Ch 14 PLATE TECTONICS FOR BETTER OR FOR WORSE Mile 65.3-66

Our initial encounter with complex geologic structures as we started walking down the Butte Fault toward Lava Canyon was not so difficult. The Butte Fault simply separates the uplifted Kaibab Plateau to the west from the lower terrain we have been travelling through for the past several days. However, while it is easy to draw a cross section, it is a bit unusual to have a fault block move upward along the top side of a steeply slanting fault plane. Overlying blocks are normally pushed over gently sloping fault planes called “thrust faults” and not up steep ones (Fig 14.1).

Fig. 14.1. Example of Thrust Fault south of Payson, Arizona.

For nearly vertical but slightly slanting planes, the block above normally slides downward to make what is aptly called a “Normal Fault.” From the stratigraphy on both sides of the fault, we saw that the Butte Fault indeed started life as a Normal Fault with the west side Chuar Group sliding downward thousands of feet long before any of the Paleozoic sedimentary layers were deposited. Hundreds of million years later and after all the Paleozoic and its overlying strata had accumulated, the west side pushed back up along the same fault plane to make a monocline with this deep-seated fault underneath (Fig 14.2).

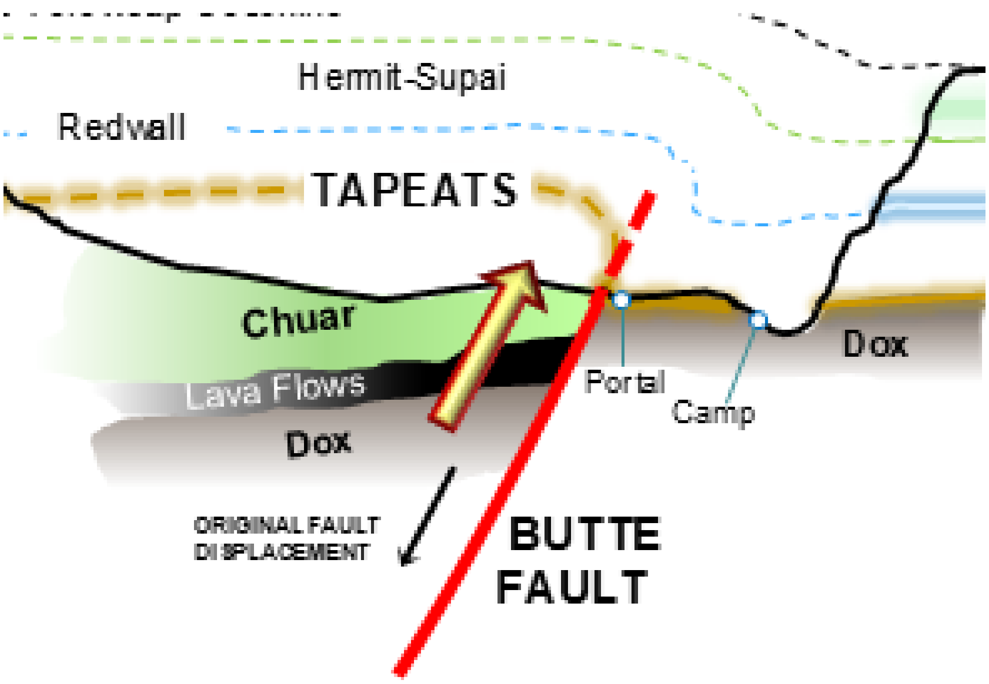

Fig. 14.2. Detail from Fig. 13.22. Everything to the left of the Butte Fault plane originally went down thousands of feet in the Precambrian (black arrow). This happened because of regional extension; left and right pulled away from each other. About 50 million years ago, the region was subjected to compression. The fault was reactivated with the left side pushing back up over the old fault plane for over a thousand feet (yellow arrow).

This reactivation of the fault with the down-dropped side moving back up along the original, high-angle fault plane is called a “Reverse Fault.” The longstanding mystery of what causes reverse faults is now debated in terms of changing stress regimes (squeezing or stretching) that occur over large regions of the continental crust. Terminology and causes aside, we at least understand the first part of our walk to the south along the Butte Fault; the tectonic block to our right was uplifted to juxtapose the older Chuar Group with the younger Tapeats Sandstone on our left. Alas, within 500 yds, another major fault known as the “Palisades Fault” takes off and heads southeast. The Butte Fault continues heading south with the uplifted Kaibab Plateau block still to the right. We were following a dry stream channel that developed along the pulverized fault zone (as often happens) and did not notice this new fault taking off to the southeast. Soon, however, everyone notices that the Tapeats originally to our left has been replaced by hundreds of feet of thick black layers. They are layers of black lava flows, one on top of another stacked up and tilted toward us in the direction we are hiking. One geologist once counted 14 of them. They are completely unlike anything we have seen so far. An observant hiker trying to stay tuned to the geologic layers will be gobsmacked by the sudden presence of this little mountain of lava flows embedded in all these sedimentary rocks. The simplicity of the cross section (Fig 14.2), while applicable to the first part of our hike, has vanished. A west to east cross section like the one in the figure is here completely different. It can make you want to throw up your hands. This is a good thing because “arm-waving geology” is necessary to understand the remarkable and important events that happened here when all this faulting was going on deep down in the Earth.

The Carbon Canyon to Lava Canyon loop hike is frequently taken on raft trips and is worth it for the scenery alone. Understanding the geology is a real challenge without benefit of geologic maps, explanations, and a view from on high. It hardly seems worth it to try to explain the geologic goings-on for a fast hike through such a small area. The next part of this discussion attempts to do this and may be of most interest to those who have done this hike, plan to do so in the future, or want to understand better how geologists observe, get surprised, decipher, and then interpret physical events of great import that happened long ago. It is not bedtime reading, but the general ideas might be understandable.

The narrative begins not surrounded and immersed in geology but with an overview of the area from Cape Final on the North Rim some 4,600 feet above and 4.5 miles to the west of the hiking route (Fig 14.3).

Fig. 14.3. View southeast at Cape Final where there is a clockwise panoramic view from west of north all the way to the southwest. At 7,800 feet, this may be the highest panoramic ground view of the Grand Canyon.

Cape Final has a unique view of the Grand Canyon. It juts out into the vast arc-shaped excavation where the river bends around to cut a wonderland through the Kaibab Uplift (Fig. 14.4.

Fig. 14.4. View south from Cape Final into the wonderland created by the river turning west and cutting right through the great Kaibab Uplift.

No road goes out to this viewpoint. It requires a visitor to the North Rim to take a pleasant two-mile hike through a lush ponderosa pine forest (Fig. 14.5).

Fig. 14.5. Two-mile hiking trail on the North Rim to Cape Final.

The well-marked trail starts from a parking area beside the paved road to the popular tourist viewpoint at Cape Royal. It ends at the tip of a great promontory with the only 270-degree panoramic view up and down the Grand Canyon. It is also probably the highest ground-view of the gorge. Yet, there are usually few people there because it is not famous and requires you to walk a significant distance. If you get to the North Rim Backcountry Office soon after it opens in the morning, you can likely get a permit to backpack there and spend the night (Fig. 14.6).

Fig. 14.6. View to the north of the author years prior to the pilgrimage heading to Cape Final with camping and camera gear to experience sunset and sunrise on a single trip. (Photo by Mark Beeunas).

This allows mind-boggling sunset views as colors blaze on west-facing walls separated from each other by chasms filled with jet-black shadows. On a clear day, bright light from the setting sun diffuses upward from dark valleys below until the last little islands of light are engulfed (Fig 14.7).

Fig. 14.7. View south from Camp Final at sunset when wonderland sinks into darkness. This is followed by the same pageant on the more distant walls. Watching the Canyon go to sleep from this viewpoint is one of life's great experiences.

In the final phase of the pageant, the whole canyon is bathed in a darkening blue haze which seems to rise and envelope you when perched out on this point. Soon all is deep twilight as the canyon goes to sleep. It is profoundly moving unless you have no soul. If camped there in July or August during the Arizona summer monsoon season, you might witness awesome lightning displays far away that develop and continue into the night. If one gets near, you will find yourself hunkered down in one of the big crevices there clutching a poncho amidst an unforgettable (and dangerous) spectacle of nature. If clear and calm, watching a full moon rise over the chasm from Cape Final will be unforgettable. After sleeping under the moon and stars, you get the sunrise splendors which can also be life-changing. Few spend the night there, and even fewer note the informative view you get of the Carbon Canyon to Lava Canyon loop hike that the pilgrim is leading the group on now (Fig. 14.8).

Fig. 14.8. View east from Cape Final. The river runs left to right along the base of the far wall of the canyon. The deep gorge coming out of the far wall toward the left of the image is the Little Colorado River. The entire set of Paleozoic strata is visible on the far wall. The red band is the Supai Formation. The top of the cliff is the Kaibab Formation over 1000 feet lower there than here in the foreground. The monocline that connected here to there has been removed by erosion. Note that the Kaibab on the far wall is slightly higher than the huge skyline area behind it. It slopes down and levels off as the final part of the eastward sloping monocline. The Carbon Canyon to Lava Canyon loop hike goes around the dark hump of rocks (not the shadow) just above and to the right of center deep down in the valley.

