The Peach Spring Tuff, its source caldera, and implications for structural geology of the Colorado River Extensional Corridor

View to the northwest from the crest of the Black Mountains, near Oatman, Arizona. The Gold Road Mine in the foreground is near the head of Silver Creek, which flows to the west through the middle of the Silver Creek caldera, source of the 18.8 Ma Peach Spring Tuff. Photo by Charles Ferguson https://arizonageologicalsociety10.wildapricot.org/

We promote and encourage interest in the science of geology and in the geology of the State of Arizona.

Arizona Geological Society 2016 Fall Field Trip

The Peach Spring Tuff, its source caldera, and implications for structural geology of the Colorado River Extensional Corridor

by
Charles Ferguson

Dedicated to Nick Priznar
July 26, 1952 – May 16, 2014

Introduction
The 18.8 Ma Peach Spring Tuff's presence over nearly 20,000 km^2 of the southern Basin and Range province makes it the principal strain and time marker in one of the world's most intensively studied extensional belts (Glazner et al.,1986). After decades of intensive study however, the search for its source caldera yielded nothing. Then, during a routine, 2006 highway survey suggested and funded through the vision of ADOT geological engineer Nicolas M. Priznar. the elusive caldera was identified by Arizona Geological Survey geologists along the eastern edge of the Colorado River Extensional Corridor (CREX) near Oatman, Arizona.

New discoveries directly descendent from Nick Priznar's vision are impressive. Continued mapping (Pearthree et al., 2009) showed that the caldera's rim near Oatman, now deeply eroded, projects to about 1,400 m above sea level. Two fragments of the caldera rim at 600 m and 700 m above sea level were soon discovered riding in the hangingwall of the Sacramento Mountains detachment fault in California 40 km southwest of Oatman (Ferguson et al., 2013; Ferguson and Howard, 2014). The resulting 215° azimuth extension vector is a perfect match to slickenline lineations on the Sacramento detachment fault (Simpson et al., 1991), but at least 45° more southerly than the previous regional extension direction estimates based on weighting westerly mylonite fabric >> northerly Miocene dike orientations in the footwall (Campbell-Stone et al., 1999; Pease and Argent, 2000; Pease et al., 2000). The plutonic emplacement component of the total extension seems to have been undervalued.

Concurrent and continuing detailed petrologic, mineralogic, and chemical analyses of the intracaldera ignimbrite, its associated volcanics, and hypabysaal plutonics have created a new understanding, and posed new questions, regarding how so-called "supereruption" magma chambers evolve, erupt, and crystallize (Pamucku et al 2013; McDowell et al, 2014, plus 30 student abstracts at the last 3 GSA annual meetings).

This field trip focuses on the Peach Spring Tuff, its caldera, how the caldera did or did not influence gold mineralization in the Oatman district, and how the caldera, between 18.5 and 15 Ma, was structurally dismembered and tectonically strewn out across a wide expanse of the CREX.

History of investigation
That a major silicic caldera played a lead role in the evolution of the Oatman epithermal gold district is nothing new. John Thorson (1971), under the direction of Cliff Hopson at the University of California, Santa Barbara, very accurately and convincingly described breccias within a monotonous pile of trachytic volcanic rocks near Oatman that could only have formed inside a caldera. Based on the stratigraphy of Ransome (1923), Thorson's (1971) caldera fill was thought to

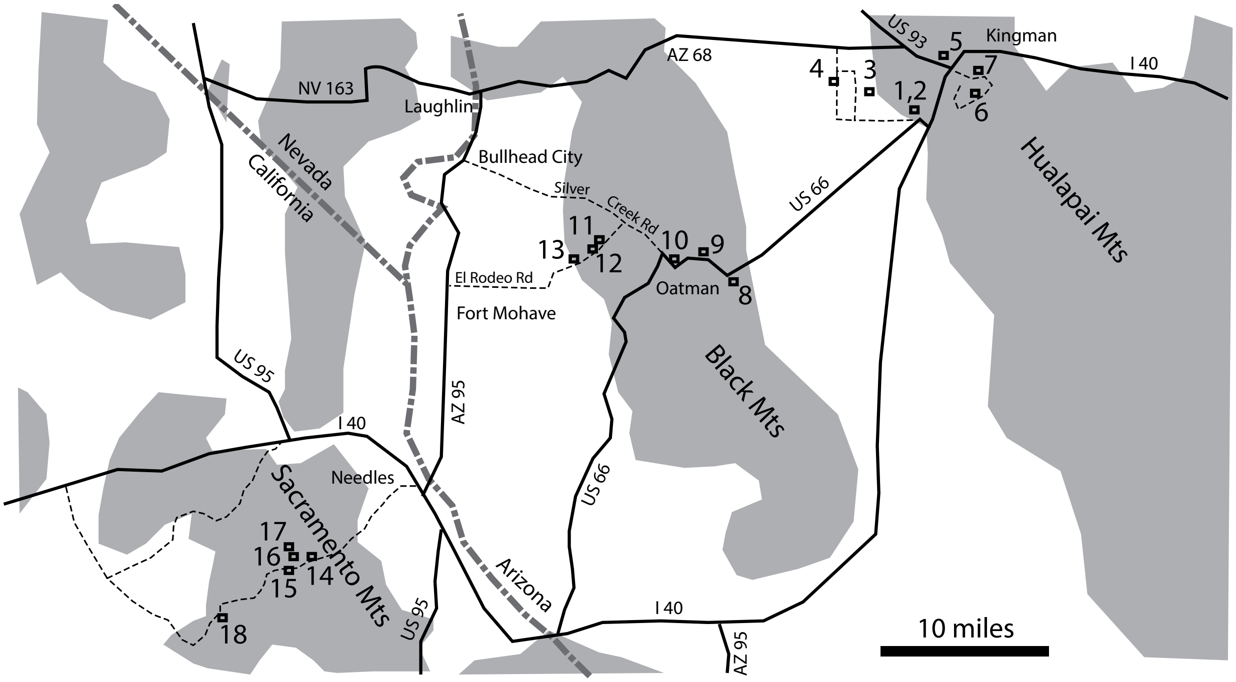


Figure 1 Arizona Geological Society fall, 2016 field trip route. Stops 1-7 are on day 1 with stops 1-3 requiring 4WD and some hiking. Stops 1 and 2 are in Laramide dikes and mineralized Proterozoic basement rocks. Stop 3 is a lithic swarm in the upper Peach Spring Tuff. Stops 4-7 are concerned entirely with stratigraphy of the Peach Spring Tuff, and do not require 4WD or significant hiking. Stops 8-13 constitute a 2WD traverse of the Black Mountains on day 2 (full day) that starts in post-caldera volcanics on the east side of the range and concludes along the western foot of the range along the Silver Creek caldera margin in Times Gulch. Stops 14-18 constitute a 4WD traverse of the Sacramento Mountains, California concerned mainly with intracaldera Peach Spring Tuff exposures along the Eagle Wash road.

be the basal volcanic unit in the range, and therefore the "oldest" volcano in the pile. Even though the study of large silicic calderas was, at that time in its infancy, it was universally accepted that big calderas were always erupted into a precursor lava field. Thorson recognized this as a problem and discussed it at some length in the appendix to his 1971 Ph.D. dissertation. His caldera was therefore regarded with some suspicion in the geologic community, especially since the only major ignimbrite he could point to that might represent the caldera's "supereruption" producing ash-flow was the conspicuous cliff-forming ignimbrite at Kingman that Young and Brennan (1974) were soon to name the Peach Springs Tuff. The cliffs at Kingman are clearly rhyolite, overlie a thick volcanic pile, and resemble not the dense, trachytic intracaldera ignimbrite west of Oatman.

As will be seen on this field trip, the dark, dense, phenocryst-rich (34%) caldera-filling trachyte ignimbrite near Oatman looks nothing at all like the light, moderately phenocryst-poor (2-15%) rhyolite ignimbrite that constitutes over 99% of the Peach Spring Tuff's outflow sheet. But Thorson was right. The phenocryst ratios in the Peach Spring Tuff at Kingman, subsequently reported by Young and Brennan (1974) are nearly identical to the ratios he had reported in 1971 for the intracaldera trachyte ignimbrite near Oatman. The ratios are somewhat unusual and usefully unique (K-feldspar >> plagioclase and virtually no quartz). Keying on the "uniqueness of the phenocryst assemblage" argument stressed in Glazner et al.'s (1986) discussion of why mapping the Peach Spring Tuff was so important, Ferguson (2008) suggested that Thorson's intracaldera trachyte ignimbrite was the Peach Spring Tuff, and consequently, that it was not the oldest volcano in the pile. Concurrent mapping efforts (Pearthree et al., 2009) confirmed that the intracaldera ignimbrite was not the oldest unit in the volcanic pile. Instead of underlying a thick pile of dacitic lavas at the western base of the Black Mountains, the trachyte ignimbrite overlay these rocks along an arcuate, west-facing, buttress unconformity that delineated the caldera's eastern margin. Subsequent detailed study of the Peach Spring Tuff in the southern Black Mountains in cooperation with Calvin Miller and his Vanderbilt University based research group showed that the outflow sheet, previously thought to be rhyolite from top to bottom, was in fact strongly zoned with a thin, phenocryst-rich trachytic cap essentially identical to the intracaldera trachyte (Ferguson et al., 2013, Pamucku et al., 2013). Until recently, the uppermost phenocryst-rich trachyte zone was thought only to be present in remote areas of the southernmost Black Mountains. Recent mapping by the Arizona Geologic Survey west of Kingman (Ferguson and Cook, 2016a,b, 2017) identified the uppermost trachyte in isolated hogbacks in Golden Valley, and in the eastern foothills of the Black Mountains.

Synopsis of the field trip

The route of the field trip is shown in Figure 1. Estimated travel times and stop durations in minutes are given throughout the log.

Day 1

Highlights of new maps of the Kingman area (Ferguson and Cook 2016a,b) illustrating the volcanic stratigraphy of units above, below, and including the Peach Spring Tuff are the focus of Day 1 and can be done in a half day (afternoon) with 2WD vehicles. Supplemental stops to make it a full day, with visits to the area's Paleo-, Meso-, Neo-Proterozoic, "Laramide", and mid-Tertiary plutonic rocks, are provided at the start of the road log. These stops require 4WD.

Day 2

Day 2 is a full day trip for 2WD vehicles that starts with two stops in pre- and post-caldera (19-16 Ma) silicic lavas of the Snaggletooth, and Patsy Mine volcanics tilted gently to the west, and erosionally overlain by flat-lying conglomerate and mafic lava (~15-10 Ma) of the Mt Davis Volcanics on the east flank of the Black Mountains. The dip of westerly tilted older rocks, bounded by east-side-down faults, decreases towards the crest of the range and gradually, the same age rocks become gently east-dipping on the west side of the range. Here, the easterly tilt, accommodated by west-dipping faults is demonstrably younger. Just west of the range crest at Sitgreaves Pass, one of the westernmost east-side-down older faults is intruded by the famous Gold Road vein. The vein is visited in mid-morning, and shown by analogy with similar veins in Oatman to be cut by west-side-down faults in the west part of the range.

The second day concludes with a tour of Silver Creek caldera's west-facing caldera margin along Times Gulch with 3 stops: **1)** at an important lacustrine limestone that defines the contact between the two main pre-caldera lavas exposed in the caldera wall, **2)** a visit to the northwest-facing caldera margin, almost everywhere else a recessive contact buried by alluvium, preserved between two intrusive contacts at the Times - Big Lode Mine complex, and **3**) another exposure of the caldera margin, facing north, where basal Mid-Tertiary conglomerate overlying Proterozoic granite basement is exposed in the caldera wall and stitched by a pair of cross-cutting dikes.

Day 3

Day 3 requires 4WD and can be a full day, or if a hike to view an unconformity interpreted by Spencer and Turner (1983) and McClelland (1984) as a detachment fault is skipped at Stop 17, travelers within 200 hundred miles of home can reasonably return on the same day. Day 3 starts with Stop 14, a view or hike to the unconformity (that is probably the same as the one at Stop 17) that underlies the 14.1 Ma Eagle Peak Rhyolite where it overlies chloritic altered gneissic basement in Eagle Wash of the Sacramento Mountains, California. The unconformity had been interpreted as a post-14.3 Ma, low-angle detachment fault (McClelland, 1984). Next**,** an undisputed low-angle fault is visited farther up Eagle Wash (Stop 15) where a hangingwall of >18.8 Ma limestone-bearing lacustrine volcaniclastic rocks is juxtaposed with a footwall of chloritic altered gneissic basement. At the next stop (16) the same >18.8 Ma volcaniclastics are seen to underlie, and/or occur as megablocks within a large expanse of Peach Spring Tuff meso- and mega-breccia. Also at Stop16, an important megablock outcrop of pre-caldera andesitic lava clearly floating within the matrix of mesobreccia Peach Spring Tuff is visited. Then, 3km to north, mesobreccia Peach Spring Tuff is observed carrying megablocks of "welded outflow" Peach Spring Tuff which grades to the north across a <1 km stockwork-like transition zone into massive, continuous Peach Spring Tuff outflow (Stop 17). The exposures at Stop 17 are interpreted to overlap the south-tilted hinge of a southeast-facing, trap-door margin of the caldera. A gently dipping contact above exposures of the trap-door hinge that has been interpreted as a detachment fault can be visited. Finally, a fault repeat of the same south-to-north, intracaldera-to-outflow Peach Spring Tuff facies transition is

