grew on the flanks of Mount Mazama more than 20,000 years ago. Because it formed so long ago, Red Cone must have been part of an eruptive episode prior to the one that shaped Crater Lake—one that helped build the mountain rather than blasting it apart.

- One of the most striking landforms in the park appears south of Crater Lake, at the Pinnacles. Accessible from the Godfrey Glen Trail, these peculiar thin gray spires rise above the landscape where a thick ash layer emerges along the walls of gorges. They are fossil steam vents, or fumaroles. Hot and acidic water and gases venting through ash shortly after Mazama's eruption cemented particles of ash through which they passed, later leaving these fluted columns behind as the surrounding ash eroded away.

- The rocks of the surrounding cliffs at Crater Lake come in an exquisite mix of colors. This is the same palette of pastel colors that paint the Grand Canyon of the Yellowstone River: red, pink, orange, yellow, brown, and cream. In both parks, it's the signature of hydrothermal—that is, hot water—alteration of rock and ash ejected from the more silica-rich volcanoes that form the continents.

- Wizard Island is another highlight of any visit to Crater Lake. In the millennia since the major eruption of Mount Mazama, this island has grown more than 2,000 feet from the submerged floor of the volcano's caldera, rising more than 760 feet above the surface of the water. It's a large cinder cone surrounded by lava flows, and it last erupted about 800 years ago—the most recent eruption at Crater Lake.

- At its deepest spot, the bottom of Crater Lake lies more than 1,940 feet below the surface, making it the deepest lake in the United States and the ninth deepest on Earth. Crater Lake also has some of the clearest water found in any natural lake on the planet. As a result, living creatures that require light for photosynthesis can grow to amazing depths.

- Much as we have John D. Rockefeller Jr. to thank for the creation of Grand Teton National Park as we know it today, we owe a debt of gratitude to William Gladstone Steel for the existence of Crater Lake National Park. Steel lobbied to see the lake protected from 1885 to 1902, when Theodore Roosevelt declared it America's sixth national park.

Olympic National Park

- In the Olympic Peninsula, North America's leading edge has scraped igneous rocks and marine sediments from the descending oceanic slab, causing them to pile up into the jagged, snow-capped mountains that form the core of Olympic National Park.

- The Olympic mountain range is pushed where it is by collision with the North American continent. Together, sediments carried seaward from highlands on the continent and deposited on the continental margin toward the trench offshore, along with seafloor sediment and basaltic volcanic rocks scraped from the descending slab, make up the groceries.

- Geologists call these piles of scraped-off and stuck-on rocks at the edge of a subduction zone an accretionary wedge. Rising from the timbered slopes of the Olympic Peninsula, that wedge is a remarkable sight to behold.

- Although the highest summit here crests just below 8,000 feet, the mountains pack a tremendous punch. The Olympics rise in an ultra-sheer jumble so challenging to explorers that the interior of the Olympic Peninsula wasn't mapped until the 1890s, more than a century after navigators charted the surrounding waters and coast.

- Collision, compression, erosion, and isostatic uplift here at the continent's bleeding edge have raised relatively buoyant sandstones and coarser conglomerates that formed near or below sea level to the jagged summits of some of the mountains on the Olympic massif.

Olympic National Park.

- A massif is a compact, self-contained, and often fault-bound mountain range or other highland. Erosion continuously carves the landscape and has preferentially removed finer-grained shales, leaving the more durable sandstones.

- The Crescent Formation—a horseshoe-shaped, upturned wall of basalt, open to the west—surrounds the center of the range. It appears in outcrops around the Olympic Peninsula. From east to west within the horseshoe, the rocks typically get younger, with the youngest nearest to the Pacific Coast.

- Looking south from Hurricane Ridge in the park, the Olympic Mountains rise in a craggy line. Despite their relatively low elevation, glaciers and snowfields paint many of their flanks white year-round. The park's roughly 60 active glaciers have carved out cirques and narrow ridges and have made sharp horns of many of the summits.

- Just like the windward flanks of Hawaii's volcanoes, the western side of Olympic National Park gets a lot of rain. The heavy snowfall higher up on the mountains helps sustain their icy cloaks. Lower down, heavy rain supports temperate old-growth rain forests with some of the highest biomass per acre found anywhere on Earth.

- Some visitors to Olympic National Park enjoy basking in the natural mineral waters of the Sol Duc Hot Spring. Unlike the hot springs at Yellowstone and Lassen Volcanic National Parks, Olympic's are not due to a shallow magma chamber beneath the park. Instead, vertical fractures in faulted sandstones inside the Crescent Formation horseshoe provide conduits that allow groundwater to circulate deep enough to get heated before rising in the springs.

- West of the peninsular mountains and forests, Olympic National Park also includes a coastal segment of wilderness shore more than 70 miles long. The Olympic coastline encompasses rocky cobblestone beaches, wave-battered headlands, and sea stacks—remnants of former coast eaten away by the violent surf.

North Cascades National Park

- As long as subduction continues, an accretionary wedge can grow wider at the prow of the continent, extending it. From time to time, volcanic islands or pieces sheared off other continents might ride in on a subducting marine-floor slab and slam into the wedge. When this happens, the collision can raise huge mountains and extend the continent still more. Regions that were once near shore become farther and farther inland, farther from the trench, closer to the zone where magma rises from below to form subduction-arc volcanoes.

- Such is the case with North Cascades National Park. Inland to the northeast of the Olympic Peninsula, the park features more than 300 glaciers, 300 lakes and ponds, and almost 9,000 feet of vertical relief from its lowest valley floors to the summit of its tallest peak, Goode Mountain.

- Two active Cascade stratovolcanoes, Mount Baker and Glacier Peak, sit near but not within the boundaries of the park. North Cascades National Park's mountains are not volcanoes, although some formed as portions of volcanoes.

- The park's geological story is far from simple. The range is a geological mutt that includes granites, seafloor basalts and sea-basin sediments, slivers of ancient volcanic islands, and fractured slabs of broken continent.

- This mongrel mosaic formed over a span of about 400 million years. Pieces traveled with ocean crust, following convergent or laterally moving strike-slip faults on a collision course with North America until they ended up where we find them today.

- Multiple collisions faulted the rocks and raised high mountains, since eroded. Granitic magma intruded metamorphic rocks deep underground, the Skagit Gneiss and the Cascade River Schist. The granite it became forms the Chilliwack Batholith, which has risen from the depths to core many of the park's tallest mountains.

Mount Baker, North Cascades National Park.

- Pegmatites, granites with exceptionally coarse crystals, filled fractures in the metamorphic rocks. They give a veined, marbled texture to many of the outcrops in road cuts along Highway 20, the main park road, as it passes through the mountain range near the middle of the park.

- A fault to the east created a zone of weakened rock that was later excavated by Pleistocene glaciers to create the basin for Ross Lake. Subduction of the Juan de Fuca Plate offshore to the west, still ongoing, lifted the roots of the old mountains into the imposing jumble that is the North Cascade Range we find here today.

- The many glaciers of North Cascades have put a sharp edge on the park's saw-toothed peaks, sculpting troughs, cirques, horns, and knife-edged arêtes across the tallest of them. No U.S. national park outside Alaska hosts as many glaciers, but the ice is on the wane and has been for more than a century.

- The glaciers of North Cascades are thinning, too. The reduction of glacial ice has consequences for the many streams and rivers draining the park, because meltwater helped sustain their flow rates and ensure that the streams flowed year-round.

Suggested Reading

Alt and Hyndman, *Roadside Geology of Washington.*

Miller, *Roadside Geology of Oregon*.

Mitchell, "Nature's Champion."

Tucker, *Geology Underfoot in Western Washington*.

Questions to Consider

1. Plan an imaginary (or real) vacation itinerary through the Cascades parks. Begin in Sacramento, California, and visit Lassen Volcanic, Crater Lake, Mount Saint Helens, Mount Rainier, Olympic, the San Juan Islands, and North Cascades, ending in Seattle. How long would you need to complete the trip? What else could you see along the way?

2. The Sol Duc hot spring is only one of many hot springs in the national parks. Yellowstone's geothermal fields contain many more. Which other national parks contain hot springs?

Lecture 8

Volcanoes of Alaska: Katmai and Lake Clark

The grandeur, scale, and solitude of Alaska's eight sprawling national parks give new meaning to a concept of wilderness for many of the people who have the privilege of visiting them. Two of Alaska's national parks, Katmai and Lake Clark National Parks, lie along one of the volcanic arcs that encircle most of the Pacific basin. This is the Pacific "Ring of Fire," which includes the Cascade volcanoes of northern California, Oregon, and Washington, as well as the Andes in South America and the volcanoes that dot the islands of Japan.

Alaskan Volcanoes and Earthquakes

- Alaska's Katmai National Park contains the volcano that had the largest volcanic eruption anywhere on Earth during the 20th century. In addition, more than a dozen of the 50 or so volcanoes that have erupted in Alaska since Russians began arriving and started keeping records in the mid-18th century have been inside the current boundaries of Katmai National Park.

- Fewer in number, but active much more recently, are the pair of volcanoes inside Lake Clark National Park—with two more just outside the park—and landscapes so varied and majestic that they've been described as "the epitome of Alaska."

- Both Katmai and Lake Clark National Parks contain active composite volcanoes, and both are similar to those found far to the south in the Cascades. Similar landscapes and geological features typically suggest similar geological origins, and that's the case with these parks. For each of these parks, volcanic activity has its source in subduction and partial melting of oceanic crust as it's overridden by continental crust.

- In the seafloor beneath the North Pacific and the Gulf of Alaska, the deep waters of the Aleutian Trench mark a lengthy crescent along which the floor of the Pacific vanishes, descending back into the upper mantle from which it once emerged at a mid-ocean ridge. Volcanoes erupt and huge earthquakes occur along the entire length of this so-called Aleutian megathrust fault, a vast line where the oceanic plate meets and slides below the continent of North America.

- In the case of the Cascades, seafloor subducts below the continent from the northwest, so we find the Cascade volcanoes to the southeast of the trench. Off Anchorage, Seward, Kodiak Island, and the Alaska Peninsula, seafloor descends in the opposite direction, from the southeast to the northwest, so the Aleutian volcanoes in the region rise northwest of the trench.

- The average rate at which the colliding plates are coming together, or converging, is high. It varies from two inches per year in the east to three inches per year far out in the Aleutian Islands near Kamchatka. Measurements of seismic wave rates and locations of earthquake epicenters reveal that the descending slab of oceanic crust has flexed downward at a steep angle, about 45 degrees.

- Portions of the slab lock with the rock above as compressive pressure builds up over years. Both sides strain under the stress like tensing springs until the accumulated energy releases in earthquakes—sometimes severe.

- The most devastating of these Alaskan quakes—in recorded history, at least—took place on March 27, 1964, which happened to coincide with the Christian commemoration of Good Friday, the Friday before Easter. The rupture that produced the earthquake occurred about 15 miles underground and 75 miles east of Anchorage. The quake shook the ground for nearly five minutes. It had a staggering moment magnitude—a measure of the energy released by an earthquake—of 9.2, the highest ever recorded in North America and the second-highest recorded anywhere.

- Because of the intensity of the subduction occurring in this region, southwestern Alaska—including its parks—regularly experiences smaller earthquakes and remains vulnerable to occasional big ones. In fact, the state of Alaska accounts for more than half of all earthquakes in the United States—more than twice as many as California—with as many as 4,000 earthquakes at all depths each year.

- The landscapes of southern Alaska's national parks have been shaped by subduction of the Pacific Plate beneath the North American Plate. In Kenai Fjords National Park, which lies north of the Good Friday earthquake's epicenter, the land along the coast shifted downward so that much of the former coastline was submerged.

The Volcanic Eruption of Mount Katmai

- Beginning on June 6, 1912, a volcanic eruption put Katmai on the map for much of the world, with a blast heard 500 miles away in Fairbanks to the north and 750 miles away in Juneau to the southeast. That roar signaled the start of the largest eruption that would take place anywhere on our planet during the 20th century.

- Over the next few days, it buried the small village of Katmai Bay to the east under a thick layer of ash, rendering it uninhabitable. It blanketed more than 3,000 square miles of land, including much of nearby Kodiak Island, under a foot or more of ash and pumice. It sent fine ash particles and aerosols high into the atmosphere, where they cooled temperatures across the Northern Hemisphere by about two degrees Fahrenheit for the next two years.

- Strong tremors preceded the eruption for about a week, so people living in the region had time to evacuate, and there were no witnesses close by to record the details of what took place. Based on the succession of strata—the rock and ash layers—produced by the eruption, geologists have since pieced together the sequence of events.

- Ash vented into the air as if from a jet in huge volumes for the first two days. Soon, ash was accompanied by pyroclastic flows—glowing avalanches of volcanic material and hot gases. Finally, more ash covered all. Magmatic mixing produced a peculiar form of banded pumice with black and white stripes.

- People originally believed that the volcanic material vented directly from Mount Katmai. After all, the blast lowered the summit of Katmai from about 7,500 to 6,700 feet. It left a summit caldera on Katmai that is three miles wide, two miles long, and 3,700 feet deep. It seemed clear that a magma chamber beneath Katmai must have been the source of the ash and lava that erupted in 1912.

- More than four decades later, however, geologists would determine that the magma did indeed originate beneath Katmai, but it first traveled six miles underground to a new vent called Novarupta (which means "new break" or "newly erupted") before erupting to the surface. Geologists could see this because the ash layers from the time of the eruption reach their maximum depth in and around Novarupta—and thin progressively toward Katmai.

- National Geographic underwrote several research expeditions to the Katmai region after the blast to document its effects and, in particular, successive stages of plant recolonization in and around the volcano. They made the first detailed maps of the region's volcanic terrain. Botanist Robert Fiske Griggs led five of these expeditions.

- During the second of his visits, in 1916, Griggs and the team observed tens of thousands of steam vents in the valley, some of which shot steam hundreds of feet into the air. Griggs named the remarkable steaming, sulfurous basin the "Valley of Ten Thousand Smokes." The valley, incidentally, no longer smokes.

- Unlike fumaroles at Yellowstone and Lassen Volcanic National Parks, which remain active due to the presence of extremely hot rock or magma at shallow depths underground, the heat of the newly erupted ash caused the Valley of Ten Thousand Smokes to smoke. As the ash cooled, the steam vents simmered down. By the 1930s, only a handful of the thousands that Griggs and his colleagues originally witnessed were still smoldering.

- Today, after more than a century, the ash has cooled enough that apart from isolated fumaroles, only mist and fog cloud the view of the valley. In addition to steam rising from the countless fumaroles, some of the wonders of the newly transformed landscape include thick layers of ash, already deeply eroded by streams and rivers, leaving tall cliffs; caves melted beneath ice by steam vents; vents hot enough that Griggs and his colleagues could cook meals over them; and pumice so light that person-sized chunks of it could be lifted and tossed around with little effort.

- Griggs's team's photos, newsreels, and articles about Katmai brought public attention. Griggs and National Geographic agreed to work for its preservation as a national park. But it was easier, from a political standpoint, to get the land protected as a national monument.

- On September 24, 1918, President Woodrow Wilson signed a proclamation setting aside an area half the size of Yellowstone as Katmai National Monument. The monument was later expanded several times to include vast tracts of bear habitat, salmon-spawning grounds, and nearby islands in Shelikof Strait and Cook Inlet.

- Katmai finally became a full-fledged national park by act of Congress in December 1980, with more than 3 million acres protected as wilderness, which makes Katmai larger than Yellowstone and Yosemite combined. Congress also set aside several hundred thousand additional acres in which subsistence and sport hunting are allowed in the adjacent Katmai National Preserve.

Katmai National Park and Preserve

- Four distinct physiographic provinces, each reflecting distinct facets of the geological processes at work in the region, characterize the park from the waters of the Shelikof Strait southeast of the park into and across the Alaska Peninsula to the northwest.
  - At the far southern end of Katmai's coastal strip, the Katmai River crosses a broad mudflat of ash and other volcanic debris

Katmai National Park.

carried down to the coast by lahars and huge volumes of glacial meltwater.

- Moving inland to the northwest, the land rises abruptly into the Aleutian Mountains.

- Progressing farther west across the park, the foothills of the Aleutians appear amid a series of long, parallel lakes.

- Northwest, past the foothills, between and beyond the large lakes, a mix of boreal forest, marshland, and tundra define the lowland landscapes.

- Simply getting to Katmai is an adventure. Most visitors to the park's interior travel by air from Anchorage to King Salmon, a town off the park's western boundary, and then catch a floatplane to Brooks River Camp on Lake Naknek.

Lake Clark National Park and Preserve

- A few hundred miles to the northeast toward Anchorage, Lake Clark National Park and Preserve shares much of Katmai's geological story and, therefore, many of Katmai's landscapes. Similar to Katmai, four physiographic regions characterize the park from east to west.
    - A coastal strip adjoining Cook Inlet.
    - A rugged mountainous zone (the Chigmit Mountains) crowned by active volcanoes and glaciers.
    - Westward-descending foothills interspersed with lakes and wild rivers (spawning grounds for salmon and trout).
    - Lowlands that include patches of boreal forest and tundra plain.
- The Neacola Mountains of the Alaska Range also lie in the northern part of the park.
- No roads traverse this wilderness park, which visitors must access by floatplane or boat. A multitude of natural hazards—including volcanic eruptions, rockslides and mudslides, earthquakes, and floods—pose ongoing threats.
- Two massive, active composite volcanoes, Redoubt and Iliamna, rise to elevations above 10,000 feet and overshadow the park near the southeastern coast. Two more active volcanoes rise just outside the park's boundaries: Mount Spurr to the northeast and Augustine, an island in Cook Inlet south of the park. All of these have erupted violently during historical times, sometimes raining ash on nearby Anchorage and wreaking havoc there.

Lake Clark National Park.

- Although no roads traverse Lake Clark National Park, there is a way to appreciate it by car. From the Sterling Highway, along the west coast of the Kenai Peninsula, there are stunning views on a clear day of Mount Iliamna, Mount Redoubt, and lower peaks of the Chigmit Mountains, 50 miles away, across Cook Inlet.

Suggested Reading

Connor, *Roadside Geology of Alaska.*

Riehle, *The Geology of Katmai*.

Questions to Consider

1. Active volcanoes and big earthquakes define the Ring of Fire around the North Pacific Basin. Find and read about examples of major eruptions and earthquakes on the Ring of Fire beyond the Pacific Northwest and Alaska.

2. Ash from Mount Redoubt's 1989 eruption nearly downed a large KLM passenger plane. What other volcanic eruptions have caused plane malfunctions or flight cancellations?

Lecture
9 Alaska's Glacier Bay and Kenai Fjords

At the top of the Alaska panhandle, across the Gulf of Alaska from Katmai and Lake Clark National Parks, is a region of mountains, inlets, islands, and fjords that seems almost designed by nature for the purpose of manufacturing glaciers. Today, we know this place as Glacier Bay National Park and Preserve. On the western shore of the Gulf of Alaska is an icebound area known as Kenai Fjords National Park. Both Glacier Bay and Kenai Fjords National Parks are magnificent kingdoms of ice.

Glacier Bay National Park and Preserve

- Glaciers aren't just large snowfields that persist through the summer. They are ice on the go—from places where more of it accumulates than is lost each year to places where the supply and the loss of ice balance. Four helpful factors contribute to the production of glaciers near Glacier Bay.
    - Abundant moisture: The prevailing westerly winds bring humid air from the Gulf of Alaska.

    - Tall mountains: The Fairweather Range stands along the coast, with Mount Fairweather, the tallest, rising from sea level to an elevation of more than 15,000 feet. To the east across Glacier Bay lie the Takhinsha Mountains, and to the north lie the Saint Elias Mountains.

    - Cool temperatures, even in summer: The relatively high northern latitude and coastal setting contributes to cool overall temperatures across the park year-round, and particularly on the high slopes of the mountains.

    - Many overcast days: Conditions along the Gulf of Alaska coast resemble those along the Pacific Coast at Olympic National Park and help produce similar foggy and cloudy weather to shade ice and snow.

- Thick ice filled Glacier Bay to its mouth on Icy Strait when Russian explorers first viewed it in 1741. But the Tlingit Indians, who inhabited the region, recalled a time when the then-glaciated bay had been open water and they camped and fished on islands within it.

- When Captain James Cook reached Glacier Bay in 1778, enough ice had melted from its mouth that his ships could enter. The retreating ice blocked further progress, but he named Mount Fairweather before sailing on.

- When a team from the HMS *Discovery*, captained by George Vancouver, surveyed the bay in 1794, the glacier that still filled it to Bartlett Cove near its mouth stood up to 4,000 feet thick and 20 miles wide.

- Over the next century, Glacier Bay's ice retreated up the bay at a prodigious pace. By the time naturalist John Muir made his first of many visits in 1879, ice had receded nearly 50 miles, exposing most of Glacier Bay as open water.

- Muir had come to witness and study glaciers in their prime. Over his years of hiking in and around Yosemite Valley in California's Sierra Nevada, Muir had reached the conviction that glaciers had carved Yosemite's exquisite landscape. Much of the academic geological establishment dismissed the notion, so Muir came to Alaska—in part, at least—to seek proof.

- Muir would continue visiting and studying the glaciers in this location for the next 20 years. His dispatches to California newspapers about the marvels of Alaska and Glacier Bay helped spread the word that there were wonders to be seen. Muir lobbied for the bay's protection as a national park.

- Although it didn't happen during Muir's lifetime, President Calvin Coolidge would declare the bay a national monument in 1925. And in 1980, Glacier Bay expanded almost 20 percent and became a

Glacier National Park.

full-fledged national park, with a much smaller national preserve to the northwest.

- In Glacier Bay National Park, the mountain ranges and waterways trend northwest to southeast, parallel to the Gulf of Alaska coast. Bands include the Saint Elias Mountains and Fairweather Range, the Brady Icefield and Glacier, Glacier Bay, and the Takhinsha Mountains and Chilkat Range to the east.

The Influence of Plate Tectonics

- As with the Pacific Northwest and the Alaska Peninsula, the country around Glacier Bay has seen millions of years of subduction and accretion as it slid above descending oceanic crust. Over the millennia, several chunks of more buoyant crust have rafted in with the surrounding seafloor. Those were islands, seamounts, or slivers of older continents that had split off as new ocean basins formed. And these rafting pieces of crust collided with the continent and slid along its edge. As these chunks slammed in, land on both sides of the collision zone crumpled.

- High mountains formed. Erosion has carried rock off the summits and slopes of these mountains. As the weight has been removed, their deep igneous and metamorphic roots have been buoyed up by denser, ductile rock in the mantle below, so the roots now stand revealed as mountain peaks.

- When blocks from one plate are piled up in this way against the plate of a continent, geologists call them terranes. From west to east, several named terranes underlie Glacier Bay National Park, including the Chugach, the Wrangellia, the Alexander, and the Yukon-Tanana.

- Sutures define the boundaries between the terranes, and these sutures are marked by deep, parallel faults. This is why the topography of the land includes highlands and lowlands, mountains and glaciers, and waterways. Parallel valleys and Glacier Bay follow fault lines deepened by preferential stream and glacier erosion.

- More resistant rocks within the terranes form ridges and mountains, particularly where ongoing compression continues to cause ridges to rise, as in the Fairweather Range. The park's highest peaks differ from its lower peaks: Alpine glaciers and frost wedging have hewn the highest peaks into sharp, jagged shapes. Lower peaks, by contrast, have been smoothed and rounded by the passage of thick, moving glaciers above them.

The Mechanics of Glaciers

- In the highlands—snowstorm after snowstorm and season after season—snow and ice pile to dozens, then hundreds, of feet, and then sometimes to a thousand feet or more. As ice piles up, it exerts tremendous pressure on the ice below.

- Eventually, the weight compresses irregularly shaped air pockets, squeezing some air out and trapping the rest in tiny bubbles. Eventually, even the bubbles disappear, as molecules from the air become trapped within the molecular lattice of the ice.

- Ice near the surface of a glacier forms a brittle layer to a depth of about 120 feet. Within this layer, the rigid ice responds to stress by fracturing, and that creates chasms, or crevasses, in the ice. Beneath that depth, dense ice becomes ductile, so it begins to flow outward and downward.

- The weight of all the ice above also can cause a thin layer of ice in direct contact with rock below to melt. For pressures greater than about 100 times atmospheric pressure at Earth's surface, ice will melt at temperatures lower than those on the surface of Earth. This layer of water helps glaciers slide across rocks beneath them.

- Glaciers also can glide on a layer of moving soil. As they move, glaciers pluck and scour rocks, gravel, sand, and soil from their beds. They trap and carry rocks that fall on them from cliffs they are flowing past and volcanic ash that falls on their surfaces from the sky.

- Rocks and sand dragged along the base and the sides of glaciers scrape away soil. Rocks and sand gouge and polish the bedrock they pass over and the valley walls they pass beside, widening, deepening, and exploiting any erosive weakness in the underlying rock.

- Glaciers lose ice in three primary ways.
    - Melting.

    - Sublimation, which is the transformation of ice directly into water vapor in the air above a glacier.

    - Calving, which is when chunks of glacial ice break off into water to become icebergs.

- The spot where a glacier finally loses ice as rapidly as new ice arrives is the terminus—also called the snout or toe of the glacier.

- Myriad glaciers feed into Glacier Bay and the Gulf of Alaska, descending like rivers of ice—which is what they are—from the park's white snow and ice-clad highlands. Some of these are tidewater glaciers, which have a terminus that floats on water and is subjected to sometimes-large tidal changes. Others are terrestrial glaciers, which terminate on land. As they have receded over the last few centuries, many of the glaciers at Glacier Bay have evolved from tidewater to terrestrial.

- Large icebergs frequently calve from its face to form icebergs and reveal fresh ice surfaces that appear a deep blue. Parallel, horizontal, or folded bands across the calving front of the glacier and visible in icebergs result from a combination of seasonal snow cycles that produce annual bands and volcanic eruptions or avalanches that can deposit thick, dark layers of ash or rock debris on the ice.

- One highlight of a visit to Glacier Bay today, as in Muir's time, is the opportunity to witness glaciers as they calve with a mighty splash. Icebergs as tall as skyscrapers routinely tumble from tidewater glaciers or—where the base of the glacier lies deep below the water—shoot up from the depths without warning. Freshly calved glacial ice often makes a popping sound, like bacon sizzling, as compressed bubbles in the ice, which originally formed under great pressure, burst and release their air.

- Ice's slightly lower density relative to water, especially saltwater, causes about 10 percent of an iceberg to float above the water while the rest lurks below. As they melt in contact with saltwater, icebergs can become top-heavy, and then tumble and roll and invert themselves with little warning, creating an endless variety of evocative shapes.

Kenai Fjords National Park

- If Glacier Bay National Park reflects the power of both ancient tectonics and glacial change to shape the landscape, Kenai Fjords National Park remains an icebound kingdom on the western shore of the Gulf of Alaska, about 125 road miles south of Anchorage.

- Ice covers more than half of this national park. Much of the ice resides in the Harding Icefield, a 300-square-mile snowcap amid the Kenai Mountains. Portions of the ice field can get 1,000 inches of snow in a single year. Outlet glaciers from the ice field have carved now-drowned steep-walled valleys—fjords—on their way down to the sea. Tidewater glaciers calve directly into the sea in some of these embayments.

- Exit Glacier, one of the most popular destinations in Kenai Fjords National Park, is one of many outlet glaciers, or glacial tongues, that originate with the Harding Icefield. But it's in the only part of the park that's accessible via car from the nearby town of Seward.

- Bear Glacier, another of Harding's outlet glaciers, calves into a breathtaking turquoise ice-filled lagoon that empties into Resurrection Bay. Small and perfectly transparent pieces of ice from the glacier wash ashore to form so-called ice diamonds that glitter like sculpted gems in the mud and sand.

Kenai Fjords National Park.

- The Kenai Fjords coastline is strikingly crenulated, with islands dotting the water where ridges bend down to the sea. Glaciers carved the fjords, but there's more at work. Sea level in the Gulf of Alaska is rising relative to the coast. In part, this is due to rising sea levels, which is a larger global trend fed by melting glaciers. But in this region, the land is also on the move—the land is falling.

- During the 1964 Good Friday earthquake that rocked Anchorage and the region, stretches of the Kenai Fjords coastline dropped between seven and nine feet. Bathymetric studies of the seafloor offshore reveal glacial troughs submerged up to 300 feet along the continental shelf.

- So, along the coast, the park is actually sinking, and it would be even if sea level were to remain the same. Its mountains have grown too tall to sit as high as they do above the ductile mantle below, and they're depressing their roots deeper underground. But while its coastline might shift inland, the land of Kenai Fjords National Park will exist for a long time to come.

Suggested Reading

Connor, *Roadside Geology of Alaska.*

Questions to Consider

1. Explore Glacier Bay using the satellite imagery on Google Earth or Google Maps. Find all the tidewater glaciers that currently enter the bay. Count the valleys that end at the bay and estimate the number of tributary glaciers that would have joined the glacier that filled Glacier Bay several centuries ago.

2. Locate the Harding Icefield on satellite imagery of Kenai Fjords National Park and identify as many of its outlet glaciers as you can.

Lecture

10 Yosemite: Nature's Cathedral

Yosemite Valley might be the most beautiful valley anywhere on Earth. Iconic views of Yosemite Valley reveal the legacy of long-vanished volcanoes, rivers and streams, and recently melted glaciers that together define its extraordinary landscape. This legacy of subduction-driven volcanism and glaciers unites Yosemite with other national parks of the western United States, from the Cascades to Alaska. The story of Yosemite National Park's origins is written all over the Yosemite landscape, just waiting to be read and understood.

Yosemite Valley

- It is one of the most inspiring vistas on Earth, east into the heart of the valley of California's Merced River—Yosemite Valley. Just seven miles long and a mile wide, this is a place of incomparable beauty, of falling water and rising rock.

- At the end of the Wawona Tunnel, millions of visitors every year catch their first glimpse of the valley. The cliffs rise 3,000 feet or more above a carpet of pines and meadows. The granite monoliths that surround the valley bear names that resonate with nature lovers everywhere, including El Capitan, Half Dome, Sentinel Rock, and the Three Brothers. For climbers, faces of these spires present a multitude of challenges and epitomize the term "big wall."

- Waterfalls, some of North America's tallest, trace white ribbons as they cascade down toward the valley floor. They roar and fill the air with mist throughout the spring and early summer, when some fade away to a trickle until the next snowmelt.

- It is a wonder, a masterpiece of landscape, where a range of geological forces has combined to create a place of inexpressible beauty.

The Origins of Yosemite National Park

- In 1864, Congress passed, and Abraham Lincoln signed, a bill that set aside Yosemite Valley and the nearby Mariposa Grove of giant sequoias in perpetuity under the state of California's management. Although Yellowstone would later become the world's first place designed as a national park, Yosemite was the first natural wonder in the United States designated by the federal government for eternal protection.

- Soon after, a young Scottish immigrant—John Muir—came to Yosemite, hiking in and around Yosemite and sharing his rapturous insights and mounting appreciation for the region's wonders with visitors he led up into the hills.

- Following a three-night camping trip with Muir at Yosemite in 1903, President Theodore Roosevelt signed a bill in 1906 that receded the grant to California and combined the valley with surrounding lands, including the Mariposa Grove, into a single national park.

Granite

- Granite defines Yosemite. It underlies most of the national park and towers above the valley. Sometimes you might encounter granite that is rounded to a stream cobble. But in nature, most often, granite will be sparkling beautifully in an outcrop. Its color might vary from pink to orange to black and white.

- Granites typically have a grainy, speckled, salt-and-pepper appearance. Because granite is an igneous rock—one that formed from a melt, from magma—its coarse-grained texture tells us that the granite formed several miles or more underground. It had to, because it had to have time to cool slowly in order for the large-grained crystals to form.

- Large-grained igneous rocks, such as granite, are intrusive. By contrast, extrusive igneous rocks are small-grained, such as basalt, andesite, or rhyolite.

- The following is a list of minerals that can be found in granite, and all are silicates, or minerals formed within various frameworks of silicon and oxygen.
  - Quartz is a translucent gray mineral with a glassy texture.

  - Potassium feldspar is hard like quartz, but it's opaque. It's usually pink, pale orange, or white and might have flat, reflective crystal surfaces, called cleavage planes. Because the symbol for potassium on the periodic table of the elements is the letter "K," geologists will sometimes refer to this mineral as K-spar.

El Capitan, Yosemite Park.

- Plagioclase feldspar is darker, although not black. It's a milky white to pale gray, dark gray, or charcoal—it could be blue. It's a rectangular mineral with reflective surfaces, some of which appear on close inspection to have parallel grooves running along them.

- Mica biotite is a dark mineral that flakes off in tiny sheets. Granites can also have a lighter-colored mica called muscovite.

- Hornblende is a hard, dark, bladelike mineral. It has reflective cleavage surfaces.

- Igneous petrologists—geologists who specialize in the study of volcanic rocks—distinguish a number of different varieties of granitic rocks based on the proportions of quartz, potassium feldspar, and plagioclase. Granitic rocks found at Yosemite include true granites, which contain lots of potassium feldspar with less quartz and plagioclase.

- Yosemite's granites also include quartz monzonites and granodiorites, which contain more and still more plagioclase and less K-spar. These seemingly subtle variations are important to the landscape, because they help determine how well the rock resists fracturing—and, therefore, whether it will form immense monoliths such as El Capitan or narrow towers such as the Cathedral Spires.

- In general, the true granites have a tightly woven grain. They tend to resist fracturing and erosion a bit better than the monzonites and granodiorites. However, Half Dome is composed predominantly of granodiorite, and it has managed to hold its own pretty well.

- Another remarkable feature of some of the granitic rocks at Yosemite—such as some exposed in the face of El Capitan—is the very large grains of potassium feldspar crystals, which had longer to grow in the melt and therefore grew to larger sizes before other minerals solidified and filled in the gaps between. Geologists call such large crystals in a matrix of smaller ones phenocrysts.

They call rocks that have a texture with two distinct grain sizes porphyritic or porphyries.

- Differential erosion has left potassium feldspar phenocrysts jutting out from the faces of some of Yosemite's big walls. It has done the same for some of the narrow veins of extremely quartz-rich rock that filled fractures in many of Yosemite's granites after they formed. These are called pegmatites.

Volcanoes and Mountains

- The stone grandeur that surrounds the Yosemite Valley is a suite of crystallized magma chambers that fed volcanoes just like the Cascades and the Aleutians—only 80 or more million years ago. Yosemite's enormous granitic rocks have about the same composition as the fine-grained rhyolite and dacite tuffs that erupted from Mount Saint Helens, Mount Rainier, Mount Mazama, and Mount Redoubt. Just like the composite volcanoes erupting today, Yosemite's granites were a product of seafloor subduction off the western continental margin of what has become North America.

- In intermittent pulses from about 120 to 80 million years ago—during a geologic time period called the Cretaceous, which was dominated on land by dinosaurs—Cascade-style volcanoes formed above the big rocks exposed in Yosemite Valley. At that time, the coast to the west was much nearer than it is today, and seafloor subduction occurred there, with now-familiar consequences.

- As oceanic crust and accreted sediment descended eastward beneath the overriding continent, it partially melted, partially melting the continental rocks above, as well. Fluid produced by this melting rose through overlying rocks to fill magma chambers miles underground. These magma chambers sent pulses of melted or partially crystallized rock to the surface, where they erupted as ash and lava and volcanic bombs in explosive composite volcanoes.

Yosemite Valley.

- As residual magma cooled and crystallized in these magma chambers, they transformed into what geologists call plutons. Imagine underground balloons filled with spongy, fiery melts that "froze," over tens of thousands of years, into bulbous masses of granitic rock.

- Over millions of years, the consumption of an ocean west of the continent created a continuous sequence of plutons along a north-south band parallel to the ancient coast. Such a cluster of plutons—the roots of a chain of bygone volcanoes—is called a batholith, for deep or immersed rock. The entire Sierra Nevada range, including the rocks that tower above Yosemite Valley today, is a cluster of plutons called, collectively, the Sierra Nevada batholith.

- As weathering and erosion wore down the volcanoes and surrounding crumpled mountains over millions of years, the plutons were more buoyant than surrounding rocks of Earth's upper mantle, and the plutons rose as soon as they could to their sky-high heights of today.

- The rise and westward tilting of the Sierra Nevada's eastern slope along normal faults due to stretching of the continent near the California-Nevada border also has helped raise the Sierra Nevada batholith over the last several million years to form some of the world's most beautiful mountains.

- The fossilized magma chambers on display at Yosemite intruded into older sedimentary and metamorphic rocks, called country rock, which would prove far less resistant to erosion than the tough crystalline plutons. So, as the land rose, most of the country rock was eroded away near Yosemite Valley.

- Chunks of it, however, fell from the walls and ceilings into the magma chambers and got preserved within them, while other chunks of older rock are preserved east and west of the national park or atop the plutons as so-called roof pendants, helping geologists piece together a picture of the full history of the region.

- One of the most fascinating projects undertaken by scientists at Yosemite in recent years is an effort to make finely detailed geological maps of the cliffs that surround Yosemite Valley. Funded in part by a National Geographic Society/Waitt grant, this work involves high-resolution photography, laser mapping, and hands-on observations by climbers on the rock faces.

Streams and Rivers

- Over tens of millions of years, as the Sierra Nevada batholith made its long, lumbering way to the surface from miles underground, the rocks within it experienced a multitude of stresses. Some involved flexing, which opened parallel sets of vertical fractures, or joints, within the rocks. The largest and most extensive of these joint systems is called master joints.

- The presence of master joints likely helps account for the existence and orientation of many of the sheer vertical cliffs at Yosemite, such as the broad, relatively flat face of Half Dome. Major joint systems also helped determine which way streams flowed as the Sierra Nevada Batholith rose, and that in turn helped determine where valleys would form.

- Two major watersheds, or drainage systems, dominate Yosemite: the watershed of the Merced River, which helped carve Yosemite Valley, and that of the Tuolumne, which did the same for the Grand Canyon of the Tuolumne and Hetch Hetchy. The Tuolumne's headwater tributaries also helped carve the breathtakingly gorgeous basin surrounding Tuolumne Meadows.

- Both rivers appear to follow pathways of least resistance defined by large-scale joint systems. As the Sierra Nevada mountains rose, the block of land that includes Yosemite tilted to the west. This caused these west-running rivers to become steeper and swifter, giving them the power they needed to carve canyons along joints through the granitic bedrock.

- As Yosemite's plutons rose from miles underground, the confining pressure on the plutons diminished dramatically. As the weight of all the overlying rocks diminished, the rocks of the plutons expanded, and they began to fracture from the outside in concentric layers.

- At their exposed surfaces, chips of rock began to spall off. The process is called exfoliation, or sheet jointing, and it's ongoing. It tends to round the corners and sharp edges of large granitic rocks into broad, gentle curves, leaving rounded cores behind. Exfoliation domes can be found all over the park. Exfoliation has even curved the corners and edges of El Capitan.

Glaciers

- If Yosemite's story is a tale of granite and water, it's also a tale of ice. Today, just a few remnant glaciers remain near the highest peaks in Yosemite National Park.

- John Muir discovered one of these, the Lyell Glacier, on the northern slopes of Mount Lyell in 1871. Since then, it has melted into two smaller glaciers occupying side-by-side cirques on the mountain, and it's estimated to have lost more than two-thirds of its surface area.

- On Mount Maclure's northern slope, the Maclure Glacier also has dwindled remarkably since its discovery. It now covers less than one-tenth of a square mile.

- Despite their small extent, Muir was pleased to find glaciers in Yosemite, because it helped demonstrate that glaciers had once descended from the tall slopes of the Sierra Nevada range to polish and sculpt the Yosemite and Hetch Hetchy Valleys and the incomparable granite promontories that surrounded them.

Suggested Reading

Alt and Hyndman, *Roadside Geology of Northern and Central California*.

Glazner and Stock, *Geology Underfoot in Yosemite National Park*.

Hill, *Geology of the Sierra Nevada*.

Jenkins, "Yosemite. Daring. Defiant. Free."

Questions to Consider

1. John Muir had a lot to say about Yosemite and the importance of preserving natural places. Read more about Muir and find a favorite quote of his that speaks to you and to our time.

2. While rocks in the granite family predominate at Yosemite, you might encounter many kinds of igneous rocks in the park, including granodiorite, tonalite, monzonite, diorite, and gabbro. Search for photographs of these rocks online to see some of the visual differences between them.

Lecture 11

Redwoods, Sequoias, and the Sierra Nevada

From Yosemite to Sequoia and Kings Canyon National Parks, the mountains that exist are due to subduction of ocean crust beneath the western edge of North America. Subduction produced magma chambers, which cooled slowly into granites far underground before rising as the Sierra Nevada mountains. Glaciers shaped the risen plutons, leaving behind four treasures of the Sierra Nevada: landscapes with soaring granite, gold, freshwater, and accreted land along the northern California coast that has become a home to the tallest trees on Earth.

Yosemite's Glacial History

- Over the last few million years, glaciers ground their way down to Yosemite Valley and retreated along the course of the Merced River in a series of successive pulses. As the glaciers ground through, they plucked jointed blocks of rock wholesale from the slopes to create the Giant Steps. The glaciers left behind the long, sheer downstream drops over which Nevada and Vernal Falls now tumble.

- Liberty Cap's asymmetrical shape results from the flow of ice around and past it. The mammoth rock is smooth, rounded, and more gently sloped on the side facing up the Little Yosemite Valley and ragged and steep on the opposite side. Liberty Cap is an outsized example of what geologists call a roche moutonnée—a "woolly" or "fleecy" rock in French.

- Geologists believe that even the deepest and most extensive glacial ice never overtopped Half Dome. But glaciers still buffed some of the rock's sharp edges. Scouring ice would have promoted the natural erosion process called exfoliation by removing loose layers of rock from the flanks of Half Dome, so the glaciers helped smooth and curve Half Dome's domed side.

- Glaciers wiped broad expanses of undulating Sierra Nevada granite clean of whatever soil might have accumulated on them, leaving a

Half Dome, Sierra Nevada.

sparkling, glittering landscape dotted with boulders dropped where they stand when the ice melted. These large and ice-displaced boulders are called glacial erratics. Glaciers had transported some of these erratics more than a dozen miles from the outcrops, where they originated near the crest of the Sierra Nevada range.

