Chapter 6 **ICE AGE SYMPHONY** Mile 7.5-20.8

After our quick stop to see ancient animal tracks, we reboard and notice that JP has become more concentrated and serious. We motor out into water that has become smooth and unhurried as if we are in a long narrow lake. Dead ahead the river is sharply defined by a perfectly horizontal surface going bank to bank. No river is visible beyond it, but froth and splashes squirt up and fall back behind this flat river horizon. A roaring sound starts reverberating off the walls. There is river violence on the other side of that smooth lip, and we are moving straight into it. Jackass Creek coming from the south meets Badger Canyon from the north at the same spot on the river. A frenzy breaks loose on the river surface (Fig 6.1).

Fig 6.1 Badger rapid flowing right to left. The first big rapid encountered on a Grand Canyon raft trip. Debris flows following monster rainstorms surge out the gulch on the other side and dump piles of boulders that try to dam the river. Until they are pushed away, the water level upstream is higher as apparent in this photo.

Knowledge is power against irrational fear. I have been here many times before and know that past debris flows from violent rainstorms have sent boulders, gravel, and sand surging out into the river here from both sides. The river has topped this ragged, piled-together dam, and turned into a maelstrom as it flows over the jumbled mass. It is Badger Creek Rapid, the first of the dozens of large rapids we will encounter. My knowledge power gives way to a primordial concern about what might happen as we float toward this seething mass of water that is filled with more power than we floaters can possibly muster.

Several small rowboats from a private group are tied to shore with their occupants now standing on large boulders staring intently. They are plotting a possible route that will avoid the biggest waves. The rapids are different at different water levels. Badger is always nasty, and the concerned scouters in their fresh, colorful clothes know that many row trips have come to grief right here. One of our own passengers on a past trip regaled us one evening with an incredible story of how he and some friends on a private trip flipped their boats here, got hurt, and had to climb out for help. On this trip, most of our people don't know what to expect and are hanging on silently as we approach what looks like the end of the world. JP has run this rapid countless times and knows what he is going to see without having to climb up and scout. The observers at the bank focus on us with morbid concentration hoping to learn as we go through. In the concerned silence on our boat, JP yells, "Hang on tight and have a nice day." We get to the lip. He has the bow perfectly positioned and slows the motor because we certainly do not need to add to the speed of the water now. We go nose first right on in along a super smooth tongue of water flowing at "supercritical" velocity as hydrology engineers officially call such fast moving waveless water.

People scream. The big boat starts heaving and pounding. Heads and bodies jostle and jerk. Ice cold water shoots up in big violent jets and splats hard against anything sticking up. Which is us. Fear gives way to fun as the initial violence instantly passes and JP powers us through rollicking waves at the lower end of the rapid. We spin around at the end of the ride to watch our next boat make the traverse. People are whooping and applauding, but JP is staring intently. If there are any troubles with our second boat coming through, he will have to go into action. This will be a ritual practiced throughout the trip.

Large aprons of rock debris are piled up at the base of the river cliffs on both sides of us. Here it is fallen blocks of Kaibab/Toroweap Limestone and Coconino Sandstone. We have passed through their source layers now high above us and such piles will line the riverbanks throughout most of the remaining voyage. Some of the freshest rock examples to interpret and contemplate are in these fallen blocks, and we will wander among them at every stop. As the excitement of the rapid fades, we see a very different, red laminated layer called the Hermit Shale peeping through the increasingly extensive pile of rock debris mantling every slope (Fig 6.2).

Fig 6.2 Maroon colored Hermit Shale in an extraordinary exposure. Above it is the Coconino Sandstone overlain by the slope forming Toroweap Formation overlain by the Kaibab Limestone.

This shale cannot withstand rainwater flowing over it very well and easily washes into the river. As it undercuts the sandstone and limestones above, blocks of all sizes cascade down to form the rock litter below. The few almost vertical cliffs of shale near the river are clearly the freshest and most recently exposed parts of the Hermit. Here would be the place to look for fossils in this fragile rock if it were possible to hover in the hair against the cliff face. The Hermit is rarely exposed in such splendor and has yet to be extensively studied by geologists and paleontologists. Its beautiful red/maroon/purple color injects a magnificence to the walls that will persist for the rest of our raft trip.