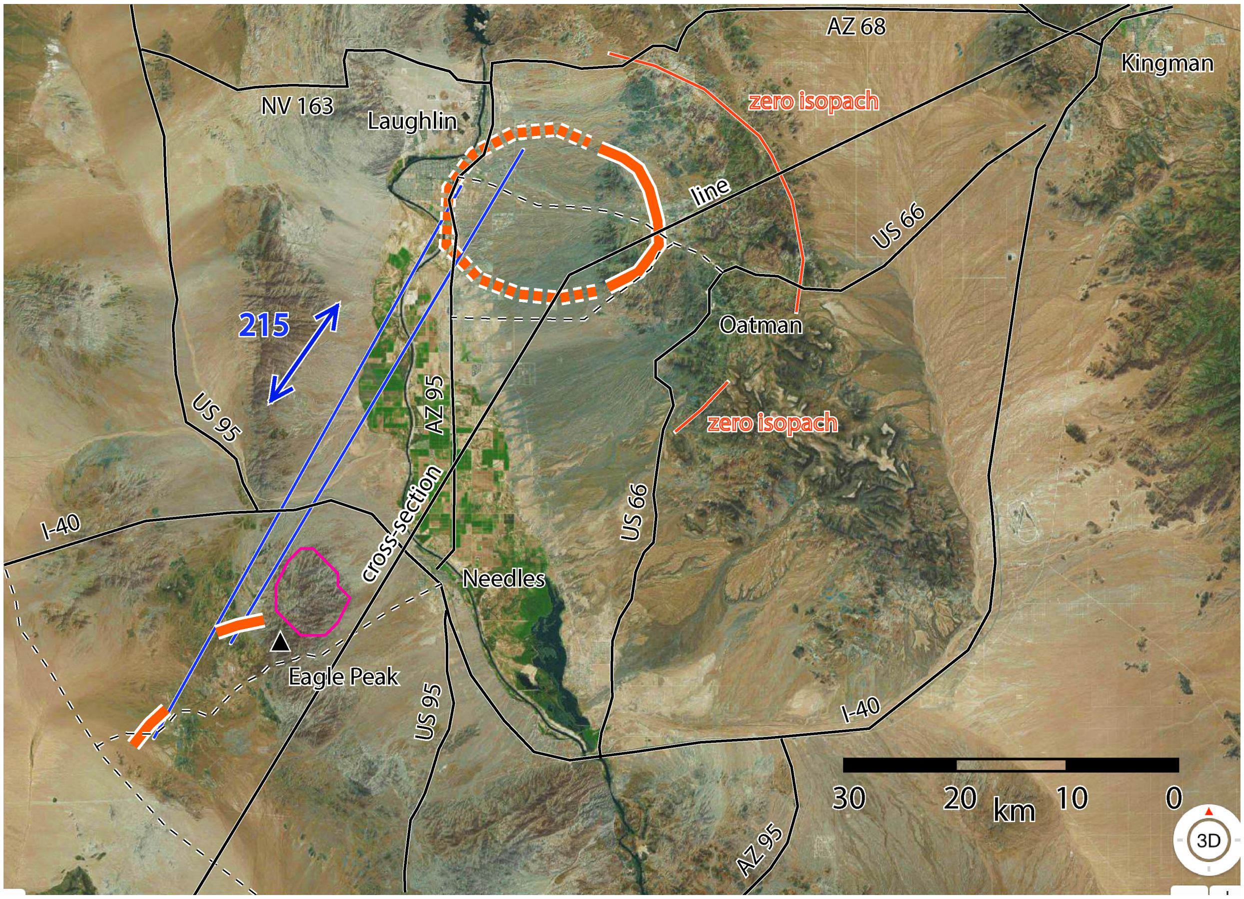


Figure 2a Satellite image of the Kingman, Arizona, Laughlin, Nevada, Needles, California region showing known caldera margin segments of the 18.8 Ma Silver Creek caldera in solid red. Outline of the 18.8 Ma Eagle Wash mesozonal pluton is shown in purple. The dashed margin in Mohave Valley is a reasonable, pre-extension (with respect to the Black Mountains) configuration of the caldera. Blue lines represent extension vectors across Mohave Valley for the two southeast-facing caldera margin segments in the Sacramento Mountains. The 215° vector represents the average of slickenline lineations on low-angle normal faults near Eagle Peak in the Sacramento Mountains. The zero isopach line for outflow Peach Spring Tuff in the Black Mountains is also shown.

visited along the southwestern margin of the Sacarmento Mts. The two southeast-facing (ie. northwestern) caldera margin segments in the Sacramentos are treated as strain markers that indicate an extensional vector plunging 1° towards 215°, for this part of the CREX (Figure 2a). That a tectonically exhumed granodioritic pluton (Pease et al, 1999) of identical (18.8Ma) age is present in between the dismembered fragments and the main caldera at Oatman supports a cross-section and reconstructed cross-sectional view of the crust in this area (Figure 2b) that differs markedly from the conventional view of extension in this area.

Optional Stops in the Kingman area

Because Stop 2 of the field trip requires travel on an extreme 4WD road (it would be best visited using ATVs), a list of optional stops are provided in the South Kingman area that can be visited instead.

Directions to Stop O-1: 10-15 minutes

Take the Shinarump Road exit on I-40. Go southwest on the eastern frontage road 1.7 miles and turn east onto a gravel road that takes you under the railroad tracks, and turn southwest on the road that parallels the southeast side of the railroad tracks for 0.2 miles. Then turn southeast and drive 0.5 miles to the other railroad underpass. Drive under the tracks and turn northeast on a road that parallels the southeast side of the railroad tracks 0.35 miles to a pipeline road that intersects your road (and the tracks) at a 20 angle. Turn northeast onto the pipeline road and take it 1.9 miles, crossing several Laramide dikes on the road, the

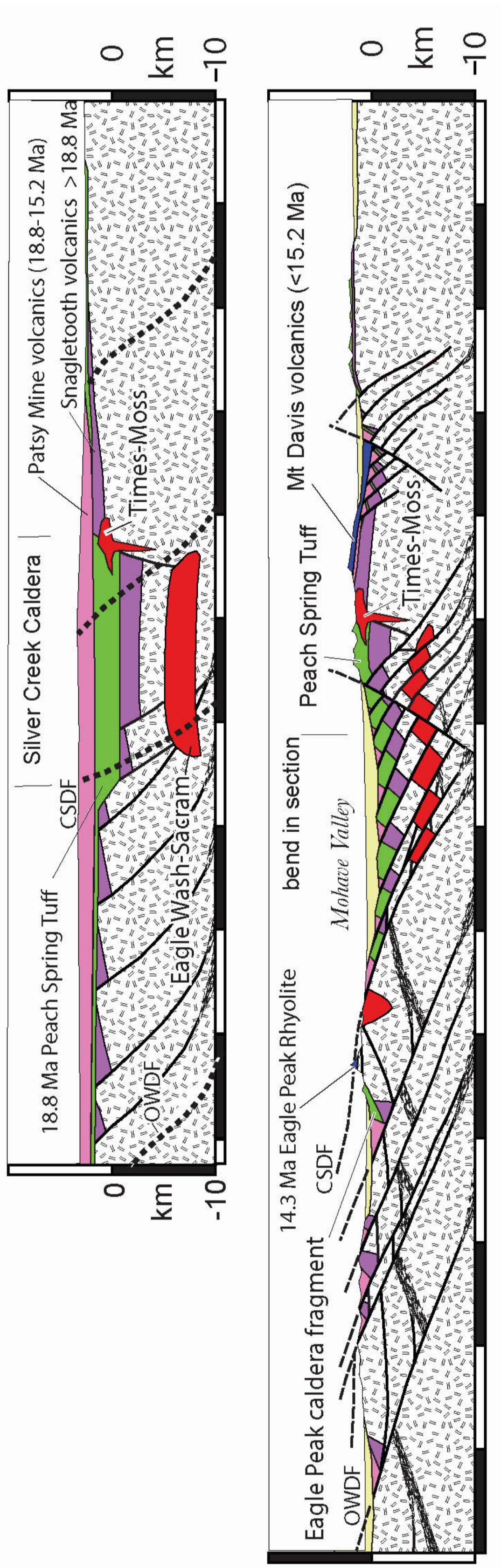


Figure 2b Cross-section from Kingman through the Oatman area, and bending south- southeasterly through Needles showing how ~18.8 Ma plutonic rocks in the Sacramento Mountains northeast of Eagle Peak might be parts of the sub-caldera pluton responsible for the Peach Spring Tuff supereruption. Restored (upper) cross-section corresponds to a time just after formation of the caldera. CSDF=Chemehuivi Sacramento Mts detachment fault. OWDF=Old Woman detachment fault.

thickest of which form resistant ridges that are a bit challenging to cross. Use caution. After 1.9 miles, turn to the right onto a power line service road and go 0.2 miles south to the base of a tower. Park and follow route delineated on the imagery and geologic map of Figure 3 for stop 0-1.

Stop O-1 Metasomatic contact zone in Proterozoic crystalline rocks A: 90-120 minutes

This hike includes a scenic hike into a wonderland of perched tors, narrow slots, and stockwork maze complex in coarse-grained megacrystic granite (red) that concludes (or starts) with crossings of its

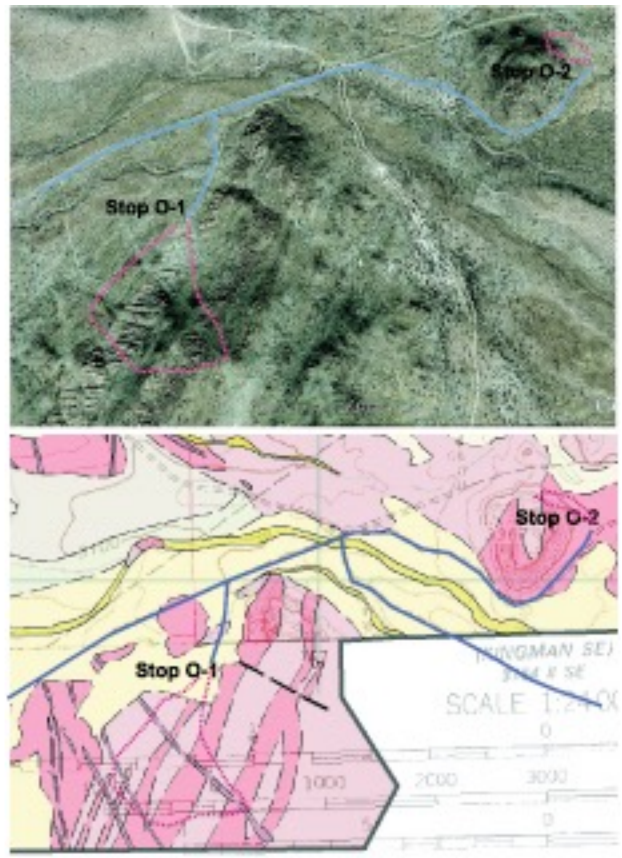


Figure 3 Satellite imagery and detailed geologic map for Stops O-1 and O-2. Roads in blue, hikes in red.

gradational contact with banded gneiss (pink). The gradational "metasomatic" contact is illustrated in Figure 4 (UTM NAD83 3890252N, 766468E). The sample location for Kessler's (1976) 1335 +/- 35 Ma Rb/Sr date of the coarse-grained granite is near here.

Directions to Stop O-2: 15-20 minutes from the start of directions to Stop O-1

Figure 4 Metasomatic contact between coarse-grained megacrystic granite and banded gneiss from an area of nearly 100% outcrop along the hike of Stop O-1.

Return to the pipeline road and continue northeast 0.2 miles to a four-way intersection. Take the southeast road and drive 0.6 miles around the south end of prominent knob and park near the north end of that knob.

Stop O-2 Metasomatic contact zone in Proterozoic crystalline rocks B: 10-30 minutes

The megacrystic granite is beautifully exposed around the base of this steep knob. On the north slope of the knob, just a few meters from the road, both gradational "metasomatic" and sharp intrusive contacts with the gneiss are exposed (Figure 5).

Directions to Stop O-3: 35 minutes from the start of directions to stop O-1

Return to the four-way intersection, and turn south (left) onto road that goes southwest along the crest of an interfluve. Take this road for ~1.2 miles, cross the wash, and within 0.1 mile turn north. Go 0.4 miles and turn left (north) for 0.15 miles and stop at the mine dump. Hiking route from here is shown in Figure 6.

Figure 5 Intrusive contact between coarse-grained megacrystic granite and banded gneiss at Stop O-2. Photos courtesy of Roy Grieg.

Stop O-3 Diabase "sills" near Holy Moses mine: 90-120 minutes

A diabase dike cutting granite and gneiss in this area is oriented acutely to the sub-Cenozoic unconformity. The gently east-dipping dike, oriented as if it were emplaced as a sill, occurs several meters below the unconformity and pieces of it occur abundantly in dumps related to this small mining district which is probably related to monzonitic dikes of probable Laramide age in the area. In some prospected areas to the north, the dike is preserved as a several meter-thick slab of gently dipping diabase whose down-facing contact is clearly intrusive into the granite-gneiss crystalline basement. Its upper contact with Cenozoic lava is poorly exposed and might also be construed as intrusive. Of course the contact is actually a regolith overlain by lava, and proof that the lava's basal contact is depositional (which is not obvious in almost all exposures at this locale) is by tracing the contact to the south, upslope, where the dike's upper contact is with granite and gneiss.

Diabase dikes oriented nearly parallel to the sub-Cenozoic unconformity, are quite abundant throughout the Colorado River Extensional Corridor (CREX) and are the subject of a Keith Howard (1991) paper that convincingly argues that the myriad of steeply dipping diabase dikes which crop out abundantly in highly extended parts of the

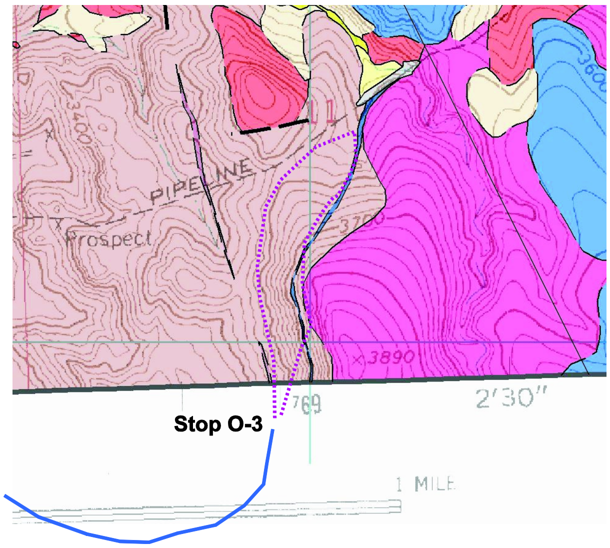


Figure 6 Geologic map for hike at Stop O-3.