- One striking product of Yosemite's vanished glaciers that you can find on many of the park's granite outcrops is glacial polish, which results when hard sand and silt dragged along the bottom of a glacier creates a polished rind on the surface of underlying rocks. Glaciers retreated recently enough from Yosemite's highlands that glacial polish remains where exfoliation, rockfall, or other mass-wasting processes haven't removed it.

- As far back as the 19th century, John Muir and other park visitors recognized that Yosemite had a complicated glacial history. Glaciers advanced and retreated across the high sierra and down into Yosemite and the Hetch Hetchy Valley many times over the last few million years.

- Three distinct glacial episodes in Yosemite, with ice retreats between them, roughly correspond to what's called the Wisconsinan glaciation—the most recent major advance of Pleistocene glaciers—elsewhere in North America.

- The last of these ice pulses probably retreated from the valleys about 10,000 years ago. An older glacial episode called the Sherwin glaciation appears to have been the most extensive. It filled Yosemite Valley with ice to a depth of about 4,000 feet and overtopped all but the highest of the surrounding summits.

- The more recent glacial advances filled much of Yosemite Valley about 1,000 feet deep in ice but not enough to clear away relatively fragile towers, such as Cathedral Spires. The snouts of these more modest glaciers didn't reach all the way to the mouth of the valley and therefore left some of the older piles of rock from earlier rockfalls.

- The record-setting free falls of Yosemite's waterfalls—including Yosemite Falls, Bridalveil, and Ribbon Fall—owe much to the glaciers. In fact, water and ice both played a part, along with the ubiquitous granite, in giving us Yosemite's incomparable waterfalls.

California's Gold

- The California Gold Rush began in January of 1848 when James Marshall discovered gold while building a sawmill for Captain John Sutter at Coloma in the foothills of the Sierra Nevada range west of Yosemite.

- As word got out, prospectors drawn to the region in hopes of making their fortunes began hunting upstream and throughout the Sierra Nevada foothills for sources of gold. The sources were veins of quartz formed by the same tectonic processes of plate collision and subduction that ultimately created the batholiths of the Sierra Nevada range—the large, linear, regional collections of 80- to 120-million-year-old plutons encountered at Yosemite and along the entire mountain belt.

- The largest collection of gold-bearing veins, the so-called Mother Lode, formed in parallel fractures along a suture zone, where what was sutured to the old continent was what geologists call an exotic terrane—possibly an arc of islands—which slammed into the western margin of the continent.

- Valuable metals, such as gold, silver, and copper, often get concentrated in such environments, because collision and compression produce steep vertical fractures in rock. The fractures become conduits for warm, circulating, quartz-rich fluids. At depth, the fluids can dissolve and concentrate scarce elements, such as gold. As pressure and temperature and saturation conditions change, the fluid suddenly becomes supersaturated and the precious metal precipitates out. The process collects and concentrates the metals.

- So, it came to pass that many of the quartz veins filling fractures in the Sierra Nevada foothills contained rich seams of visible, glittering gold. The ’49ers found these seams and began working them—first by hand, and then through industrial mining techniques.

- California was initially built, in large part, on this mineral treasure that geological processes had stored up in the ground 100 or more million years ago.

- Although the Mother Lode and California’s gold fields lie outside the official borders of Yosemite National Park, they point to an intrinsic source of conflict in the creation and long-term preservation of many of the parks: The same processes that make monumental landscapes worth preserving due to their scenic splendor often embed precious mineral resources in and around those very landscapes. The choice of whether to forego or exploit these resources can involve significant trade-offs.

Yosemite’s Water

- Millions of people visit Yosemite Valley every year. Far fewer make time to visit its neighbor, the Hetch Hetchy Valley, also within the national park. When they do visit, they’re greeted by the O’Shaughnessy Dam and a big blue reservoir.

- The floor of the Hetch Hetchy Valley—once home to wildlife, meadows of wildflowers, and the meandering Tuolumne River—has been completely submerged beneath the reservoir. The choice more than a century ago to dam the Tuolumne River and drown Hetch Hetchy was the culmination of a decade-long political battle and probably the greatest disappointment of John Muir’s life.

- The Tuolumne’s watershed, including Hetch Hetchy, already had been designated for eternal preservation within Yosemite National Park—set aside for posterity. But in the emotional aftermath of the San Francisco earthquake and fire of 1906, the overwhelmingly popular opinion was to build a dam.

- Muir’s voice, along with the voices of other conservationists who sought to preserve Hetch Hetchy, was drowned out in a tide of support for the beleaguered city. The U.S. Congress opted to support the cries to build the dam that would flood the valley and, not incidentally, also provide water to the emerging agricultural empire in California's Central Valley.

- Although the Hetch Hetchy Valley got submerged, this fight and its outcome swelled what had been a nascent conservation movement. And the reservoir in the Hetch Hetchy, square in the middle of Yosemite National Park, still fills a valley that once rivaled Yosemite for scenic splendor. It still provides water, now if anything more in demand than ever by thirsty Californian agriculture and communities.

Sequoia Trees

- The original legislation President Lincoln signed in 1864 setting aside Yosemite Valley for conservation also set aside the Mariposa Grove, with its roughly 500 sequoia trees, for "public use, resort, and recreation."

- These trees still tower and thrive on what is now the park's western slopes—in what is still called the Mariposa Grove, along with two other, smaller groves. These groves sit outside Yosemite's great granite-bound valleys and highlands. In extreme cases, sequoias—Earth's largest, most massive trees—are known to have grown to heights of more than 300 feet, trunk diameters at the base of more than 50 feet, and ages of 3,500 years or more.

- For more than 50 million years, giant trees resembling Yosemite's sequoias thrived across much of what is now the western United States. Fossil specimens of giant trees appear in Wyoming at Yellowstone National Park, in Arizona at Petrified Forest National Park, and at many other locations.

- Over the last few million years, Pleistocene glaciers and associated climate shifts eradicated the last of the huge trees in all but a narrow strip, found in two places: along the western Sierra Nevada and along Northern California's Pacific Coast, where the towering coastal redwood include the tallest trees of all.

Sequoia tree in Yosemite Park.

- It's no accident that the trees survived where they're found. The landscape provided nutrient-rich stream-and-glacier-fed soils from the Sierra Nevada batholith's granitic highlands. And it created a rise over which moist air that is blown as westerly winds from the Pacific must travel, cooling and watering the trees with ample rain. The mountains also insulated the trees growing to the west from the cooler, dryer conditions in the continent's interior, conditions under which related species perished to the east.

- To the south of Yosemite in the Sierra Nevada lie several larger groves of protected giant sequoia trees in Sequoia and Kings Canyon National Parks. Although nominally distinct because of the legislation that created them, the park service administers these adjacent parks together as if they were a single park.

- The wholesale destruction of large sequoias in the 19th century provided the original impetus to create Sequoia National Park and the smaller precursor to Kings Canyon, General Grant National Park.

- With a single tree able to provide 300,000 board feet of lumber, the sequoias were good as gold to lumbermen. During the 1870s and 1880s, they rapidly felled many of the largest trees, reducing entire ancient groves to stumps. John Muir, who had worked in a small sawmill in Yosemite Valley, decried the loss.

- The establishment of Sequoia National Park on September 25, 1890, halted the felling of at least some of the mammoth trees, including the General Sherman—the largest tree on Earth by volume—in a grove Muir named the Giant Forest.

- Together, Sequoia and Kings Canyon National Parks share much of Yosemite's geological history and many of its soaring landscapes. Granitic plutons of the Sierra Nevada batholith define the highlands and steeply walled valleys of the eastern portion of both Sequoia and Kings Canyon, most of which is only accessible by trail.

Redwood National and State Park

- Redwood National and State Park on the northern California coast is a patchwork quilt of protected land, signed into existence in 1968 and later expanded in the late 1970s. It's a relatively recent creation, intended to bridge portions of the redwoods range left unprotected by the older parks. By the time the park was created, more than 90 percent of the old-growth coastal redwoods had been logged.

- National Geographic, the Sierra Club, and California's Save the Redwoods League collaborated to make the case for the creation of the national park. The Geographic also funded a study on which sites should be included within the national park.

- Geologically speaking, Redwood National and State Park has more in common with Olympic National Park than with Yosemite, Sequoia, and Kings Canyon. Redwood runs right along the coast.

It sits atop another accretionary wedge, where the North American Plate has overridden the tiny Gorda Plate, a small chunk of the Pacific seafloor to the east of the submarine Gorda ridge.

- Just as at the Olympic Peninsula in northwestern Washington State, the leading edge of the North American continent has scraped off sediments and surface rocks from the descending slab of oceanic crust.

- The coast redwoods found in the park might not be Earth's largest trees, but they're certainly the planet's tallest, reaching heights of up to 360 feet. They grow in a narrow band along the flanks of the coastal range that receives from about 50 to 100 inches of rainfall per year, plus plenty of fog even when it isn't raining to keep the trees cool, moist, and growing.

Suggested Reading

Alt and Hyndman, *Roadside Geology of Northern and Central California*.

Glazner and Stock, *Geology Underfoot in Yosemite National Park*.

Hill, *Geology of the Sierra Nevada*.

Jenkins, "Yosemite. Daring. Defiant. Free."

Questions to Consider

1. The question of whether to build new dams or remove old ones has sparked heated debates in and near a number of national parks. Find examples of national parks where this is the case.

2. Locate several of Yosemite's roches moutonnées on a topographic map of Yosemite National Park, such as National Geographic's Trails Illustrated map of the park. Contour lines will be spaced more closely on the steeper downstream sides of these rocks. Use this information to determine which direction glaciers moved over the rocks.

Lecture 12

Pinnacles to Joshua Tree: The San Andreas

National parks along the length of the San Andreas Fault bear witness to the extraordinary transformations that occur along transform boundaries, where sideways relative motion of adjacent tectonic plates creates transform, or strike-slip, faults. From Point Reyes National Seashore, Golden Gate National Recreation Area, and Pinnacles National Park in the north to the Santa Monica Mountains National Recreation Area, Channel Islands National Park, and Joshua Tree National Park to the south, evidence of offset, shearing, and rotation of the land is everywhere.

Point Reyes National Seashore and Golden Gate National Recreation Area

- The San Andreas Fault is classified as a right-lateral transform fault, because the land on either side of it keeps moving right relative to land on the other side. Motion along this portion of the fault has not been continuous. Rocks on either side of the fault lock together after an earthquake.

- Then, tension mounts over dozens or hundreds of years. Eventually, the stress becomes so great that it overcomes friction and the strength of rocks straddling the fault, and some of the accumulated energy gets released in an earthquake.

- Major transform faults such as the San Andreas typically consist of a number of parallel surfaces—parallel faults—across which motion occurs. The San Andreas Fault comprises a series of such parallel surfaces with sheared slivers of land between.

- The slivers of intact rock tend to form parallel ridges and mountain ranges along the fault. Shattered and deformed, the fault surfaces themselves are usually much more prone to erosion than the intact bedrock on either side of them, so they erode.

- Point Reyes National Seashore and the long, narrow strip of land that forms Tomales Point is attached to the Pacific Plate on the western side of the San Andreas Fault. Tomales Bay is underlain by the San Andreas. The bedrock in this location has been ground up between the plates, chewed up, and readily eroded away. So, today, it's submerged between higher ground on either side of the bay.

- Apart from sitting right next door, land to the east of Point Reyes and the San Andreas, including the Golden Gate National Recreation Area, bears no geological kinship to Point Reyes, which is an exotic terrane. The bedrock at Point Reyes is granite formed from magma chambers similar to those that formed the Sierra Nevada batholith. The Sierra Nevada range sits inland, well to the west of San Francisco and the coast.

Point Reyes National Seashore.

- Geologists originally speculated that the chunk of plutonic rock known as Point Reyes had traveled more than 300 miles north and west along the fault from a place of origin far to the southeast. Nuances in the chemical makeup of the granite lead many to believe now that Point Reyes originated instead near Monterey, California. In either case, the Point is a vagabond traveler from the south, and it is headed north.

- By contrast, to the east of Tomales Bay and Point Reyes, an accretionary wedge formed along the leading, westward edge of the North American continent. Sedimentary and volcanic rocks were scraped from descending Pacific crust, and then folded and otherwise deformed and in some cases metamorphosed.

- Rocks in the Golden Gate National Recreation Area record the long millennia of subduction that occurred along what is now the California coast. These rocks—which reflect deposition of sandstones, mudstones, and cherts offshore, along with submarine volcanic rocks—make up what geologists call the Franciscan Complex. Alcatraz is formed from Franciscan Complex rock.

Pinnacles National Park

- Theodore Roosevelt originally set aside a little more than 2,500 acres of the southern Gabilan Mountains in California's Central Coast Range in 1908 as Pinnacles National Monument. His goal was to protect a peculiar and stunning landscape of rock towers, narrow gorges, and rock-pile caves. The monument was expanded over the years and, in January of 2013, became a full-fledged national park, at a size of 26,000 acres.

- Pinnacles gets its name from the strangely eroded boulders, balconies, and spires made of 23-million-year-old volcanic rhyolite. Like the Reyes Point granites, the rhyolite has traveled a long, long way.

- The pinnacles are situated on the western, Pacific Plate side of the San Andreas Fault. Right-lateral motion along the fault split the Neenach Volcano—some of which stayed southeast, near Lancaster, California—while the western portion was dragged a few hundred miles northwest to its present location, at a pace of about one to two inches per year.

- The chemical composition of the Pinnacles rhyolite resembles that of granites at Point Reyes and closer by in the Gabilan Mountains. However, the fine-grained rhyolite at Pinnacles is much more susceptible to weathering and erosion than the coarse-grained granites. Fractures in and fault lines through the rhyolite have widened over time, with the help of wind and water, into countless narrow ravines between the rocks that crisscross the landscape.

- Boulders shaken loose by the tremors that rock the region have tumbled down from above and wedged between ravine walls to form roofs—the so-called balconies—on talus-field caves. These small caves offer habitats for the several bat and frog species found in Pinnacles National Park.

- To the north and the south, the San Andreas Fault tends to lock in place for years and relieve stress in bursts that can be accompanied by major earthquakes. Along the central California coast near Pinnacles National Park, by contrast, the relative motion of the Pacific and North American Plates past one another causes a gradual creeping motion across the fault. Tremors still occur, but they are frequent smaller ones rather than infrequent enormous ones.

Channel Islands National Park

- Continuing south along the San Andreas Fault, there is a point near Santa Barbara where the fault bends slightly to the east. Over millions of years, this kink in the fault has rotated and compressed blocks of land caught between the plates, producing a series of east-west-running mountains called the Transverse Ranges. The ranges find their westernmost extremity south of Santa Barbara and west of Los Angeles in Channel Islands National Park.

- The islands cluster in two groups, north and south. All of the northern Channel Islands—San Miguel, Santa Rosa, Santa Cruz, and the Anacapa Islands—and the waters surrounding them are protected within the national park. The Santa Barbara Island, one of the southern Channel Islands, also is protected.

- Although these islands have been influenced, and indeed rotated clockwise en masse, by the relative motion of the Pacific and North American Plates, each of them tells a distinct geological story.

- San Miguel, the westernmost island in the national park, rises about 500 feet to form a high, windswept plateau above the Pacific surf with a few rounded hills rising to 800 feet. The bedrock consists primarily of sedimentary rock layers that dip to the northeast. Overgrazing by livestock during the 18th and 19th centuries decimated native vegetation and transformed most of the island into dune-scape, but native vegetation has been making a slow comeback, and San Miguel is now home to a unique diversity of life.

- At about 15 miles long by 10 miles wide, Santa Rosa Island is larger than its neighbor San Miguel. The island rises higher than San Miguel, as well. An east-west-trending fault bisects the island, and a mountainous ridge follows the southern margin of the fault where the land has risen relative to land on the fault's north side. Deep stream canyons dissect the landscape to the north down to the coast. To the south, step bluffs rise from the sea.

- Santa Cruz, the largest of the Channel Islands, presents a diversity of landscapes and biodiversity. Like Santa Rosa next door, the island is bisected by an east-west-running fault. Twin mountain ranges rise on both sides of the fault. Dramatic sea caves and arches fringe Santa Cruz Island.

- Unlike the rest of the Northern Channel Islands, the three islets that comprise Anacapa aren't primarily formed from sedimentary rocks. Rather, they're part of a volcanic ridge that erupted as basalts from the ocean floor. Lava flows, cinders, and ash abound. Waves have eroded the islets into towering cliffs, sea caves, and natural bridges.

- Santa Barbara Island resembles Anacapa in that it's also primarily formed from volcanic basalts. The one-square-mile island is crossed by numerous small faults created by the millennia of shifting and compression that finally brought it to the place it sits today.

Santa Monica Mountains National Recreation Area

- The mountainous peaks and ridges that are particularly prominent on Santa Rosa and Santa Cruz Islands are the westernmost extension of the Transverse Ranges that mark the passage of the San Andreas Fault into southern California. Back on shore, those mountains continue through the Santa Monica Mountains National Recreation Area north and west of Los Angeles.

- The Santa Monica Mountains National Recreation Area is a complicated patchwork of national park, state park, private reserve, and other lands. The Santa Monica Mountains rise abruptly above the famous and beautiful Malibu coastline.

- The bedrock is also a complicated patchwork. Several faults bound and cross the mix of marine sedimentary and volcanic rocks that form the hills.

- Although Santa Monica geology is complicated, the underlying story is still the same: Just as with the Channel Islands, submarine deposition and accretionary processes resulting from the subduction of the Farallon Plate off North America's west coast created the rocks that are found in this region. The crustal block that contains them was later rotated by shearing motion at the bend of the San Andreas Fault and compressed—squeezed from the north and south—causing east-west-oriented mountain ranges to rise.

Joshua Tree National Park

- Joshua Tree National Park sits at the far eastern end of California's Transverse Ranges. This enormous park—nearly 800,000 acres—straddles two deserts. To the east lies the low-elevation Colorado Desert, part of the Sonoran Desert. It's particularly arid and dominated by the creosote bush. To the west lies the higher, cooler, and wetter Mojave Desert, home to the Joshua trees that give the park its name.

- When tested, some of the banded metamorphic rocks in the park have yielded radiometric formation dates as old as 1.65 to 1.70 billion years. These rocks were fragmented and caught up in the subduction occurring along the west coast of the continent over the last few hundred million years and then became scattered amid the Transverse Ranges, and sizable blocks ended up in Joshua Tree.

- A succession of granitic plutons then intruded these ancient rocks. In general, a pluton is a magma chamber deep underground that feeds a volcano for a while, and then slowly crystallizes into solid rock.

- The plutons at Joshua Tree might be viewed as a southern extension of the Sierra Nevada Batholith. The same long-lasting collision between continental and oceanic crust that would create the granites on display in Yosemite, Kings Canyon, and Sequoia National Parks to the north also produced the granitic plutons that are found in Joshua Tree.

- Just as at Yosemite, the rock formations at Joshua Tree draw climbers and many other visitors from all over the world. Joshua Tree's freestanding piles, ridges, and towers of rounded rocks come in a multitude of shapes and sizes—some unusual, some improbable. It's a wonderland of rocks.

- Joshua Tree's kinship with the Sierra Nevada parks doesn't end with granite. Just as up north, deep vertical fractures associated with faulting formed conduits along which gold and silver from the depths was concentrated and precipitated in a multitude of veins.

Joshua Tree National Park.

The national park contains many old prospecting claims and about 300 historic mines.

- Just as at Yosemite, water is also an important part of the Joshua Tree story—which might come as a surprise given the park's arid desert landscape. A combination of impermeable rock layers and faults to act as conduits through them has created several springs in Joshua Tree National Park that support green patches in the desert—oases.

- Being home to two deserts, Joshua Tree National Park naturally includes a number of the most common desert landforms. Features resembling river courses, but that only carry water several hours or days per year, cross the map of Joshua Tree: Big Wash, Pinto Wash, Fried Liver Wash, and more. These are arroyos, or dry washes. Shimmering dry lake beds, called playas, are also found in the park, as well as alluvial fans, which are fan-shaped piles of rock and sediment that develop at the base of mountains in arid regions.

Suggested Reading

Lynch, *Field Guide to the San Andreas Fault.*

Sharp and Glazner, *Geology Underfoot in Southern California*.

Questions to Consider

1. National Geographic offers earthquake safety tips here: http://environment.nationalgeographic.com/environment/natural-disasters/earthquake-safety-tips/. Review them so that you know what to do if you're ever caught in an earthquake.

2. The San Andreas Fault and parallel transform faults, such as the Hayward Fault near San Francisco, make long, linear marks on the landscape that are striking from the air. Find aerial photos of these faults online as examples. Try to determine the direction of relative offset based on visual clues, such as offset roads.

Lecture 13

Denali to Gates of the Arctic

Located in northern Alaska, the Wrangell–Saint Elias, Denali, and Gates of the Arctic National Parks and Preserves are the largest in the U.S. national park system. Transverse faulting and crustal collisions raise the mountain ranges that span all three parks, along with Kluane National Park in Canada, the effects of the geotectonic train wreck that built the region. Glaciers scour the landscape and shroud it with ice. Copper, silver, and gold were concentrated in the hills. Lateral motion on transverse, or strike-slip, faults move crustal terranes, or microplates, far from their places of origin. The landscape of today juxtaposes radically different rocks, formed elsewhere, and at different times.

Wrangell–Saint Elias National Park and Preserve

- The largest U.S. national park and preserve is the 20,600-square-mile Wrangell–Saint Elias National Park and Preserve. Like Switzerland, it's mountainous. But it's larger than Switzerland, about one-third larger. The sprawling park sits at the top of Alaska's eastern panhandle, just a short distance up the coast from Glacier Bay National Park. Ice covers more than a quarter of the park—more than 5,000 square miles of it.

- Wrangell–Saint Elias gets its name from the two high ranges that form one mountainous belt and span it from northwest to southeast: the Wrangell Mountains to the northwest and the Saint Elias Mountains to the southeast.

- The Saint Elias is North America's tallest coastal range, rising from sea level at Icy Bay to elevations as high as 18,008 feet at the summit of Mount Saint Elias over a stretch of fewer than 15 miles. Mount Saint Elias is the second-highest mountain in the United States. Nine of the 16 highest peaks in the United States are found in the park. The Saint Elias Mountains continue down through Glacier Bay, but while Wrangell–Saint Elias contains portions of the same terranes that appear at Glacier Bay, it also has several others.

- In the order of their arrival, from oldest to youngest and from north to south, these include the following: the Windy-McKinley Terrane, the Gravina-Nutzotin Belt, the Wrangellia and Alexander Terranes, the Chugach Terrane, the Prince William Terrane, and the Yakutat Terrane.

- The subduction of ocean crust attached to the Yakutat Plate (or microplate) has caused partial melting of overlying crust. Over the last 5 million years, this has created some of the volcanoes that we find in Wrangell–Saint Elias, including Mount Sanford, Mount Drum, Mount Wrangell, and Mount Blackburn. Mount Wrangell remains active.

- But the jamming of land from the Yakutat Plate into the trench has mostly brought an end to subduction there and, therefore, to the partial melting that generates magma and volcanism to feed the volcanoes. The added crustal thickness as one chunk of buoyant continental crust got partially jammed under another helps account for the extreme elevation of the Saint Elias Mountains.

- The uniquely long and abrupt rise of the Saint Elias Mountains adjacent to the humid Alaska coastline causes the high slopes of the range to receive an outlandish amount of snow—about 600 inches, or 50 feet, per year. This in turn gives Wrangell–Saint Elias National Park the largest collection of glaciers on the North American continent, with many superlatives, including the Malaspina Glacier, the Bagley Icefield, and Hubbard Glacier (named for Gardiner Greene Hubbard, National Geographic's first president).

- Just as in California and elsewhere in Alaska, subduction and terrane accretion created the right conditions to concentrate valuable elements in some of the rocks of Wrangell–Saint Elias. Several gold deposits were mined north of the Wrangell Mountains.

- South of the Wrangell Mountains is the town of McCarthy, near which major copper lodes in the Nikolai Greenstone, which were laced with silver and some gold, led to the development of the Kennecott Mines. A century ago, though incredibly remote, this was the most productive copper mine anywhere on Earth, yielding more than 200 million dollars worth of ore.

- The geology of Wrangell–Saint Elias National Park includes metamorphic rocks, volcanic debris flows from Mount Wrangell, basalts and the metamorphically altered basalt called greenstone, the braided Chitina River, glacial moraines, a type of peat bog called a muskeg, limestone, marble, sandstone, and mudstone. A smorgasbord of different rock types and environments reflects the complicated geological history of the park.

- Down the Alaska Highway across the border from Wrangell–Saint Elias is Canada's Kluane National Park and Reserve. Canada's five tallest mountains, including Mount Logan (which is second only to Mount McKinley in North America), rise in the park. They're a continuation of the Saint Elias range, which contains virtually all of Canada's 20 tallest mountains, including Mount Fairweather, which straddles the border between British Columbia and Glacier Bay National Park.

- Kluane is at the intersection of air masses from the Pacific and the Arctic, which contributes to exceptional biodiversity in this part of Canada. Kluane also lays claim to some of Earth's fastest and longest glaciers: The Lowell Glacier is in Kluane, and Alaskan glaciers, including the Hubbard and the Logan, originate in part on the flanks of Mount Logan. The 11 peaks that form the Logan massif have the largest base circumference of any nonvolcanic mountain on Earth.

Denali National Park and Preserve

- The tallest peak on the North American continent, which a prospector named on a whim for a new president, is Mount McKinley. The native Athabascan people knew it by another

Denali National Park.

name—Denali, "the high one"—and that's what it's called in Alaska. From the lowest points nearby to the sentinel's summit, it has the highest vertical relief of any mountain on Earth.

- The Pacific Plate subduction, compression, and collision that give rise to the tall ranges of Wrangell–Saint Elias have their effect here, too, with Denali the supreme example, the jewel of the Alaska Range.

- The mountain is aided in its march skyward by being composed of incredibly tough rock. It's a granite pluton, so it's made of the same hard, weathering- and erosion-resistant stuff as Yosemite's soaring cliffs. Freezing, thawing, and glacial grinding can't make the headway on this relatively intact granite pluton that they could on more friable sedimentary and metamorphic rocks.

- Like Mount Everest, it helps that Denali's rock core is young relative to the sedimentary rocks that are hundreds of millions of years old and form many of the lower mountains surrounding it. At just 56 million years, Denali is a few million years younger than Mount Everest.

- Ongoing earthquake activity right under and around Denali reflects the fact that the mountain continues to rise. Although most of the measured earthquakes are too small for people to notice, larger quakes can trigger snow and ice avalanches on the mountain, and these in turn can pose a serious hazard for climbers.

- The overall geological story of Denali National Park resembles that of Wrangell–Saint Elias: It's all about exotic terranes. Displaced and accreted scraps of islands, slivers of continents, slabs of sediment, and slices of seafloor arrived here over the millennia, rafted on descending ocean crust or slid along on transform faults. Too buoyant or thick to subduct, the chunks piled on.

- Continued compression raises mountains. Major faults bounding the blocks have eroded to form lowlands, river and glacier courses, and lake basins. Ice covers one-sixth of the park year round—more than a million acres.

- The oldest terrane in the park, the Yukon-Tanana, joined the continent about 225 million years ago. The Yukon-Tanana and the Talkeetna Superterrane—composed of the Wrangellia, Alexander, and Peninsular Terranes—form the bulk of the landforms visible in the national park, with contributions from several smaller terranes.

- Denali National Park and Preserve was originally established to protect the Dall sheep, grizzly bears, caribou, and other large mammals that live there today. But big wildlife is nothing new to the region: In the last decade, thousands of dinosaur tracks and other fossils have been discovered, documenting the thriving Late Cretaceous ecosystem that lived there 65 to 71 million years ago.

- While taiga forest, high alpine tundra, and ice prevail in the park today, the climate was warmer when dinosaurs prowled there, and park fossils record a diverse plant community of large trees.

- As soils that have remained locked in ice for thousands of years currently thaw, a multitude of tiny lakes form, filling depressions formed by soil collapse. The amount of ice varies throughout the soil, so the places with the most ice deflate the most when the ice thaws, and that's where the s are found. The result is a landform called thermokarst.

- Bubbles of methane stream to the surface of some of Denali's thermokarst lakes. The same is occurring at the surface of some of the park's larger lakes, which had previously remained frozen year-round. The methane gas is created by microbes, which metabolize organic matter that is newly released from the permafrost by thawing.

- The amount of potential methane bound up as carbon in permafrost is many times more than what is currently in the atmosphere, and methane is 25 times more potent than carbon dioxide as a greenhouse gas.

Gates of the Arctic National Park and Preserve

- America's northernmost and second-largest national park is Gates of the Arctic. The Noatak National Preserve flanks the park to the northwest, and—across a corridor for the Dalton Highway and the Trans-Alaska Pipeline—the Arctic National Wildlife Refuge flanks the park to the east. Together, all three form an 800-mile-long conservation corridor that protects the entire length of northern Alaska's Brooks Range, which geologists estimate began forming more than 120 million years ago.

- The national park encompasses half a dozen designated wild rivers and the Endicott and Schwatka Mountains of the central Brooks Range.

- Processes similar to those seen elsewhere in Alaska helped raise these mountains. But because the collisions happened longer ago, and because convergence is now happening farther away, near Alaska's southern coast, the Brooks Range is lower and more eroded.

- The Arrigetch Peaks, among the most spectacular features in the range and the national park, have been eroded by ice into almost razor-sharp arêtes and pinnacles from dark granite.

- Gates of the Arctic sits entirely above the Arctic Circle. This means that for a portion of the North American summer, the Sun never sets on the park—there is 24 hours of light, no night. In the dead of winter, the converse is true: The Sun never rises above the horizon, and there is 24 hours of darkness, with sometimes just a feeble twilight in the hours near noon.

- Being so far north, during the months when the park gets some nighttime darkness, Gates of the Arctic frequently experiences one of our planet's most awe-inspiring natural phenomena: a display of the aurora borealis, or northern lights. Denali is far enough north to be another choice.

Endicott Mountains.

- The northern lights are caused by the interaction of the solar wind and Earth's upper atmosphere. At lower latitudes, Earth's strong magnetic field creates the magnetosphere, which is a sort of shield that deflects most solar wind particles. But in the Arctic, under certain conditions, particles penetrate the atmosphere and produce fabulous displays of shimmering color.

Suggested Reading

Chadwick, "Denali."

Connor, *Roadside Geology of Alaska.*

Mitchell, "Alaska's Giant of Ice and Stone."

Questions to Consider

1. Denali has the highest summit in North America. What are the tallest mountains on the other continents, and how did they form?

2. Gates of the Arctic is the northernmost national park in the United States. What is the northernmost national park in the world? (HINT: This question is answered later in the course.)

Lecture 14 Death Valley and Great Basin: The Rift Zone

Stretching of the continental crust in a large rift zone causes huge blocks of land to sink between high mountain belts, producing Basin and Range topography and the lowest, hottest, driest place in North America. Crustal extension and continental rifting will continue on landscapes of the Basin and Range. Dry conditions prevail across the region today in the rain shadow cast by the Sierra Nevada range. But in the future, an ocean might flood the lowlands and North America might separate along the rift zone, a process that has already begun in the Gulf of California.

Death Valley National Park

- Death Valley National Park is 5,000 square miles of scorched Mojave Desert painted by mineralogy, evaporation, and extreme contrast. It surpasses Yellowstone in size as the largest national park in the contiguous United States.

- Death Valley is also the epitome of America's Basin and Range Province, a land rifting apart, torn asunder, where giant blocks of continental crust are sinking between tall mountain belts. In the future, an ocean could fill this parched and desolate valley.

- In Death Valley—and across the broad region of the western United States and Mexico called the Basin and Range Province, or the Great Basin—a process called rifting could tear the continent in two.

- Over about the last 20 million years, a swath of North America between the Sierra Nevada mountains and the Colorado Plateau, as well as north into Oregon and Wyoming and south into Mexico, has stretched and thinned, nearly doubling in width from east to west.

- As this has happened, the thinning of the crust above has reduced pressure on the upper mantle below, causing some of the rock within it to transform into magma and rise, buoying up the entire region and stretching the crustal rocks further. It's a self-reinforcing cycle.

- As the continent has extended, rocks of the lithosphere—the brittle crust and uppermost mantle—have fractured and pivoted along normal faults. Meanwhile, the more fluid rocks of the asthenosphere below have simply stretched and thinned. Downward motion of huge blocks of crust has created the deep basins, while the fault escarpments define the fronts of tall mountain ranges.

- Geologists use the German words "horst" and "graben" to describe the elevated and down-dropped blocks, respectively. Death Valley is a graben. The Panamint and Amargosa Ranges are neighboring horsts. The floor of Death Valley is covered by thousands of feet of sediment that have come down from the Panamint mountains as they rise across the bounding fault.

- If that sediment weren't there, the western edge of Death Valley's floor would be not a few hundred but many thousands of feet below sea level. Much of the sediment that has filled the valley has come down from the surrounding mountains during infrequent flash floods.

- The lowest place in North America is in the middle of Badwater Basin, sitting 282 feet below sea level. Stretching away from Badwater Basin is a broad and barren salt flat, a salt pan, with large crystals and crusts of mostly sodium chloride—common table or rock salt, or simply halite.

- The lowest point in the valley is not the driest. The driest point is a few feet above the lowest point, at a point called the Devil's Golf Course. This is an expansive salt pan in which some of the halite crystals have grown quite tall, giving the surface a rugged, jagged appearance. These salt pans might look devoid of life, but in fact, microbes called extremophiles inhabit the salt pans.

- During times when the climate was more humid, some surface streams flowed into the valley and filled a lake about 80 miles long to a depth of hundreds of feet. Geologists have given this vanished lake the name Lake Manly. As the climate cycled between wet and dry, dissolved salts carried down in stream water repeatedly


Death Valley National Park.

precipitated out on the valley floor and accumulated. This is the origin of the salt for Death Valley's salt pans.

- In another of the park's basins, between the Cottonwood and Last Chance Ranges in the north, sits Racetrack Valley, the site of one of the great geological mysteries in America's national parks, a mystery that persisted for more than half a century: How do rocks move across the racetrack?

- Three miles long and two miles wide, the valley is actually a playa—the floor of an evaporated lake. Instead of salt, Racetrack Valley's floor is covered with a fine and uniform brown mud. Rocks, small and large, tumble from the surrounding hills down onto the racetrack playa, onto the mud. And for years and years, unseen, they have moved across it. We know this because they leave tracks.

- In August of 2014, the mystery was solved when a paleobiologist and an engineer filmed thin sheets of ice that had formed on Racetrack Valley, gliding across the mud and dragging along embedded rocks, making more tracks. The ice evidently makes the friction with the mud so slight that the sheets can glide across the mud with the slightest bit of wind, or in response to the slightest change in elevation.

- One of the most spectacular and popular destinations in Death Valley is Zabriskie Point, located in the Amargosa Range, the mountains that flank Death Valley to the east. It's a magnificent, colorful, and highly eroded landscape with tinted and sculpted muds. The eroded, fanciful mudstones are a fine example of a geological feature called badlands—so called because vegetation for the most part won't grow on them.

- As with many of the other parks in the American West, mining played a crucial role in the history of Death Valley. Prospectors in 1904 found gold-laced quartz veins in a hill east of the valley, and it triggered a rush and a boom in the so-called Bullfrog District.

- This find gave birth to the town of Rhyolite, just east of the park's boundary. The presence of the prolific Montgomery Shoshone mine nearby transformed Rhyolite, in just a few short years, into a mini-metropolis of between 5,000 and 10,000 people.

- By 1911, however, the Montgomery Shoshone mine was shuttered, and in 1916, power to the town of Rhyolite was shut off. Portions of Rhyolite's structures—including its bank, school, train station, and prison—still stand today.

- Another facet of Death Valley's mineral past made perhaps one of the most noteworthy contributions to National Park Service history. Hot springs circulating through rhyolite—the volcanic rock the town was named for—concentrated and then precipitated boron in the form of sodium-boric acid salts called borax. The money earned by borax mined in Death Valley helped create the National Park Service.

- The Ubehebe Crater, 600 feet deep and half a mile wide, appears at the north end of the park. It is a maar volcano crater. Maar volcanoes form when underground magma comes into contact with a large pocket of groundwater, causing an explosion. It might have formed as recently as 300 years ago, and Little Hebe Crater—visible from its rim—is even younger.

- More such craters dot the landscape south and west of Ubehebe. They mark the rise of magma along fractures through the thinning crust from the upper mantle below and might be a prelude to basaltic eruptions in the years ahead as extension and thinning continue.

- Looking beyond Death Valley, we see the volcanic consequences of rifting elsewhere in the Basin and Range Province. To the far north, in Lava Beds National Monument, we find the largest volcano by volume in the Cascade Range: Medicine Lake volcano, formed primarily from gently flowing basaltic lava. The park has lava flows in abundance, along with cinder cones, spatter cones, and more than 700 lava-tube caves.

- Newberry National Volcanic Monument in Oregon, Sunset Crater Volcano National Monument in Arizona, and Capulin Volcano National Monument in New Mexico all contain volcanoes associated with the spreading, stretching, and rifting that have created the Basin and Range topography in the western United States.

Great Basin National Park

- Geographers use the name "Great Basin" to describe the entire large region characterized by closed drainage basins within the Basin and Range Province. A portion of this region in northeastern Nevada has been set aside as Great Basin National Park, which encompasses Wheeler Peak, along with other peaks of the southern Snake Range—another of the many fault-bounded ranges that characterize the Basin and Range.

- On the high slopes of the Snake Range sit protected groves of ancient and gnarled bristlecone pines, Earth's longest-lived tree. They grow in the high, dry reaches of the subalpine zone, 9,500 to about 11,500 feet. Most precipitation in the rain shadow of the Sierra Nevadas falls as winter snow. The trees' dolomite substrate contains few nutrients.

- One of the ways in which these trees have adapted to survive in such a high and dry region is that they get little competition. Having the high slopes more or less to themselves, bristlecones can spread their roots broadly. The same goes for their crowns—there's no canopy to fight through.

- Bristlecones have evolved to keep their needles for 30 to 40 years, so they don't drop many at a time. With little debris beneath them and a low density of other ground-cover plants, there's not too much risk of getting engulfed in a forest fire. In addition, the trees' dense, resinous wood wards off insects and disease.

- Tree rings from core samples taken from bristlecone pines, which widen and narrow in response to annual weather trends, have given scholars a detailed window into the climate of the region over nearly the last five millennia.

- Like at Death Valley, the basins on either side of the Snake Range—Spring Valley and Snake Valley—contain dry salt pans. Much of the salt would have accumulated during Pleistocene ice advances when Great Basin's climate was cooler (therefore, less prone to inducing evaporation) and characterized by higher precipitation.

- During some of these damper days, Spring Valley was an inundated arm of ancient Lake Bonneville. Nearly as large as one of the Great Lakes, Lake Bonneville encompassed Utah's Great Salt Lake and a number of other neighboring basins in the now-arid west.

- Thick sequences of sedimentary rocks, more than 14,000 feet of them, deposited in ancient oceans hundreds of millions of years ago define much of the geology of Great Basin National Park. Sandstone transformed by heat and pressure into tenacious quartzite comprises the glacially sculpted summit of Wheeler Peak.

- Carbonates such as limestone and its metamorphically altered cousin marble define most of the rock sequence. One of the carbonate rock units, called the Pole Canyon Limestone (in fact, a low-grade marble), contains one of the highlights of Great Basin National Park: Lehman Caves.

- In 1922, before the rest of the park was established in 1986, President Warren Harding proclaimed the highly decorated Lehman Caves a national monument. Spelunkers have mapped more than 10,000 feet of subterranean passages through Lehman, and visitors to the park can schedule a guided tour through the cave.

- A visit to Great Basin isn't complete without following the trail from Lexington Creek up to Lexington Arch. This natural arch, soaring 75 feet above the hillside it stands on, is carved from limestone. The arch might be a remnant of a large cave passage exposed by weathering and erosion.

Great Basin National Park.

Suggested Reading

Cahill, "Death Valley."

Sharp and Glazner, *Geology Underfoot in Death Valley and Owens Valley*.

Questions to Consider

1. The East African Rift Valley, where humans first evolved from other primates, is an extensional basin akin to the Great Basin and larger Basin and Range in the United States. Find this rift on a map and learn about its geological history.

2. Many of the most interesting and unusual minerals form as evaporites in settings such as the floor of Death Valley. Name and find photos of some of these minerals.

Lecture 15

Shenandoah: The Collision of Old Continents

The collisions of ancestral Africa and Eurasia with what would become North America built mountains on the scale of the Himalayas, and their eroded vestiges can be found in Appalachia. In the middle of the Appalachian Mountains is Shenandoah National Park in Virginia. The Blue Ridge that comprises most of Shenandoah National Park and the Ridge and Valley landscape that unfolds beyond it present two responses to the same titanic compressional forces, two solutions to the same problem: How do you shorten a continent?

The Origins of Shenandoah National Park

- Shenandoah National Park—and, indeed, all of Appalachia—manifests the extraordinary consequences of continent-to-continent collisions. The most recent such collision in this region built a mountain range on the scale of the Himalaya where the Blue Ridge stands today.

- The oldest rocks exposed on ridge crests in the range bear witness to an earlier collision, twice as long ago. Ancient and gnarled, fractured and metamorphosed, metagranites and gneisses sparkling in the sunlight whisper of cycles of continent formation and rifting that date back well over a billion years.

- About 500 million years ago, the Atlantic Ocean's aquatic ancestor, the Iapetus Ocean, began to close, as ocean basins do, via subduction. The floor of this old ocean descended into trenches as neighboring continents overran it, and the waters narrowed. Across the sea, Gondwana—a protocontinent comprising what would become Africa, South America, Antarctica, and Australia—was drawing closer.

- So, too, were volcanic island arcs called the Taconic and Avalonia, akin to New Zealand or Japan, that would become much of northeastern North America. Ancestral Europe also came grinding in toward what would become North America's northeastern coast.

- Earth scientists have another name for the core of North America back then: Laurentia. The Laurentian coastline, traced by the Appalachian Mountains today, had an appointment with destiny.

