

Arizona Geological Society

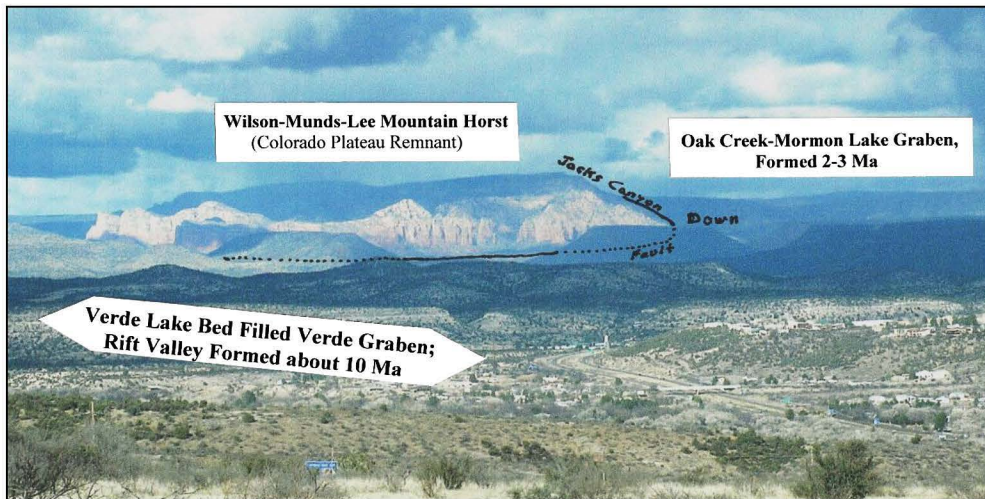
Spring Field Trip

Oak Creek-Mormon Lake Graben

North-Central Arizona



Saturday, May 2, 2015



Guidebook compiled by Paul A. Lindberg

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Field Guide, Oak Creek-Mormon Lake Graben, North-central Arizona

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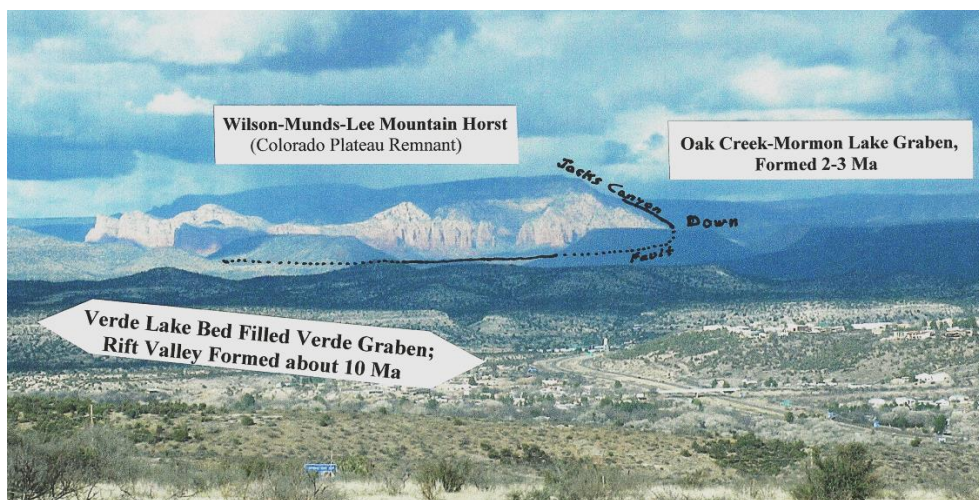
Contributed to AZGS by Paul A. Lindberg, AZ Prof. Geologist #22226, AIPG #6344

This field guide was prepared for the Arizona Geological Survey and Arizona Geological Society for public use. It presents a personal interpretation gained over many decades of field work and observations of one of Arizona's newest basin and range tectonic feature that is still actively forming. Since 2012 the writer has led this field trip for members of the Oak Creek Watershed Council, Arizona Hydrological Society, American Institute of Professional Geologists and local organizations.

Introduction:

The Oak Creek-Mormon Lake **graben** (a rift valley formed by extension of the earth's crust) has been faulted into the southwestern margin of the Colorado Plateau as basin and range crustal extension has migrated eastward across Western U.S. over time. The graben may be as young as 2-3 million years old, based upon the youthful appearance of numerous V-shaped canyons (Oak Creek, West Fork, Munds, Woods and Rattlesnake Canyons) that cut the minimally eroded original surface of the largely basalt covered core of the graben. That morphology is in sharp contrast to more maturely eroded landforms along the northeast margin of 10 Ma Verde graben near Sedona. Timing of the genesis of the Oak Creek-Mormon Lake graben may be contemporaneous with the main eruptive cycle of San Francisco Peaks north of Flagstaff, Arizona. At Flagstaff the surface of the graben is composed of Permian Kaibab Limestone but a short distance to the south is a southeast-thickening succession of basalt lava forms the core surface of the graben all the way to Camp Verde (photo below).