CREX were tilted into that position during Cenozoic extension. According to Howard (1991) they were originally emplaced as horizontal sheets at depths ranging between 1-13 km into crystalline basement during a phase of compression approximately 1.1 Ga. Since the basement of the CREX is nearly everywhere granitic or gneissic, the dike's original orientation's are unknown. According to Howard (1991), because a similar suite of diabase intrusions occur as sills (intruding Mesoproterozoic stratified rocks) in areas to the northwest and southeast of the Kingman Arch, it is likely that the diabase dikes in the CREX, most of which are currently steeply dipping, were emplaced originally as horizontal "sill-like" dikes. Of course, since the dikes are only seen intruding Paleoproterozoic crystalline rocks in the Kingman area, it is conceivable that some or all of them could be as young as Upper Cretaceous, the approximate age of the monzonitic dikes of probable Laramide age which intrude the diabase dikes in this area.

Day 1 Morning Stops 1-3

Directions to Stop 1: 5-10 minutes from I-40

Return to Shinarump Road, go under I-40 and drive northwest 1 mile to Prescription Road. Turn east (right) on Prescription Road and go < 0.3 miles to a jeep trail that heads north. Follow this road ~0.8 miles past several old mines, dumps and prospect areas.

Stop 1 Cross-cutting Laramide dikes with shafts and prospects in coarse-grained K-feldspar megacrystic granite: 10-30 minutes

Several short shafts and a large prospect complex. occur within granite along this road, but none of them seem closely associated with the "Laramide" dikes that criss-cross this area. Cross-cutting dike relationships are well exposed on this piedmont and indicate that the biotite porphyry dikes (Tkb) cut dioritic dikes (TKd) which cut hornblende porphyry dikes (TKh). The cross-cutting relationships are exposed within several hundred meters of the road and easily walked to and found using the geologic map for this stop (Figure 7). The mineralization is not impressive, consisting mostly of iron-oxide alteration.

Directions to Stop 2: 30 minutes

Continue north ~0.1 mile along the east edge of fenced private land and turn west along the fence line, and continue for ~1 mile to a road that heads north opposite a locked gate to the private land. This road climbs a steep alluvial fan for nearly 0.7 miles and is rough in several spots. Use caution. Near the high point of this road turn around and park.

Stop 2 Laramide and Miocene dikes with multiple prospect pits 30-60 minutes

This steep peidmont is underlain by coarse-grained granite intruded by a series of monzonitic "Laramide" dikes. Several short shafts, adits, and prospects are present. At some of the prospects Miocene feeder dike(s) for the overlying biotite-phyric, xenolithic mafic lava are also present and suggest that some of the targeted mineralization might be related to Miocene magmatism. The Miocene lava is locally exceptionally biotite-phyric with zones of pyroclastic agglomerate at the base containing up to 10% biotite phenocrysts up to 4mm in size. Alkalic rocks of this sort are known to be associated with alkalic gold mineralization throughout the Rocky Mountains.

Directions to Stop 3: 15 minutes from Stop 1

Return to the base of the piedmont and continue west 0.4 miles along road to a sharp left (south)

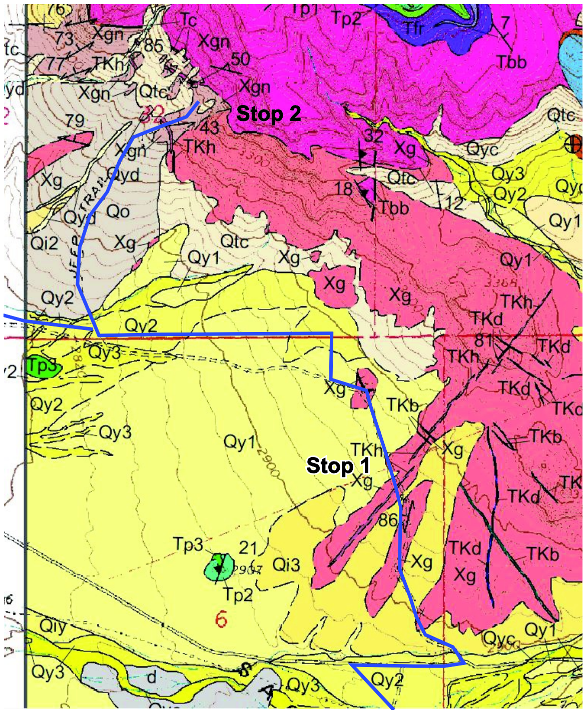


Figure 7 Geologic map for Stops 1 and 2.

Figure 8 Weathered out lapilli wood fragment (Alligator Juniper?) from the Bonelli Tuff Golden Valley hogback east of Bacobi Road. Photo by Joe Cook.

turn that takes you to the east end of Patagonia Road. Take Patagonia Road 1 mile west to Shinarump Road.

Drive west 1.5 miles on Shinarump Road, and turn north (right) onto Bacobi Road. As you drive north, note the low hogback to the east that includes the uppermost two zones of the 18.8 Ma Peach Spring Tuff capped by the 17.7 Ma tuff of Bonelli House, a unit we will see at Stop 5. The tuff of Bonelli House characteristically includes weathered out lapilli that appear to be molds of wood fragments. Perhaps the most convincing example is from this hogback (Figure 8).

Two miles north of Shinarump Road, turn east (right) from Bacobi Road onto Bolsa Road. Please drive slowly as you pass the homes along this very dusty road. Take Bolsa Road 1 mile to its end and turn south on Tooman Road. Take Tooman Road south 0.5 miles (800m), turn around and park.

Stop 3 Lithic blocks in the upper Peach Spring Tuff: 45 minutes

Walk ~ 0.3 miles (500m) east, southeasterly (using the UTM coordinates given in the Figure 9 caption to navigate) across the gentle piedmont to a series of gully bottom outcrops of zone 4 (Hilltop zone) of the Peach Spring Tuff containing conspicuous, large, rounded lithic blocks, mostly of rhyolitic lava (Figure 9). The lithic blocks are just below the size limit considered possible for transport in an ash-flow. Blocks much larger than these (>1.8m) contained within ignimbrites are in fact used as evidence to indicate that an ignimbrite is within or near its source caldera (Wright and Walker, 1977).

The fact that lithic blocks of this composition occur high within the Peach Spring Tuff is interesting in light of a new paper (Roche et al., 2016) that concluded that large lithic blocks of this kind (that is, lithic blocks that were entrained by the moving pyroclastic flow, and not ones that were part of the eruption cloud) are indicators that the Peach Spring Tuff's pyroclastic flow must have been very dense, and therefore also rather slow-moving. So slow, in fact, that it is said that a fast bicyclist would have been able to outrun the ash-flow. Proof that the rhyolite lithic blocks at this locale had to have been entrained by, rather than being blown out of the caldera during the eruption, is that the blocks are rhyolite, a lithology that is conspicuously absent from the caldera walls or anywhere near the caldera. According to Roche et al.'s (2016) paper,

Figure 9 The largest of several (outlined in red) dense, rhyolite lava lithic blocks within zone four of the PST in an isolated outcrop in the western foothills of the Cerbat Mountains near Kingman, Arizona (35.17704, -114.14262). Inset is photo from near the yellow notebook (with 8cm scale bar) showing the moderately phenocryst-rich texture of the ash-flow tuff matrix typical of zone four of the PST. The dense, flow-foliated rhyolite lava block contains ~5% phenocrysts of 2-10 mm sanidine > plagioclase, <1% 1-3mm biotite, and sparse <4mm quartz.

large lithic blocks can be entrained by their dense, slow-moving flow, but, apparently, they cannot be carried very far, or lifted very high within the resulting ignimbrite. All of Roche et al.'s (2016) examples of entrained lithic blocks occur within 1 km of their source, and within 2 meters of the base of the flow.

Whereas lithic blocks at this locale occur at least 100 meters above the base of the tuff, the conclusions of Roche et al.'s (2016) paper require that a 100 meter high hill composed of rhyolite lava must be present within 1 km of this locale. Clearly, there is no way to prove (or disprove) that a hill of this size and composition exists in the subsurface of Golden Valley, but there are no rocks of this type known from the area. Thus, the large lithic blocks at this location suggest that some other process may be involved, and that the conclusions of Roche et al. (2016) may need revision.

Day 1 Afternoon Stops

Directions to Stop 4: 20 minutes from I-40 (Beale Street or Shinarump exits)

Return to the cars and return to Bacobi Road. Turn right (north) on Bacobi Road and drive 1 mile to Red Wall Drive. Turn left (west) on Red Wall Drive and go 0.8 miles. Park as close to the north end of the hogback as possible.

Stop 4 Uppermost (Warm Springs) zone of the Peach Spring Tuff: 20-30 minutes

The north end of the lone hogback near the intersection of Aztec Road and Red Wall Drive includes a small exposure of the uppermost Warm Springs (Tp5) zone of the Peach Spring Tuff, which, unlike the rest of the outflow sheet, is a phenocryst-rich (34%) trachyte. The Peach Spring Tuff was for a long time thought to be a rhyolite whose phenocryst abundances never got higher than 15-18% by volume of the rock. These conclusions were based on the observation that its outflow sheet was everywhere a good match to the section in the Kingman area, the proxy type section for the ignimbrite (Young and Brennan, 1974). The tuff is rhyolite from top to bottom in the immediate vicinity of Kingman, and the maximum phenocryst content is never greater than 18%. As discussed in the introduction, this was a problem for anyone wanting to correlate the thick intracaldera ignimbrite near Oatman, a trachyte with ~34% phenocrysts, with the Peach Spring Tuff.

The Warm Springs zone of the Peach Spring Tuff, named for a remote site in the southern Black Mountains (Ferguson et al., 2013; Pamucku et al. 2013) is a vital link between the mostly rhyolitic, moderately phenocryst-poor outflow sheet, and the almost entirely trachyitic, phenocryst-rich intracaldera ignimbrite near Oatman (Figure 10). This zone's gradational contact with the underlying rhyolite is essential. Until recently, to see this gradation, you had to make the arduous journey into the Warm Springs Wilderness. Luckily, scraps of the gradation are preserved in hogbacks in Golden Valley and in thin exposures of the Peach Spring Tuff along the eastern slope of the Black Mountains.

Directions to Stop 5: 25 minutes

Take Red Wall Drive to <0.2 miles to the west and turn south (left) onto Aztec Road (paved). Go 3 miles south on Aztec Road which ends, and turn left (east) onto Shinarump Road (also paved). Take Shinarump Road 5.2 miles to I-40 and go north (left) on I-40. Take I-40 4.5 miles to the Beale Street exit. Turn left (west) on Beale Street (also US 93) and turn into the first gas station (Union 76) west of I-40. Park in the back parking lot. Simplified geology showing the afternoon stops (5-7) in Kingman is show in Figure 11.

Stop 5 Gas Station exposure of the tuff of Bonelli House, top of the Peach Spring Tuff and strike-slip fault: 10-30 minutes

This is a restroom break at a parking lot cut into an interesting view of the uppermost Peach Springs Tuff as it is typically preserved in the Kingman area; the upper phenocryst-rich trachytic Warm Springs zone is not present. Instead, the Hilltop zone (Tp4) is overlain by ~5 meters of pumice-rich volcaniclastic sandstone and nonwelded pumice lapilli fallout tephra. These strata are overlain by the tuff of Bonelli House, a 17.72 +/- 0.1 Ma rhyolite ignimbrite which consists of two distinct flows, a lower <1 m flow and an upper flow up to 15 m thick. To see the tuff of Bonelli House, climb up the backside of the cut in order to get to the top of the cut, or let someone toss down chunks of the tuff for you to examine.

The fault contact exposed in this cut is interesting since, even though it clearly shows down-to-the-northeast offset, its fault and fault splays have mostly strike-slip to oblique slip slickenline lineations. The upward curving splay to the right is half of a classic flower structure. To see the other half of this flower structure, which splays upward to the left (also looking northwest) look at the roadcut at the low end of the off-ramp from I-40 to Beale Street which is only a few minutes walking distance from this parking lot. The main fault at both of these exposures is probably synthetic with a larger, ~2km dextral strike-slip fault exposed just northeast of here, strands of which can be seen in parts of old downtown Kingman (one of the better exposures can be seen at the Mohave County Parole Office), and at the original Fort Beale site on the northwest edge of town. Low-angle lineations abound along this and other strands of the fault.

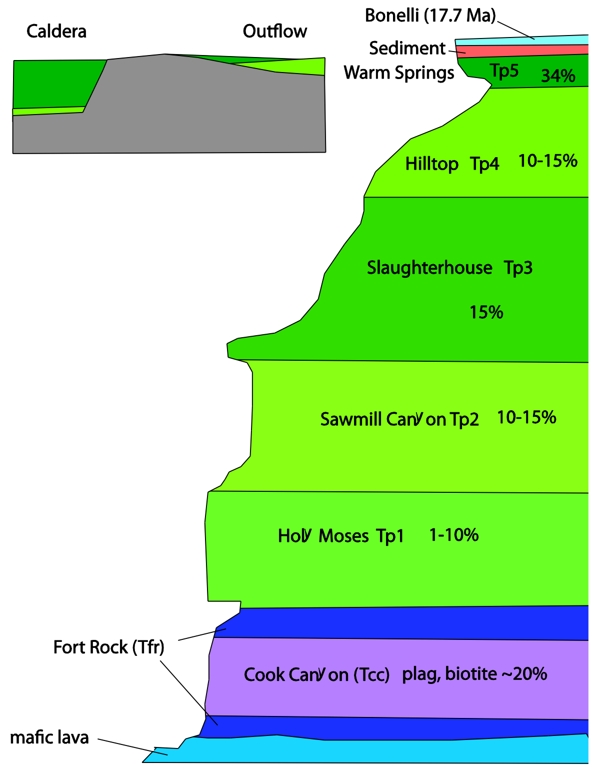


Figure 10 Simplified section of the Peach Spring Tuff and associated volcanic strata in the Kingman area.