With binoculars, the geology along our hike is laid out in all its glory (Figs 14.9 and 14.10).

Fig. 14.9. Binocular view of the loop hike area. The river is visible in the deep notch to the far right of center.

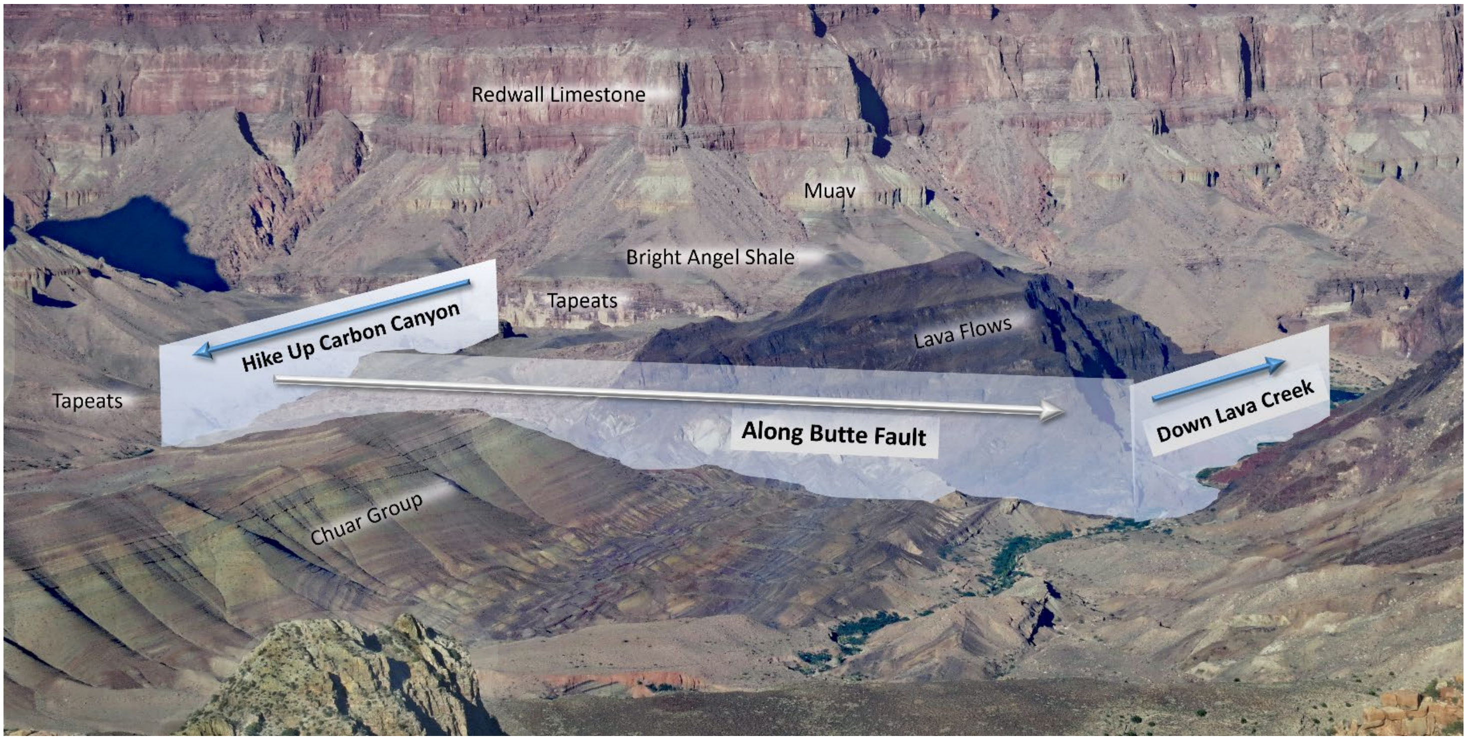

Fig. 14.10. The loop hike goes west up Carbon Canyon--and then south along the Butte Fault--and then back to the river via Lava Creek.

Examining these figures, we can progress slowly through a momentous time in the geologic history of the Grand Canyon. The river runs unseen in this view from left to right along the base of the far wall until it goes behind the hump of stacked-up lava flows. There it peeps out where Lava Creek joins it. The green striped hill filling the lower left quadrant is the hill of Chuar Group strata we just saw from the ground looking west from the Butte Fault (Fig 13.20). The stack of Paleozoic layers from the Redwall Limestone down to the salt-encrusted Tapeats Sandstone constitute the far wall of the canyon we have been floating down through (see labels, fig. 14.10). The top of the almost horizontal Tapeats layer extends toward us across the river and is seen here with Carbon Canyon cut through it and stripped of its overlying strata. Our hike so far has taken us Carbon Canyon from our campsite on the river until we reached the Butte Fault. There we turned south (to the right in this view) and walked the fault zone down to Lava Creek where we will follow the stream to its junction with the river. Along the way, we passed through large blocks of rubble in the fault zone near the white patch directly in the center of Fig. 14.9. Our whole hiking route is visible from Cape Final. Magnifique!

More magnifique is how a geologist might view the scene (Fig. 14.11).

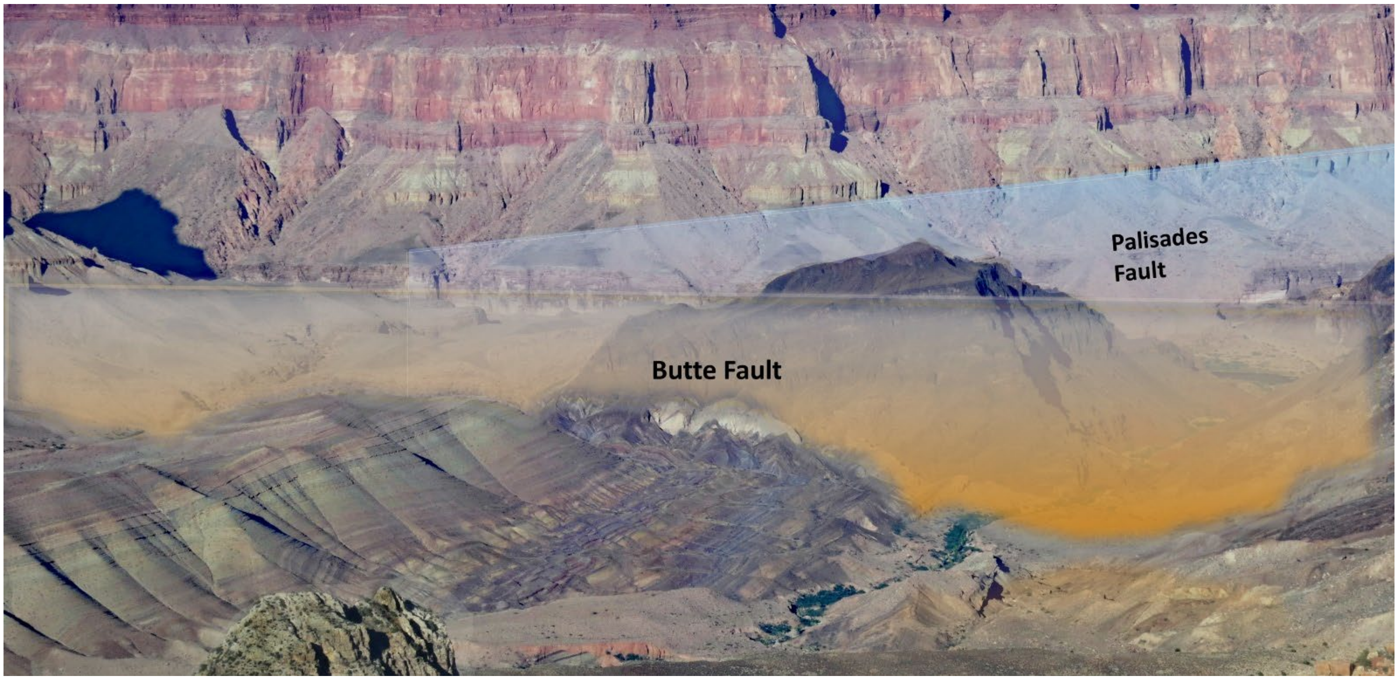

Fig. 14.11. Visualization of the Butte and Palisades fault zones as intersecting planes.

First, the Butte Fault appears in the mind's eye as a planar feature extending up from the ground and running left to right across the center of the figure. It also extends thousands of feet into the subsurface and for miles to the left and right of the image. The plane of the Palisades Fault is shown coming in behind the black hill of lavas to get cut off by the Butte Fault.

With this figure in mind, imagine a poster board with a diagram on it cutting into the scene perpendicular to the Butte Fault plane (Fig. 14.12).