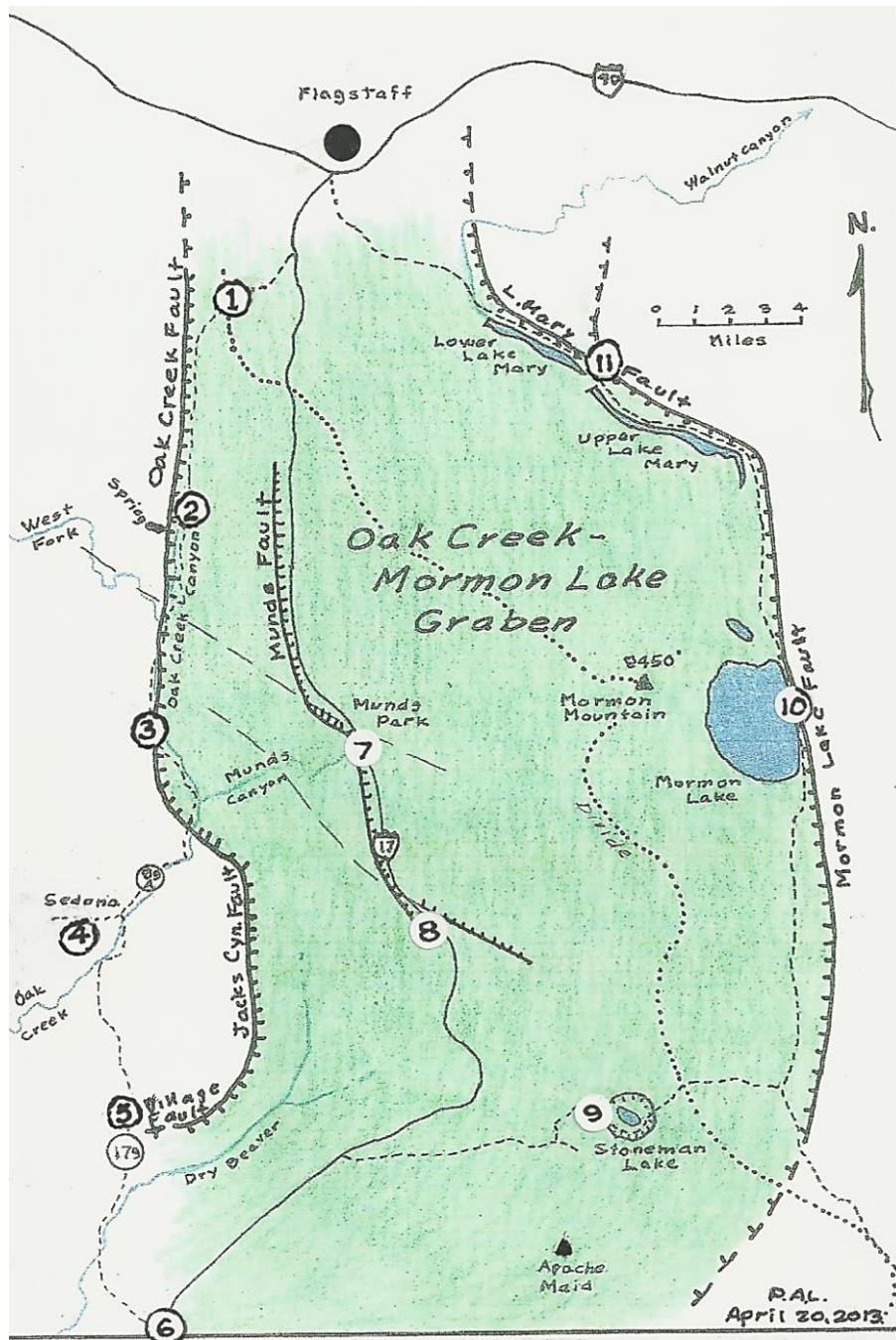
Interstate 17 from Flagstaff to Camp Verde traverses the basalt lava flow surface that drops about 3000 feet (~910 m) where the graben surface is capped by Verde Lake beds at its southern junction with the older Verde graben (see illustration below). Age dating (Holm and Cloud, 1990 and Holm, 2001) shows that the top end member basalt flows are 6-8 million years old, implying that eruptions of the "ramp volcanics" were younger than 10-15 million year old Hickey and House Mountain and Hickey Basalt volcanic successions further to the west. This current guide maintains that the so-called "plateau basalts" are simply an eastward continuation of the Hickey Basalt and House Mountain volcanic eruption cycle with only the top end member being younger. Deep canyons that cut into the new graben expose multiple overlapping basalt flows east of Interstate 17 with ages of 14.6 Ma, equal to their western counterparts (Billingsley, 2015). Miocene basalt flows pre-date and post-date the generation of 10 Ma Verde graben (Lindberg, 1986). The tour described in this guide begins at the High Country Convention Center in Flagstaff at the north end of the University of Northern Arizona campus and travels in a counter-clockwise direction to visit key geological features of the graben. The route is passable by ordinary vehicles. Because of plateau elevations, however, the dirt road past Stoneman Lake may be impassable during winter snow conditions. Except for one short rock scramble in Oak Creek Canyon, most field trip stops are close to vehicles.



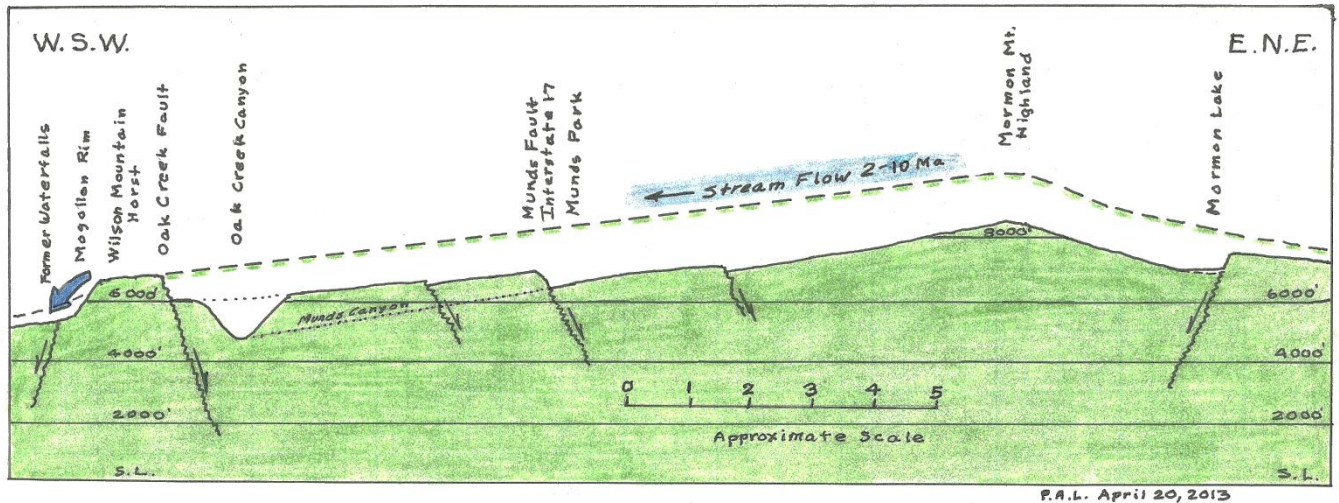
Northeasterly view from I-17 Exit 288 entering Verde Valley from the south. Oak Creek-Mormon Lake graben merges with the older Verde graben north of Camp Verde. Oak Creek fault (beyond photo) becomes Jacks Canyon fault to the south before curving to the west through Village of Oak Creek. **Stop 5** (behind hill, 1/5th of way in from the left side of the photo in Village of Oak Creek) is at the margin of the Verde and Oak Creek-Mormon Lake grabens. During the Laramide orogeny the east and south sides of the Oak Creek and Jacks Canyon faults experienced high-angle reverse offset with the east and south side raised up. Post-Laramide (65-70 Ma) erosion of the Central Arizona Highlands to the southwest by northeast-directed stream flow removed the uppermost Paleozoic strata lying east and south of the ancestral Oak Creek and Jacks Canyon faults. By 15 Ma Rim Gravels, bearing Precambrian clasts, filled stream channels cut into a regional peneplain before burial by Miocene basalt lavas. Basin and range extension generated the Verde graben 10 Ma (left and foreground) and is backfilled with Verde lake beds. Younger Oak Creek-Mormon Lake graben, estimated at 2-3 Ma, dropped the region east and south of Wilson-Munds-Lee Mountain horst (colorful plateau remnant in center of photo) by about 1400 feet (~425 m).