Directions to stop 6, the 2WD, short version: 5 minutes

For sampling fresh Peach Spring Tuff, the Cook Canyon Tuff and fall-out tephras of the unit of Fort Rock, the big cut along I-40 just west of the Beale Street exit is wonderful. To access this cut, drive ~1 mile west from the exit and pull over to the far right just past a deep canyon (Cook Canyon) overpass. The big road cut exposes the contacts between zones 3, 2, and 1 of the Peach Spring Tuff and all of the underlying sub-units of the Fort Rock and Cook Canyon tuffs.

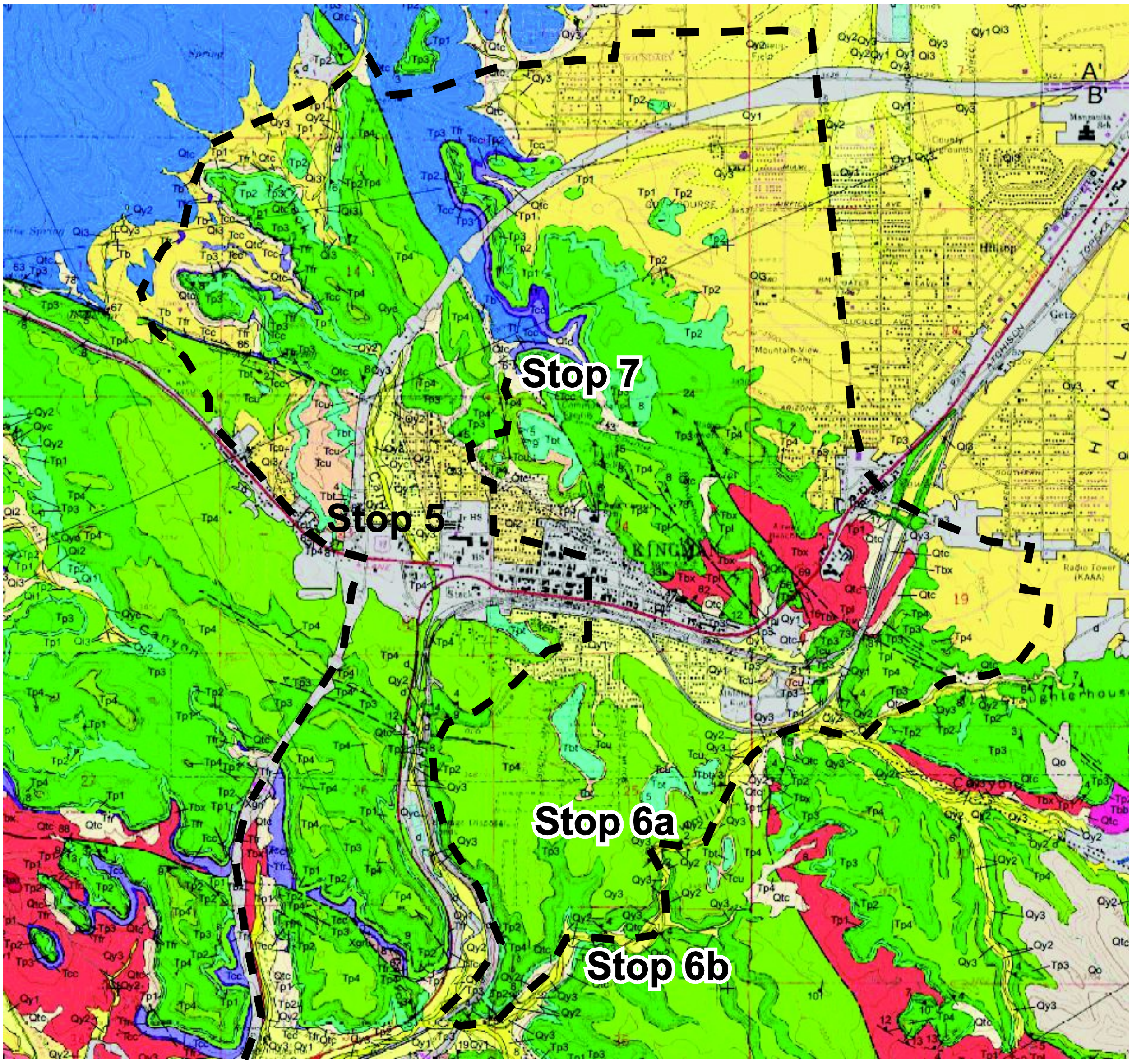


Figure 11 Geologic map of Kingman showing field trip route and locations of stops 5-7.

Stop 6, short version: 20-40 minutes
For those who prefer to walk the section from bottom to top, which takes a bit longer, proceed to the low end of the outcrop about 400 meters past the crossing of Cook Canyon and park. Walk up the cut to the northeast, turn around and return to the vehicles. The quicker way is to drop most of the people at the top of the outcrop, just past the canyon crossing, and walk down-section. Drivers can take the vehicles to the low end of the outcrop.

Directions to Stop 6, the 4WD, scenic version: 15 minutes

From the Union 76 gas station on Beale Street (US 93), turn right (northwest) onto Beale Street and drive 0.4 miles to Fort Beale Drive. Turn right (north) on Fort Beale Drive. If you miss this turn, be sure to take the next turn to the right (north) onto Belty Lane (which joins Fort Beale Drive), because if you miss it, the next place to turn around is over 3 miles farther along US 93. Take Fort Beale Drive around the north edge of town with scenic views of the lower cliff-forming zones of the Peach Spring Tuff wonderfully exposed in several fin-shaped ridges. After ~2.5 miles, Fort Beale Drive makes a hairpin turn and changes into White Cliffs Road which climbs over a ridge and turns into Anson Smith Road at a series of large water tanks. Stay on pavement. Anson Smith Road descends into a residential area and eventually ends at North 6th Street. Turn left (north) on North 6th Street and go 0.15 miles (two blocks) to Sycamore Ave and turn right (east). Take Sycamore 0.75 miles to Stockton Hill Road (a major four-lane city street) and turn right (south). Take Stockton Hill Road south 2 miles under I-40 and through its intersection with Andy Devine Avenue where it turns into Hualapai Mt Road and continue east over the double railroad overpass ~0.7 miles to Jackson Street (the third street past the railroad overpass). Take a right (south) onto Jackson and go 0.2 miles to Mission Blvd. Turn left (east) onto Mission and take Mission 0.1 miles to Slaughterhouse Canyon Road. Turn right (south) onto Slaughterhouse Canyon Road and take it ~0.3 miles to where it drops into the canyon. Descend into Slaughterhouse Canyon and check your mileage for the scenic drive down the combined Slaughterhouse – Sawmill Canyon – Holy Moses Wash.

Stop 6 Zones of the Peach Spring Tuff: 45-90 minutes

Three stops are planned while driving down Slaughterhouse - Sawmill Canyon, the transitions between zones 4 and 3, 3 and 2, and a stop in a quarry into zone 2 near the mouth of Sawmill Canyon. The wash is sandy and can be hazardous for 2WD vehicles, but since it is all downhill it is feasible for 2WD vehicles to make the excursion if they are accompanied by 4WD rigs. It is important for all vehicles to turn off of the main two-track onto hard packed sections of the wash when stopping. This allows for the sparse, but common through-going recreational traffic to pass through, and makes it easier to start again.

From the start of Slaughterhouse Canyon Road, go ~1.2 miles and continue from the main road into the wash. Keep moving! For the next ~0.2 miles, the wash is full of sharp turns with rip-rap and garbage strewn about. At approximately 2.1 miles pull over just upstream of a sharp left (south) turn in the canyon: 5-10 minutes.

Stop 6a Hilltop – Slaughterhouse zone transition: 10-30 minutes

Walk down through the sharp turn in the wash and look back to the east, upstream, for excellent exposures of the gradational transition between zones 3 and 4 of the Peach Spring Tuff. This transition is characterized by a rapid – yet gradual over 2-4 meter – change from strongly compacted ignimbrite of the Slaughterhouse zone (Tp3) and weakly compacted Hilltop zone (Tp4) which is characterized by abundant large, equant pumice and an intense vapor phase recrystallized texture. The poorly welded texture makes it difficult to see phenocrysts, even on fresh surfaces, in the Hilltop zone. The more densely welded Slaughterhouse zone is little better even though its pumice fiamme are strongly compacted. The transition is clearly gradational. No flow-unit boundaries have been identified within the Peach Spring Tuff even though some models argue that a boundary might exist at this important transition.

Continue down the wash approximately 0.7 miles to another prominent turn where the next transition is exposed in the canyon bottom: 5 minutes.

Stop 6b Slaughterhouse – Sawmill Canyon transition: 10-30 minutes

This transition is characterized by an abrupt – yet gradual over 2-5 meter – change from pumice-poor densely welded ignimbrite of the Sawmill Canyon (Tp2) zone upwards into the pumice-rich, lithophysal-rich densely welded ignimbrite of the Slaughterhouse (Tp3) zone. The phenocryst abundances are fairly constant across this transition. The transition is marked by a change from vertical jointing below to horizontal jointing above. Standing at this locale, and looking up at the canyon walls you can also see that the top of the Slaughterhouse (Tp3) zone is marked by another somewhat diffuse horizontal jointing zone. The contrast between recessive ledge and resistant cliff with their vertical and horizontal joint patterns is quite photogenic. Be sure to walk down the canyon a short distance for wonderful, late afternoon views of the transitions looking upstream.

Continue down the wash until the railroad overpass downstream comes into view and take a branch of the wash road that turns right towards a quarry into a cliff of the Sawmill Canyon (Tp2) zone: 5 minutes.

Stop 6c: 5-10 minutes

The rock here is very fresh and is the best place to sample non-weathered ignimbrite. Note the sparse pumice content.

Directions to Stop 7: 10 minutes

Continue downstream 0.6 to 0.7 miles to the mouth of Sawmill Canyon and its confluence with Holy Moses Wash. Drive under the railroad underpass and turn right (north) onto Old Trails Road. Take Old Trails road back into old Kingman ~ 2 miles and turn left (north) on South 4th Street. Take 4th Street north ~ 0.5 miles, across the tracks into the downtown district and turn left (west) onto Spring Street at the Mohave County Courthouse, which, like the historic Bonelli House, is constructed almost entirely of blocks of the Bonelli Tuff, not Peach Spring Tuff. Take Spring Street west 0.3 miles to 1st Street and turn north (right) at the football stadium. Take 1st Street north 0.25 miles (6 blocks) to Copper Street and turn left (west). Take Copper Street 1 block to Cerbat Avenue, and turn right (north). Take Cerbat Avenue 1 block north and turn right (east) onto Lead Street. Take Lead Street up the hill which curves to the north (left) into Darby Lane and take Darby Lane over a rise to the end of the pavement at a City Park for our final stop of the day.

Stop 7 Basal Peach Springs Tuff (zone 1) and the Cook Canyon Tuff: 20-40 minutes

No hammers east of the parking lot please. This is a City Park. The basal nonwelded cliff-forming Holy Moses zone of the Peach Spring Tuff is wonderfully exposed in the cliffs at this park along with a complete section of the thin, distinctive underlying pyroclastic units. The lower units consist of a dark brown weathering nonwelded ignimbrite called the Cook Canyon Tuff which contains abundant plagioclase and biotite phenocrysts, but essentially no quartz or sanidine. The Cook Canyon is enveloped by two pairs (one below and one above) of 1-2 meter-thick lapilli fall-out tephras. The pairs are virtually indistinguishable from each other and are separated by a few centimeters of volcaniclastic sandstone. The pyroclastic units are separated from the basal zone of the Peach Spring Tuff by a few meters of volcaniclastic, pumice-rich sandstone. The basal Peach Spring Tuff is a fascinating ~ 1-2 meters thick unit consisting of thin-bedded to laminated nonwelded tuff that has been interpreted as a fallout tephra by some (Wilson and Self, 1990), but is more likely a surge deposit (Valentine et al., 1989). See for yourself. The unit's weakly cross-stratified structure, and its poor sorting is indicative of a surge deposit. But also note the exceptionally fine-grained thin (<1 cm) ash layer near the top of the bedded sequence which might represent an ultra-plinian fallout tephra.

The abrupt contact of silicic ash beds at the base of the lower pyroclastic sequence with underlying mafic lava autobreccia is well-exposed at the top of the trail leading away from the parking lot. Note the wagon wheel ruts carved into the soft ash deposits.

Also exposed within easy walking distance just west of the parking lot is an outcrop (where hammers are allowed) of the Tp3-4 transition in the hangingwall of a northwest-striking normal fault.

