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A Grand Canyon

FINALLY I TOOK the last step and reached the top. It had taken all day, but I had fulfilled an ambition to hike up through the world's best-exposed story written in stone. Standing on the rim, I turned and looked down almost a mile to the bottom of the Grand Canyon, still marveling over the extraordinary tale preserved in the rock walls along the trail. Elated and exhausted, I left the rim and walked over to the National Park Service gift shop.

I picked up a small coffee-table book intriguingly titled *Grand Canyon: A Different View*. It told of how Noah's Flood ripped up the surface of the world like a geological blender, laid down the great pile of rock exposed in the canyon walls, and then deftly excavated the canyon as the waters receded.¹

Digging deeper into the book, I read that the canyon itself was carved when the sediment that formed the rocks now exposed in its walls was still soft. I was puzzled that the authors did not try to explain how a mile-high stack of saturated sediment remained standing without slumping into the growing chasm—or how all the

Reprinted from THE ROCKS DON'T LIE: A Geologist Investigates Noah's Flood by David R. Montgomery.
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loose sand and clay later turned into solid rock. The book simply stated that, according to the Bible, Noah's Flood formed the Grand Canyon and all the rocks through which it's cut in under a year. There was no explanation for the multiple alternating layers of different rock types, the erosional gaps in the rock sequence that spoke of ages of lost time, or the remarkable order to the various fossils in the canyon walls. The story was nothing like the tale I read in the rocks I had spend the day hiking past.

The long plod out of the canyon still rang in my head as I returned the book to the shelf and stepped back outside. I savored the view and my day immersed in geologic time. Reading about earth history is one thing; to see and feel it for oneself is another.

I thought back to the beginning of my day, just after dawn. The towering rock walls rising above the bottom of the canyon baked in the early morning light as they've done for countless years. My knees still ached from the hike down two days ago; and the trail rising a vertical mile ahead promised another brutal hike under the Arizona sun. There was no alternative. I was committed to climbing out of one of the deepest holes in the world, passing through time from the dawn of life in the depths of the canyon to the modern desert at the top.

I approached the Colorado River, the clear turquoise water marking the start of the trail back up to the canyon rim. Watching the river flow beneath me as I crossed the footbridge, it dawned on me that the sediment-trapping Glen Canyon dam almost a hundred miles upriver robbed the river of the sand and erosive power that together cut a narrow slot into the hard rock exposed along the canyon floor.

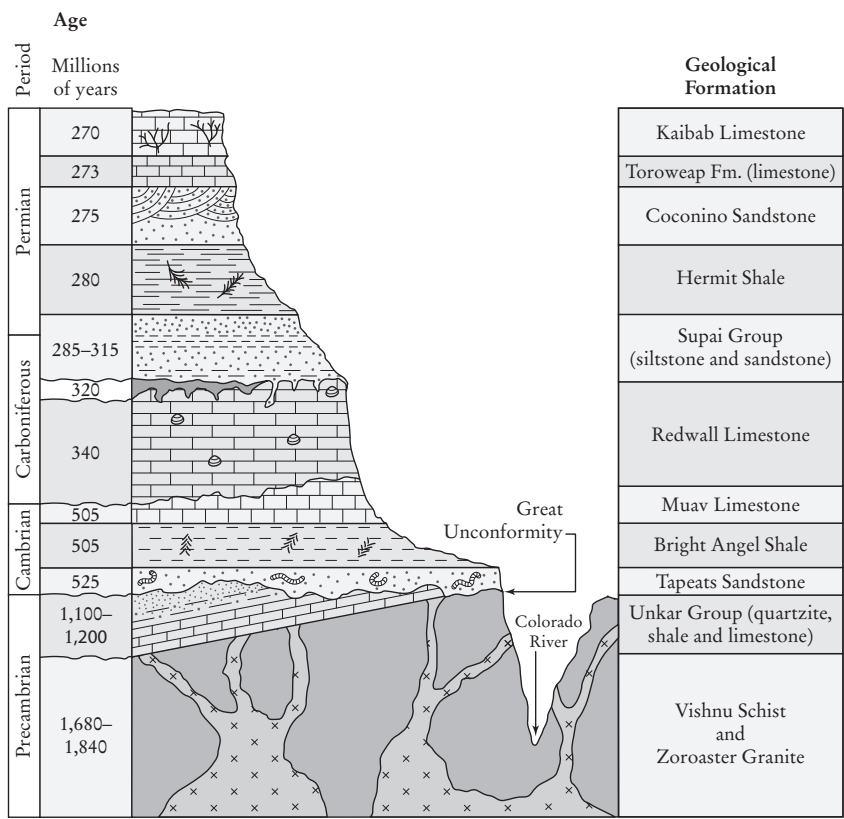
Halfway across the river, at the far side of the bridge I saw a tunnel enter the rock wall rising from the river's edge. I entered it and felt like I'd stepped back into deep time.