Earthquake Activity:

On November 30, 2014 a magnitude 4.7 earthquake occurred approximately 12 miles north of Sedona at a depth of about 6.2 miles, suggesting that the graben is still actively subsiding, albeit slowly. Another magnitude 2.5 shock took place on January 28, 2015 about halfway between Flagstaff airport and Munds Park. A series of moderate earthquakes have been recorded in the Flagstaff region over the past 120 years. Larger earthquakes and the possibility of future volcanic eruptions, especially along the northern end of the graben in the Flagstaff area, is highly probable. Regional volcanism has been on-going over the past 14-15 million years and the pristine Sunset Crater cinder cone and lava flow to the northeast of Flagstaff erupted less than a thousand years ago! Relatively young fault scarps bound the graben margins and numerous north-south and northwest-southeast fault scarps occur within the core of the graben. One conspicuous graben fault scarp at **Stop 6** just west of I-17 freeway at Munds Park will be examined. The faulted and down-dropped core of the graben influenced the routing of I-17. Google Earth images show numerous fault scarps and joint patterns within the graben.



Oak Creek-Mormon Lake graben. This field trip guide starts in Flagstaff (black dot) and proceeds counter-clockwise around the perimeter of the graben. Field trip stops are shown as bold numbers. Selected key bounding faults and internal features of the graben in the Munds Park and Stoneman Lake areas will be examined.



Cross Section looking northerly between the Mogollon Rim on the east side of Sedona to Mormon Lake to the east-northeast. The Oak Creek-Mormon Lake graben is estimated to have begun dropping about 2-3 million years ago with most of its original surface barely eroded. Oak Creek fault forms the western margin of the north-south graben and the Mormon Lake fault forms its eastern boundary. Deep, youthful, V-shaped canyons like Oak Creek, Munds, Woods and Rattlesnake Canyons cut into the basalt lava covered surface. Interstate 17 follows the south dipping graben surface from Flagstaff on the north to Camp Verde on the south, dropping over 3000 feet (>910 m) on route. The rift valley displacement diminishes to about 150 feet (45 m) to the north but increases substantially to the south where it merges with the 10 million year old Verde graben.



View to east across Margs Draw toward the Mogollon Rim and the Munds/Lee Mountain horst. The eroded landscape in the foreground displays a mature weathering surface along the northeastern margin of the 10 million year old Verde graben. North-south Jacks Canyon fault, a southerly continuation of the Oak Creek fault, lies immediately behind Munds Mountain. Prior to the far side dropping an estimated 2-3 million years ago, surface stream drainages from the Mormon Mountain highland flowed over the Mogollon Rim and carved valleys like Margs draw (see cross section above). In addition, surface streams flowed southward from the San Francisco Peaks volcanic high where it carved the Hermit bench in West Sedona and Dry Creek Valley to the north of town. Once the Oak Creek-Mormon Lake graben dropped (behind Munds Mountain above) that flow of surface water was forever cut off, leaving behind now-dry valleys once cut by active stream flow.

ROAD LOG

If you have passengers, have them read out road log geological features on route.

Start: High Country Convention Center. **Set odometers to zero.** Leave parking garage to south, then right, then left along one-way road through NAU campus.

Mile 0.5: Turn right onto Riordan Road just past NAU Ardrey Auditorium.

Mile 0.7: Turn left at traffic signal onto Milton Road and move over into right lane going south.

Mile 1.5: Turn right at traffic signal onto Forest Road and after 1 block at traffic light turn left onto Beulah Blvd. Note the Permian Kaibab Limestone outcrops alongside road and absence of volcanic cover.

Mile 2.3: Cross Lake Mary Road at traffic light and continue south. For the next 3.5 miles the road traverses Kaibab Limestone outcrops at an elevation of about 7000 feet (2135 m) with no basalt cover. This location near the Flagstaff airport is close to the surface divide at the north end of the Oak Creek watershed that leads into Verde Valley.

Mile 4.8: Pass new traffic circle and continue south on Highway 89A heading toward Oak Creek Canyon and Sedona.

Mile 5.8: Beginning of the topmost northern end member of southeast-thickening pile of Miocene basalt lava flows.

Mile 6.5: Pass entrance to Forest Highlands housing development.

Mile 8.3: Stop #1, but stay in car: Pull over to right shoulder for a brief look at the Oak Creek fault scarp straight ahead. At this location you are sitting on the original lava-capped surface of the down-dropped Oak Creek-Mormon Lake graben. The same surface is seen in the distance at the top of the western fault boundary of the graben. The normal fault displacement at this location on the latest stage of normal down-to-east offset of the Oak Creek fault is about 520 feet (160 m) with the fault scarp offset diminishing northward to about 150 feet (~45 m) near Exit 190 on Interstate 40 to the west of Flagstaff. Proceed south on 89A, paralleling the fault scarp off to the right or west side.



View to west along Highway 89A past the Forest Highlands development. In the distance is the modern normal, down-to-the-east Oak Creek fault scarp that forms the western boundary of the Oak Creek-Mormon Lake graben. The basalt surface that the highway is built on is the same surface seen at the top of the Colorado Plateau in the distance.

Mile 13.6: Start of Highway 89A switchbacks dropping down into head of Oak Creek Canyon. Pass viewpoint.

