Arizona Geological Society Spring Field Trip

Basin Evolution, Deformation, and Mineralization in Big Sandy Valley, Mohave County, northwestern Arizona

April 27-28, 2024

Brian F. Gootee, Carson A. Richardson, Lisa A. Thompson, Bradford J. Johnson, and Philip A. Pearthree

OPEN FILE REPORT OFR-25-2

February 2025

Arizona Geological Survey

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UA SCIENCE ARIZONA GEOLOGICAL SURVEY

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Led by Arizona Geological Survey:

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Cover: Spectacular view of tilted Tule Wash formation sandstone lithofacies, punctuated a rock-avalanche or sturzstrom deposit. Note folded beds, boulders of mixed lithologies, and shear planes. Immediately below the avalanche deposit, a vitric tuff dated at 10.4 ± 0.2 Ma is partially included in the avalanche deposit as white clasts seen center right. The overlying ca. 5 Ma Big Sandy Formation fanglomerate caps the sequence.

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Acknowledgements

This trip is supported by the Arizona Geological Survey (AZGS) and Arizona Geological Society (AGS). We thank landowners in Big Sandy Valley for their support, discussions, and access. Special thanks to landowners Anita and Sherwood Waite, Big Sandy Range, and Nick Ballard. Andy Cohen and Jay Quade from the University of Arizona provided insight into the formation of carbonate and siliciclastic systems in southern Big Sandy Valley. Boise State University provided U-Pb zircon geochronology. The University of Nevada, Las Vegas, provided $^{40}Ar/^{39}Ar$ geochronology. Tammy Rittenour (Utah State University) is providing OSL/IRSL/cosmogenic geochronologic dating of younger Quaternary sediments (forthcoming). John Douglass (Paradise Valley Community College) provided critical insight into landscape geomorphology and drainage integration in Big Sandy and Burro Creek basins.

Hervé Rezeau, Jonothan Chappell, Camila Sojo-Aguero (GEOS), Tim Marsh (Bell Copper) provided insight and information related to Diamond Joe pluton & Big Sandy porphyry prospect. Brendan Fenerty & Joey Wilkins (Bradda Head) helped with discussions about context and emplacement of lithium in southern Big Sandy and environs. Subsurface modelling and seismic processing and interpretations in northern Big Sandy valley were provided by Donna Shillington and Emily Kunkle (NAU).

Geologic mapping was funded in part by the U.S. Geological Survey National Cooperative Geologic Mapping Program under STATEMAP, awards G20AC00374 (2020) and G21AC10848 (2021). Adjacent mapping in the Burro Creek area provided valuable context to Big Sandy Valley geology., funded by Earth Mapping Resources Initiative (MRI), agreement No. G20AC00166 (2022).