In the smooth rock walls I saw the signature of abrasive sand-charged floods surging down the canyon. The surface of the hard,

crystalline Vishnu Schist was a polished face made of intergrown quartz, feldspar, and mica stretched and folded at high temperature and pressure, deformed into great swirling patterns. Deep within the earth, below a now-vanished mountain range, the schist in front of me had crystallized long before dinosaurs, about a third of the way back through geologic time. But it didn't start out as hard rock. Ghost beds of sand lie preserved as light-colored, quartz-and-feldspar-rich layers sandwiched between dark layers of ancient mud now baked into aluminum-rich mica and garnet. This layering is a telltale sign that the schist formed when the sand and mud of an ancient seabed were buried deep enough to recrystallize and deform like melting ice cream.

To get hard rock to flow requires both extreme heat and high pressure. Recrystallizing and deforming the particular combination of minerals in the Vishnu Schist takes temperatures of 900–1300°F and more than three thousand times atmospheric pressure. Geologists know from temperatures measured at the bottom of deep drill holes that it gets 104–122°F (40 to 50°C) hotter with every mile below ground. We can surmise from this that the schist was approximately ten miles below the surface when it formed, twice as far down as Mt. Everest is tall. The bottom of the canyon exposes the roots of an ancient mountain range, visible today only because of the erosion of the overlying rock that had to have lain above the canyon walls to turn all that sand and mud into solid rock in the first place.

How long ago did the schist form below those ancient mountains? More than a billion years ago, although no one can tell just by looking at the rocks. Using the right tools, the age of a rock can be read like a geologic clock because radioactive isotopes decay at a fixed rate. Radiometric dating is based on the fact that younger rocks have more of the initial parent isotopes of their radioactive elements and older rocks have proportionately more of the daughter isotopes produced by radioactive decay. If you know the half-life of an isotope—



Stratigraphic column showing the rock formations exposed in the walls of the Grand Canyon (based on a sketch by Véronique Robigou).

how long it takes for half the remaining amount to decay—then the ratio of the parent-to-daughter isotope now in a rock tells you how long ago the rock crystallized.

Uranium-lead dating is the radiometric method commonly used to date the oldest rocks. The 4.47-billion-year half-life for the decay of uranium 238 (²³⁸U) to lead 206 (²⁰⁶Pb) is about the planet's age. Zircon, an uncommon mineral found in rocks like granite, is ideal for this dating method, as it strongly excludes lead from its structure upon crystallization. Because of this, all the ²⁰⁶Pb in zircon had to have come from the decay of ²³⁸U, since the mineral cooled. Geolo-

gists use a mass spectrometer to measure the amount of ^{206}Pb and ^{238}U in a grain of zircon and determine the age of the rock from the ratio of the two isotopes.

Continuing along the trail, thin bands of pink granite rise like fossilized stripes and cut through the swirling Vishnu Schist. These narrow lines of granite, called dikes, have uranium-lead ages of up to almost 1.7 billion years and neatly truncate the banding in the schist, adding a geometric flourish to the fluid forms crystallized in the inner canyon's rock wall. I could tell the schist is even older because the granite dikes cooled in cracks within it. The schist was already there when the granite cooled.

I felt like an ant crawling along the narrow trail as I snaked my way out of the inner gorge. Once I gained enough elevation, I could look down on the river and across to the other side. There, I could see a sequence of tilted rock layers on top of the Vishnu Schist and tucked in below the flat-lying Tapeats Sandstone that defined the upper lip of the inner gorge. Pitched up at a jaunty ten- or twelve-degree slant, this stack of limestone, shale, and quartzite (a hard rock made when sandstone is heated deep within the earth) records the changing depth of water in an ancient sea, deep-water limestone on the bottom giving way first to shale made from offshore mud and then to sandstone from a fossilized shoreline.