- As they arrived in a succession of collision events over more than 150 million years, the buoyant, continental landmasses slammed into Laurentia. The incoming plates pushed sediments on what had been the quiet, trailing edge of Laurentia, as well as much of the Taconic and Avalonian island arcs, up and over rocks farther west, making a double thickness of folded and faulted continental crust. Geologists name each of the collision events an orogeny—in particular, the Taconic, Acadian, and Alleghenian orogenies.

- To get a sense of the consequences of these island-to-continent and continent-to-continent collisions of long ago, we need to look no further than the Himalaya, the Hindu Kush, and the Alps. From the Himalayas to the Alps, we have the world's tallest extended mountain range today.

- The Appalachians might have been the world's tallest mountain range back then, along with their extensions, now an ocean away in Africa (Morocco's Atlas Mountains) and Greenland, Svalbard, the British and Irish Isles, and Scandinavia (the Caledonian Mountains).

- At 4,050 feet above sea level, the summit of Hawksbill Mountain is the highest place in Shenandoah National Park now. But when these old mountains were new, their tallest summits might have stood about five miles taller.

- Because continental crust is too buoyant to subduct into the upper mantle, it obducts instead—that is, it sutures itself, or accretes, to the landmass it collides with. The result of all this colliding and obducting and mountain building as the Iapetus Ocean closed was a megacontinent called Pangaea. The Appalachian Mountains we trace through Shenandoah National Park are the enduring vestiges of Pangaea's birth.

Shenandoah National Park.

- After about 100 million years of dominating the nonaquatic scene, Pangaea began to rift apart. As Africa and Europe departed for the eastern horizon, the Atlantic Ocean filled the widest of the widening basins, and unburdened mantle rocks began to rise and convect and spread, creating the Mid-Atlantic Ridge. Africa left behind a slice of what had once been Gondwana, now Florida, along with parts of southern Georgia and Alabama.

Old Rag Mountain

- One of the most popular hiking destinations in Shenandoah National Park, and a great spot to examine its geology up close, is Old Rag Mountain. Old Rag stands tall, a resilient outlier, to the east off the main axis of the Blue Ridge and Skyline Drive.

- Unlike much of the rest of the park, which is mantled by soils, plenty of bedrock is well exposed on Old Rag. A steep and rugged challenge, a hike up Old Rag will give you ample opportunity to study the Old Rag granite, which dates back to a mountain-building event more than a billion years ago called the Grenville orogeny. This event occurred during the construction of a supercontinent called Rodinia, which predated Pangaea.

- These granites are some of the oldest rocks exposed anywhere in Shenandoah National Park. They resulted from the closure of an ocean that predates even the Iapetus Ocean. This was a collision and mountain-building event more than twice as old as the creation of the Appalachians, from a time called the Mesoproterozoic, part of what is more loosely called the Precambrian.

- Like all granites, the Old Rag granite crystallized very slowly underground. For millions of years, it lay beneath thick sequences of younger volcanic and sedimentary rocks—beneath many of the rocks exposed at the surface across the region, in fact. As a result, it is called basement rock.

- Long after the granites crystallized underground, when Gondwana rammed Laurentia, compressive forces from the collision pushed these old basement rocks up and over younger rocks. The basement rocks slid for tens of miles along low-angle faults called thrust faults, stacking them up above the younger rocks they rode over.

- The result was a shortening and thickening of the continental crust. Thrust faulting, then, is one of the two means by which the crust was shortened during the formation of the Appalachian Mountains. It's the prevalent method along the Blue Ridge proper. In fact, it's what formed the Blue Ridge highlands.

- Subsequent weathering and erosion have removed overlying rocks. When weight is removed from the crust, a buoyant adjustment causes the rocks below to rise. And that is what has brought the

Old Rag Mountain.

ancient basement rocks to the surface in the crests and summits of Shenandoah's tallest mountains, such as Old Rag.

- Two other kinds of rock you'll encounter on the hike to Old Rag, as well as elsewhere along the Blue Ridge, are basalt and an igneous rock called diabase. Even though diabase is darker than basalt, is most often coarser grained, and has more iron and magnesium, the two rocks share the same chemical and mineralogical composition.

- The diabase on the trail up Old Rag fills approximately vertically oriented fractures in the surrounding granite. These are feeder dikes—channels along which magma flowed to the surface during the rifting and breakup of Rodinia.

- The magma that poured through the dikes, some of which finally cooled and solidified to produce the rocks that remain, might have exceeded temperatures of 2,000 degrees Fahrenheit when it coursed through these narrow channels. Today, parts of the trail pass through the fractures where the diabase has preferentially eroded away.

The Geology of Shenandoah

- When Rodinia began to split apart, basaltic volcanoes erupted fluid lava flows along the margins of the rift zone. The same thing is happening today in the volcanoes that fringe the widening Basin and Range Province, such as Medicine Lake at Lava Beds National Monument in California.

- Basaltic lava flows poured across the landscape, inundated it, filling every low place. As the rift continued to widen, more basalts poured in to fill the gap, and eventually they would become the floor of the Iapetus Ocean.

- In the vicinity of Shenandoah, basalt lava created a broad, flat plain. The subsequent collision of Gondwana that formed the Appalachian Mountains subjected the basalts to elevated pressures and temperatures, transforming them into a rock called greenstone.

Today, we call this thick stack of metamorphically altered lava the Catoctin Formation.

- One of the most fabulously decorated caves in the eastern United States, Luray Caverns, lies under Page Valley. The south fork of the Shenandoah River meanders along the valley floor, and beyond rises a set of closely spaced parallel ridges collectively called Massanutten Mountain.

- Limestones, dolomites, and their metamorphic product, marbles, predominate in the valleys in this region, along with a fine-grained sedimentary rock called shale. Both the limestones and the dolomites of the Shenandoah Valley formed in long reef banks. The reefs occupied the shallow and quiet, tectonically passive margin of the Iapetus Ocean during the millions of years after it opened and before the suturing together of Pangaea destroyed it.

- Carbonate rocks, such as limestones and dolomites, will either resist weathering and erosion or not depending on how much moisture happens to be around. In arid climates, such as those of the American Southwest, carbonates form steep cliffs. In and around Shenandoah, by contrast, carbonate rocks simply dissolve, creating caverns. The carbonates in the vicinity of Shenandoah form valley floors and are riddled with caves, including Luray Caverns, Skyline Caverns, and Shenandoah Caverns.

- Materials that cap the tall ridges of the Ridge and Valley must be more resistant to physical and chemical weathering, so sandstones and conglomerates cap the tall ridges of the Ridge and Valley. The long, narrow ridges of the province with rocky outcrops along their high spines are called hogback ridges, which evoke the bristly back hairs and crested backs of wild boars, or razorbacks.

- As you look anywhere on the Blue Ridge in Shenandoah National Park, you survey mostly sedimentary rocks of the Ridge and Valley province. These rocks have been compressed and folded like a carpet pushed along the floor into a wall. Geologists call this crustal shortening. Just as thrust faulting led to crustal shortening in the Blue Ridge province, intense folding in response to the Appalachian collision has led to crustal shortening in the Ridge and Valley province.

Gros Morne National Park

- Following Appalachia north to Atlantic Canada, to the island of Newfoundland, we find Gros Morne National Park. This island's Long Range Mountains are an eastern extension of the Appalachian Range. Granites and metamorphic gneisses core the Long Range Mountains. Just like the Old Rag granites, they date back more than a billion years to the late Proterozoic, the Grenville orogeny, and the formation of Rodinia. Then, Rodinia came to an end with the rifting of the continent and the opening of the Iapetus Ocean, the proto-Atlantic.

- As the Iapetus Ocean got subducted into nonexistence, a slice of the ocean floor got sheared up. We can walk that slice of ancient ocean floor today atop the Tablelands in Gros Morne National Park. The slice includes both basalts and coarser-grained gabbros, which come from deeper in the oceanic crust. But this slice also includes the contact between the gabbros and even deeper, denser rocks of the upper mantle.

- Croation seismologist Andrija Mohorovičić became the first to discover the boundary between what we now call Earth's crust and the upper mantle in 1901. He inferred its existence to explain the refraction (or bending) of earthquake waves that occurred when they crossed from crust into mantle. Whatever rock type existed just below the crust, certain types of waves moved more quickly through it. That's the boundary between the deep-crust gabbro and the denser rocks that lie below.

- In the seismologist's honor, we call this boundary the Mohorovičić discontinuity, or the Moho for short. Gros Morne National Park is one of the best places on Earth to see and touch a slice of what was once the Moho. This is where you can see the Appalachian range where it has come directly in contact with rock of Earth's mantle.

Suggested Reading

Bryson, *A Walk in the Woods*.

Frye, *Roadside Geology of Virginia.*

Questions to Consider

1. The Appalachian Trail is just one of several national scenic trails administered by the National Park Service. Find maps of the others to see where they go.

2. Geology played a decisive role in the outcome of the Battle of Gettysburg. In what other North American battles has geology influenced the outcome, and how?

Lecture 16

Great Smoky Mountains and Hot Springs

The collision of continents that created Pangaea raised mighty mountains from Atlantic Canada down North America's Eastern Seaboard to Georgia—the Appalachians—and shaped the Great Smoky Mountains in the heart of Appalachia. The line of continental collision can be traced along the Blue Ridge Parkway to America's most visited national park: Great Smoky Mountains National Park. Intercontinental collision built another mountain belt in Arkansas and Oklahoma, the Ouachita Mountains, and created the plumbing for the hot springs found in Hot Springs National Park.

The Blue Ridge Parkway

- When you take the Blue Ridge Parkway south, your journey culminates in the Great Smoky Mountains. This is where the Alleghenian orogeny—the last phase of Appalachian Mountain building, when Africa and Europe collided with North America—built a swollen bulge in the Blue Ridge whose highest summits scale the sky to more than 6,000 feet.

- One window into the geologic story of this part of the United States is along the Blue Ridge Parkway at Grandfather Mountain in North Carolina, where erosion has opened a window through the pushed-up rocks of the Blue Ridge into the younger rocks below.

- The overlying rocks are primarily a banded metamorphic rock type called gneiss, which forms when pressures and temperatures get so high that minerals recrystallize, segregating and aligning themselves in alternate dark-and-light-colored bands. Along the Blue Ridge Parkway near Grandfather Mountain, some of the gneiss is more than a billion years old.

- The Blue Ridge–forming gneisses and associated old Proterozoic rocks were created from even older rocks during the mountain-building event that built Pangaea's supercontinent precursor,

Blue Ridge Parkway.

Rodinia. Some of them were buried to depths of 10 miles or more below Earth's surface. That was before all the ensuing events that resurrected them and placed them where they sit by the road and trail.

- Perched high atop Grandfather Mountain are conglomerates, sedimentary rocks full of cobbles shed down into a rift basin that might have resembled Death Valley the better part of a billion years ago as Rodinia began to split open.

- Nearby, a rock called quartzite has formed from sandstones deposited on the margin of the Iapetus Ocean after Rodinia had rifted apart. Hundreds of millions of years later, Gondwana collided and drove the old gneisses up and over the sedimentary rocks exposed in and around Grandfather Mountain on the Blue Ridge Parkway. But subsequent erosion scoured away the gneisses along this stretch of road, opening a window to the younger rocks below.

- Near Grandfather Mountain on the Blue Ridge Parkway, Linville Falls tumbles through narrow, vertical slots in the surrounding rock. These slots follow stress fractures called joints, which cause the rock to break into rectangular blocks, opening chasms within the rock.

Great Smoky Mountains National Park

- Continuing south along the Blue Ridge Parkway, we arrive eventually at Great Smoky Mountains National Park—the most visited of all U.S. national parks, with close to 10 million visitors per year.

- Cades Cove ranks high on the list of must-see destinations for visitors to the park, drawing about 2 million of the park's visitors annually. The park service preserves Cades Cove as a meadow, and it's populated by historic old homesteads. It's a window into a way of life that came to an end in these hills when the land for the park was acquired and dedicated—or, actually, before, because many of the more modern homes were removed after the park acquired the land.

- Cades Cove is another geological window as well as a historical one. The cove's fertile lowland soils developed on limestone and dolomite, carbonate rocks laid down hundreds of millions of years after the billion-year-old Thunderhead Sandstone and other resistant rocks that form the peaks of the surrounding Great Smoky Mountains.

- As with Grandfather Mountain, the continent-to-continent collision that created Pangaea had pushed the older rocks along a low-angled thrust fault up and over the carbonate rocks below. Geologists named this major fault the Great Smoky Fault.

- Cades Cove is a window, à la the rocks exposed at Grandfather Mountain, where erosion has worn completely through the displaced older rocks above. Near Cades Cove but just outside the national park, Tuckaleechee and Wear Coves originated in precisely the same way.

- Where you find carbonate rocks, there's a good chance you'll find caves, and Cades Cove is no exception, with both Gregory's Cave and Bull Cave nearby. With a depth of nearly 1,000 feet, Bull Cave is the deepest known cave in Tennessee.

- Atop Clingmans Dome, the tallest mountain in the park, you can walk a spiraling path to an observation deck for a breathtaking panoramic view of the Great Smoky Mountains. Ridges and balds stretch to the horizon in all directions.

- The cool temperatures atop Clingmans Dome—at 6,643 feet—resemble those typically found at much higher latitudes. As a result, the vegetation here is what you'd expect to find in Canada rather than the southeastern United States. The intermediate plant and animal communities found at other elevations throughout the park, along with the relatively high annual rainfall, make the Great Smoky Mountains one of the world's biodiversity hot spots.

- Thunderhead Sandstone forms some of Great Smoky Mountains National Park's highest promontories. Thunderhead Mountain rises above Cades Cove and gives the sandstone its name. The Thunderhead Sandstone is part of a collection of rock beds, or strata, called the Ocoee Supergroup that collectively accounts for most of the rocks exposed along the crest of the Smoky Mountains.

- Another noteworthy rock formation caps a spectacular high ridge on the eastern slope of Sugarland Mountain called Chimney Tops. The exposed ridgeline makes for an inviting scramble. The fine-grained metamorphic rocks here, part of what's called the Anakeesta Formation, have a pronounced foliation, or leaflike, layering due to aligned clay minerals.

- The many streambeds in the park are filled with stones of all sizes—from pebbles to boulders—that once formed an integral part of the mountains upstream. Occasional heavy rains in the hills make flash floods a common enough occurrence. The largest of these floods can suspend pebbles, even cobbles, and transport them along, careening into one another, breaking off sharp edges and rounding the stones. Big floods can push larger rocks down streambeds, too.

- The folded, faulted, and fractured nature of the bedrock in the Great Smoky Mountains, along with all of the rainfall the park receives, also make the Smoky Mountains particularly prone to landslides. You can find V-shaped scars from landslides on the faces of Mount LeConte and Anakeesta Ridge.

Hot Springs National Park

- Far to the west of the Great Smoky Mountains National Park, in the Ouachita range of central Arkansas, warm waters flow to the surface from a line of geothermal springs at the base of Hot Springs Mountain.

- The Ouachita Mountains surrounding Hot Springs National Park are not technically a part of the Appalachian chain, but they formed during the same wave of continental collisions that created Pangaea. Specifically, the convergence of North and South America folded and faulted the strata in which we find the springs, and which formed the mountains. That mountain-building episode is called the Ouachita orogeny.

- The collision of the continents helpfully laid the groundwork for the plumbing system that feeds the springs, too. The springs are a fortuitous by-product of the arrangement of dipped beds and faults in and near the park.

- Between them, the springs in the park deliver between 750,000 and 950,000 gallons of water every day, with the highest flow occurring during winter months. The seasonal ebb and flow helped to resolve a question that naturalists, geologists, and hydrologists debated for more than a century: What is the source of the water that rises in the springs at Hot Springs?

- Surface water that originated as rainfall—some recently, some not so recently—is the source of the groundwater that flows from the springs at Hot Springs National Park. But several questions remain: Why is the water hot? What heats the water? And what causes the water to rise and flow at the springs in such volume, rather than simply remaining underground?

- In active volcanic settings—such as Yellowstone, Lassen Volcanic, and Hawaii Volcanoes National Parks—shallowly placed magma below the surface cooks the ground above. The magma in these settings heats groundwater as well, producing hot springs, fumaroles, and other geothermal features.

- This is not what is happening at Hot Springs. Rather, Hot Springs National Park owes the first word in its name, "hot," to something called the natural geothermal gradient. As you go deeper underground, there is a lot of heat, primarily because of the decay of radioactive isotopes within our planet. This heat radiates outward from Earth's interior. Consequently, the deeper you travel underground, the hotter it generally gets, although the rate at which the temperature climbs varies.

Grandfather Mountain, North Carolina.

- The spring water at Hot Springs has made its way far enough underground (many thousands of feet) to heat to the temperatures measured when it emerges from the springs. These vary from more than 90 to nearly 150 degrees Fahrenheit. Cold water is denser than warm water, so cold rainwater sinks into the ground where it falls if the substrate—the soil and rock it falls on—is permeable and not fully saturated. As the water gets heated at depth, it expands, becomes more buoyant, and begins to rise back toward the surface.

- These fractures form a quick and ready conduit to help the water flow back toward the surface, a sort of pipeline. Therefore, the water doesn't cool back down with the geothermal gradient as it rises; it retains much of the heat it acquired at the deepest point on its subterranean journey.

- Still, in order to flow at the surface as so-called artesian springs do, without pumping, something else is required: a sort of water tower. It's the pressure of higher-standing water in a closed system that is pushing the spring water out. And this is what occurs at Hot Springs National Park.

- The springs recharge through higher-elevation rock units called the Bigfork Chert and the Arkansas Novaculite. Groundwater in the recharge areas for the springs fills little spaces in the rock, or interstices, forming a water table that sits higher than the springs. This elevated water creates something called a hydrostatic head, and its weight pushes water down through the groundwater plumbing system and out through the springs.

- Continent-to-continent collision created the Ouachita Mountains and set the stage for all the warm baths at Hot Springs. The collision of South and North America (technically then Laurentia) near the end of Pangaea's formation was gentle compared to the Gondwana-Laurentia collision that created the Appalachian Mountains in Shenandoah and Great Smoky Mountains National Parks.

- The gentle mountains at Hot Springs National Park rise to between about 1,000 and 1,400 feet, with the tallest summit—that of Music Mountain—perched at 1,405 feet.

- Still, the convergence of the continents was intense enough to crumple, fold, and fault the layers of sedimentary strata that underlie the park. The beds had formed as layers hundreds of millions of years ago (from Ordovician to Mississippian time) in the mostly quiet waters offshore of Laurentia before the big collision. Their folds form tight U-shaped anticlines (upward folds) and synclines (downward folds).

- Some of these folds have had one side overturned, so that older rocks lie above younger ones. The faults are so-called reverse faults, with their upper, or "hanging," walls pushed up over their lower, or "foot," walls. These are all classic consequences of convergence, signatures of the final suturing together of our planet's most recent supercontinent.

Suggested Reading

Clark, *Birth of the Mountains*.

Questions to Consider

1. Charlie's Bunion is one of the most popular day hike destinations in the Great Smoky Mountains. Search online to determine how this geological feature was made and how it got its name.

2. People often have attributed healing properties to hot spring waters. How does the chemistry of water from springs in Hot Springs National Park, or in other natural springs at famous spa resorts, differ from that of distilled water?

Lecture 17

National Rivers: Gorges, Falls, and Meanders

River parks expose and celebrate the many ways that rivers transform the landscape and enrich our lives. Along the Eastern Seaboard fall line, cascades and rapids due to underlying geology dictated the locations of great cities. Watersheds separated by the Continental Divide proved a challenge to exploration, but not an insurmountable one. Across North America, streams and rivers drain the highlands surrounding mountain belts, from Appalachia to the Rocky Mountains to California's coastal ranges, pulling the mountains down, one grain of sand at a time.

Rivers of America's Eastern Seaboard

- Rocky runs and waterfalls are the centerpiece of a story that plays out on river after river along America's Eastern Seaboard, in port city after port city. In an era before railroads, airports, and semitrucks, rivers were highways, the easiest ways to get people and goods into the continent. The limit of upstream navigation on the river was a natural place to put a port.

- The Eastern Seaboard fall line is the 900-mile boundary between two great geographic provinces: the Piedmont and the Atlantic Coastal Plain. From the falls west to the Appalachian Blue Ridge Mountains is a plateau called the Piedmont, where bedrock is a mix of ancient metamorphic and volcanic rocks sutured onto the continent during the formation of Pangaea. Below the falls and east of the fall line is the Coastal Plain, a wedge of sediments shed from the western mountains and deposited eastward, toward the coast.

- Rivers running east to the Atlantic east of the Blue Ridge make their way across the dense, erosion-resistant rocks of the Piedmont and then tumble across the fall line onto the more readily eroded sediments and sedimentary rocks of the Atlantic Coastal Plain.

- The rocks of Mather Gorge and those underlying the Great Falls of the Potomac River are metamorphically altered sandstones and mudstones that formed more than half a billion years ago, along with igneous intrusions that are nearly as old.

- The Potomac follows fractures through the rocks that were created by faulting. It deepened its channel to create Mather Gorge during colder times of the Pleistocene, when higher precipitation and spring snowmelt surges made the river run extra high.

The Missouri River

- The Missouri River shaped the course of one of the great voyages of discovery across the North American continent, as commemorated in the Lewis and Clark National Historic Trail.

- After the Louisiana Purchase, President Thomas Jefferson wanted to know what the young nation had acquired. He sent his secretary, Meriwether Lewis, and William Clark to find out—and also to discover, if possible, the mythic Northwest Passage, an all-water route across the North American continent.

- No such water route was found; in fact, a watershed boundary known as the Continental Divide presents huge obstacles to any body of water realizing the dream of a Northwest Passage across the United States.

- At the Upper Missouri River Breaks National Monument, the upper Missouri River is also designated a National Wild and Scenic River. The best way to access this stretch of the river is by canoe or kayak on a multi-day trip.

- The white cliffs of the Missouri Breaks were laid down as flat-lying sediments in an inland sea between about 80 and 70 million years ago, during the Cretaceous Period. Muds and clays settled out to be transformed into shales. Sands were carried to the sea by rivers and were deposited along the shore in deltas and beaches.

- Together, the shales and sandstones form the thick stratigraphic sequence that has been exposed by the Missouri River in the

Missouri River.

tall white cliffs of the breaks. These are eroded sequences of sedimentary rocks, and they have eroded into peculiar and astonishing forms.

- Vertical fractures in the sandstone have been exploited by weathering processes. Volcanic dikes also crossed some of the sedimentary rocks after they had formed. These dark dikes have remained after the sedimentary rocks surrounding them eroded away to create memorable features such as the Grand Natural Wall.

- Glaciers also helped shape the current course of the upper Missouri River, whose original path was north, to Hudson Bay and on to the Arctic Ocean. Glacial ice intervened and changed that. With a wall of thick ice barring the route north, the Missouri altered its course and flowed south, joining the Mississippi to flow to the Gulf of Mexico and the Atlantic.

New River Gorge National River

- The New River Gorge National River in West Virginia is a dramatic example of a river that has carved a deep, steep-walled canyon for itself. Up to 1,500 feet deep, the spectacular gorge of the New River cuts into and through the Appalachian Plateau, into and across valleys and ridges of Appalachia's Ridge and Valley province.

- The New River and its gorge began to take shape 500 million years ago as the Teays River, which flowed north and west to an inland sea. But as pieces of North America and Africa—known as Laurentia and Gondwana—began to collide and form Pangaea, the Appalachian Mountains rose. Those mountains invigorated the Teays River, increasing its gradient and pouring more water into it—thereby enhancing its power to erode down into the landscape.

- As the mountains continued to rise and the land beyond began to buckle, the Teays River stayed its course, incising itself into the landscape. Today, the New River follows the canyon begun when it was the Teays, making the New River one of the oldest rivers on the North American continent.

- The New River Gorge Bridge on U.S. Route 19 offers one of the best and most dramatic vantage points in the national park. From the bridge or one of the adjacent viewpoints, you can view the classic V-shape of this mature, river-carved canyon.

- Another popular destination is Sandstone Falls, which marks the New River's entrance into the boulder-strewn gorge. Stony Gap Sandstone, a quartz-rich sandstone that might have formed as a beach about 325 million years ago, underlies the falls. Upstream, the river is wide and relatively flat. Downstream, it tumbles and roars through the V-shaped canyon and onward to its confluence with the Gauley River.

- From there, the combined rivers become the Kanawha, which flows into the Ohio, which flows into the Mississippi, which flows into the Gulf of Mexico south of New Orleans. From the New River's headwaters near Boone, North Carolina, it's a 2,000-mile journey to the Gulf.

- A layer of readily eroded conglomerate—a sedimentary rock comprised of rounded stones held together by a finer-grained matrix—underlies the tough sandstone over which the Sandstone Falls drop. As the river water dismantles the conglomerate and transports it away, it undercuts the rim of the falls. Eventually, chunks of undercut sandstone collapse. So, Sandstone Falls will gradually migrate upstream. Sandstone also forms cliffs along portions of the New River Gorge.

- The Nuttall Sandstone exposed in the lower gorge is extraordinarily rich in quartz, which makes up about 98 percent of the rock. Blocks of this sandstone have fallen into the river, where they create interesting rapids and eddies for white-water enthusiasts. This sandstone is also extraordinarily popular with rock climbers.

Cuyahoga River

- About 280 miles north of the New River Gorge lies the Cuyahoga Valley National Park. Nestled between Cleveland and Akron and traversed by interstate highways, the park bridges the distinct terrains of the Appalachian Plateau and the Central Lowlands of the American Midwest. Steep hills near the park's northern boundary mark the end of the plateau, the last vestige of rocks elevated and folded by the continent-to-continent collision that raised the Appalachian Mountains.

- Beyond lie the city of Cleveland and the broad, flat lowlands of the American Midwest. These Central Lowlands are underlain by sediments laid down in an interior seaway or along the coast, where rivers brought sand, silt, and mud from eastern mountains formed during the Taconic and Acadian mountain-building events.

- The Cuyahoga follows the general course of a valley carved before Pleistocene glaciers reworked the landscape. This river fed the now-vanished Erigan River that would have run the length of Lake Erie before glaciers depressed the land, leaving the lake in their wake. After the last glacial retreat, the Cuyahoga began flowing north up the valley where it lies within the park and into Lake Erie.

Cuyahoga River, Cleveland.

- The floor of the Cuyahoga Valley has ample sediment—gravels, sands, silts, and muds—left behind by the glaciers. The gradient of the valley floor is relatively low, meaning that the river doesn't lose much elevation as it travels to Lake Erie. The river carries an ample load of sediment, but it is not in a hurry, so it wanders around, tracing a sinuous pattern of tight curves called meanders along the valley.

- Over time, water in a meander loop can erode its outer bank so much that it overtakes the next loop. Water spills across the new shortcut. When this happens, the river abandons its old channel to follow a more direct path downstream. But it also leaves behind a teardrop-shaped lake called an oxbow lake. Over time, the river continues to evolve, with meanders meandering, the channel evolving, and some river banks eroding and collapsing as new banks form.

Niagara Falls and River

- Niagara Falls is one of North America's grandest marvels. These renowned falls and the Niagara River that spills over them sit on the border between the United States and Canada. Technically, the National Park Service doesn't manage parklands on the American side of the falls, but it provides oversight and funding for the Niagara Falls National Heritage Area.

- Like so much of what we encounter across the northern United States, the Niagara River formed in the aftermath of the glaciers. As the two-mile-thick ice sheet melted away, it left behind the water-filled basins that became the Great Lakes. The Niagara River began to carry water north from Lake Erie to Lake Ontario.

- Once the river had cleared out glacial drift, it began incising its way into the underlying layers of sedimentary bedrock—sandstone, siltstone, and carbonates (limestone and dolomite). The dense carbonates resist erosion by the river better than the siltstones and sandstones below them.

Niagara Falls.

- As the river scooped out the underlying rocks, it began undercutting the limestone, which fell away to leave vertical cataracts—the falls. Through ongoing erosion, Niagara Falls has migrated about seven miles upstream to the site where it's located today.

- The Niagara River divides around Goat Island to form the American and Canadian Falls. Huge boulders at the base of the falls underscore the fact that they continue to migrate upstream toward Lake Erie.

- Nearly as memorable a sight as Niagara's twin waterfalls is a downstream feature called the Whirlpool. It's located where the Niagara River takes an abrupt right turn, exploiting a chasm carved by an older river. The vortex created as water enters, then tries to escape this L-junction, produces huge standing waves.

- Water from Niagara flows downstream to Lake Ontario. From there, it continues on northeast toward the Atlantic via the Saint Lawrence River, flowing past the islands of Canada's Thousand Islands National Park along the way.

Suggested Reading

National Wild and Scenic Rivers System, http://rivers.gov.

Van Diver, *Roadside Geology of New York*.

Questions to Consider

1. The Mississippi River delivers an immense amount of sediment to the Gulf of Mexico. Research the evolution of the Mississippi Delta.

2. In addition to the national rivers administered by the National Park Service, more than 200 rivers across the United States are designated national wild and scenic rivers. Wherever you live, find the nearest free-flowing, protected stretch of river near your home.

Lecture 18

Great Dune Fields of North America

Desert dunes come in many shapes and sizes, and they can form from many different types of sand. Producing a dune field requires a source of sand, wind, and a place to collect the sand—such as a mountain-ringed holding pen at Great Sand Dunes and Kobuk Valley or a broad coastal flat in the Altar Desert. Dunes are dynamic, traveling with the wind one grain at a time. Supply some moisture and shelter, and vegetation can stabilize dunes and transform them into rolling green hills. But dry them out, or disturb the vegetation, and dunes will begin to march downwind again.

Great Sand Dunes National Park and Preserve

- In south-central Colorado, beneath the tall peaks of the Sangre de Cristo Mountains, lies an ocean of sand. Vast dunes rise abruptly from the floor of the San Luis Valley. Some of the dunes crest more than 700 feet above the valley floor, making these the tallest dunes in North America.

- Like waves on the surface of the sea, some of the dunes rise gradually to form linear ridges that fall off down steep flanks on the opposite side. Some migrate, like waves approaching shore, gradually but inexorably across the landscape.

- But this is no ocean. The San Luis Valley is a sheltered desert, parched and arid. It sees fewer than a dozen inches of rain in a typical year.

- The dune field at Great Sand Dunes National Park and Preserve covers 30 square miles. To make and sustain sand dunes on this gigantic scale, there are some essential things you need as well as additional factors that might be helpful.
    - You need sand—lots and lots of sand. As the Sangre de Cristo Mountains rose in the east and the volcanic San Juan Mountains grew in the west, they created the enclosed San Luis Valley. Thick layers of sand accumulated in the now-

vanished Lake Alamosa on the valley floor. It is this sand that now forms the dunes.

- ○ You also need wind to pile up the sand. A southwesterly, a wind that blows from southwest to northeast, is the kind of wind that is most prevalent at Great Sand Dunes National Park, and particularly during the spring. Strong, steady winds from the southwest blow sand across the San Luis Valley floor and up into the dunes.

- ○ It helps to have something that will slow or stop the wind, or make it more turbulent. This allows the sand to pile up in place rather than migrating downwind. At Great Sand Dunes National Park, summits of seven Sangre de Cristo Mountain peaks within the park reach elevations above 13,000 feet and form a natural barrier to the valley's prevailing winds. It helps that three passes in the mountains funnel winds coming across the valley into a narrow pocket, helping to concentrate the sand in this compact corner.

- ○ It also helps to have something that will carry any stray stand that gets away downwind back to its starting point upwind of the dune field. At Great Sand Dunes, Medano Creek, which runs across the eastern margin of the dune field, fills this role.

- In general, where there's plenty of sand and a steady wind, dunes naturally begin to form. Over time, sand grains slide along the surface or bounce up the face of the dune facing the wind, the windward side. When the grains slide, geologists call their motion surface creep or traction. When they bounce along on the wind, they call their motion saltation.

- Geologists call windswept dune environments eolian. Because of saltation, sand grains in eolian dune environments tend to become frosted. For geologists looking at sandstones in the field, close examination of sand grains to see if they're frosted can provide a helpful clue as to whether rock beds were originally created on land or underwater.

- Over time, saltation tends to reinforce surface irregularities such as bumps and small sand ridges. This results in the development of natural, undulating ridges on the windward slopes of dunes, as well as on broad sand flats.

- Beyond the dune crest on the leeward side, sand avalanches give the dune a steeper slope. This downwind side is referred to as the slip face of the dune. Avalanches occur when the slip face becomes steeper than a threshold angle. For dry sand dunes, this angle is about 34 degrees, or a bit less. So, dunes form asymmetrical ridges with steep faces downwind.

Sand Dunes National Park.

- When they're linear, we call such garden-variety dunes with a gently sloped windward face and a more steeply sloped leeward face transverse dunes. At Great Sand Dunes National Park, we encounter transverse dunes primarily toward the southern and eastern margins of the dune field.

- Most of the dunes in the park, however, are a variety called reverse dunes, or reversing dunes. Reverse dunes have relatively symmetrical slopes, or sometimes have one side gently sloped, but have what look like small dunes along their crests with their gentle slopes on the opposite side—a phenomenon called counterdunes. Reverse dunes, with or without counterdunes, form where winds frequently reverse direction.

- Where winds blow across dunes from several different directions, star dunes form. These dunes may resemble a starfish when viewed from above. Conditions are right for star dune formation in the northeastern corner of the dune field. The national park's tallest sand dune, 750 feet tall at its crest, is a star dune named the Star Dune.

- Toward the western end of the dune field, we encounter longitudinal dunes, which run parallel to the prevailing breezes instead of perpendicular to them.

- Fringing the main Great Sand Dunes dune field you might find barchan dunes, which are crescent- or boomerang-shaped dunes with arms pointing in the direction toward which the prevailing winds blow.

- Parabolic dunes assume U shapes resembling horseshoes. Unlike barchan dunes, with their arms pointing downwind, the arms of parabolic dunes point upwind. Parabolic dunes occur in a region known as the sand sheet southwest of the main dune field at Great Sand Dunes.

- Nebkha or coppice dunes form as hills of sand around clumps of vegetation.

- Sand avalanches get started on the steep leeward slopes of the dunes, either naturally or because people walk or jump on the dunes and get a slide started. As the sand gathers momentum along with more sand, air carried downslope between the sand grains finds resonant frequencies, creating deep, audible vibrations. People call the phenomenon singing or booming sands.

Kobuk Valley National Park

- As with its neighbor Gates of the Arctic National Park, Alaska's Kobuk Valley National Park's 1.7 million acres lie entirely north of the Arctic Circle. The Baird Mountains, a western arm of the Brooks Range, cross the northern portion of the park.

- Streams and rivers descend from the Baird Mountains, forming a pattern like the branches of a tree on a map as they flow to the Kobuk River. This drainage pattern suggests that the metamorphic bedrock north of the river is relatively uniform across the park, without significant regional fault or fracture lines or particularly erosion-resistant or erosion-prone strata.

- From the confluence of Kavet Creek with the Kobuk River, a short hike of a few miles brings you to the Great Kobuk Sand Dunes, the largest active dune field in Arctic North America. These dunes top out at about 100 feet—modest compared with the Great Sand Dunes in Colorado, but impressive nonetheless. A separate dune field, the Little Kobuk Sand Dunes, occupies the southeastern corner of the park.

- Sizable inland dune fields require relatively dry conditions, wind, and a source of sand. The Great Kobuk Sand Dunes have all of these. Only about 16 inches of rain falls each year on Kobuk Valley National Park. Dry polar easterly winds blow with intensity for most of the year, from September into May, and get channeled straight through the park by the east-west running valley of the Kobuk River. And glaciers helped to create plenty of sand to form the dunes.

- As with the Great Sand Dunes, which pile up toward the Sangre de Cristo Mountains, Kobuk's sand dunes accumulate toward the foot of mountains—in this case, the Waring Mountains, which run along the southern margin of the national park.

- Parabolic dunes characterize the windward sides of the Great Kobuk and Little Kobuk dune fields; barchans typify the leeward, or downwind, portions of the fields. Some of the barchans are on the move, and they can migrate downwind several miles per year.

- Though it's well above the Arctic Circle, summertime temperatures in the Great Kobuk dune field can exceed 100 degrees Fahrenheit.

- Dune sands can derive from almost any source of sand-sized grains, be they quartz-rich sandstones and volcanic rocks, as at Great Sand Dunes, or glacially-scoured metamorphic rocks, as at Kobuk Valley.

White Sands National Monument

- In the Tularosa Basin in New Mexico, at the northern end of the Chihuahuan Desert, sits one of the strangest wonders on Earth: White Sands National Monument. The park encloses much of a 275-square-mile brilliant white dune field, the world's largest gypsum dune field.

- The dunes at White Sands National Monument reach heights of up to 60 feet, and some of the dunes migrate up to about 30 feet per year. The gypsum that forms the white sands precipitates to the west of the dune field in a playa or ephemeral lake basin called Lake Lucero.

- Rain and snowmelt dissolve calcium and sulfate while descending to the basin from surrounding mountains. Once the water arrives on the floor of the basin, it evaporates beneath the blazing Sun, precipitating out gypsum crystals in the form of a soft mineral called selenite. Wind breaks off tiny fragments of selenite, which eventually get blown into the White Sands dune field.

Sand Dunes National Park.

Death Valley National Park

- The largest national park in the contiguous United States, Death Valley, contains a number of dune fields, some quite sizable despite the fact that they cover less than one percent of the desert land within the national park.

- Crescent, linear, and star dunes rise to heights of up to 100 feet in the Mesquite Flat Dunes in the north-central part of the park near Stovepipe Wells.

- Remote Saline Valley in the park is home to the low, undulating Saline Valley Dunes.

- The Panamint Dunes are star dunes perched on a slope above the Panamint Valley floor.

Death Valley National Park.

- Near Saratoga Springs, the Ibex Dunes are home to the Mojave fringe-toed lizard.

- The Eureka Dunes, California's tallest sand dunes, occupy a patch three miles long by a mile wide in the isolated Eureka Valley.

The Altar Desert

- At the top of the Gulf of California, just across the Arizona border in Mexico, lies the Altar Desert, part of the El Pinacate y Gran Desierto de Altar, a biosphere reserve and world heritage site. The desert is a part of the larger Sonoran Desert that encompasses much of the southwestern United States and northwestern Mexico.

- The Colorado River, which has its delta immediately to the west and just upwind of the Altar Desert, supplied abundant sand for the desert's dunes until dams upstream began impounding the river's sediment load.

- A variety of different dune types occupy the dune field, which is considered the largest and most active in North America. Tectonic rifting occurs in the Altar Desert as the Gulf of California continues to open. Evidence of volcanic activity in the desert, as at Death Valley, is found in the form of the Pinacate volcanic field.

The Nebraska Sand Hills

- The Nebraska Sand Hills cover more than a quarter of the entire state of Nebraska. The Sand Hills aren't a national park, but they have been named a National Natural Landmark—a National Park Service designation that recognizes and encourages the conservation of outstanding examples of the natural history of the United States.

- The Sand Hills cover a huge region—about 20,000 square miles—and include dunes that are more than 330 feet tall. But what makes them so intriguing is that they're stabilized dunes in what was, perhaps as recently as 1,000 years ago, a desert with active, windblown dunes.

- Today, grasses have stabilized these former dunes. The underlying Ogallala Aquifer has made some low-lying portions of the Sand Hills wetlands. Nebraskans have used their Sand Hills, too sandy for cultivation, as prime cattle-grazing land for generations.

Suggested Reading

Connor, *Roadside Geology of Alaska.*

Hopkins and Hopkins, *Hiking Colorado's Geology*.

Williams and Chronic, *Roadside Geology of Colorado*.

Questions to Consider

1. For a sense of scale, compare the size of the Kobuk Valley and Great Sand Dunes dune fields, along with the Nebraska Sandhills, with the Sahara Desert.

2. Earth isn't the only orb in the solar system with dune fields, or ergs. Large ergs exist on Mars, and dunes cover an area about the size of the United States on Saturn's largest moon, Titan. What other planets and moons in the solar system are home to dune fields?

Lecture
19 National Seashores and Lakeshores

A discontinuous, 2,000-mile ribbon of long, thin, low-lying islands traces the Atlantic Coast of the United States from New England to the bottom of the Florida Keys. Another traces the Gulf Coast west from the Florida panhandle to the Mexican border and beyond. Behind these so-called barrier islands sit protected bays and sounds, along with salt marshes and sometimes mangrove forests. The islands evolve and change on human timescales. Barrier islands define much of the coastline at all but one of the current U.S. national seashores—Point Reyes, the only national seashore on the Pacific Coast—due to the very different geology of the coast near the San Andreas Fault.

Cape Hatteras National Seashore

- Located in the Outer Banks of North Carolina, Cape Hatteras is America's first national seashore. Like other seashores, there are several zones that are characteristic of these areas.
    - The region from the spot where waves begin to break to the limit of water's reach on shore is the surf zone. Wave energy suspends sand-sized mineral grains and shell fragments here and transports them along the shore, creating a sort of river of sand that hugs the coast.

    - The foreshore, also known as the beach face, faces the ocean and is the sloping portion of the beach between the limits of water's reach during high and low tides.

    - The berm, or backshore, is the sandy terrace that sits beyond the reach of waves during high tide. The berm crest defines the boundary between the foreshore and the berm.

    - A dune ridge rises beyond the berm. Dunes are often stabilized by pioneering grasses that have adapted to the extreme conditions in beach dunes—frequent cycles of wetting and drying, high salt due to sea spray, high winds, sand blasting, and occasional burial.

- Beyond the dunes lie overwash terraces, where sand gets deposited during particularly large storms. Small shrubs as well as grasses populate the overwash terraces.

- Fine sediments, such as silt and clay, finally get their turn to settle down in the area known as the salt marsh, because waters on this side of the barrier islands are sheltered from the ocean surf. The salt marsh is a muddy environment, unlike the higher-energy ocean beach. Healthy salt marshes are one of our planet's most productive ecosystems.

Cape Hatteras Lighthouse.

  - Beyond the salt marsh lie the protected waters of the sound. Without strong, ocean-wave-driven longshore currents to smooth the shoreline, the sound or bay side of barrier islands is typically ragged, with lobes of land extending out into the water wherever overwashing storm waves happened to drop sediment.

