AEG 57th Annual Meeting

September 2014

Guidebook for Field Trip #1

Grand Canyon – Geologic Tour of Central and Northern Arizona

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Guidebook Edited By: Chase White

Field Trip Sponsored By: Duane Kreuger

Field Trip #1: Grand Canyon – Geologic Tour of Central and Northern Arizona

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Field Trip Overview

This three-day trip will traverse all three of Arizona's geologic provinces (Basin and Range, Central Highlands/Transition Zone, and Colorado Plateau) and will include stops and points of interest in each province. The feature of the trip will be a visit to the South Rim of the Grand Canyon with an introduction to the geology and history of the canyon and a guided walk along the Trail of Time. Traveling to and from the Grand Canyon, we will be presented with a roadside geology overview of central and northern Arizona and will see evidence of past faulting volcanism, and landsliding, engineering geology of historic and current transportation routes, historic and current mining operations, geologic hazards, and other associated environmental and engineering geology sites of interest.

The tour will travel by bus and leave from Scottsdale on the morning of Saturday, September 20th and travel a scenic route northward to Flagstaff, AZ where we will be staying the night at the Embassy Suites. The Day 1 itinerary includes stops at several sites of interest in the Central Highlands/Transition and Colorado Plateau geologic provinces of Arizona, including Sunset Point, Jerome, Sedona, and Oak Creek Canyon.

The next day we will travel to the South Rim of the Grand Canyon from Flagstaff via Highways 89 and 64. We will make stops at sites near Sunset Crater, at Cameron, and at Desert View on our way to the Grand Canyon South Rim Village to walk the Trail of Time. Hiking into the canyon is strongly discouraged due to time constraints. A group dinner will be provided at the Maswik Lodge and accommodations for the evening will be at the Yavapai West Lodge in the South Rim Village.

We will leave the canyon on the morning of Monday, September 22nd to head back to Scottsdale via Flagstaff, Ash Fork and Prescott to provide a loop route with opportunity to see and visit new and different geologic environs on our return. We will stop at the Red Mountain cinder cone near Flagstaff, an exposure of the Little Chino Fault near Paulden, and Watson Park in the Granite Dells area near Prescott during the day.

Field Trip Itinerary and Guide: Day 1, September 20, 2014

**Day 1 – Scottsdale to Flagstaff via Interstate 17, AZ State Highways 260 and 89A
(Guide: Phil Pearthree)**

Figure D1-1. Map of the field trip route for Day 1.

- After departing from the Doubletree Hotel, we will Drive north on Scottsdale Road, east on McDonald Road, north and then west SR101, the Pima Freeway.

We are now driving through Paradise Valley, located in the northern part of the much larger Phoenix Basin. The Phoenix Basin is a broad physiographic valley composed of several deep structural basins, including Paradise Valley, and numerous low mountain ranges and bedrock hills such as the Phoenix Mountains to the visible to left. The terrain you see around you is typical of the Basin and Range Province (BRP), characterized by discontinuous mountain ranges separated by deep sedimentary basins. This type of terrain developed through a large swath of the Southwest in the past 20-30 million years. The geology of the BRP is complicated, reflecting a long and complex geologic history. Prior to the dramatic extension and crustal thinning that formed the modern terrain, this region was shortened by compression for tens of millions of years and the crust thickened substantially. The thicker, buoyant crust supported a broad highland region. Large rivers flowed from this highland to the north and east onto what is now the Colorado Plateau, more or less the opposite of the modern situation.

The high terrain that we can see to the north and east is part of the “Transition Zone” of Arizona (Peirce, 1985). This part of Arizona has been so named because its geologic structure and physiography are transitional between the BRP here and the Colorado Plateau farther north and east. Most of our drive today will be in the Transition Zone, which is characterized by mountain ranges and plateaus, some sedimentary basins, and large rivers that are deeply incised into plateaus and basins. The geologic units commonly found in the Transition Zone are Precambrian basement rocks – primarily granitic and metamorphic rocks – and Miocene and younger sedimentary and volcanic rocks. The Paleozoic and Mesozoic sedimentary rocks that are widely exposed on the Colorado Plateau are for the most part missing from the Transition Zone, because they were removed by erosion during the time when the BRP was a highland area. As you will see today, the Transition Zone contains a wide variety of vegetation assemblages and some of the most spectacular topography and scenery in Arizona.

- Exit north on Interstate-17

As we drive north we are approaching the northern margin of the Phoenix Basin. North of the Carefree Highway / SR74 interchange with I-17, a low range of hills marks the approximate southern boundary of the Transition Zone – although it is not really well-defined here. The vegetation is typical of the Lower Sonoran life zone. This zone is characterized by saguaro, cholla, creosote bush, paloverde, and ocotillo. Saguaro may reach 50+ feet in height and weigh 10 to 18 tons after a wet season, and may live 300 years.

Proceeding north toward Anthem (a relatively new satellite community), a fresh road cut on the right reveals interbedded volcanic flows and tuffs with numerous examples of "burned" soil profiles, where emplacement of the hot volcanic unit scorched the underlying surface and paleosol horizon. The sequence dips moderately steeply northward, and thus has been tilted by since the rocks were deposited in the middle Miocene.

Continuing north on I-17, we are on the interface between a high gravelly relict terrace deposited by New River (a large drainage we can see to the west and which we will be crossing soon), and tributary alluvial fans coming down from Daisy Mountain to the east. This terrace has not been directly dated, but based on its height above the modern river channel and strong soil development, it is likely at least tens of thousands of years old. The high surface on the west side of New River is generally correlative with this terrace, and they were both part of a large alluvial fan deposited by the river. New River has cut down about 70 feet in this area since these gravels were deposited.

As we cross the bridge over New River, you should see some pretty obvious evidence of recent floods, including boulders in the bed of the modern channel and piled up organic material. Several dwellings and ranch buildings along New River just west of I-17 were inundated by a monsoonal flash flood event on 19 August 2014. The roadcut on the north side of the river shows the cross-section of an erosional surface (strath) cut onto bedrock by New River, which is capped with a thin layer of old river gravel. We are on top of or next to this terrace for several miles as we parallel New River to the east. The highest river terrace across New River to the east is about 200 feet above the modern channel, and is much older than the terrace we are driving on.

The mountainous upper watershed of New River opens to the east as we approach the Table Mesa Road exit. Just after this exit, we cross a low divide and enter the valley of the Agua Fria River, one of the larger drainages of the Transition Zone. Downcutting by the Agua Fria and its tributaries over the past 10 million years or so has deeply dissected this sedimentary basin. Roadcuts expose layered tuffaceous sandstone, conglomerate, and limestone of the Chalk Canyon Formation; these rocks were deposited in and around marshes and lakes about 15-17 Ma (million years old).

As we drive down into this valley, observe the high, gently undulating surface of Black Mesa to the north. The mesa is underlain by Precambrian basement and Miocene interbedded volcanic flows, tuffs, clay, sand and gravel, all capped with ~10 Ma basalt flows. Deposits similar to those beneath Black Mesa once filled this valley prior to incision by the Agua Fria River. We will get a closer look at these geologic units as we drive up I-17 to the top of the mesa.

As we pass under the Rock Springs overpass, look north to see several prominent gray stripes high on hillside – these light-colored outcrops of basalt have recently been exposed by movement of the Black Canyon City landslide, the topic of Stop 1.

Cross the Agua Fria River channel. The boulders mantling the channel floor consist mostly of resistant basalt clasts eroded from Black Mesa and Perry Mesa farther east. The large, deep valley to the northwest (left) is Black Canyon. The large, deep valley to the northeast (right) is the Agua Fria River valley. Both of these drainages had substantial floods on 19 August 2014 resulting in extensive inundation of low-lying areas along the channels, including Black Canyon City. In December 1978, a flash flood in the Agua Fria scoured away the abutments of the original bridge constructed over the River for I-17.

- Exit I-17 at Coldwater Canyon Road, turn right on South Coldwater Canyon Rd, turn right immediately and then into bladed area to east.

• STOP 1: Black Canyon City landslide

Mass movements ranging from debris flows to landslides to rock falls are common in the rugged topography of the Transition Zone. The primary purpose of this stop is to discuss the Black Canyon City (BCC) landslide, which has been active in the past few decades and can be observed on the steep slopes above us to the northeast.

The BCC landslide was initially reported as "fissures" in 1962, along with other instances of fissure development that were related to groundwater withdrawal and land subsidence in Arizona (Robinson and Peterson, 1962). These fissures are headwall features that developed as the landslide mass slid down to the south toward the Agua Fria River. The age of initial development of these fissures (and thus movement of the landslide associated with them) is not known, but the discovery by local residents of dramatic new fissures was reported in Phoenix newspapers in early 1962. Robinson and Peterson (1962) observed traces of east-west-trending fissures on aerial photographs of the area taken in 1936, so the landslide has existed since at least the early 1900s. The landslide caught the attention of Nick Priznar, long-time engineering geologist with the Arizona Dept. of Transportation, and was investigated as part of a series of class projects by Arizona State University students under the direction of Ramon Arrowsmith and P.A. Pearthree in the late 1990s; the description of the landslide presented here relies heavily on this unpublished work.

The landslide forms a ridge extending from the high plateau remnant to the north (Figure D1-2). The ridge is bounded on both sides by moderately deep valleys drained by small washes. The landslide mass is about 1800 ft long, 1900 ft wide at its upper end and 500 ft wide near the toe. The upper limit of the landslide is defined by large E-W trending fractures (Figure D1-3). As noted above, most of these fractures had clearly formed by 1962, and most have partially filled in with sediment since that time. On the west and east flanks of the ridge, the large fractures transition into multiple smaller, discontinuous fractures that continue to near the base of the ridge. Based on review of recent aerial photographs of the landslide, some of these lateral fractures have continued to develop in the past few years. The sides of the landslide mass are quite steep (25°); the nose of the landslide is less steep (10° to 15°). The base of the landslide is a very gently south-dipping to subhorizontal clay-rich layer. This clay-rich layer is exposed in steep slopes around the margins of the ridge. The main mass of the landslide consists of moderately indurated Miocene conglomerate capped by volcanic flows. These overlying units are fairly competent, but the slide mass itself is broken up into numerous, complex blocks, some of which are rotated 10° to 45° to the south. Based on fracturing in the main slide mass, it appears that it is spreading to the south on its longitudinal axis, but also spreading to the east and west toward the steep sides of the ridge.

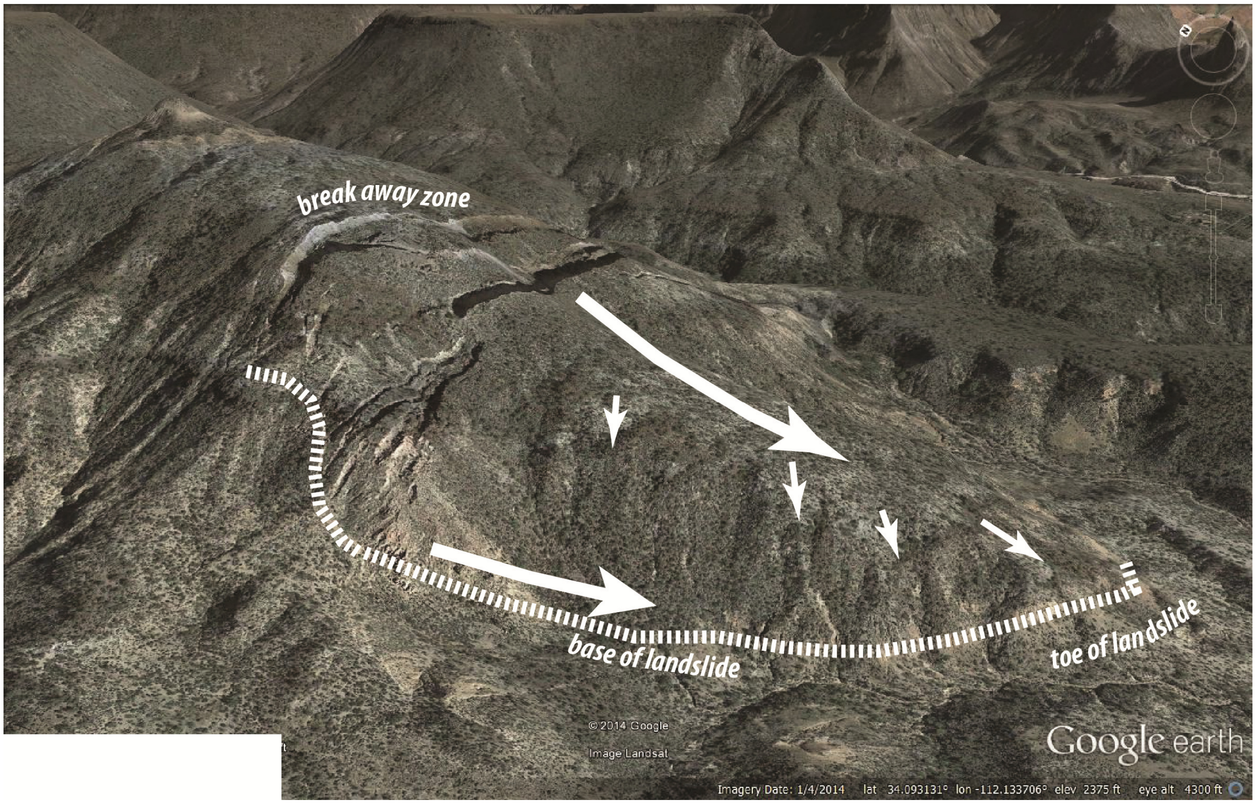

Figure D1-2. Diagram of the BCC landslide as seen from a southwest perspective. The area on the ridge above the headwall fractures apparently is stable; the landslide mass is moving slowly or intermittently to the south over a clay-rich sedimentary layers. Base image is from Google Earth.

Figure D1-3. The large fissure that forms the headwall of the BCC landslide forms an obvious notch on the ridge at the skyline, viewed from the west near I-17.

Detailed geologic mapping of this area (Ferguson et al., 2008) revealed that there are multiple generations of landslides, so the geology and topography of this area are obviously conducive to the development of landslides (Figure D1-4). This is a very important process modifying and eroding the margins of the high mesas to the north.

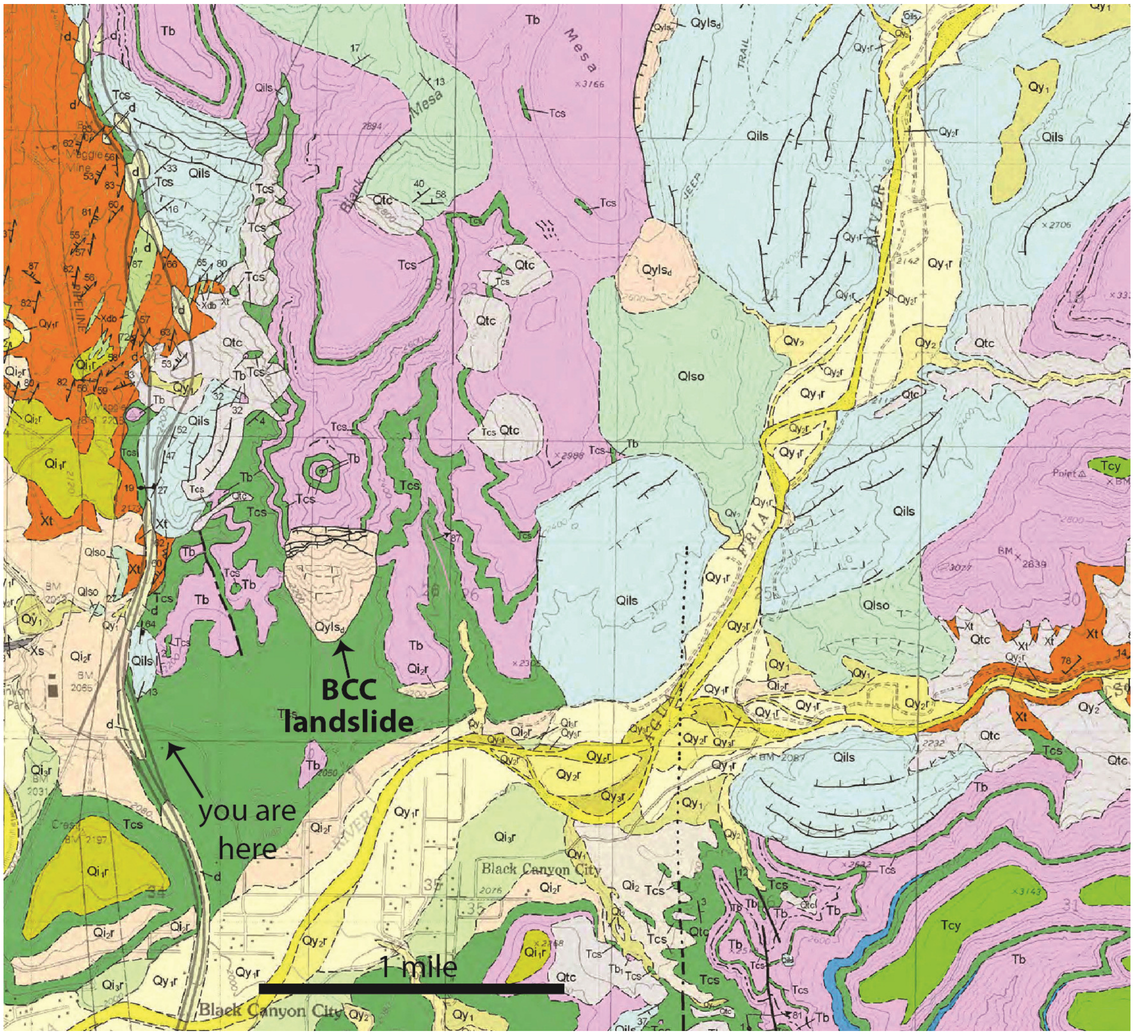

Figure D1-4. Geologic map of the BCC landslide and vicinity (Ferguson et al., 2008). The BCC landslide is the most recently active feature, but landslides of various ages are very common in this region and they are probably the most important mechanism eroding the margins of Black Mesa.

- ➢ We will next return to I-17, proceed north and begin the long climb up to Black Mesa and Sunset Point.

The road cut along the entrance ramp exposes fine-grained deposits overlain by basalt; this part of an older landslide block. Looking back to the east soon after entering I-17, there is a nice view of the headwall features of the BCC landslide. As we continue up the long grade to the north, stratigraphic relationships of Tertiary volcanic flows and terrestrial deposits are evident. In these outcrops note the presence of numerous dark reddish brown "burned" or “baked” soil profiles, where flow of hot volcanic material over the land surface altered the underlying soils and strata. These Miocene deposits rest on Precambrian metamorphic and granitic rocks such as you see exposed in the Bradshaw Mountains to the west. The Miocene sediments and volcanic flows gradually buried erosional topography (paleohills) formed on the Precambrian rocks.

Rockfall is a ubiquitous hazard along this climb, and frequent maintenance required. There is a jersey barrier and Brugg rockfall fence just south of MP248 where rockfall has been particularly common from a high rock cut on the right shoulder of the northbound lanes. The interbedding of the Tertiary tuffaceous and lacustrine sediments and basalt flows contributes to differential weathering and raveling of the slopes.

As we approach the top of the grade, there is a dramatic exposure of the basalt flows that cap Black Mesa. In the southernmost part of this exposure, the basalt flows banked up against and eventually buried a paleohill formed in Precambrian rocks. As we continue north to the top of the grade, several stacked basalt flows that underlie Black Mesa are evident. The basalt flows and sediments exposed near the top of the grade are part of the Hickey Formation, a 10-15 Ma unit that is widespread in this part of Arizona.

As we emerge onto the top of Black Mesa, note the vegetation change to the prickly pear-grasslands. I-17 traverses Black Mesa for the next four miles or so.

- ➢ Exit for Sunset Point Rest Area; proceed south for about 0.5 miles to the rest area.

• STOP 2: Sunset Point Rest Area – Regional Geology and Landslides

The Sunset Point Rest Area was presumably chosen for its relatively flat ground and the spectacular views to the west of Black Canyon and the Bradshaw Mountains. It is also located in a very interesting geologic setting, which gives us a few things to discuss as we snack and re-hydrate. As we have already noted, Sunset Point is on the western margin of Black Mesa, which is capped by ~10 Ma basalt flows. The general slope of these flows is down to the west and south. These flows and the sediments beneath them filled a broad valley formed in the Precambrian rocks (Figure D1-5). Looking across I-17 to the east, the low hill in the middle distance is an eruptive center (old volcano) called Joes Hill. It has been dated at 10.8 Ma, and is certainly among the youngest flows in this sequence. The Agua Fria River has carved a deep canyon between Joes Hill and our current location, obviously sometime since 10 Ma.