Whether eroded by rivers, wind, or waves, the truncated upper surface of the schist, together with the hardened marine sediment sitting right on top of it, is evidence that rocks once buried miles underground were brought to the surface, exposed to the elements, and then buried again deep below the bed of an ancient sea. After all this, the whole package got tilted up and planed off by erosion for a second time before being capped by the sediment composing the still flat-lying rocks rising far above. I could see it all laid out in the cliff, right across the river—two rounds of uplift and erosion buried beneath a three-thousand-foot-high wall of rock. An ancient

story only unveiled because the Colorado River carved the Grand Canyon.

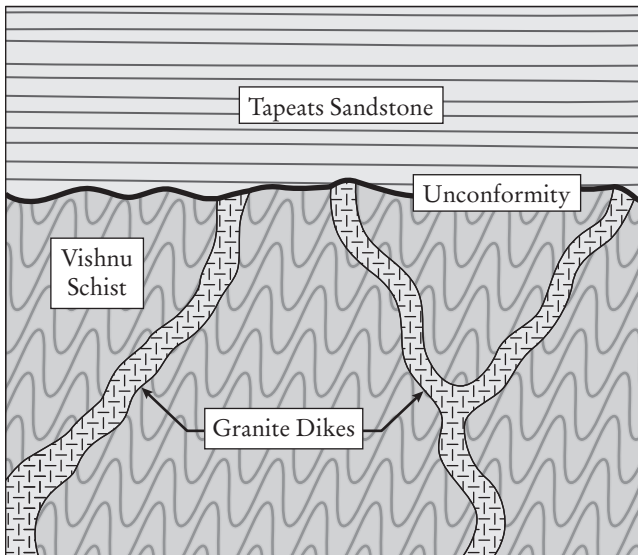
The striking outcrops of the inner gorge illustrate several simple rules geologists have used for centuries to read the story of rocks the world over. The first is that layers of sedimentary rock that accumulate in depositional environments, like sandstone and shale, represent time and are deposited horizontally. This makes sense, since these rocks form by settling through water under the influence of gravity, the way mud settles to the bottom of a glass of water. The second is that rocks at the bottom of a pile are older than those above them. This, too, seems obvious. And where one formation cuts off another, it is the younger that cuts across the older. Using these simple rules—determining what's above what, and what cuts through or across what else—is how geologists decipher stories of time and change written in stone. Of course, there is more to knowing how to read Earth's story, such as how two other types of rocks—igneous and metamorphic—are made, but simple interpretive rules apply to all rock types.²

Everywhere on Earth is either eroding and losing material or receiving deposits of material eroded off of somewhere else—one geologic realm sheds sediment, the other accumulates it. But the places where each is happening change over time. The most obvious change apparent in the walls of the Grand Canyon is that the marine rocks exposed in it have switched from one domain (deposition) to the other (erosion). Eroded upland environments are not preserved in the rock record because there's nothing left to see—they've vanished. The geologic signature of mountains is recorded by its absence, a gap in the record of time, while the story of our planet and life on it is archived in the sediments of depositional lowlands and marine environments—the places where sediment piles up over geologic time.

Deciphering earth history involves establishing the basic relationships between different rock formations and the nature of the

boundaries, or contacts, between them. Two layers of sedimentary rock deposited one atop the other without any discontinuity are considered conformable—they accumulated with minimal interruption. An eroded surface leaves a discontinuity between two rock units, a gap representing missing time that geologists call an unconformity. An unconformity represents how far down erosion wore into an ancient landscape before additional sediment was deposited on top. A whole series of unconformities exposed in the canyon walls tell of multiple rounds of deposition, deformation, and erosion before the whole package of rocks rose from the sea to the level at which we find them eroding today.

After far too many switchbacks, I made my way out of the inner canyon and across a cliff of flat-lying rock. In passing, I traced my finger along the surface of the unconformity where the Tapeats Sandstone rests on the irregular surface of the Vishnu Schist. The now



The great unconformity at the base of the Grand Canyon where the Tapeats Sandstone truncates the Vishnu Schist (based on a sketch by Véronique Robigou).

solidified grains of sand settled onto a rocky seabed in the Cambrian Period, about 100 million years before plants began colonizing land.