- One of the iconic attractions of the Cape Hatteras National Seashore is its black-and-white-spiraled lighthouse rising above the trees and the dunes. At 208 feet, it's the tallest masonry lighthouse in the United States.

- Built in 1870 to replace an older light, the Cape Hatteras Lighthouse was originally situated well inland, a good 1,500 feet from shore. It warned ships that they were drawing close to the infamous Diamond Shoals. The shoals, a collection of constantly shifting submerged sandbars, lurk up to 10 miles offshore of Carolina's Outer Banks near the coastal bend at Cape Hatteras.

- Situated as they are, where the Gulf Stream traveling up from the south encounters the Labrador Current from the north, the Diamond Shoals present an extraordinary hazard to maritime navigation.

- Over the century after the lighthouse was built, strong storm-surge tides repeatedly swept over Hatteras Island, eroding sand from the ocean side and redepositing it on the Pamlico Sound side. Slowly, the island has migrated west, and it continues to do so.

- This process of shoreward migration of the barrier islands has been ongoing for thousands of years. The pace of migration has averaged more than a foot per year toward land for more than a century. If it continues, eventually Pamlico Sound will close, and the Outer Banks won't be outer anymore—they will have merged with the mainland Carolina coast.

- Cape Hatteras and the adjacent Cape Lookout National Seashore enclose a 125-mile stretch of North Carolina's coastal waterways.

Why do these islands sit where they do—up to 25 miles across the sound from the mainland, in some cases?

- As the most recent of the Pleistocene glaciers retreated over the last 10,000 years, sea levels rose dramatically. By about 5,000 years ago, a long zone of dunes had formed along the coast where the Cape Hatteras and Cape Lookout barrier islands lie today. As sea level continued to rise, the broad lowlands behind the coastline flooded to become Pamlico Sound, Albemarle Sound, and other interior waterways.

- Incremental changes occur daily throughout the outer banks, as wind and water move the sand they're built from onto, off, and along the shoreline. But decades worth of change can occur in hours when a hurricane or other strong tropical storm makes landfall.

Assateague Island National Seashore

- On the Delmarva Peninsula in the mid-Atlantic, a 1933 hurricane breached what had been a continuous barrier island in two places, separating Ocean City, Maryland, from Fenwick Island to the north and Assateague Island to the south.

- Jetties were built to make the southern breach, Ocean City Inlet, a permanent channel so that boats could pass between the Atlantic and the Isle of Wight Bay. This prevented sand from migrating south with longshore currents to replenish beaches on the northern portion of Assateague Island, now a national seashore.

- Over the rest of the 20^{th} century, while Ocean City held its ground, Assateague across the inlet migrated 350 yards to the west, toward the mainland. Its beaches thinned, and its dunes grew lower with every major storm.

- At the start of the new millennium, the U.S. Army Corps of Engineers was called in to design the North End Restoration Project, intended to shore up northern Assateague Island before its dunes and beaches eroded away entirely. Their efforts helped

Assateague Island National Seashore.

sustain North Assateague's beaches, but in the long run, all such efforts appear to be mere holding actions.

- It's the nature of barrier islands to migrate landward with each big storm wash-over—to roll over. The current trend of rising sea levels and larger, more frequent storms can only accelerate the landward migration, if it doesn't fragment and break up the barrier islands first.

- The management team for Assateague Island National Seashore has embraced the inevitability of change and has begun replacing permanent structures with mobile ones that can migrate with the island and be carted to safety before destructive storms pass through. They have stopped trying to build artificial barriers to protect against the waves.

Canaveral National Seashore

- Like Assateague and the Outer Banks, Canaveral National Seashore includes miles of barrier island beaches. The Mosquito Lagoon on the Intracoastal Waterway lies on the landward side of the island. NASA's John F. Kennedy Space Center sits just to the south.

- This park encompasses the important transition zone from salt marsh ecosystems at its north end to subtropical mangrove forests to the south. Both play a similar role in harboring life, cleaning water, and helping buffer the mainland beyond from the storm surge associated with hurricanes and other big tropical storms.

Cape Cod National Seashore

- Along the Atlantic Coast of Massachusetts, the Cape Cod National Seashore stretches the length of the Cape Cod peninsula from Nantucket Sound to Provincetown. Where the peninsula ends in Cape Cod Bay, sandspits trace a tightening spiral around Provincetown Harbor. That spiral is defined by the eddies of longshore currents.

- Although Cape Cod has its share of sandy beach strands and dune fields, and similar coastal processes are at work here, its origins differ from those of the barrier island systems to the south.

- During the last major Pleistocene glacial advance, the Laurentide Ice Sheet eroded tons upon tons of material from the continent's interior, transporting it to the fringe of the ice sheet and dropping it where the ice melted.

- The ice-borne material, glacial drift, varies in size from fine muds, silts, and sands to coarse gravels and boulders. Where unsorted by later transport in water, we call this material glacial till. The islands were born as glacial till left as moraines by ice age glaciers, plus some outwash that was better sorted and stratified.

- As the climate warmed and the ice retreated, it paused for years and built Cape Cod in the same manner. After several cycles of advance and retreat during which some moraines were overridden, by about 18,000 years ago, the ice had drawn back farther, leaving the cape. Today, steep bluffs at Cape Cod erode to reveal the mix of grain sizes, from fine to coarse, associated with glacial moraines.

- Dunes cover about one-third of the Cape Cod National Seashore. Two other features of the Cape Cod National Seashore are kettle ponds and cranberry bogs. Kettle ponds form where large blocks of ice got buried amid glacial sediments and melted slowly, leaving behind deep depressions. Although streams don't flow into them, they intersect the water table and form enclosed ponds. Low areas between some of Cape Cod's dunes formed bogs that were colonized by wild cranberries.

Indiana Dunes National Lakeshore

- Ice age glaciers also played a critical role in the creation of our country's national lakeshores: Sleeping Bear Dunes and Indiana Dunes on Lake Michigan as well as Pictured Rocks and Apostle Islands on Lake Superior.

- At Indiana Dunes National Lakeshore, we find four successive dune complexes marking four different shorelines as we head inland from the beach. Sandy dunes along the current lakeshore are still active.

- The tallest of these modern dunes crest at heights of nearly 200 feet. Mount Baldy, the tallest moving sand dune in the park, has half-buried trees along its southern slopes and continues to march inland.

- Grass-covered ridges mark early stages of dune stabilization, while blowouts occur where vegetation has been disrupted, allowing an erosive gap to open in a line of dunes. Landward lie the Tolleston dunes, then the Calumet dunes, and then the Glenwood dunes. A mature oak forest covers the two oldest of these dune fields.

Sleeping Bear Dunes National Lakeshore

- At Sleeping Bear Dunes on Lake Michigan's northeastern shore, enormous sand dunes crest up to 450 feet above the lake.

- These perched dunes formed atop headlands that are in fact glacial moraines. As erosion has undercut the moraines, boulders and gravel have fallen down toward the lake while wind has blown fine sand up to the headland crests and dropped it there, forming the tall perched dunes.

- Dunes in the park are still on the go: The Sleeping Bear Point Life-Saving Station had to be moved from the point to Glen Haven in 1931 because it was about to be buried by shifting dunes. It's now part of the U.S. Coast Guard Maritime Museum.

Pictured Rocks National Lakeshore

- Pictured Rocks National Lakeshore rims Lake Superior, the largest, coldest, and deepest of the Great Lakes. Like at Sleeping Bear Dunes, the park encompasses dramatic perched dunes, the so-called Grand Sable Dunes, visible from the Log Slide Overlook.

- Stony till left behind by retreating glaciers formed the Grand Sable Banks. Subsequent erosion of the banks when the water level was higher, between about 4,000 and 6,000 years ago, carved the rocky cliff face and freed up sand. Winds blew the sand atop the banks to form the perched dunes.

- The feature that gives this park its name is the 15 miles of multicolored sandstone cliffs that extend along its shoreline. Towering from 50 to 200 feet above Lake Superior, the sands that form the cliffs were deposited in a shallow inland sea that covered what is now northern Michigan more than 500 million years ago.

Apostle Islands National Lakeshore

- The 22 islands of Wisconsin's Apostle archipelago, also on Lake Superior, form the centerpiece of Apostle Islands National Lakeshore. Like the sandstone cliffs at Pictured Rocks, the islands are composed of ancient sandstone bedrock, here about a billion years old. Erosion due to centuries of both wave action and freeze-thaw cycles has carved steep cliffs, some containing sea caves, around the margins of some of the islands.

Apostle Islands National Lakeshore.

- Sea caves develop particularly well in sandstone of the so-called Devils Island Formation. These sandstones were deposited in an environment with many shallow ponds that collected finer-grained sediment in thin beds. The thin-bedded rock that resulted is particularly susceptible to wave erosion at the base of cliffs.

Suggested Reading

Alt and Hyndman, *Roadside Geology of Northern and Central California*.

Frye, *Roadside Geology of Virginia.*

National Park Service, "Coastal Geology in Our National Parks."

Questions to Consider

1. Dunes can form along beaches and in deserts. How might geologists looking at a cross-bedded sandstone formed by ancient dunes distinguish between these two settings?

2. Beaches along the eastern coast of the United States are vulnerable to hurricanes and other tropical storms. Pick a stretch of the coast and research how often it's been affected by a major storm making landfall nearby. Based on the average interval between storms, how long will it be before the next big storm is due?

Lecture 20

Reefs: Virgin Islands, Florida, Texas

In Virgin Islands, Biscayne, and Dry Tortugas National Parks, corals and other reef creatures are helping create new carbonate rock—the limestones and dolomites geologists of the future will map and explore. They're also critically important today, supporting incredibly productive ecosystems, harboring biodiversity, and helping shelter the communities behind them from the brunt of calamitous forces such as tsunamis and hurricanes. Each park differs from the other, and each has natural wonders besides reefs. In addition, Guadalupe Mountains National Park is home to one of the world's largest fossil coral reefs.

Virgin Islands National Park

- The U.S. Virgin Islands sit atop the Caribbean Plate, not far south of a submarine trench that defines the local portion of its boundary with the North American Plate. Subduction of ocean crust beneath more ocean crust at the trench has created volcanic islands, such as Saint Thomas and Saint John.

- Between them, Virgin Islands National Park and the adjacent Virgin Islands Coral Reef National Monument encompass more than half of Saint John, a central island in the archipelago, and nine square miles of surrounding territory. The park also includes most of Hassel Island off Saint Thomas and several small historical parcels on other islands.

- Corals helped build the terrain we walk over when we visit the Virgin Islands, and they're building submerged reefs within the parks today. There are at least five conditions that have to be met in order for reef-building corals to thrive.
    - Corals require sunlight. This is because most corals rely on photosynthesis by algae called zooxanthellae to produce the organic material and energy sources such as glucose that they use to sustain themselves. In return, the coral shelters the zooxanthellae.

- Because corals require access to abundant sunlight, they require relatively clear water. They won't grow in settings that get lots of sediment or in which algal blooms frequently cloud the water, preventing the Sun's rays from reaching the coral for long stretches of time.

- Reef-building corals need relatively warm water in order to survive. They're typically found in settings where the water temperature ranges from 68 to 90 degrees Fahrenheit.

- Reef-building corals grow in saltwater, rather than freshwater or even brackish water. We don't find reefs in large freshwater lakes or estuaries, even if the water is slightly salty.

- Corals need clean water to thrive. Water that is enriched in agricultural runoff and organic waste can cause certain kinds of seaweed and other destructive colonizing algae to cover, displace, and destroy corals.

- We encounter beautiful coral reefs in the national park waters surrounding the island of Saint John, so we know that all five of these conditions have been met.

- The park on land is a beautiful collection of steep-sloped forested mountains that rise to more than 1,000 feet, small bays fringed by fine white-sand beaches, salt ponds, and mangroves. Although reefs have added to Saint John throughout the last few million years, volcanic eruptions, not corals, forged this and most of the other Virgin Islands.

- All of the volcanism that occurred accompanied the opening of a seaway and formation of a spreading ridge between North and South America. The complex dance of the continents has continued to shape the entire Caribbean Basin.

- Quiet periods during which the Virgin Islands were submerged and accumulated limestone were followed by renewed volcanic episodes. Basaltic lavas filled fractures on Saint John and chilled to produce fine-grained black dikes that crisscross older rocks. Flows erupted across the Virgin Islands seascape. During the glacial advance and retreats of the last few million years, the Pleistocene, corals took hold and began building reefs in earnest.

- Reefs come in several varieties, including barrier reefs, fringing reefs, atolls, and patch reefs. Fringing reefs predominate in the Virgin Islands, and they can be found in the waters surrounding Saint John.
  - Fringing reefs resemble barrier reefs in that they parallel the coast, but they're much closer to shore, with relatively narrow, shallow lagoons behind them.

  - Barrier reefs parallel the coastline. But the distance can vary: Some lie many miles offshore across a deep, wide lagoon.

  - Atolls form when fringing reefs encircle islands that either erode or subside away below the water. Even if the seafloor beneath the reefs is sinking, if it happens gradually enough, reef creatures can keep building up their reefs to stay close to sea level. What's left in the end is a beautiful ring of coral reefs surrounding an enclosed lagoon. Atolls often develop around marine volcanic islands as they subside on their way to becoming seamounts.

  - Patch reefs form as isolated patches, typically in quiet, shallow-water environments such as lagoons and sheltered bays.

- Marine biologists have identified about 50 coral species, several of them threatened, in the reefs off Saint John. In a forest on land, different species are adapted to widely varying conditions in the canopy, in the understory, and on the forest floor. This is also the case with complex coral-reef ecosystems, some of the forests of the sea.

- At spots such as Coral Bay and Denis Bay, durable elkhorn and brain corals predominate along the reef crest, the portion of the reef that experiences the highest wave energy. These corals have denser structures that can withstand the churn.

- Less brawny staghorn corals become prevalent as you move away from the crest. On the seaward, or fore reef, and landward, or back reef, areas well away from the crest, you'll find fragile finger corals. You'll also encounter a rich community of fish, urchins, shrimp, sea whips, sea fans, possibly lobsters, and more marine life.

- Reef corals are a colonial species, with individual genetic clones staking places on the reef as polyps and precipitating hard calcium carbonate dwelling places for themselves. It's these shelters, along with limestone muds and fragments, that coalesce to form the solid foundations of reefs.

- But carbonates can precipitate out of clean, shallow waters inorganically, as well. Such inorganic precipitation can create submarine fields of tiny, round nodules called ooids. With time and burial, ooids get cemented together to form oolitic limestones. Some of the exquisite white-sand beaches of Virgin Islands National Park are comprised of ooids that weathered out of oolitic limestones on the island.

Biscayne National Park

- Biscayne National Park begins just south of Miami and includes Sands and Elliott Keys, the northernmost of the line that forms the Florida Keys. The park extends west across Biscayne Bay to encompass a thin stretch of the mainland along the shore and extends east to include a line of offshore reefs: Triumph, Long, Ajax, and Pacific.

- Unlike the Virgin Islands, with their volcanic origins, everything at Biscayne National Park—above water or below it—is underlain by carbonate rocks. The keys themselves—in the park, south to Key West, and on to the Dry Tortugas—formed as coral reefs on the North American continental shelf during times of glacial retreat, when sea level was higher than it is today.

Biscayne National Park.

- The highest point in any of the keys now stands fewer than 20 feet above sea level, so another substantial glacial retreat could put the entire chain underwater.

- Many of the same coral species encountered in the Virgin Islands proliferate in Biscayne's reefs, as well—elkhorn coral, staghorn coral, brain coral, and finger corals. Star corals and finger corals populate the patch reefs within Biscayne Bay. They are better suited than other species to withstand the rapid swings in temperature and salinity that occur in the bay's shallow waters with storm runoff and changing seasons.

- In addition to the reefs, another important ecosystem that is building and protecting the Biscayne landscape is the park's coastal mangrove swamps. Red, white, and black mangroves, along with buttonwood trees, are adapted to survive in saline water.

- Hurricanes inevitably blow in along this stretch of coastline. When they do, the mangrove swamps at Biscayne and elsewhere in the Keys help blunt the erosional force of the storms and mitigate the progress of storm surges—high waters blown inland by powerful winds.

Dry Tortugas National Park

- At the extreme other end of the Florida Keys, 75 miles beyond the end of U.S. Route 1 at Key West, sits a collection of tiny islands called the Dry Tortugas. You'll need a boat or a seaplane to reach these remote islands, which occupy less than one percent of Dry Tortugas National Park. The rest of the park lies underwater.

Fort Jefferson, Dry Tortugas National Park.

- The iconic image of the Dry Tortugas is of the massive Fort Jefferson, a hexagon of brick fortifications constructed during the 19th century to guard the entrance to the Gulf of Mexico. The brick and other materials used to build the fort were all imported from far-off places on the mainland. No sooner did construction begin than the fort's foundations began to crack and fail, sitting as it does on an island that's largely made of sand.

- Three large submerged carbonate mounds underlain by fossil reefs and a number of smaller ones define the underwater landscape at Dry Tortugas National Park. Most of the park's islets sit atop one of these three large mounds. Reef-building coral communities cover less than five percent of the park's shallow waters today, with sea grass and soft coral communities much more extensive.

Guadalupe Mountains National Park

- Just as reefs form today in warm, shallow waters of the Atlantic and the Caribbean, reefs formed about 270 million years ago, during a time called the Permian Period. In what would become the eastern United States, the collision with Gondwana had recently built the Appalachians. But across the continent, an embayment similar in size to the Black Sea filled a low structure called the Delaware Basin.

- Nowhere near the state of Delaware, the basin straddles southeastern New Mexico and western Texas today. It connected to several similar basins and—via a narrow seaway—to the Panthalassa Ocean, the ancestral Pacific, which encircled Pangaea. The thriving Capitan Reef encircled most of the ancient Delaware embayment. At the time it formed, Pangaea sat astride the equator, with the Delaware Basin just south of the line.

- You don't need diving gear to explore the reef: Time has raised it in the middle of the Chihuahuan Desert and transformed it into the limestone mountains exposed to spectacular effect at Guadalupe Mountains National Park.

Guadalupe Mountains National Park.

- Long ago, the Capitan Reef grew upward thousands of feet and outward away from shore, chasing shallow-water sunlight as the surrounding landscape slowly sank.

- Viewed from Guadalupe Pass along Route 62 and 180 south of the main park visitor center, the sheer limestone cliffs of El Capitan and Guadalupe Peak—with the highest summit in Texas at 8,749 feet—suggest the immense scale of the reef.

- A network of marine-creature skeletons, cemented in place where they grew, form the bulk of the Capitan formation limestones exposed in these imposing buttes.

- Unlike what we witness today in the waters off Florida and in the Caribbean, corals weren't the primary architects of the Capitan Reef. Rather, calcareous sponges and algae constructed the framework of the reef, with help from a diverse mix of marine creatures, including small colonial organisms called bryozoans.

- The greatest mass extinction recorded in our planet's fossil record occurred at the end of the Permian Period, with more than 90 percent of Earth's species believed to have perished. Many of the species that thrived in the Capitan Reef exposed at Guadalupe Mountains National Park would vanish forever in this singular extinction event. Based on the fossil evidence, scientists estimate that it took 1.5 million years for the first reefs to reemerge in the early Triassic, after the Permian extinction.

- Scleractinian corals, the foundation of most of today's coral reefs, appeared during the Triassic but only came to dominate reefs much more recently after successive waves of evolution and extinction. While the dominant members of the reef-building community have come and gone over hundreds of millions of years, reefs have remained an important marine ecosystem.

Suggested Reading

Alt and Hyndman, *Roadside Geology of Montana.*

Bryan, Scott, and Means, *Roadside Geology of Florida.*

Frye, *Roadside Geology of Virginia.*

Van Diver, *Roadside Geology of New York*.

Questions to Consider

1. National Geographic has been striving to get many of the world's last relatively pristine marine environments protected. Search online for the Pristine Seas Expeditions and find where some of the world's most pristine reefs are located. Why do you think they're located where they are?

2. List the many threats to reef environments discussed in the lecture. Given these threats, what signs might suggest that a reef is in fact healthy?

Lecture 21

National Marine Sanctuaries and Monuments

America's National Marine Sanctuaries and Monuments are, in many ways, the nation's underwater national parks. The Marine Sanctuaries comprise more than a dozen locations up and down both the Atlantic and Pacific Coasts, plus the Gulf of Mexico, the Great Lakes, Hawaii, and beyond. They encompass some of the country's greatest natural and cultural treasures. National Marine Monuments include some of the largest and most extraordinary protected spaces anywhere on Earth. The National Oceanic and Atmospheric Administration manages these marine protected areas. Like National Park Service sites, these are protected areas that welcome visitors.

Thunder Bay National Marine Sanctuary

- In a bay in the middle of North America, beneath the waters of Lake Huron off the mitt of Michigan, the Thunder Bay National Marine Sanctuary preserves more than 300 known shipwrecks.

- As with the other Great Lakes, thick Pleistocene glaciers filled a natural basin and depressed the underlying continental crust to help create Lake Huron. By about 7,000 years ago, the glaciers had receded enough to leave the lake's basin ice-free.

- Huron contains a staggering number of islands, about 30,000 of them, created by the irregular retreat of the glaciers. With its long shoreline and all those islands, it has plenty of shallows, where most of the lost ships foundered.

Stellwagen Bank National Marine Sanctuary

- About 900 miles to the east, between Cape Cod and Cape Ann at the mouth of Massachusetts Bay, sits the Gerry E. Studds Stellwagen Bank National Marine Sanctuary.

- As at Thunder Bay, Pleistocene glaciers laid the foundation for Stellwagen Bank and for Cape Cod just to the south. The glaciers brought enormous loads of sand, gravel, and larger rocks to their margins and dumped them on the continental shelf at Stellwagen. The pile accumulated over thousands of years to form the banks.

Monitor National Marine Sanctuary

- America's first marine sanctuary consists of a single nautical-mile-diameter column of water in the Atlantic off Cape Hatteras above the wreck of the Civil War Union ironclad USS *Monitor*.

- While portions of the ship have been salvaged and are on display at the Mariners Museum in Newport News, Virginia, the bulk of the wreck remains where it sank 230 feet below the surface, now severely corroded by saltwater and colonized by sea creatures to form a small reef.

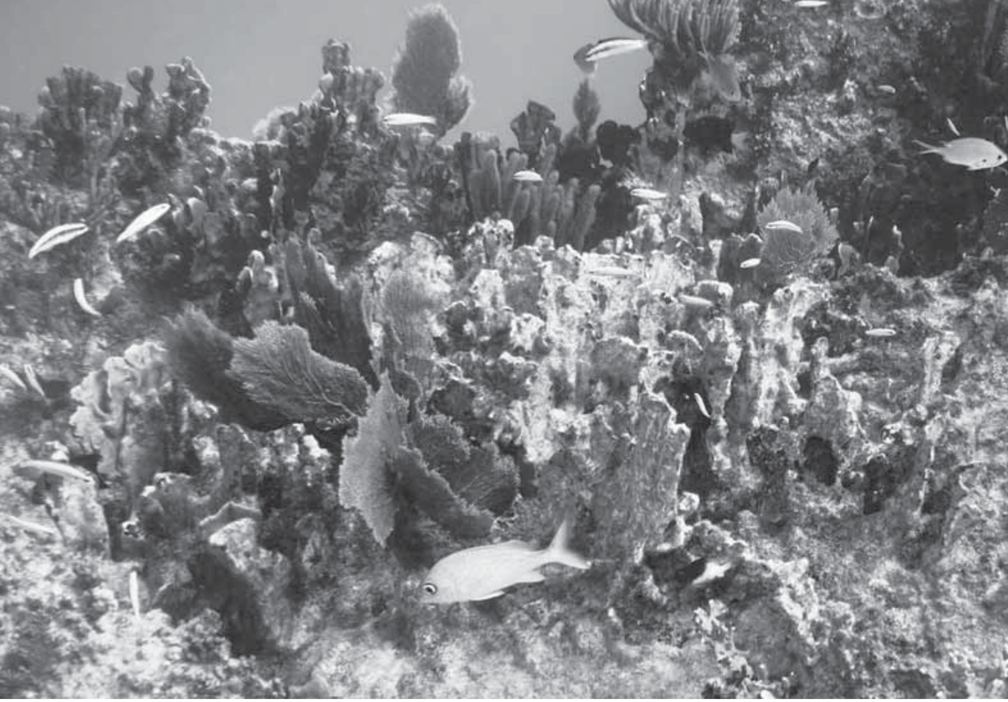
Florida Keys National Marine Sanctuary

- The Florida Keys National Marine Sanctuary includes the waters surrounding all the keys except those contained within the adjoining national parks. In this sprawling protected area lies North America's most extensive living coral barrier reef system—and the third largest in the world.

- Fossil reefs created by corals when sea level was higher than today now form the islands that we call the keys. Amid the shallow waters, we find diverse environments, including living reefs formed by corals—so-called biogenic reefs—and sandy sea-grass beds. Shattered wrecks of the ships of early explorers, of Spain's treasure fleets, and of the vessels that followed lie scattered amid the Florida Keys reefs.

Gray's Reef National Marine Sanctuary

- The Gray's Reef National Marine Sanctuary off Sapelo Island, Georgia, encompasses an entirely different kind of reef community than those found in the Florida Keys. Corals, atypically, don't provide the foundation for Gray's Reef. It's what's called a hard-bottom reef, and the hard seafloor is so well colonized by living creatures at Gray's Reef that the marine habitat is called a "live bottom."



Florida Keys National Marine Sanctuary.

- Sediments shed from the continent cover most of America's southeastern continental shelf, but at Gray's Reef, hard sandstone ledges rise from the surrounding loose sand to depths of about 60 feet. Marine invertebrates attach themselves to the rocky ledges, covering them in a dense profusion of life.

Flower Garden Banks National Marine Sanctuary

- Off the Texas and Louisiana coasts in the Gulf of Mexico, corals and other marine creatures have constructed lush reefs atop the East and West Flower Garden Banks and Stetson Bank. Together, these occupy the Flower Garden Banks National Marine Sanctuary. Loggerhead turtles, whale sharks, manta rays, and many other reef animals make their homes in the protected area.

- Although these are traditional coral reefs, they've established themselves atop extraordinary rises. These rises—the banks themselves—result from buoyant salt flowing under pressure that has collected in expanding pockets underground. The structures the rock salt forms are called diapirs, or simply salt domes. Salt domes populate much of the seafloor of the northwestern Gulf of Mexico.

Olympic Coast National Marine Sanctuary

- Turning to the Pacific, we come to the Olympic Coast National Marine Sanctuary. Krill, marine mammals, fishes, and seabirds thrive in the sanctuary, which is one of North America's most productive aquatic ecosystems.

- This sanctuary, which is the submerged counterpart to Olympic National Park, also encompasses miles of pristine, undeveloped coastline flourishing with kelp and tide pools.

Cordell Bank National Marine Sanctuary

- A seamount off California's Point Reyes peninsula sits at the center of the Cordell Bank National Marine Sanctuary. A little more than four miles wide by nine miles long, the submerged mountain rises to within 115 feet of the ocean's surface at the edge of the continental shelf.

- Dolphins, sea lions, endangered humpback and blue whales, fur seals, elephant seals, and numerous other marine mammals frequent the rich waters of Cordell Bank. Seabirds throng above the bank, plucking fish from the water. Pelagic (open-ocean) jellies, marine sunfish, and sea turtles ply the waters above the bank. Benthic (bottom-dwelling) invertebrates, such as sponges, corals, sea squirts, and anemones, cover the shallow seafloor.

Gulf of the Farallones National Marine Sanctuary

- Adjacent to Cordell Bank, the Gulf of the Farallones National Marine Sanctuary encompasses the gulf itself, which stretches from the California coast to the Farallon Islands, as well as deeper waters above the Farallon Escarpment on the continental slope. It also includes the familiar waters near the Golden Gate Bridge at the mouth of San Francisco Bay.

- In 2015, the size of both sanctuaries more than doubled. The Gulf of the Farallones sanctuary now completely embraces Cordell Bank to the north, east, and south.

Monterey Bay National Marine Sanctuary

- Just to the south, the Monterey Bay National Marine Sanctuary spans 276 miles of coastline—that's about a quarter of the California coast—and an area larger than Yellowstone National Park. Its diverse ecosystems include a dense kelp forest in Monterey Bay that's as complex and productive as many mature forests on land, with some of the kelp plants rising as tall as trees.

- There are also more than 700 known prehistoric sites, more than 1,200 reported shipwrecks, and even the 1935 wreck of a dirigible that carried small planes as a flying aircraft carrier. And the largest canyon anywhere off the coast of North America is here, the spectacular submarine canyon of Monterey Bay.

Channel Islands National Marine Sanctuary

- Continuing down the California coast, Channel Islands National Park has an aquatic counterpart in the Channel Islands National Marine Sanctuary. The sanctuary includes the encircling rings of water from mean high tide to six nautical miles offshore of Santa Barbara, Anacapa, Santa Cruz, Santa Rosa, and San Miguel islands.

- Here, the islands sit on a sheared block of continental crust along the California coast, where lateral motion of plates has rotated the block of crust like a cog, extending a line of mountains and hills westward into the sea.

Hawaiian Islands Humpback Whale National Marine Sanctuary

- About five and a half hours by jet west-southwest of southern California, we arrive at the Hawaiian Islands Humpback Whale National Marine Sanctuary. It protects critical habitat for the thousands of humpback whales that visit the islands from late December to May of each year during their 6,000-mile annual

Monterey Bay National Marine Sanctuary.

migrations. They breed, give birth, and nurture calves here before returning to the colder waters of Alaska for the summer.

- Hawaiian monk seals, spinner dolphins, sea turtles, sea grasses, both shallow and deep corals, sea birds, and more also make a home in these waters.

Papahānaumokuākea Marine National Monument

- Continuing westward along the Northwestern Hawaiian Island Chain, we find America's first marine national monument, which was created by presidential proclamation under the Antiquities Act—the same piece of legislation that Theodore Roosevelt and subsequent presidents used for initial protection of so many American parks on land, including the Grand Canyon.

- This one "monument" is larger than all the national marine sanctuaries combined. This enormous preserve includes nearly 140,000 square miles of ocean and encloses islands, atolls, banks, and shoals atop seamounts.

National Marine Sanctuary of American Samoa

- South of Hawaii, in the South Pacific Ocean, is the National Marine Sanctuary of American Samoa, which has the only true tropical reef in the U.S. Marine Sanctuary system. Originally established in 1986 to protect the reef in a quarter-mile square area, it was expanded in 2012 across parts of four islands, a seamount, and an atoll to become the largest of the marine sanctuaries, at more than 12,500 square miles.

- It occupies Fagatele and an adjacent bay at the southernmost tip of the island of Tutuila. The sanctuary extends to Rose Atoll, also known as Muliava, one of the world's smallest atolls. Also included is the nearby Vailulu'u Seamount.

Pacific Remote Islands Marine National Monument

- Pacific Remote Islands Marine National Monument—the largest marine reserve in the world, three times the size of California—is located between American Samoa and Hawaii and straddles the equator.

- National Geographic Explorer and marine conservationist Enric Sala led an expedition here to document the rare, pristine coral environments found at places such as Kingman Reef and to raise awareness of the need for protection. The effort helped prompt declaration of the national monument by President Bush in January of 2009, followed by its sixfold expansion by President Obama in 2014.

- The monument now encompasses almost half a million square miles, making it larger than all the land-based national parks combined. It encompasses seven islands and atolls, plus all the territory in between, and includes Wake Atoll, which might be the oldest living coral reef in the world.

Marianas Trench Marine National Monument

- The Marianas Trench Marine National Monument, the deepest marine reserve in the world, encompasses portions of the Marianas Trench, some of the deepest waters on the planet. The sanctuary also protects volcanic islands, undersea volcanoes, and thermal vents.

- Maug Island is a volcanic crater that's one of the few places on Earth where life based on thermal vents coexists with life based on photosynthesis.

- Just outside the park, in territorial waters of the Federated States of Micronesia, lies the Challenger Deep. At 6.83 miles, it's the deepest place in any of the world's oceans. It's some of the planet's oldest seafloor at 170 million years.

Suggested Reading

Chadwick, "Blue Refuges."

National Oceanic and Atmospheric Administration, *National Marine Sanctuaries*.

Questions to Consider

1. The U.S. Geological Survey reports that sea level was about 410 feet lower than it is today during the last Pleistocene glacial maximum. Find the 400-foot depth contour on maps of coastal bathymetry to get a sense (not correcting for shifts in land elevation) of how much more of the continent was exposed at that time.

2. The Papahānaumokuākea Marine National Monument protects nearly 140,000 square miles of marine environments, an area larger than all of the U.S. national parks combined. Based on the areas of U.S. states, which combinations of states could fit within the area of the national monument?

Lecture 22

Acadia's Highlands and Islands

When the Sun rises on the continental United States, you can see it first at Acadia National Park, which centers on what is the second-largest island on the Eastern Seaboard of the United States. The rocks of coastal Maine reveal a gripping legacy of lost oceans, harrowing collisions, epic mountains, furious volcanoes, and icy glaciers. Evidence of all this and more is etched into the storied and storytelling islands and highlands of Acadia.

Acadia's Volcanic and Sedimentary Rocks

- At 1,530 feet, the summit of Cadillac Mountain—the highest peak on the U.S. East Coast—offers splendid vistas of the rocky archipelago that comprises much of Acadia. Seven summits in the park rise to elevations greater than 1,000 feet.

- What made these mountains are the same continent-on-continent collisional forces that built all the Appalachian Mountains, including Shenandoah and the Great Smoky Mountains. The same forces built mountains an ocean away, too, across the Atlantic in Ireland, Britain, and Scandinavia, before the Atlantic had opened to divide them.

- The entire mountain is made of coarse-grained granite. It's a pluton: an igneous intrusion that cooled slowly deep underground. The plutons at Yosemite—and all of the Sierra Nevada range—are less than half as old as the plutons at Acadia, but Yosemite's landscapes in the west and Acadia's in the east reflect a multitude of similar processes, a common history offset by a few hundred million years.

- Cadillac Mountain and other granitic rocks at Acadia didn't just arrive where we find them today. They intruded into yet older rocks beneath the ground, the so-called country rock for Acadia's plutons. The oldest of these, which can be found along the North


Acadia National Park.

Shore of Mount Desert Island, is a sequence of rocks called the Ellsworth Schist.

- These rocks began their lives as fine sediments derived from other rocks, along with volcanic ashes and tuffs. The rocks then got buried, heated, and subjected to high pressures. The experience transformed them principally into two kinds of metamorphic rock. The first type is layered, or foliated, schists full of flaky silver micas that break apart along parallel planes; the second type is denser gneisses.

- Schists and gneisses are metamorphic rocks. Other quite old rocks that predate the plutons at Acadia include the Bar Harbor formation of gravels, sandstones, and siltstones and the Cranberry Island series.

- Another group predating the plutons is the Cranberry Island series of volcanic and sedimentary rocks. These record an era of volcanism due to the subduction of ancient seafloor, akin to what's happening today in Cascadia and along Alaska's Aleutian coast and the Gulf of Alaska.

- All of these various older rock units accumulated ahead of a microcontinent called Avalonia, which might have split off from the proto-African continent of Gondwana and was driving northeast on a collision path with Laurentia—the predecessor to North America.

- Avalonia was an exotic terrane that got sutured onto proto-North America. As Avalonia came driving into and onto Laurentia, its rocks were folded, some of them got buried, and very tall mountains rose. This Acadian mountain-building event, or orogeny, was the first of three such events that produced the Appalachian Mountain Chain and built the global supercontinent of Pangaea.

- The convergence and ultimate collision of the microcontinent of Avalonia with the macrocontinent of Laurentia also created the granitic magma that formed and filled Acadia's plutons. As the plutons intruded to form Acadia's granitic core, pieces of the old country rock fragmented, broke off, and fell into the molten magma.

- The result was, and is, a bulls-eye ring called the shatter zone that is exposed in the southern and eastern portions of Mount Desert Island. Up to a mile wide, the zone forms a boundary between coarse-grained granites of the core and the park's much older metamorphic, sedimentary, and volcanic rocks.

The Rocks of the Schoodic Peninsula

- The Schoodic Peninsula is located up the Maine coast to the east of Mount Desert Island, a short hop across Frenchman Bay. The rocks of this peninsula also form an integral part of Acadia National Park and showcase an important chapter of the park's story.

- At Schoodic Point, a fine-grained gray and black basaltic rock called diabase fills fractures in the massive pink-and-white granite bedrock. Where the incessant ocean surf has had an opportunity to chisel away at the rocks along Frenchman Bay, the diabase has preferentially worn away to leave yawning slots in the granite.

- Like on Mount Desert Island, the granites of Schoodic Point resulted when Avalonia's incoming edge finished devouring an ocean and piled up and over the edge of the Laurentian continent. Rocks at and below the contact between the plates, subjected to intense frictional heating, partially melted to generate magmas that rose to become granite plutons.

- These granites, exposed now at Schoodic Point, shrank and fractured as they cooled underground, creating conduits called joints. Basaltic magmas poured into these joints from below as they opened.

- This fiery-hot liquid of basalt magma filling the vertical fractures then chilled and solidified to become the diabase we find today—diabase dikes, that is, crossing the granite terrain. And this happened multiple times as the granites continued to cool and shift and shrink, causing new dikes to cut across earlier dikes and to be crossed in turn by later ones.

- Near the margins of the dikes, intense heat from the intruding magma led to a phenomenon called contact metamorphism. When searing-hot magma pours through a crack in another rock, it essentially blisters the rock it touches. And it can happen fast.

- Mineral grains within the granite—baked by proximity to fresh, red-hot molten magma—became recrystallized into higher-temperature forms along a narrow band on either side of the dikes, altering the color and texture of the rock. That's the blister. The closer to the dike, the more severe the alteration, while a short distance away we find no alteration.

- Even as the intruding magma altered the country rock by heating it up quickly and intensely, the granite chilled the magma immediately adjacent to it the most quickly, causing it to freeze before sizable crystals could grow in it. So, we see the finest mineral grain textures right next to the granite, where the magma chilled most rapidly, and somewhat coarser textures toward the middle of the dikes.

- After all the tectonic mountain-building and intrusive igneous activity had metamorphosed some of Acadia's oldest rocks and created the park's plutons, Pangaea split apart. As it rifted open, some of the exotic Avalonian terrane remained on the western shore of the brand new Atlantic Ocean. Some of it traveled east with Ireland, England and Wales, the Iberian Peninsula, and northern Africa.

- For the next 200 million years, the mighty mountains that loomed above Acadia weathered and eroded. As they did, the buoyant roots of the mountains rose. It took ages, but the plutons and metamorphic basement rock finally reached the surface.

Pleistocene Glaciers

- North Bubble and South Bubble sit side by side in Mount Desert Island's eastern lobe along the north shore of Jordan Pond. The Bubbles are classic roches moutonnées—"wooly," or mutton, rocks that have been completely overridden by large glaciers.

- As the Pleistocene glacier ice made its way along the upstream, northern faces of the Bubbles—headed south toward lower ground—it smoothed, contoured, and polished the rocks.

- This was not the case on their downstream surfaces: In the ice eddy of the Bubbles, ice under pressure transformed into liquid water that penetrated tiny fractures, or joints, in the rock. As it refroze within them, it wedged the joints open, prying and loosening pieces of granite on this down-ice, or leeward, slope. Ice froze around these pieces and plucked them away from the Bubbles as it kept traveling south.

- During successive Pleistocene glacial advances, glacial ice more than 1,000 feet thick completely covered Acadia's granite mountains, which crest at 872 feet (North Bubble) and 766 feet (South Bubble).

- Atop South Bubble, we also come across one of the most striking glacial features at Acadia: Bubble Rock. This huge, rounded granite boulder sits precariously at the edge of a sheer cliff. Bubble Rock is a glacial erratic, one of many large boulders strewn about Acadia. The glacier plucked it from whatever pluton Bubble Rock rode in on, dragged or carried it along to its improbable perch, and then melted away and left it here.

- Another distinguished roche moutonnée that has become a must-see Acadia destination is the Beehive. It's situated near Mount Desert Island's southeast shore south of Champlain Mountain and north of Sand Beach.

- Glaciers have altered the entire landscape of Acadia National Park. Tectonics transported the Avalonian terrane to the coast of Maine and collision created the granite plutons, but ice sculpted the raw rocks into the beautiful forms we see. Ice cleared away pesky soils, exposing bare rock for our geological contemplation and enjoyment. Ice swept away exfoliating layers from the park's highest domes, helping transform these rugged, bald tops into textbook mathematical arcs.

- Grinding glaciers hollowed out U-shaped basins for a series of parallel ponds, running north-south: Seal Cove Pond, Long Pond, Echo Lake, Jordon Pond, and Eagle Lake. Where glaciers left tall piles of debris as moraine dams—like at Jordan Pond and Long Pond—their surfaces sit higher than in the other lakes.

- What cleaves Mount Desert Island practically in two, dividing it into its eastern and western lobes, is the trough of Somes Sound. Five miles long, glacially scoured, and flooded from one end by the sea, the sound resembles a fjord in many ways and was once mistaken for a fjord.

- The Pleistocene glaciers left their sculptor's signature all over Acadia's granite highlands, in the form of the linear grooves called striations and the bite-like indentations called chatter marks. Similar grooves and gouges are in the Yosemite highlands. At roughly the same times in both places, during Pleistocene glacial advances, the granite was etched as glaciers dragged rocks across the underlying bedrock when they flowed over it.

The Acadia Shoreline

- The sea put the finishing touches on Acadia National Park. The retreat of the last of the Pleistocene glaciers over the last 20,000 years caused sea level to rise, inundating the Acadia shoreline.

- Rising water transformed what had been a number of connected pieces of land near the coast into a multitude of separate islands. It made a harbor at what is now Bar Harbor. It brought in the surf so that it could continue its work of hammering away on the rugged and rocky coast.

- The Maine coast continues to rise as well, rebounding from its burial beneath the weight of thick sheets of ice. We find some old, abandoned shorelines perched above the current coast, where they've risen with the rebounding land from the sea.

