Ch 12 BENEATH THE CRYSTAL SPHERES Mile 52-65

There is a famous wood engraving of a pilgrim in the Middle Ages who crawled to where the sky meets the edge of the flat Earth and stuck his head through to see the wonders beyond (Fig 12.1).

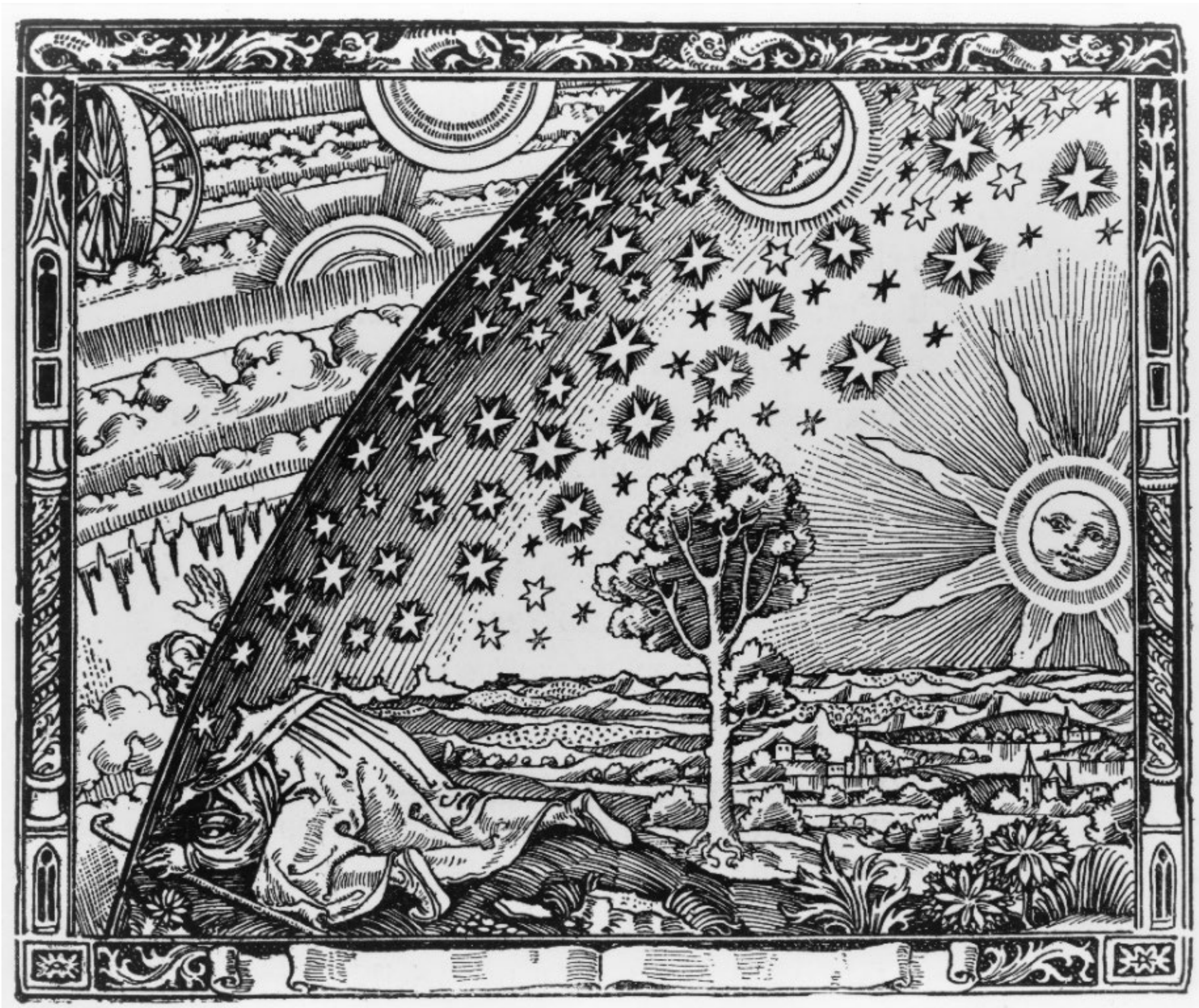

Fig. 12.1 A medieval pilgrim crawls to the edge of the flat Earth and peers beyond the crystal sphere of the sky to see worlds upon worlds. (Famous engraving by unknown artist first published in 1888 book by C. Flammarion).

In this stretch of the Canyon, I feel like our descent through the Paleozoic layers is about to do an analogous thing. We are going to descend through one more layer and then punch through the bottom of the flat-lying Paleozoic strata to see what lies beneath. That famous geology diagram on the souvenir bandanna (Fig 3.9) is a little confusing about that (Fig 3.9 repeated here).