The span of time this unconformity represents is staggering. More time lies missing between the 1.7-billion-year-old Vishnu Schist and the 525-million-year-old Tapeats Sandstone than is recorded in the enormous wall of rock soaring thousands of feet overhead. All the lost time was enough to erase a mountain range and hide the ruins of ancient worlds, familiar in design but alien in detail. My imagination wrestled with how a thousand million years could vanish from the geologic record. Two worlds had come and gone, leaving nothing behind but their rocky bones.

I kept walking up, leaving the unconformity behind, and noticed burrows and tracks of simple wormlike animals in the cliff of Tapeats Sandstone through which the trail ran. The fact that marine life was crawling around the bottom of an ancient sea, as documented in the solid evidence right in front of me, presents a serious problem for the creationist view of the Grand Canyon. How could fragile worms have been crawling around on and burrowing into the seafloor during a flood powerful enough to remodel the planet? The biblical flood would have to have dumped more than ten feet of sediment every day for a whole year in order to have deposited the thousands of feet of sediment exposed in the canyon walls.

Finally I reached an area known as Indian Gardens, a broad bench a third of the way up the canyon. This scrap of flat ground offered shade and a welcome break from slogging up switchbacks. Trailside exposures of the hard-baked mud of the Bright Angel Shale showed why this relatively flat ground graced the side of the canyon. Rock fragments burst from beneath my boot as I kicked an outcrop in passing. The shale was too weak to hold a cliff.

I looked closely at the shale and saw more signs of life in the tracks and burrows preserved on paper-thin layers of stone. Here was proof of an ancient seabed made from slowly accumulating mud

in which animals crawled, foraged, and died. People more patient or lucky than I in inspecting these rocks have found trilobites, distant cousins of spiders and crabs that roamed the seas from 515 million years ago to when they perished in the Permian Period, almost 200 million years before the demise of the dinosaurs.

Pausing on the gentle terrain of Indian Gardens offered me a panorama of grand vistas. Yet the far rim lay out of sight. As I surveyed the staggering expanse of the canyon, it was hard to fathom how long it would take to erode the cliff at the canyon's edge back beyond the horizon, one rockfall at a time.

Lingering in the tree-shaded oasis of Indian Gardens, I reflected on how people see the land in different ways. More than rocks and topography, beliefs and experiences have shaped attempts to explain the formation of the Grand Canyon. People living along the canyon were curious about how it formed long before geologists and creationists formed their views.

Like the Tibetan villagers along the Tsangpo, Native Americans living along the Colorado River have stories about a giant flood. A Havasupai story attributes the carving of the Grand Canyon to a catastrophic flood that occurred when the mischievous god Ho-ko-ma-ta unleashed a tremendous rainstorm. Another, more thoughtful god, Pu-keh-eh, put his daughter in a hollowed-out log to save her from the monstrous current rushing down to the sea. After the floodwaters receded, she crawled out from her improvised vessel and became the mother of all humanity. The story shares the same broad outline as that of Noah's Flood—only with a matriarchal figure.

Still soaking up the geologic story, I began climbing again toward the canyon rim. At the far end of Indian Gardens the shale gave way to the Muav Limestone, a section of carbonate rock sitting directly on top of the Bright Angel Shale. The sequence of sandstone, shale, and limestone I had just walked told me that the water deepened over time. At the upper boundary of the Muav Limestone, another

unconformity lies at the base of a formidable cliff. This gap in the rock record documents another hundred million years lost to erosion above sea level.

What you find directly on top of the Muav Limestone depends on your location in the canyon. From where I was, the trail snaked up a looming wall of red-stained rock rising several hundred feet upward. Climbing through a slot in the dark cliff, the trail followed a fractured zone in the aptly named Redwall Limestone. Along the trail I spotted clamlike fossils, evidence that life in the rocks was starting to become more visible, more complex, and more familiar. Yet another unconformity lies atop the Redwall, this one perforated by caves and sinkholes that formed when percolating rainwater dissolved soluble limestone and made a Swiss cheese-like landscape. This unconformity represents another 25 million years between the deposition of the Redwall Limestone and the overlying rocks of the Supai Group.