Day 2

Directions to Stop 8 and overview of the geology of the eastern Black Mountains: 45 minutes

Drive I-40 southwest from Kingman to the Shinarump Road – Oatman Highway exit and go west on Shinarump Road < 0.5 miles. Turn left (southwest) onto the Oatman Highway (old US route 66) and take it ~15 miles across Golden Valley. The only outcrop along this road in Golden Valley is a road cut composed of the Slaughterhouse zone (Tp3) of the Peach Spring Tuff. Stop and consolidate vehicles at the Cool Springs parking area at the eastern edge of the Black Mountains. Restrooms are available here. The Black Mountains are a gently east-dipping range whose east flank is composed almost entirely of post- Peach Spring Tuff volcanic strata. To the north of the Oatman Highway, there are exposures of older volcanics that include thin intervals of the Peach Spring Tuff, but these are fairly difficult to access. The volcanics along the Oatman Highway on the east side of the Black Mts consist of rhyolitic lavas and associated nonwelded tuff deposits that are overlain by a suite of mafic lavas which cap the range. Thimble Butte to the northeast is a prominent example of the mafic lava sequence which becomes more andesitic up-section. The bluffs at Cool Springs are composed of rhyolitic lavas which appear to be interbedded with thick basalt lava flows. In fact, the basalt is all intrusive and forms a massive network of sills and interconnected wide dikes that were injected into the rhyolitic lavas apparently from a thick basalt lava lake that accumulated along the eastern edge of the range front. The steep east-facing range front you see today may be very similar to its geomorphic shape in the later Miocene when mafic lavas flooded this part of the volcanic field. Apparently, this is similar to the way thick Columbia River basalt flows banked up against Eocene through Miocene paleocanyon walls cut into sedimentary rocks of the Astoria Basin in western Oregon which resulted in the injection of massive sills and dikes into the country rock (Wells et al., 2009). The intrusive bodies are shown in dark purple on the map of this area and our first stop of the day will be along one of the dikes near Cottonwood Spring.

From Cool Springs, drive west on the Oatman Highway ~2 miles to a couple of small parking areas on both sides of the highway just before crossing a bridge over a fairly big wash. There are spaces for 4, maybe 5 vehicles to the right, and 6 or 7 vehicles to the left in an old quarry that vehicles will have to back out of. When vehicles back out of the quarry, have at least one person stand along the other side of the road to direct drivers. Overflow parking is a few hundred yards east of this site at a wide parking area to the right (north) of the highway near a Cottonwood grove.

Stop 8 Basaltic dikes and contact metamorphosed (fused) silicic "nonwelded" tuff: 10-30 minutes

The quarry at this stop is in the same pile of nonwelded rhyolitic tuffs that form the prominent light colored cliffs that continue from here to the crest of Sitgreaves Pass. The tuffs were formally referred to as the Sitgreaves Tuff, but in fact there are multiple intervals of nonwelded tuff that occur interbedded with nearly all of the silicic lavas on this side of the range. The tuffs are quartz-phyric and clearly not akin to the Peach Spring Tuff, yet when contact metamorphosed the "nonwelded" tuffs appear to be welded and for that reason some have confused these (and other) outcrops with the Peach Spring Tuff. The contact metamorphic zone along the big basaltic dike at this stop is < 4 meters wide, and is wonderfully exposed along the western wall of the quarry.

Directions to Stop 9: 5 minutes

Proceed west ~2.5 miles along the Oatman Highway to Sitgreaves Pass and park on the west side of the pass at a large parking area.

Stop 9 Sitgreaves Pass overview: 10-20 minutes

Views to the east and west from the pass afford good overviews of the pre-Peach Spring Tuff (west) and post-Peach Spring Tuff volcanic stratigraphy (Figure 12).

To the east, note the prominent boundary between the nonwelded tuff cliffs to the north and dark lavas to the south (Figure 13a). This is a north-facing buttress unconformity that is one of at least two similarly oriented buttresses that run, more or less, east to west through Sitgreaves Pass. The buttresses overlap down-to-the northeast normal faults. Another buttress occurs to just to the south of here which morphs down-section into the down-to-the northeast normal fault intruded by the Gold Road vein that will be visited at Stop 10.

To the west, dark dacitic volcanic units that predate the Peach Spring Tuff dominate the near ground (Figure 13b). Farther to the west, along the foot of the range, the interior of the Silver Creek caldera is visible. A generalized east-west cross-section through the crest of the Black Mountains is shown in Figure 13c illustrating how westerly tilted strata on the east side of the range become gently east-

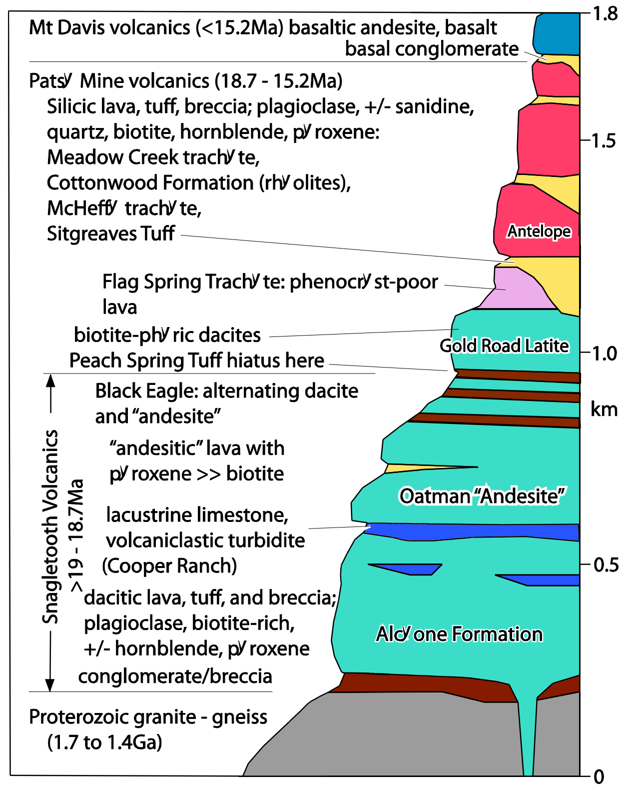
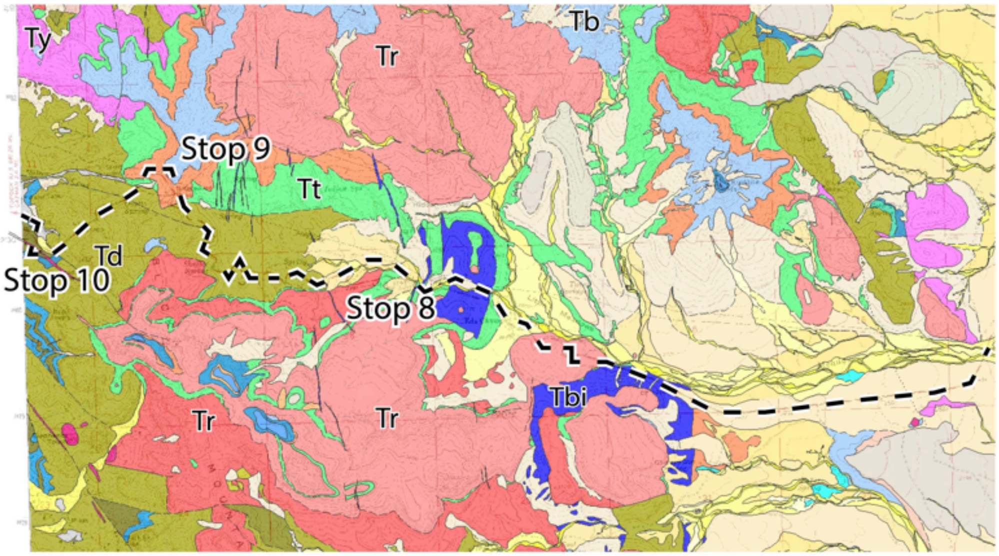


Figure 12 Miocene stratigraphy of the southern Black Mountains.

dipping on the west side of the range.

Directions to Stop 10: 5 minutes

Proceed west along the Oatman Highway ~1.2 miles and park at a wide area to the south (left) of the highway just past a mine adit in a prominent quartz vein that crosses the road.



Tr rhyolitic lavas, Td dacitic lavas, Ty trachytic lavas, Tb basaltic lavas, Tbi basaltic intrusions, Tt nonwelded tuff

Figure 13a Field trip stops 8, 9, 10 along old US route 66 through the Mt Nutt quadrangle on the east side of the Black Mountains.

Stop 10 Gold Road Vein: 10-30 minutes

The Gold Road Vein is a classic low-sulfidation epithermal, banded quartz, calcite, adularia vein (Lausen, 1931, Clifton et al., 1980; DeWitt et al., 1991). Note the weathered out, bladed calcite crystals and the banded texture of alternating quartz and calcite. The light pink color is very fine-grained adularia. This vein (similar to the vein in the Oatman area shown in Figure 13d) intrudes a down-to-the northeast normal fault that morphs up-section into one of the buttress unconformities that run through Sitgreaves Pass. The fault juxtaposes two map units whose boundary, exposed in the cliffs just above and to the south of here, probably represents the hiatus during which the Peach Spring Tuff was

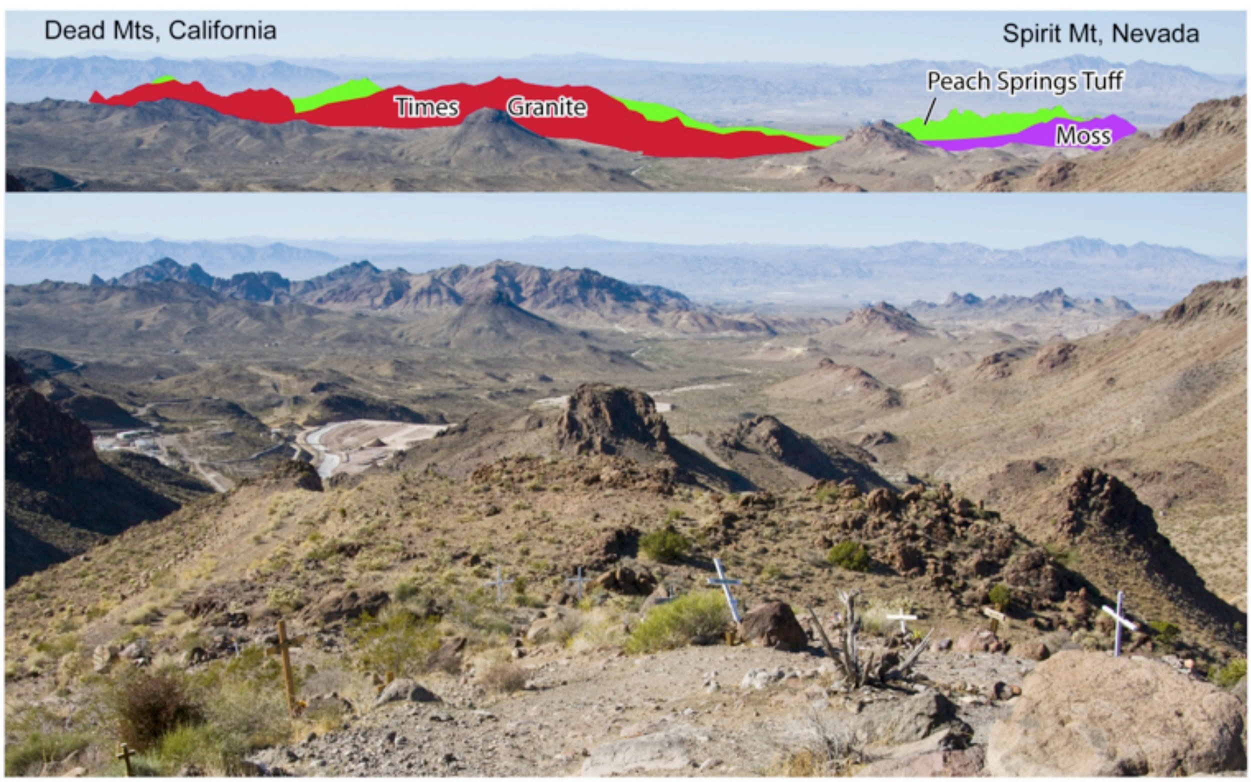


Figure 13b View to the west from Sitgreaves Pass on old route 66 a few miles east of Oatman, Arizona of the Silver Creek caldera. Gold Road Mine in the middleground and main components of the caldera-fill depicted in solid colors in the upper view: intracaldera Peach Spring Tuff, Times granite, and Moss monzonite porphyries.

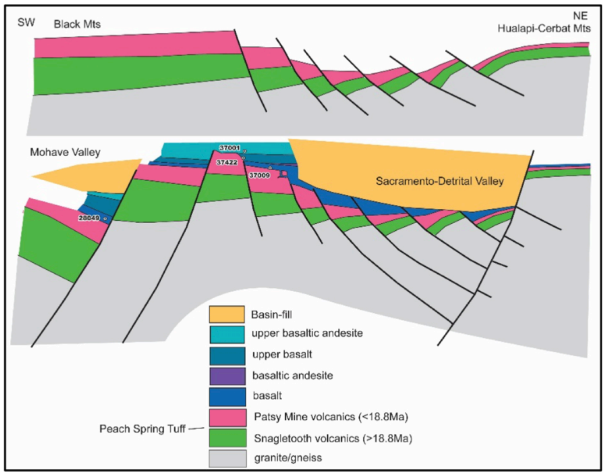


Figure 13c Two schematic cross-sections looking north along crest of Black Mts showing time shortly after eruption of the Peach Spring Tuff (top), and current configuration (bottom). Note basalt lava lake intruding Patsy Mine volcanics along east flank of the range.

erupted but not deposited in this area (see the zero isopach line on Figure 2a). The Peach Spring Tuff is absent from the volcanic section along the crest of the Black Mountains for several kilometers north and south of Sitgreaves Pass. Rocks on the southwest (footwall) side of the fault – vein are an alternating sequence of biotite-phyric dacitic and pyroxene-phyric andesitic lavas informally referred to as the Black Eagle lava sequence. These are overlain by the biotite-phyric dacitic rocks of the Gold Road lavas which are exposed on the northeast (hangingwall) side of the fault – vein. Down-section, to the west, the Black Eagle sequence overlies a very thick and monotonous pyroxene dominant andesitic lava sequence called the Oatman andesite whose base will be seen at Stop 12. The Black Eagle sequence and the Oatman andesite are the main host rocks for mineralization in the Oatman area.