Looking over Black Canyon to the west, the skyline is formed by the Bradshaw Mountains. These impressively high, wide and long mountains extend for 40 miles to the southern edge of Prescott, Arizona. The Bradshaw Mountains are composed mostly of strongly metamorphosed Precambrian rocks, with a few much younger plutons. The older rocks may have originally formed as part of an island arc 1750 Ma that was accreted onto the edge of the North American continental margin shortly after that time (Anderson, 1989). These are some of the oldest rocks exposed in Arizona. In the valley below us, a major north-south-trending shear zone separates the really old rocks of the main mountain mass from slightly younger metamorphic rocks closer to us. Historically there extensive mining for gold, silver and zinc in the Bradshaw Mountains, and at one time a railroad was constructed through this difficult terrain to Crown King, a mining community at about 6000 ft above sea level. Today Crown King is a pleasant, small vacation community reached by many miles of gravel road.

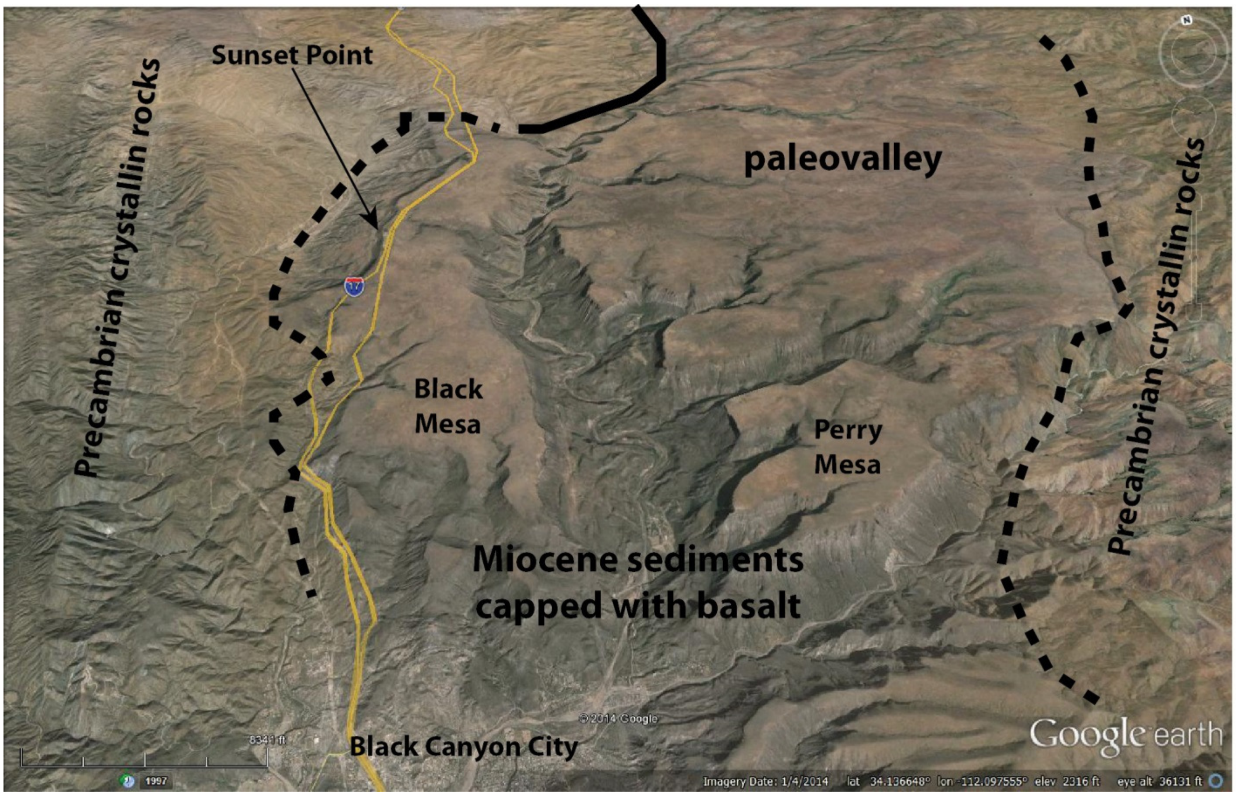

Figure D1-5. Broad, relatively shallow paleovalley was filled with deposits and basal flows of the Hickey Formation 10-15 Ma. The Agua Fria River and Bumble Bee Creek have eroded deeply into the margins of the paleovalley fill since 10 Ma.

The steep western margin of Black Mesa has formed as a result of long-term incision of Bumble Bee Creek since the mesa-capping flows were erupted. Looking at the situation a little more closely reveals a more interesting story - the margin of Black Mesa is very steep and sharply defined because it is the headwall scarp of a large landslide or more likely a complex of multiple landslides. Immediately below this scarp, there are several low ridges formed by pieces of the former mesa surface that have been dropped down and rotated to the east, toward us (Figure D1-6). Younger sediments have accumulated in the area between the main headwall scarp and these low ridges. Although this landslide complex has not been studied as far as we can discern, it is large and obvious in Google Earth (Figure D1-7). One reasonable scenario is that downcutting and lateral erosion by Bumble Bee Creek in the valley below us cut into the edge of Black Mesa, and the mass slid on the contact between Miocene sediments beneath the capping basalt and the Precambrian rocks that form the basement here.

Figure D1-6. View of the western edge of Black Mesa from the Sunset Point Rest Area. The low ridges below are the upper part of a large landslide complex. They are remnants of the basalt flows that cap Black Mesa that have been dropped down, and probably rotated back to the east, by landslide movement. The fine deposits between the ridges have accumulated in troughs formed by landslide movement.

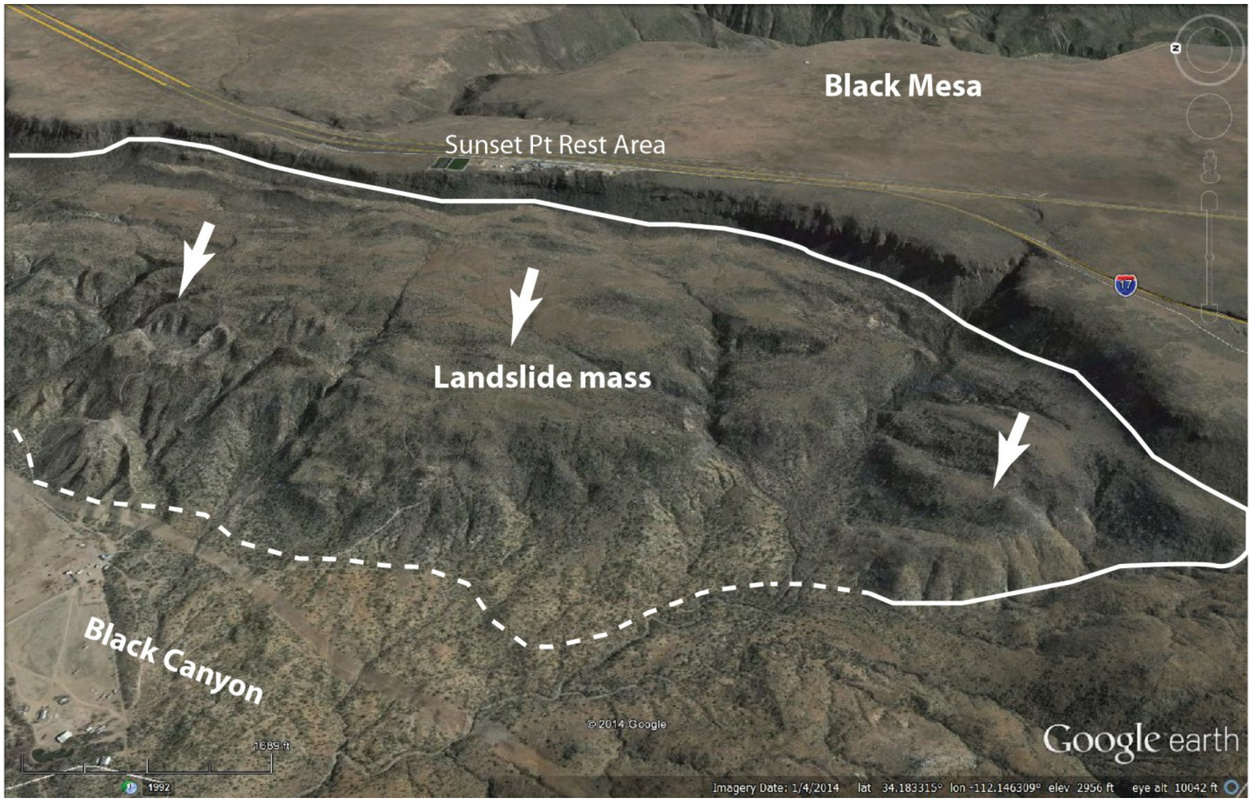

Figure D1-7. Sunset Point landslide complex viewed from the west, with interpretation of some of the landslide features. Base figure is from Google Earth.

- Return to I-17 North, drive toward the Verde Valley.

As we proceed north on the surface of Black Mesa, note the slightly higher, orange-tinged hills to the north. These hills are composed of Precambrian granite. They were a more impressive set of hills until they were surrounded and partially buried by deposits and basalt flows by 10 Ma. In the Cordes Junction area, we return to a gently undulating landscape formed on Hickey Formation basalt and sedimentary deposits. About 2.5 miles north of Cordes Junction, we cross the Agua Fria River again. To the north, the hills on the skyline are the Black Hills, which are capped by Hickey Formation basalt flows and somewhat older volcanic units. The "backside" of the Black Hills, which we are approaching, is fairly subdued and gradual. As we will see, this is in dramatic contrast to the northeastern margin of the Black Hills facing Verde Valley.

About 2 miles north of the junction with SR169, we begin down a dramatic incline into Verde Valley. Putting a freeway through this area was obviously quite a challenge. Here, the engineers took advantage of a relatively large drainage, Copper Canyon, which is eroded into the Black Hills and drains into Verde Valley. Rockfalls are a continuing problem along the south-bound (climbing) lanes in particular, and the Arizona Dept. of Transportation has just completed a multi-year construction project to widen the highway and stabilize the steep slopes above it. This work has resulted in spectacular roadcuts that reveal some of the basalt flows and sedimentary units of the Hickey Formation; farther down the grade we see exposures of Precambrian granitic rock – the basement rocks on which the Hickey Formation accumulated. As we near the edge of the Black Hills, roadcuts reveal coarse alluvial fan deposits tucked into the valley and several strands of the Verde fault zone at the mountain front. We will discuss this fault zone and the development of Verde Valley at Stop 3.

Verde Valley is a large structural basin that has been dropped down across the Verde fault zone, a major normal fault zone at the base of the Black Hills. As the basin dropped down, it filled with sand and gravel deposits shed from the Black Hills and the Colorado Plateau margin to the north, and carbonate (limestone) and silt and clay that accumulated in marshes and shallow lakes that existed in the valley as it subsided. These deposits collectively are the Verde Formation (Nations et al., 1981). The Verde Formation deposits accumulated in Verde Valley from about 8-2 Ma (Bressler and Butler, 1978). Since 2 Ma, the Verde River and its tributaries have eroded deeply into the Verde Formation deposits, and we will see lots of Verde Formation remnants in the next part of our trip.

- Exit I-17 at Camp Verde and turn NW on SR260 toward Cottonwood.

Almost immediately on the left there are nice exposures of Verde Formation (pale green fine deposits) overlain by younger, brown sand, silt and gravel deposits shed from the Black Hills, with an erosional contact between them. The Verde Formation was deposited to levels much higher than this ~2 Ma, and subsequently has been deeply eroded and partially covered by younger alluvial fan and terrace deposits. For the next several miles, we will see these younger deposits almost exclusively, but before reaching Cottonwood, Arizona, there are extensive and obvious outcrops of white limestone, pale green marl, and tan to reddish silt and clay beds of the Verde Formation.

- At the first major intersection in Cottonwood, turn left on SR 89A, then another left following SR89A toward Jerome.

As we continue northwest out of Cottonwood, note the very high gray ridges extending out from the Black Hills; these are deeply dissected alluvial fan deposit that accumulated as the valley was filling with sediment prior to 2 Ma.

- Turn left on SR 89A, head upslope toward Jerome

At this intersection we can see a large Portland cement plant to the west. This plant was originally developed for the construction of Glen Canyon Dam on the Colorado River near Page, Arizona. It subsequently supplied much of the cement that has been used to construct the Phoenix metropolitan area. The rocks that are being processed are Paleozoic limestone that is mined in the higher terrain to the west. The limestone exposed in the vicinity of the plant is part of the Verde Formation.

As we reach the base of the higher ridges mentioned earlier, there are exposures of Paleozoic limestone along the road. We are now in a structural block between 2 normal faults, each of which has down-to-the-northeast displacement. The margin of the deep sedimentary basin is behind us, but another major normal fault separates this block from the higher mountains to the southwest. As the road continues to climb toward Jerome, Tertiary basalts are exposed, and they are capped by tens of feet of coarse alluvial fan deposits. These fan deposits were emplaced when the basin was not dissected, and were graded to the highest level of the Verde lake deposits.

- ➢ Continue into Jerome and stop at the substantial parking lot on the left side of the road.

• STOP 3: Jerome – Lunch, Landslide, Regional Geology

The primary objectives of this stop are to eat lunch, enjoy a brief excursion in the interesting community of Jerome, and discuss the local geology and more regional geology of Verde Valley from this high vantage point.

Jerome is an old mining town founded in 1876. Its population peaked at about 15,000 people in the early 1900s, and the large open-pit copper mine in the hills behind the town operated until 1953, after the deeper underground workings played out. This open pit is unusual because it exploited massive sulfide deposits in Precambrian metavolcanic rocks (Cleopatra rhyolite), as opposed to the low-grade porphyry copper deposits typical of the other large mines in Arizona. The two primary mines in Jerome, the United Verde and the United Verde Extension, produced more than 1.8 million tons of copper metal during production from 1895 to 1975. The town was moribund for several decades, but in the past 30 years has been reborn as artist community and tourist destination.

This area has undergone major dissection driven by downcutting of the Verde River and its tributaries over the past several million years, and that dissection along the trend of the Verde Fault is responsible for the steep slopes upon which Jerome is built. As we have seen, steep slopes can be vulnerable to landsliding, and indeed part of Jerome was destroyed in the “Hull Street” landslide of 1936-37. We are currently near the top of the landslide, and the area downslope from here where no buildings exist is the main portion of the landslide. Apparently, the landslide involved failure of a moderately thick layer of hillslope colluvium over bedrock (Nick Priznar, Arizona Dept. of Transportation, oral communication, 2003). The landslide was not catastrophic, but the mass moved downslope in a shallow valley (Figure D1-8) and surface deformation destroyed many structures, including the city jail (Figure D1-9) and swimming pool. Later slope instability problems in the 1990s affected the state-owned highway through town, and the Arizona Department of Transportation conceived and constructed a set of rock-faced tieback retaining walls to preserve and mimic the character of the original 1930s era rockery-style retaining walls that were built in the town.

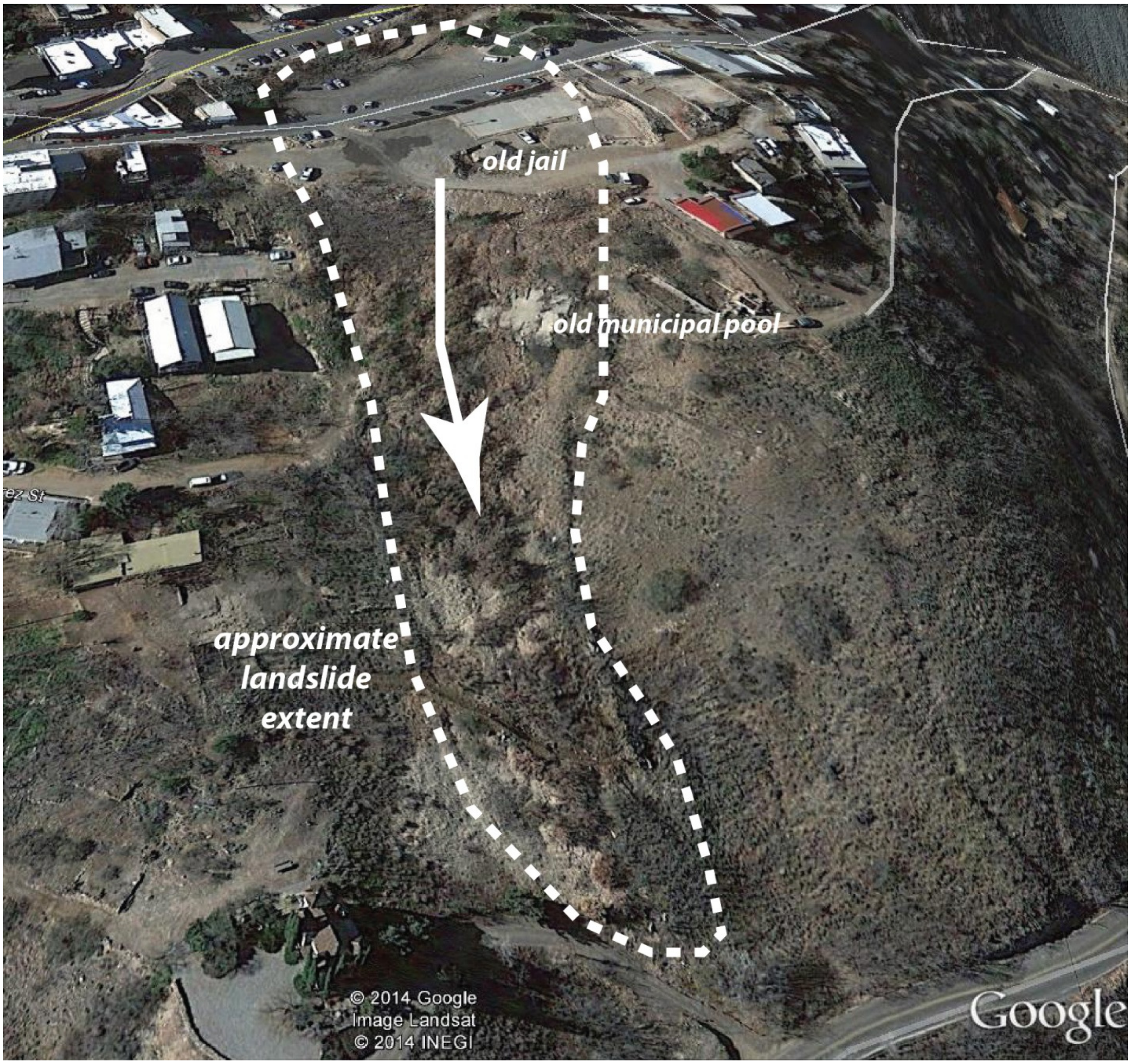

Figure D1-8. Interpretation of the Hull Street landslide in Jerome. Base image is from Google Earth.

Figure D1-9. Former Jerome city jail that was deformed by the 1936-37 Hull St. landslide.

This high vantage point is also a nice place to consider the structural development and evolution of Verde Valley. It is a late Miocene-Pliocene structural basin formed primarily by down-to-the-northeast displacement across the Verde fault zone (Figure D1-10). Volcanic rocks of the Hickey Formation that cap Mingus Mountain at about 7000 feet above sea level have been dated as young as 11 Ma. Equivalent volcanic rocks encountered in deep wells in the axis of Verde Valley at about 1500 feet above sea level; thus, there has been about 5500 feet of net displacement across the Verde fault zone. There is not much evidence of Quaternary displacement across the fault zone, so most of the activity occurred between 10 and 2 Ma (Bressler and Butler, 1978). As the basin was subsiding it filled with sediment from the surrounding highlands (the Verde Formation), and for most or all of that time it was a closed basin. This resulted in the accumulation of gravel, sand, silt, clay and limestone beds to a level not far below us. Once the Verde River began to drain to the southeast about 2 Ma, downcutting began. This has resulted in dramatic dissection and erosion of Verde Formation deposits in the valley.