Mile 13.8: Stop 2: Once heading downhill, pull over to right shoulder. Here at the head of Oak Creek Canyon the down-dropped eastern side of the Oak Creek Canyon is evident. North-south Oak Creek fault lies within the canyon to the south, favoring its western side. Down-dropped Oak Creek-Mormon Lake graben lies east of Oak Creek Canyon and extends 17 miles (27 km) to the east to the east edge of Mormon Lake. The terrain to the west is un-faulted Colorado Plateau with a thin basalt lava capping that thickens southeastward. Net offset of the down-to-the-east modern phase of the Oak Creek fault at this stop is about 550 feet (170 m). The ancestral offset on the Oak Creek fault formed during Laramide compressional uplift, however, was up-on-the-east by an estimated 400 feet (~120 m). Following the onset of the Laramide orogeny that raised the entire region to the modern plateau elevation, the topmost Paleozoic sedimentary strata (Kaibab Limestone) was differentially eroded away from the east side of the Ancestral Oak Creek fault but was preserved to the west. In post-Laramide time, up until about 15 Ma, the erosion surface was cut by northeasterly-directed stream channels that were filled with Rim Gravel conglomerates that contain clasts of Precambrian and lower Paleozoic sediments that were derived from the Central Arizona Highlands lying far to the southwest in the Verde Valley and Prescott region. Rim Gravels were later capped by Miocene lava flows. The Thomas Point Rim Gravels exposed on the eastern side of Oak Creek Canyon are, in the opinion of the writer, time-stratigraphic equivalents of the “Beavertail, Tertiary and Distant” gravels exposed within the down-faulted Verde graben and Jerome areas lying to the west. Reactivated faults, such as this example, are widespread throughout the region. Without taking into account the dual age of faulting history, with opposite directions of offset and intervening prolonged post-Laramide erosion, no accurate palinspastic reconstruction is possible. **Stop 3**, later on, will demonstrate that duality of faulting history.

- Mile 14.6:** Base of Miocene basalt lava rests on truncated Coconino Sandstone in roadcut to the right.
- Mile 14.7:** At the first major switchback is a broad zone of weathered Coconino Sandstone that is exposed within the dual-age Oak Creek fault zone. Un-weathered Coconino Sandstone can be seen on the west side of the fault on the far side of the switchback. The wide zone of faulting was the result of high-angle reverse faulting on the Laramide-age Ancestral Oak Creek fault where the east side was thrown up, with modern reactivation of the Oak Creek fault 2-3 Ma with the east side dropping back down. As a result, increased porosity was formed within the reactivated fault zone.
- Mile 15.5:** At the next switchback the road passes in and out of the same wide dual-age Oak Creek fault. A recent “sinkhole” formed in the road pavement near this location. Arizona Department of Transportation (ADOT) personnel attributed the small hole as “being caused by poor original road fill containing rotted wood” and not the collapse of subsurface limestone cavern that may have been related to recent earthquake activity. Time will tell if their interpretation was correct.
- Mile 15.7:** Below highway level is the Sterling Spring State Fish Hatchery. Water emanates from a spring that is released from a subsurface water-filled Redwall Limestone cavern that has formed along the plane of the Oak Creek fault. That sustained artesian outflow forms the perennial headwater of Oak Creek. Next, cross Pumphouse Wash.
- Mile 16.9:** Pass Pine Flats campground on right.
- Mile 17.1:** On the left side of the road, opposite Pine Flats mailbox kiosk, is a lone sycamore tree (pale tree trunk with smooth greenish bark). Sycamore trees require well-watered roots, indicating that this tree, located well above stream level, is situated above a hidden small water seep or spring. Further down canyon there are several additional seeps and springs that add water to Oak Creek. Recharge from those springs comes from precipitation within the down-dropped Oak Creek-Mormon Lake graben lying to the east of Oak Creek Canyon and Highway 89A.
- Mile 18.0:** The roadcut to the left exposes bleached and crumbly Coconino Sandstone, indicating that the plane of the Oak Creek fault lies close to the west side of the highway curve.
- Mile 18.9:** Pass turnout to West Fork of Oak Creek parking area. Across the canyon to the west is a magnificent cliff of Coconino Sandstone with original dune slopes indicating a southerly-directed wind flow 260-270 Ma. Coconino Sandstone is capped by Kaibab Limestone caprock. Not far south of this location on the east rim of Oak Creek Canyon is Thomas Point where Miocene basalt lava overlies an erosion channel filled with Rim Gravels that were deposited in a north- to northeast- directed stream channel. The conglomerate contains abundant clasts of Mississippian Redwall Limestone, Schnebly Hill Sandstone and lesser amounts of mixed Precambrian rock lithologies that originated from the Central Arizona Highlands provenance lying far to the southwest. Isolated remnants of Rim Gravels can be found on either side of Oak Creek Canyon walls to the south where they are overlain by Miocene basalt lava flows.
- Mile 20.9:** In sharp curve, just before reaching the Junipine Resort, there is an east-west oriented 18 inch wide diabase dike. It is difficult to see while driving. To examine it, stop at the resort and walk back to see it.
- Mile 21.2:** Note sycamore tree (hidden spring) on east side of road just before passing entrance to Garlands Resort. On Google Earth imagery there is a major east-west linear to the west that pre-dates Miocene basalt lavas.
- Mile 21.5: Stop 3:** Pull into the one-way entrance into the Halfway Picnic site, immediately past the yellow highway pedestrian sign. A restroom is available. Hike from the parking lot down one of several steep trails west to the bank of Oak Creek. This stop offers a pristine location to observe the effects of two ages of oppositely-directed offset on a fault plane. On the west side of Oak Creek the normally flat lying Permian Schnebly Sandstone has been sharply bent up by east-west directed crustal compression associated with the Laramide orogeny and regional uplift. The Ancestral Oak Creek fault raised the east side up by at least 400 feet (~120 m) relative to the west side.