The shale itself is mostly made of pressed together clay minerals which form when rainwater reacts with the kinds of silicate minerals found in lava flows, granites, and rocks of all kinds. Water is a caustic substance with respect to the everyday rocks we envision as eternally sturdy. Silicate rocks are made up mostly of silicon (Si) atoms bonded to oxygen (O) atoms with a smattering of 6 other common atoms carefully tucked into specific sites in the crystalline atomic sea of mostly Si and O. During weathering, water molecules nudge into the ordered array of atoms we call crystals and chemically tear the ordered lattice apart. The assaulted atoms combine with the water molecules to make microscopic crystals of clay minerals, the major constituent of dirt. Quartz in the weathering rocks resists this attack and gets released as small grains of sand when the newly formed clay minerals fluff apart on the rock surface. Any freed iron atoms in the parent minerals react with oxygen dissolved in the water to form rust, or hematite as the geologists call it. As rainwater flows over rock surfaces, the clay minerals, quartz sand, and hematite created by this chemical weathering are physically washed into streams. The streams wash into rivers, and the rivers wash into the seas. Calcium atoms (Ca) in the parent rocks don't fit well in the microscopic clay minerals and these end up dissolved in the flowing water. Thus, the rocks uplifted into great mountain ranges are converted slowly and relentlessly by reaction with rainwater into sand, clay, hematite, and dissolved calcium. All are delivered to the sea where they accumulate as quartz-rich sands and clay mineral shales along with $CaCO_3$ seashells made from the dissolved Ca and atmospheric CO_2 dissolved in the sea. The hematite grains are about the same size as the clay minerals, so they tend to accumulate mainly with the shales. In the case of the deep red or maroon Hermit shale, there was an inordinate amount of red hematite. Why is something that requires research. So far, no one I know of has tried.

We quickly arrive at Soap Creek Rapid, a short thumper of a traverse with an unexpected wallop near the end. People really scream. It has started. A buzz infuses our passengers because this is a lot of fun. Our big boats and experienced crew mean that the rapids are going to be as terrifying as a roller coaster ride instead of the life-threatening terror inexperienced people encounter in the small row boats. Many thrive on danger and come to the river to face their fears and push themselves through it. But that is not our trip. Amidst the daily roller coaster thrills, our minds are free to enjoy and contemplate the messages about Earth history and nature being shouted out around every bend, in every side canyon, and up every wall.

Only 12 miles along on our raft trip and not yet stopped for lunch, we have moved backward tens of million years in time and traversed through several chapters of a geology textbook. This geology lesson is coming at us fast and furious. We have contemplated how carbonates (limestones and dolostones), sandstones with giant cross beds, and shales form. It is a huge gulp for those learning for the first time and a constant reverie of past worlds for those in the know watching the walls go by. By day's end, we will have considered how all the common sedimentary rock materials form and get deposited. I begin to fret a bit that explaining all this to people already distracted by the fun of running the rapids is going to be a tough sell. We still must understand how the original sediment turns into the hard rocks we see, why the layers accumulated in the order they did, why we encounter them tilted, folded, faulted, and currently fractured. Another issue ahead is that in several days we will reach the bottom of the sedimentary stack and encounter a new universe of black, shiny, jagged, ragged, streaked and tortured-looking walls confining rapids that make all before look like child's play. I already know what geological science has to say about it all, but can I convey the wonder and impact it can have on the soul as I myself am now experiencing.

Around lunch time, we enter yet another new world. The canyon has become narrow and is now deeply entrenched in 1,500' high walls and getting deeper by the minute. The top of the cliffs is the top of the Kaibab Limestone, as it is most everywhere in the Grand Canyon. The sunbaked bright part of our trip is behind us. We have descended below the Hermit Shale into the more confined world of the red Supai Formation made of thin and thick sandstone layers tightly interbedded with dark red shales. The red shales wash out easily in rain and flow down the rock surfaces as muddy films. As the muddy water dries, the sandstone layers get coated with a thin film of red adobe. Crags, jutting layers, and smooth rock faces abound. And everywhere, and in every rock are vertical fractures. Fractures, fractures everywhere, as all the rocks did crack. The scenery is bizarre and extraordinary; its spell captures us now and forevermore on this river. It begins to bond our group with collective awe. The scenery is speaking to everyone, and signs of euphoria are already setting in.