Field Trip Agenda

Friday, April 26

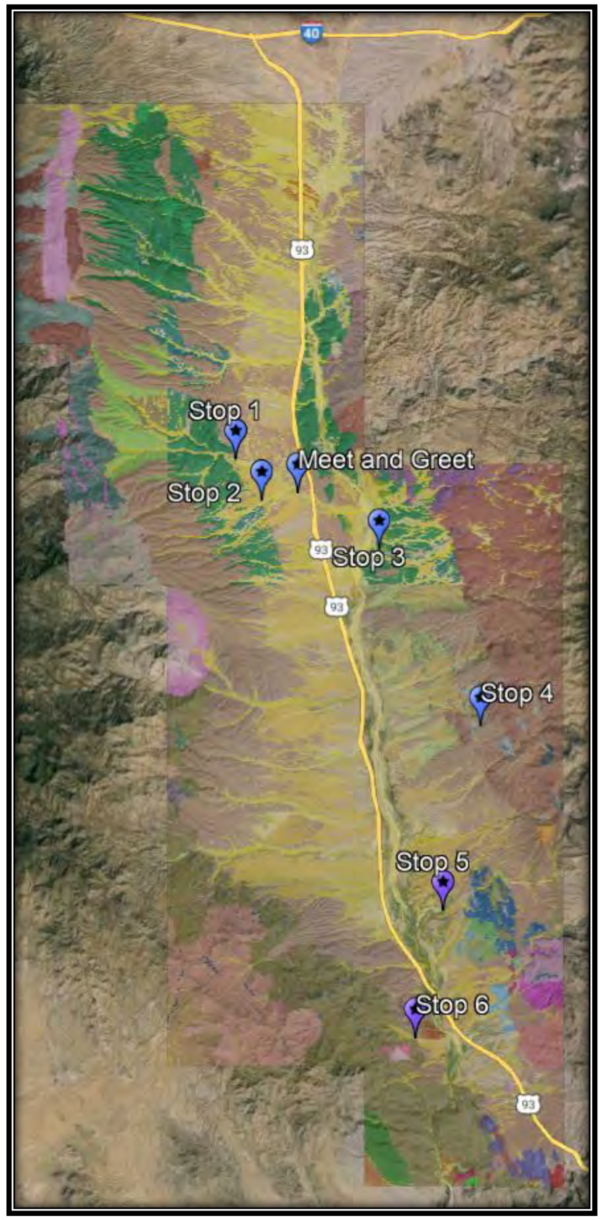
- Camp or lodge prior to meeting Saturday morning. See Friday night camping options for details.

Saturday, April 27

- Stop 0: Meet at 8:00 AM. Introduction and overview at Cane Spring Corral
- Stop 1: Carpool from camp to middle Cane Springs Wash 8:30-11:30 AM
- Stop 2: Quaternary Fault & Lunch, 12:00-1:00 PM
- Stop 3: Back Rd. near Tom Brown Canyon, 1:30-2:30 PM
- Stop 4: Upper Burro Wash, 3:30-5:30 PM
- Return to Camp: 6:00 PM

Sunday, April 28

- Break Camp and depart, 7:00 AM
- Pitstop: Wikieup for gas and carpool, 8:00-8:15 AM
- Stop 5: Big Sandy Formation Type Locality, 8:30-10:30 PM
- Head south on County Rd 159 to Stop 6
- Stop 6: Hualapai fault & Lunch, 11:30 to 1:00 PM
- Head back to Wikieup and End Trip, 1:30 PM



Map of field trip stops on Saturday (blue) and Sunday (purple) between I-40 and Burro Creek Bridge along US Hwy 93. Generalized geologic map compilation of AZGS mapping areas in the basin.

Friday Night Camp Options, April 26

Camp Option 1 – Knight Creek (Fri/Sat) (unlimited, primitive): Knight Creek Canyon at 34.971°, -113.654° (AZ State land). Going northbound on Hwy 93, exit right (east) immediately after mile-marker 105. Continue north about 100 ft to an unlocked gate (please close gate behind you) and proceed east down an unnamed wash for 1.0 mile to an opening in Knight Creek. The Creek is sandy, all-wheel or four-wheel drive recommended. Camping will be dispersed and can accommodate all trip participants. This is also the main group camp on Saturday night.

Camp Option 2 – Burro Creek Campground (limited): Located at 34.536°, -113.452° (BLM land). Sites can be reserved on www.recreation.gov though there are 12 sites on a first-come first-serve basis (sites 1-6 and 18-23). There are facilities here and it offers some shade and access to running water in Burro Creek.

Camp Option 3 - Lower Box Canyon Wash (limited, primitive): Located at 34.610°, -113.549° (BLM land). Exit US Hwy 93 at mile marker 132.1 and drive south on Signal Road (dirt road) for 1.3 mile to a small wash, turn right into wash; sandy though mostly compacted. Proceed down small wash 0.5 mile to Box Canyon Wash into an opening. This site should allow for dispersed camping up to 10+ vehicles, though be cautious of turning around in sandy, gravelly wash. It offers some protection from wind and afternoon/evening sun.