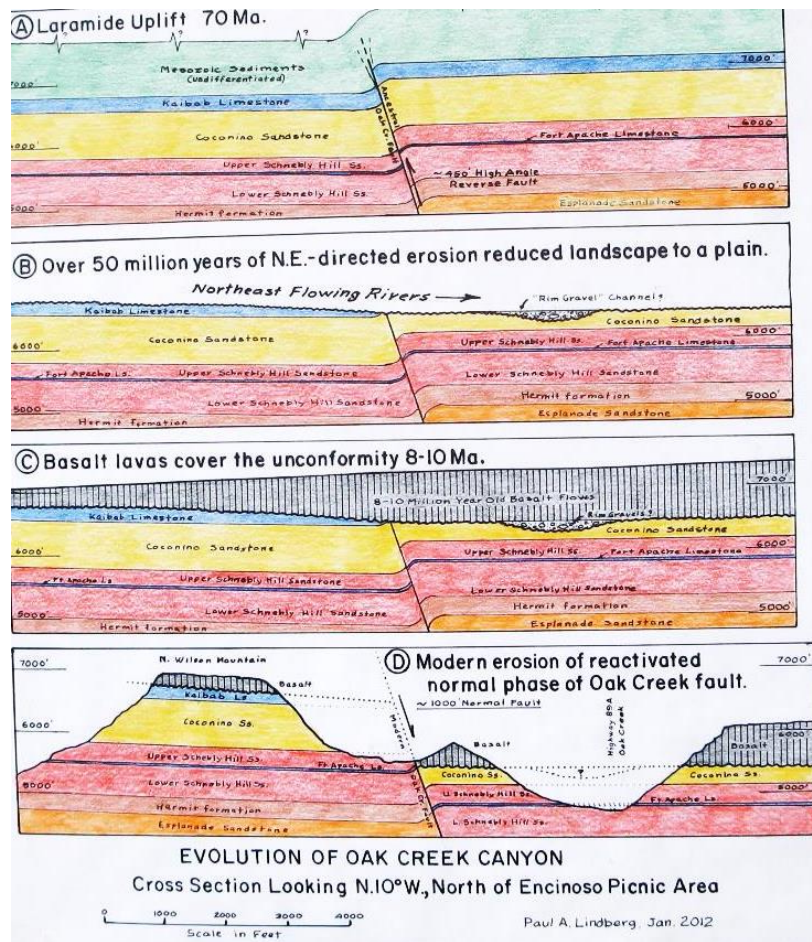
Upturned and partially bleached Schnebly Sandstone along Oak Creek below Halfway Picnic Area. The view looks north and shows compressional folding when the Laramide Ancestral Oak Creek fault shoved the east side up relative to the west side.

During the Laramide orogeny this region was raised up several miles to its current elevation. During that tectonic Episode upwelling connate water, hydrocarbons and possibly hydrogen sulfide was released along the ancestral phase of the Oak Creek fault zone. That fluid dissolved hematite (iron oxide) out of the otherwise red stained Schnebly Sandstone and bleached it to a pure white color, with little volume loss. The small amount of red iron oxide pigment That was dissolved away was later re-deposited higher up in the overlying Coconino Sandstone where it can be found in localized iron oxide replacement zones. A short distance to the east of the picture below is the plane of the modern phase of the Oak Creek fault where Coconino Sandstone was down-dropped on the east side of the fault zone. This location marks the western boundary of the Oak Creek-Mormon Lake graben.



View to south of Ancestral Oak Creek fault immediately east of the previous picture. Note the overturned and severely bleached Schnebly Sandstone caused by the upwelling of connate water bearing hydrocarbons and possibly hydrogen sulfide released from depth during the regional Laramide uplift that began 65-70 million years ago. The modern normal phase of the Oak Creek fault, whereby the east side dropped back down, was reactivated perhaps as recently as 2-3 million years ago. Modern Oak Creek fault lies immediately to the left of this photo where Coconino Sandstone is exposed east of the fault.

- Mile 21.7:** Immediately after re-entering Highway 89A there are vertical beds of bleached white Schnebly Sandstone exposed along the left edge of the roadway pavement just past the concealed plane of the ancestral and modern planes of the Oak Creek fault. Upturned Schnebly Sandstone is exposed immediately to the south. The fault zone heads up to the left (east) side of the canyon as we head to the south.
- Mile 22.4:** Pass Slide Rock State Park on right. Note the bleached Schnebly Sandstone with remnants of normal red-stained rock layers on east side of highway. At this point the fault zone is uphill from those bleached outcrops and not in the bottom of the canyon. Bleached Schnebly Sandstone has been mistaken for Coconino Sandstone at this location.
- Mile 23.1:** The highway crosses the Oak Creek fault once again where it passes through a small gully on the right (west) side of the road. The same bleached sandstone can be seen at this point where the fault zone continues south-southwest uphill to the saddle between the first and second benches of Wilson Mountain.
- Mile 25.5:** Pass through Indian Gardens. [Lunch service and a public restroom are available at this location.] V-shaped Munds Canyon off to the east joins Oak Creek Canyon at this point. Later in the trip, at **Stop 7**, the tour will visit the headwater of Munds Canyon at Munds Park where the drainage breaches a down-to-the-east fault scarp located near the central part of the Oak Creek-Mormon Lake graben. What is of particular interest from a hydrological standpoint is that Munds Park's municipal waste water treatment plant is located at the head of the Munds Canyon drainage. The potential of groundwater contamination from that site into Oak Creek Canyon will be discussed later.
- Mile 26.2:** Final crossing of the Oak Creek fault. To the north the Oak Creek fault has a nearly north-south orientation but at the south end of Wilson Mountain, at the separation of the first and second bench, the fault makes an abrupt turn to the southeast and crosses Highway 89A at a 45 degree angle before resuming a southerly course along Jacks Canyon (see map). Just as in the case of **Stop 3** the southwest side of the fault zone at the highway crossing displays an abrupt fold where Laramide compression has folded Schnebly Hill Sandstone up against the northeast buttress of the fault plane.



Mile 27.0: Pass Grasshopper Point day use area.

Mile 27.6: Cross Midgley Bridge. The highway and bridge deck are situated at the top of the cliff-forming Permian Esplanade Sandstone at this point. The more recessive slope above highway level has been eroded into the softer Permian Hermit formation, a somewhat silty sandstone that weathers more readily than the overlying cliff-forming Schnebly Sandstone that forms the imposing red-colored cliffs on either side of the canyon.

Mile 28.9: As you enter Uptown Sedona you cross the Sedona fault that down-drops the more massive Esplanade Sandstone, crossing into Hermit formation. You leave behind the youthful V-shaped canyons found within the Oak Creek-Mormon Lake graben and enter a more maturely eroded terrain associated with the headward retreat of the northwestern margin of the 10 million year old Verde graben. Most of the Sedona town infrastructure is built upon the recessive Hermit formation that forms a distinctive "bench" that will be discussed at **Stop 4** on Airport Mesa above West Sedona.

Mile 29.5: Double roundabouts where Highway 179 turns south from Highway 89A. Continue straight through roundabouts on Highway 89A and head uphill past outcrops of cut and fill tide flat deposits of Hermit formation.

Mile 30.6: At first traffic light turn left onto road leading up to the Sedona airport.