Once above the cliff, the trail crossed back and forth countless times from siltstone to sandstone to siltstone and back to sandstone again. I was climbing a geological staircase made of shale treads and sandstone risers. Each step recorded the rise and fall of an ancient sea, with harder sandstone forming cliffs, and weaker shale forming gentle ledges. This means that the ancient sediments turned to stone before the canyon carved down into them. If the now solidified rock had been wet and loose when the canyon was cut, the canyon walls would reflect the strength of loose sediment rather than that of the rock. The sandstone would not hold cliffs because loose sand can only support slopes of at most 30 to 40 degrees, as you can see for yourself in the produce section of any grocery store by pulling an orange from the bottom of the pile. And that's when it's dry. Saturated sand can hold a slope only about half that steep—nowhere near a vertical wall. In contrast, wet clay is cohesive enough to support short vertical cliffs. If the creationist view held water—that the

canyon's slopes formed when the sediment was still saturated—then the slopes today would have shale cliffs and sandstone benches, the opposite of what's visible along the trail.

How long does it take for the finest sediment to settle out? Even in a bucket of still water it can take weeks for fine clay to drop to the bottom. The distinctive microrhythm of coarse to fine, coarse to fine, coarse to fine in the walls of the canyon proves how the now rock-solid sediment settled out from a series of flows. The hundreds of thousands, if not millions, of layers of silt could not have settled out and separated from the intervening layers of sand during the passage of a single violent current because turbulence would have resuspended the fine sediment. Individual layers of clay, silt, and sand take a long time to segregate out—and far longer to do so over and over again to build up a pile it takes hours to hike up through.

Every step brought me closer to the canyon rim, and I passed into the soft, easily eroded Hermit Shale, where the slope relaxes and piñon pines and juniper trees manage to hold down a thin soil. Within the rust-colored shale below the soil, fossil ferns, conifers, and the tracks of reptiles and amphibians revealed the former nature of the region. I had climbed out of an ancient ocean and into the remains of a temperate coastal jungle.

Passing out of the Hermit Shale, I started up more switchbacks and crossed onto a massive, strikingly white sandstone. Composed of pure quartz sand, the Coconino Sandstone exhibits cross-beds that define the faces of fossilized sand dunes rising diagonally through cliffs along the trail. Invertebrate tracks and burrows are preserved in these fossil dunes. One outcrop near the trail preserves reptilian footprints that displaced the sand, sending it slumping back down the face of a dune. Such fine-scale features would have been obliterated if they had formed underwater, the way waves running up a beach erase footprints in the sand. These dunes were made by wind.

Continuing my trudge, I passed through the yellow-gray Toroweap Formation, evidence that a sea submerged the desert sands of the underlying Coconino Sandstone. Then a final, grueling climb up the nearly vertical white wall of Kaibab Limestone. Plodding past day hikers heading down the trail, I could see 270-million-year-old fossil coral and mollusks that reminded me of the complexity and diversity of life I'd seen learning to scuba dive on Australia's Great Barrier Reef. Finally, I reached the top.

Standing on the rim, I reviewed the story I read hiking up through ancient worlds—missing mountains, shallow and deepwater seas, coastal jungles, windswept sand dunes, and coral reefs. The few simple organisms in the lowest layers offered an obvious contrast to the complex reef community at the top. I had completed a grand tour through geologic time telling of the rise and fall of ancient mountains and seas, with the rocks at the bottom reaching back to the dawn of life and those at the top predating the dinosaurs. That the cliffs were solid rock right up to the canyon rim testified to erosion of all the formerly overlying rock that provided enough pressure to solidify a pile of sand and mud in the first place. Whole worlds came and went before the one we know today.

One doesn't need to hike up through thousands of feet of rock outcrops to refute the notion that the Grand Canyon formed during a flood that somehow managed to lay down all those rocks right before carving through them to create the canyon. A simple experiment you can conduct at home will prove the point. Get a glass-walled box (a fish tank will do nicely), fill it with water, and pour in a mix of clay powder, sand, and pebbles. Larger particles and denser material will settle out first, forming a pile with pebbles on the bottom, sand in the middle, and clay on top. Then, pour in rocks or sand all of the same grain size but a mix of colors, and you'll get a collage for a deposit. In order to sort by color, you have to add one color at a time. The rocks exposed in the walls of the Grand Canyon could not

have settled out during a single flood because they alternate many times in color, grain size, and composition.