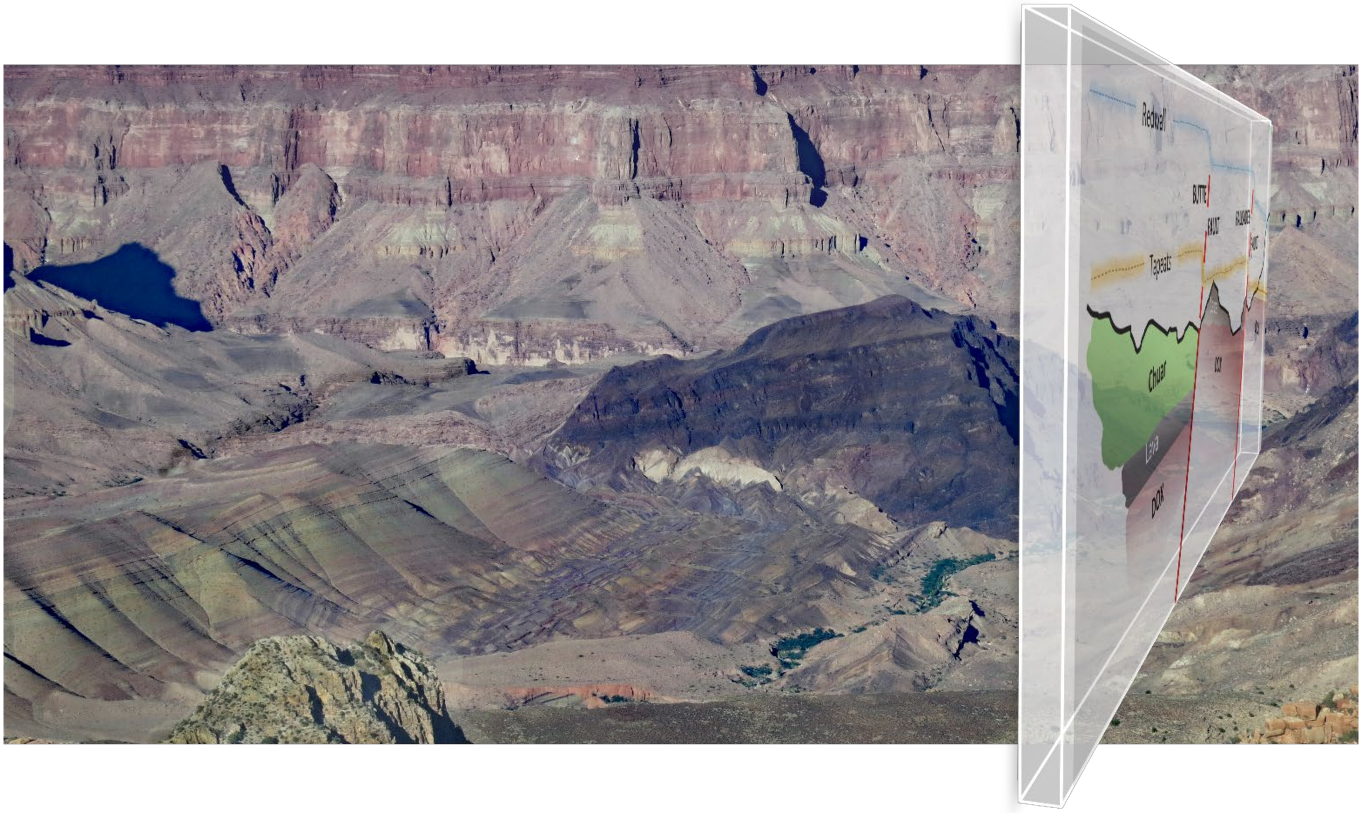

Fig. 14.12. Geologic cross section constructed on poster board set almost perpendicular to the image.

We look at that from the right side and see a cross section of the topography, the geologic layout below, and the inferred position of the eroded-away layers as they were when folded into monoclines above the two faults (Fig 14.13).

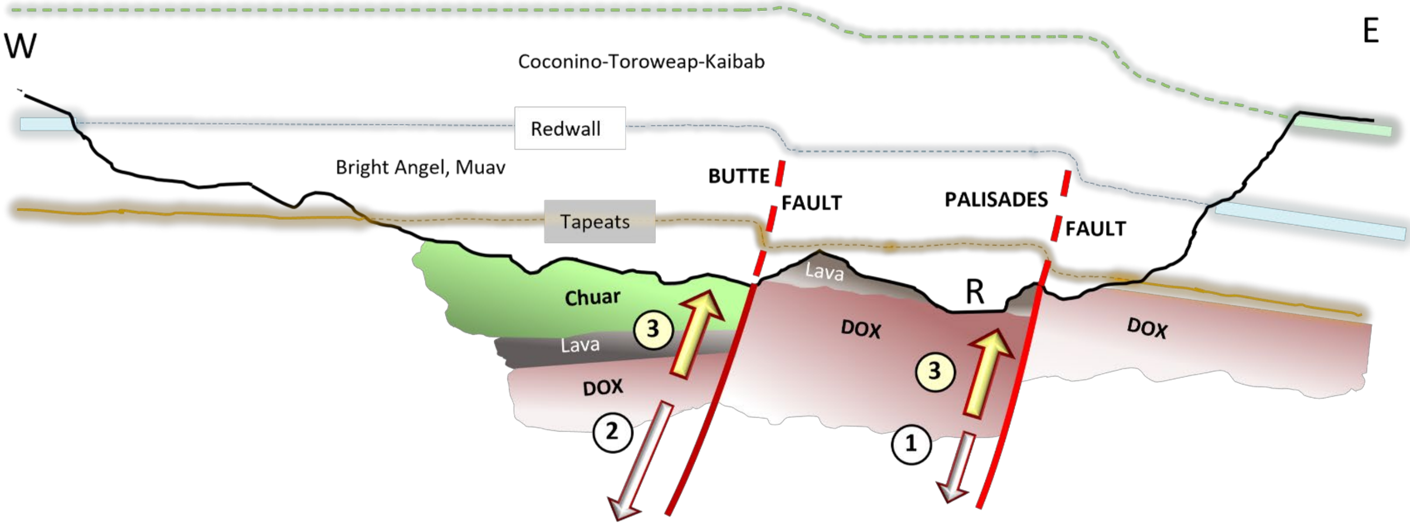

Fig. 14.13. Simplified cross section running west to east near Lava Creek. The river channel (R) is between the Butte and Palisades faults. The numbers to be discussed refer to the sequence of three displacement episodes along the two faults.

The river (R) is now understood to be flowing over the block between the Butte and Palisades faults. Two monoclines in the folded Paleozoic strata indicated by the dashed lines have been eroded away but likely once existed draped over the faults approximately as shown. The Butte Fault is a plane running almost perpendicular into the plane of the cross section. The Palisades Fault slices inward diagonally to the left and intersects the plane of the Butte Fault just south of Carbon Canyon one mile to the north (behind the page). The central block thus shrinks and finally disappears if the cross section is imagined closer and closer to that intersection. That is why the cross section in Fig. 14.1 only shows the displacement on the Butte Fault as we emerge from the portal at the top of Carbon Canyon.

The tilted block holding the lava flows that appeared on our walk south down the Butte Fault is thus sandwiched between the Butte and Palisades faults. The subsurface configuration with the sequence of events that produced it must be inferred from the nature of the layout and additional information about adjacent areas. The subsurface layout can be interpreted by how contacts between the different units interact with the topography. This is something geology students learn to do at summer field school by mapping rock units around the countryside and visualizing how things must be laid out underneath to produce what they see. Aspiring geology students should study the following with regard to interpreting this complex region which all hikers doing the loop hike encounter. Seriously! The pilgrim was once flagged to the phone booth walking back years ago from the shower to the group camp site at the Mather Campground on the South Rim. His summer field school troops had finished an exercise halfway down in the hole that day. One of the troops was talking on that pay phone to a friend at a midwestern university who had attended the program the year before and asked to talk with me. The midwestern chap thanked me profusely because he had just beaten two other applicants for a high-paying job at a major oil company--both of which had PhDs in geology, while he only had a Masters. The interviewer pulled out a geologic map, laid a straight edge on it, and asked the applicant if he could quickly sketch out a cross section and interpret the geologic history. The ASU Field School alumnus did this quickly. The pleasantly surprised interviewer said, “You’re hired!” Then he looked up, and said, “Finally! Praise the Lord.” The two PhDs couldn’t do it. The pilgrim walked away from the booth kind of thrilled and flattered but then realized that this was just one of the things he was getting paid to do. It was a good student. Ah, well. Here goes:

One general interpretation geologists have proposed involves 6 steps:

(1) *The Precambrian stratigraphy appears to be the Dox Formation overlain by a stack of lava flows overlain by the Chuar Group as shown west of the Butte Fault in Fig 14.13. Each formation was deposited one over the other prior to deposition of the Tapeats Sandstone. The lavas yield ages of 900-1100 billion years old, although they have proven difficult to obtain. The Tapeats at the base of the overlying Paleozoic strata has been argued to be 515 million years here. So, prior to 515 million years*

ago, the Precambrian strata were apparently uplifted an unknown amount before breaking into three blocks-- each of which slid down the side of its neighbor to the east (Fig 14.13).