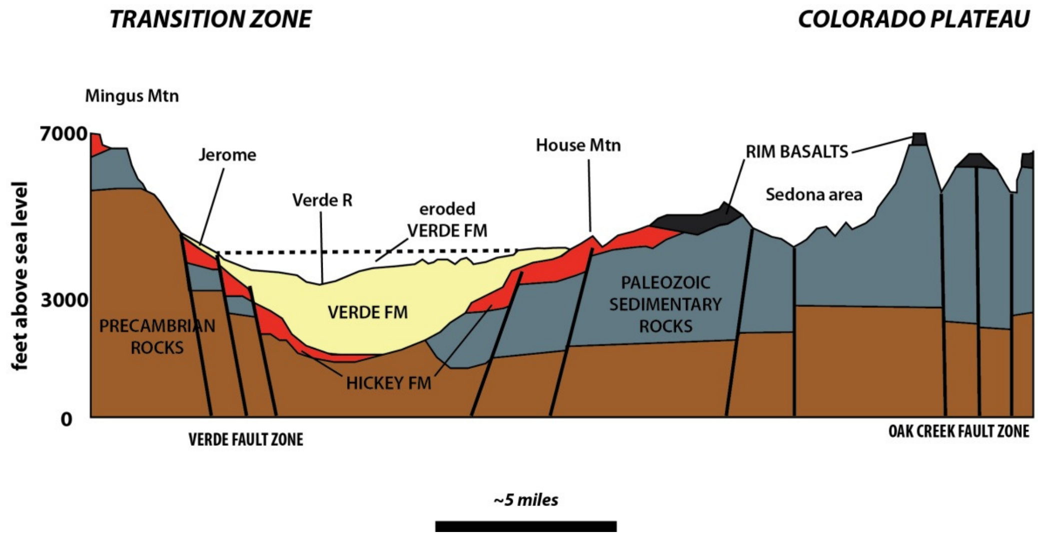

Figure D1-10. Interpretative cross section from the Black Hills to the Colorado Plateau margin, across Verde Valley.

- Drive back down SR 89A to Cottonwood. Dissected high remnants of the Verde Formation lake and marsh deposit are obvious across valley
- Stay on SR 89A through Cottonwood and cross the Verde River, a beautiful perennial stream. The small hill of Verde Formation to the left is capped by a degraded archaeological site, a remnant of the same Sinagua inhabitants who constructed the much better preserved ruins at Tuzigoot National Monument upstream.

We continue to drive northeast over eroded Verde Formation, and thin Quaternary deposits derived from the Verde Formation weathering and erosion. White limestone beds are typically resistant to erosion and form cliffs and steep slopes, whereas sand, silt and clay beds are easily eroded and their remnants are draped across this surface.

The broad dome-shaped mountain ahead and to the right is House Mountain. It is a 13-15 Ma volcanic center that predates deposition of the Verde Formation (Ranney, 1988). If you look closely you can see some white ledges on the flanks of House Mountain. These are some of the very highest remnants of the Verde Formation that were deposited against the sides of House Mountain, and subsequently deeply eroded.

Continuing along, we leave the Verde Formation and encounter some 11-15 Ma basalts in the Spring Creek area; similar to House Mountain, Verde Formation deposits lap onto these volcanic rocks. A bit farther along the road, some striking-looking gravel deposits with red and black cobbles are exposed along the road. The mix of lithologies includes abundant red sandstone and gray basalt; this is very similar to the mix of modern Oak Creek and other large tributaries in this area. As the road bends to the east, we encounter the first exposures of Paleozoic sedimentary rocks that make up the cliffs of the Sedona area. As we proceed into the Sedona area, much more of this bedrock is exposed, and some of the higher ridges and mesas are capped with late Cenozoic sediments and basalt flows.

- Turn right on Airport Road at a stoplight, and proceed up the winding road to the top of Airport Mesa.

• STOP 4: Sedona Airport Mesa – A Spectacular View

The primary purposes of this stop are to enjoy the beautiful geologic scenery of the Sedona area, briefly consider the geology and geomorphology of the Colorado Plateau margin here, and discuss the history of Oak Creek.

The spectacular scenery of this area results from the combination of colorful red rocks and complex patterns of erosion.

Stratigraphers have argued about the details in this area for many decades, but generally the red rocks for which Sedona is famous are part of the Pennsylvanian-Permian Supai Group and the Permian Hermit and the Schnebly Hill Formations [some authors consider all of these units to be part of the Supai Group (Weir et al., 1989; Bezy, 2012)]. These consist of siltstone and sandstone, with minor conglomerate and limestone, and were deposited in shallow marine or marginal marine settings. These rocks are overlain by the lighter-colored Permian Coconino Sandstone with common, large-scale crossbeds, which records a period of subaerial deposition. The Toroweap (mostly sandstone, smaller crossbeds, with dolomite) and the Kaibab (dolomite and limestone) Formations record a return to shallow marine deposition. A geologic map of the Sedona area and stratigraphic section of the bedrock units in the area are provided as Figures D1--11 and D1-12.

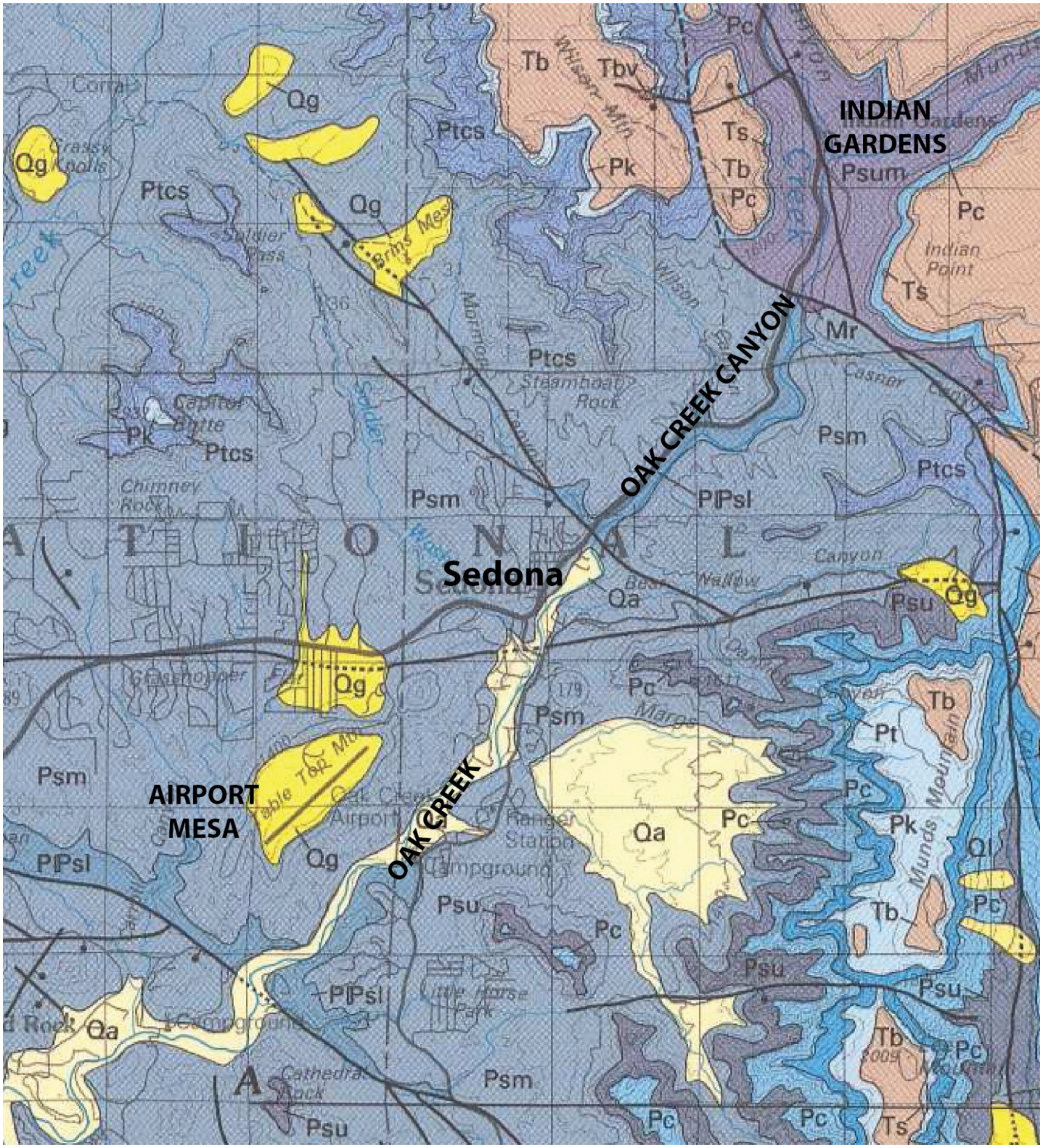

Figure D1-11: Geologic map of the Sedona area.

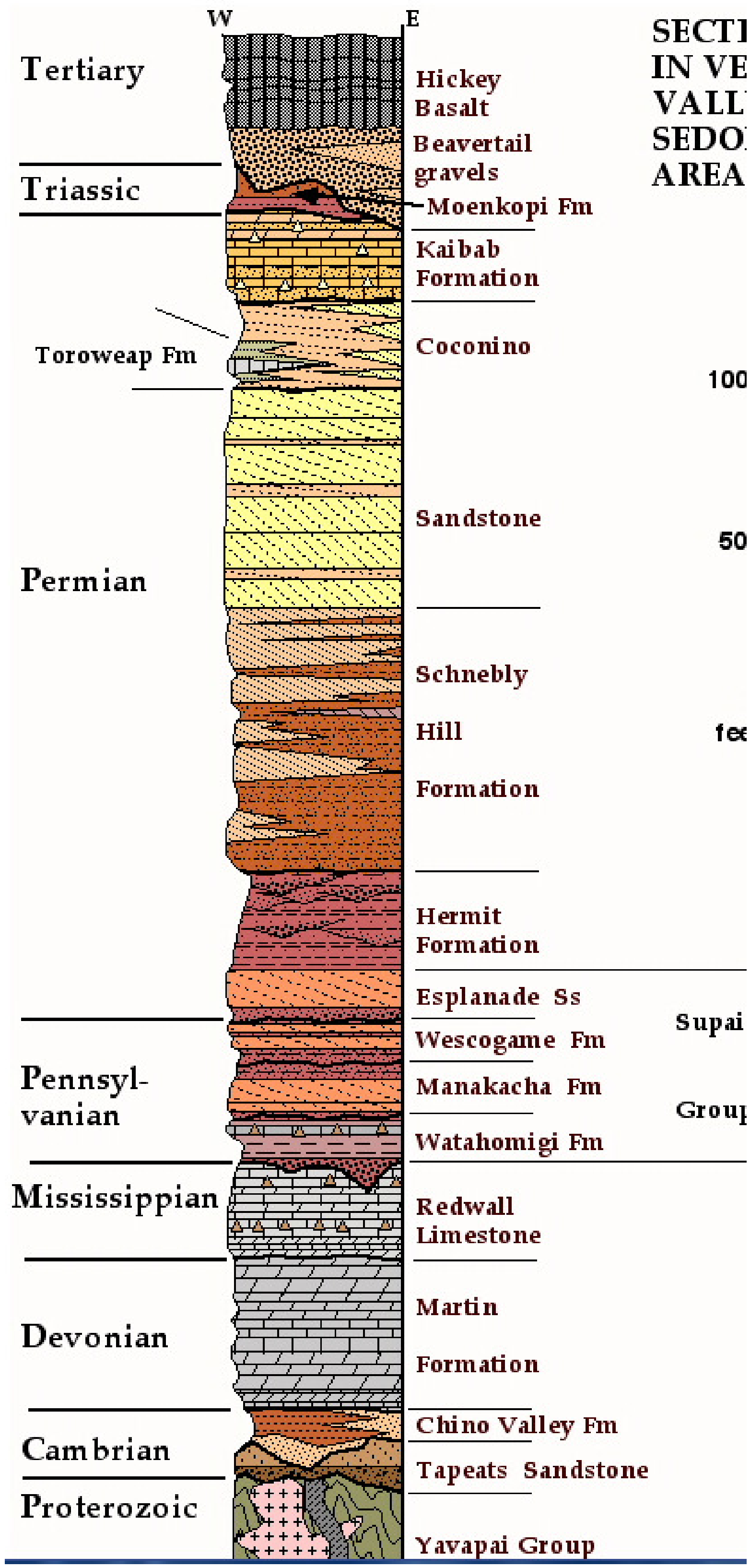

Figure D1-12: Stratigraphic section showing bedrock units in the Sedona area.

The complex patterns of erosion in this area are the result of tens of millions of years of erosional modification of the margin of the Colorado Plateau. The front of the Black Hills on the southwest side of Verde Valley is quite linear, because the valley was dropped down along the Verde fault zone in the past 10 million years. The escarpment on this side of the valley is similarly high but much more sinuous and complex. Part of this is due to the fact that the northeast side of Verde Valley was dropped down along several widely spaced fault zones, none of which have a lot of displacement. In addition, the original topographic differentiation between the Colorado Plateau and the area that is now Verde Valley occurred as much as 30 Ma (Peirce et al., 1979), and the topographic escarpment has been eroding ever since.

The upper 30-50 feet of Airport Mesa consist of rounded, coarse gravel deposits (Figure D1-13). They are about 700 feet above the modern channel of Oak Creek, but the lithologic composition of the gravel is essentially the same as the modern stream; these gravels record a time when the bed of Oak Creek was much higher than it is today, when it was graded to a level in Verde Valley that was much higher than the modern Verde River. This is consistent with the story of deep incision in Verde Valley in the past 2 million years. These gravels predate most or all of the incision in the valley, and thus are probably about 2 Ma. They are the highest well-preserved terrace associated with the Verde River and its major tributaries in Verde Valley.

Figure D1-13. About 30 feet of coarse rounded river gravel caps Airport Mesa in Sedona. The gravel predominantly consists of basalt and Paleozoic sandstone and is very similar to gravel in the modern channel, so these deposits obviously record a time when the bed of Oak Creek was 700 feet higher than it is today.

- Return to SR 89A, turn right, stay on SR 89A through 2 traffic circles, into downtown Sedona. Drive thru Sedona into Oak Creek Canyon along SR 89A.

Most of the walls of Oak Creek Canyon are formed in red rocks of the Supai Group, capped by the Permian Coconino, Toroweap, and Kaibab Formations; on the east side of the canyon, the Paleozoic sedimentary rocks are capped by extensive late Miocene basalt flows. Oak Creek is obviously deeply incised into the surrounding landscape, but the cliffs to the west are substantially higher than those to the east. The general course of Oak Creek Canyon follows the Oak Creek fault zone, which has dropped strata to the east down by about 700 ft in this area. Most likely Oak Creek developed along the fault zone because this was a relatively low area, and it may well have eroded into the fault zone because it is a zone of relative weakness.

Rock falls and slope instability are common problems along the SR 89A in Oak Creek Canyon given the steep topography, the geology of the area and minimal to inadequate catchment ditch conditions. The road was originally built in the 1930s by realigning and improving older wagon and pioneer roads, and required very steep to vertical cuts in existing slopes that have required significant ongoing maintenance, repair, and reconstruction over the years since. Rock fall from steep natural and cut slopes in bedrock along the highway is generated by slide-plane failures and wedge and toppling failures. Rock fall also occurs from hillslope colluvium due to basal erosion and raveling of fine matrix, and debris flows derived from the colluvium. Rock falls vary in caliber from pebbles to large boulders, and nearly all require maintenance personnel to remove the material, and in some cases, repair the highway. Existing ditches catch some smaller debris but are inadequate to catch most rock fall.

• STOP 5: Indian Gardens – Debris Flows and Wildfire in Oak Creek Canyon

The primary purpose of this stop is to discuss geology hazards related to mass movements in a steep, narrow canyon subject to forest fire. SR 89A in Oak Creek Canyon is an amazingly scenic highway that provides a relatively direct connection between Sedona and Flagstaff (and was the primary access route between the cities before construction of I-17). It also provides access to many lovely spots along Oak Creek that are occupied by commercial lodging places, private dwellings, and U.S. Forest Service campgrounds and picnic areas. Because of the interesting terrain and the narrow space in the canyon bottom for roads and dwelling, the area is subject to several geologic hazards. We stop in Indian Gardens because it has experienced several debris flows in the past 50 years – and because of many of the public lands and recreation areas in upper Oak Creek Canyon above Slide Rock State Park are temporarily closed (as of August 2014) due to potential post-fire flooding and debris flows resulting from the Slide Fire in early summer 2014.

Debris flows are essentially the extreme end member of flood hazards on the steep tributaries that join Oak Creek in the canyon. They occur in response to extreme precipitation events and, after moderate to severe forest fires, more garden-variety storms. Indian Gardens has experienced both of these situations in the past 45 years (Figure D1-14). On 5 September 1970, the mountains of central Arizona experienced prolonged and intense rainfall caused by a Pacific frontal system interacting with moisture from dissipating Tropical Storm Norma (the Labor Day Flood of 1970). As much as 11.4 in. was recorded in 24 hours, flooding was widespread, and debris flows were generated in many places, including Indian Gardens (Figure D1-15). A debris flow occurred in a small steep drainage at the northern end of Indian Gardens (Morrison, 1970), approximately where the Sedona Fire Station is now located.

More recently flooding and debris flows occurred in this area immediately after the Brins Fire burned the steep watersheds west of Oak Creek in June 2006. Debris flows occurred in July 2006 just south of and west of the U.S. Forest Service Visitor Center at the southern end of Indian Gardens (Figure D1-16). These debris flows occurred on small but very steep watersheds in response to fairly common monsoon thunderstorms, because runoff was greatly increased by extensive high-severity burn in the watersheds (Haessig, 2006). Debris flows are very common in steep watersheds following severe burns, and can be triggered by 1- to 10-year rainstorms (Cannon et al., 2003).

Figure D1-14: Aerial image of Oak Creek Canyon and Indian Gardens. Debris flows occurred in very steep, small watersheds during the extreme precipitation event of 5 September 1970, and during monsoon storms after the Brins Fire. Base image is from Google Earth.

Figure D1-15. Photograph of bouldery deposits recording a sizable debris flow that occurred at the north end of Indian Gardens on 5 September 1970.

Figure D1-16. Photograph of boulder deposits emplaced by a debris flow that occurred in July 2006 after the Brins Fire burned the watersheds above Indian Gardens. The debris flow partially buried SR 89A prior to clean up.

Debris flows are not a concern along Oak Creek itself, except where steep tributaries enter and drop their coarse sediment. Oak Creek Canyon is a very popular recreation area and flooding is a concern. In the aftermath of the 2014 Slide Fire, all U.S. Forest Service recreation areas along Oak Creek in the canyon are closed for the summer out of concern for the increased risk of flooding in the wake of the fire. The largest recorded flood on Oak Creek occurred since 1940 was 26,000 cubic feet per second in February, 1993. Recreational use of the valley bottom is much less of a concern in the winter (cold water!).

- Continue the drive north on SR 89A up beautiful Oak Creek Canyon.

The Slide Fire of 2014 burned many steep watersheds west of Oak Creek beginning at Slide Rock State Park. Most of the severely burned slopes from the Slide Fire are fairly high above the valley bottom, but some are obvious and not far away. As of the time that this field guide was prepared, no debris flows had been documented, but we are actively monitoring this area.

As we drive up Oak Creek Canyon along the route of SR 89A, we will pass the site of the beautiful and heavily-visited Slide Rock State Park and a pair of recent bridges that carry the highway over Oak Creek from the west bank to the east. From here, the highway hugs the eastern canyon wall and shattered rocks and gouge from the Oak Creek fault are visible in roadcuts within the first couple of miles or so beyond Slide Rock. Further north, across from the Call of the Canyon trailhead for the West Fork of Oak Creek, note the faux-rock shotcrete facing of a custom mechanically stabilized earth (MSE) retaining wall that was designed to resemble and blend in with the natural sandstone formations. This wall will be visible on the right side of the bus as we travel up the canyon.

Continue north to the junction of Pumphouse Wash and Sterling Canyon. From here, the road ascends the head of the canyon via several switchbacks through Paleozoic sedimentary rocks. Near the top of the grade we encounter Miocene basalt flows again. Turn out to the right almost immediately at the top of the grade to enter the parking lot for the Oak Creek Vista scenic overlook.

• STOP 6: Oak Creek Vista – Scenic view, Native American crafts, Quaternary faulting

The primary purpose of this stop is to provide a scenic overview of the northern part of Oak Creek Canyon. At the overlook, we are perched above Pumphouse Wash and can see to the south into Oak Creek Canyon. The Paleozoic sedimentary rocks that form most of the walls of these valleys are capped by late Miocene to Pliocene basalt flows (Ulrich et al., 1984).