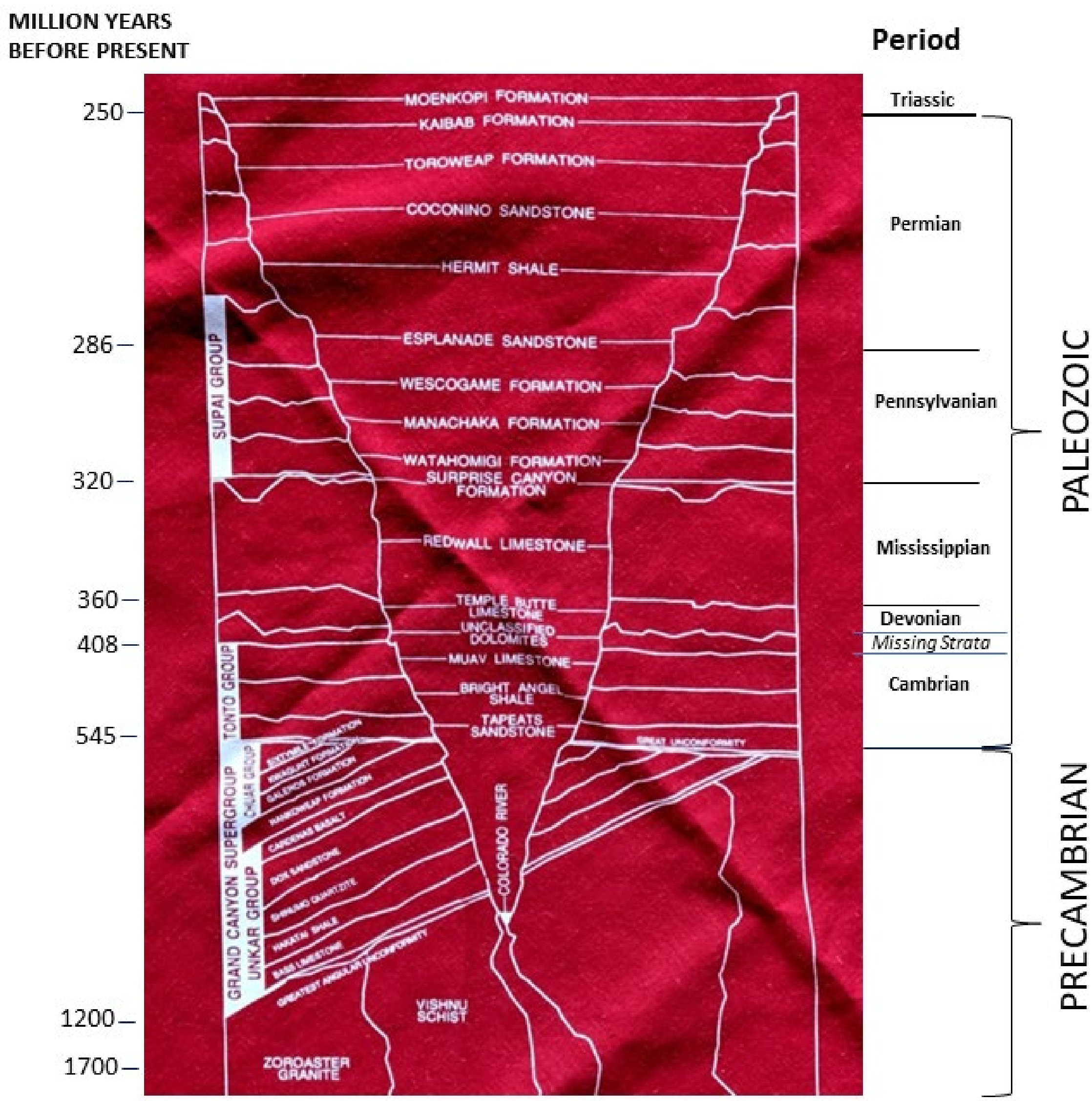

Fig 3.9 (repeated). Depending upon the location in the Grand Canyon, the Paleozoic strata are sometimes found on the tilted Precambrian strata or on the basement rocks (Vishnu Shist and Zoroaster Granite in this diagram).

The actual situation is even more complicated. What you encounter depends upon where along the length of the river you are. In places, it is sedimentary layers of a very different sort interbedded with jet black solidified lava flows. All are tilted like the slopes on a roof. In other places, it is the “Basement Rock.” This can be made of granite and/or hard shiny rock made of pressure-cooked mudstone now composed of platy minerals that split out along planes and layers parallel to each other. The fracture zones in the basement are typically somewhat vertical but are often wrapped like layers into folds, or they are themselves broken and shattered. Veins of white quartz crisscross the tightly packed layers and are frequently associated with granite fingers, pods, and irregular masses. Without a geologic map, there is no way to predict which of these possibilities we will encounter ahead. All we can be sure of is that the Bright Angel shale we are in is one of the thinner layers of the Paleozoic and that the layer below should appear soon after departing the Nankoweap Delta.

Sure enough, about five miles downstream a much more resistant ledge appears at river level. Then another and another of the same thing, each about 3-10 feet thick. These are the gritty layers of the Tapeats Sandstone (Fig. 12.2).

Fig 12.2 The Cambrian Tapeats Sandstone makes its first appearance on a raft trip. Coarse gritty sandstone with low angle crossbeds.

Unlike the sandstones of the Supai formation, these consist of large, irregular sand grains. The weathered surface of each is rough to the touch, and all are crudely cross bedded. The sandstone layers can alternate with much thinner layers of siltstone and mudstone that wash out easily. The coarser sandstone thus juts out in an endless number of ledges that people can climb on and rattlesnakes can hide under. Some of the ledges stick out far enough that people can take shelter from the hot sun.

We pull in on our right at the lower end of 60 Mile Rapid and all tuck under a big shady overhang for lunch. It is a pleasant spot to look at crossbedding and burrow trails in a Cambrian unit yet older than the Bright Angel Shale. As I throw my life jacket on a gritty rock bench, I see small rusty red lumps and bumps ranging in size from BBs up to marbles embedded in the sandstone itself (Fig. 12.3).

Fig 12.3. Spherules weathering out of Tapeats Sandstone at Mile 60 rapid. The large broken one reveals that they are spherical zones of the coarse sand held together with dark red, hematite-rich quartz cement. The cement in the concretions is stronger than the quartz cement between individual sand grains in the host sandstone. Spherules like these are common in many sandstones of the Colorado Plateau.

The spherules are scattered within the sandstone but are often more concentrated in certain areas. The crew begins setting up lunch while we crowd into this rather confined space. So, I start a river seminar on these little features called "concretions" because they have recently taken on a surprising significance.

I pass around a hand lens and engage a few of the curious to look at the normal sandstone here under magnification, then at some of the concretions, and then tell us what is different. Someone willing to seriously participate reports that it is easy to see rounded sand grains in both but that the concretions have a dark red stain on or between the individual grains. Clearly, these little nubbins weathering out of the rock are not separate entities but are simply spherical zones of sand grains with dark cementing agents that resist weathering. Cementation in sands occurs during burial when large amounts of water weep through the pore spaces. Quartz is slightly soluble such that water moving through sand becomes saturated with dissolved silica that can precipitate in pore spaces somewhere down the flow path. Microscopic quartz crystals then grow in the voids and cement the sand turning it into sandstone. Here the cementing agent apparently contains dark, microscopic hematite inclusions. Iron was apparently being carried in solution and precipitated along with the quartz growing in the voids. The issue of why it is sometimes concentrated into spherical domains rather than being uniformly distributed throughout a deposit has never been really studied or resolved. The source of the iron was likely black sand particles made of the mineral ilmenite. This is a minor but common mineral in many igneous rocks. Upon weathering, it travels with the quartz sand and is noticed by beach combers where it accumulates at the top of ripples in the swash zone. During deep burial, the iron apparently gets chemically redistributed into the growing quartz cements. It appears to be more concentrated in spherical zones that define the concretions. Why this should happen is an unsolved mystery. We will encounter another manifestation of this mystery as we hike through more extensive exposures of the Tapeats tomorrow.