Mile 31.7: Stop 4: At top of mesa turn left into parking lot and assemble at viewpoint overlooking West Sedona. This viewpoint affords a good look at the imposing Mogollon Rim comprised of the upper portion of the Paleozoic sedimentary rock succession. The rim was formed by headward erosion into the Colorado Plateau along the northwestern margin of the 10 million year old Verde graben lying off to the west. *It should be emphasized that the Mogollon Rim is not the erosional scarp formed from the northeastward retreat of rock strata removed from the Central Arizona Highlands off to the southwest. It did not exist prior to the basin and range generation of the Chino, Verde and Payson grabens.* Note the conspicuous flat "Hermit Bench" upon which West Sedona is located with its more durable cliff-forming Permian strata. Schnebly Sandstone (red colored) is capped by Coconino Sandstone (buff colored) and overlain by grey Kaibab Limestone. Note also the capping of Miocene Basalt on the summit of Wilson Mountain to the north-northeast. The lava flows thin to the west and thicken eastward into multi-layered flows that filled an old post-Laramide river valley that once flowed northerly above present day Oak Creek Canyon and capped the Thomas Point Rim Gravels (refer to note in caption for **Mile 18.9**). The surface of the isolated Airport Mesa is covered by large stream-borne basalt boulders that were much later eroded from the Mormon Mountain area when stream flow carried debris back to the west into the 10 Ma Verde graben depression. Still later westward- and southward-directed erosion carved the now-dry West Sedona and present day Oak Creek water course.

(Stop 4 continued)

Wilson Mountain is a projection of the Colorado Plateau called a horst that separates the more mature eroded terrain within the 10 million year old Verde graben to the west from the estimated youthful 2-3 million year old Oak Creek-Mormon Lake graben to the east. Look to the northeast past Uptown Sedona and observe the down-dropped dark basalt covered surface of the new graben through the notch cut in the horst by Oak Creek where it enters Sedona. Prior to the genesis of the newest graben, surface water that originated from the former high-standing Mormon Mountain highland, up until 2-3 Ma, had flowed over the Mogollon Rim and carved out the expansive series of now-dry valleys you see before you (see the photo of the Mogollon Rim on page 3). The erosional bench that was carved through West Sedona and Dry Creek valleys further north and Margs Draw to the east, once had large amounts of surface water flowing through them between 10 million years ago and 2-3 million years ago when the Oak Creek-Mormon Lake graben dropped, thereby forever cutting off stream flow through West Sedona, Dry Creek valley and Margs Draw that are now totally dry except for seasonal runoff. Only in the relatively recent past has Oak Creek breached the Wilson-Munds-Lee Mountain horst.

Return back down to Highway 89A, turn right and proceed downhill and turn right at double roundabouts to join Highway 179 heading south through the Chapel area.

Mile 42.5: Stop 5: Turn left into Bell Rock Pathway parking area on the north side of the Village of Oak Creek. At this location there is a distinct contrast between the high cliffs on the north side of the valley from the basalt capped lower cliffs on the south side of the valley. The valley bottom is composed of relatively incompetent Permian Hermit formation that results in a similar erosional bench as seen from the airport overlook above West Sedona. On the north side of the Village of Oak Creek is prominent Courthouse Butte composed of Permian sedimentary strata. The competent cliffs are composed of reddish colored Schnebly Sandstone, buff colored Coconino wind-blown quartz sandstone and a capping of grey Kaibab Limestone. In contrast, the south side of Village of Oak Creek displays lower cliffs that are capped by Miocene basalt lava flows covering a severely truncated Permian section that shows only Schnebly Sandstone and thin remnants of basal Coconino Sandstone. The interpretation is that during the Laramide uplift the east side of the Oak Creek and Jacks Canyon fault was raised up under compression. The southern end of the ancestral Jacks Canyon fault curves westward through the axis of the valley occupied by the Village of Oak Creek and diminishes in offset where it reverses motion and heads northwestward as the Cathedral thrust fault (see map). Following the Laramide regional uplift there were numerous stream channels directed in an overall northeasterly direction across this region. After a prolonged period of erosion that eventually removed the Paleozoic sedimentary formations and bared Precambrian rocks in the Central Arizona Highlands off to the southwest, northeast flowing streams removed all of the Kaibab Limestone and nearly all of the Coconino Sandstone from the east and south sides of the ancestral Oak Creek and Jacks Canyon fault zones up through about 14.3 -14.6 Ma. That profound erosion surface was coursed by sinuous stream channels filled with "Beavertail Gravels" that contain Precambrian rock clasts plus basal Paleozoic rocks. Those gravels are contemporaneous in time and composition with "Rim Gravels" found on top of the Colorado Plateau surface to the northeast where the conglomerates are capped by Miocene basalt flows that began erupting ~15 Ma as part of the Hickey Basalt and House Mountain basalt flow cycles except that volcanism lasted longer along the Interstate 17 corridor. By age-dating only the topmost end members of the volcanic cycle, and not its much older basal lava flows, many geologists have interpreted that the "plateau basalts" are a much younger volcanic cycle that are independent from the Hickey Basalt at Jerome and the House Mountain volcanic succession southwest of Sedona (Holm and Cloud, 1990 and Holm, 2001). This report contests that conjecture. Basalt caprock covers "Beavertail" and "Tertiary Gravels" on the western and central part of the Verde Valley to the west where they crop out or have been drilled into at wildly different elevations in numerous basin and range fault blocks. The onset of volcanism underlying the Interstate 17 highway corridor also began erupting over 14 Ma as exposed at the base of the thick pile of basalt flows exposed in Munds, Woods and Rattlesnake Canyons to the east (Billingsley, 2015). Only the topmost end member flows that have been dated yielded ages of 6-8 Ma. Therefore, the so called "ramp volcanics" underlying I-17 are not an independent volcanic cycle but are the continuation of Hickey and House Mountain age basalt eruption cycles that have migrated eastward over time. Once the Oak Creek-Mormon Lake graben dropped ~2-3 Ma, the ancestral phase of the Oak Creek and Jacks Canyon faults were reactivated as normal faults, thereby dropping the eastern and southern sides of the new graben to the elevation we now see on the south side of the Village of Oak Creek.