Directions to Stop 11 (Figure 14, 15): 15-20 minutes (without stopping in Oatman)
Proceed west along the Oatman Highway ~ 2.6 miles to Silver Creek Road, a graded gravel road to the right (west) of the paved highway. For those who need a restroom break, before taking the Silver Creek Road, proceed south ~1.3 miles to Oatman: 20-40 minutes. Well-maintained public restrooms in Oatman are next to the large public parking area just to the south of the main downtown area. Watch out for the burros and gunfighters!

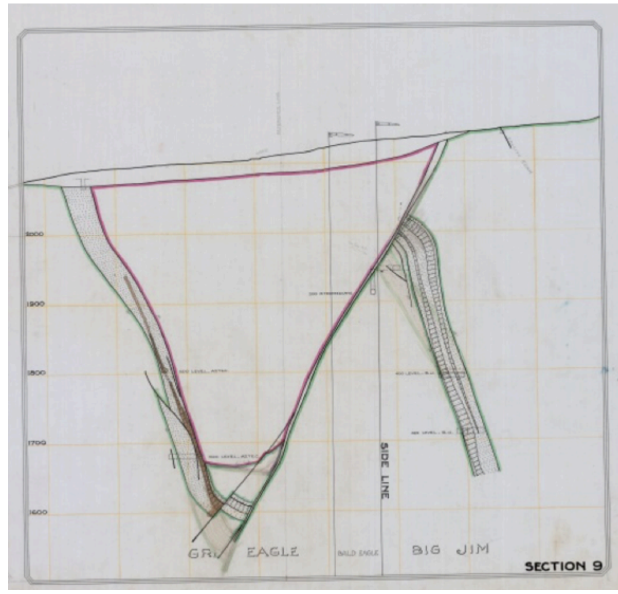


Figure 13d View to the north of one of the major Oatman gold veins emplaced along an east side down fault and cut by a west-side down fault.

Take Silver Creek Road 2.4 miles west through monotonous dark plagioclase-pyroxene phenocryst dacitic lavas of the Oatman "andesite" and turn left (south) onto a road just before you get to Hardy Mountain, a large massif of leucogranite porphyry to the west. An old real estate sign marks this road. Take this road south 0.7 miles and turn right (following the main traffic flow) onto a primitive road that climbs over a low divide between Silver Creek and Times Gulch. The first 0.1 mile is fairly rough.

Continue down Times Gulch. About 1.0 miles down the Gulch (from the start of the primitive section), look for Gary Cooper's ruined ranch house to the right (north) at the mouth of a major side canyon. Turn right and follow this road 0.3 miles and park at the end of the road near a mine adit. There are places for 6 vehicles here. Alternatively, multiple vehicles can park at the ruined ranch house and you can walk up the canyon to the mine.

Stop 11 Times and Big Lode Mine complex and the caldera margin (Figure 16): 45-90 minutes
The intracaldera Peach Spring Tuff ignimbrite is very well exposed to the north of this mine complex. The adit here is along the contact of a composite dike that intrudes Times leucogranite porphyry to the south and Peach Spring Tuff to the

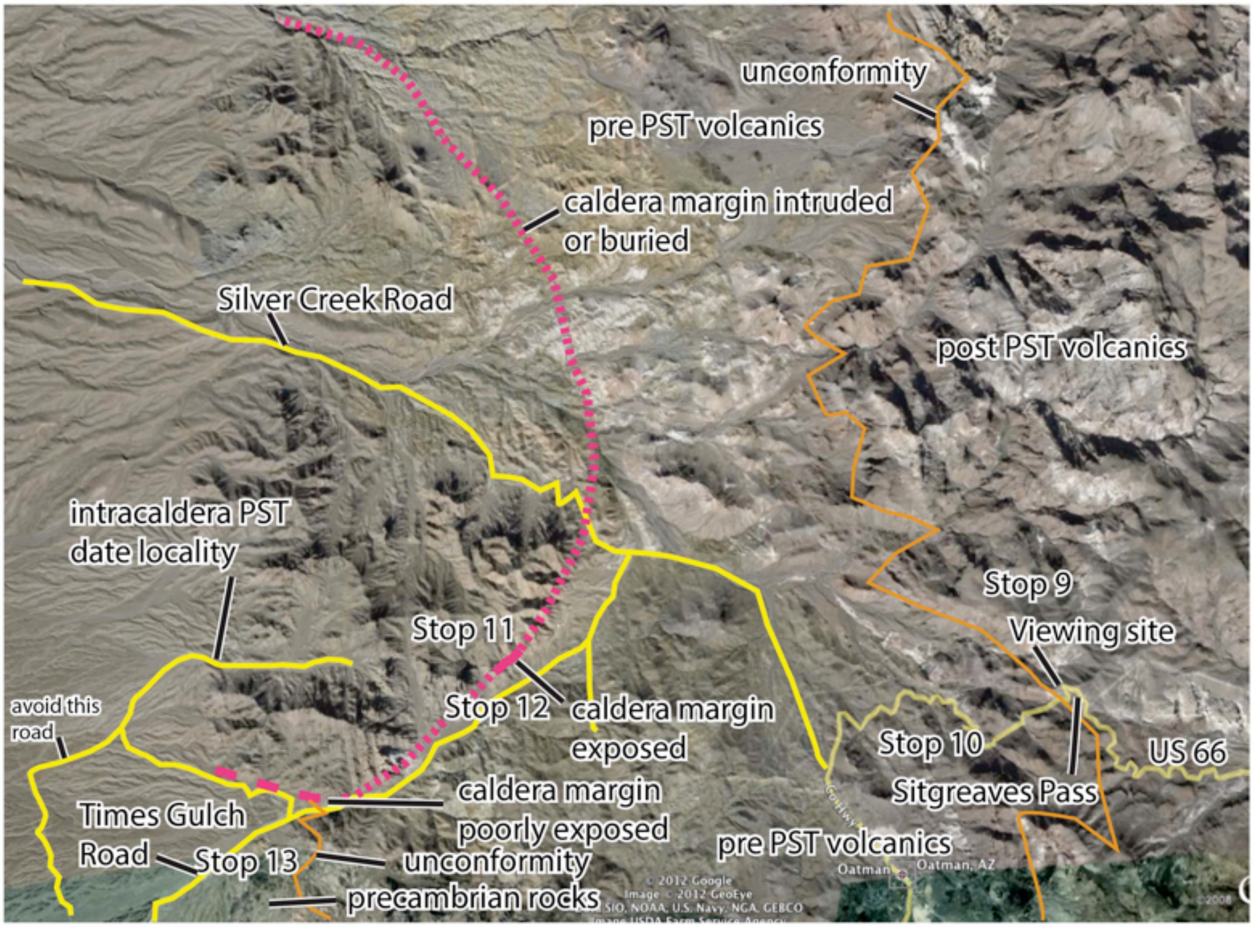


Figure 14 Satellite image of the western Black Mountains showing the Silver Creek caldera and stops 11, 12, and 13 along Times Gulch.

north. The composite dike consists of a 5-10% feldspar-quartz porphyry and a 30-40% feldspar-quartz porphyry which is usually, but not always, on the north side of the dike. In some places a bit of the phenocryst-poor porphyry occurs on the north side of the dike implying that the inner phenocryst-rich porphyry is younger. Note also an older thin, rimmed feldspar porphyry dike intruding the Times leucogranite porphyry that is either intruded by the quartz-phyric dike to the north and/or cut by a fault that either runs parallel to the big dike's contact or is intruded by the dike (or some combination of the two). At any rate, there is a breccia of the older, thin dike at the adit.

From the adit, walk up the canyon to the northwest. Where the canyon turns into a gorge. Notice how the intracaldera Peach Spring Tuff looks nothing like the light colored rhyolitic ignimbrite at Kingman. It is, however, an exact petrographic, and geochronologic match to the phenocryst-rich trachyte that makes up the uppermost zone of the Peach Spring Tuff seen at Stop 4. The intracaldera ignimbrite here also passes the paleomagnetic test (Bob Varga, personal communicaiton - there are differences, but they are compatible and typical of intracaldera – outflow pairs elsewhere). The dark ignimbrite is a porphyry that looks quite a lot like the dark dacitic porphyry exposed along the southeast side of Times Gulch, but with some very important differences. The dacitic porphyry contains only plagioclase phenocrysts and the crystals are quite large, ranging to > 1cm. The distinctive sanidine > plagioclase phenocryst assemblage of the intracaldera ignimbrite here is key. Even in hand specimen you should be able to discern that the ignimbrite contains two types of feldspar.

After ascending the canyon gorge for a hundred meters or so, and climbing up through a couple of short waterfalls, climb out of the gorge at the first place where you can abandon the canyon and climb to the east. Ascend to the crest of the ridge and

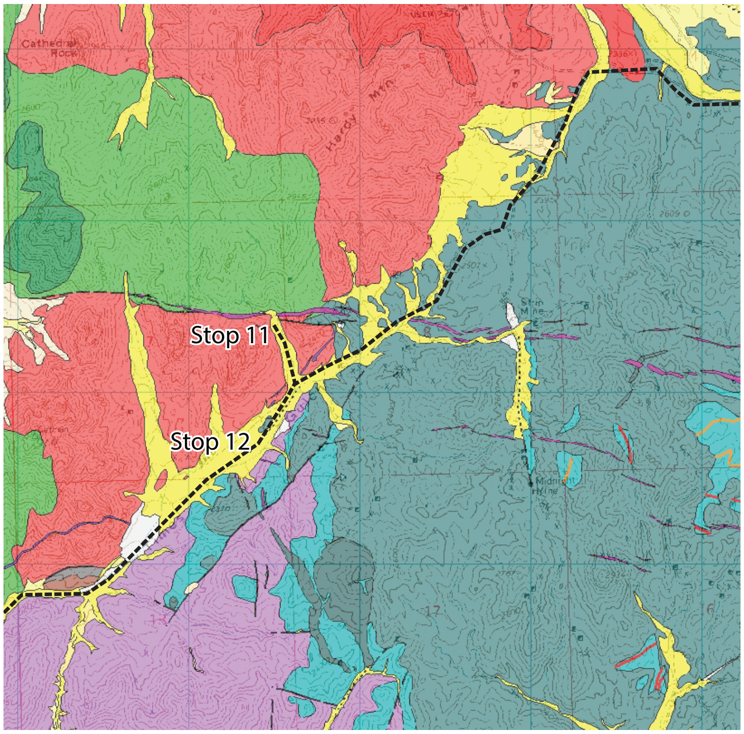


Figure 15 Geology along Times Gulch in the western Black Mountains showing stops 11, 12, and 13.

against Proterozoic granite. At this locality, the crumbly nature of the contact, which appears to be a buttress unconformity, is preserved near intrusive contacts of the dike and Times leucogranite porphyry. As you cross the septum towards the south, look for the contact between the 2 feldspar trachyte ignimbrite on the north and the plagioclase porphyry lava to the south. In some places the contact is cut by steep faults like the one seen at the Big Lode Mine shaft north of here. Follow the contact down and cross the composite dike again, going north so you can trace the "caldera margin" northeast until it is cut off by a large body of the Times leucogranite porphyry. Note how this section of the caldera margin is so altered that it is virtually impossible to put a finger on the contact. Instead the contact is a zone about 10 m wide (Figure 17). Is the contact a fault, an unconformity, or both? An intriguing possibility is that

contour around to the mine shaft on the map (Figure 16). There is a good game trail that will lead you past another short caved prospect pit. The mine shaft at the Big Lode Mine on the crest of the ridge is very deep, uncovered, and surrounded by a loose waste pile. Be sure to restrain any pets or children at this locality. Note the steep fault exposed in the shaft. Faults of this orientation are abundant along the caldera margin.

Walk down the ridge to the south from the mine shaft and cross through the composite dike just to the east of the crest of the ridge. Look carefully at the rocks in this septum between the composite dike and the prominent fault contact with the Times leucogranite porphyry to the south.

Actual exposures of the contact between the intracaldera ignimbrite and the caldera wall are sparse, and present at only 3 localities. The two others are at the bedrock mouth of Times Gulch, both

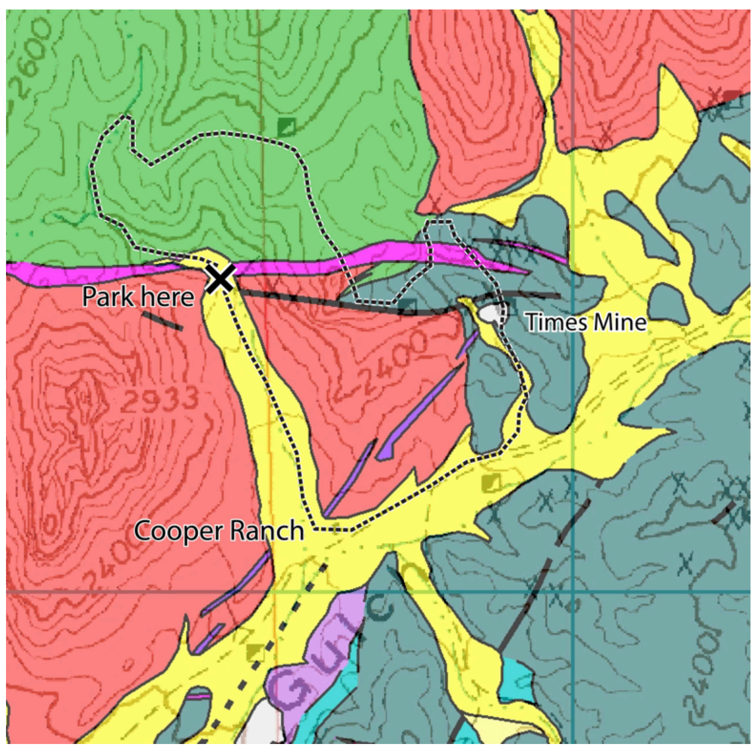


Figure 16 Geology of the Times Mine area along Times Gulch showing a hiking route for viewing the caldera margin intruded by a composite rhyolite dike (pink), and the Times leucogranite porphyry (red). Peach Spring Tuff in green and Oatman andesite in gray.

the Oatman Andesite plagioclase porphyry intrudes the ignimbrite. Lithic blocks of the Alcyone dacite and of the lacustrine limestone that will be seen at the next stop occur within the intracaldera Peach Spring Tuff here and in the Sacramento Mts (Stops 16, 17, 18), but blocks of the Oatman Andesite, which look a lot like the Alcyone dacite, have not been unequivocally identified within the intracaldera ignimbrite or seen as substrate to the intracaldera ignimbrite in the Sacramento Mts. The Oatman Andesite might simply never have been deposited on the west side of the caldera (Sacramento Mts). It seems highly improbable that the Peach Spring Tuff was erupted before the Oatman Andesite was emplaced in the Black Mountains, especially in light of the stratigraphic relationships established to the south of Oatman in the Boundary Cone 7.5' quadrangle (Spencer et al., 2006) just south of the zero ispoach line (Figure 2a) where mafic lavas of the Black Eagle lava sequence are overlain by the thin proximal edge of the Peach Spring Tuff.