Many of the sandstones in southern Utah and northern Arizona host these dark or rusty concretions. They are often called "Moqui Marbles," apocryphally suggesting that ancient Native American children played games with them. They may have, because little concretions weather out of sandstones in this area and can lie around on the surface by the thousands. Long considered only a geologic curiosity, studies have shown that the cement holding the concretions together amounts to less than a few percent or so of the total bulk and is highly variable in composition. The cements are often also rich in tiny clay minerals along with the calcite and quartz growths. Red coloration is significant. Iron will not dissolve in significant amounts in oxygenated water. Instead, it reacts with the dissolved oxygen to form rust. If the water is free of oxygen as happens in the deeper subsurface, iron will go into solution and be carried along as the pore waters slowly weep between sand grains. If the water mixes with oxygenated waters as it rises to shallower depths, the iron reacts with the oxygen and hematite forms. One story thus goes that rusty concretions form in sandstone when deep ground waters mix with shallow ground waters causing an interval when tiny cement-forming crystals formed between the individual sand grains. If so, we are likely looking here at what was a mixing zone between such ground waters long ago, possibly after most or even all the Tapeats had accumulated. There is no way to age-date concretions, and the variable depths at which they form have never been established.

The pilgrim rants again about NASA Mars science.

The study of concretions was not considered very important, and only a few of us geologists had devoted much time to them until 2004 when America landed roving instruments on Mars at two separate locations. One landed in a 103-mile-wide crater which was thought from orbital images to hold lake sediments but instead was just the usual lava flow rubble. The other was far away where "specular hematite" was inferred from orbital measurements. Specular hematite is a shiny, dark variety of hematite with a metallic luster. It is common on Earth in metamorphic rocks and where hydrothermal waters circulate at depth. The Mars site was thus interpreted from orbit as a hot spring deposit the size of Oklahoma. Vastly smaller hot springs in Yellowstone National Park host certain microbes that tolerate temperatures normally thought to be sterilizing. So maybe microbes could be fossilized in such huge deposits on Mars. However, hematite is relatively uncommon in the Yellowstone hot spring deposits. Indeed, the rock chemistry and mineralogy are utterly unlike anything detected yet on Mars. The comparisons and the assertions that specular hematite indicated hot springs were thus puzzling to many geologists familiar with hematite and with hot springs. Shortly before the landing, one of the mission team leaders publicly suggested that maybe it was not a hot spring deposit after all but more likely an "Iron Formation"--a sedimentary layer that contains abundant non-specular hematite. In fact, neither interpretation was even close. Instead, the surface was covered with millions of tiny spherules the size of blueberries which were either coated with or made up mostly of hematite.

Images and data from the rover finally indicated that it had landed on a deposit of cross bedded layers made of sulfate-rich "basaltic materials." The initial announcement was that it had landed on the former shoreline of a shallow salty sea. The spherules were embedded in the sediments but had somehow become concentrated on the surface, possibly as a lag deposit from strong winds that blew away the basaltic materials. Someone on the small team NASA had assembled to provide a consensus interpretation for the public knew about Moqui Marbles in Utah, so the blueberries which superficially resembled them were announced to be hematite concretions formed by the flow of abundant groundwater. Indeed, it was concluded that the groundwater surfaced between small wind-blown dunes and flowed to make crossbeds out of the basaltic materials. What?? Utterly unlike the martian examples, the Moqui Marbles are made of quartz sand with a tiny amount of hematite in the cement—as these at 60 mile rapid. This profound discrepancy was never acknowledged, and to this day our geology and astronomy textbooks commonly feature side by side images of Moqui Marbles in Utah and Mars blueberries with the caption explaining that this shows there was once groundwater on Mars. Thankfully, no mention was made that hematite concretions form in the subsurface and likely require pore fluids to rise from deep down up into oxygenated ground waters. That would imply Mars had oxygen in its atmosphere when these formed and would thus provoke claims that photosynthesizing plants were once present. Then there was that bizarre claim about emerging groundwater between sand dunes to make small-scale crossbedding they thought they had discovered. Alarm!

Don Burt (shown in Fig 11.12), Ken Wohletz, and I published a long article in the professional journal Nature explaining that everything seen on this mission can be readily explained as blast beds from enormous explosions as observed on Earth including those of nuclear bomb tests, volcanic eruptions, and past asteroid impacts. The martian surface is covered with impact craters. Every square foot of the martian surface has been swept by hurricane force winds from giant impacts repeatedly for 3.8 billion years. Wind blasts from impact explosions can produce the low angle crossbeds observed in the "basaltic materials" as well as the "blueberries" which form like hailstones in the turbulent blast clouds of volcanic explosions on Earth. There was no need to invoke groundwater and surfacing groundwater. Later missions continue to send back images easily understood in terms of impact blast deposits, but NASA interpretations remain unrelentingly fitted to the water interpretation. Force fitted? Our paper and several subsequent on the same subject did not go over well with the NASA community, but many individuals secretly communicated support. Even though I was receiving NASA "Exobiology" grants and was in the NASA Astrobiology Institute, I felt uncomfortable in the NASA science environment. There was not much geologic expertise in planetary geology, and younger colleagues seemed unwilling to challenge whatever the designated interpretative teams pronounced. I decided to abandon Mars science altogether. Maybe the interpretive teams are correct but count me out. It just didn't seem like science as I understood and practiced it.

Lunch is called, so there is no chance for blowback from those unhappy to hear contrarian views like this. Other guides may have told people about concretions, but their listeners probably never experienced a story that challenged NASA science. The recognition of problems with the scientific method as practiced by real people is apparent to research scientists but not so much to the public. Major disagreements among scientists can diminish trust in science, but they should not. Better interpretations can eventually emerge out of the controversies. That is the integrity of science. The major lesson for the crowd is to not necessarily believe everything you hear in science news releases, popular articles, and even professional papers in peer-refereed journals. Things usually need to settle a bit before becoming trustworthy. And, above all, never take as gospel that which a geologist tells you on a trip like this one because he or she could be wrong.

The Journey Continues

We float away and marvel at something new on the walls. Giant tongues and patches of gray rock that look like concrete drape over rock ledges and perch like protective caps on some of the protruding cliffs and pinnacles (Fig. 12.4).

Fig. 12.4. Travertine mass slanting down across the Bright Angel Shale likely formed from large springs emanating from the Redwall Limestone. That its lower end has been eroded into a cliff face suggests it formed when the river channel was at a higher level.

It does not look natural, but it is travertine like we saw on a much smaller scale at the fountain of youth yesterday. Here, much larger springs must have emerged from the Redwall Limestone during a wetter time. However, Don Elston noted that much of the talus lining the riverbanks all the way back to about mile 10 is cemented together with travertine. What we see here is probably just an inordinate amount of the travertine relative to the embedded talus. Don thought all these examples dated back to a time when the river stopped flowing for a long interval and filled up with wall debris that stood high above the present river level. The travertine in his scenario formed in slow moving ground water in the filled channel. Some have tried to age-date the travertine component, but we will understand the difficulties of doing this meaningfully when we encounter larger deposits of it in a few days. For now, we just gawk at this surficial coating and peer downstream as we approach a gaggle of commercial and private boats tied up on the left bank.