These basalt flows (and the underlying units) have been dropped down to the east across the Oak Creek North fault zone, part of the same fault zone that we have been following through most of Oak Creek Canyon. Here, the fault has displaced the basalt flows by as much as 500 feet. Thus, it clearly has been active since the late Miocene, and probably has been active in the Quaternary. This fault zone continues to the north to the southwest edge of Flagstaff.

This is one of many Quaternary faults around the Flagstaff area (Figure D1-17). None of these faults have high slip rates, but the presence of so many potentially active faults indicates that seismic hazard is significant in this area. That is also indicated by historical seismicity, including three magnitude 6 events in the early 1900s (Pearthree and Bausch, 1999).

- ➢ Continue the drive north on SR 89A to Flagstaff where we will stay the night at the Embassy Suites hotel.

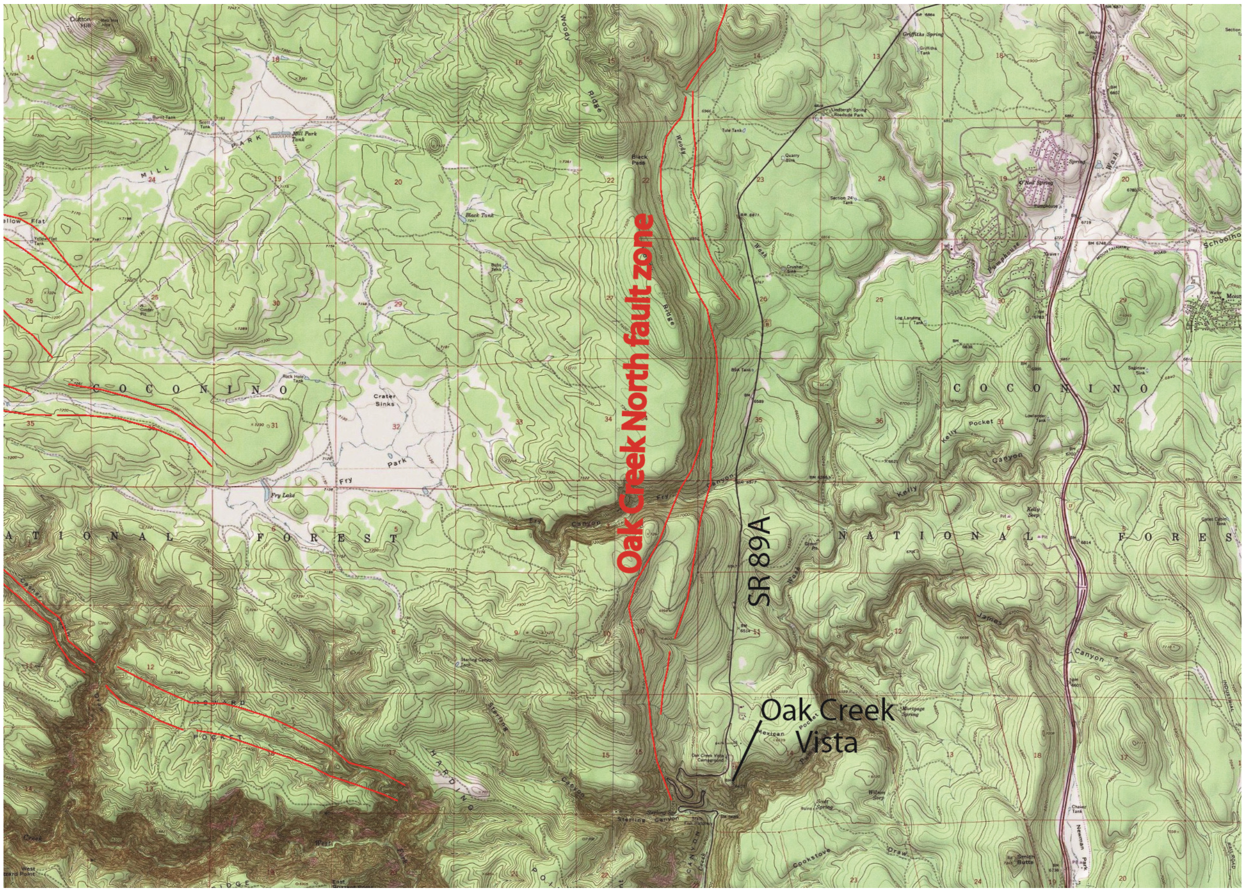

Figure D1-17. Map of the Oak Creek North fault zone and other possible Quaternary faults near the margin of the Colorado Plateau in the greater Flagstaff area. Many faults offset Pliocene or Quaternary volcanic rocks in this region, and several M 6 earthquakes occurred there in the early 1900s.

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Field Trip Itinerary and Guide: Day 2, September 21, 2014

Day 2 – Flagstaff to Grand Canyon South Rim via Old Route 66, US Highway 89 and AZ State Highway 64, Desert View, and Grand Canyon Village (Guide: Wayne Ranney)

<u>Field Trip Highlights</u>: *A day and night at Grand Canyon National Park, a walk along the world's largest geologic exhibit - the Trail of Time, a drive through the eastern portion of the San Francisco Volcanic Field, with spectacular views of the Grey Mountain and East Kaibab monoclines, the Little Colorado River Gorge, and perhaps more rocks can be seen in a single view.*

Today's field trip takes us to the brink of the Grand Canyon of the Colorado River. Known as one of the original Seven Wonders of the Natural World, this canyon is perhaps planet Earth's greatest geological spectacle. As geologists we are privileged to know that a field trip is much more than just anticipating the arrival at a specific destination. As we make our journey toward Grand Canyon, there will be many interesting things to see and discuss along the way.

Flagstaff to Sunset Crater – The day begins in Flagstaff, Arizona a small city with a population of 68,000 and established in 1882 with the arrival of the third trans-continental railroad, the Atlantic and Pacific, then a subsidiary of the Atchison, Topeka, and Santa Fe, and now called the Burlington Northern Santa Fe (BNSF). The area around Flagstaff had a small spring to support the settlement, and a very large forest, which supplied timber for the rails. Flagstaff is located at an elevation of 7,000 feet (2,133 m) and is situated at the southern edge of the Colorado Plateau. It is also set upon the San Francisco Volcanic Field and a number of features in the field will be observed on the drive toward the Grand Canyon. The city is famous for its four seasons, Northern Arizona University, Lowell Observatory (where the ex-planet Pluto was discovered), the Museum of Northern Arizona, and a field office of the United States Geological Survey.

Upon leaving the hotel, our itinerary takes us north, then east along old US Route 66 (current US 89). We pass through the historic downtown district of Flagstaff, relocated here in 1889 after a disastrous fire destroyed the original town site located one-third mile west of here. You will note many brick and native red stone buildings (see discussion below) mandated in the construction of "New Town" after the fire. Flagstaff was built along the historic course of the Rio de Flag, a small tributary stream that ultimately trends northeast toward the Little Colorado River. City fathers dug a channel west of "New Town" to reclaim the course of the natural stream. As such, Flagstaff traded the perils of fire for those of floodwaters, with many notable floods occurring in 1896, 1903, 1916, 1920, 1923, and 1938. The city is today discussing various engineering options to mitigate a potential 100-year or 500-year flood.

Leaving downtown, pass the traffic light Enterprise Avenue and to the left is the site of a rock quarry where blocks of the Triassic Moenkopi Formation were obtained in the construction of buildings in Flagstaff and other US cities. Rocks from here were used to construct the old Los Angeles County Courthouse in 1889, the Brown Palace Hotel in Denver, and the Whittier Mansion in San Francisco, to name only a few (Jackson, 1999). The quarry yielded a popular building stone known as Arizona Red but was abandoned in 1893. Although the stone was widely used it deteriorates rapidly in wetter climates due to its weak cement. We also pass an obvious road cut on Route 66 in the Moenkopi Formation (Figure D2-1).

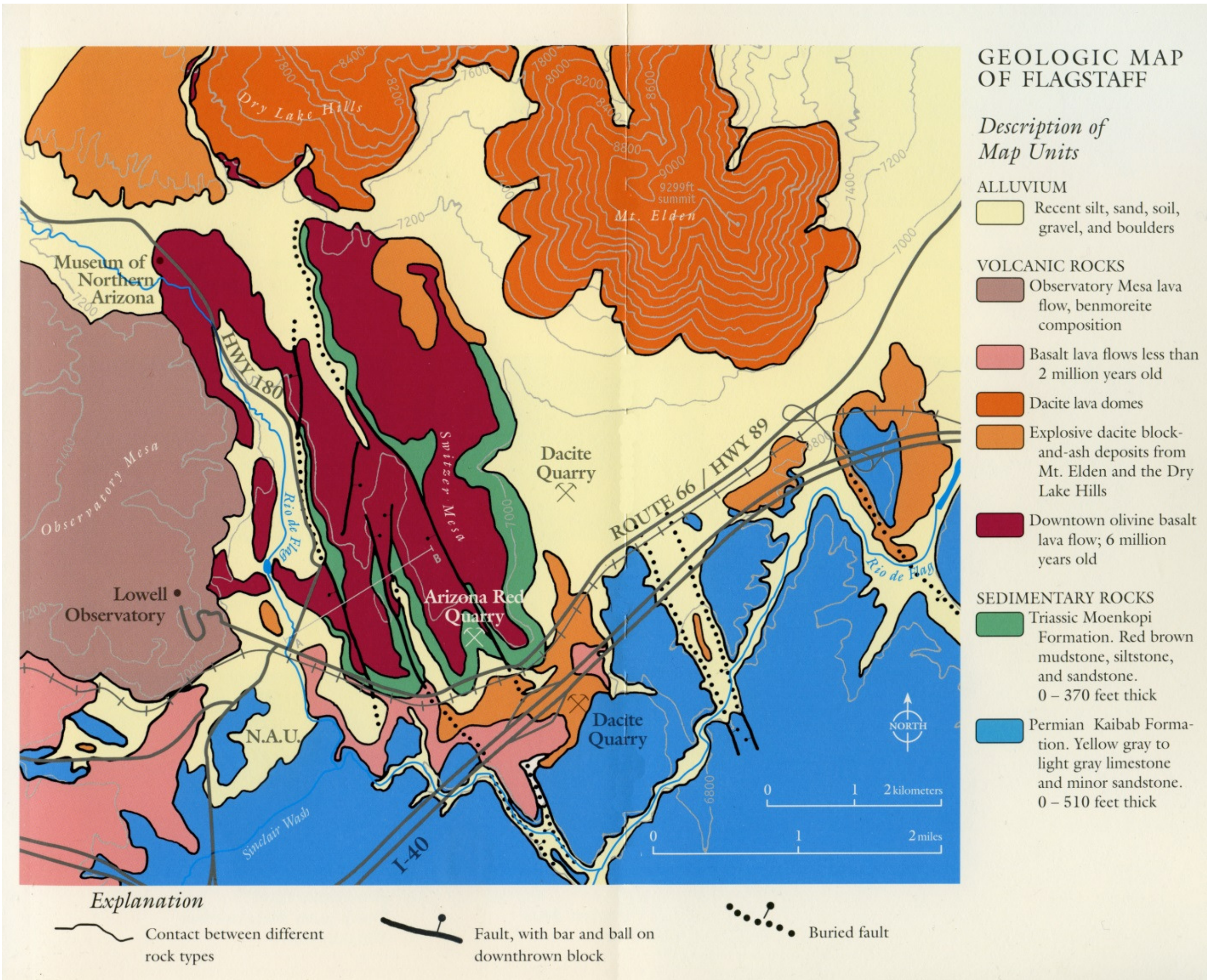

Figure D2-1 – Simplified geologic map of the Flagstaff area showing the location of the various rock units and quarries near here (taken from Jackson, 1999).

As the road transitions from an easterly trend on Route 66 to a more northerly direction on US Highway 89, the eastern side of Mt. Elden will be illuminated on the left in the early morning light. This large mountain rises 2,300 feet (700 m) above the city to an elevation of 9,298 feet (2,834 m). Mt. Elden is a dacite dome volcano that was extruded and emplaced around 0.49 Ma $\pm$ 0.6. This is one of five dome volcanos located on the periphery of the San Francisco strato-volcano, and thus can be considered a part of the composite volcano complex. It curiously displays evidence for extrusive lava flows and intrusive laccolith or "trap-door" volcanism. These eastern outcrops reveal where the entire Paleozoic section, to be seen later in the day in the walls of Grand Canyon, has been turned upright into near vertical exposure. The sedimentary rocks are eroded into low hills and overgrown with vegetation so are not visible from the highway. Strata from Devonian through Permian age are upturned and truncated, making this area perhaps the easiest place to observe rocks of the Grand Canyon without having to descend into it – if only they were better exposed (Figure D2-2).

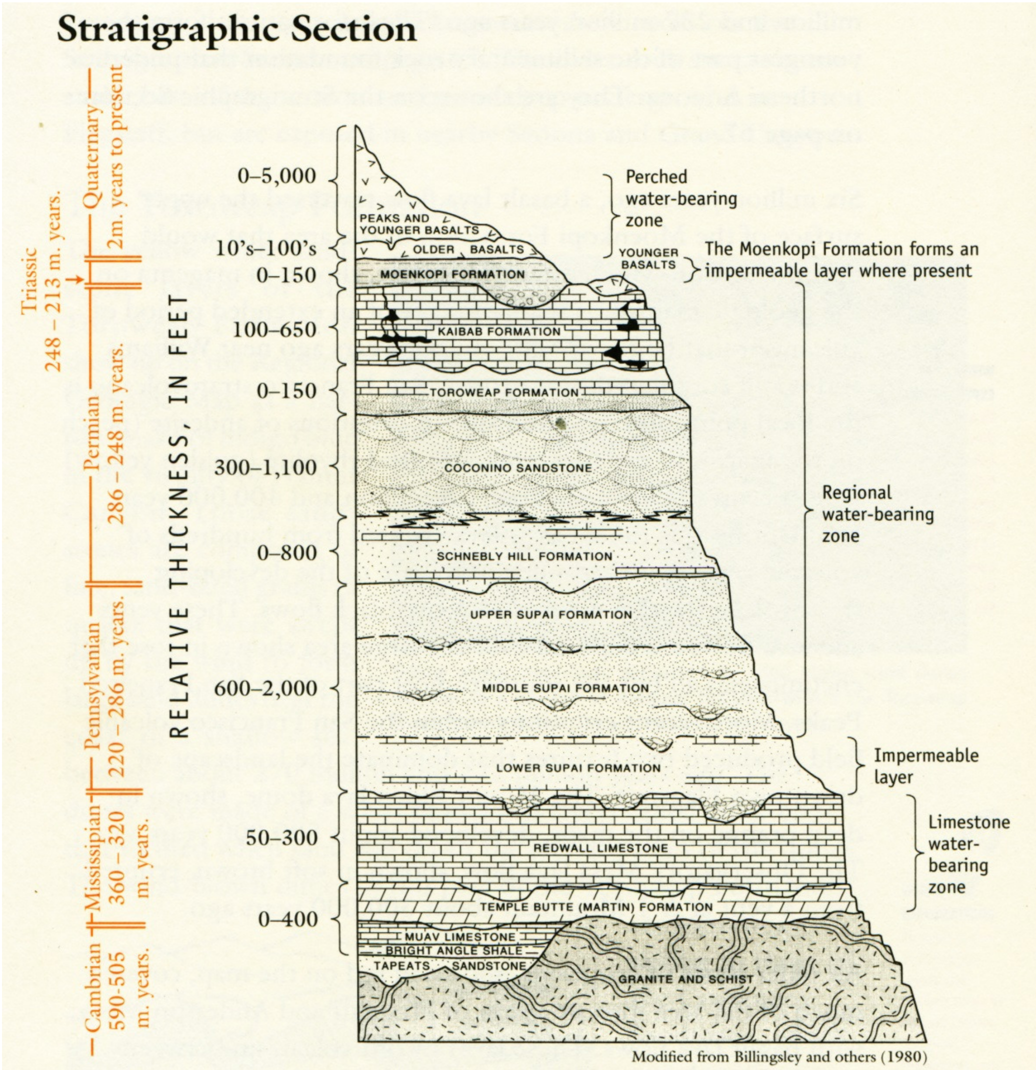

Figure D2-2 – Stratigraphic column for rock units in the Flagstaff area (taken from Jackson, 1999).

Continuing north, evidence for the Schultz fire is evident on the eastern flank of San Francisco Mountain. This 15,000-acre (6,070 hectare) burn was ignited on June 30, 2010 by an abandoned campfire and quickly consumed most of the trees on the eastern slope of the mountain. The Ponderosa pine forest has a natural resistance to low intensity fire but 120 years of intensive fire suppression allowed the forest to grow too densely, creating a "fire ladder" that when ignited is able to climb into the forest canopy and kill the trees. Intensive thinning projects are now underway throughout the four million acres (1.62 million hectares) of forest that stretches southeast to the New Mexico border. Fire ecology is a major area of study at Northern Arizona University and the US Forest Service in these pine forests of northern Arizona

- After about 17 miles, we make a one-mile detour onto the scenic Sunset Crater Road. Here we will disembark the coach for a 15-20 minute stop (no facilities) to discuss the San Francisco Mountain composite or strato-volcano and the Sunset Crater scoria cone. Our coach will turn around 0.7 miles (1.1 km) up ahead and return to pick us up but only after the discussion is over. Take your daypack and water bottles with you as the coach will be positioned elsewhere while we discuss the geology at this stop.

Stop 1 – **San Francisco Volcanic Field, San Francisco Mountain and Sunset Crater**

San Francisco Volcanic Field – The San Francisco Volcanic Field covers about 1,800 mi^2

(4,662 km^2) and contains over 600 volcanoes (Figure D2-3). The field extends nearly 50 miles (80 km) from west to east. Radiometric dating within the field shows that volcanism migrated from west to east beginning about 6 Ma. The oldest cones are found near the town of Williams, AZ with the youngest cones in this vicinity east of Flagstaff. Because of this trend in radiometric ages, many have suggested that a regional "hot spot" exists beneath the crust at this location and that volcanism migrates to the east across the surface, as the North American plate moves westward over the "hot spot." The average recurrence interval within the field is several thousand years and the latest eruption was not quite 1,000 years ago at Sunset Crater (see discussion below). The majority of the volcanoes in this field are scoria (or cinder) cones. There is one composite or strato-volcano called San Francisco Mountain, about a dozen or more lava domes, and at least one shield volcano (partially buried beneath the strato-volcano).

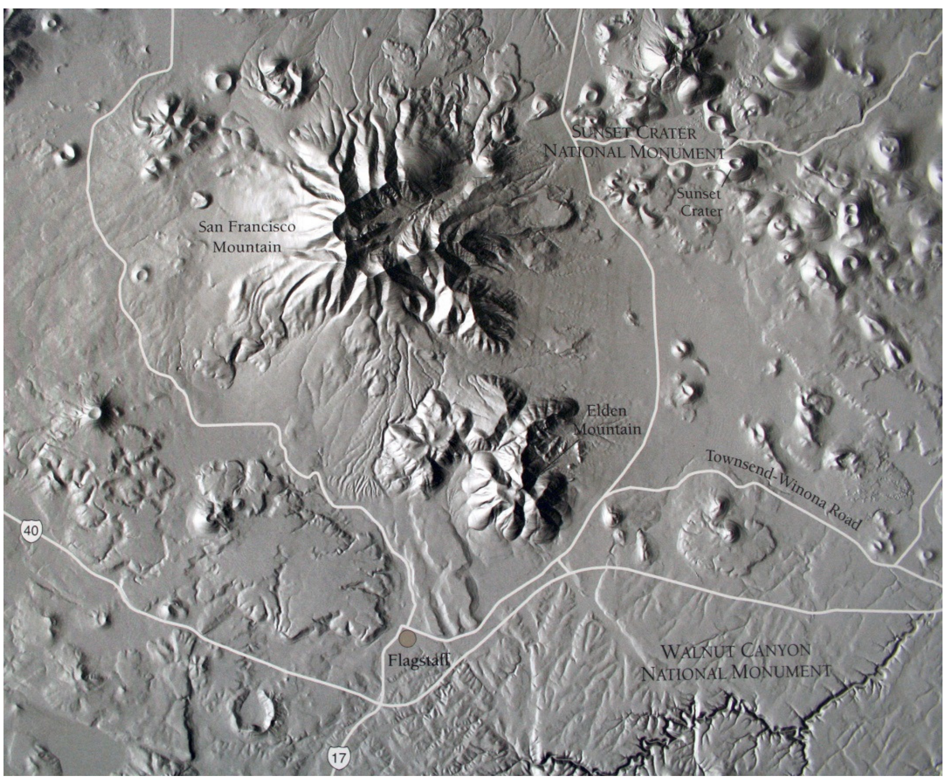

Figure D2-3 – Digital elevation map of the southeastern corner of the San Francisco volcanic field. Note the northeast-trending Inner Basin within the San Francisco Mountain strato-volcano.