Figure 17 Photo, looking southwest of the Silver Creek caldera margin (blue) intruded by composite rhyolite dike near Times Mine.

Continue down the trail that leads to the Times Mine, a very deep, uncovered shaft with water at the bottom – again restrain children or pets. The mine, like most in this district is along a fault. Note the thick fault gouge intruded by calcite > quartz vein material. The fault here dips to the south and is probably also south-side-down, but what about the fault just to the west, which lies along strike with the one at the Times Mine? That fault is essentially vertical and has riedel shears that indicate opposite (down to the north) motion.

Continue down the trail and back to Times Gulch and return to the vehicles.

Directions to Stop 12: 2 minutes

From Gary Cooper's ruined ranch house, drive down the wash ~0.2 miles and stop at the base of an old mine dump strewn with white magnesitic carbonate blocks.

Stop 12 Cooper Ranch: sub-Oatman Andesite volcanic lake deposits in the wall of caldera (Figure 18): 30-45 minutes

The unit of Cooper Ranch is a sedimentary sequence capped with beds of magnesite carbonate that overlie dozens of meters of siltstone, marl, sandstone, and subaqueous biotite-rich plagioclase phenocryst-rich ignimbrite. These lacustrine deposits mark the contact between the two main, pre-Peach Spring Tuff volcanic units in the eastern wall of the Silver Creek caldera. All rocks to the northwest of Times Gulch are either intracaldera Peach Spring Tuff or Times leucogranite porphyry. All rocks to the southeast of the Gulch are either pre-caldera dacitic – andesitic volcanics or sedimentary rocks of the unit of Cooper Ranch. Underlying the unit of Cooper Ranch are biotite-phyric dacitic lavas and ignimbrites that contrast strongly with the pyroxene-phyric dark dacitic to "andesitic" lavas of the overlying Oatman Andesite. This contact can be seen at a mine shaft (filled with water) in the slope just to the southeast where dark plagioclase porphyry overlies and/or intrudes the white carbonate and evaporite rocks you see in the dump. The slope is steep and rugged, so go around just to the south and walk up a side canyon where you can see the biotite-phyric dacitic lavas of the underlying Alcyone / unit of Cooper Ranch overlain by biotite-rich sandstone, siltstone, and bedded ignimbrite. The limestone and evaporite beds are only exposed in the rugged slope above the dump. Follow the basal contact of the sedimentary rocks to the north from the side canyon to a low saddle which represents the top of the Alcyone dacite (note the abundant biotite phenocrysts), and then climb up to the carbonate rocks through an ~20m thick interval of

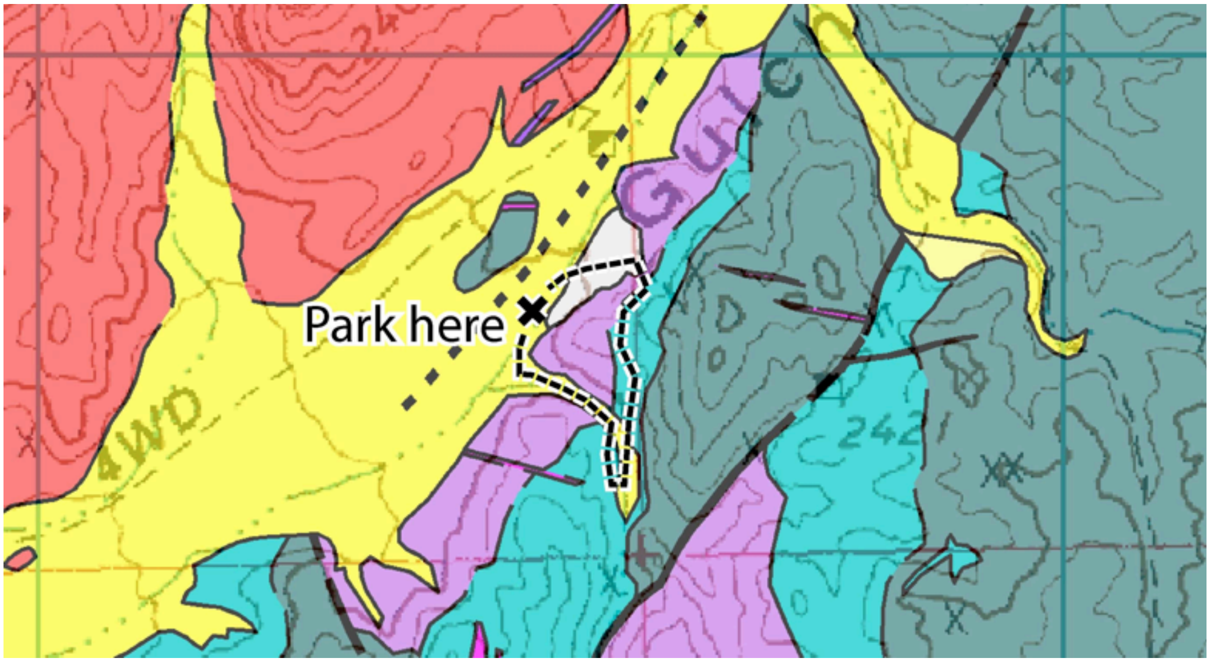


Figure 18 Geology in the wall of the Silver Creek caldera along Times Gulch showing a lacustrine volcaniclastic unit (light blue) that occurs along the contact between the Alcyone dacite (purple), and Oatman andesite (gray).

argillaceous dacitic volcaniclastic rocks. From here follow a game trail a few meters to the north to the mine shaft where the depositional/intrusive contact at the base of the Oatman Andesite is exposed.

Directions to Stop 13: 10 minutes

Proceed down Times Gulch past the big quarry (note the big green dike that cuts the Times leucogranite porphyry in the quarry). ~1.9 miles from stop 12 there are good exposures of intracaldera Peach Spring Tuff next to the road on the right (north) and exposures of Alcyone dacite lava to the left (south). A few hundred meters to the northeast (upstream), an intrusive contact between the intracaldera ignimbrite and the Times leucogranite porphyry is exposed running steeply up the slope. Note the lighter color and bolder character of the granite porphyry to the east.

Proceed west along the Times Gulch road and as you drive down the canyon note that the caldera margin swings to the northwest away from the canyon bottom, and you descend into an extensive sedimentary sequence of volcanic and granite clast breccia, conglomerate, sandstone, and mudstone that underlies the pre-caldera Alcyone dacite lava pile. These are wonderfully exposed along the cliffy outcrops to the left (south). The sedimentary rocks persist for ~0.5 miles down the canyon where they eventually overlie regolith breccia altered coarse-grained granite basement. Finally, just before crossing out of outcrop altogether, note a prominent leucogranite porphyry dike that cuts the coarse-grained basement ~0.1 mile west of the basement unconformity. Stop at this dike.

Stop 13 Times Gulch: Caldera margin (Figure 19): 20-60 minutes

Follow the leucogranite dike a few hundred meters north to see it intruded by the green, rhyodacitic porphyry dike that is so prominently exposed in the big quarry up the canyon. View to the east up Times Gulch is shown in Figure 20. Only a few hundred meters farther north, the leucogranite porphyry dike stitches the caldera margin. However, colluvial cover is fairly thick, and the actual contacts are not spectacular in this area.

Following the leucogranite dike to the south of the Times Gulch road a couple hundred meters takes you to a fault that partially cuts the dike, but also appears to be intruded by it. The fault can be traced to the east where it cuts the contact between basement and Tertiary cover as well as the contact between the basal sedimentary rocks with the base of the Alcyone dacite. Farther to the east, the dike dies out or becomes intruded and/or overlain by the dacite.

Directions to the Sacramento Mountains and stop 14: 60-75 minutes

Take the Times Gulch Road approximately 8 miles (it becomes paved after about 3 miles) to its intersection with Arizona Highway 95 in Fort Mohave. Turn south on Arizona Highway 95. At 3 miles intersect Boundary Cone Road which heads back to Oatman. At 10 miles Highway 95 changes from 4-lane to 2-lane and a turn to the left at a stop light will take you to Golden Shores and Topock and the quickest way to east-bound I-40. Continue south on Arizona Highway 95 for 1.4 miles (crossing into California and the Colorado River at 1.2 miles). Turn right (west) at the 4-way stop and go 3 blocks (0.2 miles) and turn left (south). Go 0.4 miles to L street and turn right

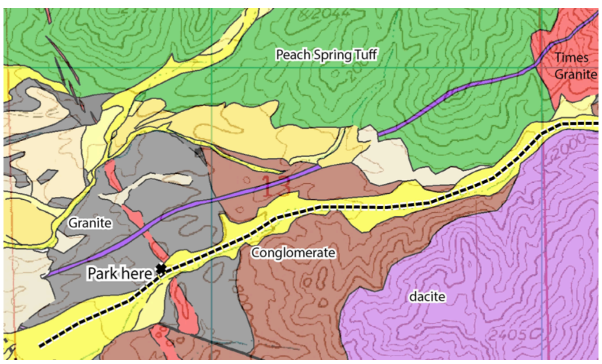


Figure 19 Geology at the bedrock mouth of Times Gulch where the Silver Creek caldera margin runs due west (north of the gulch) and is stitched by a pair of dikes. Photo of Figure 20 is taken looking east from near the dike intersection.

(west) going under I-40, and take an immediate right (north) onto Eagle Pass Road which goes 0.2 miles parallel to I-40 before it turns hard to the left (west). Proceed 0.2 miles through a large equipment yard and continue to the top of a levee. At the top of the levee proceed forward and descend into a big wash staying on the middle track which crosses the wash. Look for BLM sign identifying this as road 085. At about 6.7 miles the Eagle Wash Road (085) climbs over another levee. Upstream of the levee, continue forward up the wash for a short section of primitive road before the road settles into the main wash. Drive up the

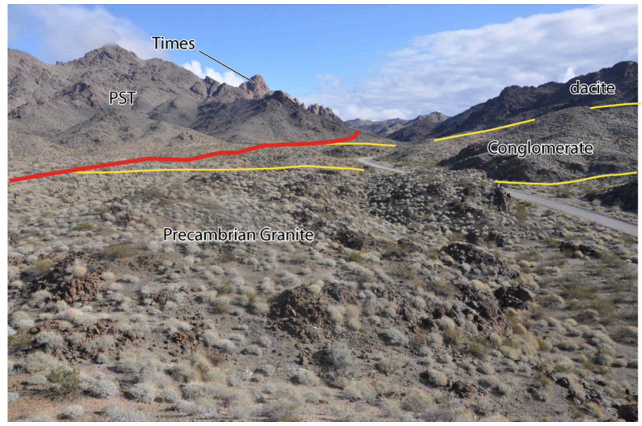


Figure 20 Annotated view of the north-facing Silver Creek caldera margin looking up Times Gulch (east) with granitic basement in the near ground overlain by conglomerate and dacitic lava. Photo taken from near the dike intersection in Figure 19.

wash 2.8 miles and park just before getting to the big cliffs of Eagle Peak to the west.

Stop 14 Unconformity at the base of the 14 Ma Eagle Peak Rhyolite (Figure 21, 22, 23): 30-90 minutes

The base of the major cliffs just west of here are composed of the 14.3 Ma Eagle Peak Rhyolite which overlies chloritic altered banded gneiss on a contact that had been mapped as a detachment fault (McClelland, 1984). The contact is pretty clearly an unconformity as illustrated in Simpson et al. (1991, Figure 8). Climb up onto the southeast side of the canyon a hundred meters or so to view the contact with binoculars. To visit the contact follow the track illustrated in Figure 23 and be sure to wear hard hats since the exposure is at the base of a very tall vertical cliff. The last few meters of the approach to the outcrop are challenging.

Directions to Stop 15: 20-30 minutes

Drive up Eagle Peak Wash 2.9 miles. Stay in the main wash passing where the main BLM road 085 climbs out of the wash and heads to the southwest at ~ 1.5 miles from stop 14. Stop 15 is where the first prominent cliff of contorted limestone and thin-to medium-bedded subaqueous ignimbrite looms over the north side of the wash floored by outcrops of chloritic altered basement gneiss.

Stop 15: 10-20 minutes

Low-angle fault exposed at the base of the cliff separates contorted limestone and subaqueous

Figure 21 Satellite image of the Eagle Peak area showing locations of field trip stops 14, 15, 16, and 17.

plagioclase-biotite-rich ignimbrite in the hangingwall from chloritic altered gneiss in the footwall.

The hangingwall rocks here strongly resemble the unit of Cooper Ranch limestone and lacustrine volcaniclastic rocks exposed in the wall of the Silver Creek caldera along Times Gulch in the Black Mountains. These rocks underlie a large area of light matrix mesobreccia and megabreccia Peach Spring Tuff to the north and east of this exposure.

Directions to Stop 16: 5 minutes
Turn around and drive down the wash 0.8 miles, park.