The crowd of boats seems about average today, for this is the confluence of the Little Colorado and the Rio Colorado which everyone stops at. It can be a very fun place. People on our boat are standing, pointing, and expressing amazement at a bright azure blue stream flowing straight out from this huge side canyon into our emerald, green river (Fig 12.5).

Fig 12.5. The base flow of the Little Colorado River emerges into the Colorado River. The color is due to a myriad of microscopic calcite crystals that precipitate as a floc at a spring in the Redwall Limestone several miles upstream on the floor of the channel. Sunlight reflects between the suspended crystals preferentially absorbing all but this blue component.

An onboard air compressor used to inflate pontoons in the morning fires up. Colorful, fluffed up innertubes and floaties of varies kinds get handed forward as people sort through their day bags in preparation to disembark. This place is not only beautiful but is noteworthy in ways historical, spiritual, political, recreational, and geological. Just as the different colored water streams ahead are slow to mix, the joyous excitement of the group mixes poorly with my somewhat darkened spirits after having just relayed a story of science affected by money, publicity, and politics. I started on a scientific pilgrimage to exalt and exult in the greatest nature has to reveal at this stage of our scientific understanding. The dark side of the Cambrian and the dark side of certain government-funded science are mental burdens in the morning sunshine--and I am about to be deserted for a swim party. Ah, well, avaunt ye dark clouds! Time to go swimming!

Several of our group have been here before and charge along a path around the corner of rough-edged ledges of Tapeats Sandstone. Following instructions from the crew, everyone is carrying their life jacket--with some additionally lugging the colorful plastic inflatables. People gasp at the fantasy scene before them when they turn the corner and enter the stream valley of the Little C (Fig 12.6).

Fig. 12.6. The astonishing beauty of the spring-fed base flow of the Little Colorado River.

Vibrant aqua blue water is slowly flowing around numerous angular boulders out in the stream. It flows in stark contrast with the light brown desert walls eroded back from the main river on this side. Splashes of lush greenery on the far side contrast with gritty ledges that step upward toward blue sky on our side. The procession scrambles up successively higher ledges as it proceeds upstream until it arrives at a small set of rapids in the surreal waters. People from the other groups are scattered along the banks and some are bobbing around in the current. A small group of observers is tucked under a shady overhang with a good view of the little rapids. Veterans from my previous trips are explaining how to put on life jackets upside down to cushion bounces on the bottom. They wade out in their hard-soled river sandals, and line up facing downstream. Once linked together, a chain of screaming child-adults floats and then shoots downstream through small rapids. Some just drop in and go it alone, reveling all the way (Fig 12.7).

Fig 12.7. Small rapids in the glorious water of the Little Colorado Rivere upstream from the confluence are a favorite spot for river runners to frolic. Here, one of the author's daughters shows one way to do it.

They quickly exit to do it again in front of witnesses of spent swimmers and those ready to dry out. The other groups depart, and we have the place to ourselves. The cavorting in splashy waters is a riot to watch. I have seen it many times before and return almost immediately back toward the confluence. At a lonely spot, I plunge in feet-first clothes and all into the refreshingly cool water. The climb out is not trivial because the banks and ledges here are covered with white, oozy mud. Sinking a foot into it is a guarantee that you will have to dig your footwear out. Grab a muddy ledge and your hand slides off. I glop and slop my way to stand up, swirl a foot around one at a time to wash off the white sludge, and step up several rock ledges to a shady spot under a ledge of the Tapeats Sandstone. Pants and shirt get spread out on the hot rocks leaving me in a wet swimsuit to dry out in the sunshine. Then, with a half hour to kill, I climb up higher for a shady view of this remarkable place and start sorting out the jumble of hard thoughts crisscrossing my head like swords penetrating a pumpkin from all angles. A new concern is how to explain why there is such a small pile of rubble where the Little C joins in here. Astounding! Even little side canyons have produced big rapids and Nankoweap dumped an enormous delta when joined the flow. The Little C is a major tributary—and only this?? I have an idea why this is so, but we will have to wait until the river starts to cut directly into the Kaibab Uplift before I can sensibly explain it to the swimmers—who could care less right now. I have never even heard this addressed by geologists who have written on the Canyon.

From the sights I see from here, I get lost in the profundities we infer regarding life in ancient seas, the bobbing up and down of continents above white-hot, sticky turbulence in the mantle below, erroneous science that can retrograde human understanding, the nature of light and human perception, the upcoming tragedy of overpopulation, and the darker side of human consciousness. I want to expound to the group on at least some of this while the scenery suits with it, but they are going to return exhilarated from their romps, and we need to get going if we want to snag our desired campsite this afternoon. So, lost in thought--45 minutes shoot by. I become aware that a group is gathering below jabbering and probably in want of at least a snippet of wisdom to legitimatize all this fun. The main question seems to be why the water is this amazing blue color.

The story you hear about the awesome color of the Little C from some boat crews, guidebooks, and likeable passengers is that this stream has magnesia in it, and it will make you sick if you swallow a mouthful. JP quipped before we left, “It will give you diarrhea and constipation at the same time.” None of it is true, although the condition JP describes may account for the behavior of some river runners here. The stream originates at a spring 12 miles up the creek where this erosional valley has carved down into the Redwall Limestone. Somewhat like the gushing groundwater back at Vasey’s Paradise, water bubbles out of big mounds of travertine and white mud at a place called the “Sipapu” by the Hopi Indians. This is called the “Blue Spring” on some maps. It is very difficult to come downstream in the channel from Cameron to that place because of abundant quicksand, and it is a long difficult hike from here. Visits and photographs of the big mound of travertine around the spring are therefore rare. Where the turquoise waters first appear in the canyon gorge can often be seen from lowflying aircraft. Steve Hatch once flew me in his private plane from the Hatch Warehouse to Flagstaff, and we did a circle around the location to see what we could of this sacred site for the Hopi Indians (Figs 12.8 and 12.9).

Fig. 12.8. Great pilot Steve Hatch (right) and the co-pilot you would never want.

Fig 12.9. Location of the Sipapu (arrow) in the canyon of the Little Colorado River about 12 miles upstream from its confluence with the Colorado River. North is toward the bottom of the image. Some glare from the airplane window is apparent. The blue color of the water flowing downstream (toward the bottom) is visible in the lower center of the image.