(2) *The Palisades Fault is not parallel to the Butte Fault plane, nor is it the same age. Regional studies suggest the Palisades Fault is one of many NW-SE trending fault planes that developed about a billion years ago. Here, the block immediately to the west of it slid down the plane hundreds of feet as represented by event #1 in Fig. 14.13.*

(3) *Several hundred million years later, the Butte Fault formed in a similar way--but now in a more N-S direction.*

(4) *All west of the Butte Fault subsided 8,000 and possibly up to 10,000 feet (event #2). The Chuar Group filled the depression as it developed to the west.*

(5) *The tilted Fault blocks were finally all worn down to sea level as the Tapeats sea migrated in from the west. Thereafter, regional subsidence allowed deposition of the overlying Paleozoic strata we had floated down through on the previous days. We were not aware of all this geologic complexity deep under us.*

(6) *About 70 million years ago, the whole region here underwent crustal compression known as "The Laramide Orogeny" which affected all western North America. This squeezed all three blocks back up the old planes of the Butte and Palisades Faults (event #3 in both figures). All the strata lying over the faults were bent into monoclinal folds as indicated in the cross section and as observed both north and south of this area.*

An observer high above on Cape Final can thus see more than just scenery. Here the tectonic down-drops and uplifts can be felt in relation to the fault planes in a dramatic way (Fig. 14.14).

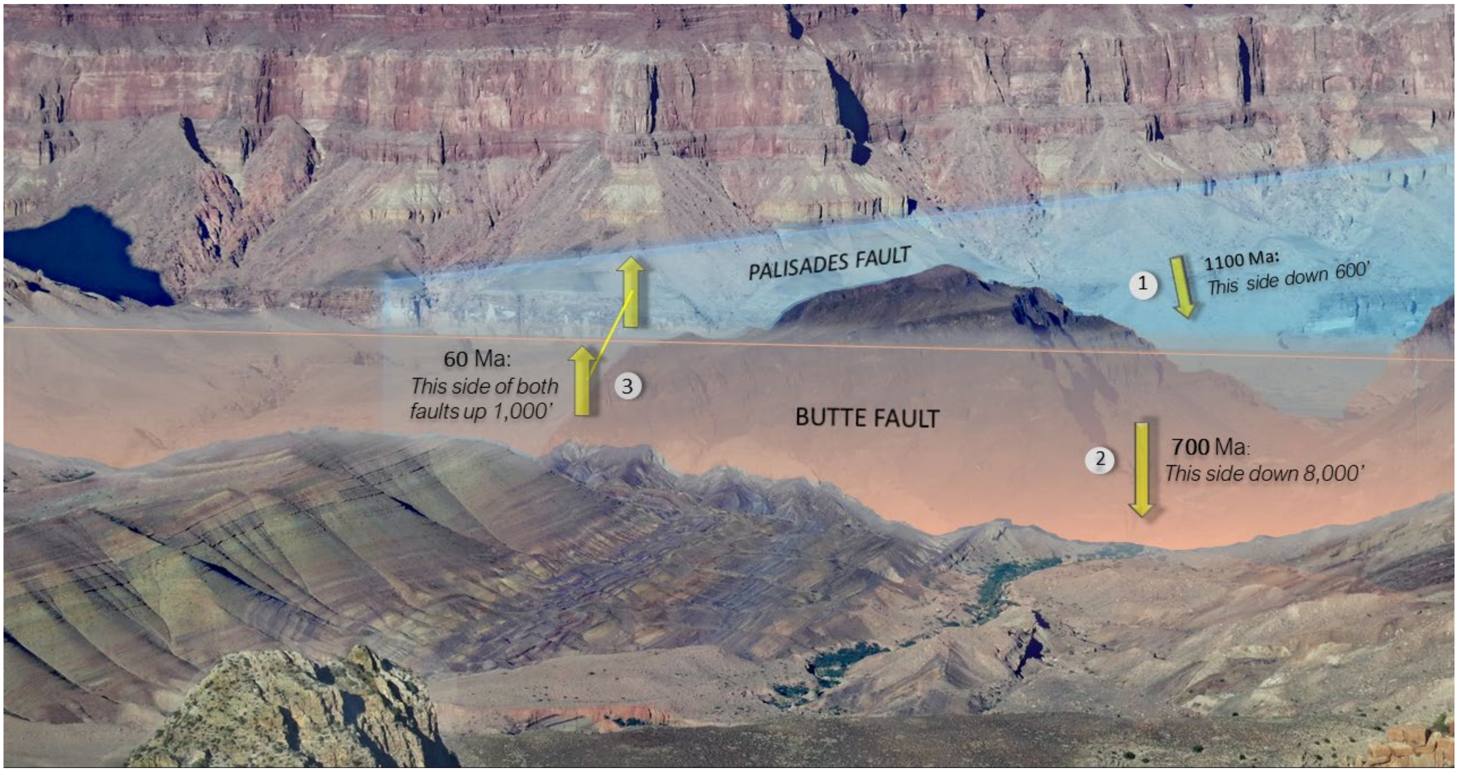

Fig 14.14. Geologist view imagining the Butte and Palisades fault planes. All this side of the Palisades Fault dropped 600 ft or more about 1,100 million years ago (event #1). The Butte Fault formed about 700 million years ago and everything on this side of it slowly descended possibly 8,000 ft (event #2). The pastel Chuar strata accumulated during this long fault event. The whole area was subsequently eroded down to sea level in the late Precambrian, and the Paleozoic strata seen on the far wall were deposited starting about 515 million years ago. They once extended across the area of the whole image. About 60 million years ago, all this side of the Butte and Palisades faults rose upward about 1,000 ft along their reactivated fault planes (event #3). The Paleozoic strata were pushed up as well but have now been mostly eroded away between this viewpoint and the river to create this vast exposure. Cape Final itself is capped by the Kaibab Limestone which was uplifted as part of this last tectonic event.

Now our hike makes sense. Carbon Canyon lies to the north of the intersection of the Palisades Fault with the Butte Fault. So, we arrive straightaway at the Butte Fault without having to cross an older one that only affected the Precambrian layers. This is good because most people can readily understand this major fault that lifted the Kaibab Plateau up to form the North Rim area. We quickly got confused when we started hiking down the Butte Fault southward. We suddenly discovered tilted lava beds forming a high mountain to our left as we walked southward. That is the tectonic block between the Butte and Palisades faults. Note that had we stayed on the rafts, we would have crossed the Palisades Fault just north of Lava Canyon. The river then flows over that central block and will for another 2 miles until it bends to the west and crosses the Butte Fault. In essence, our loop hike this morning is a traverse through a tectonic block bounded on two sides by major faults.

How “true” is this story inferred from the geologic maps and published papers? I do not know. It is an interpretation. Ask a different geologist and you can probably get a different version with better jargon and a lot more complexity--especially among those who have labored long and hard to get the data. Ask me 20 years ago just looking at the data and publications then, and I might have given you a different synthesis. Deducing Earth history is difficult. The most likely explanations can change as more geologic data are obtained. This is science.

The great faults of the Precambrian were apparently created by extension of the continental crust while those of the last 70 million years resulted from compression of the whole western part of North America. What causes these different stress regimes that clearly change with time? The answer to that involves processes at work over vast areas—indeed within the whole globe itself.

Here, a danger arises. Interpretations guided by “big picture” models and paradigms can sometimes distort observations in the field. Conclusions working “up from the rocks” are often quite different from those working top down from big picture models. Philosophers of science warn of “confirmation bias” where you are tempted to observe what you expect or fear to see. This form of common sense was best described by Shakespeare: “Or in the night, imagining some fear, how easy is a bush supposed a bear!” On the other hand, the predictive power of big picture models often guides geologists to features they might otherwise miss or misinterpret. The great Gene Shoemaker predicted from his studies elsewhere and from subtle aspects of the regional topography centered on the city of Nördlingen, Germany, that an enormous asteroidal impact had occurred there. Geologists who first studied the area without benefit of modern topographic maps and high-altitude photographs attributed the strange character of the rocks they observed there to ancient glaciers (Fig. 14.15).

Fig. 14.15. Astronomer Howard Bond standing on striated surface overlain by boulders of all sizes supported in a matrix of much smaller material exposed in a quarry near Nördlingen, Germany. These are the classical features of a glacial deposit and were interpreted as such by boots-on-the-ground geologists until Gene Shoemaker brought in a big picture perspective to argue for an asteroidal impact event and not a glacier.

Shoemaker went there and found compelling evidence of impact that had been previously overlooked. Interpreting successively what is seen in the field often requires more than boots on the ground. The bouldery jumble even contains highly rounded cobbles previously interpreted as glacial melt-water river deposits that got caught up in the supposedly advancing glacier (Fig 14.16).

Fig. 14.16. Bond holding rounded cobbles in the rubble deposit that would normally be interpreted as compelling evidence of past rivers here.

The sheet of ground-hugging rubble that expanded outward from Shoemaker's impact would have been a cosmic rock tumbler that easily accounts for the rounding. No rivers are necessary.