Strato-Volcano Growth – Locally, San Francisco Mountain is known as the San Francisco Peaks or simply the Peaks. Today it is the highest point within the state of Arizona at 12,633 ft. (3,850 m) but in former times the mountain was even higher. Estimates given for its former height range upwards to about 15,420 ft. (4,700 m), which would have made this the highest mountain in the lower 48 states. One can use extended arms with fingertips tracing the outer slopes of the cone to get a sense of where the top of the composite cone used to exist (an interpretive sign at this stop also aids in this exercise).

The composite volcano is a combination of stratified andesite lavas and blocky flows that involves a complex growth history (Holm, 1988). Andesite was extruded principally from central vents while silicic lava tended to erupt on the flanks and along the base of the central cone. Large plugs and dikes in a central conduit system supplied the strato-cone, while radial dikes fed some flank eruptions. Holm outlined a possible sequence of events called stages leading to the edifice we see today:

> **Stage 1** – 2.78 to 0.91 Ma. An initial stratocone built to a height of about 5,600 ft (1,700 m) above the surrounding terrain. Destructive mechanism unknown.
>
> **Stage 2** – 0.87 to 0.58 Ma. A second stratocone built to a height of about 6,900 ft (2,100 m). This cone was destroyed by a Plinian eruption with associated pumice tephra at about 0.80 Ma.
>
> **Stage 3** – 0.75 and 0.43 Ma. An ancestral valley formed after destruction of the second cone, with a third stratocone constructed to a height of about 8,200 ft (2,500 m).
>
> **Stage 4** – 0.75 and 0.43 Ma. Lateral collapse of the third stratocone.

Strato-Volcano Erosion – The view to the west from here looks into the Inner Basin, a deep valley located within the core of the volcano and ringed by mountain peaks that formed when the top of the cone was removed (Figure D2-4). Much discussion has been generated on the exact mechanism for how the volcano lost its top, an event that is bracketed between 430 $\pm$ 3.0 and 91 $\pm$ 3.0 ka. (For many years the minimum age obtained on Sugarloaf (K-Ar method) was 220 $\pm$ 2.0 ka, but a more recent $^{40}Ar/^{39}Ar$ date now places it about 130,000 years younger). The range of ages for removal of the top is constrained by dates on the highest flow on the strato-cone crest and the emplacement of the Sugarloaf dome on the floor of the caldera.

There are four possibilities for how composite volcanos lose their tops: 1) downward collapse as a result of magma removal; 2) explosive decapitation by cataclysmic eruption; 3) simple erosion; or 4) lateral collapse due to slope failure. At San Francisco Mountain, explosive decapitation and lateral collapse have been offered as the most likely possibilities. Regarding explosive decapitation, the shape of the Inner Basin led one prominent researcher to suggest that the top was removed in a Mt. St. Helens type of eruption known as a lateral blast (Duffield, 1997). Although these two volcanoes display striking similarities in morphology, another worker noted the lack of outburst tephra that should have been found from such a blast (Holm, 2004), proposing instead that the cone collapsed in a cold debris avalanche. In this scenario, no hydrothermally altered rocks or eruptions are required; non-volcanic forces cause the downward collapse of the cone top. This is the preferred interpretation geologically, although a lateral blast remains a popular and oft-cited scenario.

Figure D2-4 – View of the Inner Basin of San Francisco Mountain from the east (photo by author).

To support his interpretation, Holm described the location of the Inner Basin at the apex of a large fan of boulder-rich and poorly sorted volcaniclastic debris. This fan is mostly buried with an estimated 39 mi^2 (100 km^2) documented beneath younger lava flows and an additional 13 mi^2 (34 km^2) exposed in the floor of the Inner Basin. A borehole drilled to 730 ft. (223 m) for the water well at Sunset Crater National Monument (visible at the water tower south of here) intersected the subsurface portion of this fan between depths of 200 to 500 ft. (63 to 150 m). A log of the borehole was created from borehole cuttings at 10 ft. (3 m) intervals and several samples contained partly cemented, silt- and clay-rich material. The entire 300-foot (91 m) section has the same bulk composition as the strato-volcano, composed of andesite (87%), dacite (12%) and rhyolite (1%). Thus, the deposit likely represents material that was removed from the top of the strato-volcano. No pumice was found in this interval.

Holm next estimated that the volume of material removed from the cone at about 2 mi^3 (8.3 km^3). The restored volcano is estimated to have contained 26 mi^3 (110 km^3) of rock, meaning that only about 7% of the estimated volume of the original cone has been removed. The fan deposit may thus contain 80% of the missing volume and suggests that most of the material removed since the eruptions subsided reside in this debris fan. Of the 10 principle preconditions that individually may lead to a lateral collapse on composite cones, San Francisco Mountain contains 7 of them. These are: cone height over 8,200 ft (2,500 m); overloaded top; cone inflated by dikes; underlying buttress effects; vent migration; regional slope; and hydrothermal alteration.

Glaciation – It may seem incongruous in desert-dry Arizona that evidence for Pleistocene glaciation exists, but San Francisco Mountain was high enough to preclude complete summer melting of winter snow and ice during the Ice Age. Three separate glacial episodes have been documented on the Peaks (Péwé et al, 1984).

The oldest glacial deposits are the most extensive and are found just beyond the lower limit of the Inner Basin. The glacier that left these deposits flowed from seven major cirques at the head of the basin and extended 4 miles (6.2 km) down the valley, filling the basin to a maximum ice thickness of 650 feet (200 m). The best-preserved landform is a lateral moraine on the upstream (west) side of Sugarloaf Mountain that stands 115 ft (35 m) above the valley floor. Péwé et al estimated the age of this glacier between 212 to 125 Ka.

The Core Ridge Glaciation is dated about 100 ka and contains a medial moraine that extends down the valley from the Core Ridge central vent. These glaciers extended only 2.6 miles (4.2 km) from the headwall cirques but left terminal moraines as much as 210 ft (65 m) high. Because of their excellent preservation, these deposits can be correlated to those of Bull Lake age in the Rocky Mountains.

The Snowslide Spring Glaciation records the youngest ice advances at 30 to 25 ka and originated in the individual cirques with no down valley coalescing. These are usually only a little more than 1.3 miles (2.1 km) long with the lateral and terminal moraines well preserved in each canyon. The moraines appear fresh and the maximum relief is 65 ft. (20 m). These would have been some of the southernmost glaciers in North America.

Sunset Crater – Although not atypical in any sense, Sunset Crater is unique for its extremely young age, how the people who lived near here interacted with and responded to the eruption, and the circumstances under which it became preserved as a national monument in 1930 by Presidential proclamation. Geologist John Wesley Powell of Grand Canyon fame first named it Sunset Peak on an expedition to the region in 1885, in reference to the reddish scoria on its crest, which “seemed to be on fire.” Today Sunset Crater stands approximately 1,000 ft (305 m) above the surrounding terrain (Figure D2-5) at an elevation of 8,041 ft (2,451 m).

Age – Nearly anyone who has ever visited Sunset Crater in the last 60 years has come away with a definitive date for its eruption - the winter of A.D. 1064-1065. This date was firmly fixed in the local lexicon by dendrochronology studies of roof beams at the nearby ruins of Wupatki, 13 miles (20 km) northeast of here (Smiley, 1958). Early workers had suspected a young age for the cone based on its youthful appearance and that of the Bonita and Kana’a lava flows. The specific date however, recently has been called into question because the provenance of the roof beams cannot be accurately determined and a growing understanding that numerous other factors can affect diminished tree ring widths (such as drought, fire or insect infestations). Paleomagnetic studies now only constrain the age of eruption between A.D. 1040 and 1100 (Ort et al, 2002). A pronounced Sr-isotope spike in tree rings within this range suggests that the eruption began between A.D. 1075 and 1090. Sunset Crater therefore erupted about 940 years ago.

Figure D2-5 – View of Sunset Crater from the west (photo by author).

Eruption – Volcanic activity undoubtedly began with increasingly shallow earthquakes as the magma moved toward the surface. After a few months, the lava broke through to the surface first as fountains erupting along a “curtain of fire” that issued from a fissure some 6 miles (10 km) long that trended southeast/northwest across the landscape. Several coeval cones were formed in this initial eruptive phase but ultimately the venting was concentrated at the northwest corner of the fissure to create Sunset Crater. Strombolian eruptions likely lasted a few months to perhaps a few years and ultimately covered an area of more than 750 mi^2 (2,000 km^2) in tephra. The eruptions were likely visible as far as 30 miles (50 km) distant, while the ash plume may have been visible from a hundred miles away or more.

As the gas within the magma was progressively released, the melted rock likely lost buoyancy and welled up into the newly established cone. On two occasions, this de-gassed magma broke through the base of the cone to form two lava flows, the Bonita and Kana’a flows. Mounds of layered agglutinate found on top of the Bonita flow show that an early incarnation of Sunset Crater was rafted away from the cone and destroyed. Subsequent fountaining from the crater likely filled these scars in the side of the cone. The Bonita flow traveled west from the crater but ponded against the uphill side of the local terrain, therefore it is much shorter in length that the Kana’a flow, which traveled 7 miles (11 km) down the regional slope.

Witnesses – People of the Sinagua cultural group inhabited the area at the time of the Sunset Crater eruption. They lived in small, relatively independent groups that subsisted on the cultivation of corn and other crops, supplemented by hunting and gathering. Archaeological investigations in the early 1930’s discovered pit house structures that were filled and buried by Sunset Crater tephra. The eruption likely caused population movement and disruptions to their subsistence, economic, and ritual systems.

One of the interesting responses by these ancestral peoples to the eruption was to take advantage of the mulching qualities of the scoria apron. Experiments in this arid landscape show that when scoria depths exceed 6-8 inches (15-20 cm) corn germination is reduced because of the depth of percolation of the meteoric water (Ort et al, 2008). Thus, the area adjacent to Sunset Crater that received the thickest tephra blanket was likely abandoned after the eruption. However, areas farther downwind that received only 1 to 3 inches (3 to 8 cm) of tephra likely saw germination rates increase due to the moisture retaining qualities of the vesicles within the scoria. Indeed, Wupatki and a host of other small population centers, otherwise too low in elevation and too arid for successful growing, saw their populations rise after the eruption. The tephra thickness contour lines show Wupatki located beyond the 4-inch (10 cm) contour (Figure D2-6).

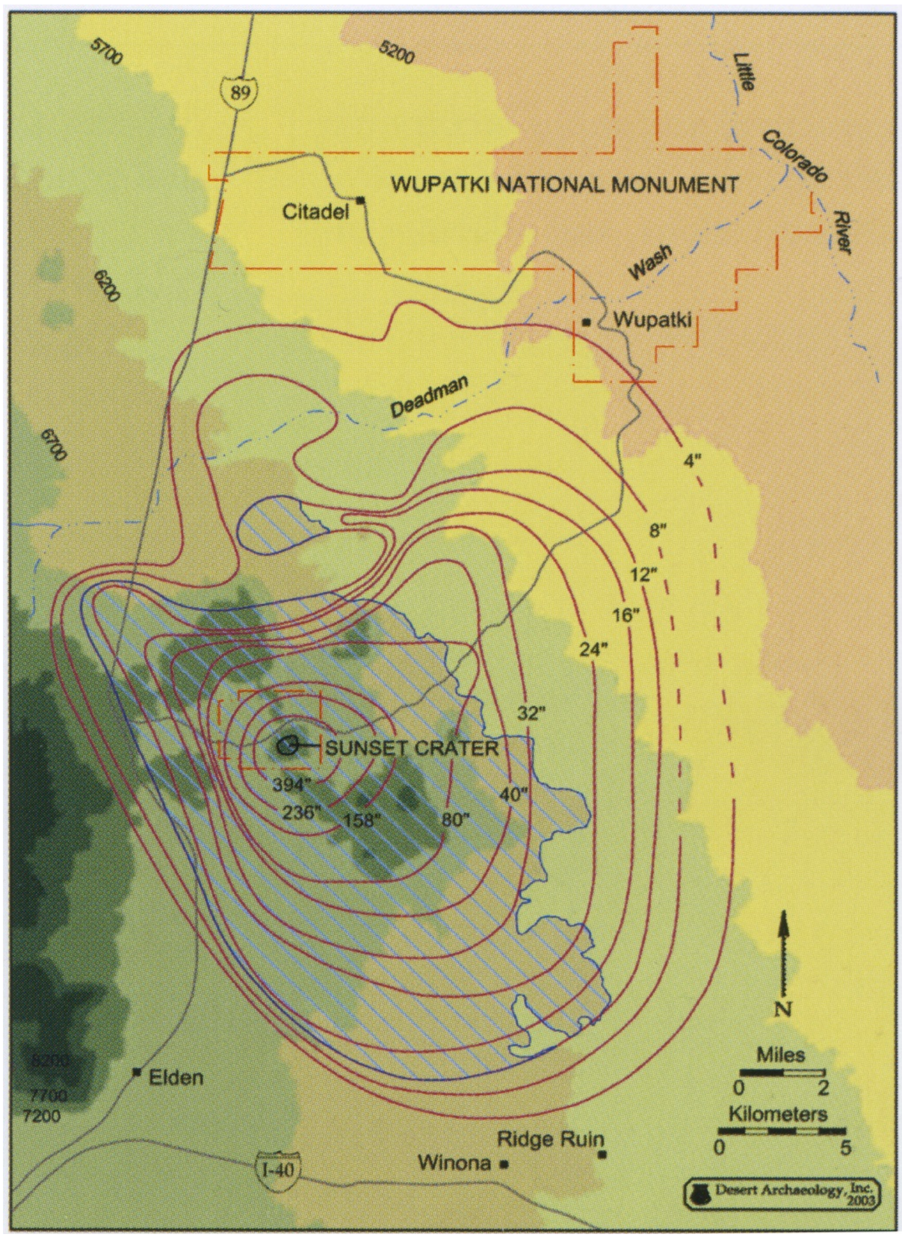

Figure D2-6 – Contour map of Sunset Crater tephra with thicknesses in inches. Note the location of Wupatki ruin just outside the 4-inch contour (taken from Ort, 2002).

“Corn rocks,” agglutinate spatter with corncob impressions, have also been discovered near Sunset Crater and likely represent a ritual means to appease the gods (Figure D2-7). Apparently, people placed ears of corn on the lip or base of hornitos where spatter covered them. The resulting corn molds were then retrieved and incorporated into masonry walls at habitation sites nearby. Ort et al (2008) favorably compared the human response to the eruptions at Parícutin, Mexico (1943-1952) and the archaeological findings at Sunset Crater.

Figure D2-7 – Photo of basalt rock with corn impressions (taken from Ort, 2002).

Preservation – In 1928 a Hollywood film crew proposed to film a screen adaptation of a Zane Grey novel, Avalanche. The script called for a western town to become buried in a landslide and the producers proposed the construction of a movie set town beneath a mountain. It would effectuate the landslide with dynamite charges set inside the flank of Sunset Crater. When Dr. Harold Colton, founder and director of the Museum of Northern Arizona, found out about the plan he rallied local opposition to it and petitioned the government to protect the archaeological and geological resources. Colton was a dominant scientific force in northern Arizona, having established the Museum of Northern Arizona with the express purpose of keeping local artifacts in the area and away from institutions back east such as the Smithsonian and the American Museum. On May 26, 1930, President Herbert Hoover used the Antiquities Act (1906) and signed the order to create Sunset Crater National Monument. In 1990 the name was changed to Sunset Crater Volcano National Monument.

- The coach returns, re-board, and continue north on US89 to Cameron.

Sunset Crater to Cameron – On this 35-mile segment of the field trip US Highway 89 descends nearly 2,700 ft (823 m) before arriving at the Cameron Trading Post, located at a historic crossing of the Little Colorado River. Numerous features of the San Francisco Volcanic Field can be seen, as well as two regional monoclines and rocks that sit at the Paleozoic/Mesozoic boundary. Note that as our elevation decreases, the vegetation changes dramatically from the Ponderosa pine forest, to the Pinyon /Juniper woodland, to grassland, to bare, naked rock. Precipitation drops considerably with elevation in this part of the world.

Soon after connecting to the main highway, the road crosses the pass at 7,276 ft (2,218 m). After traveling about 5 miles (8 km) on the highway, the Deadman Mesa dacite lava flow (170 ka) is seen on the right hand side. Another 5 miles (8 km) beyond look for an area on both sides of the highway of mounds and disturbed ground (the area can also be located where the green highway sign announces the 6,000 foot elevation). Here there is a deposit of pumice from a Plinian eruption on the San Francisco strato-volcano about 800 ka. In the early 1960's this deposit was quarried for pozzolan and used as an additive to increase the strength of the concrete used in the construction of Glen Canyon Dam. This was before enactment of the National Environmental Policy Act (NEPA) and reclamation of the quarry was not required at the time.

Many cinder cones, lava flows and weathered hornitos can be observed to the left of the coach. Within this group are some of the youngest volcanic features in the San Francisco Volcanic Field. Of particular importance is a rather flat-topped cone known as SP Crater (Figure D2-8). It is a basaltic cinder cone with steeply sloping sides composed of loose scoria, a rather flat carapace of welded agglutinate and an associated lava flow that emerged from the north side of the cone (not seen from the highway). The flow is characterized by prominent lava levees and squeeze-ups that retain original flow textures. SP Crater has a geomorphically young appearance with an original date of 70 ka (using K/Ar, Ar/Ar, and cosmogenic ^{21}Ne and ^{3}He techniques). More recently, optically stimulated luminescence (OSL) on quartz xenocrysts in the flow yielded a date of about 6 ka. However, this date may be too young. Houts (2013) measured cosmogenic ^{3}He concentrations in pyroxene crystals in the flow and her results place it at a mean age of 59 ±1 ka to 50 ±1 ka.

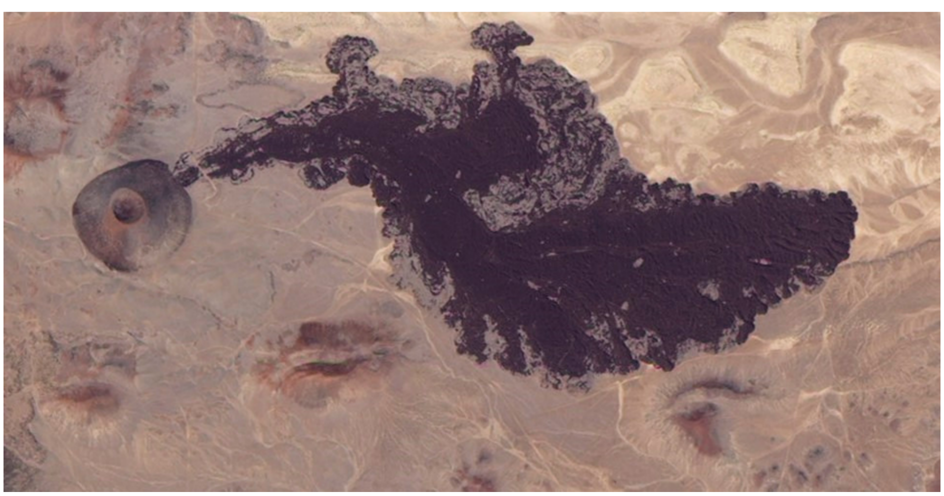

Figure D2-8 – Satellite image of SP Crater and its lava flow. The black flow is about four miles long. (Note: Photo rotated so North is to the right)

After passing the small settlement of Gray Mountain, enter the Navajo Indian Reservation, the largest in the United States both in terms of area and population. It is larger than the state of West Virginia at 27,413 mi² (71,000 km²) and has a population of over 175,000 people. The road now descends on the back of the Black Point monocline. It is named for a flow that can be seen to the right. This flow partially blocked the Little Colorado River about 2.43 million years ago (Figure D2-9).