As we enter this stretch, picturesque cross beds of sandstone in the Supai Formation jut out as inclined benches reaching almost to river level (Fig 6.3).

Fig 6.3 Sloping cross beds and fracture surfaces of sandstone as the river begins cutting down into the approximately 300-million-year-old Supai Formation. On a raft trip, this exposure is something of a portal to the beginning of drastically different, truly spectacular wall scenery that will last throughout the journey. The crossbeds are being etched out of a layer of a homogenous sandstone that appears as an almost featureless band on the wall downstream.

These crossbeds are smaller and not as numerous as in the Coconino we observed upstream. They could have been coastal dunes or formed in fast moving water, marine or non-marine. Somewhere after entering this fantasy land, we passed from the Permian aged strata into an older geologic era called the "Pennsylvanian." The Permian-aged sequence of uppermost Supai, Hermit, Coconino, and Toroweap Formations accumulated for a period of 30 million years. It is an exceptionally thick sequence rising upward to the great extinction of most lineages of animal life that had started about 540 million years ago and progressively evolved for almost 300 million years. During the climax of this early faunal evolution in the Permian, this area was still slowly subsiding. It was always near sea level, but the net subsidence rate was just slightly greater than the sediment accumulation rate. It is as if this part of the world was trying to desperately hang on and leave a maximal rock record of this great interval known as the Paleozoic.

The Supai is the thickest formation we have encountered, and we will be in this Pennsylvanian time interval for the rest of the day. We stop for lunch under a shady ledge. The river is a transparent emerald green flowing slowly past us. Large trout bred in fish hatcheries swim around after having been released upriver at Less Ferry and surviving the gauntlet of sport fishermen there. I stare at these creatures and wander off into philosophy. No matter how intelligent these fish might become, they will never comprehend fire. It just isn't in their universe even though it might be on a bank only 20 feet away from them. Just what do we humans think we can know about our universe? Surely there are similar simple things as fire to fish that will elude us forever. Maybe even that which I see in my huge telescope or even in the rocks around us. Like fish, we can never know. My philosophic diversion ends as I join the lunch line to make a turkey sandwich.

From this point on, we are entirely immersed in this unique world of the Supai formation. It is space contained and defined by the walls of the chasm which are already so high that we are unaware of what may be above and behind them. But they don't just rise straight up. There are tiers of walls that step back as you look upward. They are intermittently obscured by ledges and ridges that jut out. Contrasting with intervals of smooth walls, great piles of rubble mantle the lower slopes. Inaccessible alcoves, scallops, and slots penetrate the walls to various depths and are too numerous to count. All but intermittent swaths of smooth walls are gnarly and rugged. The rubble slopes are precarious and obviously prone to come crashing down if disturbed. The rock debris is highly angular with sharp edges, so hiking around in this hostile debris does not seem like an option. Having done so on slopes where every step sends rocks tumbling down, I cringe at the thought. Although it seems like we are moving through mountain ranges, there are no ultimate summits here. If you were to climb up to the skyline, you would be looking over a broad flat surface. We are, in fact, in a giant ditch (Fig 6.4). That is something I will not point out to the crowd.

Fig 6.4 The northeast part of the Grand Canyon is a grand ditch. From the river, the walls look like towering mountains. The Kaibab and Toroweap formations form steep cliffs above the dark red Hermit Shale which washes down over thin layers of sandstone and shale that make up the Supai Formation. This aerial view is to the south.