Camp Option 4 – Upper Kaiser Spring Wash (limited, primitive): Located at 34.618°, -113.428° (BLM land). Exit US Hwy 93 at mile marker 132.1 (same exit as Box Canyon Wash option, and drive north on dirt road for 6.4 miles (20 min) to Kaiser Springs Wash. There is an open space south of road in the wash and down wash for several vehicles.

Camp Option 5 – Southern Corrals Wash (limited, primitive): Located at 34.724° -113.658° (BLM land). Exit US Hwy 93 at MM 122.6 on a dirt road north of Wikieup development, about 0.1 mile north of "Snoopy Rocket". There is a gate labeled "Please Close Gate". Turn here and drive west 2.5 miles. There will be a wash and opening on the south side of dirt road. About six vehicles should fit in the wash.

Camp Option 6 – Northern Corrals Wash (limited, primitive): Located at 34.742° -113.689° (BLM land). Exit US Hwy 93 at mile marker 121.3 west onto Clementine Road, which is opposite the turnoff to Pump Station Road. Follow Clementine Road to the T-junction about 300 ft and turn right, head 0.5 mile north to a fork and take a sharp left onto an unnamed dirt road. Drive 4.0 miles and look for a smaller road on the left, south side. Turn and proceed 0.2 miles to a dead end and opening on the edge of a dissected alluvial fan about 120 ft above Natural Corrals Wash. This site is more remote and offers a scenic view of the valley.

Camp Option 7 – Upper Deluge Wash (limited, primitive): Upper Deluge Wash at 34.809°, -113.686° (BLM land). Exit Hwy 93 at mile marker 117.5 and drive west up a graded dirt road 3.4 miles to an opening on the left, just before the dirt road descends. This site is on the south side of wash on high alluvial fan remnant about 100 ft above the wash floor. This site can fit roughly 7-10 vehicles and about 10-15 tents, is quiet and offers excellent views of the valley.

Camp Option 8 – Wild Cow Campground (limited, BLM site with facilities): This site is about 1 hour from our meeting spot on Saturday morning. Located at 35.065° -113.869°. From US Hwy 93, exit Blake Ranch Rd at mile marker 105.9. Drive west on County Hwy dirt road 129 for 14.2 miles and turn left on dirt road. Drive for about 4.1 miles and turn right on Hualapai Mountain Rd. Drive for about 0.1 mile and turn left following signage to the campground.

Map of campsite options for Friday night. Only one site can fit all participants and their vehicles: Knight Creek located in the northern part of the basin.

Abstract

Basin evolution, deformation, and mineralization in Big Sandy Valley, northwestern Arizona

Big Sandy Valley in northwestern Arizona is a large, exceptionally well-exposed extensional basin with complex Proterozoic bedrock, multiple Laramide porphyry stocks, the Miocene Kaiser Spring volcanic field, two generations of Miocene to Pliocene basin fill, interbedded rock-avalanche deposits, and middle Miocene and younger faults. Systematic geologic mapping in this basin was initially motivated by several factors: ongoing copper and lithium exploration, 3D structural and stratigraphic controls on mineralization and groundwater, and U.S. Hwy 93/Interstate 11 infrastructure.

Proterozoic rocks in the Hualapai Mountains were intruded by the Cretaceous Wikieup, Diamond Joe, and Wheeler Wash stocks with associated (but variably developed) porphyry alteration. A fourth Laramide stock near Devil's Canyon is not exposed, and instead a monzonite to quartz monzonite porphyry dike swarm is present.

A poorly exposed, east-dipping, low-angle normal fault, first inferred by Frost and Heidrick (1996) and later by Morgan et al. (2009), is present along the eastern margin of the northern Hualapai Mountains. While this fault has not been documented farther south near the Diamond Joe pluton, Bell Copper's Big Sandy prospect has rocks of the same composition and age and is interpreted as the faulted top of the Diamond Joe pluton transported ~13 km to the ENE (Bell Copper, 2021). Still farther south, a moderately ENE-dipping normal fault is exposed near the Wikieup pluton and may be the southern continuation of this same fault. Thermochronologic cooling ages (AHe, AFT, and ZHe) of the major footwall plutons suggest rapid middle to late Miocene exhumation of the Hualapai Mountains, while Late Cretaceous to Paleogene cooling ages (ZHe and AHe) of a Cretaceous dike in the Aquarius Mountains east of the valley imply this area was a structurally higher level of the crust by that time.