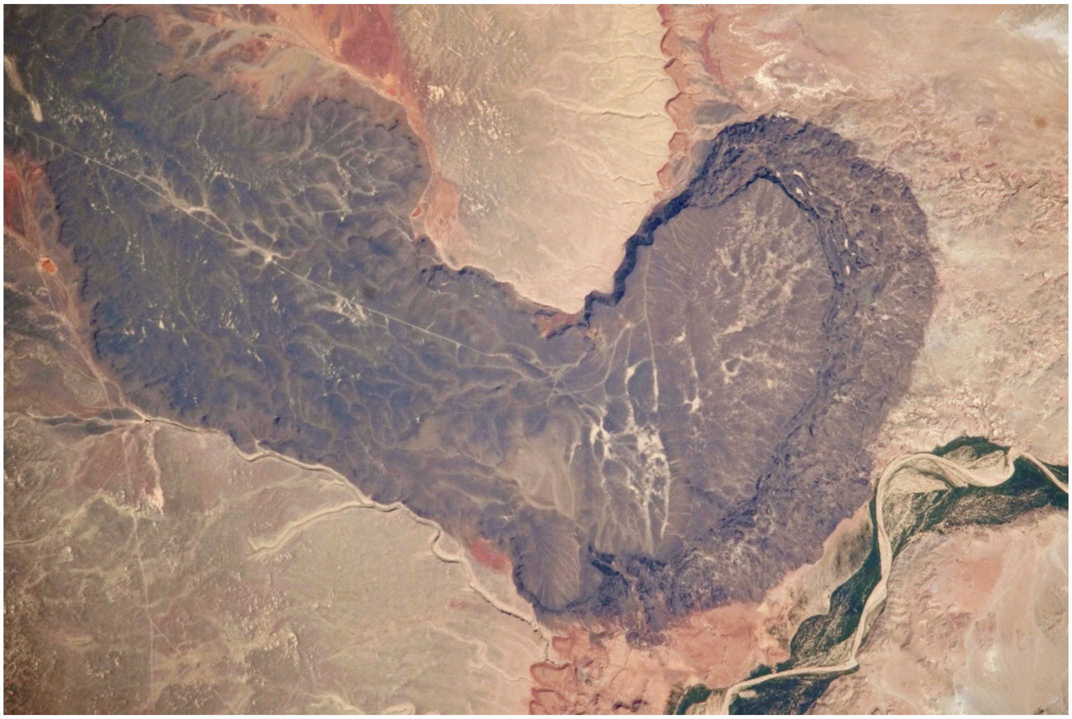

Figure D2-9 – Satellite image of the Black Point lava flow. Note the channel of the Little Colorado River in the lower right.

Numerous other monoclines are present in the area with surfaces capped by the Permian Kaibab Limestone. The Gray Mountain monocline is visible to the left (west) and exposes rock units down through the Coconino Sandstone. The monocline is one of many Laramide-age (70-40 Ma) structures found across the Colorado Plateau. Compression resulting from the subduction of the Farallon plate beneath the edge of the westward migrating North American plate likely crumpled the previously flat-lying sedimentary rocks. More will be said of this as we pass beneath it after leaving Cameron.

Farther down the hill, note where the brick red Moenkopi Formation overlies the whitish Kaibab Limestone. This is the contact representing the boundary between the Permian and Triassic time periods and the Paleozoic and Mesozoic eras. An unconformity lasting perhaps 25 to 35 million years is represented here. Road cuts in the Moenkopi are easily visible in the next few miles. The light-colored Shinarump Conglomerate Member of the Chinle Formation caps small mesas in this area. Both of these Triassic-age deposits are fluvial in origin with their rivers headed in the Ouchita belt in Texas and Oklahoma and trending northwest across the area of the Colorado Plateau to the sea in modern-day western Utah and Nevada (Figures D2-10a, b). Paleogeographic maps for all of the Flagstaff/Grand Canyon strata can be found in Blakey and Ranney (2008).

Figure D2-10A – Paleogeographic map of the Moenkopi Formation, about 240 Ma (from Blakey and Ranney, 2008).

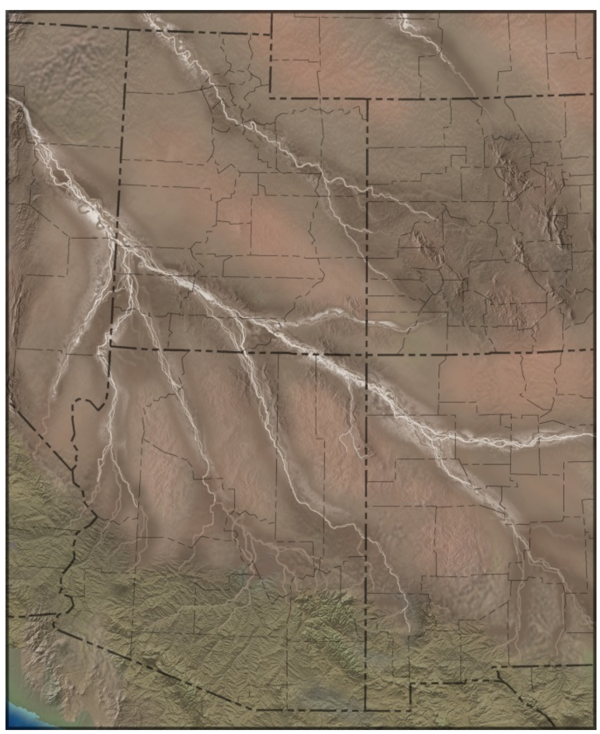

Figure D2-10B – Paleogeographic map of the Shinarump Conglomerate Member of the Chinle Formation, about 225 Ma (from Blakey and Ranney, 2008).

Stop 2 – Cameron Trading Post

This will be a comfort stop with at least three different restrooms located inside the trading post. The planned time for the stop is only 25-30 minutes so please be efficient with your time. While here you may buy a hot drink, see a metoposaur trackway in a flagstone block at the entrance to the Gallery, or walk over to the lip of the Little Colorado River canyon to the north of the trading post. The original historic black bridge spanning the canyon was constructed in 1911 and carried traffic until 1959 (it now carries a gas pipeline). The Cameron Trading Post came five years after the bridge in 1916.

The Arizona Department of Transportation (ADOT) has a major construction project underway here at this time. Construction will occur in two major phases with completion expected in the fall of 2016. Work on the $36.7 million job includes widening US 89 to four lanes through Cameron, installing a roundabout at the existing intersection of US 89 and SR 64, as well as sidewalks, streetlights, and pedestrian/livestock underpasses, and the removal and replacement of the existing US 89 Truss Bridge built in 1959. Two new bridges will carry traffic at this location.

- **Cameron to Desert View** – Return to the coach and take Arizona State Highway 64 west toward Desert View in Grand Canyon National Park.

Since leaving Sunset Crater, our route has taken us to progressively lower elevations but now we regain all of it and more as we approach the Grand Canyon. Just after making the turn off of US Highway 89 onto State Highway 64, cross the bridge over Tappan Wash, floored with a basalt lava flow that came from the south and is dated at 0.52 Ma. Note that the flow is partially dissected by runoff in the normally dry wash. Farther on, exposures of the red Moenkopi Formation and tan Shinarump Conglomerate are visible on both sides of the road.

The topographic prominence ahead on the left is Gray Mountain, formed at the intersection of five monoclines collectively known as the Gray Mountain monocline (Barnes, 1987). These structural features formed during Laramide compression at a time when the rocks visible today were still deeply buried. When compression deformed the rocks there was likely as much as 5,000 to 10,000 feet (1,524 to 3048 m) of Mesozoic-age strata in this area and post-Laramide erosion has exposed what is seen today. Some of the rocks near the axis of the monocline are tilted to near vertical or, in some instances, an overturned position.

To the south is a view of the east-facing limb of the monocline, and as it trends north toward the highway and our coach, notice the sharp bend in the fold of almost 90 degrees that changes its orientation from north-south to east-west. Near the "nose" where the change in trend occurs is a complex inter-fingering of monoclines, thrust faults, graben fields, a large-scale graben, and a slip sheet that places a block of older Kaibab Limestone on top of vertical Kaibab and Moenkopi formations. The structural geology at Gray Mountain is complex (Figure D2-11) and interested attendees are encouraged to seek out the Barnes (1987) reference for more detailed information.

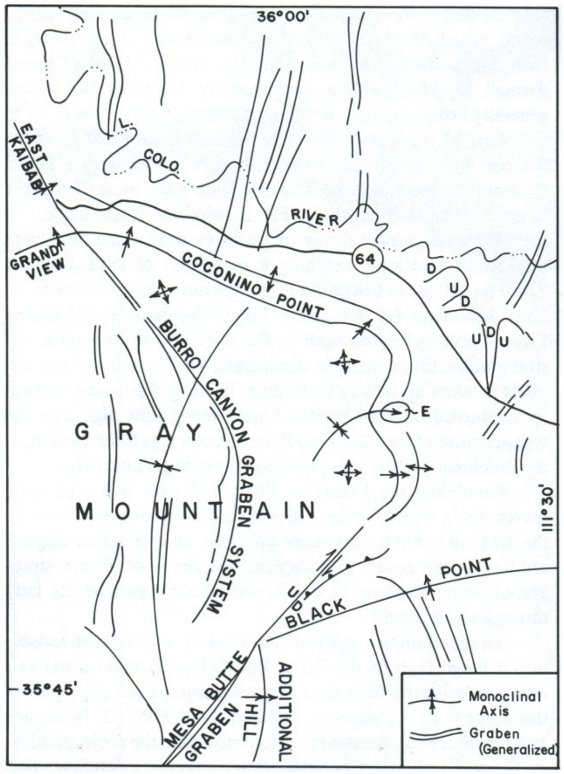

Figure D2-11A – Structure map of the Gray Mountain area (from Barnes, 1987).

Figure D2-11B – Satellite photo of the Gray Mountain area (from Barnes, 1987).

Now, turn your gaze north to the right side of coach and notice the deepening gash in the landscape that is the gorge of the Little Colorado River. In this reach and far below us, the river runs intermittently, yet by the time we climb the East Kaibab monocline (and where the highway is pinched between the monocline on the south and the canyon to the north), the gorge will be twice as deep as it is wide – about 2,500 feet (762 m) deep and a width of only 1,200 ft (366 m). If this gorge were located anywhere else except adjacent to the Grand Canyon, it would likely be its own national park or World Heritage Site. It was near this place on June 23, 2013 that acrobat Nik Wallenda crossed the "Grand Canyon" in a high wire act. The high wire stunt was at a place 1,500 feet (460 m) above the canyon floor and 1,400 ft (430 m) wide. Some local critics faulted him for calling it a walk across the Grand Canyon, but the USGS considers the gorge of the Little Colorado River as part of the Grand Canyon.

The East Kaibab monocline is clearly visible to the right side of the coach as we climb, with a sense of motion that is up to the west, similar to the majority of large monoclines on the Colorado Plateau. This is the structural feature that crosses the Colorado River in Grand Canyon and has uplifted the Kaibab and Coconino Plateaus, which in turn cause the Grand Canyon to be so deep. We will get deep-seated views of this structure from our stop at Desert View. There is no safe place to pull over and photograph this spectacular warp in the strata so have your cameras ready as we slow down as much as possible for the view. Note the small hill on the downthrown side of the monocline. This is an erosional remnant of Moenkopi and Shinarump strata called Cedar Mountain (Figure D2-12). It will be clearly visible again at Desert View. Beyond our view from the coach, this monocline trends north into southern Utah with a total length of about 120 miles (193 km). As we climb this monocline look behind on the right hand side for a spectacular view of the Little Colorado River Gorge (Figure D2-13).

Figure D2-12 - View to the north of the East Kaibab monocline. The surface is composed of Kaibab Limestone and Cedar Mountain (center) is an erosional remnant of Mesozoic-age sedimentary rocks (photo by author).

Figure D2-13 – View of the Little Colorado River gorge from State Highway 64 (photo by author).

When the highway levels out, leave the Navajo Indian Reservation and enter the Kaibab (KY-bab) National Forest. Note the high-standing landform to the left known as the Coconino Rim formed by the Grandview monocline, which is one of the two branches of the Gray Mountain monocline. The word Coconino is a corruption of a Hopi Indian word, Cohonina, for the Havasupai people who live in the bottom of the canyon about 50 miles west of here. The Hopi had a trail through this area that went from their homeland to the Havasupai lands. The highway will veer to the right (north) and the flat area known as Coconino Basin is rich in archaeological sites.

➢ Enter Grand Canyon National Park with the entrance station four miles ahead.

Stop 3 – Desert View

This stop includes restroom facilities, a visitor center with Grand Canyon-related books for sale, a small grocery store and cafeteria, and of course the Watchtower built in 1932 by architect Mary Jane Elizabeth Colter. The area is large and we will be here about 45 minutes so please be efficient with your time and don't wander away too far. You will first see the Visitor Center and can follow the signs toward the restrooms where it will be obvious where the Watchtower is located. Since the viewing platform near the Watchtower is quite small and crowded, our geology talk will take place about 150 feet (45 m) to the west of the Watchtower. You will see a small amphitheater with logs used for seating. The talk will commence about 30 minutes after arrival at Desert View, meaning that you will have time for everything else before the talk. This includes walking up to the top of the 70-foot (21 m) Watchtower to obtain a spectacular view of the canyon. The talk will be the last thing we do here and will last about 15 minutes.

An introduction to the Grand Canyon necessarily involves a discussion of its immense size. On average it is one-mile (1.6 km) deep, 10 miles (16 km) wide, and 277 miles (446 km) long. A few other places on Earth proudly announce greater depths but often these are measured from a single peak making this the longest and largest single canyon on the planet. Three major packages of rocks are found: 1) Paleoproterozoic crystalline basement rocks formally named the Granite Gorge Metamorphic Suite and the Zoroaster Plutonic Complex (but more commonly known as the Vishnu Schist and Zoroaster Granite, or simply Vishnu basement rocks); 2) the Meso- and Neoproterozoic Grand Canyon Supergroup (tilted sedimentary and volcanic rocks); and 3) Paleozoic shelf and nearshore continental sediments (flat-lying rocks). All three of these packages will be seen on this field trip and observed closely on the Trail of Time (Figure D2-14).

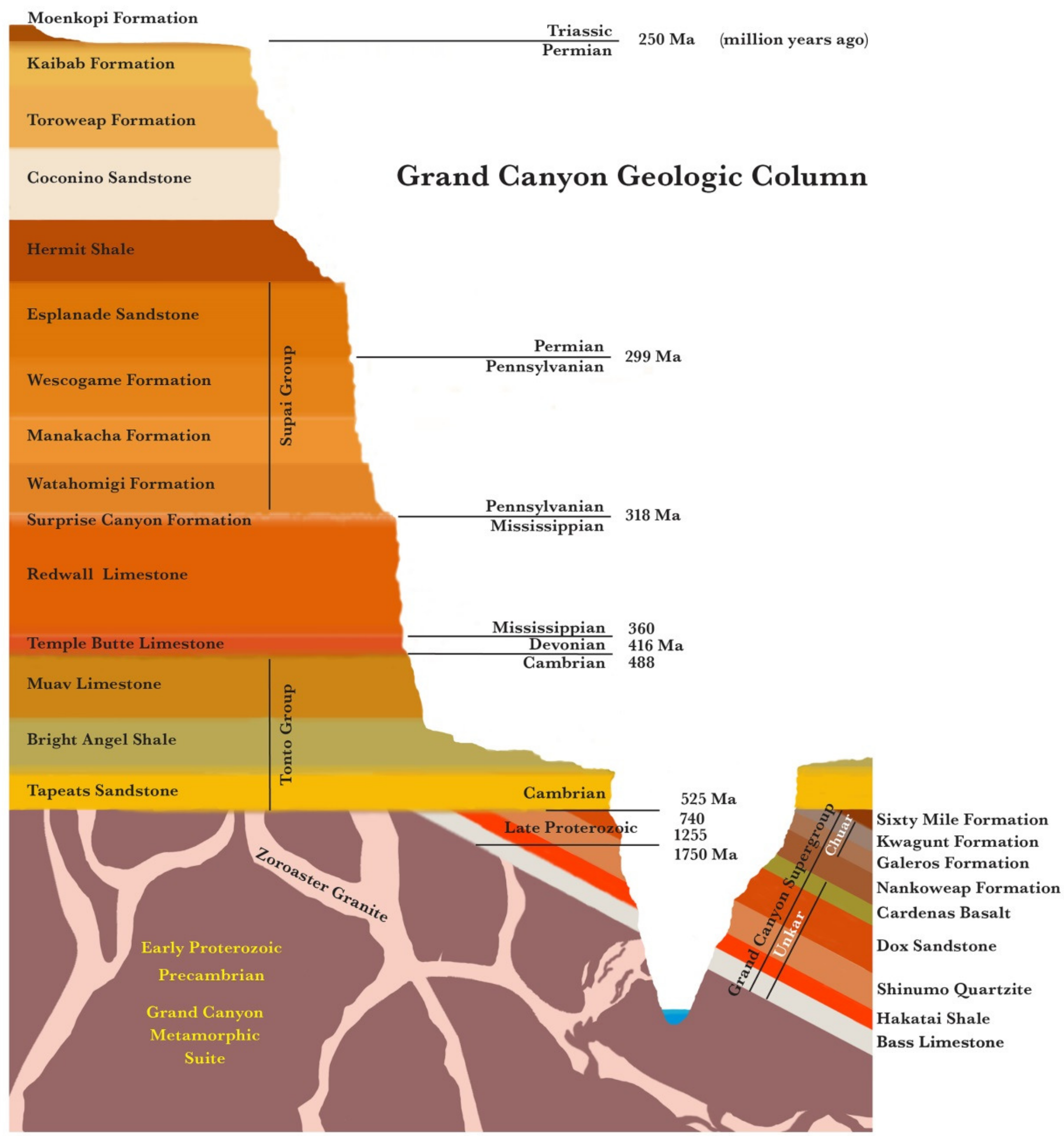

Figure D2-14 – Stratigraphic column for the Grand Canyon.

The vista at Desert View encompasses many spectacular features in the Grand Canyon. First, this is the highest elevation on the South Rim at 7,438 ft (2267 m), with the Colorado River below at 2,650 ft (810 m). The relief here is 4,750 ft (1,450 m). As your gaze drops down to the river note the sedimentary rocks that are tilted down to the right (actually northeast). They are a part of the Grand Canyon Supergroup (Figure D2-15), which has nine different formations in two groups called the Unkar and Chuar Groups (two of the formations are not part of these two groups). The Supergroup rocks were originally over 12,000 feet (3,658 m) thick before they were block faulted and extensively eroded (Timmons and Karlstrom, 2012). The basin in which the Unkar Group was deposited is perhaps related to the Greenville Orogeny (1250 to 1000 Ma), which likely documents the amalgamation of the Rodinia supercontinent.

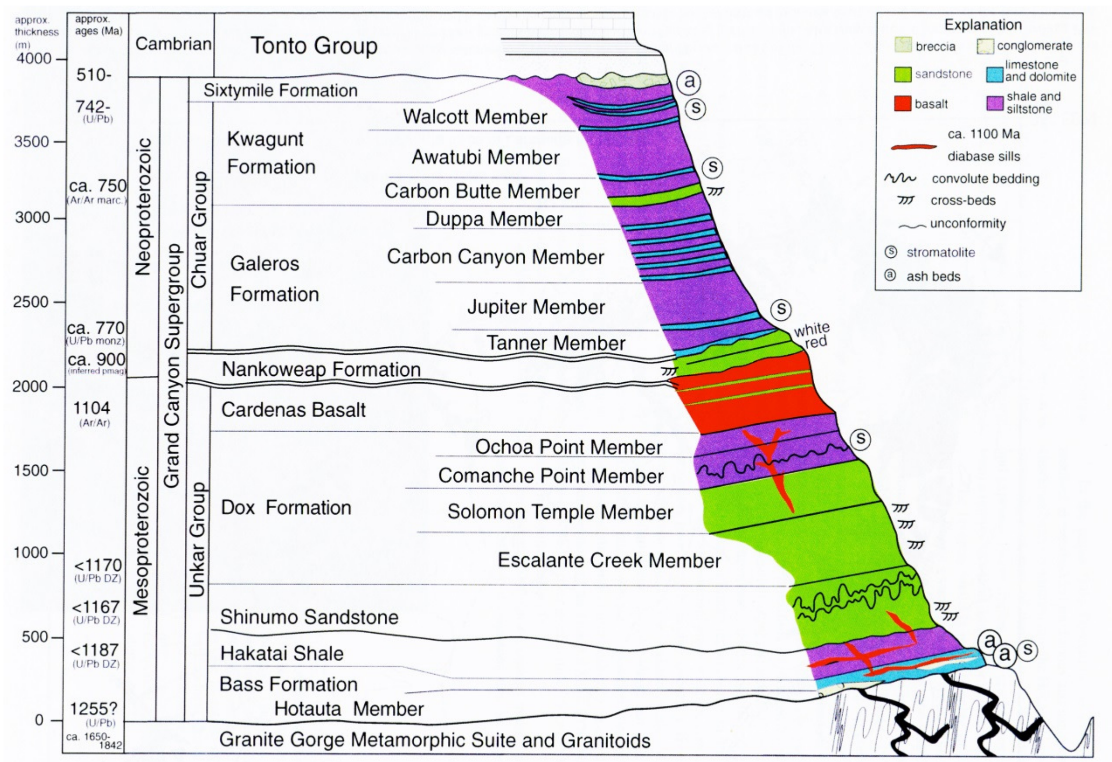

Figure D2-15 – Stratigraphic column of the Grand Canyon Supergroup (taken from Timmons and Karlstrom, 2012).