Geologists drill deeply into flat areas with subsurface rocks like this to figure out what is down below. They pull up core samples about 4" wide and try to extrapolate and then imagine what the 3D layout of the rocks is between the scattered drill sites. But here is this resplendently scenic trench cut by Nature deeply into the Earth and exposing its innards like nowhere else. To see so vividly what is going on "downstairs" is a geologist's dream. The scenery is lagniappe, but it is the scenery and adventure that lures so many to make the dangerous journey down the length of this zig zag slash in the ground.

As part of my overall plan to share the geologic ecstasy with my fellow rafters, we pull in after running House Rock Rapid for a short hike up Ryder Canyon. The deafening roar of this scary rapid resonates off the walls as I lead the troops over a small boulder field and up into the shade and quiet of a long narrow slot canyon sanctuary. The higher walls of this side canyon are almost vertical, and near the bottom they are scrubbed clean by frequent flash floods. Narrow ledges step upward along the dry stream course and define easy staircase routes until all is blocked by a dry waterfall cliff that requires skill and effort to get up and around. Here I wait while everyone gathers into this wonderful, shady classroom. Most of our adventurers arrived at the starting point of this raft trip anxious and exhausted from last minute packing and stressful travel. They did not get much sleep this previous night, had a bounteous lunch, and have been in the sun and fresh air all day. They have been bounced and jostled through several rapids and are starting to get the hang of things. Once they sit down relaxed in this deep shade, I know I'm going to see people lay back and doze off. When you see dark glasses tilted on drooping heads, you know they are goners. I taught college classes for 44 years, so I know this inspirational geology talk is going to be a tough sell. I give it a shot, because here we can see the story of the sea coming in and the sea going out in all its grandeur. It is one of geology's major themes and the key to everything we will see for the rest of the trip.

The walls of Ryder Canyon are simply alternating layers of sandstone and mudstone-- not something particularly scenic or something you would expect to be spectacular. Sandstone is just loose sand that got buried and turned into hard rock when tiny crystals of quartz and/or calcite grew in the water-filled pore spaces between grains. Mudstone started as microscopic sized clay minerals settling in quiet water, and then got pressed and compacted together by the weight of overlying materials during burial. Following subsequent tectonic uplift of this region, running water washed out gullies. Mudstone quickly turns to gumbo when exposed to water and is washed away to become muddy water all over again. The sandstone is harder and resists weathering. Thus, the walls of Ryder canyon have projecting ledges of thick sandstone separated by thin, horizontal, deep recesses where the mudstone washed out (Fig 6.5).