The Hopi creation myth supposedly has it that people emerged from out of the Earth in that place. Groundwater deep in fractures of the Redwall is colder than the summer temperatures, under higher pressure, and charged with carbon dioxide gas probably from decay of bits of organic debris that come down the fractures. Upon exit, the pressure drops, the temperature increases, and the CO_2 bubbles out. Chemistry tells us that this is a powerful inducement for the dissolved carbonate to instantly precipitate. It does so in the form of billions of microscopic crystals that form a suspended floc in the turbulence and make the water look milky. The tiny crystals are transported in suspension downstream, eventually stick together, and settle out to form the white sludge that lines the bottom and the banks. All us swimmers have it in our clothes, ears, and navels now. When it dries out, it slowly turns to travertine by recrystallization--much like putting those loose ice cubes in your freezer and discovering they are all stuck together after a few hours. Indeed, small patches of recent travertine from flood waters are coating some of the ledges here. As explained by University of Washington atmospheric chemist Stephen Warren on a previous trip, we are simply seeing the true-blue color of water for light rays that have passed through a critical distance of about several meters. The other colors of sunlight are preferentially absorbed by the water. Sunlight penetrates from above and reflects off one of the white microparticles suspended in the water, then reflects off one particle after another to rapidly travel this critical distance before emerging out to our eye. It has nothing to do with magnesia; the water is just water with billions of little calcite crystals. A swimming pool is the color of the Little C because light goes this critical length when it reflects from a white bottom. All who accidentally swallowed a little of the Little C during their swim are relieved by this explanation; they are not going to experience the debilitating condition JP warned about.

I choose not to talk about how this very spot was and may still be targeted for a riverside restaurant accessed via a tram that will bring thousands of visitors down from the Rim-World above. Future river runners thinking they have embarked on a wilderness adventure will be shocked to arrive here. The spell will be broken as it will be for millions of visitors at Desert View high on the South Rim who will look directly at the parking lot, and possibly even a casino, airstrip, and buildings at the top of the tram. The Park Service cannot prevent it. The whole left side of the river we have been coming down so far is on Navajo Nation land. Jobs are scarce, so outside developers have found a few willing partners among a minority of those Navajo who might not view this spot as special. Most recognize that the confluence is important to Native American culture and successfully fought the latest attempt at tawdry development. One can only hope now. It is wonderful how long the Canyon corridor has been protected, but population grows, the reservations need jobs, outside entrepreneurs are relentless--and humanity is what it is.

Following the lunchtime discussion about the human nature of science, this is certainly not the time to talk about this threat with people now made euphoric by the magical waters of the Little C. It was certainly on my mind this past hour when I sat hunched in the shade like that figure in Albrecht Dürer's famous "Melencolia" engraving (Fig. 12.10).

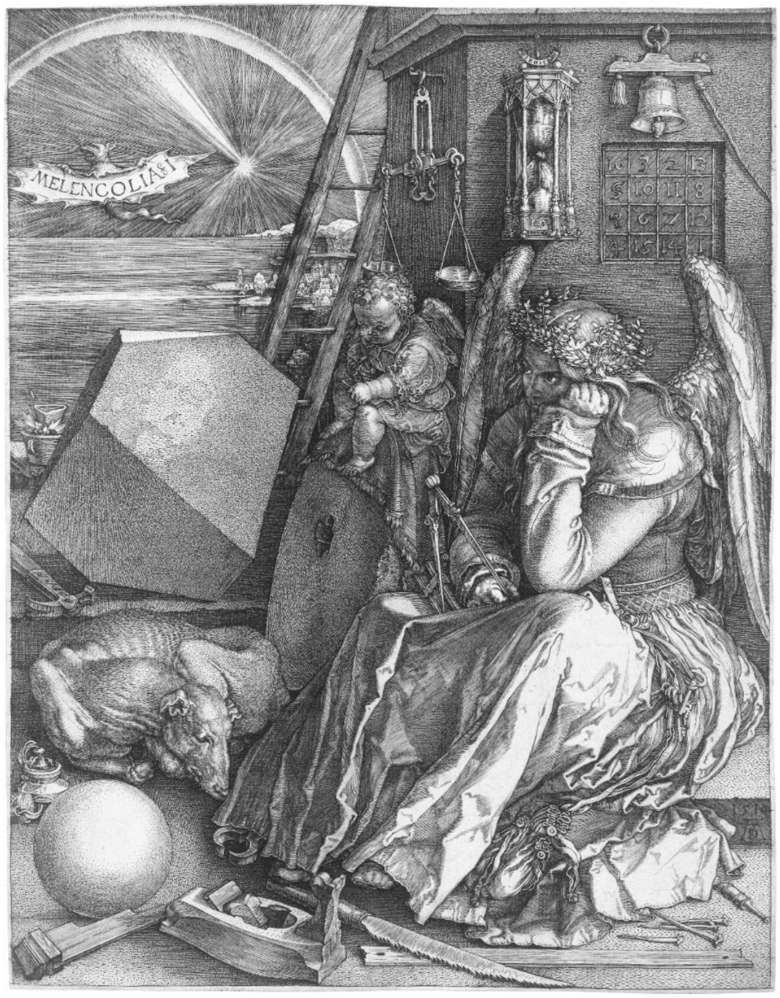

Fig. 12.10. Distressed angel in Albrect Durer's 1514 engraving "Melencolia." A pilgrim can sometimes sink into this state (Public Domain via Wickipedia)

Fortunately, I was able to transition into the mind of John Wesley Powell, leader as he sat here possibly on this identical rock ledge during his 1869 first-ever boat traverse down the river. His three boats were badly damaged, clothes were in tatters, and food was dwindling at an alarming rate. Nor did he have any idea of how far he had yet to go and what they would encounter to get out of their canyon prison. The expedition camped here for several days patching boats, avoiding rattlesnakes, and taking a rare rest. Powell wrote an eloquent and manly description of their situation six years later, but the crew diaries reveal general despair.

Powell was a geologist, and he surely noted the prominent display across the main river where the now fully emerged Tapeats sandstone is overlain by the Bright Angel shale which grades up into the Muav Limestone (Fig 12.11).

Fig 12.11. The upper half of this image shows the light brow Tapeats Sandstone (T) overlain by the dark, finely bedded Bright Angel Shale (BA) overlain by the gray, cliff-forming Muav (M) Carbonate layers. This vertical succession is the classic "transgressive sequence" in which the sea advanced over the area to form coastal sands overlain by offshore muds overlain by accumulations of shell debris that converted into carbonate rock. On this day, rafters from a commercial company hoping to encounter the azure, blue waters of the Little C instead find muddy water discharging. After flowing out around piles of gravel washed in during major floods, the muddy water flows along the left bank as a separate chocolate stream for almost a mile until finally mixing in with the major flow.

Powell could not know at that time in the history of geological investigations that these form an upward sequence of middle to upper Cambrian strata that can be traced from here west to California and east to Missouri (Fig 12.12).