- Rocks characterize nearly all of Acadia's stark and beautiful shoreline. Granites weather and break to make beaches of spherical cobblestone. Where the shatter zone intersects the shore, we typically encounter jumbles of large, angular rocks. Elsewhere, siltstones and schists form flattened beach rocks.

- Acadia National Park's most unexpected feature might be the sand found in a few of the park's protected coves. Here, we encounter small pocket beaches—gemlike counterpoints to this park's many stonier shores.

- If you drive slightly north and mostly east for 10 hours, you can reach Cape Breton Highlands National Park in northern Nova Scotia. Almost three times the size of Long Island, Cape Breton Island is the easternmost point of what French colonists meant by

Harbor, Acadia National Park.

"Acadia." Here, steep cliffs plunge from a forested and canyon-carved plateau to the blue waters of the Atlantic.

- Three or four ancient continents contributed to the creation of this single island. The island, like all of Nova Scotia, came together with Pangaea. But when Pangaea later broke apart, Cape Breton stayed in one piece, a hybrid island with an intercontinental pedigree.

- Rising from 1,000 to more than 1,500 feet, the highlands plateau covers more than two-thirds of the national park. It is yet more of the Appalachians, the seam along which Europe, North America, and Africa had stitched themselves together more than 300 million years ago.

Suggested Reading

Caldwell, *Roadside Geology of Maine.*

Mitchell, "Autumn in Acadia National Park."

Questions to Consider

1. John D. Rockefeller Jr. underwrote the construction of carriage roads and bridges made from local materials at Acadia National Park. What are the bridge facings made from, and why is this appropriate to the park?

2. Describe the similarities and differences between the granitic terrains at Acadia and Yosemite National Parks.

Lecture 23

The Dakota Badlands

In the badlands of North and South Dakota, erosion in a relatively dry region was able to carve flat-lying sedimentary strata into fantastic forms. This is the landscape that helped transform Theodore Roosevelt into an ardent conservationist of wild places and a crusader for the national parks. As President, Roosevelt would personally create or sign into law 5 national parks, 18 national monuments, 51 federal bird reserves, 4 national game preserves, and 150 national forests—along with the U.S. Forest Service that manages them.

Theodore Roosevelt National Park

- In the western Dakotas of the Great Plains is a magnificent landscape that helped inspire Theodore Roosevelt to conserve America's wild lands as national parks and monuments. The Dakota Badlands are the product of deposition, uplift, and erosion in the heart of the North American continent—its relatively stable core, the ancient craton.

- In Theodore Roosevelt National Park, only the stone foundation of Roosevelt's Elkhorn Ranch survives, but the true foundation of this untamed wilderness—the landscape itself—persists much as Roosevelt himself experienced it. The contours of these weirdly weathered bluffs and buttes helped shape the character of America's 26th president and inspire his love for natural places.

- The term "badlands" originally came from the region's native Lakota people, who spoke of *mako sica*—or "land bad"—due to lack of water and extreme temperatures. But this landscape also exemplifies what geologists mean by badlands in a more general sense: They are exposed, incised, and horizontally bedded, and the exposed rock layers are primarily sedimentary.

- The earliest sedimentary layers we see date from the last years of the dinosaurs, about 75 million years ago. At that time, global sea level was high, and the interior of the continent east of the Rocky Mountains had flexed downward. The Western Interior Seaway had flooded the land east of the Rocky Mountains from the Arctic Ocean to the Gulf of Mexico. Intermittent deposition continued until about 25 million years ago.

- By contrast, the erosion in the Badlands has been underway for only about half a million years. Traveling about the park, we encounter a number of amazing features associated with the many geological processes at work here.

- While most of the park's sedimentary strata lie flat, there are noteworthy exceptions. We can view one of these from the north unit's Slump Block Overlook, where erosion of the badland slopes has caused a large block of rock to begin rotating as it slides downslope. There are numerous examples of such slumping throughout Theodore Roosevelt National Park.

- From the overlook at Cannonball Concretions Pullout, we can view several large, spherical examples of the concretions that are common in the park. The Cannonballs weathered out of a specific set of rocks within the park, called the Fort Union Group. These rocks were originally deposited by streams carrying sediment from the Rocky Mountains as they rose to the west of the Dakotas. They also include layers of ash from volcanoes associated with the rise of the mountains. As the softer matrix of these rocks weathers and erodes away, resistant concretions emerge and collect at the bottom of the bluffs.

- Similar conditions to those that produced some of the park's concretions also infused the limbs and trunks of trees growing on ancient floodplains where the park's rocks were first forming. Their limbs and trunks became infused with silica after they were buried in fine clays and silts. Like concretions, chunks of petrified wood now weather out of the rock as it erodes away.

- On the Petrified Forest Plateau, we encounter a number of particularly strange-looking hoodoos. These are eroded rock and

Theodore Roosevelt National Park.

sediment towers topped by a resistant caprock, which is often a dense sandstone concretion. Softer rocks below have weathered out to leave strange spires, pinnacles, and toadstool-like hoodoos.

- The environments in which many of the sedimentary rocks that form the park's badlands formed were generally much warmer and wetter than the park today. Organic material accumulated in forests and peat bogs. Burial, compression, and time have transformed this organic matter into a low-grade coal called lignite. You can see outcropping brown and black bands of lignite throughout the national park.

- The Bentonitic Clay Overlook highlights blue beds derived from volcanic ash that contain a mixture of clay minerals called bentonite. One of the most important features of bentonite is that it swells to many times its original volume when it comes in contact with water. The expansion and contraction of this mineral helps pry rocks apart and contributes to the exceptionally fast rate at which the badlands erode.

- From the Edge of Glacier Pullout in the north unit of the park, you can hike out into a field to find boulders carried hundreds of miles from Canada before they were dropped where they lie by continental glaciers. These boulders are glacial erratics. The course of the Little Missouri River, and the Missouri River to which it flows, were both influenced by the advance of the Pleistocene glaciers.

- Water eroding and reworking the land is the dominant geological force at Theodore Roosevelt National Park. Beneath the Oxbow Overlook, the Little Missouri River has created a meander loop on its floodplain. As a natural part of the river's evolution, it eventually will find a more efficient path across the loop it has made beneath the Oxbow Overlook. When it does, it will abandon the loop, leaving it to become an oxbow lake.

Badlands National Park

- South Dakota's Badlands National Park includes some of the nation's most spectacular badlands terrain, as well as the mixed-grass prairie landscapes that typify this part of the Great Plains. One striking, must-see feature of the park and one of the first that most visitors encounter is the erosional escarpment, or cliff, known as the Wall, which is a few hundred feet tall and runs for scores of miles through the park's easily accessible north unit.

- Atop the wall and extending to the north of it is the Upper Prairie, an expanse of grassland that is nearly flat. The weathering and erosion of the badlands is eating into the Upper Prairie, causing the Wall to migrate to the north over time.

- South of the Wall and about 150 to 200 feet lower sits a grassy pediment, or slope, interrupted by the channels of intermittent streams and so-called sod tables. The sod tables are isolated remnants of the strata that underlie the Upper Prairie. These were left behind as the Wall cut its way northward and will eventually erode away.

- Differential erosion rates contribute to the countless strange forms that the badlands take in the park. Loose volcanic ash layers can erode up to six inches per year, and mudstones about an inch. The resistant sandstones and concretions that cap many of the formations, by contrast, might erode at only about one inch every 500 years. They resist weathering and persist, while the ash and rock beneath them get eaten away. Finally, inevitably, chunks of the caprock fall, and the process continues.

- The stratigraphy exposed at Badlands National Park dictates many of the features of the current landscape. It also records a geological story of the evolution of this portion of the North American continent—from submerged to exposed, from quiescent to volcanically ashen. From oldest to youngest, the base of the sequence to the top, we have the seabeds of an ancient ocean, soils from the past, rivers and forests, mudflats, and volcanism.
    - The Pierre Shale was deposited as black muds during the final years of the Western Interior Seaway, which was called the Pierre Seaway during that time.
    - Yellow Mounds is a thick layer of old soil created after the Pierre Sea was gone, exposing the marine muds to weathering and erosion.
    - The gray Chadron Formation was created between about 37 and 34 million years ago as floodplain deposits from rivers draining the Black Hills.
    - The tan Brule Formation forms the bulk of the Wall.
    - The pale, mostly fine-grained rocks of the Sharps Formation were deposited between about 30 and 28 million years ago. The bottom-most layer of the Sharps Formation is a thick, white volcanic ash layer called the Rockyford Ash, which marks the divide between Brule below and Sharps above.
- The most rugged of the fantastic eroded hillsides and buttes in Badlands National Park are etched into the upper layers in this

Badlands National Park.

sequence—in particular the savannah and volcanic layers of the Brule and the Sharps Formations.

- These contain examples of many of the fabulous badlands features at Theodore Roosevelt National Park: deeply gullied and colorful slopes; hoodoos and toadstool rocks; pinnacles; and bentonite clay layers that expand and contract with the weather, accelerating erosion.

- The fact that the youngest rocks remain atop the sequence, with progressively older ones as you descend deeper and deeper through it, illustrates one of the most fundamental rules of geology: the law or principle of superposition, which states that the oldest strata (rocks) appear on the bottom while the youngest appear on top.

Mount Rushmore

- Theodore Roosevelt presides at Mount Rushmore, along with George Washington, Thomas Jefferson, and Abraham Lincoln. At Mount Rushmore, the sedimentary layers found at the Badlands are gone, exposing Black Hills rocks that are more than a billion years old. The rock into which they're carved is granite. The lines that give their faces a time-weathered appearance are dikes.

- The Black Hills is an elliptical-shaped region centered on very old metamorphic and igneous rock. Uplift of the hills, which are in fact mountains, began about 70 to 75 million years ago with the Laramide orogeny that raised the entire Rocky Mountain range.

- Outward from the old rock is a ring of limestone, which along its southern end is home to Wind Cave National Park. A thin outer ring of the Black Hills is a soft and eroded shale known as the Red Valley, which runs all the way around the Black Hills.

- Near the center of the old rock, not far from Mount Rushmore, sits Harney Peak, the tallest in South Dakota at 7,242 feet. Both mountains are capped by tough Harney Peak granite.

- About 1.7 billion years ago, the granite was injected as a fiery molten blob into even older sedimentary rocks. Contact led to metamorphism, as nearby rocks were scorched to forge an aureole of schist and quartzite.

- Fractures opened within the granite as it cooled and after. Those fractures were filled with additional silica-rich magma that crystallized into light-colored dikes. These ancient rocks rose to the surface over millions of years as overlying rocks were eroded away, and then they were reburied under thousands of feet of sedimentary rock during Paleozoic and Mesozoic time.

- The Laramide mountain-building event that raised the Rocky Mountains to lofty heights west of the Dakotas starting 70 million years ago also elevated an oblong bulge that would become the Black Hills. As the overlying cover of sedimentary rock eroded away once more from the interior of the bulge, the Harney Peak granite emerged to define the summits of the tallest of them, including Mount Rushmore.

Mount Rushmore.

Suggested Reading

Eliot, "Reefs in a Prairie Sea."

Gries, *Roadside Geology of South Dakota*.

Questions to Consider

1. Gullies and eroded hillsides and other sites where rapid erosion is occurring often resemble badlands, albeit on a smaller scale. Have you encountered locations near your home that bear a resemblance to the Dakota Badlands?

2. The coal-seam fires that produce scorched "scoria" layers at Teddy Roosevelt National Park aren't unique to the park. Learn about the condemned town of Centralia, Pennsylvania, where an underground coal fire that was probably accidentally ignited has been burning for more than 50 years.

Lecture 24

The Grand Canyon's 2-Billion-Year Staircase

From the rim of the Grand Canyon, we behold rock layers in a Grand Staircase that began almost 2 billion years ago—that's nearly half of the 4.5 billion years since our planet was born. Just as they paint the landscape, the rocks and the fossils they contain paint pictures of bygone eons in the grand Earth story, of ancient oceans and distant shores—distant in time, at least, if not in space.

The Grand Canyon

- A mile deep, 9 to 18 miles wide, and 277 miles long, the Grand Canyon, carved by the Colorado River, might be the most celebrated geological feature in the United States and among the most celebrated on Earth.

- The Colorado River and its tributaries are the drainage system for the entire Colorado Plateau, a major geographic province of 130,000 square miles that encompasses no less than 10 national parks. The Grand Canyon is in the southwest corner of this vast Plateau, which has provided a remarkably stable home to the Canyon for more than 600 million years.

- However, as we survey the canyon, we view deep patterns in its supremely chiseled intricacy. Like at Badlands and Theodore Roosevelt National Parks, though on a much more enormous scale, horizontal planes tend to divide the colorful sequence of rocks exposed within the canyon.

- We can follow imposing cliffs and gently sloped platforms called benches as they trace their path along the canyon's walls. The overall impression created by these cliffs and gentle benches as they ring freestanding buttes (tall hills with steep sides and flat tops) and mesas (larger table hills and table-shaped mountains, typically wider than they are tall) is of many staircases.

The Kaibab Limestone

- The story of how the rocks of the Colorado Plateau came to the Grand Canyon is a chronicle that spans nearly half of Earth's history. Throughout the sequence, we encounter gaps in which rocks that might have provided glimpses into hundreds of millions of years of Earth's history have simply weathered away, later to have their place taken by younger rock layers—or the rocks were never laid down in the first place, leaving gaps called unconformities.

- The Kaibab Limestone was deposited about 270 million years ago in the Permian Period, a time of early biodiversity that created all this limestone and that ends with the greatest of the five mass-extinction events in Earth's history, the Permian extinction.

- The giant mountains that would erode to become Shenandoah and Great Smoky Mountains National Parks were still rising. Looking out across the canyon, we can trace the gray, layered cliffs of the Kaibab on both near and far walls. It underlies the far North Rim as well as the South Rim.

- The outcrop of the Kaibab Limestone near the rim has a rough, knobby texture due to numerous hard nodules within it. The nodules are made of chert, a microcrystalline form of silica with a chemical composition similar to that of quartz.

- Chert has a biological origin, and most of the chert nodules contain fossils, although some of the fossils are so completely encased that they're not visible. In addition to fossils of shelly creatures called brachiopods, you can find fossils of horn corals, stems of sea lilies called crinoids, small treelike and netlike fossils of bryozoans, and fossil sponges.

- It's the sponges that put the chert in the Kaibab Limestone. While most of the other fossils were made of softer calcium carbonate, the sponges contained a framework of small interconnected rods made of opaline silica. Shortly after the sediments were deposited,

The Grand Canyon.

the opaline silica dissolved and then reprecipitated as chert, which formed the hard nodules.

- The presence of these nodules near the top of the Kaibab Limestone also has played an important role in the development of the Grand Canyon. Chert's hard nodules make the Kaibab layer particularly resistant to erosion.

- Younger rocks deposited atop the Kaibab have eroded away on both sides of the canyon, but this erosion stopped when it reached the hardened, knobby surface of the Kaibab Limestone. So, this rock crowns the stratigraphic sequence on both walls of the canyon.

- The marine creatures in the Kaibab Limestone grew together in a warm, shallow sea during the geological period called the Permian. About 270 million years ago, standing near the South Rim of the Grand Canyon, we would have been offshore, underwater, at the edge of a sea—indeed, off the western edge of the supercontinent Pangaea.

The South Kaibab Trail

- The deeper we descend into the canyon along the popular South Kaibab Trail, the farther back we travel in time. We begin by traversing a series of switchbacks, which had to be cut into steep cliffs during the 1920s by the National Park Service in order to make the trail.

- There is also the Bright Angel Trail to the west, which descends through the Kaibab Limestone and onto the bottom of the canyon. Bright Angel is a natural trail that follows the line of the Bright Angel Fault, which had disrupted the cliff enough to create a natural trail.

- The South Kaibab trail opens up when we reach the gentler slopes of the Toroweap Formation. Mudstones and salt layers called evaporites predominate in the Toroweap, along with a few limestone layers. These were deposited before the Kaibab Limestone, about 273 million years ago.

- The gypsum in the evaporite layers is less dense than most of the minerals that form the mudstones and limestone bands. As a result, the salts don't remain flat but instead break their way upward through the overlying layers. You can see the migrating salt bursting its way up through overlying rock layers in some of the exposures beside the trail.

- The mudstones and evaporites mixed together suggest that Toroweap rocks formed in an arid tidal flat environment. Fossils we find within the formation bear out this conclusion. So, before the sea level rose or the land sank beneath the sea here to create the Kaibab Limestone, we would have been right at about sea level on the continent's edge.

- We continue out the broad slope of the Toroweap, making our way back in time another few million years. Finally, we come to Ooh-Aah Point, a spectacular view of the Grand Canyon, and switchbacks that lead down a sheer sandstone cliff called the Coconino Sandstone, which forms a wall that is visible all around the canyon.

- Within the Coconino, we see wedges of steeply angled beds—one atop another atop another. From side to side, they interfinger with one another across the bright cliff face. These are called cross-beds. They are the product of large desert quartz-sand dunes, akin to those farther north at the national parks of Great Sand Dunes and Kobuk Valley.

- The scale of this desert was much larger, too; it spanned much of the region now occupied by the Colorado Plateau. Had we been on hand as the Coconino cliff face rocks were getting made 275 million years ago, we would have been deep in the midst of a Sahara-style desert.

- At the base of the Coconino, the trail traverses a broad, red, muddy bench. The soft, fine-grained sedimentary layers that form this bench go by the name Hermit formation, or simply the Hermit shale. About 280 million years ago, this was a broad coastal plain,


Kaibab Trail.

crossed by ancient rivers and arroyos—channels for ephemeral rivers in dry regions that fill only during occasional floods. It was flooding that deposited the muds, silts, and fine sands that would become the Hermit shale in their banks, on their floodplains, and in their channels.

- Continuing down the South Kaibab Trail, we segue from the Hermit shale into the Supai Group. Unlike the rocks above, which tell a fairly compact story spanning roughly 10 million years, rocks of the Supai Group straddle about 30 million years, from about 315 to 285 million years ago.

- As we work our way farther down through the Supai and back in time, we see cross-bedded sandstones, sandy limestones, and siltstones mixed with limestones. Abundant iron oxide distributed through these rocks colors them mostly a rusty red.

- At Skeleton Point, the trail leaves the Supai Group and begins its steep descent of the thick Redwall Limestone, which formed on the bottom of a shallow tropical sea about 340 million years ago. Like the Kaibab Limestone perched high above it near the canyon's rim—and 70 million years later in time—the Redwall contains the fossils of numerous marine creatures, many of them preserved in cherty nodules.

- At the base of the Redwall Limestone, we pass through another limestone, the Temple Butte Limestone. Despite both being limestones, as we step across the boundary from Redwall to Temple Butte, there is an unconformity: We step back perhaps 50 million years.

- The Temple Butte was deposited beginning roughly 385 million years ago, and then it elevated and eroded, and then deposition resumed with the Redwall tens of millions of years later.

- At the base of the Temple Butte Limestone, we cross another unconformity. This gap in the rock record spans more than 100 million years. Whatever rocks were deposited during this time are gone. Significant erosion took place, creating cliffs and valleys atop the underlying Tonto Group before deposition began again.

- From top to bottom, the Tonto Group includes three formations: the Muav Limestone, the Bright Angel Shale, and the Tapeats Sandstone. Together, they record a process called marine transgression—the arrival and deepening of an ocean as it lapped its way up onto the land from the west.

- Running the film backward as we make our way down into the canyon, we pass from calcium carbonate muds deposited on the continental shelf far from shore to fine clays and silts that settled nearer to shore, to sands deposited along the coast. Throughout the Tonto Group strata, we find fossil trilobites, characteristic of warm seas of the Cambrian period and some of the first denizens of the oceans.

- Being a shale—and therefore much more easily eroded than limestones and sandstones in the Grand Canyon—the Bright Angel Shale has weathered back to form the broad Tonto Platform. Below the Tonto Platform lie the Lower Canyons and the Inner Gorge of the Colorado River. We arrive at last on a black bridge 70 feet above the river that was constructed in 1928.

- Here, within this innermost sanctum of the Grand Canyon, we encounter its primordial basement, the Vishnu Schist, where we cross the biggest unconformity of all. These rocks were originally deposited as sands, silts, muds, and ash almost 2 billion years ago.

- During a mountain-building event 1.7 billion years ago similar to those that created the Sierra Nevada, perhaps, or the Appalachians, these old sedimentary rocks were buried miles deep and metamorphosed into schist. In places along the Colorado's banks, the Vishnu Schist was intruded by granitic magmas that formed the Zoroaster Granite.

- Long ago, all those miles of material overlying the Vishnu Schist eroded away, and the basement rocks rose to the surface, only to be buried again beneath rocks of the so-called Grand Canyon Supergroup. We can't see these rocks from the black bridge, but they're visible atop the Vishnu Schist elsewhere in the canyon.

- Grand Canyon Supergroup rocks were laid down intermittently over a span of nearly half a billion years—from 1.2 billion to 740 million years ago. The setting was in and around a shallow sea that covered interior portions of Laurentia. A failed rift zone had depressed portions of the continent that stretch from the present-day Grand Canyon and Uinta Mountains to Lake Superior and the northern Rockies.

- Sandstones, shales, mudstones, conglomerates, limestones, and other sorts of sedimentary rocks collected in the interior sea and on beaches and other lowlands near its shores. Then, all these rocks were tilted, beveled by erosion, and the Tonto Group rocks got deposited atop them.

- The boundary between the Tonto Group rocks at the base of the layered Grand Canyon sequence and the tilted sedimentary, igneous, and metamorphic rocks below is called the Great Unconformity.

- Unlike the sedimentary rocks above, the crystalline rocks of the Inner Gorge—the Vishnu Schist and the Zoroaster Granite—do not erode differentially, and they're much more resistant to weathering. This innermost portion of the canyon is therefore steep walled and narrow, a deep notch into the basement rocks of the Colorado Plateau.

Suggested Reading

Abbott and Cook, *Geology Underfoot in Northern Arizona.*

Chronic, *Roadside Geology of Arizona*.

Chronic and Chronic, *Pages of Stone*.

Hopkins, *Hiking the Southwest's Geology*.

Morrell, "The Unexpected Canyon."

Questions to Consider

1. The rock layers that line the walls of the Grand Canyon—Kaibab Limestone, Bright Angel Shale, and so on—are about as famous as geological strata get. But named rock formations exist everywhere. Find a geological map of the place where you live and learn the names and histories of bedrock strata in the region.

2. Look closely at trails on a shaded relief topographic map of the Grand Canyon (either a paper map, such as those in National Geographic's Trails Illustrated national parks series, or a map you find online). The more closely spaced the contour lines along a trail are, the steeper the trail is. Take a few imaginary hikes on Grand Canyon trails and try to visualize the landforms you pass along the way.

Lecture 25

Carving the Grand Canyon

Viewed from the rim of the Grand Canyon, the Colorado River far below resembles a small green ribbon in the distance, mostly hidden by fins, bluffs, buttes, and spires. It's difficult to imagine that this industrious river managed to remove all the vanished rock of the canyon. Even more remarkable, it appears to have done much or all of this work perhaps over as little as the last 6 million years and no more than the last 70 to 80 million. Relative to the billions of years it took for nature to create the rocks, this seems the blink of a geological eye.

The Rise of the Colorado Plateau

- The stage needed to be set in order for the river to accomplish so much in so little time. This is conjectured to have taken place in three steps: the elevation of the Colorado Plateau, the rifting of the west, and the tilting of the land. Whatever the precise sequence of steps, the region was prepped so that the river could sculpt out a monumental canyon.

- Before any river could carve the Grand Canyon, it needed potential energy—in the form of elevation—that it could transform into kinetic energy—as in rapid motion, the kind that could abrade the canyon's rock walls and carry away sediment by the truckload.

- The Colorado Plateau, all 130,000 square miles of it, needed to rise. And rise it did. Remarkably, it did so with only a little bit of flexing and fracturing and while leaving the thousands of feet of rock beds above the Canyon's Great Unconformity relatively flat and undisrupted.

- One of the fascinating mysteries that has challenged North American geologists for decades is how the Colorado Plateau could rise so high without becoming wildly crumpled and deformed.

- As we can see in a multitude of other national parks, it's easy to build high mountain chains through continent-ocean or continent-continent collisions. This gives us high landscapes defined by volcanoes, thrust faults, accretionary wedges, or intensely folded sedimentary layers. In all these cases, preexisting rocks get pierced and baked, or folded, twisted and faulted in remarkable ways by the processes that ended up elevating the rocks.

- How, instead, do you elevate a plateau extending for 130,000 square miles by more than a mile without producing much ancillary damage? One way to buoy up a slice of continent is with crustal thinning, the sort that occurs with crustal extension and rifting.

- As the continental crust and upper mantle—the rigid lithosphere—thins, the warm asthenosphere below can rise to buoy up the overlying land. This appears to explain in part why the ranges of the Basin and Range Province immediately to the west and north of the Colorado Plateau rise so high.

- Conversely, thickening the continental crust can also cause it to bob up higher on the fluid asthenosphere. This appears to be what has happened with the Colorado Plateau. Seismic profiles and gravitational maps reveal that the Colorado Plateau is underlain by an unusual thickness of continental crust.

- Geologists debate how this occurred. But it's generally believed that the rise of the Colorado Plateau began shortly after the Rocky Mountains began to rise to the east about 70 million years ago. At this time, the Farallon Plate below the eastern Pacific Ocean was plunging beneath the western edge of North America, filling plutons that would become Yosemite, Kings Canyon, and Sequoia National Parks.

- One compelling and widely adopted model holds that as the edge of the continent approached the mid-ocean ridge where new seafloor was forming, the ocean plate became warmer and less dense.

Rather than plunging down steeply into the mantle, therefore, the plate began sliding along shallowly beneath the continental crust.

- Some of the upper surface of the Farallon Plate remained behind to buoy up the Colorado Plateau. Farther inland, to the east, the Farallon Plate also pushed up wedges of continental crust along thrust faults and other reverse faults. These would become the Colorado Rockies.

- How did the Plateau avoid becoming another region of mountain building? The Colorado Plateau remained intact while the crust surrounding it absorbed most of the force of the collision, buckling and crumpling accordingly.

- By about 40 million years ago, subduction had completely consumed the Farallon Plate, and active uplift would have come to an end. Erosion then became the dominant force, removing thousands of feet of strata from the top of the high plateau and leading to another kind of uplift—isostatic rebound or erosional exhumation. This is what occurs as mountain belts erode away and their buoyant roots rise, ultimately exposing deep rocks.

The Formation of the Colorado River

- Once the Colorado Plateau had risen, west-flowing water needed to find a path through what would become the Grand Canyon. And that would be forthcoming.

- Basin and Range extension and rifting began to chew away at the western margin of the high tableland, creating lowlands to the west and causing rocks to tilt that direction and to the north. Deep rocks flexed along long bends called monoclines, opening some faults and fractures at the surface.

- The bending down to the west gave extra erosive power to westward-flowing streams. Until this time, about 6 million years ago, most streams and rivers on the Colorado Plateau flowed from the south and southwest toward the northeast.

Colorado River.

- But now a river running west began to carve its way through what would become the Grand Canyon—or so one theory of the canyon's formation would have it. As rifting continued and the Gulf of California began to open, this river became a buzz saw.

- Rivers flow more swiftly down steeper gradients (or inclines). A river with a high flow velocity can carry more sediment and coarser sediment, such as sand, gravel, and even boulders. The more sediment a river can carry and the faster it flows, the more rapidly it can erode its channel, deepening it. As they scour out their channels, rivers extend themselves upstream through a process called headward erosion.

- The Lower Colorado River could have experienced just such rapid headward erosion as it downcut its channel into the rock layers of the Colorado Plateau. Eventually, the river might have captured what are now the headwaters of the Colorado River and its tributary streams by extending its channel upstream until it intersected them.

- Scientists have proposed a few other possible explanations for the integration of rivers that formed the Colorado River. Perhaps a lake overtopped the divide between an upper river flowing northeast and a lower river flowing west, and perhaps that lake quickly eroded its way through the barrier, connecting the two rivers.

- Perhaps the upper and lower rivers encountered karst—essentially cave systems in limestones beneath the Kaibab Arch—and dissolved their way through to form a single river. One way or another, whatever the final event that pieced the river together, the westward-flowing Colorado River as we know it was formed.

- Many geologists don't believe this could have taken place before about 6 million years ago. A few tantalizing lines of evidence suggest that the Grand Canyon—or at least a predecessor to it—might date back as far as the initial uplift of the Colorado Plateau during the rise of the Rocky Mountains.

The Development of the Grand Canyon

- Mild tilting of the land has had remarkable consequences for the development of the canyon. To the north, the Kaibab Plateau slopes gently toward the North Rim and into the canyon. To the south, the Coconino Plateau slopes away from the South Rim and away from the canyon.

- Much of the runoff from the Kaibab Plateau therefore makes its way down to the Colorado River via some of the roughly 40 tributaries and nearly 500 ephemeral streams that travel to the river within the canyon. Coconino Plateau runoff flows away from the canyon.

- The North Rim sits at higher elevation than the South Rim, gets more precipitation, and gets more of its precipitation in the form of snow that accumulates through much of the winter and melts off in the spring. In fact, the Grand Canyon north of the river is, remarkably, a water world—a water world hidden in a desert.

- This is why the North Rim sits so much farther away from the Colorado River than the South Rim, and this is why the stratigraphic staircase to the north has more gradual steps up from river to rim. With more water to do the work of erosion, the benches are broader and the tributary canyons are longer to the north.

- Water—not scorching sun and dry wind—made the canyon. We see this in the sinuous forms of slot canyons leading down to the river and in the dry washes and gulches of ephemeral streams. But we feel the presence of the water that made this enormous canyon in the sheltered green oases below the North Rim.

- This isn't to say that the south bank doesn't have its share of gorgeous side canyons. One of the most remarkable of the Colorado River's tributaries, a creek called Havasu, crosses tribal land on the Havasupai Indian Reservation before entering the national park from the south. Havasu Creek joins the Colorado River east of Great Thumb Mesa and northeast of Grand Canyon Village.

- The creek has created one of the most exquisite waterfalls anywhere, Havasu Falls. The falls tumble almost 100 feet into a pool of turquoise water surrounded by cottonwood trees and an inviting beach. The creek then cascades over a series of ornate terraces, each forming its own gemlike pool.

- Because of floods and landslides, Havasu Creek and its side canyon can experience dramatic changes, even on a human timescale, with floods sometimes breaking fragile dams and new ones forming.

The Past, Present, and Future of the Colorado River

- The Colorado River was first traveled in 1869 by a group of 10 men led by one-armed Civil War veteran, geologist, and National Geographic cofounder John Wesley Powell. While the Colorado

North Rim, Grand Canyon.

River had millions of years to carve out its channel, debris flows regularly reshape it, adding new rapids. The river Powell explored continues to change.

- In 1963, the Glen Canyon Dam turned much of the upper Colorado River above the Grand Canyon into a reservoir, named Lake Powell. The dam has dramatically reduced the flow of water through the Grand Canyon.

- The dam also has greatly reduced the sediment carried by the river. Because sediment stabilizes features such as beaches along the river, many of the beaches and backwater sandbars were carried away and vanished, with no source of sufficient sand to replenish them. Fish and other animals and plants that had used these settings as habitat began disappearing from the canyon.

- The Colorado River just beyond the Grand Canyon was transformed during the 1930s by completion of the Hoover Dam. Originally called Boulder Dam, this created another reservoir immediately below the canyon, called Lake Mead, which has the largest capacity of any reservoir in the United States. It's protected with another reservoir downstream, Lake Mohave, in the Lake Mead National Recreation Area.

- When Lake Mead is full to capacity, its water floods the lower 40 miles of the Grand Canyon, turning this portion of the Colorado River into a lake. Lake Mead hasn't been full, though, since 1983 due to droughts and increasing demands for water from the lake. In fact, from 1998 until 2014, no Colorado River water reached the Gulf of California. This had a devastating effect on natural ecosystems in the river's delta that were overtaken by saltwater.

- In 2014, an encouraging experiment in partial restoration began, with one percent of the Colorado River's discharge permitted to flow back to the Gulf of California. Time will tell if this solution helps reverse some of the changes wrought by 16 dry years on the delta.

Suggested Reading

Abbott and Cook, *Geology Underfoot in Northern Arizona.*

Chronic, *Roadside Geology of Arizona*.

Chronic and Chronic, *Pages of Stone*.

Hopkins, *Hiking the Southwest's Geology*.

Morrell, "The Unexpected Canyon."

Questions to Consider

1. The Glen Canyon Dam created the Lake Powell reservoir and submerged some magnificent canyons and archaeological sites of the Colorado River and its tributaries. Find photographs online of landscapes that were flooded by the dam.

2. Together, we took a river trip on the Colorado through the Grand Canyon in this lecture. Cataract Canyon in Canyonlands National Park and the Glen Canyon National Recreation Area is another popular stretch of whitewater on the Colorado River upstream of the Grand Canyon. Consulting maps and videos, take an imaginary trip down Cataract Canyon, noting the unique geological features that make it such an exhilarating and challenging stretch of whitewater.

Lecture 26

Petrified Forest and Other Fossil Parks

Fossils are an important part of the geological story in many of America's national parks, and a number of national parks and monuments have been designated to protect fossil-rich sites and the unique specimens they contain. Parks created primarily to preserve, protect, and celebrate fossils enable us to travel through time, exploring conditions in the parks at the time fossils formed. They make it abundantly clear that the communities that came long before us—like those that will come long after we're gone—are as varied and as marvelous as anything a person could possibly imagine.

Petrified Forest National Park

- Arizona's Petrified Forest National Park protects colorful badlands, aptly named the Painted Desert, about 120 miles southeast of the Grand Canyon at the southern edge of the Colorado Plateau.

- Logs and limbs that have turned to stone now lie scattered across the landscape here. These pieces of petrified wood and the rocks and other fossils associated with them provide us with one of the most detailed glimpses we have into the fascinating time when they lived: the Triassic Period.

- The tropical forests in which this fossilized wood once grew shaded some of Earth's first dinosaurs. In fact, paleontologists have found the bones of some of them in the national park.

- Petrified Forest has dark, gemlike chunks of petrified wood that surround the Giant Logs Trail near the southern entrance to the park. Pieces of trunk dozens of feet long lie alongside broken fragments and cylindrical slabs. They weather out of layers of reddish mudstones and brown sandstones roughly 210 to 215 million years old, the Petrified Forest Member of the Chinle Formation.

- Just below the Petrified Forest Member of the Chinle, the Sonsela Member contains even more fossilized wood. The technicolor petrified logs found in the national park's Rainbow Forest were buried in the Sonsela Member amid a conglomerate of pebbles, cobbles, and sandstones.

- These rock beds, 216 million years old, formed in an environment of braided stream channels and bars. Sonsela Member beds cap the mesa north of the Rainbow Forest, and they also cap the Blue Mesa and Agate Mesa.

- Theodore Roosevelt used the Antiquities Act to declare Petrified Forest a national monument in 1906 with an eye to stopping the removal of its fossil timber. Although it became a national park in 1962, as of 1999, visitors were stealing an estimated 24,000 pounds of petrified wood from the park every year. It's a battle the National Park Service continues to wage.

Petrified Forest National Park.

Fossil Cycad National Monument

- One of the parks created to preserve North America's prehistoric past is most noteworthy because it no longer exists. South Dakota's Fossil Cycad National Monument was established in 1922. However, within little more than a decade, illicit collectors had removed virtually every visible fossil from the park.

- With nothing left for the public to see, Congress abolished the park in 1957. Sadly, Fossil Cycad National Monument was itself driven to extinction.

Florissant Fossil Beds National Monument

- Designated in 1969, Colorado's Florissant Fossil Beds National Monument west of Colorado Springs and Pikes Peak preserves another prehistoric forest, this one about 34 million years old. For geologists, this is at the transition from the late Eocene Epoch to the Oligocene, the time when a relatively large-scale extinction took place.

- The name "Florissant" means "flowering," and the monument's beds harbor an abundance of insects and flowering plants, a total of about 1,700 identified species. But of all the fossils, perhaps the most striking and famous here are the petrified stumps of massive sequoia trees—some up to 14 feet wide. Some of these trunks even retain petrified roots.

- Nearby volcanoes helped to create the right mix of conditions, or paleoenvironment, for fossil preservation at the Florissant Fossil Beds.

Agate Fossil Beds National Monument

- Even more geologically recent, dig sites at Nebraska's Agate Fossil Beds National Monument—designated in 1997—reveal a world of exotic mammals that thrived 20 million years ago, during what geologists call the Miocene Epoch.

- Two hills, named Carnegie and University for the institution that mounted research expeditions here, have yielded remarkable specimens.
    - *Daeodons*, which were originally named *Dinohyus*, meaning "terrible pig." (Although not in fact closely related to modern pigs, this creature was the size of a bison.)
    - A type of small, North American rhinoceros named *Menoceras*.
    - *Daphoenodon*, meaning "blood-reeking tooth," representative of a family of extinct carnivores known as bear dogs.
    - *Palaeocastor*, a beaver that lived on land and dug tight, spiral-shaped burrows in the ground.
- When these Miocene monsters prowled the region, the climate had dried, causing grasslands to proliferate, as they do today on the Great Plains.

John Day Fossil Beds National Monument

- A longer span of time is protected at Oregon's John Day Fossil Beds National Monument, a park that illuminates life across the middle two-thirds of the Age of Mammals, otherwise known as the Cenozoic.
- The Cenozoic began 65 million years ago, with the extinction event that snuffed out most of Earth's dinosaurs. It's a time when mammals rapidly evolved to fill suddenly empty ecological niches.
- Different fossil beds exposed across far-flung John Day sites date back as far as 44 million years and as little as 7 million. They preserve thousands of species of plants and animals, including more species of petrified wood than any other location on Earth.
- This park, designated in 1975, contains three sites, all in the basin of the John Day River, a tributary of the Columbia.
    - The Painted Hills Unit consists of volcanic ash layers that have weathered and eroded into colorful pink and red and tan

John Day Fossil Beds.

badlands—similar to the Painted Desert at Petrified Forest National Park.

- ○ The Clarno Unit, situated 18 miles west of a town named Fossil, includes the Palisades, 44-million-year-old volcanic lahars, or mudflows that entombed plants and animals alike. They're now eroded into fabulous spires.

- ○ The Sheep Rock Unit surrounding Sheep Rock Peak includes 30-million-year-old ash layers that have formed colorful green claystone. As the ash weathers away, bones continue to emerge from the beds here.

Hagerman Fossil Beds National Monument

- Idaho's Hagerman Fossil Beds National Monument, also designated in 1975, protects a far more recent geological time. This park shelters fossils of the world's first true horse: *Equus simplicidens*, or the Hagerman Horse.

- The fossil beds hail from the Pliocene Epoch, which lasted from 5.3 to 2.6 million years ago. Horses evolved on the North American continent, and the monument's Hagerman Horse Quarry has yielded numerous bones of this transitional fossil.

- The fossil beds at Hagerman also include specimens of many of the continent's most renowned pre–Ice Age megafauna. These large and extinct Pliocene mammals include the mastodon, the ground sloth, and the sabertooth cat. The bones of an extinct genus of camel called *Camelops*, long vanished from the continent, also turn up in the fossil beds.

- All these creatures lived here about 3.5 million years ago on the floodplains of rivers that drained into ancient Lake Idaho.

Fossil Butte National Monument

- A little farther to the east, a more ancient lake was the basis for Wyoming's Fossil Butte National Monument, designated in 1972. Here, Fossil Lake was one of three great inland lakes that were present in Wyoming, Colorado, and Utah about 50 million years ago during the Eocene Epoch.

- Muds of the ancient lake bed preserve exquisitely detailed fossils of numerous fish, turtles, alligators, insects, and bats—even an extinct stingray. They're preserved in a rock unit that's legendary among paleontologists, the Green River Formation.

- The beds that contain Fossil Butte's beautifully preserved freshwater fossils exhibit alternating light and dark layers that are less than 100^{th} of an inch thick on average. These alternating bands go by the name "varves."

- Each pair, or varve, represents a single year of sedimentation in the lake. The dark layers correspond to the growing season, when organic material accumulated in the lake. The light layers include inorganic sediment that continued to settle in the lake through the winters.

- Green River Formation deposits provide a continuous, high-resolution, fossil-rich record that spans 6 million years of Earth's history.

Dinosaur National Monument

- Also on the Green River but to the south on the Colorado Plateau, Dinosaur National Monument takes us much further back in time. It protects portions of the exquisite canyons of the Green and Yampa Rivers in Utah and Colorado.

- Dinosaur fossil beds are the centerpieces of the park. The beds have been quarried in a steeply sloping rock exposure in the Uinta Mountains, which were raised during the Laramide mountain-building event that also lifted the Rocky Mountains.

- Dinosaur National Monument's bone beds lie in river sands, gravels, and cobbles laid down about 150 million years ago in what we know today as the Morrison Formation.

- Floods likely swept the animals downstream and quickly buried them. Thrust-faulting that occurred as the Uinta Mountains rose tilted the beds. Then, subsequent erosion has unearthed them, revealing their trove of dinosaur bones.

- The National Park Service has enclosed a long stretch of the Carnegie Dinosaur Quarry in an exhibition hall. About 1,500 dinosaur bones emerge from the rock face on display within the hall. The quarry contains bones of a number of recognizable species, 11 in total. These dinosaurs lived on an open savannah of ferns and conifers, rather than the grassy savannahs we know today.

Yoho National Park

- In British Columbia's Yoho National Park, on a lofty ridge between Wapta Mountain and Mount Field, lies one of the most rich, bizarre, and important records of early life ever discovered. This famous site along Fossil Ridge bears the name of the rocks that contain the specimens: the Burgess Shale.

Yoho National Park.

- Most fossil sites preserve hard parts, such as bones or shells, or trace fossils, such as burrows, of long-dead creatures. The Burgess Shale does that, too, but it also preserves much more: carbon films left by rarely preserved soft-bodied marine organisms that lived more than half a billion years ago.

- This was the Cambrian Period. The Burgess Shale offers us a window into this explosive period, during which life on Earth evolved into a multitude of new and complex forms. We call this stunning diversification of life the Cambrian Explosion.

- Studies of these specimens reveal that as much as 98 percent of this Cambrian community was made up of soft-bodied creatures that would never have been preserved in a more typical fossil setting.