Several rounded cobbles were found in a deposit on Mars by the Perseverance Rover and offered by NASA Mars scientists as "proof" that there were rivers on Mars. Alas, Mars is covered with impact craters and their ejected fragments. The pilgrim and several of his colleagues (most noticeably Donald Burt at ASU) have offered easier explanations involving impact blast beds for every feature observed by the rovers on Mars. Unlike impacts that created the craters on the moon, Mars has an atmosphere where impacts create ground hugging layers of debris that spread out laterally. The rounded cobbles could readily form around impact craters on Mars as they did here. The warm, wet, early Mars paradigm may be an example of paradigms gone awry. Another such paradigm with possible problems is about to be encountered on our hike. Paradigm-driven science brings about great discoveries but can also yield erroneous results. Danger! Especially for pilgrims and those building philosophies on them. Once again, the pilgrim must carry alternative explanations and reveries when considering natural history.

If we follow the Palisades Fault to the south on a geologic map, it rejoins the Butte Fault deep in the subsurface somewhere just east of Desert View. My descent on HW 64 from Desert View several days ago actually crossed that merger sight unseen. Reactivation of old faults was widespread during the Laramide Orogeny. Lines representing faults on geologic maps of the larger region can look like a drunken spider web. The monoclines that were above us in this area can thus be more complicated than the cross section of the Butte Fault depicted in Fig 14.1. Farther to the north, the Butte Fault splits and bends in response to all these complexities as well. A raft trip avoids that complexity unless hikers slosh two miles up Nankoweap Creek to see it--an excursion few river trips have time for.

Walking along the Butte Fault toward its junction with Lava Creek, JP suddenly takes us up a steep trail to the left climbing a hill of shattered, weathered chunks of the lava beds that got mangled in the fault zone. Everyone wonders why we are leaving the soft stream bed to detour up this trail in the increasingly hot sunshine. We top the hill and take switchbacks down the far side into the stream bed again and immediately see why we did this—there is a dry waterfall there that hikers must go around. Never count on an easy hike in the Grand Canyon. A few more steps and we are in Lava Canyon high stepping from gravel bar to gravel bar in the shallow braided flow of this babbling brook.

The one-mile hike down gurgling Lava Creek back to the river is magical in the morning or late afternoon. It makes six bends often amidst leafy thickets growing beside the trickling stream. The walls rise as broad slopes up almost 1,000 ft. It is one of the widest of the slot canyons with slopes more gentle than usual. Looking north to our left we have several views of the black Precambrian lava flows lying on the red sandstones, siltstones, and mudstones of the Dox Formation (Fig 14.17).

Fig 14.17 View north in Lava Canyon about 0.5 miles upstream from its junction with the Colorado River. The black stack of billion-year-old lava flows lies over the Dox Formation. Both layers extended over the area of the valley before uplift and erosion.

The Dox mudstones are much harder than shale beds we have encountered before. They clink and break out into almost ceramic-like pieces. Here they display artistic, circular patches bleached of their color (Fig 14.18).

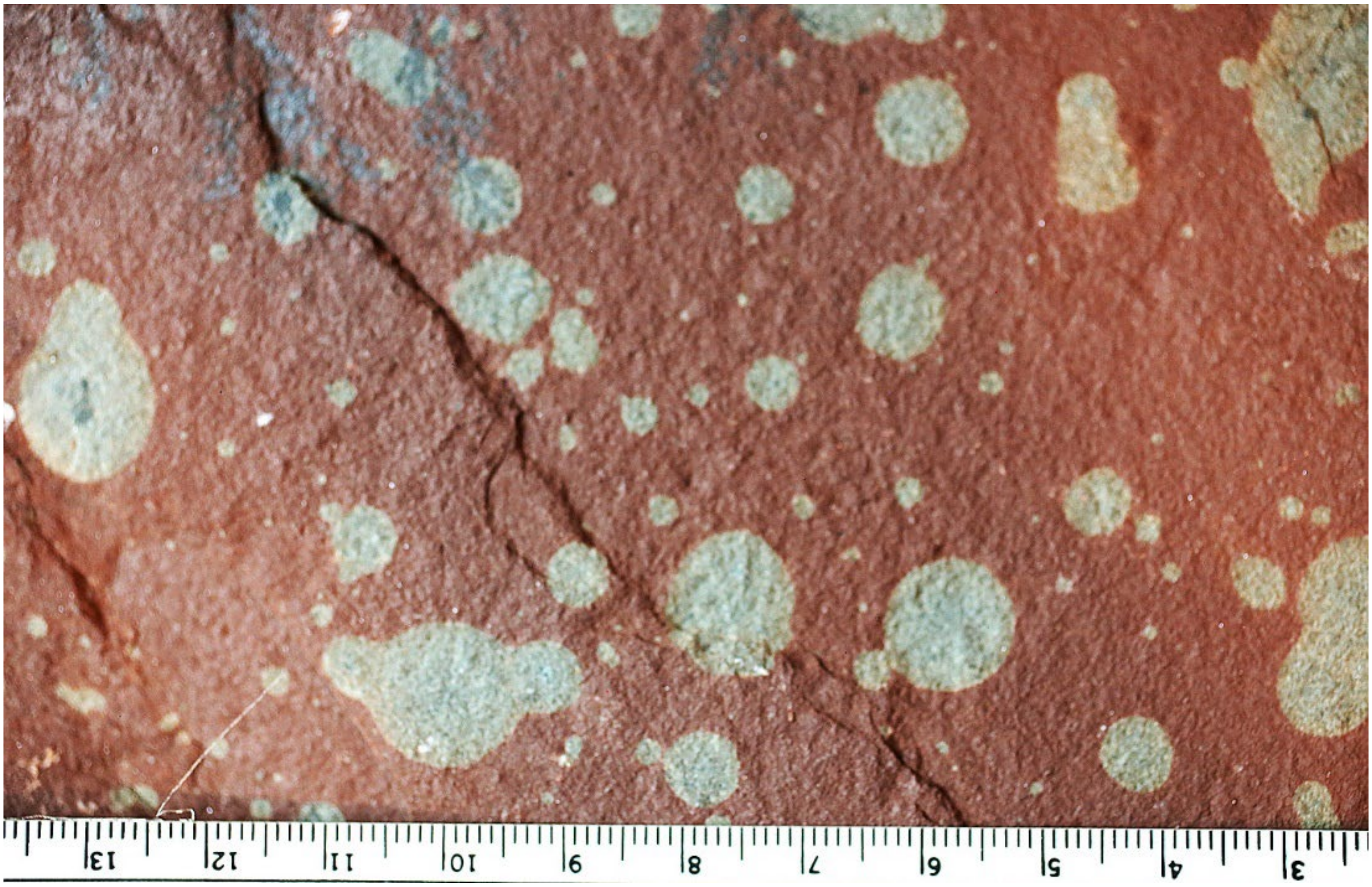

Fig 14.18. Reduction spots in the Dox Sandstone exposed on a bank of Lava Creek. Their origin is poorly understood but they may have formed in early pore waters where oxygen atoms bonded to iron in hematite deposited with the quartz-rich silts were stripped off by bacteria feeding on bits of organic matter or by chemical interaction with tiny grains of pyrite. The rock bleached of its rust becomes white.

They are called “reduction spots” and likely represent a place where there was a bit of pyrite or bacteria feeding on matter which consumed the dissolved oxygen in nearly static fluids weeping through the rusted clays that accumulated here almost a billion years ago. Nobody knows. More amazing, the more slab-like surfaces display “halite hoppers” that are as good as any you can find in sedimentary rocks anywhere (Fig 14.19).

Fig 14.19. Fossil sea salt crystals on a bedding plane surface of Dox Formation mudstone in Lava Canyon. This was likely the former bottom of a shallow pool of muddy ocean water that underwent evaporation in a coastal embayment after high tide.

These were cubic crystals of sea salt that formed on the bottom of a motionless, shallow pool of muddy ocean water undergoing evaporation--probably in an arid marine coastal embayment after high tide. The mud settled out, and the salt crystals began forming. They grew so fast that the edges outran the faces. This resulted in the "hollowed out" appearance of those seen face on. The mud did not dry out completely before another surge of ocean water brought in more mud that buried the crystals. During early burial, dirty pore waters seeped through the unconsolidated muds and dissolved the salt in gentle increments. The mud filled each tiny increment until the halite crystals (NaCl) were completely replaced before they got pressed into hard rock. Think of them as halite fossils!

Salt impressions are common in the Dox. To me, it reinforces my published arguments that salinity of the oceans was much higher in the Precambrian and that its decline due to vast evaporite deposits in the latest Precambrian elsewhere in the world allowed the oceans to oxygenate for the first time in Earth history because high salt levels cause oxygen to bubble out. If true, this oxygenation would have allowed animal life already evolved as micro-critters across all the phyla in the nonmarine (yes!) to expand and evolve in the oceans (the “Cambrian Explosion” of life). My scenario for this alternative course of evolution has not been well received by the "community" which is thoroughly locked in an absolutely no evidence-based paradigm that salt levels in the ocean are constant over geologic time. I guess others might just think that salt hoppers like this are not unusual in mudstones. Ha! They are incredibly unusual. This may indeed be evidence that the oceans were much saltier in the Precambrian. My suggestion is that preservation of crystal impressions like these could occur because the muds in a shallow embayment along a coastline would not have to dry out so much for salt to precipitate. Whatever, these are spectacular examples.