Next, note that the Colorado River is easily visible at this viewpoint (Figure D2-16), which is the exception to the rule along viewpoints at Grand Canyon. There are two reasons for this. First, the river below Desert View is slicing through relatively soft Dox Formation shale and mudstone, whose ease of weathering creates a rather open landscape (the Dox Fm. undercuts and collapses overlying layers even if they are well indurated and this same process is important in determining the overall profile throughout the Grand Canyon). The second reason for the wide view is that Desert View is situated above the "big bend" of the Colorado River, where its course turns from a general north-south to an east-west direction. This allows views upstream and downstream along the river corridor. Many ideas have been forwarded to explain this change in the rivers course (Ranney, 2012). The most common reasons are a stream capture event occurring near the confluence with the Little Colorado River, a spillover event from a postulated lake east of here, or the collapse of karst in the Redwall Limestone to create a surface channel for the river. Each of these will be examined and discussed during our stay here. There is never a shortage of topics when discussing the geology of the Grand Canyon.

Figure D2-16 – View of the Colorado River from Desert View (photo by author).

Desert View to Grand Canyon Village – It is about 25 miles distance to historic Grand Canyon Village and large coaches are not permitted to stop at most of the viewpoints along the way. However, the canyon will be visible occasionally out of the right hand windows, and along the way we can take questions over the microphone and discuss other aspects of its interesting geology and history. Listen to announcements for when and where we will have lunch.

This eastern part of the canyon is where historians have traditionally thought people of European descent first saw and entered the Grand Canyon in 1540 (as part of the Coronado Expedition). It is a practical assumption because Hopi Indian guides were leading these Spanish conquistadors from the east and this is the first place to view the canyon from that direction (the Spaniards were seeking a location to resupply their outfit by ship and had an awareness that this river connected with the Sea of Cortez or Gulf of California). However, this long held interpretation was recently questioned when a geologist suggested that an Iberian-like rock inscription within the canyon about 40 miles west of Desert View might have been made by members of this group (Kenny, 2012). The inscription may or may not date from this period but the study highlighted how the previous interpretation was not landscape-based and thus at least subject to reinterpretation. The sheer walls of the eastern Grand Canyon do not provide a viable path for casual exploration or travel in the canyon. The area of the inscription does.

After driving about 8 miles from Desert View, we pass the unmarked trailhead for the Hance Trail to the river. John Hance was the first Anglo to permanently settle at the Grand Canyon (1883) and did so for the purpose of mining the serpentine asbestos (chrysotile) found in select localities near the river. The asbestos formed by contact metamorphism where Proterozoic-age sills of Cardenas Basalt intruded into magnesium-rich Bass Limestone. The trail today is one of the hardest of the dozen or so routes that were constructed before National Park status was achieved in 1919.

The road soon climbs back into Ponderosa pine forests on the back of the Grandview monocline, last seen in the Coconino Rim before Desert View. This fold trends into the canyon near Grandview Point, where another historic trail descends to the location of the Last Chance copper mine. This mine was established in 1892 and the ore was incredibly rich – 70% pure copper – and won a prize at the Columbian Exposition in Chicago in 1893. The ore was likely emplaced as the monocline formed during the Laramide Orogeny. The ore body was small however, and ultimately William Randolph Hearst bought the property hoping to construct a mansion on associated properties on the rim. He sold these properties to the National Park Service in 1940.

Just before entering Grand Canyon Village, we pass the South Kaibab trailhead. This is one of the few trails that were built expressly for a national park clientele, but its purpose is related to mining nevertheless. Ralph Cameron constructed the Bright Angel Trail in 1895 with the intent to mine there but was soon caught up in the increasing tourist trade that hit the canyon after the arrival of the railroad in 1901. He charged a $1.00 toll to access his trail and held the rights to it after the park was established. The National Park Service tried to invalidate the mining claims but could not, even though there were no economic minerals to be found in this part of the canyon. The NPS eventually built the South Kaibab Trail in 1928 to provide free access into the canyon. Seven years later the Park Service obtained the rights to the Bright Angel Trail and that is why there are two trails from the Village area to the Colorado River.

Stop 4 – Grand Canyon Village and the Trail of Time (TOT)

- We should arrive here by about 12:00 noon and will disembark the coach in front of the Bright Angel Lodge. We will walk to the Trail of Time (TOT) as a group but in case you get lost, go through the lobby of the Bright Angel Hotel to the rim of the canyon. Turn right (east) and walk along the rim trail about ¼ mile (300 m) to the Verkamp Visitor Center on the rim (just past the obvious El Tovar Hotel and the Hopi House). The TOT is just past the Verkamp building on the rim. Our tour of the TOT will begin here.

REMEMBER, WE ARE A LARGE GROUP AND OTHER VISITORS WILL ALWAYS NEED TO MOVE PAST US WHEN WE ARE STOPPED TO DISCUSS GEOLOGY.

<u>PLEASE DO NOT BLOCK THE MIDDLE OF THE RIM TRAIL</u>.

Dr. Karl Karlstrom at the Univ. of New Mexico conceived the TOT in 1995 and secured funding for its implementation in 2002 from the Informal Science Education Program of the National Science Foundation. It is not possible to include all aspects of the TOT's components in this field guide; however, a few highlights are discussed with many more presented verbally on the trail.

The TOT is billed as "the world's largest geoscience exhibition at one of the world's grandest geologic landscapes" (Karlstrom et al, 2008). The entire TOT measures 4.56 km (2.83 mi), portraying the vastness of geologic time in linear fashion and within view of the Grand Canyon. Although the trail covers all of earth history between Maricopa and Yavapai Points, only the final two billion years (about 2 km) contain interpretive signs, viewing tubes, and rock samples for which the trail is most well-known. These final two billion years represent what is exposed in the walls of the Grand Canyon. This section of the trail begins immediately east of the Verkamp Visitor Center and extends to Yavapai Point where a geology Museum is located. We will have time to look at the recently redone and excellent exhibits here, as well as purchase geology-themed and other books.

The primary exhibit along the TOT is the Grand Canyon itself but because conceptualizing "deep time" is often difficult for casual visitors, constructed exhibits along the trail serves to make the topic more approachable. Each million years is represented by brass rings that are placed one meter apart (one long step) along the trail. At ten-meter intervals brass plaques display the specific time in millions of years along the trail (Figure D2-17). The last one million years depicted near Yavapai Point is a subset of the TOT and is called the "Million Year Trail," which depicts one million years in the final 140 meters. This section "stretches" time, with markers still one meter apart but representing sequentially smaller intervals of time. The last 60 meters represent one-year intervals. The "Million Year Trail" is intended to help visitors adjust their temporal human time frames (years or decades) to geologic or deep time (thousands or millions of years).

Figure D2-17 – One of the brass medallions set in the Trail of Time and located at ten meter intervals (photo by author).

Four rock monuments or portals are constructed along the trail, one at each end, another where the "Million Year Trail" begins, and another where an adjacent trail intersects the TOT near the 1,000 Ma plaque. These monuments are shaped to resemble the profile of the Grand Canyon and are built with samples from each rock layer found in the canyon (Figure D2-18). All of the rocks used in the TOT were collected on river trips and rafted by boat out of the canyon. The patio that surrounds each of the portals is laid with time-appropriate rocks for that point along the trail. At our starting point near Verkamp's, the patio is layered in rocks of the Vishnu basement.

Figure D2-18 – One of four rock portals located along the Trail of Time at Grand Canyon National Park (photo by author).

Fifteen interpretive signs are placed at key events in Earth and Grand Canyon geology along the trail. Viewing tubes at heights for adults and children are placed near most of these signs to further draw attention to the rocks or events being discussed. Most of Grand Canyon rocks have known or accepted dates and at these points along the trail concrete pedestals with a sample of the rock exist (Figure D2-19). All told, 33 pedestals are found along the trail for each formation. (The originators of the TOT were especially enthusiastic about the Paleoproterozoic and Neoproterzoic rocks in Grand Canyon and included separate pedestals for each member of those formations).

Figure D2-19 – Numerous rock pedestals are located along the Trail of Time (photo by author).

Along the way we will discuss the origin and environment of deposition for the Vishnu basement rocks and associated granites, the Grand Canyon Supergroup, the Paleozoic section, and the Mesozoic rocks that are mostly eroded from Grand Canyon but well-exposed north and east of here. As we approach the 70 million year plaque, we will begin to discuss the Laramide Orogeny and the uplift of the Colorado Plateau, controversial ideas about the age of the Grand Canyon and Colorado River, and the Pleistocene volcanic rocks that poured into the canyon about 100 miles west of here beginning about 800 ka. We will spend about 2 hours on the TOT and participants will have time to explore the Geology Museum afterwards.

- Hotel check-in and instructions for our dinner will be made before the group disassembles at the Geology Museum. Listen carefully to the field trip leaders for possible deviations from the printed schedule.

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Field Trip Itinerary and Guide: Day 3, September 22, 2014

Day 3 –Grand Canyon South Rim to Scottsdale via AZ State Highway 64, US Highway 180, Interstate 40, US Highway 89, AZ State Highway 69, and Interstate 17 (Guide: Phil Pearthree)

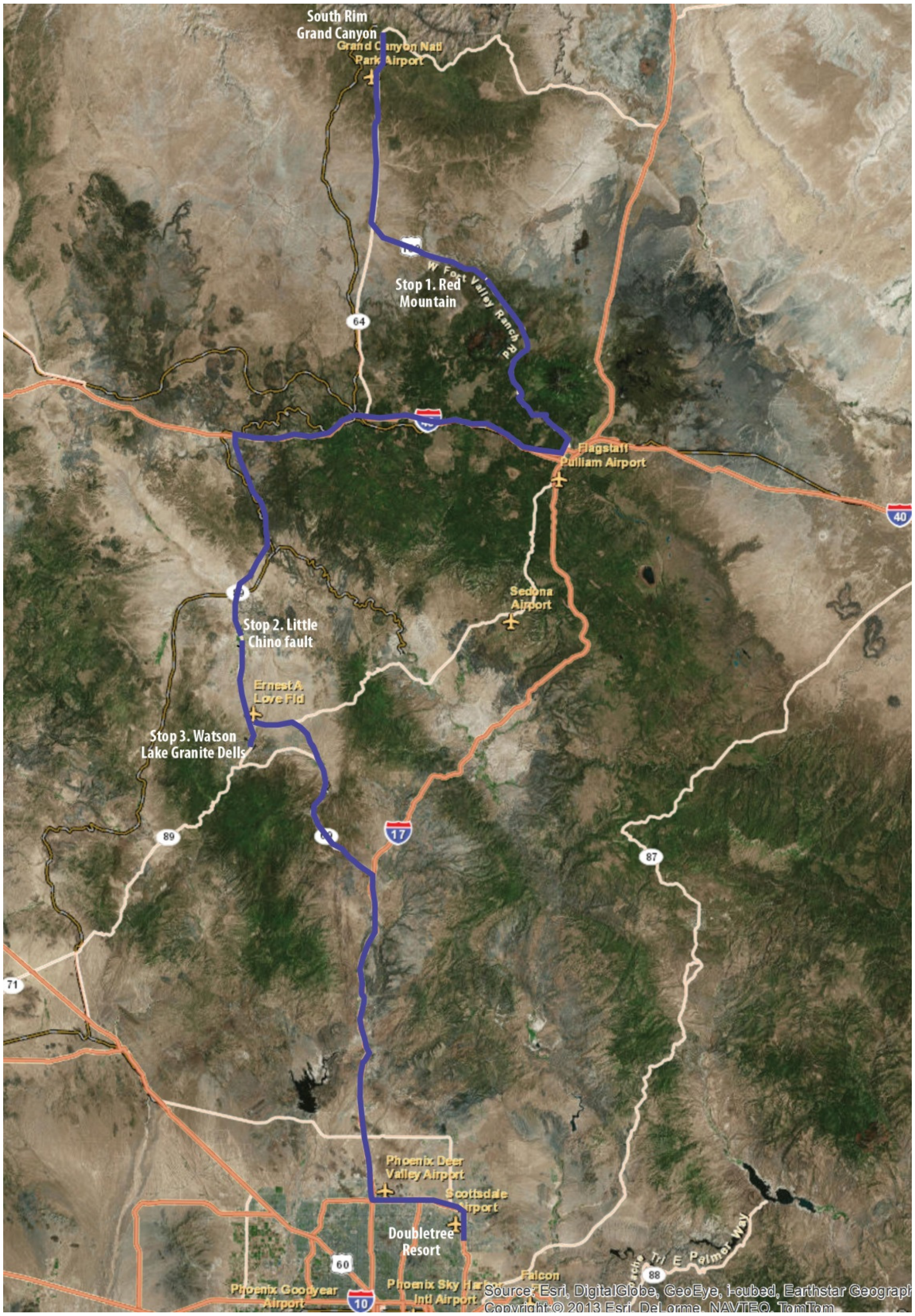

Figure D3-1: Map of Day 3 route.

This will be the final day of our trip, and much of the day will be spent onboard the bus making the journey back to Scottsdale. We have only a few stops planned with the long driving time for this day, but the beautiful scenery and fascinating geology along the route are sure to keep you interested.

- After departing from the Grand Canyon South Rim Village, we will drive about 27 miles south on SR 64 to Valle.

The community of Tusayan just outside the Grand Canyon NP boundary is located in a graben formed by displacement on 2 strands of the Bright Angel fault system. This is one of many suspected Quaternary faults that displace the broad bedrock erosion surface between the San Francisco Volcanic Field (SFVF) and the South Rim of the Grand Canyon.

Proceed south to Valle. There are no recognized Quaternary faults in the immediate vicinity, but a M5.3 earthquake in 1993 was centered about 3 miles southeast of the intersection of SR 64 and US 180. This was the largest earthquake in Arizona in the past 55 years.

- Turn east on US 180, drive about 18 miles to Red Mountain.

The first ~10 miles are primarily on an erosion surface formed on the Kaibab Formation. The erosion surface is mantled in most areas by weathered Kaibab sediments or thin Quaternary surficial deposits. The remaining 8 miles of the drive are on Pliocene and Quaternary volcanic rocks, mostly basalt flows. To the right side of the road we can see several higher mountains, from west to east Sitgreaves, Kendrick, and San Francisco Mountains. Each of these is a remnant stratovolcano, with the youngest and highest mountain in the east.

- Turn right on a dirt road at about Milepost 247 to enter Red Mountain Geologic Area, proceed 0.25 miles to the trailhead for Red Mountain. A gentle uphill walk of about 1.5 miles through open woodland will bring us into a natural amphitheater carved into the northeast flank of the mountain.

- **Stop 1 – Red Mountain Volcano**

Red Mountain is one of several hundred cinder cones within a swath of volcanic landscape that extends 50 miles eastward from Williams, Arizona, through Flagstaff to the canyon of the Little Colorado River – the SFVF. Red Mountain is an asymmetric, U-shaped cone opening to the west (Figure D3-2). In addition, a large, scenic natural amphitheater that we will visit cuts into the cone's northeast flank, revealing some of its internal structure (Figure D3-3). Red Mountain rises to almost 8,000 feet above sea level, about 1,000 feet above the surrounding landscape. Studies by U.S. Geological Survey and Northern Arizona University scientists suggest that Red Mountain formed in eruptions about 740,000 years ago. The SFVF has been active for about 6 million years, and in that context Red Mountain is fairly young.

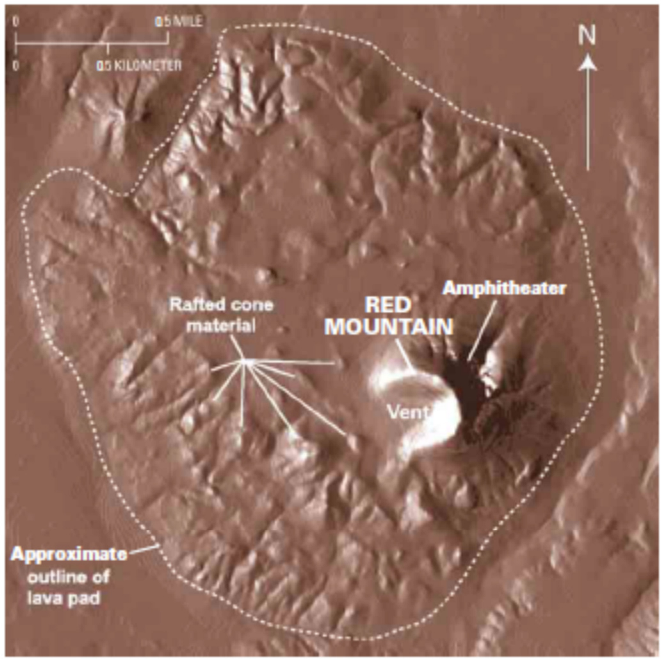

Figure D3-2: Digital elevation model (DEM) of Red Mountain area taken from Priest, et al (2002).

Red Mountain grew on a nearly flat surface that sloped gently to the north. The base of the U is a curving ridge that forms the highest part of the mountain, with ~0.5-mile-long arms of the U sloping down to the west and merging with the gently rolling surface of the Red Mountain lava flow. The waning-stage lava flow of the Red Mountain eruption most likely rafted the western section of the cinder cone away and formed the U-shaped cone we see today. Geologists have discovered several outcrops of layered cinder deposits, some of which are hundreds of feet wide and tens of feet thick, at the top of the lava flow. These "floaters" form hills on the surface of an otherwise fairly flat flow (modified from Priest et al, 2002).

Figure D3-3: View of Red Mountain amphitheater

The reasons for the excellent exposure of the Red Mountain amphitheater are not clear. Obviously the amphitheater has been modified by fluvial erosion, but that alone does not explain why the north side of the volcano is so eroded. An intriguing possibility is that one or more steam explosions created an amphitheater-shaped hole in the side of Red Mountain shortly after eruption ceased. Newly erupted cinders probably cooled to about 600°F as they fell back to earth, but remained well above the boiling temperature of water for some time. Rainwater seeping into the cone and circulating through the still hot cinders may have quickly deposited the mineral cement that bound cinders together, creating the equivalent of a sealed "pressure cooker." Eventually, the pressure of the trapped superheated water may have exceeded the strength of the seal, resulting in one or more steam explosions that blew out the surface of the cone (modified from Priest et al., 2002).

- ➢ Return to the parking spot and turn east on US 180.

Proceed toward Flagstaff over basalt flows and Quaternary sediments, between cones and larger mountains of the SFVF. As the road bends to the southeast, we have a nice view of Kendrick Peak to the south. Most of this mountain burned in a forest fire in June 2000; numerous debris flows occurred on the mountain during the summer rainy season that followed.

- ➢ In Flagstaff, turn west on old US 66 and join I-40 at west side of Flagstaff.

The northern part of the Oak Creek fault zone is just west of the junction. South of I-40, an early Pleistocene basalt flow has been displaced about 100 feet down to the east across the fault zone. I-40 and the railroad follow a valley cut through the fault scarp; the low hills to the north and south are the fault scarp.

At the Bellemont interchange a few miles farther down the road we cross another Quaternary fault, the Bellemont fault. A prominent water tower south of the highway on Camp Navajo, a former U.S. Army Depot and now an Arizona National Guard facility, sits just east of a 40-foot-high fault scarp formed in a middle Pleistocene basalt flow. This fault ruptured most recently in the late Pleistocene.