- Some taxa found here later perished. Interestingly, even here where soft bodies are preserved, animals dominate over plants, in both their fraction of the biota and the number of distinct species. The bulk of the community was comprised of arthropods and sponges.

- These, and many other species preserved in the shale, harken from taxa that persist even now in our planet's ecosystems. Their ancestors in the Burgess Shale date from more than 500 million years ago.

Suggested Reading

Abbott and Cook, *Geology Underfoot in Northern Arizona.*

Chronic, *Roadside Geology of Arizona*.

Chronic and Chronic, *Pages of Stone*.

Hopkins and Hopkins, *Hiking Colorado's Geology*.

Miller, *Roadside Geology of Oregon*.

Williams and Chronic, *Roadside Geology of Colorado*.

Questions to Consider

1. Fossils in the national parks give us windows into the past. Are fossils common in the bedrock or sediments near your home, and if so, do you know which fossils are most common and when they were formed?

2. To get the big picture of the evolution of life on Earth, do some online reading about life during the Paleozoic, Mesozoic, and Cenozoic Eras. If you could take a time machine back to another time in Earth's history, which would you choose?

Lecture 27 Bryce Canyon, Canyonlands, Arches

At Bryce Canyon, Arches, and Canyonlands National Parks, and elsewhere on the Colorado Plateau, erosion through flat-lying strata in a cold, high desert has produced some of the most remarkable geological features on display anywhere on Earth. Mysterious, forbidding, strange, and comical hoodoos survey the landscape. Rock arches and water-carved natural bridges span the sky. Pedestal rocks perch precariously, improbably, in the air. Deep canyons divide the land. Most of these features will come and go in the blink of a geological eye, but as nature destroys old ones, it gives birth to new ones.

Bryce Canyon National Park

- Even the Grand Canyon—which has cliffs, benches, and a multitude of transitionally sloped surfaces in between—has nothing as intricately wrought as what we observe at Bryce Canyon.

- Below the canyon rim, badlands carved deep into the variously resistant rocks of the Claron Formation have produced this singular landscape of hoodoos and future hoodoos called fins. Eventually, Bryce's landscape of fins and hoodoos—in colors ranging from pink and purple to orange and white—ends in the floor of the Tropic Valley, about 2,000 feet below the rim.

- Bryce Canyon is the result of a just-right combination of bedrock, tectonic history to raise and expose the rock, and climate, which has taken a deft chisel to this land. Bryce's marvels are cut within what geologist and surveyor Clarence Dutton named the Pink Cliffs. This is almost the uppermost step of the Colorado Plateau's Grand Staircase, the youngest rocks of the bunch.

- About 60 to 40 million years ago, during the Paleocene and Eocene Epochs, shallow lakes covered thousands of square miles of what would become Colorado, Wyoming, and Utah. One of these lakes, Lake Claron, was 250 miles long by 70 miles wide, about the size of Lake Erie today.

- Sediment deposited in and near this lake. Calcareous algae lived in the lake. When the algae died, their skeletons settled to the lake floor, accumulating as limey muds in deep, quiet places far from shore and muddy limes nearer shore.

- Sands accumulated near the shore while silts and muds accumulated in swampy areas just inland. When the lake dried up, as it did periodically, soils formed and streams crossed the former lake bed, leaving sands and gravels in their channels.

Bryce Canyon National Park.

- All these sediments would become the sedimentary rocks that comprise the Claron Formation. As the lakes expanded and contracted, and as more sediment pulsed down due to uplift driven by the ongoing Laramide orogeny that raised the Rockies, the layers graded between limes and muds, muds and sands, in repeating cycles. The sediments filled the basin with a sequence up to 700 feet thick. Burial and time has transformed them to the Claron's clean-to-muddy limestones, siltstones, sandstones, and conglomerates.

- The Colorado Plateau rose, and during the Miocene Epoch about 16 million years ago, east-west extension warped the land, riddling it with joints along which weathering could occur and causing Basin and Range–style normal faulting.

- A horst rose to the east of Bryce across the Paunsaugunt Fault. Motion of the fault made an upended Titanic of the block of tilted strata called the Sinking Ship, which is visible from numerous vantages around the park and up close on the Fairyland Loop Trail. Motion across the fault is why, if you look east across Bryce Amphitheater from the rim, the pink Claron Formation appears as bluffs in the distance 2,000 feet above their location in Bryce.

- Within the vertiginous badlands of the Claron Formation at Bryce Canyon lies Earth's highest concentration of rock hoodoos, or goblins. Differential erosion of limestone layers containing various amounts of silt or mud, along with other rock types, gives the hoodoos the look of totem poles—swollen in places, narrow in others, often with caprocks precariously balanced atop them.

- Oxides and hydrated oxides of iron, manganese, and other elements have tinted the rocks their magnificent shades of red, orange, yellow, and purple, while clean limestone paints some layers a bold white.

- From five to 150 feet tall, Bryce's hoodoos have earned fanciful nicknames owing to their resemblance to people (Queen Victoria), animals (the Rabbit), or objects (Thor's Hammer). It took, and continues to take, a just-right combination of warmth and chill, wet and dry, to produce the hoodoos.

- Not far to the west, across the Sevier Fault on the neighboring Markagunt Plateau, erosion has carved into the Claron Formation an even deeper amphitheater—about half a mile deep—at Cedar Breaks National Monument.

- Because the crustal block on which Cedar Breaks is perched has risen across the fault and along the Hurricane Fault to the west, the rim of the amphitheater sits at an elevation above 10,300 feet—more than 1,500 feet higher than at Bryce Canyon. The same geological forces have shaped both Cedar Breaks and Bryce Canyon, so hoodoos and fins also dominate the awesome amphitheater at Cedar Breaks.

Arches National Park

- Northeast of Bryce Canyon and Cedar Breaks, on the Colorado River upstream of Glen Canyon and the Grand Canyon, we come to the town of Moab, Utah. It's a mecca for mountain bikers, rock climbers, kayakers, and whitewater rafters. Just across the river to the north of Moab stretch more than 2,000 stone arches in Arches National Park.

- In addition to the arches, this national park contains rock fins, balanced rocks, pinnacles, and an open desert landscape. But it's the arches that put Arches National Park on the map, the world's largest collection by far of natural stone arches. They occupy a realm of severe extremes. About nine inches of precipitation defines a wet year at Arches, with just five inches in a dry year. But when rain does fall, it falls in torrents. Temperatures can span an annual range of 130 degrees Fahrenheit or more.

- Why do we get the world's greatest concentration of natural stone arches in Arches National Park, when similar stratigraphic rock units underlie much of the region nearby on the Colorado Plateau? Part of the resolution to this apparent paradox is found in a sedimentary unit called the Paradox Formation.

Arches National Park.

- During Pennsylvanian time, a portion of the Carboniferous Period ranging from about 323 to 299 million years ago, an interior basin formed over portions of what would become the four-corners states: Utah, Colorado, New Mexico, and Arizona.

- Like the Great Salt Lake today and larger Lake Bonneville in the past, a large, saline, endorheic lake filled the closed Paradox basin. With nowhere to go, this lake evaporated repeatedly over its history, depositing thick sequences of evaporite minerals—gypsum, halite or rock salt, and other salts. Near what would become Arches National Park, the Uncompahgre Highlands rose along a fault, shedding more sediment into the Paradox Basin.

- As at the salt domes beneath the Gulf of Mexico at the Flower Garden Banks National Marine Sanctuary, evaporite layers become ductile under pressure and begin to flow. As more sediment rained down in and above the thick layers of salt, the salt layers began to flow. Beneath what would become Arches National Park, they bowed upward to form structural anticlines.

- Dissolution of salts along the axis of some of these anticlines caused the land between their limbs to drop, creating long, straight, narrow valleys bounded by parallel cliffs. The arches at Arches National Park would form primarily on these cliffs above two of the valleys, named Salt and Cache.

- More than 300 feet wide and 100 feet tall, Landscape Arch makes a broad arc across the sky. One end of the span looks so thin that it's hard to believe the arch still stands. The Windows are a pair of arches formed within a single rock fin. The twin arches are so similar that they look almost like a mirror image. Double Arch has a narrow window within a hefty arch. Delicate Arch bestrides an eroded rock fin, or ridge, that resembles a wave of red stone.

- Balanced rocks in the park form by a process similar to arch creation. Also known as balancing rocks, or pedestal rocks, these are remnants of less readily eroded rock perched atop a narrow pedestal made from material that's been selectively removed.

- Another feature of the Arches National Park landscape is the biological soil crust that binds fragments of sand, silt, and clay together into small dark knobs. This makes Arches quite different from a place like Petrified Forest National Park. The hardy soils at Arches are called cryptogamic soils and can survive and thrive in the harsh summer heat, winter cold, and desiccation they experience here.

- Arches National Park has thousands of natural arches but lacks natural bridges, formed by running streams or rivers. By contrast, two nearby national monuments have remarkable natural bridges. Two national monuments, Rainbow Bridge and Natural Bridges, span tributaries of the Colorado River with massive cross-bedded sandstones.

- Unlike Arches National Park, where sparse and infrequent running water plays only a minor supporting role in the development of the arches, streams actively carved the canyons below the bridges at Rainbow Bridge and Natural Bridges.

Canyonlands National Park

- In contrast to Bryce Canyon and Arches National Parks, Canyonlands National Park is a vast and much more varied assemblage, with lots of every kind of geological wonder the Colorado Plateau has to offer: deep canyons, oxbow meanders or goosenecks, rock arches, hoodoos, fins, balanced rocks, rapids, buttes, mesas, and more.

- At the heart of Canyonlands lies the confluence of the Colorado and the Green Rivers, which join and then spill down the magnificent Cataract Canyon of the Colorado, some of the best whitewater on the planet. The rivers naturally divide the park into districts, each with its own character.
    - To the north and between the rivers sits Island in the Sky, the most accessible and visited part of the park. The White Rim Trail traces a broad bench atop the resistant White Rim Sandstone, which forms steep cliffs above the rivers far below. Upheaval Dome, near the northwest corner of the Island in the Sky district, is a remarkable crater.

    - East of the Colorado, the Needles district features a multitude of tributary canyons and arches, including Angel, Fortress, Castle, Gothic, Wedding Ring, and Wooden Shoe Arches, among others. The district is named for the towering spires, or needles, of Cedar Mesa Sandstone that rise above the canyons here.

    - To the west of the Green and Colorado Rivers lies a district called the Maze, the least-accessible portion of the park. A number of balanced rocks give the Land of Standing Rocks its name in the Maze portion of Canyonlands.

    - A separate district, Horseshoe Canyon, protects spectacular images painted on rock, known as pictographs, or petrograms. There are also petroglyphs—images etched into rock or dark rock varnish.

Canyonlands National Park.

Suggested Reading

Abbott and Cook, *Geology Underfoot in Northern Arizona.*

Chronic, *Roadside Geology of Arizona*.

Chronic and Chronic, *Pages of Stone*.

Hopkins, *Hiking the Southwest's Geology*.

Orndorff, Wieder, and Futey, *Geology Underfoot in Southern Utah.*

Questions to Consider

1. Some of the hoodoos at Bryce National Park have so much character that they've earned names such as Queen Victoria, Thor's Hammer, and E.T. Look at photographs of hoodoos from Bruce or Cedar Breaks National Monument and give names to some of the hoodoos based on what they resemble or evoke for you.

2. Canyonlands National Park includes virtually every type of geological wonder the Colorado Plateau has to offer: deep canyons, oxbow meanders (or goosenecks), rock arches, hoodoos, fins, balanced rocks, rapids, buttes, mesas, and more. On maps or in photographs of the park, find one or more examples of each of these different landforms.

Lecture 28

Zion, Gunnison's Black Canyon, Capitol Reef

The Colorado Plateau offers various wonders of canyon erosion. At Capitol Reef National Park, a bend in layer-cake beds called the Waterpocket Fold has produced a marvelous landscape that evoked the Washington, DC, skyline for those who gave the region its name. At Zion Canyon of the Virgin River at Zion National Park, what we see resembles a Yosemite carved in red and tan stone. And the Black Canyon of the Gunnison River is a shaded chasm that is very deep and astonishingly narrow.

Capitol Reef National Park

- On the Colorado Plateau, the sedimentary rocks mostly lie flat, and when the landscape is so flat, a little bend in the rocks can go a long way. That's what's going on at the Grand Canyon, where the Kaibab Arch perches the Kaibab Limestone—and therefore the brink of the canyon itself—higher on the North Rim than on the South Rim.

- The extra elevation and tilt of the Kaibab Plateau toward the canyon to the north in turn accounts for increased precipitation and surface runoff into the canyon. That extra water leads to more extensive erosion and gives a lusher feel to tributary canyons north of the Colorado River.

- A bend in the rock of the Colorado Plateau—known as the Waterpocket Fold—ultimately put the Grand Canyon on the map of the United States. We know the protected lands that enshrine this fold as Capitol Reef National Park.

- Capitol Reef is no ordinary reef. In fact, many of the rocks from which it's formed, such as the massive Wingate and Navajo Sandstones, took shape on land, not underwater. The reef in this park has nothing to do with the familiar coral reefs at Biscayne and Dry Tortugas National Parks, nor the fossil reef in Guadalupe Mountains National Park.

- What put the reef in Capitol Reef is its westward-facing escarpment, or steep wall, that posed as effective an obstacle to crossing the region as a barrier reef might to reaching an island it surrounds. Early explorers and settlers had to travel far afield to bypass or clamber across the nearly 100-mile-long north-south-trending obstacle posed by the Capitol Reef escarpment, or cliff.

- Capitol Reef has its origins in a fault hidden deep below the ground, lurking in bedrock far beneath the rock layers from which the "reef" is formed. It was a compressional, reverse fault, and it was activated by the convergence of the Pacific Plate with the North American Plate that raised the Rocky Mountains.

- Convergence also compressed and lifted without faulting the rock layers above in a geological structure called a monocline, which is a bend or kink that raises beds like the edge of a towel draped over a book. That monocline is the Waterpocket Fold.

- The rise of the elevated limb of the Waterpocket Fold triggered a cascade of geological events.
    - Streams, intermittent or otherwise, cut impressive gorges through the elevated rocks of the fold.

    - One stream (perhaps a succession of flash floods) then ate through a rock fin formed of Kayenta Formation sandstone, the gooseneck of a meander loop, to form the Hickman Natural Bridge.

    - Streams carved narrow gorges through the toughest strata, massive cross-bedded desert sandstones such as the Wingate and the Navajo.

    - Once the streams broke through to less-durable strata below, they undercut the resistant sandstone, causing it to fall and widening the canyons.

    - As water cleared out weaker strata, it left remnant mesas and buttes beneath intact vestiges of caprock.

Capitol Reef National Park.

- ○ With someplace downhill to go, volcanic boulders that had stood on the caprock got washed down gullies by occasional flash floods that produced mudflows and debris flows.
- ○ More rocks and sand, rinsed along with the floods, ground at and abraded streambeds, creating potholes.
- ○ Now, when scarce rains fall, the potholes fill to become little pools, pockets filled with water.

- This is how a long fold in the rocks at Capitol Reef became the Waterpocket Fold.
- Erosion has shaped the Navajo Sandstone across the Waterpocket Fold into gleaming white domes and cliffs, shapes that evoked the dome of the U.S. Capitol and other monuments in Washington, DC.

- Within Capitol Reef National Park, a traverse along the up-tilted strata helpfully reveals a rock-time sequence spanning nearly 200 million years, making the Waterpocket Fold a bona fide wrinkle in time. We get glimpses of ancestral life throughout the park.

Zion National Park

- Southwest of Capitol Reef across the Colorado Plateau, beyond Bryce Canyon National Park, the Virgin River has carved a canyon of its own, known as Zion. Intimate and sheer-walled, of spectacular scale, it could almost be mistaken for Yosemite Valley. But the rocks that form the canyon's walls are a deep red, not gleaming pink and gray. For sheer grandeur, though, this canyon most certainly rivals Yosemite.

- The rocks exposed at Zion begin where those at the Grand Canyon end, in terms of geologic time. Over the almost mile of relief within the park, the rock strata at Zion span nearly the entire Mesozoic, more than 100 million years.

- Over its 1,500 to 2,000 vertical feet, the great Jurassic desert-dune sands that comprise the Navajo Sandstone soar in the imposing cliffs and hulking stone temples found across the park. One of these temples—the Checkerboard Mesa—puts the Navajo's cross-beds on brilliant display.

- Right-angled vertical fractures or joint sets create a tilted, thousand-squared checkerboard on the sloping flanks of the mesa. Compression, rifting, and exhumation from the depths through erosion have put compressive and tensional stresses on the rock, resulting in the development of the joint sets and general rounding of the slopes of the mesa.

- The mile-long Zion-Mount Carmel Tunnel, completed in 1930, provides ready access to the park for drivers hailing from Bryce Canyon and the Grand Canyon. Just beyond the tunnel, the Great Arch of Zion looms over the switchbacks in the road that take travelers down to the valley floor.

- This is a blind arch, formed by erosional undercutting of the sandstone above that has created the form of a recessed arch as blocks of unsupported rock have fallen away but not yet entirely penetrated the rock to make a freestanding arch.

- Elsewhere in the park, erosion has completed the work of arch formation. The Crawford Arch sits high on a ridge above Zion's history museum.

- In the remote Kolob Canyons district of Zion National Park, Kolob Arch is one of the world's largest freestanding arches. It occupies a nearly inaccessible side canyon.

- Deeper within Zion canyon, a hanging garden at Weeping Rock clings on a sheer cliff face beneath another blind arch. The gardens sit at the boundary between porous Navajo Sandstone above and impermeable Kayenta Formation clays and silts below.

- Water falling high above on the canyon rim percolates down into and through the Navajo Sandstone, eventually arriving at the boundary between the rocks, where it can't sink straight down anymore and begins to flow horizontally. Eventually, the water emerges at a spring, watering the garden with a perennial stream of Weeping Rock tears.

- One of the most rewarding and challenging hikes in any of America's national parks takes travelers up more than 2,000 feet from Zion's valley floor along a series of switchbacks on the West Rim Trail to a lofty perch called Scout's Landing, the jumping-off point for an even more challenging destination: the red-rock summit called Angel's Landing.

- For a comparably thrilling view without the risk, although it still takes plenty of exertion, you can also hike the 3,000 vertical feet from the Valley Floor to Observation Point. From the vantage of the point, you look out from the East Rim toward Angel's Landing and down the length of Zion Canyon.

Zion National Park.

- Another of Zion's most enticing and unique trails is accessible to everyone. It's the upstream stretch of Virgin River canyon known as the Narrows. If you opt to walk it, be prepared to get wet; flash floods can raise the level of the stream 25 feet in 15 minutes.

Black Canyon of the Gunnison National Park

- A dozen miles of the steep, narrow groove that the Colorado's Gunnison River has made for itself, deep into the heart of the ancient bedrock over which it flows, has been set aside for posterity as Black Canyon of the Gunnison National Park.

- Walk the North Vista Trail to Exclamation Point and gaze deep into the inner canyon. Enclosed by steep cliffs that abruptly rise thousands of feet from the river below, the bottom-most reaches of the canyon remain shrouded in shadow much of the time. Sometimes they receive only half an hour of direct sunlight on even a brilliant day.

- A walk on the Chasm View Trail takes you to the Painted Wall—Colorado's tallest escarpment, or vertical rock face, at about 2,300 feet. The dark rock is primarily a metamorphic gneiss, formed from preexisting sedimentary and volcanic rocks that had been part of an island arc nearly 2 billion years ago.

- A collision brought the arc here and sutured it to what geologists call the Wyoming Province about 1.7 billion years ago. During that collision, the rocks were buried for tens of millions of years at depths of about seven to 10 miles underground, where they experienced the high pressures and temperatures that triggered their metamorphic transformation.

- A few hundred million years later, these dark rocks fractured underground, and a watery granitic magma flooded the cracks that resulted. That magma hardened into the light pegmatites whose veins appear in the Painted Wall, giving it the look of marbled paper.

- The pegmatites originated with plutons, akin to those exposed at Sierra Nevada parks such as Yosemite and at Acadia. Plutons form deep underground as a consequence of subduction-driven volcanism.

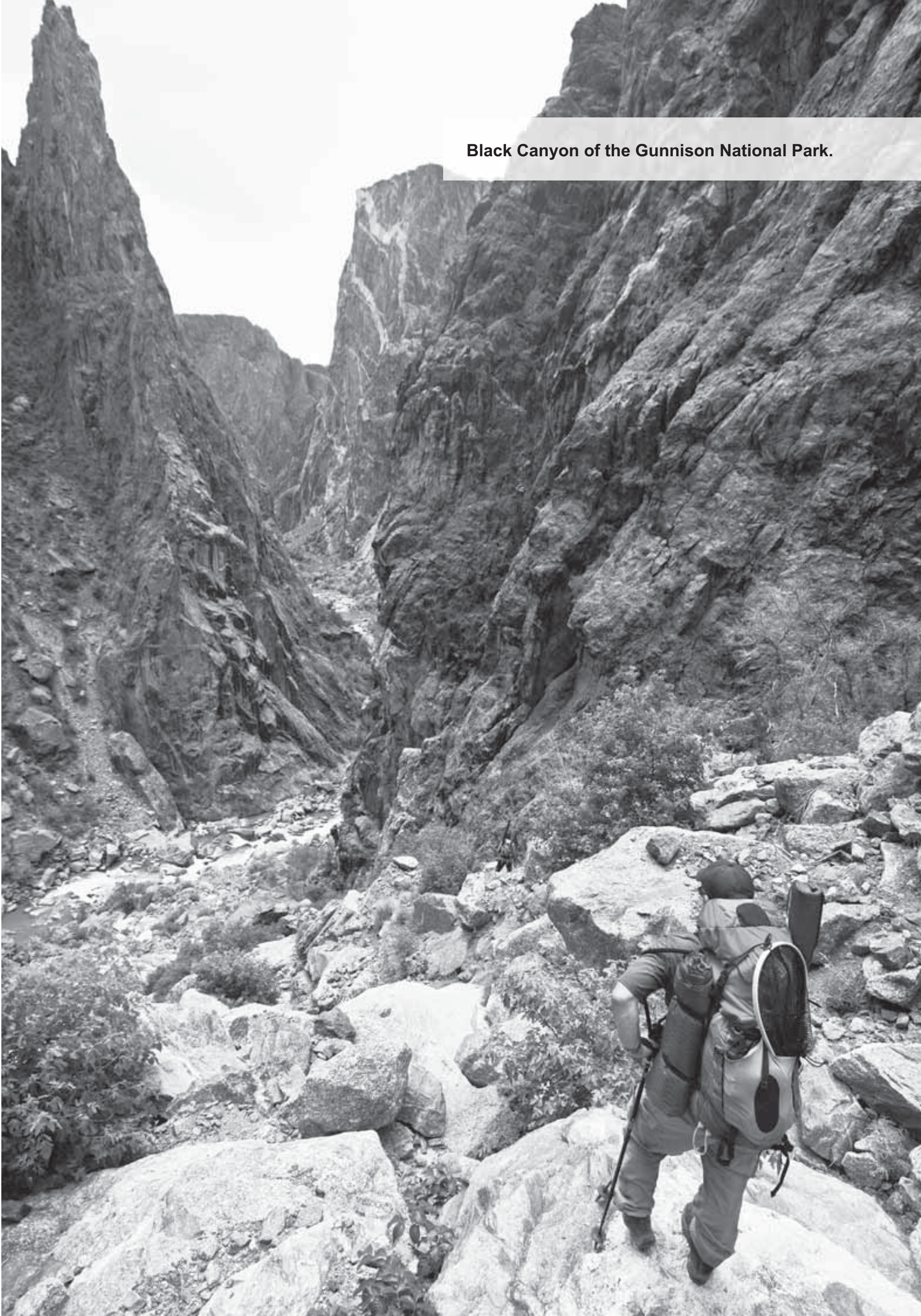
- You can view these plutons at Black Canyon of the Gunnison National Park from the Chasm View Overlook, where you'll find wonderful exposures of the 1.4- to 1.5-billion-year-old Vernal Mesa Quartz Monzonite, a rock type related to granite.

- Pegmatites also originated with plutons of Curecanti Quartz Monzonite, emplaced approximately 60 million years after the Vernal Mesa plutons. This rock forms the Curecanti Needle, a spire many hundreds of feet tall at the mouth of Curecanti Creek.

- The exceptionally ancient metamorphic gneisses and schists of the Precambrian basement reach from river to rim above much of the southwest bank of the Black Canyon. But a relatively thin, light band—pale yellow or orange or red—appears above the basement rocks along the northeast rim.

- This is the Entrada Sandstone, only about one-tenth as old as the rocks immediately below. The boundary between marks an unconformity, a gap in the rock record, spanning 1.5 billion years of geological history.

- The Entrada Sandstone formed 170 million years ago as dunes, fed by quartz and other sands shed by the rising Uncompahgre Highlands directly onto the eroded Precambrian gneisses and schists in a basin below bordering an inland sea. The rise of the Rocky Mountains during the Laramide orogeny and associated motion along faults elevated the rocks through which the Gunnison River would one day carve its canyon as the Gunnison Uplift.



Black Canyon of the Gunnison National Park.

Suggested Reading

Chronic and Chronic, *Pages of Stone*.

Hopkins, *Hiking the Southwest's Geology*.

Orndorff, Wieder, and Futey, *Geology Underfoot in Southern Utah.*

Williams and Chronic, *Roadside Geology of Colorado*.

Questions to Consider

1. The shape of a canyon's cross-section from rim to run depends on many factors, including the degree of susceptibility or resistance to erosion of the wall rocks, the gradient or steepness of the river carving the canyon, the volume of river flow, and the amount of local precipitation. Compare the rim-to-rim profiles, or cross-sections, of Zion, Black Canyon of the Gunnison, and the Grand Canyon and consider how they reflect different conditions in each park.

2. Antelope Canyon in the Lake Powell Navajo Tribal Park might be the most photographed slot canyon anywhere. Explain how Antelope Canyon and similar slot canyons formed.

Lecture 29 Mesa Verde and Ancient Settlements

North America's geology invited settlement and enabled it, to the benefit of some of our most enterprising forbears. In alcoves and caves of the southwestern United States, the Anasazi and other so-called Pueblo peoples built some of the most elaborate structures in ancient North America. On and near the Yucatán Peninsula, Maya builders constructed soaring step-pyramid temples and enduring cities. The Bering Land Bridge connected Asia to Europe when sea levels were at their lowest, making it possible for the first North Americans to venture across it to the undiscovered continent that would become their home.

Mesa Verde National Park

- On the eastern Colorado Plateau in the state of Colorado, geology helped meet the needs for both shelter and water of an Anasazi community that thrived here more than a thousand years ago. They built some of the most remarkable human dwellings on the North American continent in cliff alcoves now protected at Mesa Verde National Park.

- Mesa Verde is Spanish for "Green Table," and it was on top of this apparent table where the Anasazi primarily lived for hundreds of years before they began constructing the cliff dwellings we see today.

- Mesa Verde encompasses nearly 600 cliff dwellings, and a total of almost 5,000 archeological sites, up on the Mesa as well as down in the canyons. Cliff Palace is North America's largest single cliff dwelling and the highlight of many visits to the park. It's a complex of 150 rooms that was built and occupied between about 1100 and 1300 A.D.

- The Upper Cliff House Sandstone forms the roof on this impressive stone ruin. Black desert varnish, a mix of iron and manganese oxides, coats the surface of the sandstone where water has coursed down it or been drawn from it and evaporated above the Cliff Palace.

- The Mancos Shale was deposited in the Western Interior Seaway, the vast mid-continent waterway that flooded land from the Arctic Ocean to the Gulf of Mexico during Late Cretaceous time, roughly 85 to 75 million years ago. As the margin of the seaway shifted in response to changes in climate and the elevation of the land, the muds and silts of the Mancos Shale eventually became buried beneath sand deposits nearer the coast.

- These marine sands would become the Point Lookout Sandstone, which is named for one of the highest locations in the national park, Point Lookout. The Point Lookout Sandstone is the oldest—and stratigraphically the lowest—member of what's called the Mesaverde Group. This sandstone forms the rim of an escarpment above the entrance to Mesa Verde.

- Technically, Mesa Verde isn't a mesa, which is a flat-topped table-like mountain; rather, it is a cuesta, which is a ridge with one steep face, or escarpment, similar to the escarpment that completely encircles a mesa, but also one gently sloping face.

- Above the Point Lookout Sandstone, the Menefee Formation includes sands, muds, and clays, along with some fine coal seams, deposited inland of the coast in swamps and on floodplains. Atop the Menefee Formation sit the Lower and Upper Cliff House Sandstone, formed from more coastal sands.

- Silts and shales of the Menefee Formation interfinger with the Cliff House Sandstone, and most of the park's cliff dwellings appear within the Cliff House above the contact between sandstones and more readily eroded shales below.

- By 1280 A.D., the Anasazi apparently began migrating south toward the Rio Grande, where they became likely ancestors of some of today's Pueblo Indians. By 1300, the site had been abandoned by the Anasazi, and they might have left in response to a drought.

Mesa Verde National Park.

- The earliest settlement atop the cuesta dates to 550 with a people called the Basketmakers. The community expanded in three successive stages of development—Pueblo I, II, and III—that culminated in construction of the great cliff dwellings and then relatively rapid abandonment of the site shortly before 1300.

Chaco Culture National Historical Park

- As at Mesa Verde, the geological story at Chaco Culture National Historical Park, in current-day New Mexico, relies heavily on the Menefee Formation and Cliff House Sandstones of the Mesaverde Group. One of the most striking landmarks within the park, Fajada Butte, reflects the character of both strata: It has Menefee Formation slopes that are topped by Cliff House Sandstones in the shape of steep cliffs.

- Chaco Canyon was a more southerly home to Anasazi pueblo builders, who shared common pottery and building techniques with their Colorado brethren. Chaco Canyon was also home to expert astronomy, as indicated by the Sun Dagger, a famous rock carving that charts the movements of the Sun.

- On the broad valley floor of Chaco Canyon, the Chacoans built traditional, multistory pueblos that endure as fascinating ruins. They used the local sandstone to form walls, cementing stones in place with mud and adding chink stones to fill tiny gaps in the structures and to brace them.

- One of Chaco Canyon's most renowned structures is Pueblo Bonito, a great house of about 800 rooms, 30 of which were destroyed by natural causes in 1941. The Chacoans built Pueblo Bonito directly adjacent to a tall sandstone slab later dubbed "Braced-Up Cliff" by the Navajo and "Threatening Rock" by National Park Service staff.

Gila Cliff Dwellings National Monument

- Elsewhere in New Mexico, at the confluence of the West and Middle Forks of the Gila River, Pueblo III–era people from the

Chaco Culture National Historical Park.

Mogollon region built homes in caves at Gila Cliff Dwellings National Monument. The region would later become the homeland of the Chiricahua Apache, including the well-known Apache chief Geronimo.

- The geology that set the stage for the Gila Cliff Dwellings is unlike that at Chaco Canyon or Mesa Verde, although some of the architectural techniques resemble those used at Montezuma Castle.

- The monument occupies the Southern Rocky Mountains volcanic field, a transitional zone between Colorado's Rocky Mountain Front Range to the east and Mexico's Sierra Madre Occidental to the southwest. Here, numerous volcanoes erupted between about 40 and 25 million years ago, as large magma chambers that would crystallize into plutons were emplaced underground.

- Although the uppermost portions of these plutons are exposed in a few places, most of the evidence for the existence of the plutons comes from gravitational maps, which chart how gravitational attraction varies from place to place on the surface of the Earth.

- Cliff Dweller Canyon along the West Fork of the Gila River sits at the eastern edge of a large collapse caldera, where an eruption disgorged the contents of a shallow magma chamber. A subsequent eruption dated to 28 million years ago filled the caldera with a fast-moving pyroclastic flow, rich in ash and pumice, that hardened to form a rock called tuff.

- Above the ashy tuff lie denser fine-grained lava flows that erupted about 25 million years ago. Rocks forming the lavas include both dark basalts and lighter-colored andesites.

- Finally, above these lie beds of the Gila Conglomerate, which include sedimentary conglomerates, sandstones, and siltstones derived from the surrounding volcanic highlands. The caves formed in the Gila Conglomerate perhaps about 260,000 years ago, when Cliff Dweller Canyon's floor would have been up at the level of the caves.

- The West Fork of the Gila River, then flowing at the same level as the caves, hollowed them out from the soft Gila Conglomerate. Later, the Pueblo of the Mogollon area found the caves and put them to use.

Montezuma Castle National Monument

- In central Arizona just south of Sedona, the remarkable cliff dwellings at Montezuma Castle National Monument demonstrate another kind of alcove. Both Montezuma Castle and its larger but less well-preserved neighbor, Castle A, occupy the mouths of caves developed in young Verde Formation freshwater limestone.

- Montezuma Castle was named for Aztec refugees fleeing the Spanish conquistadors after the demise of Montezuma II. But Aztecs did not build the cliff dwellings; rather, local Sinagua farmers built them between the years 1100 and 1425.

- "Sinagua" (*sin agua*) translates from Spanish as "without water." But that name is misleading: The people who built the castles likely had ample water from Beaver Creek, a perennial stream that flows past the cliff. Beaver Creek finds its source in springs at the base of Hog Hill. The hill is part of the Mogollon Rim, which demarks the southwestern boundary of the Colorado Plateau.

- Montezuma Castle nestles in its alcove roughly 100 feet up a 150-foot cliff. The Verde Formation limestone that it's perched within was created between 8 and 2 million years ago, when extensional rifting caused a block of land to sink, creating a basin called the Verde Valley.

- A freshwater lake filled the basin, and white limestone muds along with some brown mudstones precipitated out to form the Verde Formation limestone. Although the region is generally quite arid, a part of the Sonoran Desert, the cliff dwelling's architects might have opted to live the high life in order to escape potentially destructive seasonal flooding of Beaver Creek.

Casa Grande National Monument

- The Casa Grande National Monument in southern Arizona was first written about in 1694, and by 1892, U.S. President Benjamin Harrison had ordered a square mile around it be protected, making it arguably the first human settlement protected by the future national park system.

- Located on the Gila River between Phoenix and Tucson, the Casa Grande was the creation of another of the four main peoples of the American Southwest, the Hohokam. These were the only ancient North Americans to construct irrigation works that rivaled those of ancient Egypt or Asia.

- The Casa Grande is located at the end of an irrigation canal and would have offered a view over irrigation fields of the surrounding area. The structure we see now was part of a compound that was one of the largest in ancient North America.

Montezuma Castle National Monument.

Palenque National Park

- In the land that is culturally called Mesoamerica, the Mayans built one of geological North America's most elaborate precolonial temple complexes at Palenque. This is now a national park and UNESCO World Heritage site in the Mexican state of Chiapas.

- The site displays the sorts of monumental architecture—large step-pyramid temples, a palace with an observation tower, a ceremonial ball court—also found at other Mayan sites on the Yucatán Peninsula, such as Chichen Itza, Tikal, and Copán.

- Although the Palenque site was occupied for centuries earlier, most of the more than 1,400 buildings known today were constructed during a wave of rebuilding after attacks by the neighboring city of Calakmul in 599 and 611 A.D., during what historians and archaeologists call the Late Classic Period. Within just a few hundreds years, in or just after 799 A.D., the Mayans would abandon the site.

- As with similarly substantial and elaborate Mayan ruins elsewhere in the Yucatán, the creation of the Palenque complex required abundant carbonate rocks—limestones and dolomite limestones. The Mayans also needed lots of firewood for burning them. Burning rock transforms crushed carbonate rocks into the lime used in plaster for construction.

Bering Land Bridge National Preserve

- One of geology's greatest contributions to the peopling of the Americas might lie not in the shelter and building materials it provided, but along and beneath the waters of the Bering Strait. Here, during times when vast Pleistocene ice sheets stored enough water to cause a large drop in global sea levels, the first Americans walked east from Russia into the New World.

- Alaska's Bering Land Bridge National Preserve encompasses some of the lands they would have traveled on their intercontinental journey. Today, about 53 miles of open water separate Alaska from Siberia at the Bering Strait, but 20,000 years ago, with large ice sheets on land and sea level 300 feet lower than today, the two regions were connected.

- This land bridge wasn't narrow: 1,000 miles of land, submerged continental shelf today, would have separated the Bering Sea from the Arctic Ocean at that time. Both climate models and geological evidence suggest that much of this bridge remained free of ice.

- The Pleistocene fossil record reveals that a number of animals migrated between Eurasia and the Americas via the Bering Land Bridge. In addition, between about 18,000 and 28,000 years ago, when sea level was at its lowest, the bridge appears to have been large enough and hospitable enough that people might have settled and lived for many generations on it.

Suggested Reading

Chronic, *Roadside Geology of Arizona*.

Hopkins, *Hiking the Southwest's Geology*.

Hopkins and Hopkins, *Hiking Colorado's Geology*.

Williams and Chronic, *Roadside Geology of Colorado*.

Questions to Consider

1. From the cliff dwellings of Mesa Verde and elsewhere on the Colorado Plateau to the homes hewn in soft rock at Cappadocia in Turkey and Matera in Italy to Frank Lloyd Wright's Fallingwater, architects have been building homes in or around natural rock formations for centuries. If you could build a home into any cliff or other rock formation, where would you choose to build it?

2. The latest genetic evidence suggests that people descended from Siberians were isolated on the Bering Land Bridge for perhaps thousands of years before retreating ice allowed them to enter northwestern North

America, even as it flooded the land bridge about 13,000 years ago. Had you been among the first immigrants to North America, do you believe that you would have been eager to journey into the new continent, trepidatious about leaving home, or both?

Lecture

30 The Colorado Rocky Mountains

The Colorado Rocky Mountains owe their existence to subduction of young, warm ocean crust far away, along the Pacific Coast. The key to traversing such a vast distance was a shallow subduction. This is apparently what allowed a plate moving in from the Pacific Ocean to push up billion-year-old blocks of basement crust, located 800 miles inland from the Pacific Coast. Colorado's magnificent mountain range shows the long reach of plate tectonics, as well as the soaring peaks that can be created almost a thousand miles away from the initial point of collision.

The Rocky Mountains

- Up and down the Front Range—from Pueblo, Colorado, in the south to Casper, Wyoming, in the north—lies the 300-million-year-old Fountain Formation. It's built largely of rust-red conglomerates and a special kind of sandstone called arkose. Arkose, combined with cements made of hematite or iron oxide, gives many of these Colorado rocks their colors of pink and rust-red.

- Fountain Formation rocks were shed as sediment from a precursor to the Rockies called the Ancestral Rocky Mountains, which rose almost 300 million years ago, about the time that Africa and Eurasia collided with North America to form Pangaea.

- The cores of those Ancestral Rockies—granites, gneisses, and schists from which the sediments derived—dated back more than a billion years, to yet earlier episodes of collision, volcanism, mountain building, and burial. The Fountain Formation accumulated adjacent to the Ancestral Rockies as a sandstone skirt.

- The rocks below bowed downward, in part perhaps due to compression, in part due to the weight of all the accumulating sediment getting shed off the mountains. The resulting basin in which the sediment collected is what geologists call a forearc basin.

- Winds whipped more sands above the Fountain Formation into large dunes, and that desert later created a newer layer of pink sandstones called Lyons Sandstone. Newer still, starting about 270 million years ago, was a layer of red shale, siltstone, and sandstone called the Lykins Formation.

- Upheaval followed: A few hundred million years after the sedimentary rocks formed, the rise of today's Southern Rocky Mountains warped and lifted and upended these sandy red sheets, tilting them into the slanted orientations we find them in today. The Rockies opened up the sandstones and other sedimentary strata like a trap door as they poked through, leaving them upended.

- At Garden of the Gods, a National Natural Landmark near Colorado Springs, the upended sandstones assume uncanny and fanciful shapes. Here, you find some of Colorado's famous hogbacks, such as the Kissing Camels, atop which erosion through the Lyons Sandstone has left a window beneath two precariously balanced rocks that resemble the heads of two kissing camels. There are also strange spires and a 700-ton rock called Balanced Rock.

- To the west of Garden of the Gods, visible in the distance, rises the 14,115-foot summit of Pikes Peak, one of more than 50 "fourteeners" in the state of Colorado. The pink granite that forms the bulk of the mountain, the Pikes Peak Granite, crystallized deep underground more than a billion years ago. In much more recent times, the forces that raised the rest of the Rockies in Colorado also hoisted the much older granite of Pikes Peak.

- The colorful claystones and shales of the Morrison Formation formed on river floodplains and in marshlands at a time when dinosaurs thrived. The transition upward to the South Platte Formation and so-called Dakota Sandstones marks the arrival of the Western Interior Seaway, a shallow transcontinental sea about 400 miles wide. This inland sea stretched from the Arctic to the Gulf of Mexico and flooded the mid-continent. It advanced and retreated multiple times here, grading from sands to silts to muds and back again.

Garden of the Gods.

- When the Rocky Mountains rose, they displaced the seaway as they lifted, folded, and tilted the rock beds that floored it, bowing them upward in an enormous arch—one side of the trap door through the sedimentary rock cover. The arch rises here to the east of the mountains in the Dakota Hogback, and it descends with the same strata dipping westward more than 150 miles to the west in the Grand Hogback near New Castle, Colorado.

- Between, the sedimentary beds have eroded away entirely, supplanted by the risen Precambrian basement rocks of the Front Range. Those ancient basement rocks form the lofty heart of Rocky Mountain National Park.

- Between Loveland and Estes Park just east of the park boundary, the Dakota Sandstone and other sedimentary strata have been folded and faulted by east-west compression, rising, plunging, and rising again. The sedimentary strata finally give way to the domed granites and jagged metamorphic rocks of the mountain range's core.

- Pleistocene glaciers have shaped the Rocky Mountains above about 8,000 feet. It's at this elevation that glaciers built a sequence of moraines near the park entrance station to create Horseshoe Park on the floor of a glacially scoured valley.

- The youngest of the three moraines, established only about 10,000 years ago, dammed a lake. As the lake filled with fine clays and sands, it transformed into a flat-lying meadow—Horseshoe Park—which is crossed today by the meandering Fall River.

- Like Horseshoe Park, the neighboring Moraine Park formed beneath a glacier moving to the west from the higher mountains down into its valley. A narrow ridge separates these two flat-floored valleys.