Fig 12.12. Outcrop of Cambrian sandstone deposited over Precambrian granite near Fredericktown, Missouri near the center of North America. The Cambrian Sea advanced west to east over the continent and deposited these sands several million years after the Tapeats was laid down in northern Arizona. From here west, the continent continued to subside until at least the time the Redwall fully accumulated in Arizona. It is likely that slow uplift in this area of Missouri started then and continued to the present day possibly causing an almost "Grand Canyon thickness" of Paleozoic strata that were subsequently stripped off the rocks here. The observer is looking at the last remnant of the great Cambrian transgression from the west.

No, you cannot find outcrops of them continuously in those directions, but the sequence is encountered in this part of the stratigraphic column wherever it has been uplifted, exposed, or drilled into. This is now considered the classic "transgressional sequence" where a continental margin sagged tectonically downward to allow the sea to slowly move in over it. As western North America subsided about 540 million years ago, the sea came in from the west. First, beach sands appeared here to become the Tapeats Sandstone. As the coastline slowly moved eastward, the sands got buried by offshore muds that are now the Bright Angel Shale. The area became far offshore as the coastline migrated inland toward the continental interior. The clear shallow waters allowed shell producers of the Cambrian Fauna to thrive over a vast area. Their debris piled up above the now buried offshore muds and more deeply buried beach sands to create what we see directly across the river from this fantastic swimming park.

The concept of transgression of the sea that creates a specific vertical stack of sedimentary strata is one of the most essential themes of geology. Here as elsewhere in the Grand Canyon, this vertical sequence is displayed with incomparable clarity. To go to the far bank and look around would not be exciting because it is just gritty sandstone, crumbly shale, and cliffs of more resistant gray dolostone. However, through geologic eyes it is the tectonic drama of a subsiding continental region being flooded by an advancing sea. How many eyes have seen it this way? Probably not many. Should someone ever construct that cable car ride from the rim down to the river here, I hope that viewers who wander out from the restaurant to walk along one of the ledges will see a display alerting them to this sequence of layers and their significance. Today, I can briefly point it out to happy swimmers as they dry out before boarding the boats. I have certainly projected classroom images of the scene to many generations of students in my geology classes at ASU.

We push off and are immediately carried out into the blue waters where they mix with the river (Fig. 12.13).

Fig. 12.12. Looking downstream where the Little C joins the Colorado River. The debouching turquoise waters bifurcate around a mound of boulders and cobbles dumped here after floods. The smallness of this mound is astonishing and initially perplexing considering that this is the confluence of a major tributary. A possible explanation requires knowledge of what lies just west of here before the Kaibab Uplift is encountered. Water from these two joining rivers flows side by side by almost a mile until they mix.

The debouching current of the Little Colorado invades the river flow and retains its identity for a surprising distance downstream. Here is a large and a smaller river flowing side by side with no banks between them. All along the contact there are fantastic curls and swirls as the contrasting colors mix. Within a few hundred yards, the Little Colorado waters are stirred into the river by rapids erupting over gravels brought in by the Little C. The far wall with its better-than-textbook vertical sequence of transgressing strata seems to be more observer than observed as we float along.

Once the summer rains come, the Little Colorado becomes so muddy no one would want to swim in it. However, a few people on one of my trips once jumped in and emerged caked with mud looking like mummys blinking wildly. They wisely got to the main river and jumped in to wash it off before it dried into adobe. It was a riot—at least for the observers. When asked why, one replied, “It seemed like a good idea at the time.” I never told them that all kinds of stuff like dead cows and old tires are often jettisoned here by the Little C along with all that Moenkopi mud washed off the lands upstream. Oh, well.

On about a third of my trips, we arrive at the confluence and do not even land because the Little C is running brown. The dirty water jets out into the river forming abstract art with mesmerizing swirls and gyres along its contact with the clearer water. On those trips, emerald clear water then ends, and we ride the rest of the way on something resembling chocolate milk. The river is simply too turbulent for the suspended mud to settle out. Sometimes, the river is already muddy from rains in southern Utah and becomes even muddier after the confluence. On those trips, I claim the added weight of the suspended load that slams into you in a rapid can be felt. For sure, the mixing of watercolors at the confluence is always photogenic.

Soon we are back in a narrowing canyon with the ragged light-brown layers of the Tapeats making walls of ledges close in on both sides. I alerted everyone before we pulled away that we are about to reach the bottom of the great stack of horizontal layers. This is a geologic milestone on a raft trip, so let eyes be alert! But lo, we round a small bend and see the biggest surprise of the trip. We are still in the Tapeats Sandstone, but here on the east side of the river, the cliffs just above the river are frosty white (Fig.12.13 and 12.14).

Fig 12.13. Just before reaching the base of the great stack of Paleozoic strata, white salt is encountered coating the lowermost cliffs of the Cambrian Tapeats Sandstone.

Fig. 12.14. This is the only known wall in the Grand Canyon with a surficial layer of salt caked on its side. There are white “bathtub rings” around Lake Powell and Lake Meade that formed when those lakes began drying up. Those bathtub rigs are carbonate and not highly soluble salt like this.

The cliffs are almost blinding in the afternoon sun. Something is coating the surface, and nearly every ledge has white “ice sickles” like those hanging off the edge of a roof after a freezing winter storm. The current takes us against the steep wall, and we see little drops of water at the tip of each ice sickle. In reality, it is salt caked all over the walls with dripping “salt sickles” hanging off every ledge (Fig 12.15).

Fig 12.15. "Salt Sickles" hanging off the ledges like ice sickles. Each is dripping salty water from the tip.

No winter wonderland here; it is saltwater weeping out of the sandstone. As it evaporates, the dissolved salts are left behind plastered on the surface. Some of the larger drips develop shoulders of salt that join to form little tubules tapering downward to make salt stalactites. The fragile structures will largely dissolve in the next rain. But the salt keeps coming.

We pull close enough that pontoon riders can break off a few of these salt straws and pass them around. A taste test leaves no doubt it is mostly sodium chloride. But do not taste too much because this leaking brine is also full of carbonate and sulfates. The salts here are not pure. In some places in Grand Canyon, weeping springs leave dried out crusts of gypsum as the water starts to evaporate. It is the first mineral to form upon evaporation, and it takes almost complete evaporation before the table salt forms. Here, all is occurring on a grand scale.

There is a considerable mystery here. Why is brine weeping out of the Tapeats Sandstone at the very base of the Paleozoic Strata. It is not doing so on the other side of the river and has not done so in any of the layers we have just travelled down through. Up close, the sandstone is highly weathered. Small cavities have even formed along the surface. The salt water is vigorously attacking any feldspars amongst the quartz sand grains and any cements not made purely of quartz. (Fig. 12.16).