We finally reach the river and look at the noisy rapid created by past debris flows that came down Lava Canyon. Directly across from the junction, the Palisades Fault trending southeast slices into the layered stratigraphy. It emerges about 135 yards to the north on our side and crosses the river at an angle of about 45 degrees as it extends southeast. The fault plane is roughly parallel to the high cliff of Paleozoic strata and passes behind the black hump of stacked lava flows straight across the river here (Figs. 14.20 and 14.21).

Fig 14.20. View east of the Palisades Fault across from the mouth of Lava Creek. The Colorado River runs left to right across the bottom of the image. The far wall shows the typical Paleozoic layers of the Grand Canyon with the white, salt encrusted, basal Tapeats Sandstone at left center. A hump of black, billion-year-old lava flows sticks up to the right where the Tapeats should be if extended to the right across the image. The Palisades Fault zone separating the two is a jumble of red, black, brown, and light-colored rubble (see next two figures).

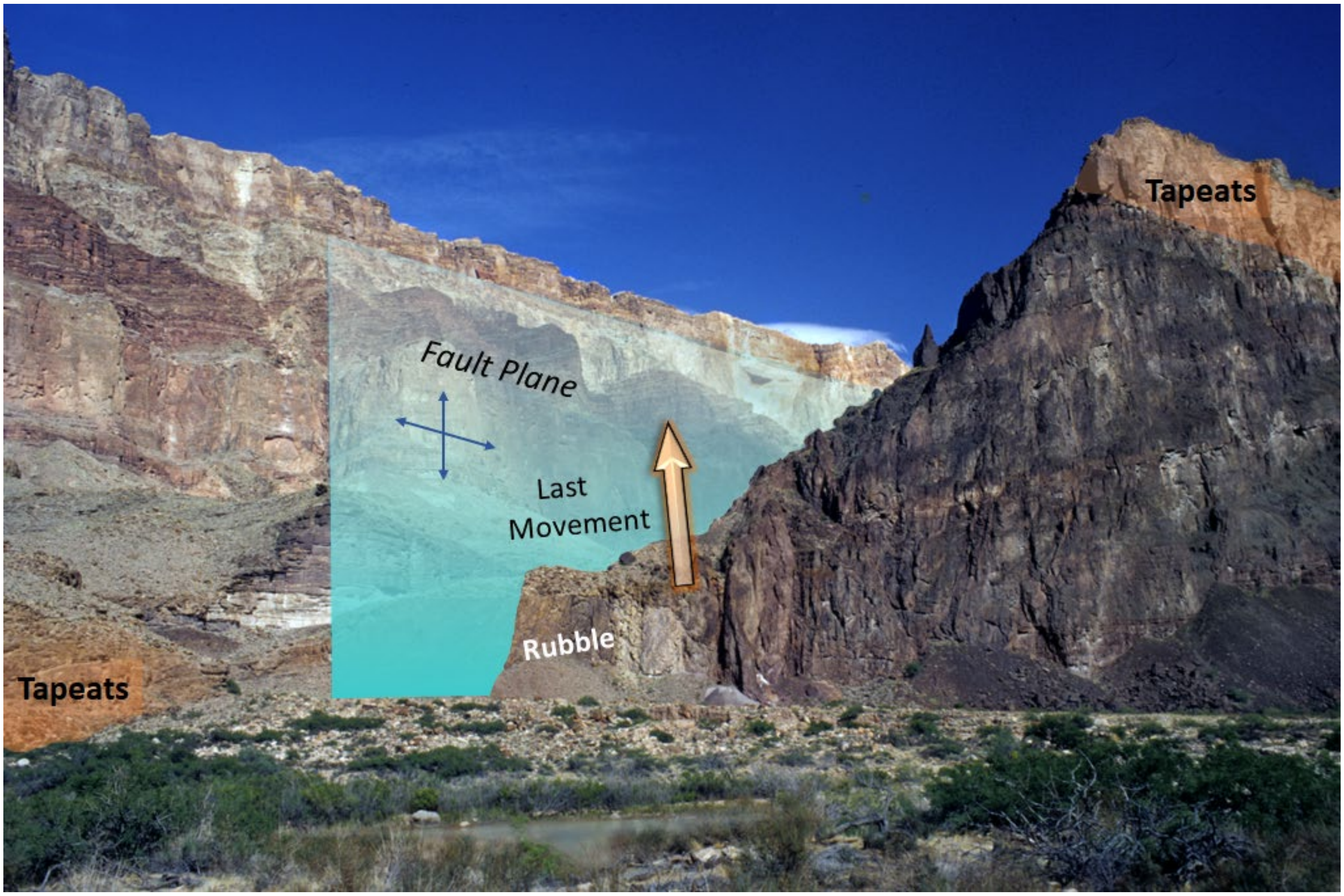

Fig. 14.21. The Palisades Fault is the oldest fault in the eastern Grand Canyon and formed about 1.1 billion years ago when the block to the right slid down the fault plane at least 1000 ft. The Paleozoic layers were deposited starting about 520 million years ago and covered the whole area. Then, the fault reactivated about 70 million years ago and the lava stack rose back up about 1000'. This pushed the Paleozoic stack up as shown by the offset of the Tapeats to the left of the fault vs its position atop the lavas to the right. Since then, all of this has been exposed by erosion as the river cuts downward here.

The fault It is a zone 200 yds wide filled with crushed rock, mangled beds, and slivers of lava layers standing straight up. The stack of lava flows once connected toward us across the river to the black mountain we just walked past coming down Lava Creek. The river simply dug out a passageway through the stack of ancient lava flows down into the underlying Dox Formation.

Across the river we see the most recent offset along the Palisades Fault. The Tapeats Sandstone coming in horizontally from the left ends suddenly and reappears on the right side of the fault high in the sky resting on the black lavas (Fig. 14.21). That whole block to the right came up the right side of the fault plane about 1,000 ft during the Laramide Orogeny. This is the reverse direction of its initial sliding down the fault plane after the lavas stacked up about a billion years ago (event #1 in Figs. 14.13 and 14.14). The entire pile of horizontal Paleozoic strata that once lay above the Tapeats capping the lavas to the right of the fault plane also rose by the amount we see in the figure. The far wall of the canyon is tilted away from us by several degrees as a remnant of the monocline that once existed prior to modern erosion high above the fault as indicated in Fig 14.13. That tilt increases to 15 degrees as it goes south before the Palisades and Butte faults join just east of Desert View to produce the great monocline that HW 64 goes down (Fig 4.1).

The shredding, pulverizing, grinding, and warping that rocks undergo in a fault zone are vividly on display here in the afternoon sunshine (Fig 14.22).

Fig 14.22. Close up of the tortured Palisades fault zone with layers of the Tapeats dragged up on left side and pulverized, bleached remnants of the lava flows jumbled on the right.

Mein Gott, this is something to behold! There on the left side of this rubble zone, mangled layers of the Tapeats that butted up to the fault plane are visibly dragged upward. Toward the right side, battered pillars of dark basalt testify to the crushing power of the original movement that dropped the lava stack down to the right followed by additional shredding during the reversed, upward, Laramide movement. Smaller displacements and adjustments probably happened numerous other times because fault zones never heal. It is all so plainly visible that it is difficult to eat in peace here. This is one of the most magnificent exposures of slow violence on a fault plane anyone is ever likely to see.

A trail on the bank takes us upriver 133.18 yards to the shade of several large mesquite trees and two tables covered with lunch fixings. Although we will just be here for lunch, this is a great campsite with happy memories (Fig. 14.23).

Fig. 14.23. Home for the night on a hill above the Lava Creek campsite. The rewards of shlepping your gear up this pile of sand is great. Lava creek joins the river just in front of the hill behind the tripod. The salt-caked Tapeats is on the left edge skyline which ends abruptly at the Palisades Fault. Note how an extension of the Cambrian Tapeats in your mind's eye would butt into the Precambrian lavas brought up on the other side of the fault. The skyline above the driftwood tripod is Desert View on the South Rim!

If the Carbon Canyon campsite is taken, it is usually possible for the crew to motor the boats from here back upstream to Carbon Canyon the next day and pick up hikers who want to do the scenic and geologically challenging loop in reverse. The geology starts off in much complexity from here, so it is better to go up Carbon Canyon first to let it unfold. However, the competition for campsites is great, so do that which is possible. Or come back for another trip; they are never the same.