- Trail Ridge Road follows this ridge, rising to about 12,000 feet, making it the highest paved road in the United States. The 1.7-billion-year-old metamorphic gneisses and schists and the more than 1.4-billion-year-old granites that outcrop along the road are the raised crustal basement complex that became the Rocky Mountains in the park. These are some of the oldest rocks to be found in any American national park.

- Granite forms the bulk of Longs Peak, the tallest in the park at 14,259 feet and the northernmost of Colorado's "fourteeners." Technical challenges continue to draw climbers to Longs Peak, which boasts a 1,000-foot sheer rock face called the Diamond. The headwall of a glacial cirque, a bowl carved out by a glacier, the Diamond is the largest, highest, and steepest wall in the Southern Rockies.

The Laramide Orogeny

- What raised Longs Peak and the rest of the Rockies between about 75 and 50 million years ago, the event we call the Laramide orogeny? Geologists generally concur that the culprit was subduction of the last remnants of the Farallon Plate along with the mid-ocean ridge from which it had emanated far to the west, near the present Pacific Coast.

- But this time, the subduction was different. In many national parks of Alaska and the Pacific Northwest, subduction of oceanic crust beneath continental crust causes partial melting of the descending slab and sediments carried down with it. That in turn creates a string of volcanoes inland of the coast, but not too far inland—not more than a few hundred miles, most often.

- At the time of the Laramide orogeny that built the Rockies, the western edge of North America approached and began to override the East Pacific Rise, which marked the eastern edge of the once-enormous Farallon Plate.

- This is similar so far, but here's where the differences begin: Ocean crust forming along the rise was brand new, relatively warm, still wet, and therefore relatively buoyant—too buoyant to descend readily into the deep mantle as older, colder oceanic crust does. The convergence rate of North America with the Farallon and Pacific Plates might also have increased at this time.

- The net result was that the oceanic crust of the Farallon Plate stopped descending at the typical, relatively steep angle that forms Cascade- or Aleutian-style stratovolcanoes close to the coast—about 50 degrees down from horizontal. Instead, it began descending toward the mantle at only a shallow angle, possibly less than 10 degrees. It then nearly leveled out and slid far to the east, bumping along just below the rigid lithosphere of continental crust and upper mantle. It had the buoyant rift zone, what had been the East Pacific Rise, right on its tail, pushing it along.

- As the last vestigial crust from the Farrallon Plate slid beneath North America, it raised the Colorado Plateau without doing much to warp it. But as it continued even farther eastward, friction developed between it and the rocks above, which it compressed and crumpled and pushed eastward and upward to form the Southern Rocky Mountain Range.

- Traction to the west of Colorado's Front Range caused a series of low-angle thrust faults. What seems to have happened was that overlying sedimentary rocks detached from old, underlying metamorphic and volcanic basement rocks and were pushed east.

- Farther east, basement blocks of ancient metamorphic and igneous rock were squeezed and lifted intact, in large pieces, along steep reverse faults. The old rocks began ascending skyward with their drapes of overlying sedimentary strata more or less dripping off on either side.

- At their tallest, the Rockies probably rose to more than 20,000 feet. Atop the elevated blocks, the sedimentary strata eroded off to expose the basement rocks below. The rise of these basement blocks into imposing ranges is what we call the Laramide orogeny.

- This is how many geologists believe the Rockies in Rocky Mountain National Park were built: While the ocean was shrinking nearly 800 miles to the west, its vagrant seafloor was unwilling to descend deep into the underworld. Instead, the seafloor continued bumping along, just below the surface, wreaking marvelous havoc topside.

- Laramide uplift elevated the entire region, so that even the local lowlands aren't low at all: Denver, on the plains below the Rocky Mountains and their foothills, is still the "Mile High City." The same goes for Boulder and Colorado Springs.

The Colorado River

- The Continental Divide is in Rocky Mountain National Park, separating waters that drain ultimately to the Pacific and the Atlantic Oceans. It traces an angled path across the park from the Neota Wilderness in the northwest to the Indian Peaks Wilderness in the south, crossing Trail Ridge Road at an elevation of 10,759 feet at Milner Pass. The Never Summer Mountains edge the northwestern margin of the park.

- The Colorado River begins in the Rockies, in snowfields on the high western slopes surrounding La Poudre Pass. The pass is located on the Continental Divide at a spot where it joins the northern boundary of the national park. A 10-mile roundtrip hike from the Trail Ridge Road at the Colorado River Trailhead will take you to the river's headwaters as a small stream rippling through alpine meadows.

- Thanks to elevation and the addition of tributaries, this same trickle became a mighty force downstream that carved Cataract Canyon at Canyonlands National Park, Glen Canyon in the Glen Canyon National Recreation Area, and the Grand Canyon of the Colorado during the river's 1,400-mile journey to the Gulf of California. For millions of years, it has all begun here, in Rocky Mountain National Park, as nothing more than an unassuming mountain stream.

- Yet not far from its source and within the park, the Colorado proves itself an inexorable force, having carved a three-mile stretch called Little Yellowstone Canyon. Resembling its more famous namesake

Denver in backdrop of Rocky Mountains.

in Yellowstone National Park, this deep and narrow canyon was carved through soft tuffs and volcanic breccias from the Oligocene eruptions that swelled the Never Summer Mountains.

Suggested Reading

Abbott and Cook, *Geology Underfoot along Colorado's Front Range.*

Hopkins and Hopkins, *Hiking Colorado's Geology*.

Williams and Chronic, *Roadside Geology of Colorado*.

Questions to Consider

1. At 14,259 feet, the summit of Longs Peak is the highest point in Rocky Mountain National Park. Mount Whitney in the Sierra Nevada range tops out at 14,494 feet. Where is the highest ground near your home, and what is its elevation?

2. In addition to the mining heritage preserved in Rocky Mountain National Park, the state of Colorado has hundreds of abandoned mines and dozens of ghost towns. Read more about the '49ers and Colorado's precious mineral history. What resources—precious metals, gems, gravel, facing stone—get mined near your home?

Lecture 31

Montana's Glacier and the Canadian Rockies

A thrust block of ancient sedimentary rock slid dozens of miles before coming to rest atop Glacier National Park. The glaciers that buried much of northern North America beneath rivers of ice shaped and sculpted this stratigraphic wayfarer, leaving the spectacular mountains, valleys, and lakes we visit and witness in the park today. Although only shrinking vestiges of the glaciers remain, the Northern Rockies landscape they shaped will persist, even if Glacier National Park might lose the last of its glaciers. Meanwhile, the world of active glaciers, while vanishing from Glacier National Park, continues to the north, in the national parks of the Canadian Rockies.

Glacier National Park

- The glaciers that gave Montana's Glacier National Park its name are vanishing on a human scale. Some models predict that Glacier's glaciers might be gone in a span of just several to a few dozen years. Whatever their fate, ice has left an indelible mark on this magnificent mountain landscape.

- A part of the Northern Rocky Mountain chain, Glacier National Park's summits, ridges, lakes, and valleys share much in common with their southern counterparts in Colorado's Rocky Mountain National Park, yet there are stark differences between the Northern and Southern Rockies that give a distinctive character to Glacier National Park.

- Metamorphic and igneous basement rock has surfaced to crown the Front Range of the Southern Rockies. In the Northern Rockies, the basement remains buried. Exceptionally old, Precambrian sedimentary strata form Glacier's tall mountains, horizontally banding their facades.

- Glacier also enjoys the unique distinction (with Canada's adjacent Waterton Lakes National Park) of being part of a larger international park, the Waterton-Glacier International Peace Park. Although the two national parks continue to be administered separately, Waterton-Glacier was designated a Peace Park in 1932 to celebrate the long friendship between the United States and Canada and in recognition of the fact that the mountains, wildlife, and ecosystems of the two parks know no political frontiers.

- The Belt Supergroup, which contributed most to the landscape's formation, is a more than two-mile-thick sequence of billion-plus-year-old sedimentary rocks that runs from west to east. These rocks were laid down over hundreds of millions of years in a world quite different from the one we know.

- During the Laramide orogeny, or mountain-building event, east-west compression squeezed this portion of the continent, dislodging the slab of sedimentary rocks that form Glacier National Park's mountains.

- The cause of this compression might have been the presence of a subduction zone in what is now eastern Washington state before the rest of the Pacific Northwest had accreted to the continent. The force slid the slab of ancient Belt Supergroup rocks more than 35 miles to the east, up and over much younger Cretaceous rocks less than a tenth their age.

- When a slab of rock is pushed long distances over a thrust fault, geologists call that a thrust sheet, or nappe. The low-angled surface along which the nappe that formed Glacier's highlands slid is called the Lewis Overthrust Fault.

- The Belt Supergroup rocks on display in the park accumulated in the Belt Sea, which formed when the platform that would become much of Siberia separated from the core of the North American continent about 1.5 billion years ago.

- Several distinctive layers of Belt Supergroup rocks are on display, including the Altyn Formation, the Appekunny Formation, the Grinnell Formation, and the Helena Formation. A dark band

Glacier National Park.

formed of a rock appears near the top of Helena Formation rocks throughout the national park. This band is called the Purcell Sill, and it's made of diabase, which has the composition of a basalt but is coarser grained.

- You can view all these geological layers on the popular drive from West Glacier to Saint Mary on the Going-to-the-Sun Road, which traverses the entire slab of displaced Belt Supergroup rocks from west to east.

- The road takes travelers up and across the Continental Divide at Logan Pass. At the outset, the road traces the shore of Lake

McDonald. Glacier's long, straight lakes—such as Lake McDonald, Saint Mary Lake, Lake Sherbourne, and Upper Waterton Lake—offer spectacular vistas of the high mountains that rise beyond them.

- The appearance that the lakes emanate from the cirque bowls, ridges, and summits of the mountain strongholds above them is no accident. The natural amphitheaters that tower above the lakes were the source of the vanished glaciers that straightened and depressed stream valleys to form their basins.

- A mixture of red and green pebbles gives a brilliant play of color to the shallow near-shore waters of Lake McDonald. The rocks originate with the mudstones of the Appekunny and Grinnell Formations. These green and red rocks line the bed of McDonald Creek, which flows into the eastern end of the lake, bringing down the pebbles that paint its floor.

- Continuing on from the lake, the road climbs the Helena Formation limestones to the west of a high, thin rock ridge: the Garden Wall. This barrier is an arête, a divide sharpened by adjacent glaciers. It coincides with the Continental Divide, which traverses the park from north to south.

- The road crosses Logan Pass at an elevation of 6,646 feet. The pass was formed where glaciers grinding away on both sides of the Continental Divide formed an arête similar to the Garden Wall, which finally toppled to form a saddle through the ridgeline.

- A high-mountain saddle formed when the walls came tumbling down goes by the name col. Other passes in the park also formed as cols between glaciers, including Marias, Piegan, and Gunsight.

- During the height of Pleistocene glaciations, ice covered the passes, smoothing the rocks high above the road, leaving a ragged line of plucked rocks far above and covering all but Glacier's tallest summits.

- A trail departs the parking lot at Logan Pass for an area called Granite Park. The Purcell Sill, formed of a basaltic rock called diabase, is visible in roadcuts on either side of Logan Pass.

- Descending from Logan Pass to the east, the Jackson Glacier Overlook offers a view of Blackfoot and Jackson Glaciers. Like other glaciers in the park, these small alpine glaciers perched high on mountain slopes are mere vestiges of what they once were.

- The same has happened with the park's larger glaciers, which are shrinking and thinning at a prodigious pace. Between 1850 and 2000, the Grinnell Glacier northeast of the Garden Wall lost more than 90 percent of its surface area and its volume.

- At the head of Saint Mary Lake, a short trail leads to the narrow, steep-walled Sunrift Gorge. This striking slot between the rocks didn't form by typical processes of stream erosion, and glaciers didn't carve it. Instead, as glaciers receded, a large block of rock detached and slid a few feet downslope, opening the gap.

- Chief Mountain in the northeastern corner of Glacier National Park is a textbook example of what's called a klippe. The mountain is an eastern erosional remnant of the Belt Supergroup rocks that got thrust eastward, an isolated portion of the leading edge of the thrust block, or nappe, that remained after surrounding rocks eroded away.

The Canadian Rockies

- If you'd like to get a feel for what Glacier National Park would have looked like centuries ago, before it lost most of its glaciers, you can do so with a drive along the Icefields Parkway, which connects two Canadian national parks, Banff and Jasper.

- With adjacent parks Yoho and Kootenay, these comprise Canada's traditional "Big Four" national parks, the heart of the Canadian Rockies. The country has its own Glacier National Park as well, established with Yoho just a year after Banff, Canada's first national park.

- High peaks crowd the Icefields Parkway, offering glimpses of the Columbia Icefield, which lies mostly hidden beyond their crests. This ice field—the largest in the Rocky Mountains—stretches from Banff National Park to Jasper National Park along the Continental Divide and astride the border of Alberta and British Columbia. The ice field feeds a number of outlet glaciers, or glacial tongues, including Jasper’s Athabasca Glacier, a popular destination for travelers on the parkway.

- Like the Northern and Southern Rockies to the south of them, the Canadian Rockies were formed by tectonic convergence that was occurring to the west, a combination of seafloor subduction as well as terrane collision and accretion.

- Together, these forces compressed the region and elevated it via a mix of low-angle faulting and block faulting, like in other parts of the range to the south. Seafloor subduction began in earnest along the northern part of the Pacific seaboard, so the rise of the Canadian Rockies led the Northern and Southern Rockies.

- It began about 100 million years ago. Blocks of ancient sedimentary rock were thrust along thrust faults toward the east, like at Glacier National Park. But in the process, many of the layers were intensely wrinkled and folded.

- No less mesmerizing are the many lakes of the Canadian Rockies. Basins depressed by the glaciers have moraine debris piles that dam the basins. One exquisite and renowned example in Banff National Park is Lake Louise. Another is Moraine Lake.

- Banff and Kootenay National Parks both feature hot springs. At Kootenay, those include Radium Hot Springs. Water from this spring contains trace amounts of radon gas, produced by the decay of small amounts of radium in rocks through which the spring water travels.

- Water from the Kootenay River enters a major extensional rift basin called the Rocky Mountain Trench as it flows through the

Banff National Park.

park. Like the relatively recent-vintage Basin and Range basins to the south, this Rocky Mountain Trench opened in response to extensional forces that have come to bear since the rise of the Canadian Rockies.

- In addition to the Athabasca and other Columbia Icefield outlet glaciers, Jasper National Park boasts Maligne Lake, the largest among many in the park. A valley glacier scoured and depressed the basin filled by the lake and left a moraine dam to back up the waters that fill it. Exceptionally photogenic, Maligne Lake is surrounded by tall mountains and a trio of glaciers, which its tranquil waters reflect, and contains tiny Spirit Island.

- Yoho, the smallest of the "Big Four" Canadian Rockies parks, makes up for its tiny proportions with its extraordinarily interesting and important Burgess Shale fossil beds. Like the other parks, it also boasts spectacular mountains, lakes, and waterfalls.

- Meltwater from the ice of still-abundant glaciers makes the Canadian Rockies an ideal destination for viewing uplifted and uplifting landscapes through a prism of striking blue-green waters. The intensity of the natural colors owes much to glaciers, which not only provide water, but also manufacture the rock flour that makes lake colors in the Canadian Rockies so famous around the world.

Suggested Reading

Alt and Hyndman, *Roadside Geology of Montana.*

———, *Roadside Geology of Washington.*

National Geographic, *Guide to the National Parks of Canada*.

Parks Canada, http://www.pc.gc.ca/eng.

Questions to Consider

1. You can find before-and-after photos and maps of Glacier National Park's retreating glaciers online. Based on the pace of ice loss you observe in the images, if the trend continues at the same average rate, how soon will the glaciers be entirely gone?

2. Although glaciers are currently retreating and thinning rapidly across most of the globe, there are locations—such as the Himalayan Karakoram Range—where glaciers are growing. Why might this be so?

Lecture 32

Big Bend on the Rio Grande and Saguaro

In Big Bend National Park, the southernmost extension of the American Rockies meets the westernmost outpost of mountains built hundreds of millions of years earlier by the birth of the supercontinent Pangaea. At this spot in the Chihuahuan Desert, volcanic eruptions and Basin and Range rifting have created a marvelous comingling of geological features. Northwest of Big Bend in another desert, the Sonoran, mountains with two different origin stories sandwich the city of Tucson, Arizona. Separate, federally protected areas within each range comprise Saguaro National Park. In addition to their desert landscapes and ecosystems, the complexity of the histories inscribed in their rocks and landforms spins a common thread that unites Big Bend and Saguaro.

Big Bend National Park

- Texas's Big Bend National Park combines features separately on view at other national parks, including continent-to-continent collisions that also built the Appalachian and Ouachita Mountains and forged the supercontinent Pangaea, the Laramide crustal shortening event that pushed up the Rocky Mountains, volcanic landscapes scorched by lava and buried beneath ash, erosional features carved into strata deposited in the Western Interior Seaway, and Basin and Range crustal extension.

- Summertime temperatures often top 100 degrees Fahrenheit. The generally sparse vegetation and thin soils across much of the park, combined with the intensely varied geology exposed as a consequence, make Big Bend a geologist's playground. The exception is atop the park's "sky islands," which see enough rainfall to support forests of maple, aspen, and Douglas firs.

- Big Bend National Park and the larger area that encompasses it, the Big Bend region, owe their names to the broad and abrupt bend of the Rio Grande. The river takes an abrupt left turn as it flows, changing course from southeast to northeast along the border of the United States with Mexico, a border that it defines.

- Within the park, the Rio Grande has carved its path through three great canyons: Santa Elena, Mariscal, and Boquillas, each associated with a north-south-trending mountain range or ridge that straddles the border.

- The oldest rocks in Big Bend National Park appear at Persimmon Gap, which is accessible via a trail that begins near the visitor center of the same name at the park's northernmost point.

- For hundreds of millions of years during the Paleozoic, from at least about 500 million to 300 million years ago, the sediments that ultimately became these rocks were shed off mountains to the north of Big Bend into an ocean trough south of the proto–North American, or Laurentian, continent. With burial and time, they become garden-variety sandstones and shales.

- But the formation of Pangaea would transform these Paleozoic sedimentary rocks forever—or at least long enough for us to arrive and admire them. The transformational trigger was the collision of South and North America about 300 million years ago during the Ouachita orogeny. This same event of mountain building and crustal shortening gave rise to the mountains at Hot Springs National Park in Arkansas, well to the east.

- The Ouachita Mountains were in fact part of a continuous range that stretched on to the east and northeast as the Appalachian belt clear to New England, Canada, and departed lands now attached to portions of Europe and North Africa.

- The distorted rocks of the range lie mostly buried between Oklahoma and west Texas, but they emerge in northeast-trending ridges at the core of a structure called the Marathon Uplift and at Persimmon Gap in Big Bend National Park.

Rio Grande river, Big Bend National Park.

- After the marriage of continents that created Pangaea and their subsequent divorce, forces related to the subduction of the Farallon Plate beneath the continent's west coast buckled the land, causing waters from north and south to flood the future Big Bend region as the Western Interior Seaway.

- Within the shallow waters of this expansive sea, marine creatures that were destined to fill seafloor sediments with remarkable fossils thrived. In these teeming waters, thick sequences of lime-rich sediments settled and became limestone.

- We encounter these limestones in the park today in rock units such as the Del Carmen, Santa Elena, Buda, and Boquillas Formations.

Muddy shales, gritty silts, and occasional sandstones also accumulated in the region of the park as fluctuating sea levels caused the waters to transgress and regress across the land.

- The popular Ernst Tinaja Trail at Big Bend provides an up-close scramble over and past several remarkable geological features carved through stones laid down in the Western Interior Seaway.

- From the Ross Maxwell Scenic Drive, it's possible to view or explore a number of the park's most compelling geological features.

- The trail through Tuff Canyon takes us into layers of basalt topped by rhyolites, pumice, ash, and volcanic debris—the tuff—formed when volcanic eruptions rocked the future park between about 38 and 32 million years ago.

- Heading downstream in Tuff Canyon—which here means going higher in the stratigraphic sequence and more recently in time—successive layers of ash and pyroclastic flows reveal that a different, more explosive kind of magma had erupted nearby, inundating the surrounding landscape. The eruption vented lava and ash that created rhyolites, a volcanic rock type that forms from a magma with the same composition as granite.

- Elsewhere in Tuff Canyon, water percolating through the frothy rock formed from volcanic glass called pumice has dissolved silica and then reprecipitated it as a mantle of rock draperies adorning the canyon walls.

- Visible to the southwest of Tuff Canyon and from other locations in the park is the landmark known as Cerro Castellan. This butte is capped by a lava dome, which was fed by a feeder dyke visible beneath the darker rocks that cap the dome. Pyroclastic flows from the same eruption that created most of the walls of Tuff Canyon sit beneath the dome, which acts as a hard caprock and inhibits the erosion of the flows.

- Near Cerro Castellan, a plug of rhyolitic magma that flowed into surrounding tuff and chilled remained after the tuff it pierced eroded away. This 20-foot-tall rhyolite tower goes by the name of the "petrified tree," though it isn't one.

- Casa Grande, another volcanic butte and Big Bend landmark, has a lava flow layer as its caprock and alternate bands of ashy tuff and lava below. And the Elephant Tusk formed, like the pseudo petrified tree, from an igneous intrusion left standing as surrounding tuffs eroded away. The Elephant Tusk is much larger, however.

- The Grapevine Hills within the park include so-called plutonic rocks, the granitic roots of eroded volcanoes that cooled deep enough underground to permit sizable crystals to form within the melt as it solidified. Erosion has carved fanciful shapes into these plutonic rocks, including Balanced Rock, perched precariously between two toothlike stone pillars.

- The most prominent of Big Bend's volcanic features, the Chisos Mountains, is also the most southerly mountain range in the contiguous United States and the only range contained entirely in a U.S. national park.

- At 7,825 feet above sea level, the summit of Emory Peak in the range is the highest point in Big Bend. The Chisos Mountains enclose an elevated trough between two volcanic calderas called the Basin. Water that collects in the Basin during heavy rains can only flow out through a single outlet, Oak Creek Canyon. The high rocks on either side of the canyon form a natural frame called the Window, which offers an exceptional view down to the desert lowlands and rolling hills thousands of feet below.

- Like at Death Valley and across the Basin and Range Province, the extension of western North America that followed the Laramide orogeny, and that continues today, caused normal faults to develop across the Big Bend region. The faults bound large blocks of continental crust, some of which have slid down to form basins and others of which rose as linear mountains or ranges. Most of Big Bend National Park lies within a fault-bound basin.

- Big Bend's hot springs and other attractions have been luring people to the region for about 10,000 years, when the first Native Americans arrived. Subsequent residents left pictographs, rock paintings, on limestone bluffs along the trail to the hot springs, suggesting that they might have enjoyed taking the waters, too.

- Fossils abound in many of the park's sedimentary strata. In addition to the marine creatures that inhabited the Western Interior Seaway, fossil species found at Big Bend include a mix of terrestrial dinosaurs and mammals, along with petrified wood.

- Together with the protected areas across the border in Mexico, Big Bend forms part of a vast trans-boundary conservation corridor. Big Bend remains to be joined someday with Maderas del Carmen, Cañon de Santa Elena, Ocampo, and Río Bravo del Norte just across the border.

Saguaro National Park

- From Big Bend, a long drive across western Texas, southwestern New Mexico, and eastern Arizona brings us to the Sonoran Desert and Saguaro National Park. Two parks in one, Saguaro's separate districts—Rincon Mountain to the east and Tucson Mountain to the west—bestride the basin occupied by the city of Tucson. Both districts protect prize forests of the immense Saguaro cactus.

- Saguaro National Park, along with the surrounding region, occupies the southern Basin and Range Province, characterized by crustal extension and the movement of fault blocks along normal faults.

- The rise and tilting of a classic Basin and Range fault block lifted the mountains of Saguaro's Tucson Mountain district. By contrast, upward doming of the land, faulting, and the resultant unveiling of

Saguaro National Park.

old, intensely metamorphosed rocks engendered Saguaro's Rincon Mountain highlands.

- In Saguaro West, the Tucson Mountain district, crustal extension that began more than 20 million years ago tilted a varied sequence of sedimentary rocks—including limestones and dolostones, shales, siltstones, sandstones, and conglomerates—that had been laid down during the Paleozoic and Mesozoic Eras, along with volcanic layers that hail from eruptions during the Jurassic and Cretaceous Periods of the Mesozoic.

- Spanish settlers built limekilns in Saguaro West to fire carbonate dolostones and limestones and produce lime for construction and other uses. The ruins of their kilns are here, as well as numerous prospecting holes and small abandoned mines in this district, where prospectors sought what turned out to be small deposits of silver and copper near the contacts between igneous intrusions and the park's carbonate rocks.

- By contrast, the taller Rincon Mountain and Tanque Verde Ridge in Saguaro East tend to be crowned by a strongly banded, coarse-grained type of gneiss called mylonite. This gneiss, named the Catalina gneiss, dates back to Precambrian time.

- The geological structure on display in this part of Saguaro National Park is an example of what's called a metamorphic core complex. Indeed, Saguaro's Rincon Mountains are celebrated among geologists for this very feature. They're renowned in part because the structure is so exceptionally well displayed.

- Traversing Cactus Forest Drive, a popular loop road in Saguaro East, you'll cross the Catalina Fault and can examine all three layers: the fault itself, along with the folded limestones above and the banded Catalina gneiss below.

Suggested Reading

Chronic, *Roadside Geology of Arizona*.

MacLeod, *Big Bend Vistas*.

Spearing, *Roadside Geology of Texas*.

Questions to Consider

1. The Rio Grande passes through three impressive canyons as it flows past Big Bend National Park. Name, describe, and contrast each of these canyons.

2. How do the east and west units of Saguaro National Park resemble and differ from one another?

Lecture 33

Mammoth Cave, Wind Cave, Carlsbad Caverns

Mammoth Cave, Carlsbad Caverns, and Wind Cave National Parks invite us into a world of unfamiliar wonders. Their most spectacular wonders lie underground, with soaring domes, yawning pits, giant tunnels, and streams and lakes. From Virginia's Shenandoah to Nevada's Great Basin, a variety of popular caves exist that are all beneficiaries of karst geology. Wherever the continent was formerly submerged by an ancient sea, there might be sufficient limestone deposits, plus protective sandstone or other caps, for the process of cave formation to begin.

Mammoth Cave National Park

- At Mammoth Cave, beneath the gentle hills and bluffs of west-central Kentucky, lurks a labyrinth hidden in darkness that has no rival anywhere on, or under, the Earth. At more than 400 miles of known, connected passage, and still going, the Flint Ridge–Mammoth Cave System has more than twice as many mapped miles as any other cave. In addition, dozens of disconnected caves, separate from the primary cave network, also occupy the park.

- It's no accident that the world's longest cave developed where it did. Geologically, the term "karst" offers a clue that limestone is involved. In fact, the majority of the world's caverns (large caves), as well as the world's longest caves, develop in carbonate rocks—limestones, dolomites, dolostones, and marbles. These are key raw materials for karst landscapes.

- The country surrounding Mammoth Cave is one of the world's most famous karst landscapes, so it's no surprise that it has carbonate rock to spare.

- Three lime-laden rock formations developed between about 350 and 325 million years ago. From new to old, they are the Girkin Formation, Ste. Genevieve Limestone, and Saint Louis Limestone.

Mammoth Cave goes all the way down through the first two and halfway into the third.

- A mix of terrain features defines the south-central Kentucky karst and karst landscapes the world over, including numerous ponds, sinking streams, closed basins, and big springs. They are none-too-subtle hints that chasms lie below, that the solid rock we stand on could be the thinnest of ceilings separating us from dozens or hundreds of feet of open air.

- But the main event in this national park isn't what's on the surface—it's underground. Mammoth overwhelms visitors today, as it has for centuries, with a mix of spectacular cave formations and sheer, audacious scale.

Mammoth Cave National Park.

- Mammoth's scale comes from the fortuitous mix of durable caprock, thick limestone, and relative stability in the region. Together, these gave the park's network of interconnected caves plenty of time and space to get large.

- Mammoth acquired its scale over about the last 10 million years as water moves underground through fractures and other voids, percolating downward first through unsaturated rock in the so-called vadose zone, where both air and water are present.

- Eventually, the water reaches a depth at which groundwater fills all the pore spaces and saturates the rock. This saturated rock is called the phreatic zone. The intersection between the unsaturated vadose zone and saturated phreatic zone defines the water table.

- Water above the water table seeks out vertical cracks, which it can widen, sometimes dissolving out long shafts. Water might also move horizontally to form subterranean stream channels, whether by following fractures or by moving through more soluble rock layers. Over time, horizontal water can create canyon passages.

- Many of Mammoth's corridors, such as Broadway and the so-called Main Cave, have the boxy profiles of canyon passages, formed by stream flow along their bottoms that has eroded the bottom downward while undercutting the walls and also promoted collapse of portions of the ceilings.

- The Green River ultimately controls what's called local "base level," the lowest level of the water table in and around the caves at Mammoth Cave National Park. As the river has eroded its way downward over millions of years, it has paused on at least five different levels, allowing major cave passage development at each.

- The fifth and newest level is the deepest. So, Mammoth, when viewed in three dimensions, resembles a succession of different interconnected caves stacked one atop another, connected by shafts and spots where one passage has broken through the ceiling of another below to create a connection.

- Like at any decorated limestone cave, formations such as stalactites hanging from the ceiling number among Mammoth Caves' prime attractions. The general term for these secondary formations is "speleothems," which is Greek for "cave deposits."

- There are several kinds, but they all have to do with water droplets, or small sheets of slow-moving water, which collect and begin to evaporate and leave their carbon dioxide behind. As droplets evaporate, the remaining water becomes saturated with calcite, causing calcite to precipitate out.

- The most familiar speleothems are formed by dripping water, such as stalactites (which cling to the ceiling), stalagmites (which grow up from the floor), and columns (which form when a stalactite descending from the ceiling and a stalagmite rising from below connect). If dripping water arrives in higher volume and isn't saturated with calcite, it can instead cut a shaft or deepen a shaft that's already there.

- Even more dramatic speleothems can be formed by flowing water, such as flowstone and draperies, which form on wet walls and sometimes descend from the ceiling along damp cracks. Calcite precipitates as undulating sheets of rock. In addition, rimstone dams can create terraced travertine pools, where water evaporates around the edges of ponds, causing small dams of calcite to precipitate.

- Other secondary deposits form with little or no movement of the water. Helictites form irregular branching shapes that appear to defy gravity. Cave pearls are spherical calcite crystals that form in the abundant quiet water of some travertine pools.

- In drier parts of the cave, water that's passed through pyrite or evaporite layers above can precipitate gypsum via the process that causes gypsum wedging. Gypsum flowers are clustered spars of gypsum (calcium sulfate dehydrate) that can grow quite long and curl like fern fronds.

- The perennial darkness of the cave has given rise to several species of peculiar, uniquely adapted creatures called troglobites that live their entire lives underground. Troglobites include the Kentucky cave shrimp, cave crickets, cave flies, and eyeless cave fish.

- Humans have used the cave since prehistoric times, beginning about 4,000 years ago. They penetrated a good six miles of Mammoth's passages and left torches made of river cane, as well as petroglyphs on the walls, baskets, and pottery, all surprisingly far from the nearest natural entrances. They also scraped minerals from Mammoth's walls, including gypsum, mirabilite, and epsomite. But the wonder of the cave itself proved to be Mammoth's most alluring and enduring asset.

Wind Cave National Park

- While Mammoth might be the longest cave system on Earth, South Dakota's Wind Cave enjoys the distinction of being the first cave to become a U.S. national park. Theodore Roosevelt signed this park in the Black Hills into existence in 1903.

- By any but Mammoth standards, Wind Cave is enormous, with more than 144 miles mapped to date. Its close neighbor, Jewel Cave—protected as a national monument—is longer still, with 177 miles of mapped and surveyed passage to date.

- Even more than Mammoth, Wind Cave is a three-dimensional maze. The cavern's tunnels form a compact lattice, with passages looping above and below one another. The entire cave is so tightly woven that it fits beneath just one square mile of land.

- Like at Mammoth Cave, the carbonate strata that host Wind Cave were deposited in a shallow sea between about 340 and 330 million years ago. The rocks are Pahasapa Limestone, a local name for rocks of the more widespread Madison Formation.

Wind Cave National Park.

- The Laramide mountain-building event, or orogeny, lifted the Black Hills and raised the beds that would host Wind Cave. Northwest-southeast-trending joints, or fractures, in the rock formed, and many of the cave's major passages would later develop along those joints at times when the water table was higher and the rock was completely submerged. As the water table fell and air filled the cave passages, sediment and breakdown material accumulated within the cave.

- Another finer network of fractures in the limestone are filled with gypsum that, over time, turned into calcite as the sulfates in the gypsum were replaced by carbonate ions. Sulfates liberated by the conversion greatly acidified the water, dissolving limestone and probably helping carve the passages that make up the cave. As the limestone dissolved away, the converted calcite filling the fractures proved more durable and therefore remains as a rare and distinctive feature called boxwork.

- Wind Cave includes several other fascinating speleothems, including popcorn, which is small rounded nodules on tiny stalks; frostwork, which results when popcorn nodules also have needles of a mineral called aragonite attached; cave ice, or thin rafts of calcite one to three inches across that form on and glide atop the surface of water in subterranean pools; dogtooth spar, or crystals of calcite that are well formed; and helictites, which are surface-tension formations similar to those at Mammoth Cave.

- The surface landscape in Wind Cave National Park deserves mention, too. Two ecosystems come together here, with Western prairie mixed grass meeting Eastern ponderosa pine forest in what is an exceptional sanctuary for bird and mammal watching.

Carlsbad Caverns National Park

- Where Mammoth, Wind, and Jewel Caves score bragging rights for length, New Mexico's uniquely spectacular Carlsbad Cavern brings the depth. This cave, developed on three major levels, spans more than a thousand vertical feet from its entrance at the top to the bottom of the caverns at Lake of the Clouds.

- Mammoth Cave's Bottomless Pit stretches 105 feet from tip to pit. At more than 140 feet deep—370 feet if you count the distance to the ceiling of the Big Room above it—Carlsbad Cavern's Bottomless Pit could swallow Mammoth's with room to spare.

- The Big Room is roughly 2,000 feet long, 1,100 feet wide, and 255 feet high. Most memorable, however, are the abundant and unbelievably wrought speleothems that make Carlsbad one of the most- and best-decorated caves anywhere in the world.

- The more than 100 caves within Carlsbad Caverns National Park formed within the same Delaware Basin–fringing Permian reef complex that gave us the Capitan Reef at Guadalupe Mountains National Park. Carlsbad's enormous passages run through rocks formed in several distinct reef environments.

Carlsbad Caverns National Park.

- Like at Guadalupe Mountains, fossils in the limestones that form the walls of Carlsbad's caves reveal the biological diversity of this flourishing reef when it was alive.

- Carlsbad's method of formation involved brines (highly saline waters) from gas and oil deposits in the Delaware Basin. These migrated to the site of the future cave, where they mixed with oxygen-rich rainwater to create aggressive sulfuric acid. The acid accelerated the dissolution of the limestone, creating Carlsbad.

- Iceberg Rock in the park is a superb example of a collapse, or breakdown, block. Stalagmites, stalactites, and helictites appear more frequently at Carlsbad than at Mammoth or Wind Caves. The Big Room contains a number of the most impressive ones. Most of the other 100-plus caves at Carlsbad are not open to the general public.

Suggested Reading

Brucker and Watson, *The Longest Cave*.

Cahill, "Charting the Splendors of Lechuguilla Cave."

Questions to Consider

1. Just as at Mammoth Cave, exploration and mapping of new cave passages continues at both Wind Cave and Carlsbad Caverns National Parks. Search online for updates on the latest discoveries. Would you ever want to explore natural caves?

2. Both Wind Cave and nearby Jewel Cave (protected in Jewel Cave National Monument) are among the world's longest caves. How do these two caves resemble and differ from one another?

Lecture 34

The Everglades and the Congaree Bottomland

At the southern end of mainland Florida, a river of grass stretches from horizon to horizon above the slow-moving water that spreads life across the peninsula. Small clumps of pines, mahogany, and cypress gain a foothold on the smallest of rises in this flat, green landscape. Red mangrove fringes the coast, giving way to shallow estuaries such as Florida Bay. This wetland wilderness is Everglades National Park. Meanwhile, northeast up the Atlantic Coast, floodwaters rise to inundate an old-growth woodland of huge bald cypress, pines, and more. Here, in Congaree National Park, we see the swampy lowlands and primeval forests that once covered much of the southeastern United States.

Everglades National Park

- Explorer and conquistador Juan Ponce de León sailed to the Florida peninsula, a land rejuvenated each year by seasonal rains that spread water across this largest of North America's wetlands. Today, development, agriculture, and a teeming population of thirsty neighbors threaten the sprawling land of grasses, mangroves, islands, and water that we know as Everglades National Park.

- The Everglades and adjacent Big Cypress National Preserve sit atop the limestones of the southern Florida peninsula, a 400-mile-long extension of the North American continent. The peninsula itself is only the non-submerged portion of the Florida Platform, more than half of which lies beneath the shallow waters of the Gulf of Mexico.

- The Florida Platform got stuck to the North American continent during the collision with proto-Africa (then a portion of the larger continent Gondwana) that created the Pangaean supercontinent. Later, when the Atlantic Ocean rifted open, the Florida Platform got left behind.

- At the height of the Pleistocene glaciations, ice sheets bound up enough water on the continents to lower the ocean surface about

300 feet below today's level, roughly doubling the exposed width of the peninsula.

- Older sedimentary rocks of the Florida Platform include limestones formed when shallow seas covered the low-lying edges of Gondwana. There are also sediments shed from the eroding Appalachian Mountains to the northeast. But we only find more recently formed strata and unconsolidated sediments exposed at the surface on the Lower Peninsula, in and near the Everglades.

- Much of the limestone bedrock of the Everglades was deposited as the floor of the Pamlico Sea, which covered the southern portion of the Florida peninsula during the last interglacial period, roughly 100,000 to 150,000 years ago. This was only the most recent inundation episode: Repeatedly during the Pleistocene, and earlier during the Pliocene, shallow water covered the platform.

- The Tamiami Formation of sandy limestones and marine-fossil-bearing sands and clays forms the bedrock directly below much of the national park. More than 200 species of bivalve mollusks (creatures with a pair of hinged shells, such as clams) and perhaps three times as many species of gastropods (creatures such as snails) have been identified in a single unit, the Pinecrest Sand Member, of the Tamiami.

- Shark and stingray teeth and stingray barbs also proliferate in the park's substrate. Most of these creatures lived throughout the Gulf of Mexico and up the lower portion of the shallow Eastern Seaboard. And they still live there.

- Seasonal rains at the Everglades come mostly in torrential storms between May and October, while dry conditions predominate the rest of the year. This annual pulse of water is the lifeblood of the park, sustaining the delicate balance that supports the plants and animals of its ecosystems.

Everglades National Park.

- Developers and the state began digging ditches and canals to drain the Everglades, build communities and orchards on them, and provide irrigation water for large-scale agriculture early in the 20th century. This upstream disruption had, and continues to have, downstream consequences for the glades.

- They began to shrink and dry, displacing birds, critically endangered American crocodiles, and other wildlife, killing plants and exposing shallow peat soils that had developed atop the limestone platform. These vulnerable soils readily desiccate and blow away on the wind.

- Although it's only a part of this larger regional system of water flow that spans much of the Florida peninsula, Everglades National Park was intended to help stem the tide, protect the flow, and preserve at least the heart of the sprawling wetland.

- In tandem with the adjacent Big Cypress National Preserve, the Everglades encompasses a mosaic of distinct ecosystems, distinguished in large part by differences in local elevation, geology, and hydrology. The following is a list of eight key environments within the park.
    - Freshwater sloughs: The Shark River and Taylor Sloughs comprise a network of ponds, swamps, open-water courses, and grassy glades.
    - The marl prairie: This ecosystem is dominated by saw-grass sedge that looks like grass but grows to heights of up to a dozen feet. Marl prairie stretches from horizon to horizon and covers most of the park.
    - The pinelands: Stands of south Florida slash pine dot the southern end of the Atlantic Coastal Ridge where it divides Shark River Slough from Taylor Slough.
    - Hardwood hammocks: Hardwood tree species occupy the teardrop-shaped hammocks, or "tree islands," found in the freshwater sloughs and on the marl prairie.
    - Cypress groves: Pond cypress and the smaller dwarf cypress colonize the wet but earthy spots where muds and marls have filled pits in the limestone bedrock.
    - Coastal prairie: This ecosystem is near the southernmost extremity of the Everglades, on lower Cape Sable and the bottom of the Taylor Slough.
    - Mangrove swamp: Salt-tolerant red mangroves line coastal estuaries such as Florida Bay and the Ten Thousand Islands area at the northwestern end of the park.

  - Marine and estuarine zones: Along much of its western margin, Everglades National Park encloses marine waters of the Gulf of Mexico.

- Ensuring that freshwater continues to flow to and through the Everglades remains a priority for residents of southern Florida, whether or not they're ecologically minded.

- Groundwater drawn from the Biscayne aquifer provides most of the freshwater for greater Miami and the Florida Keys. This subterranean reservoir gets replenished as some of the water that travels across the Everglades sinks into the porous limestones below.

- The combination of rising sea levels, reduced recharge, and a growing population of thirsty residents has drawn down the surface of the Biscayne Aquifer and caused saltwater incursion, which spoils wells and threatens water supplies for the populous region.

- With more than 700 freshwater springs, the state of Florida might have the highest concentration anywhere on the planet. This abundance of springs is a natural consequence of the widespread distribution of limestone across the Florida Platform and its development through dissolution into karst.

Congaree National Park

- Congaree Swamp National Monument in central South Carolina became one of America's newest national parks, Congaree, in 2003. The name "Congaree" commemorates a Native America tribe that dwelled in these woods but was eradicated by smallpox in the 18th century. The national park encloses a dense forest, and a wet one, the nation's largest contiguous tract of old-growth bottomland hardwoods.