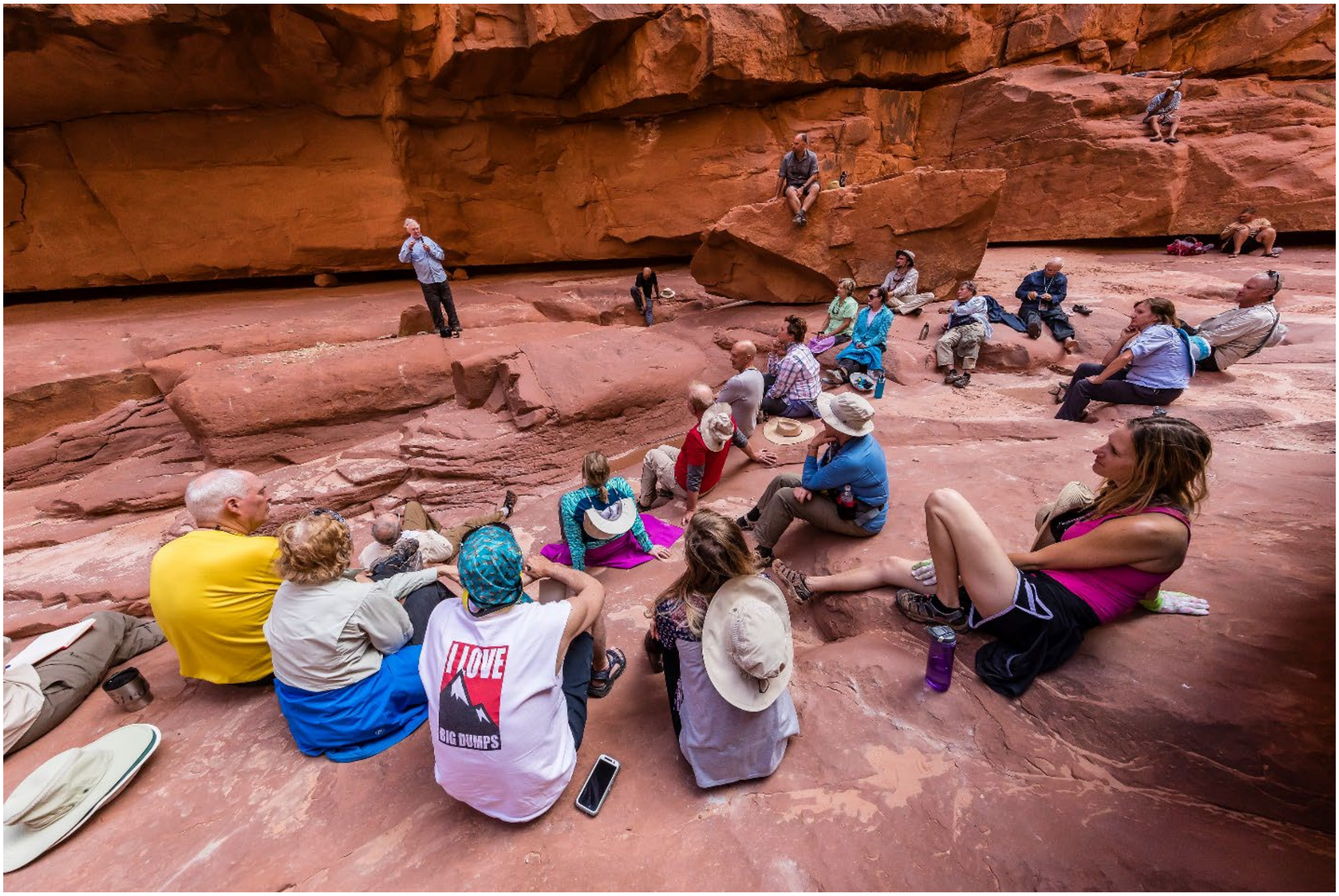

Fig 6.5. Author with audience in the Supai Formation classroom in Ryder Canyon. A thin shale layer once extended across the side canyon here but was washed away by innumerable flash floods along with everything above it-- right down to the sandstone surface people are sitting on. Horizontal slashes in the wall are left behind as the thin shales wash out. Blocks of the overlying sandstone eventually collapse and get carried down the side canyon by debris flows following major storms. (Image courtesy of Michael Dolan).

The ledges often appear as tabular stair steps and are typically great places to have a seat. So now we have seen the three kinds of sedimentary rocks that make the layers throughout Grand Canyon: sandstone, mudstone (shale), and carbonate (limestone or dolostone). Once calibrated, anyone can identify them even from a distance. In fact, here we can look down this side canyon, over the river, and up to the skyline where light gray cliffs of Kaibab Limestone are shining in the afternoon sunshine. The view up to the skyline on the other side of the river is majestic, framed as it is by the projecting ledges of Supai Formation sandstones. But did we really climb up here to look at something as mundane as sandstone and mudstone?

Shown the score of a Beethoven symphony, a musician can point out what it is composed of. Quarter notes, half notes, bar lines, letters such as ppp or ff indicating loudness, numbers indicating which notes define the beat and how many beats between bar lines, arching lines to indicate phrases, and even an indication of the speed the notes should be played. The score is interesting to a musician but meaningless to a music lover who just wants to experience the power, beauty, and profundity of the actual sound of a Beethoven symphony. Well, the sandstone, shale, and limestone on the walls here are like the notes. The thickness of each layer is often an indication of the speed of deposition. The sequence of the layers of various types stacked one over the other is musical phrasing to a geologist. The colors, textures, and internal structures of each layer indicate how each is to be interpreted. With a little geologic understanding, the walls of Ryder Canyon can erupt into a symphony--maybe even in a lethargic audience on the verge of dozing. Or maybe not. I will try because on this trip I especially want this crowd to have a chance of hearing a stratigraphic symphony.