I make a sandwich, sit in the shade, and look down toward that view of the fault zone that is visible from here, but not in spectacular cross section as directly across from the mouth of Lava Canyon. That is a view of the terrors that rocks can undergo—getting caught in a fault zone (Fig. 14.22). But that fault zone starts its crossing of the river only about 10 yards upstream from the lunch table. You can climb around in it via a short path to our left that goes to an old dig-out where some prospector of long ago noted small amounts of mineralization in the fault rubble. Ore-bearing fluids came up through the rubble at some point, but the colorful ore produced was insignificant and has been nearly entirely removed by souvenir hunters on raft trips. People camp here almost every night during the rafting season. Indeed, the well-trampled trail goes north from our lunch spot first through a small cubby hole in the vegetation where campers always set up a porta-potty. Few know about the mineralization and fault rubble they are squatting near. Alas, probably only a few see the incredible geologic display across the river. Certainly, everyone notices the striking scenery.

The story here holds special significance to geologists who wonder what caused all this faulting. This is a set of veins in the wrist, but how does it fit into the circulation system? What is the heart of the matter here? I am not very good lunch company to the happily animated crowd tucked into every shady spot here and jabbering about all they had just seen on the morning hike and all matter of other subjects. I am mesmerized. Paralyzed in thought. Lost in memories. Giddy in the profundity and problems of all I see here. How many eyes have seen this?

In the fall of 1965, I was sitting in Kansas City on the third row of a technical session of the Geological Society of America's annual convention and witnessed Canadian geophysicist J. Tuzzo Wilson give a talk on the origin of California's San Andreas Fault. I had travelled to the meeting by train from the University of Chicago where I was an undergraduate student to see what geology was like and to talk with faculty from Caltech where I had applied to graduate school. Wilson unraveled some cardboard cutouts to explain how a new global theory now called Plate Tectonics could finally explain the mystery of this great earthquake-producing fracture. A sliver of our continent was being ripped off along a fault line extending from near Los Angeles to San Francisco. The whole landmass to the west of it was moving northwest and creating earthquakes as it rubbed against the larger piece to the northeast. Later in the day, I heard Lynn Sykes from Columbia University give new precision earthquake location data that compellingly supported the idea that the ocean floor in the North Atlantic was splitting apart with each side moving laterally away from a big submarine ridge of volcanoes called the Mid Atlantic Ridge. From that point on, the new global theory called "Plate Tectonics" began to be taken seriously. Today it is considered the backbone of Geologic Science. So much so, that any past tectonic disturbance or deformation observed in the rock record is quickly interpreted in terms of this great theory—for better or for worse.

The basic idea is that interior heat escaping from the surface to outer space has allowed the outermost 100 miles or so to solidify into a relatively rigid peel called the "Lithosphere." The deeper parts of the peel became hot enough to start melting, but the pressure from the weight of the overlying rocks is great enough to keep them solid. Meanwhile, heat from deeper down finds no easy way to escape through the peel and slowly builds up. As the lithosphere cools by loss of heat to space, a plate thickens downward. The bottom parts become denser as minerals transform themselves at the higher temperatures and pressures. Theorists propose that the lowest parts of the thickening lithosphere can tear off and sink down into the hotter, less rigid depths below. This "delamination" involves solid materials, but the consistency is that of toothpaste at these temperatures and pressures. Although the movements are only about as fast as fingernails grow, millions of years can result in vast movements. Following delamination, the overlying, more buoyant lithosphere can float upward somewhat analogous to a cork with an iron weight on the bottom that falls off. This type of process has probably acted since the lithosphere first began to form when the baby Earth started to cool off following accretion. We have plenty of evidence for "vertical tectonics" all the way back in time to the oldest rocks. Something like this delamination has been suggested as a possible cause of the Kaibab uplift, although delamination purists aren't in agreement about much and might want to reserve the term for something else.

More to the point of what we are looking at across the river, we need to first imagine a truss arc support under a bridge or under the roof of a medieval cathedral. Or better, learn to "wave your arms" like a geologist. Curve your fingers and lean together both hands along the fingertips above your heart center. As you relax your arms, feel the pressure at the fingertips increase. Now, curve the fingers of your right hand downward a bit and observe them instantly slide under those of your curved left hand. Bingo, you just "arm waived" an example of "subduction," the key process in the theory of plate tectonics. Just imagine that the lithospheric peel encapsulating the globe cracks somewhere and one side starts descending downward under the other. The trailing parts would slide along behind, all being pulled by gravity. A giant extension zone opens gashes far behind the descending slab as it moves laterally. The associated release of pressure under any gash allows pressurized, toothpaste-like material from below to start squeezing up. As the pressure on the ascending material decreases, the toothpaste at this spreading center melts and volcanoes erupt all along the incipient opening. The mid ocean ridges are examples of such a spreading zone. This is where and how most of the heat of the inner Earth apparently escapes nowadays. Of course, there will be cracks along both lateral sides of the piece going down the subduction zone, and the grinding of one piece of lithosphere against the other generates tremendous earthquakes. There appear to be about 13 major areas of the global lithosphere today that are interacting with each other in this fashion. They are areas on a sphere and thus are somewhat upside-down bowl-shaped instead of like two-dimensional dinner plates. Imagine seams on a baseball and you can get a general idea of what a "plate shape" can look like--although the "plates" on a baseball are much larger with respect to the sphere than plates are on the Earth. Most of these plates are slowly moving around the Earth in a west to east direction but not all at the same rate or in the exact same direction. They thus must interact with each other on all sides. They must not be confused with continents. Continents are basically buoyant masses of less dense granitic composition of problematical origin that are embedded in the tops of plates and ride passively along. They cannot follow the denser plates they sit on as they slide down into the subduction zone. If a continent-bearing plate is carried to a subduction zone, it will collide with any others approaching it on another plate. The opposite happens when a spreading zone splits open under a continent to form two new plates. In that case, the overlying continent is split, and the separate pieces move away one from the another.

Some geologists would cringe at this simplified explanation of Plate Tectonics. Some argue that heat rising in great plumes lifts the plates and cracks them apart. Then they slide off the bulge toward subduction zones. It is kind of a “which came first, the chicken or the egg” situation--spreading centers or subduction zones first? The question eventually tangles up with the question of when plate tectonics as we envision it today originally started. Some just assume it got going immediately after the Earth formed. While evidence for vertical tectonics of some kind is present in the earliest preserved rock record starting 3.6 billion years ago, compelling evidence for subduction everyone agrees on goes back only about 900 million years. Subduction as we know it today produces zones where sediments appear to have been pressure-cooked at relatively low temperatures because the plate goes down and gets pressurized faster than it heats up. They also possess a distinctive chemical suite of rocks that melted to become lavas or solidified into masses at shallower depths. Some argue that older evidence of subduction has been destroyed by later processes. I am prejudiced that remnants of the Precambrian rock record on continents are much better preserved than many geologists imagine and am thus cautious when claims are made that something not observed must have been there. The faults and older displacements so vividly on display in the Precambrian rocks across from the mouth of Lava Canyon have been widely interpreted as the beginning of the breakup of an ancient supercontinent called “Rodinia” that may have existed here about a billion years ago. Rocks slightly younger than this elsewhere have the distinctive signature of subduction, so we can ponder if we are not seeing here rumblings of the very birth of modern plate tectonics. The idea is that Rodinia was becoming fragmented by spreading centers forming under it and pieces starting off on a long episode of “continental drift.” Here the fragments started forming and got jostled around before any rift formed. A rift tried to start here but stopped for unknown reasons. Immediately west of Death Valley, there is evidence that one or more pieces of Rodinia eventually took off and are found today in Siberia, Australia, and/or Antarctica after drifting around on lithospheric plates for hundreds of millions of years.

As I sit in the lunchtime shade looking across the river, the idea that I am possibly looking at the birth of the modern style of plate tectonics intrigues me. The idea no doubt threatens geologists who instinctively use the modern plate tectonic paradigm to interpret the fragmentary record of continents going back 3.6 billion years. What happened to the rock record older than that is a fascinating story involving the impact history of asteroidal fragments in the first billion years of Earth history. The idea that the modern cycle started only 900 million years ago has not been well received by geologists who readily and regularly apply it to rocks of all ages. Even Warren Hamilton, who was the first to study subduction geology received little support for his and other geologists' arguments that evidence is lacking for such zones until late in the Precambrian. The issue goes unmentioned in most geology textbooks nowadays.

So, I sit, stare, and wonder. More than 50 years later, Wilson and Sykes seem to be standing at the speaker's podium like ghosts projected onto those cliffs. Was the great fault zone before me here initially part of a supercontinent cracking up? This is not the situation Wilson and Sykes were talking about but not so different. A plate boundary may have been trying to form here—a zone of divergence where one side pulls away from the other to follow another side that has "broken the truss" and is starting to slide under another to form a subduction zone thousands of miles away. Outpouring of lavas in younger continental rift zones are observed elsewhere, so maybe that is why these lavas erupted here so long ago. Or maybe not. We have much to learn, and there are strong scientific personalities who would steer the consideration according to their own prejudices. For me, just knowing the potential significance is exciting.