Stop 16 Megablock within Peach Spring Tuff: 45-90 minutes

Figure 22 Geology of the Eagle Peak area from Bill McClelleand's MS thesis (1984) showing the locations of Stops 14, 15, 16, and 17.

Walk north about 300 meters towards the near camelback-shaped knob and head to the saddle between the humps. The humps are composed of welded Peach Spring Tuff which grades down into poorly welded Peach Spring Tuff mesobreccia that includes megabreccia blocks. In the saddle is one of the megablocks (about 80m long and >25m wide) composed of dark dacitic lava breccia. Blocks of this size are proof, based on the arguments of Wright and Walker (1977), that the Peach Spring Tuff here must have been deposited within or very close to its source caldera (Ferguson et al., 2013).

Directions to Stop 17: 15 minutes

Return to the vehicles and drive down the wash ~0.5 miles and turn up wide wash that comes in from the north. Drive up this wash as far as possible (about 1.0 miles). Park.

Figure 23 Looking west up Eagle Wash at the base of the ~14.1 Ma Eagle Peak Rhyolite lava, Sacramento Mountains, California. Hiking route to the outcrop described by Simpson et al. (1991) is shown by colored line. The gap in the route corresponds to a narrow, stair-like slot that hikers should descend (inset photo) after climbing over a 3-4 meter high hump of rhyolite at the base of the big cliff.

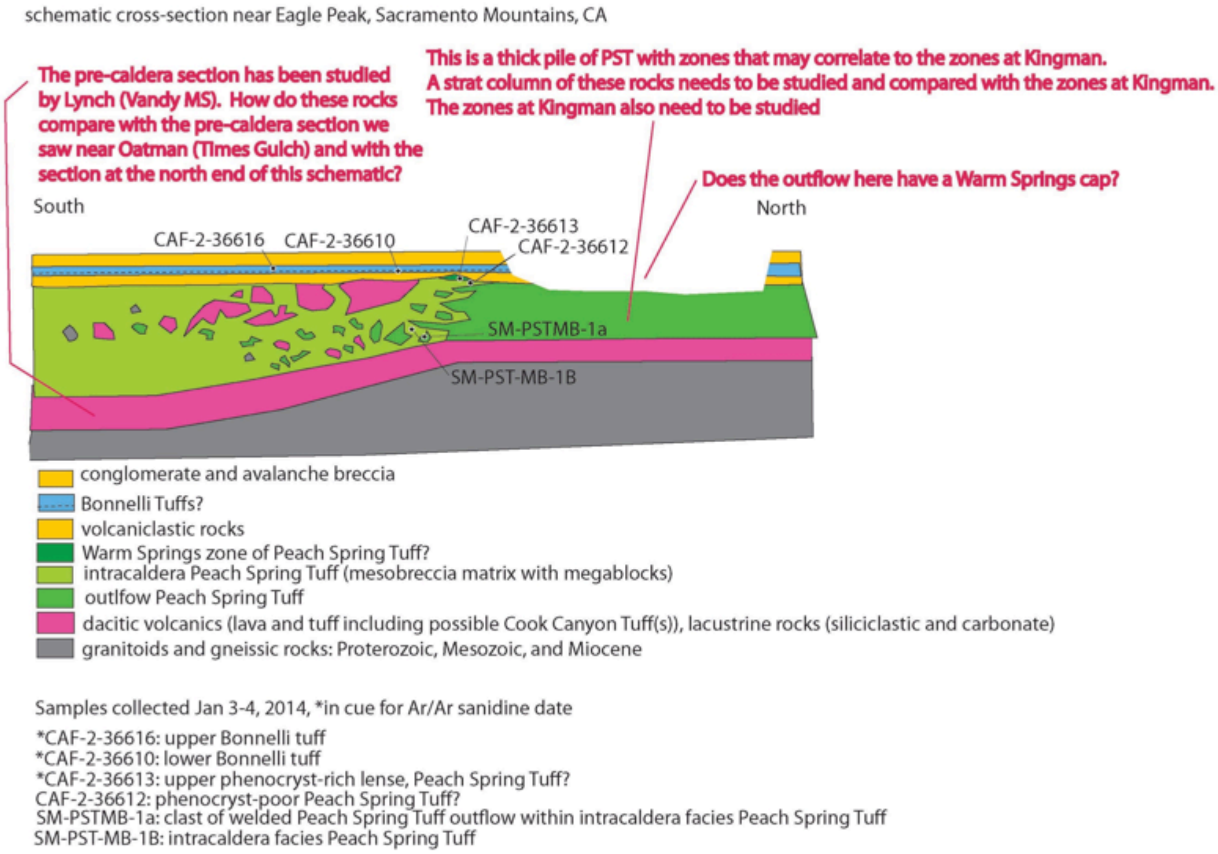


Figure 24 Schematic cross-section looking southwest of the hinge zone of "trap-door" style, south-facing caldera margin near Eagle Peak, Sacramento Mountains, CA. A recently acquired 17.7 Ma date for sample 36610 confirms that the capping ignimbrite in this area is the tuff of Bonelli House, and an 18.8 Ma date for sample 36613 indicates that all of the sequence interpreted as outflow Peach Spring Tuff in this diagram (including map units Tt2, Tt3, and Tt4 of Spencer and Turner, 1983 (see Figure 24)) is part of the Peach Spring Tuff.

Stop 17 Mesobreccia Peach Spring Tuff with megablocks of outflow facies Peach Spring Tuff (Figures 24, 25): 30-120 minutes

Walk up this wash through the waterfall constriction to see polished exposures of poorly welded Peach Spring Tuff mesobreccia with abundant megablocks of welded Peach Spring Tuff. Note the possibly crenulate contacts around some of the blocks of welded tuff, and how many of them were frozen into "jigsaw" fit positions. Continue up wash, and within < 1km, the poorly welded mesobreccia becomes less abundant while the blocks of the welded tuff increase and eventually become 100% continuous bold outcrop of welded tuff.

The welded tuff here is part of a continuous, gently dipping sequence of outflow Peach Spring Tuff that continues to the north several miles towards the north edge of the Sacramento Mountains (Spencer and Turner, 1983). This area represents the transition between outflow facies and intracaldera facies Peach Spring Tuff. Since the Peach Spring Tuff outflow sheet to the north and the intracaldera facies tuff to south both overlie similar volcanic substrate suggests that this is a trap-door style, hinged caldera margin (Figure 24).

Continue hiking to the west towards exposures of post-Peach Spring Tuff sandstone, conglomerate, dacitic lava breccia (map units Ts5 and Tt6 of Spencer and Turner (1983) as shown on Figure 25) capped by a cliff of sanidine phenocryst-poor rhyolite ignimbrite (map unit Tt7 of Spencer and Turner, 1983). The phenocryst-poor ignimbrite (Tt7) has recently been dated at 17.7 Ma (unpublished data, New Mexico Tech geochronology lab), and has a phenocryst assemblage identical to the tuff of Bonelli House which overlies the Peach Spring Tuff in Kingman, Arizona. Capping the crest of this ridge is a conglomerate and breccia (map unit colored brown

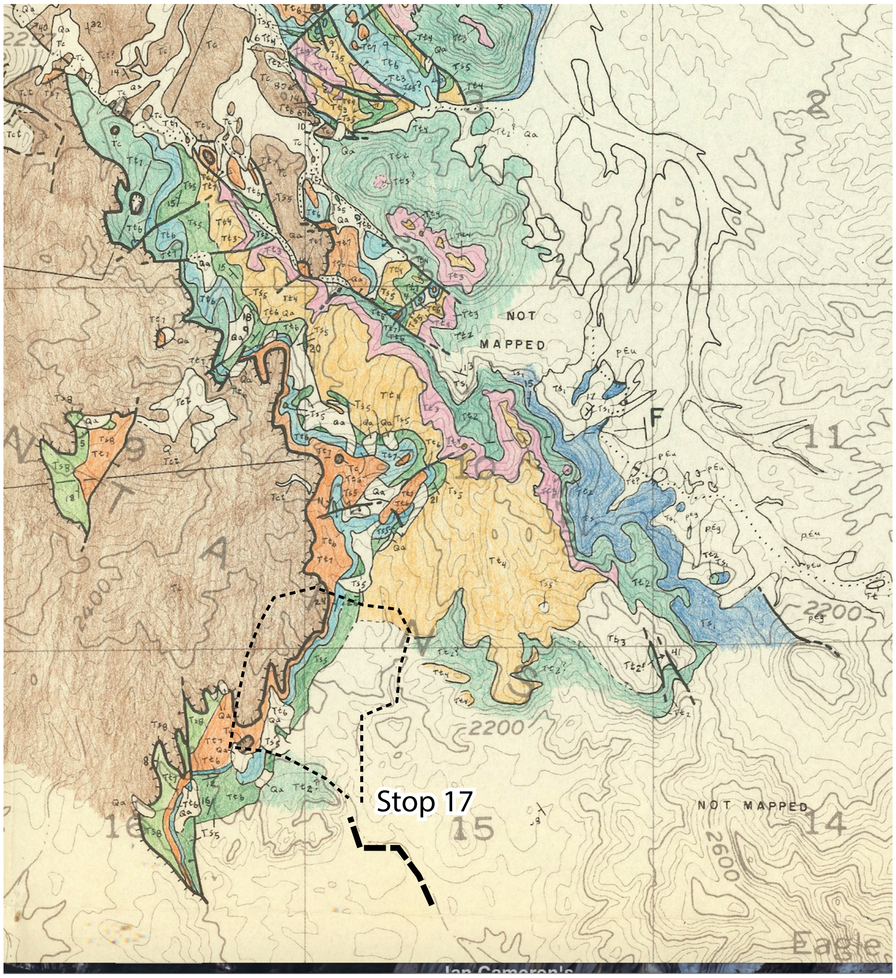


Figure 25 The southeastern corner of Spencer and Turner's (1983) geologic map of the Sacramento Mountains showing the hiking route at stop 17. Map unit Ts1 is the limestone and subaqueous plagioclase-biotite-rich ignimbrite seen at stop 15 and probably equivalent to the Alcyone dacite and unit of Cooper Ranch in the Black Mountains. Map units Tt2, Tt3, and Tt4 are cooling unit zonations of outflow Peach Spring Tuff approximately equivalent to zones 1-2, 3, and 4 of the Peach Spring Tuff in the Kingman area (Ferguson and Cook, 2016a, b). Map units Ts5 and Tt6 are sedimentary rocks and a dacitic tuff and block and ash-flow deposit. Map unit Tt7 is the tuff of Bonelli House and the brown unit capping the ridge to the west is breccia and conglomerate.

on Figure 24), that was interpreted as a low-angle detachment fault (Spencer and Turner, 1983; McClelland, 1984). Charles Ferguson and Keith Howard (work in progress) interpret this contact as an unconformity.

Directions to Stop 18: 25-35 minutes

Return to the vehicles and drive back to Eagle Wash. Near the confluence of this wash and Eagle Wash, look for BLM road 085, and take it to the south. A few dozen meters south of Eagle Wash BLM road 085 climbs out of a wash to the right (southwest). Beware of following tracks in the wash here as it will lead to a dead end. Follow road 085 4.2 miles to Stop 18. Along the way, BLM road 085 eventually gets into a major wash and 0.7 miles from Eagle Wash passes a large outcrop of limestone that is either a megablock suspended in mesobreccia of the Peach Spring Tuff or limestone that overlies the Peach Spring Tuff. Just to the south of this outcrop, mesobreccia of the Peach Spring Tuff is overlain by a monotonous pile of moderately southwest-dipping, granitic basement-clast conglomerate and breccia that is very similar to the capping conglomerate and breccia seen at the top of the ridge at stop 17. Drive up the wash through conglomerate and breccia ~1.2 miles and near an outcrop of dark lava cross a major northeast-side-down fault into granitic basement. Within the granitic basement BLM road 085 eventually climbs out of the wash to the west and circumnavigates a ridge of steeply southwest-dipping, pre-Peach Spring Tuff dacitic rocks that depositionally overlie the granitic basement along the northeastern edge of the ridge.

Stop 18 Intracaldera Peach Spring Tuff: 10 minutes

At 4.2 miles from Eagle Wash the road turns hard to the right just after a crossing a fault separating basement granite and gneiss from a sequence of steeply southwest-dipping limestone unit that overlies the dacitic volcanics of the circumnavigated ridge. The dacitic volcanics and the limestone are overlain by at least 800 meters of steeply southwest-dipping mesobreccia of the Peach Spring Tuff. The light green weathering mesobreccia is exposed next to the road and is capped by gently southwest dipping conglomerate and breccia which forms the hill to the southwest. Along strike about 3km to the northwest, magnesite bearing carbonate strata identical to those seen at this stop are overlain by typical outflow facies Peach Spring Tuff. The facies transition between intracaldera facies here and outflow facies Peach Spring Tuff to the northwest is interpreted (Ferguson and Howard, 2014) as a duplication, carried in a more southwesterly fault block (bounded by the major fault zone crossed about 2 miles back), of the southeast-facing caldera margin seen at stop 17 near Eagle Peak. The caldera margins in the two fault blocks lines up perfectly with a projection of where the northwestern margin of the Silver Creek caldera would be, just west of the Oatman area in the Black Mountains (Figure 2a). The extension vector of 215° is the same as the slickenline lineation azimuth seen along the low-angle fault at stop 15.

Directions for getting back to civilization

From Stop 18 the quickest route to anywhere, including back to Needles, is to continue southwest on BLM road 085 to a graded gravel road that parallels the power line about 2 miles southwest of Stop 18: 10 minutes. Take the graded gravel power line road either 10 miles northwest (15-20 minutes) to the Camino exit on I-40, or 17 miles southwest to US 95 just south of Snaggletooth Ridge in the western Chemehuivi Mountains (30-40 minutes). The graded gravel road, especially to the southwest, is susceptible to wash-outs where speeds greater than 5 mph can damage your vehicle.

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