"How many of you have visited the tomb of President John F. Kennedy in Arlington National Cemetery?" A few hands reluctantly rise to humor the prof. "How many of you refuse to raise your hand for any reason whatever?" A greater number of hands go up. This is going to be a particularly tough audience. No point in trying to engage using the dubious group interaction technique we profs are supposed to use nowadays, so I push on with some essential background that will allow the symphony on the walls to sing out. The story involves four simple processes, starting with President Kennedy.

(1) President Kennedy's tomb is covered with slabs of granite cut from giant boulders carried down from Canada during the last ice age and dumped on Cape Cod after the glaciers melted (Fig. 6.6).

Fig. 6.6. Weathering granite slabs at President Kenndy's tomb.

It has large pink crystals of the mineral potassium feldspar which are especially susceptible to weathering. When raindrops form, CO_2 in the atmosphere is immediately dissolved into each drop to form weak carbonic acid. Yes, all rain is slightly acidic. When it wets feldspar surfaces, the weak acid reacts with the mineral to form crystals of "clay minerals" visible if you magnify about 20,000X. Eventually, the feldspars along granite surfaces are reduced to dirt by this reaction, and any quartz in the granite (which doesn't react with rainwater) gets loosened and set free. Running water pushes the sand downhill into stream and river channels and tumbles it along the bottom as migrating ripples, dunes, and planar beds. The submicroscopic mud crystals that make up the dirt on weathered granite surfaces are easily stirred up into turbulent water to make rivers muddy. This "suspended load" is carried along in the water faster and above the white quartz sands being tumbled and shoved along the channel bottoms. That's it and that's why the surface of granite slabs at JFK's tomb are now so rough and fretted. In fact, they are slabs of special "Rapakivi" granite, in Finnish meaning "rotten rock." The feldspars in this type of granite are especially susceptible to alteration. Feldspars in all granites weather into clays and somewhere in distant mountains long ago, weathered granites shed mud and clay like JFK's tomb slabs are doing today. Their long journey ended here to make the sandstones and mudstones we see now in the walls of Ryder Canyon.

(2) Once a river reaches the sea, its velocity slows dramatically. The sand stops being pushed along the bottom and piles up trying to form a dam. Of course, the momentum of the fast-moving river punches through the wannabe dam and moves sand to the side and also farther offshore. The suspended muds take longer to settle and thus drift farther out. Meanwhile, the river breaches the shoulders of sand along the build-out to produce an array of channels resembling a bird's foot. The muds settle out farther offshore and around the shoulders forming a sort of mud web in the bird's foot. The result is a delta, and these can be huge indeed if the river is large.

3) Those who play in the surf at beaches know that when you come back to shore, you must walk back laterally from where you went in if you want to return to your umbrella/blanket/cooler setup. Yes, you have been pushed laterally down the beach by the always present "longshore" current while you played in the surf. Such ocean currents that move along coasts are always present and are stronger on some days than others. Sand grains get suspended, tumbled, and pushed toward the land as they violently surge and crash in along the beach. The wave water brought in then swiftly streams back out toward sea as a thin, smooth, gritty flow that tingles your feet. Sand grains on a beach are constantly moving in and moving out, but the longshore current ensures that the return path has a component of lateral movement. Individual sand grains are thus slowly zigzagging down the beach in the direction of the prevailing longshore current. A geologist calls a beach a "river of sand." It might seem a surprise, therefore, that it hasn't all moved away. It does move away, but it is constantly being replenished by the sand being dumped in from river deltas somewhere in the up-current direction of the longshore current. Deltas are always being destroyed by the longshore currents, but they in turn are replenished by new sand and mud coming down the river. The overall process can be quite intermittent where flow in the river depends upon melted snow in the spring. Beautiful sand beaches may shrink or disappear altogether until the spring floods bring new supplies of these quartz grains ultimately derived by weathering of granite.