- Despite its prior name, Congaree lacks standing water throughout most of the year, so technically, most of the park is not a swamp. But the Congaree River swells and floods the tracts of old-growth bald cypresses on its floodplain about 10 times per year.

Congaree National Park.

- Congaree National Park sits a few dozen miles downstream of Columbia, South Carolina, as well as the fall line demarking the transition from crystalline bedrock of the Piedmont province to sediments of the Atlantic Coastal Plain. The floodplain setting is a depositional environment, one in which sediments are currently accumulating.

- Geologic maps and observation reveal that most of what's visible at the surface in the park is unconsolidated sediment, not yet transformed into sedimentary rock, that heralds from the relatively recent time span since the Pleistocene.

- Deep below the sediments and underlying sedimentary rocks lies crustal basement rock that was pulled apart in a Ridge and Valley–style rift basin when Pangaea stretched, and then split apart, and the Atlantic began to open hundreds of millions of years ago.

- The Orangeburg Scarp, eight miles north of the park, reflects the maximum inland reach of high Pliocene seas about 2.5 million years ago. It also defines the boundary between the upper and middle Coastal Plain.

- Congaree National Park lies seaward of the scarp and therefore would have been entirely submerged beneath the ocean on the continental shelf during the Pliocene.

- Congaree National Park encompasses six distinct geological environments.
    - The river channel: The Congaree River flows along the southern border of Congaree National Park. Its channel displays typical features of a meandering stream.

    - The river floodplain: Alluvium—a mix of river-borne sand, silt, mud, and peat—covers the Congaree's floodplain. These sediments are deposited and reworked each time the river rises to flood stage and inundates the surrounding lowlands.

- River valley terraces: Three distinct terraces within the national park mark prior and higher levels of the river before it eroded its way down to its current level.

- Tributaries and alluvial fans: Tom's Creek, Dry Branch, and Cedar Creek are all tributaries to the Congaree River. The tributaries have formed alluvial fans of sandy, well-drained soil brought down from the terraces above the Congaree.

- Rimswamps: Muck Swamp near the national park's visitor center is an example of a rimswamp, formed where surface sediment near the top of the water table comes close to the surface of the Congaree's floodplain.

- Oxbow lakes: Weston Lake, the largest example of an oxbow lake in the park, formed when a meander loop of the Congaree River got bypassed and left behind.

- In the shade of its canopy, under the Spanish moss, Congaree evokes a completely different feel from the open, sunlit vistas of the Everglades. Yet Congaree, too, includes wetlands, ecosystems in which water regularly or permanently holds sway.

Suggested Reading

Bryan, Scott, and Means, *Roadside Geology of Florida.*

Mairson, "The Everglades."

Questions to Consider

1. The Everglades proved to be instrumental in altering America's appreciation for the value of wetlands. The public view has evolved dramatically from what was perceived as a nuisance to U.S. military pursuing Seminole Indians in the 1830s and 1840s and a hindrance to development requiring that the land be drained. We now recognize that a healthy Everglades supports birds, marine life, and other wildlife and that it helps blunt the impact of hurricanes and other large storms. Are there wetlands near your home or in places you like to travel to, and if so, how are they protected and managed?

2. According to the Eastern Native Tree Society, the tallest known specimens of 15 different tree species live in Congaree National Park. What other national parks are home to particularly large trees, and what factors make those parks so conducive to the growth of large trees?

Lecture 35

Voyageurs, Isle Royale, the Canadian Shield

Exposed portions of the North American craton—a vast, continent-spanning bedrock dating from the Archean eon, more than 2.5 billion years ago—are called the Canadian Shield and stretch northward from both sides of the U.S.-Canada border to the Arctic Circle. Everything from Voyageurs and Isle Royale National Parks in the United States to Canada's Baffin Island and the microcontinent of Greenland are fellow travelers on the Canadian Shield portion of the North American craton. This is the buffed, beveled, and largely leveled core of the continent.

Voyageurs National Park

- With much of Voyageurs National Park accessible only by boat or float plane, it's not uncommon for visitors to travel the park today exactly as the historical voyageurs once did: in an open boat, gripping an oar. The park encompasses more than 30 lakes, more than 900 islands. One-third of this aquatic park lies submerged.

- The Kabetogama Peninsula makes up the bulk of the park's land, while four large lakes dominate its watercourses: Kabetogama Lake is fully enclosed within the United States. The other three lakes—Rainy, Namakan, and Sand Point Lakes—all straddle the international border, separating Minnesota to the south from Ontario to the north and east.

- Voyageurs sits at the southern end of the large physiographic province called the Canadian Shield, which is the exposed portion of a stable platform of basement rock in the deep interior of the continent, known as a craton. All of the continents have cratons, which are regions that have been spared mountain-building events and any accompanying deformations for upward of a billion years.

- Voyageurs National Park, along with Isle Royale, occupies a portion of the Canadian Shield called the Superior Province. Geologic provinces of the Canadian Shield accreted and collided, much like

Voyageurs National Park.

the newer physiographic provinces and accreted terranes of Alaska and the Pacific Coast. These proto-cratons had their own distinct histories and followed their own early trajectories until—one by one, early in Earth's history—they assembled to form what is today the core of the continent.

- Precambrian basement rock prevails throughout Voyageurs National Park, with exceptions only in places where shallow, recent-vintage, unconsolidated sediments have collected over the bedrock. Across the northwestern portion of the park, the dominant rock type is a dark green metamorphic rock called greenstone. Greenstone appears in other national parks, such as Shenandoah.

- The greenstone at Voyageurs formed primarily from the compression and alteration of lavas, at least some of which formed as pillow basalts. This metamorphosis of volcanic rocks can occur during tectonic collisions, making greenstone important for understanding when and how ancient proto-continents collided.

- The oldest rocks at Voyageurs National Park are but the deepest mountain roots, exhumed to their present elevations and low relief after more than 2 billion years of erosion. They once stood as tall as the Rockies or the Sierra Nevada, or perhaps the Himalaya. This beautiful but subdued, watery landscape is the legacy, recorded in stone, of those tall mountains.

- Where we find mountains, or even the roots of former mountains, we typically find faults. And where we find faults, we often find gold and other precious minerals. This is the case at Voyageurs, and elsewhere in the Superior Province.

- Although Voyageurs' bedrock and the ore-bearing veins are both quite ancient, we also see, across the park, the relicts of the latest glaciation: the Wisconsinan. Some of the handiwork of the glaciers includes glacial erratics, large boulders transported a long way from their places of origin to spots where melting ice abandoned them. There are erratics scattered about within the park and far beyond its borders.

- Long, linear grooves called striations carved into the bedrock reveal the southward and southwestward motion of the overriding glacial ice, along with the sharp debris it dragged along with it. Rocks also were buffed to a high gloss, called glacial polish. Glaciers dumped poorly sorted debris called till to form ridges of loose material called moraines.

Isle Royale National Park

- The Canadian Shield is on view not only in Minnesota but in other border states, too, notably in nearby Michigan, where Isle Royale National Park—a remote, 45-mile-long island, and an archipelago of hundreds of rocky islands surrounding it—sees fewer visitors in a year than Yellowstone gets in a day.

- It’s Lake Superior’s largest island, but it’s located more than 50 miles from the Michigan coast and 15 miles from the Canadian shore. You’ll need a boat or a seaplane to get here, along with time and a pair of comfortable hiking shoes if you’d like to explore Isle Royale’s roadless interior.

- For thousands of years, the Native Americans who inhabited Isle Royale mined the native, elemental copper that’s found here. They worked the copper into arrowheads, knives, and jewelry. After natives ceded the island to the United States government in a treaty proclaimed in 1843, prospectors and miners invaded, excavating pits across the island. Along with many smaller specimens, they unearthed a few monstrous chunks of copper.

- Ridges of greenstone are evident when you view maps or aerial photos of Isle Royale. These greenstone ridges are layers of Precambrian basalt lava, metamorphically altered to greenstone. Here, they tilt to the southeast.

- The ridges are the outcrops of lava beds and run parallel to the long axis of the island. These ridges include Minong, Greenstone, Stanley, and Red Oak Ridges. Rocks formed from sediments deposited between the lava flows have weathered away more readily and form the island’s linear lakes, basins, and bays.

- Isle Royale National Park includes glacial features similar to those at Voyageurs: till and moraines, striations, glacial polish, and an overall landscape that has had deep soils stripped from the bedrock. As the ice sheet overriding the island surged repeatedly from east to west, it smoothed the rock and left till behind. As a result, ridges called drumlins appear near the western end of the island.

Pukaskwa National Park

- Located on the north side of Lake Superior, Canada’s Pukaskwa National Park is the province’s largest national park. Here, rivers tumble through dramatic intrusions of granite and gneiss in a landscape where a more rocky view of the Canadian Shield is clearly visible.

Isle Royale National Park.

Wapusk National Park

- Travel 600 miles directly north from Voyageurs National Park and arrive at Canada's Wapusk National Park, which borders Hudson Bay, a shallow bull's-eye at the center of the Canadian Shield. This park contains the transition zone into Arctic tundra, from the boreal forest stretching as far south as Voyageurs and Isle Royale.

- This is also the realm of the polar bear. The park protects what is one of the world's largest maternity denning sites for polar bears.

- This lowland park encloses more than 4,400 square miles of territory, a mix of lakes and the peatlands or grassy bogs known across the region as muskegs, the largest muskeg landscape in North America.

Wapusk National Park.

- The words “mire” and “quagmire” also have been applied to this terrain type, a flat landscape where bedrock and permafrost prevent water from draining. Peat formed from dead vegetation and thick mats of sphagnum moss sometimes overlie standing water, forming a hazardous tangle.

Auyuittuq and Sirmilik National Parks

- The Canadian Shield continues northeast across Hudson Bay from Wapusk to Baffin Island, which is larger than the United Kingdom and home to portions of two remote national parks: Auyuittuq and Sirmilik.

- Geographically, Baffin is part of Canada’s Arctic Archipelago, which includes several dozen major islands defined by a chain of mountain ranges along their northeast called the Arctic Cordillera.

- Politically, Baffin is part of what in 1999 was carved off from the Northwest Territories to become Nunavut, the name for Canada's newest and largest territory. Roughly 80 percent of Nunavut's perhaps 30,000 inhabitants are Inuit. In the traditional Inuit language of Inuktitut, the park name "Auyuittuq" means "land that never melts."

- The park encompasses tall peaks formed of rocks that date back as many as 2.8 billion years and spectacular fjords with broad U-shaped profiles, such as the Pangnirtung Fjord at the mouth of the Weasel River and Maktak Fjord.

- A broad ice field called the Penny Ice Cap is here, one portion of which is believed to be a relict of the Wisconsinan glaciation—it still hasn't quite ended.

- The park name "Sirmilik" means "the place of the glaciers." The national park near the northernmost tip of Baffin Island includes the Borden Peninsula, Bylot Island, and the waters of a long, narrow fjord called Oliver Sound and Baillarge Bay.

- Amid tall peaks of the Byam Martin Mountains, ice fields and glaciers cover the interior of Bylot Island, which is among the world's largest uninhabited islands. Tall peaks called the Byam Martin Range extend from east to west across the width of Bylot Island, in effect continuing the Baffin Mountain Range. Both ranges are part of the Arctic Cordillera, which spans Baffin and Ellesmere Islands before ending on the Labrador Peninsula.

Quttinirpaaq National Park

- Even farther north, at the top of neighboring Ellesmere Island and Canada, lies Quttinirpaaq National Park. In Inuktitut, the word "Quttinirpaaq" signifies "top of the world." In fact, the park is the second most northern national park on Earth. Nunavut's highest mountain, Barbeau Peak, crests here at 8,583 feet.

- Primordial ice caps dating back to the Wisconsinan glacial advance still cover the park's highlands, with outlet glaciers radiating from them in all directions.

Northeast Greenland National Park

- The world's most northerly national park is found on an outpost of the Canadian Shield that broke away about 100 million years ago yet continues to travel along with the North American Plate. This one park accounts for almost 45 percent of the entire continent-scale island of Greenland, the largest island on Earth. Here, the Northeast Greenland National Park, administered by the Kingdom of Denmark, covers a staggering 375,000 square miles, making it the largest national park in the world.

- This park includes much of the Greenland's famous Ice Sheet (Earth's second largest, after only Antarctica's), which covers more than 80 percent of the island.

- The park also includes Peary Land, Greenland's northernmost region, portions of which, ironically, have had no glaciers or ice caps for thousands of years. Peary Land also boasts Earth's northernmost mountain (Mara) and Earth's northernmost lake (Kaffeklubben Sø).

- Incidentally, although the name "Greenland" seems strange for what is the largest ice sheet in the Northern Hemisphere, it's fitting for a geological reason: Greenland is home to greenstone that includes some of Earth's oldest rocks, dated from 3.8 to 3.9 billion years ago. The Isua greenstone belt of southwest Greenland might have been the suture zone with the North American craton, making the greenstone of Greenland a window into primordial North America.

Suggested Reading

National Geographic, *Guide to the National Parks of Canada*.

Ojakangas, *Roadside Geology of Minnesota*.

Parks Canada, http://www.pc.gc.ca/eng.

Questions to Consider

1. Given the presence of greenstones, along with granites intruded during the Algoman orogeny more than 2.5 billion years ago, at Voyageurs National Park, what other national parks might Voyageurs have resembled in the past?

2. Isle Royale, the islands of Cape Hatteras National Seashore, Nantucket, California's Channel Islands, and Elliott Key in Biscayne National Park are all islands, but they all formed in different ways. Describe the different geological processes that created these islands.

Lecture

36 Assembling North America, Park by Park

North America is a story of mountains raised by the collisions of earlier continents, oceans that drowned the lowlands, volcanoes raining ash and liquid fire, glaciers that burnished bedrock and bowed down the land, desert sand that buried entire regions, earthquakes rattling the rocks, and—drop by drop—rain that carried the mountains down to the lowlands and toward the sea. All this marvelous mayhem has shaped the national parks, and it continues to shape them.

The Craton and the Canadian Shield

- With public lands roughly as large as Yellowstone, New York State's Adirondack Park encompasses the Adirondack Uplift, a portion of the Canadian Shield, the largest exposed portion of the North American craton.

- Ongoing bulging of the local strata has raised the summit of Mount Marcy to an elevation of more than a mile and the elevation of more than 40 other peaks across the Adirondacks to more than 4,000 feet. The peaks are billion-year-old igneous intrusions dominated by plagioclase and gnarly metamorphic gneisses.

- These billion-year-old rocks date from the time when the supercontinent of Rodinia formed, long before Pangaea. The collisions that built Rodinia crumpled rocks in an event called the Grenville orogeny. Deeply buried mountain roots deformed during this collision later surfaced as crests we see in Adirondack State Park.

- A continental ice sheet scoured the soil off a patch of these ancient rocks and left behind Voyageurs National Park. Later outpourings of basaltic lava associated with crustal extension emerged from Lake Superior to give us Isle Royale National Park.

The Appalachian, Ouachita, and Marathon Mountains

- Just to the south of where the Appalachian Trail terminates at Mount Katahdin in Maine's Baxter State Park, a challenging stretch of a national scenic trail known as the 100-Mile Wilderness traverses what might become a national park named for the Maine Woods or the Katahdin Woods and Waters.

- Over hundreds of millions of years, tectonic pileups crushed the eastern and southern margins of the North American craton—the core of what was then Laurentia—to create the continent's eastern mountain belt. The long series of collisions emplaced granitic magma chambers that cooled and crystallized as plutons far underground and then rose to form the bald summits of Acadia National Park.

- With Pangaea, the Appalachian mountain chain we visit today was also born, from the ridge of Skyline Drive in Shenandoah National Park and the Great Smoky Mountains to their southwestern extensions, the Ouachita and Marathon Mountains.

Skyline Drive in Shenandoah National Park.

The Atlantic and Gulf Coastal Plains

- During the ice advances of the Pleistocene, glaciers covered what would become the state of New York all the way to the coast. They dumped a pile of debris at what was formerly called Bedloe's Island in New York Harbor.

- It's the boundary between ancient basement rock altered by the Taconic orogeny and much younger sediments of the Coastal Plain. The mound formed here is a moraine, perhaps the most famous moraine in the world, thanks to the French, whose gift of a giant, torch-bearing statue commemorating U.S. independence was completed and dedicated here in 1886. Known since 1956 as Liberty Island, it's administered with Ellis Island as Statue of Liberty National Monument.

- Ancient sediments are common throughout the Coastal Plain. As the Appalachian and Ouachita Mountains rose, streams, rivers, and landslides carried sediment down their flanks and out across the surrounding lowlands.

- These sediments, which continue to flow downward today, formed the thickening wedge that extends across the coastal plains of the eastern and southeastern United States, along both the Atlantic and Gulf Coasts.

The Appalachian Plateau and Interior Lowlands

- On the Appalachian Plateau, in what is now northeastern Alabama, we find Doran's Cove on Montague Mountain. Here, water moving underground dissolved limestone to create a large cave passage called Russell Cave. This cave sits in rocks of the Cumberland Plateau, just beyond the folds of Ridge and Valley rocks warped and pushed west by a collision of continents.

- In 1956, National Geographic purchased Russell Cave, underwrote archaeological excavations, and then donated the land to the American people. President John F. Kennedy proclaimed Russell Cave a national monument in 1961.

- Shallow inland seas have repeatedly covered lowlands of the North American interior that today lie west of the Appalachian Mountains. Here, too, sediments shed from the repeated rise of mountains along the Appalachian Chain got distributed, westward in this case, across the lowlands and in the shallow seas.

- To the north in Ohio, the Cuyahoga River etched its way down through rocks at the edge of the Appalachian Plateau and out across the lowlands.

The Great Plains

- On the Great Plains, westward migrants encountered unmistakable landmarks, beckoning onward via the Oregon and Mormon Trails. The National Park Service protects these ancient billboards in what has become Nebraska's western panhandle in Scotts Bluff National Monument.

- Almost everywhere east of the Rockies, a shallow "epicratonic" sea repeatedly covered the craton, burying it with sediments, and then withdrawing. Limestones appeared and mixed with layers of sediments brought down from the rising mountains. It was after the last of the seas withdrew that this land of sedimentary layers atop the ancient, stable craton became America's Great Plains.

The Rocky Mountains

- The disappearance of relatively warm, buoyant oceanic crust below the evolving western margin of North America triggered the rise of the Rocky Mountains far east of the subduction zone. The mountains rose in discrete ranges from north to south, from western Canada to New Mexico. Shoved inland, thick slabs of sedimentary strata slid to the east along low-angle faults, producing some of the jaw-dropping mountains of the Canadian Rockies and lofty peaks of Glacier National Park.

- Compression crumpled much of the landscape surrounding Yellowstone in the Middle Rockies and reactivated old faults at

Rocky Mountain National Park, causing deeply buried basement rocks to shoot up from the ground.

- Pleistocene glaciers took a mighty chisel to Yellowstone and Rocky Mountain, polishing their bedrock, sculpting out their valleys, and giving the sharp edge to their high ridges and summits. Meanwhile, erosion of a mountain belt west of the Southern Rockies yielded mountains of sand, piled up by the wind at Great Sand Dunes National Park and Preserve.

The Colorado Plateau

- Before there was a Colorado Plateau, a Sahara-scale desert of windblown dunes covered much of what is now western Colorado, 250 to 200 million years ago. In time, some of these dunes were buried and turned into the Wingate Sandstone. With the subsequent rise of the Colorado Plateau, the sands were resurrected and revealed once more in the sheer red canyon walls of Colorado National Monument.

- The Colorado River carved the mighty Grand Canyon here. The Virgin River chiseled a more intimate, but stunning, chasm for itself through sheer cliffs of cross-bedded Navajo Sandstone at Zion National Park. And a delicate balance between what erosion claimed and what it left gave birth to fragile wonders at Bryce Canyon, Arches, and Canyonlands.

- The Gunnison River sliced an almost impossibly narrow gorge through rocks of the risen plateau to form its Black Canyon. And the natural alcoves of Mesa Verde National Park offered early Americans the chance to build some of the most elaborate cliff dwellings in the world.

The Basin and Range

- The Rio Grande Rift Basin neighbors the Colorado Plateau, with volcanism that deserves attention. Lava flows are here on the Zuni-Bandera volcanic field, covering the patch of New Mexico that’s conserved in the El Malpais National Monument.

Yellowstone National Park.

- Mexico's Sierra Madre Occidental and Central Plateau continue the Basin and Range south of New Mexico and west of Texas—but quickly turn into something else.

- Thick layers of volcanic rocks rise more than a mile. Extensional rifting of the crust, the hallmark of the Basin and Range, opens the Gulf of California to the west, energizing rivers that produce a series of canyons, called *barrancas*. The rivers eat away at their canyons until some are longer and deeper than even the Grand Canyon of the Colorado River. Collectively, the region is often known by the name of just one of these—Barranca del Cobre, or Copper Canyon.

- To the west and the east, the ranges of Mexico's Sierra Madre Occidental and Oriental enclose the Central Mexican Plateau, or Mexican Altiplano. The Trans-Mexican Volcanic Belt borders the region to the south. Tens of millions of years of seafloor subduction, collision, shearing, and volcanism built these mountains called Sierra and lifted the plateau that underlies Mexico City.

The Sierra Nevada and the Coastal Ranges

- The Pacific Crest National Scenic Trail passes through Yosemite, King's Canyon, and Sequoia and continues south and north across the entire length of California. Redwoods formerly growing in places where the trail now passes were prized by lumbermen, who had already cut most of the continent's old-growth redwoods by the early 20th century.

- A U.S. Congressman from California, William Kent, and his wife Elizabeth responded to these losses by purchasing a grove thriving amid soils derived from scraped up seafloor and other rocks of the so-called Franciscan Complex. They donated their purchase to the federal government for conservation as Muir Woods National Monument.

- As Pacific seafloor descended beneath North America's west coast, it dragged water and sediments down with it. Together they warmed, causing the sediments and overlying rocks to partially melt and then rise as magma. The magma inflated balloon-like bubbles of liquid rock deep underground, magma chambers that fed volcanoes high above. The balloons crystallized into a string of granitic plutons—a batholith. Faulting and tilting caused the batholith to rise, forming the Sierra Nevada mountains.

Cascadia

- The collision of the Wrangellia Terrane with North America about 100 million years ago created Canada's Vancouver Island, along with parts of Alaska. Old rocks at the western edge of the North American continent slid over the incoming edge of Wrangellia on

John Muir Trail & Pacific Crest Trail in the Sierra Nevada.

low-angled faults. Glaciers scoured these transported and deformed rocks. What the glaciers left is an enticing and popular archipelago called the San Juan Islands.

- San Juan Island National Historical Park protects a portion of the island that gives the group their name. In 2013, Barack Obama used an executive order to transform 75 federally managed sites across the islands into San Juan Islands National Monument. The San Juan Islands are just a corner of the region we call Cascadia.

- A continuation of the Pacific Crest National Scenic Trail passes through the entire region, including North Cascades, Crater Lake, and Lassen.

Alaska

- At the southern end of the Alaska panhandle, Misty Fjords National Monument encompasses landscapes that John Muir likened to his own Yosemite Valley. Alaska seems greedy for even more of the tectonic terrane pileup that has refolded Alaska and built the state.

- Over the last million years or so, ice has shrouded much of this northern landscape and then melted back to uncover some of it. The glacial ice ground, scoured, and depressed the land, which, irrepressibly, rebounds with vigor whenever the ice retreats.

- Volcanic fires pierce the ice, raising more mountains and destroying others, spitting ash and lava into the air and sending mudflows down their flanks.

- The gigantic glacier 4,000 feet tall and 100 miles long that stood atop what is now Glacier Bay National Park just a few centuries ago melted away, opening an exquisite fjord for people and wildlife to enjoy. Kenai Fjords' Harding Icefield still paints much of that national park white, but the recent waning of almost every glacier across Alaska suggests that larger changes are afoot.

Hawaii

- Far west of North America, on the Hawaiian chain, Mount Waialeale's summit on the island of Kauai receives 466 inches of rain in a typical year, making it one of the wettest spots on Earth. Rain coursing down the volcano's flanks and the island's other western slopes has helped carve Waimea Canyon into layered ash and lavas.

- Far below the Pacific Ocean, a hot spot in the mantle is thought to send plumes of liquid magma into the oceanic crust of the Pacific Plate above. Time and again, this magma has broken through the rock of the crust to pour out across the ocean floor. Eventually, the broad shields of rock the magma builds rise above the water's surface to form the volcanic islands of the Hawaiian-Emperor chain.

- At the chain's youngest island, the eponymous Big Island of Hawaii, the lavas that raised Kauai have also built Earth's largest mountains in Hawaii Volcanoes National Park, although most of their bulk lies hidden beneath the waves.

The Columbia Plateau and Yellowstone

- Beginning 17 million years ago, volcanic vents opened along north-south fissures beneath what would become the state of Washington. They flooded the region with basaltic lava.

- Floods generated by the failure of dams on huge glacial Lake Missoula would help the Columbia carve a spectacular canyon through these flood basalts: the Columbia River Gorge. A multitude of Washington and Oregon State Parks preserve portions of the gorge.

- More volcanic vents opened to the east, paving the landscape across much of southern Washington, northern Nevada, and southern Idaho. They painted a dark arrow across the map of North America, an arrow we can follow to Yellowstone National Park.

- The conjectured mantle hot spot that unleashed the Columbia and Snake River flood basalts also elevated the land and fueled the supervolcano that erupted in and around Yellowstone. It left the immense calderas in which we find one of the world's most sublime and surreal landscapes brimming with natural wonders.

Suggested Reading

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Alt and Hyndman, *Roadside Geology of Washington.*

Burns, *The National Parks*.

Caldwell, *Roadside Geology of Maine.*

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Hazlett and Hyndman, *Roadside Geology of Hawaii*.

Heacox, *The Making of the National Parks*.

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Questions to Consider

1. After learning the geological stories behind all of the U.S. national parks and many in Canada and Mexico, which parks that you haven't visited yet would you most like to visit and explore?

2. What geological stories are told by the parks and other places that are dearest to you, and how will you share those stories?

Bibliography

If you’re hungry to learn more about the national parks and their geology, Robert Lillie’s *Parks and Plates: The Geology of Our National Parks, Monuments, and Seashore* makes an ideal starting point. Brilliantly conceived and marvelously presented, Lillie’s textbook uses the parks to illustrate all the essentials of plate tectonics. An encyclopedic reference, Ann Harris, Esther Tuttle, and Sherwood Tuttle’s *Geology of National Parks* presents detailed historical and geological profiles of every national park. Both of these volumes are recommended to anyone fascinated with the geology of the parks.

National Geographic’s *Guide to National Parks of the United States* and *Guide to the National Parks of Canada* are brimming with evocative photos, clear maps, and vital information on every national park in both countries. Whether you’re planning a trip or merely dreaming of one, you’ll savor these books.

Long-time *New Yorker* contributor John McPhee’s award-winning book series, collected in *Annals of the Former World*, chronicles his coast-to-coast transect of the United States in the company of geologists. This inspiring volume, in which McPhee brings historical geology to life, is recommended to anyone who loves geology and fine storytelling.

The Mountain Press Publishing Company has long devoted itself to the production of regional geology guidebooks by geologists who are also authors. Titles in the *Roadside Geology* and *Geology Underfoot* series are authoritative but also make good reading.

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Williams, Felicie, and Halka Chronic. *Roadside Geology of Colorado*. Missoula, MT: Mountain Press Publishing Company, 2014. Rocky Mountain, Great Sand Dunes, Mesa Verde, and Black Canyon of the Gunnison National Parks, as well as Dinosaur and Colorado National Monuments, all get fine treatment in this colorful, graphically rich, and compelling survey. [Lectures 18, 26, 28, 29, 30]

List of Parks

National Parks of the United States (59)

1. Acadia National Park, Maine, 1919 [Lecture 22]
2. Arches National Park, Utah, 1929 [Lecture 27]
3. Badlands National Park, South Dakota, 1978 [Lecture 23]
4. Big Bend National Park, Texas, 1944 [Lecture 32]
5. Biscayne National Park, Florida, 1980 [Lecture 20]
6. Black Canyon of the Gunnison National Park, Colorado, 1999 [Lecture 28]
7. Bryce Canyon National Park, Utah, 1928 [Lecture 27]
8. Canyonlands National Park, Utah, 1964 [Lecture 27]
9. Capitol Reef National Park, Utah, 1971 [Lecture 28]
10. Carlsbad Caverns National Park, New Mexico, 1930 [Lecture 33]
11. Channel Islands National Park, California, 1980 [Lecture 12]
12. Congaree National Park, South Carolina, 2003 [Lecture 34]
13. Crater Lake National Park, Oregon, 1902 [Lecture 7]
14. Cuyahoga Valley National Park, Ohio, 2000 [Lecture 17]
15. Death Valley National Park, California and Nevada, 1994 [Lectures14 and 18]
16. Denali National Park & Preserve, Alaska, 1917 [Lecture 13]
17. Dry Tortugas National Park, Florida, 1992 [Lecture 20]
18. Everglades National Park, Florida, 1934 [Lecture 34]
19. Gates of the Arctic National Park, Alaska, 1980 [Lecture 13]
20. Glacier Bay National Park, Alaska, 1980 [Lecture 9]
21. Glacier National Park, Montana, 1910 [Lecture 31]
22. Grand Canyon National Park, Arizona, 1919 [Lectures 24–25]
23. Grand Teton National Park, Wyoming, 1929 [Lecture 3]
24. Great Basin National Park, Nevada, 1986 [Lecture 14]
25. Great Sand Dunes National Park and Preserve, Colorado, 2004 [Lecture 18]
26. Great Smoky Mountains National Park, Tennessee and North Carolina, 1934 [Lecture 16]
27. Guadalupe Mountains National Park, Texas, 1966 [Lectures 20 and 33]
28. Haleakala National Park, Maui, Hawaii, 1916 [Lecture 5]

29. Hawaii Volcanoes National Park, Hawaii, 1916 [Lectures 4–5]
30. Hot Springs National Park, Arkansas, 1921 [Lecture 16]
31. Isle Royale National Park, Michigan, 1940 [Lecture 35]
32. Joshua Tree National Park, California, 1994 [Lecture 12]
33. Katmai National Park and Preserve, Alaska, 1980 [Lecture 8]
34. Kenai Fjords National Park, Alaska, 1980 [Lecture 9]
35. Kings Canyon National Park, California, 1940 [Lecture 11]
36. Kobuk Valley National Park, Alaska, 1980 [Lecture 18]
37. Lake Clark National Park, Alaska, 1980 [Lecture 8]
38. Lassen Volcanic National Park, California, 1916 [Lecture 6]
39. Mammoth Cave National Park, Kentucky, 1941 [Lecture 33]
40. Mesa Verde National Park, Colorado, 1906 [Lecture 29]
41. Mount Rainier National Park, Washington, 1899 [Lecture 6]
42. National Park of American Samoa, American Samoa, 1968 [Lectures 5 and 20]
43. North Cascades National Park, Washington, 1968 [Lecture 7]
44. Olympic National Park, Washington, 1938 [Lecture 7]
45. Petrified Forest National Park, Arizona, 1962 [Lecture 26]
46. Pinnacles National Park, California, 2013 [Lecture 12]
47. Redwood National Park, California, 1968 [Lecture 11]
48. Rocky Mountain National Park, Colorado, 1915 [Lecture 30]
49. Saguaro National Park, Arizona, 1994 [Lecture 32]
50. Sequoia National Park, California, 1890 [Lecture 11]
51. Shenandoah National Park, Virginia, 1926 [Lecture 15]
52. Theodore Roosevelt National Park, North Dakota, 1978 [Lecture 23]
53. Virgin Islands National Park , Virgin Islands, 1956 [Lectures 12 and 20]
54. Voyageurs National Park, Minnesota, 1971 [Lecture 35]
55. Wind Cave National Park, South Dakota, 1903 [Lecture 33]
56. Wrangell–Saint Elias National Park and Preserve, Alaska, 1980 [Lecture 13]
57. Yellowstone National Park, Wyoming, Montana, Idaho, 1872 [Lectures 1–2]
58. Yosemite National Park, California, 1890 [Lectures 10–11]
59. Zion National Park, Utah, 1919 [Lecture 28]

Other Parks in the United States (85)

1. Adirondack Park, New York, 1885 [Lecture 36]
2. Agate Fossil Beds National Monument, Nebraska, 1997 [Lecture 26]
3. Apostle Islands National Lakeshore, Wisconsin, 1970 [Lecture 19]
4. Appalachian National Scenic Trail, Maine to Georgia, 1968 [Lectures 15, 16, and 36]
5. Assateague Island National Seashore, Maryland and Virginia, 1965 [Lecture 19]
6. Baxter State Park, Maine, 1931 [Lecture 36]
7. Bering Land Bridge National Preserve, Alaska, 1978 [Lecture 29]
8. Buck Island Reef National Monument, Virgin Islands, 1961 [Lecture 20]
9. Canaveral National Seashore, Florida, 1975 [Lecture 19]
10. Cape Cod National Seashore, Massachusetts, 1961 [Lecture 19]
11. Cape Hatteras National Seashore, North Carolina, 1953 [Lecture 19]
12. Captain John Smith Chesapeake National Historic Trail, Virginia to New York, 2007 [Lecture 17]
13. Capulin Volcano National Monument, New Mexico, 1916 [Lecture 14]
14. Cedar Breaks National Monument, Utah, 1933 [Lecture 27]
15. Chaco Culture National Historical Park, New Mexico, 1907/1980 [Lecture 29]
16. Channel Islands National Marine Sanctuary, California, 2000 [Lecture 21]
17. Colorado National Monument, Colorado, 1911 [Lecture 36]
18. Columbia River Gorge National Scenic Area, Oregon and Washington, 1986 [Lecture 17]
19. Cordell Bank National Marine Sanctuary, Point Reyes, California, 1989 [Lecture 21]
20. Crazy Horse Memorial, South Dakota, 1948 [Lecture 23]
21. Devils Postpile National Monument, California, 1911 [Lecture 14]
22. Dinosaur National Monument, Utah and Colorado, 1915 [Lecture 26]
23. Drumheller Channels National Natural Landmark, Washington, 1986 [Lecture 31]
24. Edward Ball Wakulla Springs State Park, Florida, 1966 [Lecture 34]
25. Fire Island National Seashore, New York, 1964 [Lecture 19]
26. Florida Keys National Marine Sanctuary, Florida, 1990 [Lecture 21]
27. Florissant Fossil Beds National Monument, Colorado, 1969 [Lecture 26]

28. Flower Garden Banks National Marine Sanctuary, Texas and Louisiana, 1992 [Lecture 21]
29. Fossil Butte National Monument, Wyoming, 1972 [Lecture 26]
30. Garden of the Gods Natural National Landmark, Colorado, 1971 [Lecture 30]
31. Gerry E. Studds Stellwagen Bank National Marine Sanctuary, Massachusetts, 1992 [Lecture 21]
32. Gettysburg National Military Park, Pennsylvania, 1895 [Lecture 15]
33. Ginnie Springs, Florida [Lecture 34]
34. Glen Canyon National Recreation Area, Arizona and Utah, 1972 [Lectures 25 and 28]
35. Golden Gate National Recreation Area (including Alcatraz), California, 1972 [Lecture 12]
36. Gray's Reef National Marine Sanctuary, Georgia, 1981 [Lecture 21]
37. Great Falls Park, Potomac River, Virginia, 1966 [Lecture 17]
38. Gulf of the Farallones National Marine Sanctuary, Golden Gate, California, 1981 [Lecture 21]
39. Hagerman Fossil Beds National Monument, Idaho, 1975 [Lecture 26]
40. Hawaiian Islands Humpback Whale National Marine Sanctuary, Hawaii, 1992/1997 [Lecture 21]
41. Indiana Dunes National Lakeshore, Indiana, 1966 [Lecture 19]
42. John Day Fossil Beds National Monument, Oregon, 1975 [Lecture 26]
43. Lake Mead National Recreation Area, Arizona and Nevada, 1936 [Lecture 25]
44. Lake Powell Navajo Tribal Park (Antelope Canyon), Arizona, 1997 [Lecture 28]
45. Lava Beds National Monument, California, 1925 [Lecture 14]
46. Lewis & Clark National Historic Trail, Illinois to Washington, 1978 [Lecture 17]
47. Marianas Trench Marine National Monument, Northern Marianas Islands, 2009 [Lecture 21]
48. Maroon Bells-Snowmass Wilderness Area, Colorado, 1980 [Lecture 30]
49. Misty Fjords National Monument, Alaska, 1978 [Lecture 36]
50. Monitor National Marine Sanctuary, North Carolina, 1975 [Lecture 21]
51. Monterey Bay National Marine Sanctuary, California, 1992 [Lecture 21]
52. Montezuma Castle National Monument, Arizona, 1906 [Lecture 29]

53. Monument Valley Navajo Tribal Park, Utah and Arizona, 1958 [Lecture 27]
54. Mount Rushmore National Memorial, South Dakota, 1925 [Lecture 23]
55. Muir Woods National Monument, California, 1908 [Lecture 36]
56. National Marine Sanctuary of American Samoa, American Samoa, 1986 [Lecture 21]
57. Natural Bridges National Monument, Utah, 1908 [Lecture 27]
58. Nebraska Sandhills National Natural Landmark, Nebraska, 1984 [Lecture 18]
59. New River Gorge National River, West Virginia, 1978 [Lecture 17]
60. Newberry National Volcanic Monument, Oregon, 1990 [Lecture 14]
61. Niagara Falls National Heritage Area, New York, 2008 [Lecture 17]
62. Olympic Coast National Marine Sanctuary, Washington, 1994 [Lecture 21]
63. Pacific Crest National Scenic Trail, California to Washington, 1968 [Lecture 36]
64. Pacific Remote Islands Marine National Monument, Wake Island, 2009 [Lecture 21]
65. Padre Island National Seashore, Texas, 1968 [Lecture 19]
66. Papahānaumokuākea National Marine Monument, Northwestern Hawaiian Islands, 2006 [Lecture 21]
67. Pictured Rocks National Lakeshore, Michigan, 1966 [Lecture 19]
68. Point Reyes National Seashore, California, 1972 [Lectures 12 and 19]
69. Rainbow Bridge National Monument, Utah, 1910 [Lecture 27]
70. Red Rocks Park, Denver, Colorado, 1990 [Lecture 30]
71. Russell Cave National Monument, Alabama, 1966 [Lecture 36]
72. San Juan Islands National Monument, Washington, 2013 [Lecture 36]
73. Santa Monica Mountains National Recreation Area, California, 1978 [Lecture 12]
74. Scotts Bluff National Monument, Nebraska, 1919 [Lecture 36]
75. Sleeping Bear Dunes National Lakeshore, Michigan, 1970 [Lecture 19]
76. Statue of Liberty National Monument, New York, 1886 [Lecture 36]
77. Sunset Crater Volcano National Monument, Arizona, 1930 [Lecture 14]
78. Thunder Bay National Marine Sanctuary, Michigan, 2000 [Lecture 21]
79. Timpanogos Cave National Monument, Utah, 1922 [Lecture 36]
80. Upper Missouri River Breaks National Monument, Montana, 2001 [Lecture 17]

81. Vermilion Cliffs National Monument, Arizona, 2000 [Lecture 28]
82. Waimea Canyon State Park, Kaui, Hawaii [Lecture 36]
83. White Sands National Monument, New Mexico, 1936 [Lecture 18]
84. World War II Valor in the Pacific National Monument, Oahu, Hawaii, 1962 [Lecture 7]

Canada

1. Auyuittuq National Park, Baffin Island, Nunavut, 1976 [Lecture 35]
2. Banff National Park, Alberta, 1885 [Lectures 16 and 31]
3. Cape Breton Highlands National Park, Nova Scotia, 1936 [Lecture 22]
4. Ellesmere Island National Park, Nunavut, 1988 [Lecture 35]
5. Fundy National Park, New Brunswick, 1936 [Lecture 22]
6. Glacier National Park, British Columbia, 1886 [Lecture 31]
7. Gros Morne National Park, Newfoundland, 1973 [Lecture 15]
8. Jasper National Park, Alberta, 1907 [Lecture 31]
9. Kluane National Park and Preserve, Yukon, 1972 [Lecture 13]
10. Kootenay National Park, British Columbia, 1920 [Lecture 31]
11. Pukaskwa National Park, Ontario, 1978 [Lecture 35]
12. Quttinirpaaq National Park, Ellesmere Island, Nunavut, 1988 [Lecture 35]
13. René-Levasseur Island, Lake Manicougan, Quebec [Lecture 36]
14. Sirmilik National Park, Bylot Island, Nunavut, 2001 [Lecture 35]
15. Thousand Islands National Park, Ontario, 1904 [Lecture 17]
16. Waterton Lakes National Park, Alberta, 1895 [Lecture 31]
17. Wapusk National Park, Manitoba, 1996 [Lecture 35]
18. Yoho National Park, British Columbia, 1886 [Lectures 26 and 31]

Greenland

1. Northwest Greenland National Park, Greenland, 1974 [Lecture 35]

Mexico

1. Basaseachic Falls National Park, Barrancas del Cobre ("Copper Canyon"), Chihuahua, 1981 [Lecture 36]
2. Cañon de Santa Elena Flora and Fauna Protection Area, Chihuahua, 1994 [Lecture 32]
3. Chichen Itza Archeological Zone, Yucatan, 2010 [Lecture 34]
4. Cumbres de Monterrey National Park, Nuevo León, 2000 [Lecture 30]
5. El Pinacate y Gran Desierto de Altar Biosphere Reserve, Sonora, 1993 [Lecture 18]
6. Itzaccihihuatl-Popocatepetl National Park, Estado de México, 1935 [Lecture 6]
7. Maderas del Carmen Flora and Fauna Protection Area, Coahuila, 1994 [Lecture 32]
8. Palenque National Park, Chiapas, 1981 [Lecture 29]
9. Pico de Orizaba National Park, Veracruz and Puebla, 1937 [Lecture 6]
10. Sierra de San Pedro Martir National Park, Baja California, 1947 [Lecture 12]
11. Volcan Nevado de Colima National Park, Colima, 1936 [Lecture 6]

Belize

1. Bacalar Chico National Park and Marine Reserve, Belize, 1996 [Lecture 20]

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