The large mountain looming to the west is Bill Williams Mountain, the oldest remnant stratovolcano in this area. About 14 miles west of the Bellemont interchange, we approach the Bill Williams fault at the western edge of a broad meadow / marsh. This is a significant NE-trending normal fault that displaces Pliocene to early Quaternary basalts by at least 200 feet down to the east. Continuing west on I-40, we pass the town of Williams. Both the mountain and the town were named after legendary mountain man William Sherley “Bill” Williams, who traveled widely in the West before meeting his demise at the hands of Ute warriors in 1849.

About 10 miles west of Williams, roadcuts along a long down-grade on I-40 provide a nice view of interbedded volcanic flows and sedimentary deposits. These are not directly dated here, but are likely late Miocene to Pliocene in age. The prominent peak in the distance is Picacho Butte; it is just north of the northwest end of the Big Chino fault zone, which we will be discussing at Stop 2.

- Proceed to the eastern edge of Ash Fork, turn south on AZ Highway 89.

Enjoy the views of the north end of the Black Hills to the left and Granite Mountain to the right as we head southeast over several broad basalt capped highlands. SR 89 descends gradually on one or more late Miocene basalts that flowed from the highlands behind us into the valley before us.

About 16 miles south of Ash Fork, the large facility visible east of the road is the Drake Portland cement plant, a relatively new facility that is using limestone mined from the base of the escarpment to the northeast. We cross the bridge across Hell Canyon, a fairly deeply incised tributary of the Verde River. The existing bridge, built in 1954, is scheduled to be replaced by the Arizona Department of Transportation in 2015. The existing bridge replaced a historic bridge built in 1923 that crosses Hell Canyon to the east along the original alignment of historic US Highway 89.

About 5 miles farther south along SR 89, the road cuts through Paleozoic sedimentary rocks and follows a tributary valley into the southeastern part of Big Chino Valley. The low ridges and small valleys in this area are the result of complex faulting at the southeastern terminus of the

Big Chino fault zone (Figure D3-4) – more on that at Stop 2. As we pass through Paulden, the low hills to the east are capped with Pliocene basalt flows that are displaced by several faults. In the lowest part of the valley we cross Big Chino Wash – the upstream continuation of the Verde River with a different name.

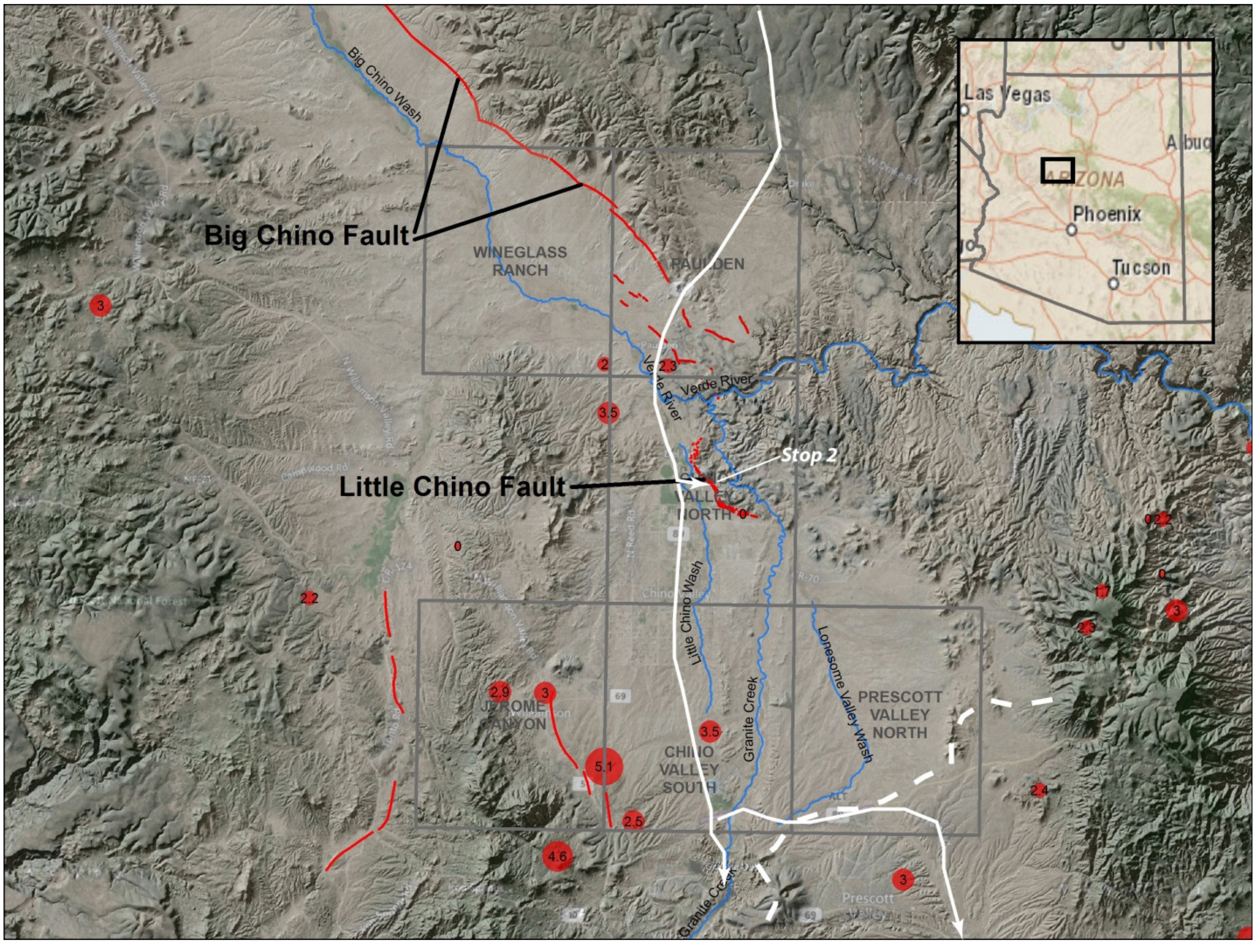

Figure D3-4: Map of the Big Chino and Little Chino fault zones. The Big Chino fault zone is fairly simple along much of its length, but the southeastern terminus consists of multiple short faults with various orientations.

➢ Turn left on E Rd 6N into Arrowhead Materials. Follow graded road up to the roadcut exposure of the Little Chino fault zone. (This part of the trip requires permission from the landowner.)

- **Stop 2 - Little Chino fault exposure**

The purpose of this stop is to examine an excellent exposure of strands of the Little Chino fault zone and discuss possible interactions between the Little Chino and Big Chino fault zones. We discovered this road cut exposure while conducting detailed geologic mapping of the Chino Valley North quadrangle (Gootee et al., 2010). Access has been graciously provided by the landowner and Arrowhead Materials.

The Big Chino fault zone has long been recognized as a fault with recurrent displacements in the late Quaternary. Fault scarps formed in middle to late Quaternary alluvial fan deposits are obvious for about 30 miles along the base of Big Black Mesa and Picacho Mountain, with up to 60 feet of vertical displacement. The Big Chino fault probably ruptured most recently between 10-20 ka (Pearthree et al., 1983; Euge et al., 1992). Recent detailed geologic mapping of the southeastern part of the Big Chino fault documented many fault strands with a variety of orientations displacing Paleozoic bedrock, Pliocene basalts, and Quaternary surficial deposits. These faults constitute the messy terminus of the Big Chino fault zone.

At our location, a major fault separates Little Chino Valley to the west from the unnamed hills to the east, with at least 700 feet of late Cenozoic vertical displacement (Blasch et al., 2005). Prior to discovery of this roadcut exposure, however, no Quaternary faulting had been recognized here (Pearthree, 1998).

The road cuts through a 10 m-high fault scarp and alluvial ridge. Fourteen individual faults form a SE-trending graben on the crest of a much larger, W-facing fault scarp. A sequence of five moderately to weakly developed buried Pleistocene soils (Figure D3-5) records 3 to 5 individual surface-faulting events during the past few hundred thousand years (Figure D3-6), with ~3 m of cumulative vertical displacement across individual faults (Gootee et al., 2013). Vertical displacement across a major fault at the NE end of the roadcut adds at least 2.5 m of Quaternary displacement. A ^{14}C date of 6.5 ka was obtained from charcoal associated with deposits that filled the youngest fault-related graben, providing a minimum age constraint for the most-recent fault movement. Since the dated material is from about the middle of the fill unit, this is consistent with a latest Pleistocene to early Holocene age of youngest rupture.

The age estimates for youngest rupture are similar on the Big and Little Chino fault zones, and the recently mapped splays leave a short gap between them. This suggests that these fault zones may have ruptured together in the most recent large earthquake. This increases the length of the fault zone from 30 miles to at least 40 miles; given length-magnitude relationships, this implies that the most recent large earthquake was >M7.

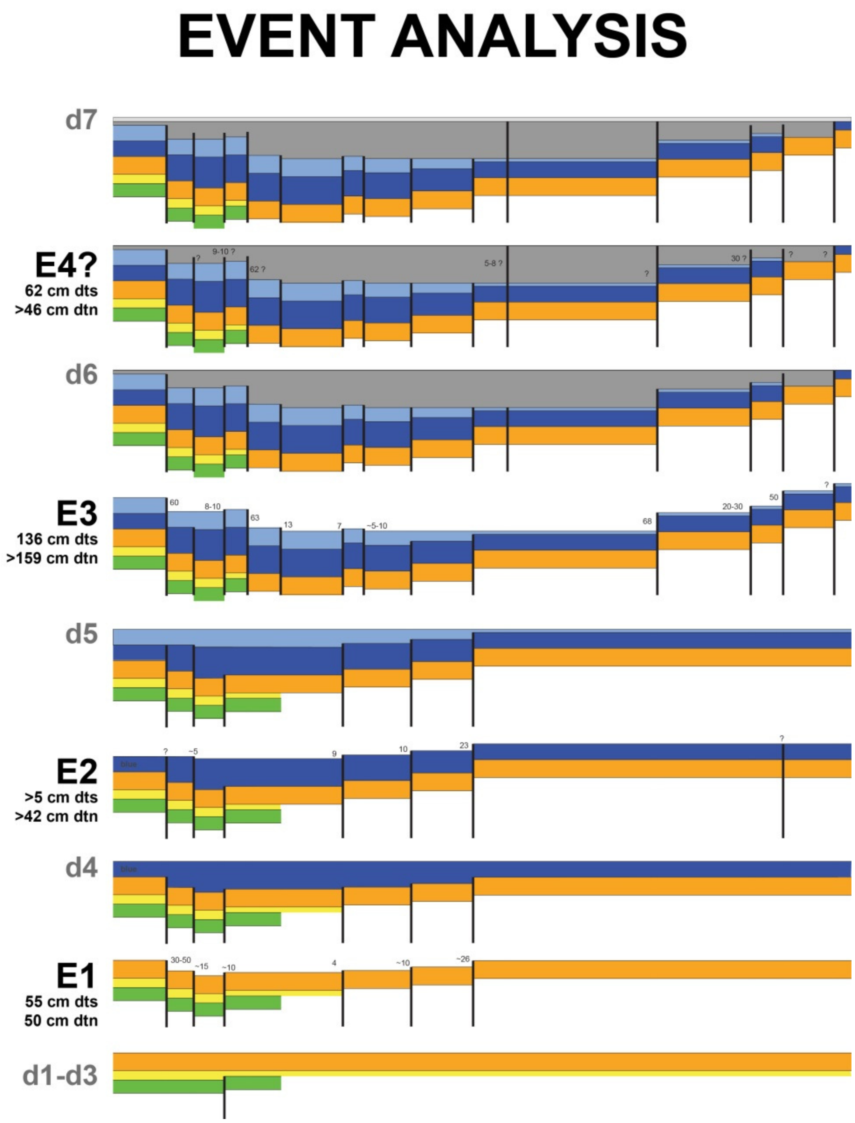

Figure D3-5: Annotated photo of part of the roadcut into the Little Chino fault zone showing faults and buried soils and stratigraphic units displaced by faults. The star shows the location and age of a radiocarbon date in deposits that post-date the youngest faulting event. The circles show locations of optically-stimulated luminescence (OSL) dates for a unit that was clearly displaced by faulting.

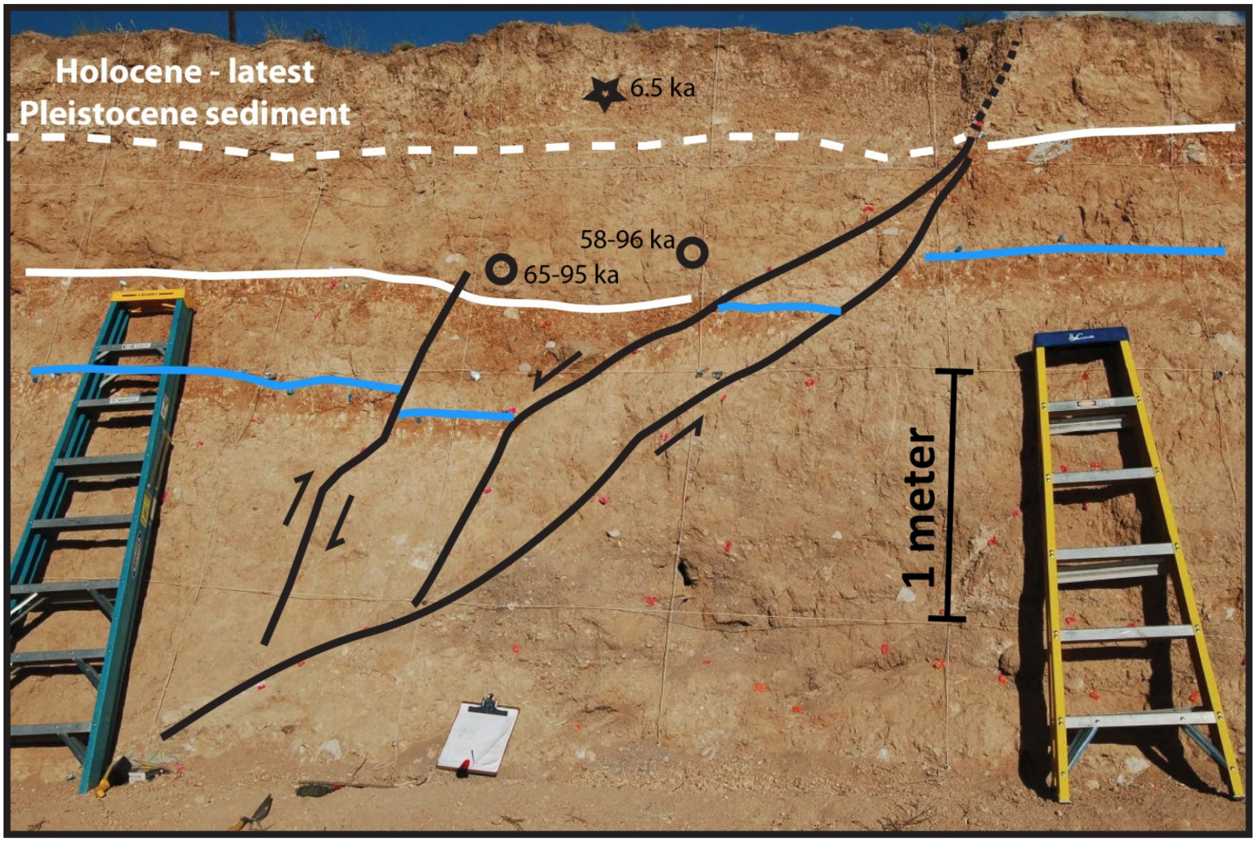

Figure D3-6: Earthquake event reconstruction for the Little Chino fault zone. Strata in the southwestern part of the roadcut record 3-4 surface rupturing earthquakes, the youngest of which probably occurred in the latest Pleistocene or early Holocene. An unknown number of older events occurred on the large fault zone near the northeastern end of the roadcut.

➢ Return to SR 89 and proceed south through the town of Chino Valley.

We are now driving over the Quaternary deposits of Little Chino Valley. The high, flat-topped alluvial ridges to the east and southeast are capped by deposits of Granite Creek, a substantially larger drainage that heads in the mountains in front of us. Those deposits were emplaced earlier in the Quaternary when Granite Creek was depositing an extensive alluvial fan across the southern part of Chino Valley. Since that time, Granite Creek has incised 100-150 ft on the other side of those ridges. Proceed south on SR 89 through the traffic circle at Outer Loop Road. About 2.3 miles farther south, we cross a low alluvial divide into the Granite Creek watershed. Continue south past the Prescott Municipal Airport and the interchange with SR 89A (Pioneer Parkway). About 1.5 miles farther south we enter a dramatic landscape of fractured, weathered, and eroded 1.4 billion year old granite; the Granite Dells.

➢ In another 1.5 miles, turn left at Willow Lake Road to enter into Watson Lake Park.

- **Stop 3 - Watson Lake – Granite Dells**

Watson Lake is a very scenic spot in the midst of the Granite Dells area, roughly 5 miles northeast of downtown Prescott (Figure 7). This landscape of unusual rock formations and spheroidally weathered boulders has developed through chemical and physical weathering of the 1.4-billion year old Dells Granite, especially along the pervasive fractures. The uranium content of this granite is unusually high, which has led to somewhat elevated radon levels in buildings constructed on or near it (Spencer, 1992). Watson Lake was created by damming Granite Creek in the early 1900s – it was purchased for use as a park by the City of Prescott in 1997.

Glassford Hill to the east is a 14 Ma basaltic volcanic center, part of or equivalent to the Hickey Formation volcanics that we saw so much of on Day 1. The crater is eroded and open on the northeast side, and a remnant cone/neck and dikes are visible from Prescott Valley to the east.

Figure D3-7: Scenic beauty of Watson Lake in the Granite Dells (Photo courtesy of Benjamin Cody and Wikimedia Commons). Horizontal patterning on bedrock records higher lake levels. Some of the multiple sets of fractures that facilitate rock weathering are evident. Glassford Hill on the skyline is a 14 Ma volcanic center.

- Return to SR 89. Turn south to Prescott Lakes Parkway and turn left. Head uphill to junction with SR 69, turn left to head eastbound.

Continue east and southeast on SR69 around Prescott and Prescott Valley in the upper reaches of the Agua Fria River watershed. Note the fairly deep incision of the Agua Fria wash in the valley and many small tributary washes – excellent examples of historical arroyo cutting, which is very common in the Southwest. A much higher relict Pleistocene alluvial fan looms above the modern valley to the west. This was deposited by Lynx Creek, a large tributary that heads in the mountains to the west. Gold exploration and mining in the Lynx Creek area led to the establishment of Prescott in 1864; Prescott served as the territorial capital from 1864-1867, and again from 1877-1889, before it was stolen away for good by Phoenix.

Turn southeast on SR 69 and parallel the Agua Fria River for several miles. Late Cenozoic gravelly alluvial fan deposits are exposed in roadcuts on our right. Leave the Agua Fria as we begin to climb into rolling hills. Reddish brown tailings piles on the right are from the Iron King Mine, which exploited massive sulfide deposits in the Precambrian metavolcanic rocks – similar to, but smaller-scale than, the open-pit mine at Jerome. The mine, tailings pile, and nearby abandoned smelter are a Federal Superfund site. Climbing up to the top of a low ridge by the VFW lodge, we are on late Cenozoic gravel deposits; proceeding farther south, we see that the gravels are a fairly thin veneer over Precambrian metasedimentary and metavolcanic rocks.

Continue gradually upslope in an erosional terrain formed in Precambrian metamorphic rocks. Cresting a low divide and turning to the southeast we enter the watershed of Big Bug Creek, a large tributary of the Agua Fria River. We will follow and cross Big Bug Creek several times in the next few miles. Pass through the community of Mayer and a fairly tight gorge cut by Big Bug Creek through complex, foliated Precambrian metamorphic rocks. The landscape that gradually opens before us should look familiar. The deposits and volcanic rocks are Miocene and younger, part of the same sequences we observed in the first part of Day 1.

- Continue several miles southeast and merge onto I-17 south to Phoenix.

We are now backtracking our route from Day 1. The perspective on the landscape is quite different looking south, however. For example, Joes Hill, the volcanic center east of the Agua Fria River, is much more obvious when seen from the north. As we descend the grade off of Black Mesa into Black Canyon, we can see many distant mountain ranges that fringe the Phoenix basin. Enjoy the view and the rest of our trip as we return to Scottsdale for the remainder of the 2014 AEG Meeting!

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