Fig. 12.16. Where the rock face can be seen along the salt walls, highly weathered sandstone is apparent. The rock is completely rotted, with elongated zones and even thin beds where the sand grains washed out. Such intense weathering of sandstones is rare. The elongated opening in the direct center is about 3 inches high.

Where joints intersect, almost tubular holes have developed. The basal sands have huge crossbeds that have cracks allowing enhanced flow (Fig 12.17).

Fig. 12.17. Note large cross-beds below the salt on the left side. These are common along the very base of the Tapeats here and allow enhanced movement of ground waters. Fractures along them have been rotted out here by the debouching brine.

The river has cut down into a brine aquifer that is draining out here on the east side. Any extension of it to the west has apparently long ago drained out completely. This might suggest that the source is only to the east. Some have speculated that this is the remnant of a huge lake to the east, "Lake Bidahochi," that the Colorado River may have drained into about 5 million years ago. The possible story goes that as it dried up, its evaporitic, salty remnants sunk into the ground are only now reaching this far west. Alas, while there is evidence of a lake or series of small ephemeral lakes that age to the southeast, geologists have been unable to find any evidence that the Colorado River once flowed into those. We will see a much easier explanation of why there is no brine seeping out on the west side tomorrow when we will go exploring over there. It actually does drain out the left side bank in many places many miles downstream from here. This is more likely just an occurrence of deep basin brines that occur on most continents.

My Personal Story Regarding Deep Basin Brines and Their Origin.

A former geologic mystery with considerable significance is on display here. It is not so much why salt water is weeping out of the rocks, but rather the grand theme that there is highly saline water at the bottom of thick stacks of sedimentary layers all over the world—the puzzling "Deep basin brines." Here, the Colorado River has cut down to the bottom of the stack that accumulated in northern Arizona, and such brine is leaking out into an arid environment where it can form crusts.

There have been long time intervals on every continent where the crust sagged downward and got covered with layers of sedimentary strata. It is only portions of a continent that get warped deeply downward, and such warps are an uneven tectonic phenomenon. In continental interiors, a bowl-shaped area often sags downward. A beautiful example is today under the state of Michigan where the center of the bowl slowly subsided over a period of 300 million years in the Paleozoic. Sea water flooded the area back and forth all through this interval and about 16,000 feet of strata accumulated over the deepest part of the basin. Similar sags occurred in west Texas, Kansas, western New York, and elsewhere. At other times in other places, the very edges of the continents can sag downwards to form half a bowl. This happened here in the Cambrian to produce the Paleozoic sections that decrease in thickness from California all the way east to Missouri and Wisconsin. This continental margin sag is over a vast area, so there are local areas that sagged more than others to form thicker piles. Little on a regional scale is uniform in geology, such are the vagaries of the slow, thermal churning going on underneath the great tectonic plates that causes it all. The basins in question and numerous others that got subsequently uplifted have now been thoroughly drilled by oil companies. In every case both here and elsewhere, ground water from eons of rain infiltration is encountered throughout the drilling. It occurs wherever there are still pore spaces or fractures in the rocks and it inevitably gets saltier and saltier as the drill stem pushes downward.

The origin of this salty water has been a mystery ever since it was discovered to be so widespread at depth. The salt on display here is a local manifestation of a global theme not many know about. Yes, global! This will become apparent in a story I will tell the group in a few days. The story now is what is going on here with these frosty walls. Oil floats on water, so oil drillers knew to stop when deep salty water started coming up the drill holes. Drillers and company geologists never explored the issue and just assumed this was old ocean water that had sunk and ponded at depth during deposition of the strata. The origin of oil field brines emerged as an issue when it was recognized that these brines were typically much saltier than sea water. In some cases, the brines were a real devil's brew of dissolved salts—not just sodium and chlorine, but also calcium, magnesium, potassium, and sulfate. In many cases, there were more molecules of these dissolved constituents in a bucket of brine than there were of water! How could such fluids form?

Inasmuch as high concentrations can be achieved when sea water evaporates, it was initially postulated that these must be old "evaporite brines" where sea water had covered salt flats and evaporated almost to completion before the dense briny residue sunk into the ground. Indeed, there are vast deposits of salt all over the world that accumulated at one time over large areas where sea water had regularly flooded regions under an equatorial sun. The Mediterranean Sea today is an enclosed sea fed by Atlantic Ocean water streaming in through the Straights of Gibraltar. As it evaporates in this warm climate, the density of the surface water increases causing it to sink. This flows out under the incoming current at the Straights to return to the open ocean. These steady but reversed currents were utilized by submarines during World War II. But imagine if there were an obstruction at depth in the straights, perhaps caused by faulting to make a "tectonic sill" above which shallow water could flow over but behind which the denser evaporite brines would pond. The brine concentration in the enclosed sea would build up until gypsum and then even salt might precipitate on the bottom without the basin ever drying out completely.

This is inferred to have happened at intervals in the Mediterranean Sea embayment about 6 million years ago because layers of salt and gypsum are buried under the modern sea floor muds there. We postulate that such geographic and topographic situations occurred in numerous other sedimentary basins in past geologic times, especially when continents drifted across the equator. Giant salt deposits can also form in shallow water along a coastline when a vast area is regularly flooded during storms and high tides. If the area is slowly subsiding and the rate of subsidence is about the same as the rate of salt accumulation, layers hundreds or even thousands of feet thick can form. If mountains go up nearby and shed sands and muds into the subsiding area, a basin deposit can form with shallow water salt beds covered by thousands of feet of detritus. A scientific case can be made that much of the salt in the subsurface of west Texas and extending on into Kansas probably accumulated in this way. The

Pennsylvanian-age strata on the Colorado Plateau including the Supai Formation here in Arizona often include significant thicknesses of salt which formed in various shallow water settings.

Brines are at least 20% heavier than water. When they sink into the subsurface, they just keep working their way downward through cracks, fissures, and interconnected pore spaces between grains over millions and hundreds of millions of years. Additionally, rainwater sinking into buried salt dissolves it and sinks downward to enrich brines at depth. So, the deeper we go, the more brine there is. Local pockets of highly evaporated sea water can remain lodged at shallower depths in some strata and astonish drillers when it starts coming up the drill stem. The story seems logical, and the origin of oil field brines was never a troublesome issue until the 1960s when isotope geochemists Bob Clayton and Irving Friedman shocked the community by publishing analyses of the water molecules themselves. There are nine different kinds of water molecules because there are two varieties of hydrogen (H and D, signifying typical hydrogen and hydrogen with an additional neutron in its nucleus) and three varieties of oxygen, depending upon how many neutrons the atomic nucleus has (^{16}O,^{17}O, and ^{18}O). Isotope geochemists (such as me) have labs where the relative amounts of these nine different atomic combinations can be measured. Ocean water, evaporated ocean water and rainwater are as different as night and day isotopically. The isotopic fingerprints of oil field brines indicated to Clayton and Friedman that the water started off as rainwater, not sea water of any kind. Somehow, descending rainwater had evolved chemically into concentrated brines!