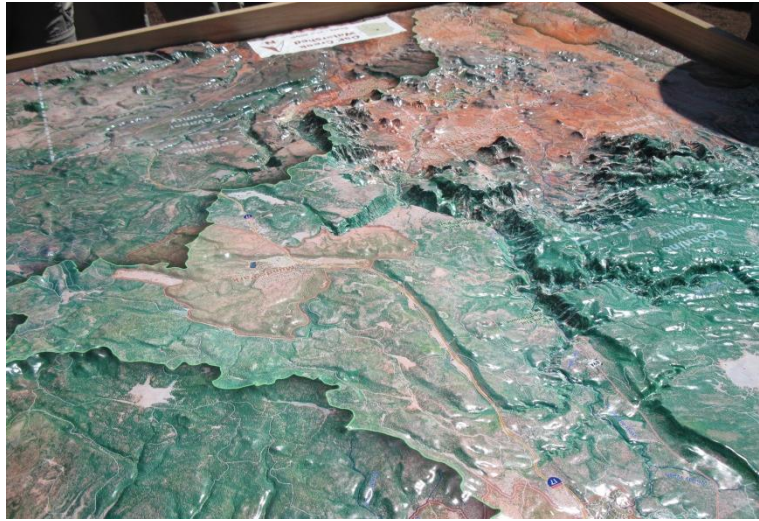
Return to Highway 179 and proceed south through the Village of Oak Creek into the down-dropped rocks of the Oak Creek-Mormon Lake graben.

Mile 44.5: Pass Red Rock Ranger Station and visitor center on left.

Mile 48.0: Stop 6: Turn to right (unmarked turnoff just before highway curves to left) into old stage stop parking area. To the northwest is prominent Beavertail Butte capped by Miocene basalt flows whose base yielded a K-Ar age of 14.3 Ma (Lindberg, 2006). It caps conglomerate bearing Precambrian clasts and abundant Mississippian Redwall Limestone clasts derived from former landforms lying well off to the southwest. At this field trip stop the present land surface lies within a thick Beavertail Gravel filled meandering erosion channel that is oriented in a southeasterly and northeasterly direction toward the Interstate 17 corridor to the east.

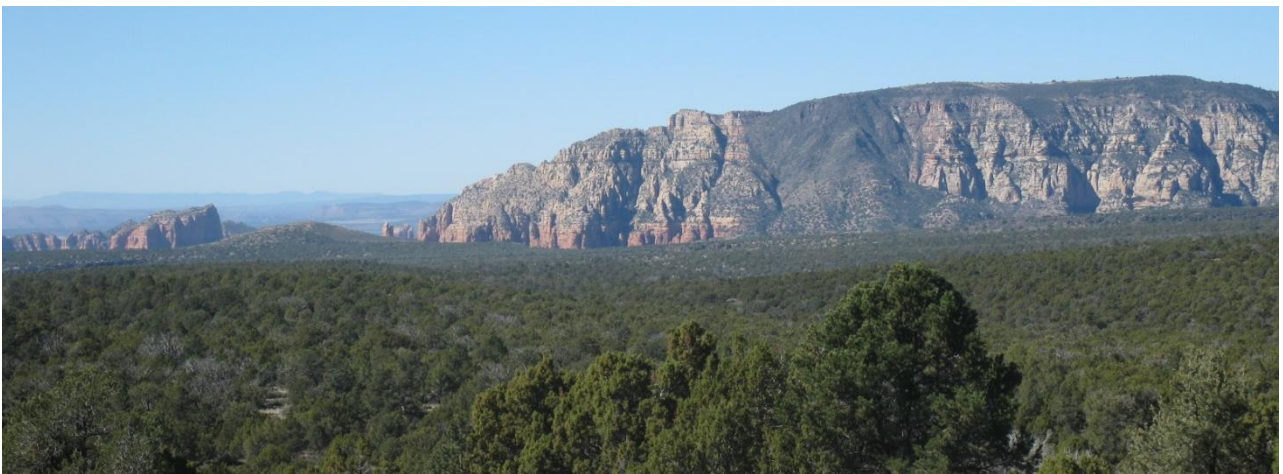
Mile 51.1: Join Interstate 17 and head north toward Flagstaff. The entire highway surface lies on a wide corridor of basalt that forms the surface of the Oak Creek-Mormon Lake graben. The route climbs the south-dipping thick succession of Miocene basalt flows all the way north to the hamlet of Mountaineer where the basalt flow thins to a single topmost flow. From there northward Kaibab Limestone is exposed the rest of the way into downtown Flagstaff.

Mile 75.0 at Exit 322 into Munds Park, Stop 7: Turn right into Munds Park and pass by two gas stations and turn right onto Fairway Road alongside golf course. Go to end of road to Pinewood Sanitary District wastewater treatment plant. The plant is located at the headwater of Munds Canyon that crosses under the interstate bridge a short distance to the south. Note the northwest-southeast Munds Park fault scarp to the southwest through which the head of Munds Canyon has been cut through. To the east there is a confluence of drainages that converge from the north, east and southeast to form the head of Munds Canyon that ultimately enters Oak Creek Canyon at Indian Gardens (at **Mile 25.5**). Prior to the drop of the Oak Creek-Mormon Lake graben the 8450 foot high (2575 m) Mormon Mountain may have been more than 3000 feet higher (+900 m), thereby once capturing substantially more precipitation than it currently does (see map). While the possibility may be remote, as Munds Park infrastructure grows there is a potential risk of wastewater contamination that could escape into Munds Canyon and downstream Oak Creek Canyon and Sedona in future years.



Oak Creek Watershed Council terrain model viewed to southwest. The model shows the Oak Creek watershed (highlighted) as well as the Interstate 17 corridor down the core of the Oak Creek-Mormon Lake graben along the eastern side of a prominent down-to-the-east Oak Creek fault scarp. The relatively smooth surface of the new graben sharply contrasts with the deeply eroded Sedona area (top right of photo) and the serrated Mogollon Rim rocks. Prominent Oak Creek fault, starting at lower right corner, heads south with a dog-leg over to Jacks Canyon fault before curving west into Village of Oak Creek.

Return to Interstate 17 and head south, crossing bridge over head of Munds Canyon. Note the similar down-to-the-east fault scarp as we cross over the narrow head of Woods Canyon further down the freeway.



View to west from Interstate 17 at the Munds-Lee Mountain horst south of Munds Park. The basalt lava surface of the Oak Creek-Mormon Lake graben (tree covered) is dropped against the Munds-Lee Mountain horst along the Jacks Canyon fault. Behind the horst is the 10 Ma Verde graben.