Sand derived from continental landscapes can only get so far offshore because there just aren't any strong currents to move it out against the incoming waves. Offshore beyond the waves, there is greatly reduced turbulence, and the subsurface water is almost calm. So, mud transported in turbulent river waters carries out some distance offshore where it too is wafted along by the longshore current. There it slowly settles to the bottom in the calmer waters. The inward motion of waves keeps any sand that washes into the sea tucked up as an apron along the coastlines of the world and it keeps any mud flakes suspended in the swirling and crashing beach waves where it can't settle. The result of all this is that the sand and dirt washed off the continents get arrayed into two belts along shorelines—sandy beaches and offshore muds. Beyond the belts of sand and mud, the water is free of detritus and becomes remarkably clear. The take-home message is that the sandstone layers we see here in Ryder Canyon were likely once on or near beaches and the mudstone deposited mainly in layers away from the shoreline in the deeper, quieter waters offshore or in quiet-water embayments. This should be revelatory to someone sitting on one of these sandstone layers, but surely it is also confusing—the layers of sand and mud here are clearly not beach-size strips. They can be traced laterally as pancake beds and layers as far as the eye can see. Ryder Canyon eroded itself down into pancake layers, not down into strips. But the interpretation is not done.

(4) Sea level is always rising or falling over timescales of centuries. A global rise can result from melting glaciers and is happening today. Many geologists recognize that continental flooding can also happen globally if large tracts of the ocean floor swell upward in response to deep Earth heat expanding their volume and trying to escape. This apparently happens in narrow zones thousands of miles long to create the famous submarine "mid-ocean ridges." As these great mountains warp up, water is displaced over the continents (think sitting in a bathtub and the water rises). Coastlines everywhere are then slowly submerged. As the coastline moves inland, a belt of old coastal beach sand is now stranded offshore and gets covered with settling mud. A new "river of sand" beach is still at the coastline, but it is also moving sideways over the land at tectonic speeds (about the rate fingernails grow). If subsidence is slow and continuous, a layer of sand slightly tilted toward the sea is made from this sideways migrating belt. The offshore muds then encroach landward and drape this sand layer with an overlayer of mud. Bingo. A layer of sandstone overlain by a layer of mudstone is created. It is a gigantic mistake to look into the Grand Canyon and wonder how it is that the sea was everywhere depositing sand and then changed to depositing mud and then back to sand, etc. No, the layering is much more complicated. A shale layer deposited over a sand layer here indicates a sea level rise.

Another possibility for landward transgression of the sea is that a whole coastal region or edge of a continent miles or thousands of miles wide in just one part of the globe can subside along great faults. Regions can sink for a variety of tectonic reasons related to the local goings-on in the churning-at tectonic-speed of hot squishy rocks a hundred miles down. We recognize mountains as areas that physically rise upward by tectonic forces. Basins are just the opposite where a large region slowly sinks downward. Local tectonism could have lowered the land here and allowed the coastline to migrate inland. But the first important recognition here is that in Ryder Canyon for one sandstone/mudstone couplet we are not looking simply at mudstone over sandstone; we are looking at an event. Had we been here at the time of sand deposition, we would been having a beach party and maybe even snorkeling out beyond the surf zone to look at the muddy bottom through almost clear water. It is not obvious from where we sit today which direction we would have had to go to snorkel over the mud. All we surmise is that eventually the sand got progressively covered as offshore muds came in from whatever direction; the belts became pancake layers as the coastline moved inland. History is emerging and if we play Sherlock Holmes a bit longer, we may be able to deduce something wonderful about Earth history here from looking at how the layers are stacked and what some of the textures in them mean.

While visiting Kennedy's tomb at Arlington Cemetery, I witnessed a tour guide get off a bus with a large group and proceed to address everyone through a wireless lapel microphone and an amplifier/speaker box slung over her shoulder. Her voice was completely audible and clear to those in the back without reaching much beyond. And--it was not at all like a raspy "now hear this" bullhorn. I got the brand from her and bought one for use in talking with students and people on my numerous field excursions. I understand that people get tired, distracted, and daydreamy listening to a professor blather on and on. So, when they are obviously dozing off, a favorite trick is to surreptitiously turn up the volume and fake a sneeze. Nay, not a sneeze; the amplified mother of all sneezes! Here it resounds off the walls of Ryder Canyon, and people bolt to attention. If they can hang with me for one final point, the scenic but dormant walls of the Grand Canyon can come alive in the mind's eye.