Something that really struck me about my hike up the canyon was how the plants and animals entombed in the walls of the canyon are extinct. If all the creatures buried in that mile-high wall of rock had been put there by the biblical flood, then why aren't modern animals entombed among them? That the vast majority of fossils are extinct species presents a fundamental problem for anyone trying to argue that fossils were deposited by a flood from which Noah saved a pair of every living thing.

A simpler, fatal problem for the creationist interpretation of Grand Canyon geology is that sandstone, such as the cliff-forming Tapeats and Coconino formations I hiked past, and shale, like the Bright Angel formation I kicked apart so easily, form under completely different conditions than limestones like the Muav, Redwall, Toroweap, and Kaibab. Marine limestone forms when organisms whose bodies are made of calcium carbonate (CaCO_3)—like coral, clams, or microscopic foraminifera—die. Their shells and skeletons pile up on the seafloor and, if subjected to enough pressure, temperature, and time, eventually form carbonate rock. Because the organisms that become carbonate rocks take time to grow and don't live in turbid waters, the alternating layers of biologically precipitated limestone and mechanically deposited sandstone and shale that settled out from turbid water could not have formed during the same event. The alternating sequence of different rock types stacked one atop the other in the canyon walls records a long series of events and environments.

A single enormous flood simply can't explain the geology of the Grand Canyon. As we'll see, geologists discredited the idea that Noah's Flood created the world's topography and deposited its sedimentary rocks in the early nineteenth century, decades before the first expedition down the Grand Canyon. When creationists argue

that they want to “teach both sides” of the argument about earth history in science classes—their view and those of the “evolutionists” they vilify—they neglect to mention that geologists had disproved the creationist view of a young Earth shaped by Noah’s Flood before Darwin ever began thinking about evolution.

Today, the real debate about the formation of the Grand Canyon is between geologists who agree about its geologic history but argue about its topographic history—exactly how and when the canyon itself formed. The conventional view is that by six million years ago the Colorado River had established its modern course to the Gulf of California. Radiometric dates on cave deposits record that the water table draining into the river dropped steadily downward at about a hundredth of an inch a year for at least the past three million years. Younger lava flows that spilled into the canyon also tell of gradual incision over the past half-million years. But a recently published study suggests that the modern canyon was preceded by an older canyon first carved by a river that drained in the opposite direction between eighty and seventy million years ago. Arguments about the topographic evolution of the canyon center on whether the modern canyon formed as a river eroded headward back into the Colorado Plateau, a plateau-bound lake spilled over a drainage divide to cut a new path to the Gulf of Mexico, or local uplift pushed rocks up around a river with enough erosive power to maintain its course.

Although a great flood did not carve the canyon itself, there is evidence of grand floods within it. Breaching of cooled lava dams that impounded the river may have launched catastrophic floods down through the canyon. One of these natural dams was over two thousand feet tall. Flood deposits found within the canyon include huge boulders perched hundreds of feet above the river. No doubt a flood capable of stranding boulders so high on the canyon walls would have been spectacular—had anyone been around to see them. But most of these floods occurred long before people made it to the

New World. Native American tales of how the canyon formed are attempts to make sense of mysterious landforms.

In contrast to how simply and directly creationist claims of a global flood can be refuted, it took centuries to compile the rough outlines of earth history. Generations of geologists competed to find key outcrops, develop new theories, and demolish the ideas of intellectual rivals. As the world became better mapped, several revolutions tied it all together—the discovery of geologic time, recognition of how both gradual and catastrophic action carve topography, and the revelation of how plate tectonics shapes Earth's surface. Geologists today are confident about reconstructing earth history because geological mapping and correlation, radiometric dating, and fossils all tell a consistent story. Geology provides an independently verifiable answer to the age-old question of how the world we know came to be.

All people, geologists included, tell stories to explain the world around them and thereby understand our place in it. Different ways to see the Grand Canyon led to very different interpretations of the canyon and what it means. It might seem reasonable to think that a global flood carved the canyon if all you have to explain earth history is what you read in the Bible. But if you let the rocks speak for themselves they tell another story, just as grand: about the unimaginable depths of geologic time instead of the devastating power of a single flood.

How did it come to be that today what one sees along the Bright Angel Trail contradicts what many consider a Christian view of the canyon? To answer this question, we need to explore a two-thousand-year-old running argument about how to interpret nature and the story of Noah's Flood. Perhaps the best place to start is at the top—of the world.