This sensational, unexpected result launched a field of frustrating inquiry that lasted for over 20 years. How could rainwater possibly evolve into highly concentrated brine by reacting with rocks in the subsurface? It did not seem possible. A possible solution was that groundwater could get filtered as it somehow migrated downward through nearly impermeable shales. A concentrated brine residue would form--and bingo we have oil field brines. Not all geochemists were happy with this paradigm that developed, and it was laughed away by oil geologists exploring sedimentary basins with drill rigs. Clayton was one of my freshman chemistry teachers at the University of Chicago. He and his technician gave me a job in his lab washing dishes and such. One thing led to another, and the job evolved into something wonderful. I got pretty good at lab work and decided to go into the new field of stable isotope geochemistry that Clayton was helping to pioneer. He gave me a recommendation letter that got me into Caltech working for the founder of the field and his former PhD mentor, Samuel Epstein. Clayton was special to me, and it never occurred to me that his conclusion regarding the brines may have been based on erroneous assumptions or incomplete analysis of the data. But it was, and it later fell on me to confront the issue in a lonely way.

I got involved when the US Department of Energy began exploring a thick subsurface salt deposit near Amarillo in the Texas panhandle. The idea was to hollow out a cavern and dispose of all the nuclear waste piling up around nuclear power generating stations. A big scientific concern was whether there was water in and around the salt that might somehow contact the waste and transport it to the surface. Quoting the work of Clayton and Friedman, some claimed that the deep basin brine below the salt beds indicated that rainwater was somehow able to dissolve its way through the salt. The salt bed, it was argued, was thus not a reasonable geologic container for highly toxic and radioactive nuclear waste.

Deep holes were drilled into this subsalt brine with unprecedented care to get pristine samples for chemical and isotopic analysis. I was engaged to do the isotope work and had access to the chemical analyses. When I put it all together, I could not reconcile the data with Clayton's now entrenched paradigm that the water started out as rainwater. Instead, it all matched perfectly with what had been subsequently discovered about how the isotopic and chemical composition of sea water evolves during evaporation. I could even see from the analyses that there were places near the edges of the deposit where rainwater had dissolved salt and mixed with all this evaporite brine that had accumulated and lodged for over 200 million years. A genius geochemist named Alden Carpenter had published two long papers in an obscure journal that showed exactly how the chemical composition could be achieved, and it matched perfectly with what I had concluded from the isotopes. Although it distressed me, I published papers arguing that the old story of evaporated sea water and not Clayton's paradigm was actually correct. The deep brines were evapo-concentrated very ancient fossil water. I even once took a drop of this devil's brew from a Silurian sample and had the first ever "Scotch and Silurian water." A local news article on that got the attention of the great science writer Water Sullivan who did a story on it for the New York Times.

The Journey Continues

So, today we encounter the bottom of the Paleozoic strata where river erosion cut downward and breached the briny water lodged there above more impermeable rocks. A wall exposure above a long sand beach downriver from the stalactites has thick salt coatings that are sincerely sacred to the Hopi Tribe living on mesas 90 miles to the east. As a rite of passage into adulthood, boys in ancient times were led by an elder on a long, arduous hike to and down the cliffs to this spot and return with small amounts of salt. The place is still visited by the Hopi for religious purposes. We see the holes dug into it that no doubt go back many generations (Fig. 12.18).

Fig 12.18. Sacred salt mine. A rite of passage for young Hopi Indians was to hike down to this spot and return with salt. Ceremonial visits by Hopis still occur and sometimes leave feather offerings. Out of respect for the Hopi traditions, river runners are not supposed to land here. The contact between the Tapeats Sandstone and what lies below it, "The Great Unconformity" is just behind the bushes but is thus inaccessible here.

On a previous trip I once saw feathers dangling as offerings to the spirits there from a recent visit. In respect of the Hopi religion, landing here is prohibited by the National Park Service. We certainly honor this constraint, but it is painful because there before our eyes we spot a group of sloping strata under the Tapeats (Fig 12.19).

Fig. 12.19. Enormous mounds of salt and talus covering the first appearance of The Great Unconformity" that separates the Paleozoic strata from the underlying Precambrian strata and crystalline rocks. This is immediately downstream of the sacred Hope salt mine. The tilted underlying strata are visibly cut off at the unconformity just above the clump of bushes on the right.

Here we have a holy spot for geologists at a holy spot for the Native Americans. It is the briny bottom of the Paleozoic strata known as "The Great Unconformity." We could go put our hands across this famous contact, but it is forbidden. We cruise near the bank, marvel, and take pictures (Fig 12.20).

Fig 12.20. An exposure of the Great Unconformity is just down the same beach from the sacred Hopi salt mine and is visible from the boats. The Tapeats Sandstone was here deposited on a tilted stack of much older sedimentary layers that had been tilted upward and then eroded down to sea level (see bandanna Fig 3.9 reproduced above). These older sedimentary rocks and their fractures are more strongly compacted and impermeable than in the overlying Paleozoic strata. Briny groundwater thus ponds above the unconformity and weeps out into the downcutting river gorge.

No need to fret about not landing because there are numerous other places farther down the river where it is permissible to do so.

Sort of like that medieval Pilgrim, we have now punched down from one world into a deeper one below. We note that the new strata are peculiar and disturbed tectonically in a way unlike anything we have seen before. The boats pull in near the mouth of Carbon Canyon just downriver on the other side. This is home for the night. It is one of the largest campsites on the river. We are a bit late, and I am relieved to see it still unoccupied since two groups left ahead of us from the Little C. People scatter to find a scenic place to set up a cot. A startled camper reports as I walk past that he just saw the most peculiar rock he had ever seen, and that it looks like a giant petrified brain (Fig. 21)!

Fig 12. 21. One of the "Brain Rock" boulders—An example of one of the most bizarre rock types in the Grand Canyon. Many are found in the boulder field at the mouth of Carbon Creek. (Image courtesy of Grand Canyon geology author and expert Wayne Ranney)

We are camped on a mix of river sand and rubble dumped out the mouth of this side canyon. Everyone will soon find brain rocks lying all over this place. Something crazy lies up this side canyon from where this brain rock came. We will go up there tomorrow on one of the most geologically amazing hikes in the Grand Canyon.