- Mile 86.5 near Milepost 313, Stop 8:** Pull over to viewpoint on tight. This stop affords a good view back to the west of the boundary between the Oak Creek-Mormon Lake graben that we are standing on and the high standing Lee and Munds Mountain horst that separates the younger graben from the older 10 Ma Verde graben off to the west. The down-dropped graben block we are standing on continues to drop steadily southward to the Camp Verde area where it merges with the older Verde graben that is many thousands of feet deep and filled with Verde Lake beds and surficial salt beds.
- Mile 9.3 near Milepost 306:** Turn right at the Stoneman Lake exit and proceed east under the freeway toward Stoneman Lake. The paved road eventually turns into a dirt road further on but is negotiable to any type of vehicle.
- Mile 97.1:** Apache Maid Mountain, off to the south, was a major source of black obsidian used by prehistoric natives to make projectile points. Turn left at road junction onto Forest Road 213 toward Stoneman Lake.
- Mile 101.1, Stop 9:** Turn left into parking area above Stoneman Lake. A restroom is available at this site. This large depression is a bit of a mystery. It appears to be a closed near circular graben within a much larger graben. The 4450 foot (1360 m) wide depression is greater than 325 feet (>100 m) deep on its northern edge. Some have proposed that it was formed as the result of a collapse from dissolution of underlying limestone strata but the writer considers this to be highly improbable. One reason is that the sheer volume of drop is greater than the combined thicknesses of projected Paleozoic limestones in the subsurface and secondly, if there was an extensive intrastratal karst channel system in the subsurface it would be prone to drain quickly. The fact that in some wetter years there is a lake at this location that could last all summer suggests that the collapse was due to subsurface outflow of basalt lava and not from subsurface limestone dissolution. This site was a well-known water hole in the past. Major indian trails and an early stage route passed by this spot. Continue east on road.
- Mile 107.1:** Junction with paved Lake Mary Road. A few miles to the south of this point is the newly constructed Discovery Telescope perched atop a small youthful cinder cone. The photo below shows a basalt flow capped layer of un-welded volcanic tephra at the road junction. Turn north toward Mormon Lake.



Basalt lava capped layered volcanic tephra at junction of Stoneman Lake and Lake Mary Roads.

- Mile 119.7, Stop 10:** Turn left onto viewpoint overlooking Mormon Lake. Depending upon seasonal precipitation this can either be dry or filled as a shallow lake. The viewpoint is at the brink of a 200 foot (60 m) high fault scarp that marks the eastern margin of the Oak Creek-Mormon Lake graben. Seventeen miles (27 km) to the east is the Oak Creek fault that was examined at the Halfway Picnic area (**Mile 21.5**) that forms the western graben boundary. Mormon Mountain to the west of this point, prior to the collapse of the graben, was once much higher than its present day 8450 foot (2575 m) elevation. Prevailing westerly winds would have made this volcanic mountain and its associated northwest and southerly ridge line as a focus for intensified rainfall before graben collapse. The eastern boundary of the Oak Creek watershed is at the summit of Mormon Mountain. The edifice still provides a significant westward water recharge for the Oak Creek and Verde Valley watersheds. Thirty miles (48 km) to the west-northwest of this stop is the imposing San Francisco Peaks volcano at 12,633 feet (3851 m). The genesis of the Oak Creek-Mormon Lake graben 2-3 million years ago may well be contemporaneous in timing with the main stage eruption of the San Francisco Peaks volcano. At its maximum height prior to about half a million years ago the peak would have been the highest mountain in the Lower 48 states. About half a million years ago it blew off several thousand feet of its summit rocks, thereby reducing its moisture collecting ability. Between 3.0 and 0.5 million years ago the peaks would have had sufficient year-round surface runoff that would have flowed over the Colorado Plateau surface and help to carve out the many now-dry valleys that surround the Sedona area below the Mogollon Rim along the northeastern side of the Verde graben.



View to north from Mormon Lake overlook. This youthful fault scarp forms the eastern margin of the Oak Creek-Mormon Lake graben. Twenty miles (32 km) to the north-northwest is the town of Flagstaff at the northern end of the new graben and ten miles (16 km) further are the San Francisco Peaks that rise a mile (1.6 km) above the Colorado Plateau surface.

Continue north on Lake Mary Road.

Mile 126.6: Upper Lake Mary reservoir on left. Note northwest-southeast fault scarp toward the east.

Mile 131.3, Stop 11: Stop on left opposite Upper Lake Mary dam. To the northeast is a 400 foot (120 m) tree covered fault escarpment marking the margin of the graben (see map). Observe the down-dropped basalt lava outcrop on the east side of the highway and the light colored Paleozoic sedimentary outcrops higher on the hill to the north.

Continue a short distance north on Lake Mary Road.

Mile 132.2: Turn right on Marshall Lake Road 129 leading uphill and stop at the first switchback.

Mile 132.7, Stop 11: Stop at switchback and view the Lake Mary fault that drops Miocene basalt lava against Permian Kaibab Limestone on the uphill side. The fault zone is vertical with calcite veining cutting through the fault gouge.



Lake Mary fault on the first switchback up Marshall Lake Road 129. Permian Kaibab Limestone on the uphill (northeast) side and down-dropped Miocene basalt lava on the down-dropped (southwest) side. Fault displacement is unknown but probably exceeds 350 feet (>110 m). This marks the northeastern margin of the Oak Creek-Mormon Lake graben.

Mile 133.7: Continue uphill to top of plateau. A USGS observatory and other instruments are located to the south. Turn around. On the way back down the road are good views of Mormon Mountain highland to the southwest. After the Oak Creek-Mormon Lake graben dropped by several thousand feet Mormon Mountain may have once been as high as present day San Francisco Peaks and capable of capturing much more precipitation than it does today.

Mile 135.3: Rejoin Lake Mary Road and head northwest below the Lake Mary fault scarp.

Mile 137.6, Stop 12: Permian Coconino Sandstone is exposed on the right roadcut. Further up the cliff face is Kaibab Limestone and basalt cover. There is no evidence here of possible Toroweap formation.

End of tour.

To return to High Country Convention Center, head north on Lake Mary Road to Beulah Boulevard and turn north to Forest Road and turn right for one block to Milton Road. Turn left and go north on Milton Road to the High Country Convention Center.

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Comment:

This summary compliments the excellent field work and age dating by Holm and Cloud but hopes to add a proposed new dimension to their findings. There is still much to learn about the geologic history of the Mogollon Rim country.

Post-trip recommendation:

If travelling either north or south along Interstate 17 into Verde Valley an additional stop is recommended. Pull off on Interstate 17 Exit 288, park, and look back at the view shown on page 1 of this field guide. The contrasting elevation difference of the down-dropped Oak Creek-Mormon Lake graben and the prominent Wilson-Munds-Lee Mountain horst becomes readily apparent. The view from this viewpoint near Camp Verde is most instructive.