The great Supai Formation is a thick stack of strata consisting of sandstones and red mudstones, one lying over the other over the other and so on. A single layer of mudstone over sandstone likely signifies a single sea level rise event. So, did we have numerous rises of sea level? That's one way to interpret it if we can understand what happens when sea level falls. All the mud and stand that was piled up during the flooding seems like it should just wash back into the sea if the coastline moves back toward deeper water. However, think about a dump truck driving down the highway and slowly leaking sand out its back tailgate. It leaves a pavement of sand. A truck following along loaded with dirt leaking out the back lays a pavement of dirt over the sand. Now they stop and back up together. The pavement now is thickened into a layer of sand overlain by a layer of dirt overlain by a layer of sand. Instead of trucks, we can return to our coastal belts of sand and mud that created a layer of sand overlain by a layer of mud as the coastline moved inward during a sea level rise. By analogy with the trucks going into reverse, a retreat of the coastline during a sea level drop could leave a layer of sand over a layer of mud over a layer of sand--but only if the whole region was simultaneously subsiding. Otherwise, it would all just wash back into the sea.

We must imagine northern Arizona slowly subsiding over tens of millions of years (not just centuries) because of tectonic goings-on deep below. Sediment from rising mountains far away is brought to this sinking area by rivers and streams. There are numerous alternating layers of sandstone and mudstone, so the shoreline advanced and retreated many times in response to some unknown global cause. Tectonics is longer range and doesn't yo-yo up and down this fast. Mid-ocean ridges probably can't swell up and sink so fast and as often as to produce sea level change that produced these meters-thick layers. But this stacked sequence is exactly what can happen during an ice age when ice freezes out on the poles causing sea level to drop and then thaws causing it to rise. Ice ages alternate periods of ice accumulation at the poles with ice melting. The great ice age we just emerged from had at least 5 major advances and retreats of high latitude glacial ice in 500,000 years, each associated with a fall and rise in sea level. So, the stack of alternating mudstones and sandstones in the Supai can be reasonably interpreted as ice caps forming and melting in the distant polar regions back in Pennsylvanian time.

This kind of sea level transgression/regression over the continents is widespread around the world for Pennsylvanian-aged sedimentary rocks. In Pennsylvania itself, coal beds occur within the sequence of this age group of rocks. The coal is plausibly attributed to lush vegetation along the coast that got buried by the transgressing sands and muds. Here there is no coal and the muds are dark red. The coasts here were thus arid with less vegetation and lots of rusting of microscopic iron particles in the sediments. Geologists studying global tectonics have independently argued that the continent of Antarctica was at the south pole during Pennsylvanian time, as it is today. They have also found direct evidence that it was then intermittently covered with ice like it is today. A continental platform under the pole allows ice to pile up to thicknesses it cannot do over water as in the case of the Arctic Ocean today. Snow falls there and turns to ice, but it floats southward instead of piling up. Submarines can surface right up through it and do. So, bingo, a reasonable and likely interpretation is that the Supai Formation is displaying a history of coastal sands and offshore muds moving in and out over northern Arizona during an ancient ice age when ice was melting and then retreating seaward when the ice froze again on non-drifting Antarctica. Ryder Canyon therefore displays a rock record of an ice age that occurred about 280 million years ago even though it itself was not directly deposited or disturbed by glaciers! The walls come to life. So do some of my fatigued fellow rafters when I sneeze into the microphone again and let them know it is time to hike back to the boats so we can raft on to our first night's camp at North Canyon. JP takes the mike and explains the logistical drill we will do when the boats arrive there. As people file out, I stare up at the walls and listen with renewed wonder to the ice age symphony. Look you how incredible this is! Just layers of mudstone and sandstone, each of itself rather nondescript but turning into something significant and magnificent when the results of geological science are brought to bear. It is a grand theme of geology in all its glory displayed here like maybe nowhere else on Earth.