I start to pick up my field microphone to relay some of this to anyone interested. But the afternoon heat is on, the shade is limited, and listening to a know-it-all geologist right after lunch can be painful. More importantly, I have concerns about Plate Tectonics. Me--who in 1972 enthusiastically introduced the new theory as a new assistant professor into my first Introductory Geology Class at Louisiana State University. It hadn't permeated my graduate training at Caltech, possibly because the famous geology program there had played no role in its development. I was right out of grad school and in a wonderful geology department with faculty colleagues who were not yet on the Plate Tectonics bandwagon. But I had kept up with the literature appearing in the journals and was on fire to incorporate it into undergraduate education. This I subsequently did during over 100 semesters of teaching first at LSU and later at ASU. Then one day toward the end of that career, I walked out of an introductory class lecture where I had been arm-waving plate tectonics and asked myself, "What in God's name have you been teaching?" It was simplistic nonsense that I had been force-fitting into my teaching philosophy regarding science and how students should think about it. I was suddenly rebelling against the expensive textbook and rethinking about what college education should be about. I quit teaching introductory geology shortly after that because I couldn't find a textbook that didn't build on plate tectonics as an undersood, essential truth. Here I was about to expound uncomfortably again.

My concern and horror is that the theory of plate tectonics is now warping the underlying philosophy that led to the success of geological science and is instead inculcating a dubious ideology regarding how all science works. Geologists aware of the complexity of what they see in the field and the enormous number of variables that led to it invoke multiple hypotheses that could account for what is going on and/or what went on. After the first possible explanation is developed, it is set aside, and a different possible explanation is then sincerely and honestly considered. Then a third and so on until no more reasonable hypothesis can be thought of. The possibilities are then ranked according to how many steps are required to achieve the observed result or according to what best fits what is observed. If one explanation stands far above the rest and survives new observations and tests while the others look far less likely, a point can be reached where time and effort should be diverted to other problems that need to be solved. At no time should the highest-ranking hypotheses be considered “truth” or “certainty” because new data may force a re-examination of the issue. An example is Meteor Crater in Arizona where the top of the list of possibilities for decades was that it was a volcanic explosion and not a meteorite impact crater or anything else. After all, it was very near to cones and vents that had been interpreted as explosive volcanos, the iron meteorites found nearby were not centered on the crater, drilling showed there was no buried iron meteorite under the crater, and it was roughly square or octagonal unlike impact craters elsewhere. A better understanding of how impactors get fragmented, vaporized, and strewn about as well as discovery in the crater of high-pressure minerals likely in impacts but not in volcanic explosions pushed the impact hypothesis to the top of the list. If you had to bet money on it, that is currently the most likely possibility. While always open to reasonable ideas, I would readily make that bet. Is it “certain” that is what made the crater? Is it a “fact?” No!

Plate Tectonic processes quickly emerged as the #1 possibility for a myriad of geological mysteries plaguing researchers. It was exciting and revelatory for us all. My teaching got transformed because I could present an array of mysteries we observe and then…wham! Plate tectonics comes to the rescue as a likely explanation. I felt it was one of my successful teaching strategies. A favorite was that long chain of extinct volcanic islands that trends from the north Pacific southward for over 1,500 miles and then bends to the southeast for 2,000 miles to terminate in the active volcanoes of the Hawaiian Islands. In the theory, this is where a localized source of melting is inferred to lie deep below the lithospheric plates. As the vast Pacific Plate initially moved north, it was like going over a blowtorch. A plume of molten rock rises from a continuing source of melting and penetrates the overlying plate to form a trail of volcanic rocks as the plate moves over it. About 45 million years ago, the plate suddenly changed course and went northwest until today the plume of hot magma is at the southeast end of the chain of extinct volcanos right under the Hawaiian Islands. A plume like that and several others elsewhere were considered deep-seated reference points above which plate motions occurred. The Hawaiian hot spot is the classic example in every textbook and sounds wonderful. But do mantle plumes known as “hot spots” really exist under the middle of plates--or anywhere else? Can a plate suddenly make a sharp turn like that relative to the “fixed” plume? Really? You cannot believe how people have squirmed to explain this convincingly. Mantle plumes are adamantly supported by famous seismologists and adamantly opposed by other famous seismologists. So, campaigns seem to always be underway to detect and describe the physical nature of the classic one under Hawaii using seismology to “image” the rising pillar of heat and/or magma. Alas, the results so far are ambiguous. One of the most detailed investigations indeed claimed detection of the plume, but it was not under any volcanos or older volcanoes in Hawaii. It was way offshore, possibly over 100 miles. Not to challenge the paradigm, the investigators argued that the vertically rising plume they thought they were observing somehow travels laterally at the last minute at shallow depths and then erupts according to theory. Alarm! Special pleading is required to sustain the predicted result. An alternative explanation proposed by others for the bent chain of volcanoes invokes a propagating crack in the Pacific Plate that triggers melting underneath as it lengthens. No "hot spot," plume, or sudden change in direction of the Pacific Plate necessary in that simple explanation.

What throws a shadow over my enthusiasm here is that there are numerous problems with how people apply plate tectonics to the faults, folds, and geologic history of the Grand Canyon and other areas. It is often simplistic and illustrated by two dimensional figures that do not consider that all this involves vertical motions downward into the inner parts of a spherical volume, the Earth. Just like uplift in such a volume creates expansion cracks in the outer crust, so motion downward involves volume compression that can't be illustrated in two dimensional cartoons. It must involve three dimensional contortions that also twist the thermal contours as minerals transform into denser phases probably insufficient to account for the shrinking volume. I eventually got tired of reading and listening to arm waivers talking about how this plate rammed into this one, how this is a piece of distant continent that rifted off and patched on here or there, this crustal slab sank, and deep mantle material squished in above to uplift this area, then squished out to make it sink, etc. You can always arm-waive your way to any result. These hypotheses are usually advanced with confidence, sound good, and may be on the right track; I think many probably are. God bless the interpreters for trying! My own interest fades when I realize that so much is undoubtedly a house of cards developed on simplistic cardboard cut outs. Simplistic models are quickly replaced by other simplistic models, often by the same people. Colorful diagrams purporting to be like "CT scans" really wowed me until I read devastating critiques that the amounts of seismic data necessary to construct realistic color diagrams of this sort are hugely insufficient. Many of the early papers that awed us have apparently been overinterpreted and did not survive the test of time. All these uses of the theory to explain specific regions are heroic efforts but are bothersome when presented as what we should now "believe" and proceed with. The number of variables is large. The amount of data yet to be compiled and interpreted is enormous. I just couldn't teach plate tectonics as THE core principle in geology that we must force-fit everything into. Let uncritical believers do it. God bless them. If we made a scale model of the whole Earth such that it was 4.2 ft wide, it would weigh seven tons and have the consistency of wet mud or putty! Push one side of a "rigid" lithospheric plate if you can and it will rumple up—not move. Rocks do not have such strength at this scale, so that concept I once saw invoked is silly. Imagining plate tectonics in realistic terms is a real challenge. It is all about how heat is trying to get out with gravity relentlessly pulling everything together. Here we see the Palisades Fault and evidence of displacements along it in the past. How to explain the cause? What plate tectonic model to use? Clearly it is a manifestation of processes happening on a global scale. I'm not sure we can ever know.

I grab the microphone and try to point out some of the goings on. I decide not to raise the issue of what that first Precambrian unit was that we saw slanting up to the Tapeats at the Hopi salt shrine. At the salt shrine where it was first seen, it was originally mapped as a separately named unit above the Dox but considered by later mappers to be in the Dox at an unknown level and next as the lowest layer of the Dox. There are problems here for this little sliver of Precambrian rock exposed only from the salt shrine along the river to a little south of Carbon Canyon where we camped. There it underlies the Tapeats Sandstone, but across the river south of the Palisades Fault the Tapeats sits directly on the lavas. This is part of the reason deposition of the Chuar is inferred to have commenced and continued during down-dropping west of the Butte Fault and not east of it. Why the Tapeats rests on the lava flows south of the Palisades Fault but on the Dox north of it requires some speculative arm-waving that ties your arms into knots and convinces you that you just don't know.

The Dox contains some wonderful concretions that Bryce Winter found about 200 yards behind our lunch spot in the hills above and not far below the contact with the lavas. Some can be seen along the riverbank approaching our spot, but we walked around that to do our loop hike. I'm not sure if giant concretions have been officially reported in the Dox, but there are certainly some humdingers in the upper layers of it just north of Lava Creek behind the campsite. I even wonder if those huge concretions we stumbled onto in Carbon Canyon might not be in a small erosional remnant of the mystery deposit sticking up into the Tapeats. We will see in a few days many examples of remnant islands that the Tapeats Sea had to progressively submerge. I thought at the time we were in the Tapeats, but I'm not sure such humdinger concretions this big occur anywhere else in it. No doubt I have inadvertently passed out a lot of bad information to people on my trips. For sure, every interpreter does.

Those fault slivers and all the deformation visible on the far side of the river are exciting, so I try to point some of it out and explain in 25 words or less those features people can actually see. Alas, the blazing noontime sun has washed out the colors and it is getting hot, hot, hot. Clearly, everyone including me is more interested in getting back on the cold water. Besides, I am reluctant nowadays to talk about regional and global processes because of my ambivalent feelings toward forcefully and immediately applying the runaway paradigm of Plate Tectonics to everything we see. So, let's go rafting!