The oldest basin-fill succession, informally named the Tule Wash formation, is a sequence of limestone, basalt, mudstone, sandstone, and conglomerate up to 1,500-2,000 m thick. In northern Big Sandy Valley, the depositional axis of the Tule Wash basin was located on the far eastern side of the valley along the present-day margin of the Aquarius Mountains, as indicated by multiple interbedded rock-avalanche breccia-flows sourced from the Hualapai Mountains and a mixing zone where clasts sourced from the Hualapai, Trout Creek and Aquarius are all present. In the southeastern Aquarius Mountains, the Kaiser Spring volcanic field, a bimodal complex assemblage of felsic lava domes, mafic lava flows, breccias, and pyroclastic rocks, was emplaced over an eroded crystalline bedrock surface from ~15-8 Ma, overlapping with Tule Wash deposition and deformation. Along the Hualapai Mountains and across much of the valley width, the Tule Wash beds are predominantly W-tilted toward E-dipping normal faults. Near the Aquarius Mountains the Tule Wash beds are in ENE-tilted fault blocks separated by N- to NW-striking faults with a dominant component of WSW-side-down normal slip. After deposition and deformation of the Tule Wash beds, a basin-wide erosional event formed an angular unconformity, followed by deposition of younger basin fill of the Big Sandy Formation, which is generally not deformed. Eroded Tule Wash basin fill was transported south out of Big Sandy basin to an unknown depocenter. Subsequently basalt and rhyolite flows sourced from the Kaiser Spring volcanic field closed off this outlet, forming the closed basin in which the basin-wide fanglomerate, sandy, muddy and carbonate assemblage of the Big Sandy Formation occupied between ~10-5 Ma. e. Known lithium mineralization near the community of Wikieup is hosted within the muddy lithofacies of the Big Sandy Formation, but the source rocks and mechanism of lithium mineralization remains debated.

By ~5 Ma, the Big Sandy Formation aggraded with sediment and water to a maximum floor elevation of ~750 m above sea level at its southernmost terminus and spilled across crystalline bedrock where the northern Poachie and southern Hualapai Mountains meet. Since then, Big Sandy Valley has undergone erosion with a series of off-lapping alluvial terraces cut into older basin fill deposits. Though evidence of deformation is limited in Big Sandy Formation deposits, one fault zone on the west side of the valley clearly offsets late Pleistocene and older deposits.

Geology Road Log of Big Sandy Valley

US Hwy 93 from I-40 to Burro Creek Bridge

By Brian F. Gootee, Carson Richardson, Lisa Thompson, Brad Johnson, and Phil Pearthree

April 2024 - ver. 1.0

Introduction

This geology road log is primarily focused on geology of the Big Sandy Valley and highlights the results of recent geologic mapping throughout the valley, its rocks, mineralization, structure, basin fill and Quaternary histories. This road log was made as part of the field trip manual for the Arizona Geological Society Spring 2024 field trip. The objectives of this road log are to 1.) Provide an overview of the basin geography, road access and general geology, 2.) Provide descriptions of specific stops planned for the AGS field trip, and 3.) Provide a visual tour in figures and photos to give the reader insight into the basin formation, history and ongoing work.

In addition to geology, the road log also references tidbits about cultural history, biology/botany, and infrastructure. The road log starts from Interstate 40 at US Hwy 93 in the north, and ends at Burro Creek Bridge a few miles southeast of Big Sandy Valley. The field trip agenda and camp options in the manual shows field trip stops and camping options for Friday & Saturday night. The road log uses highway mile markers (MM-), that are the same for northbound and southbound travel.

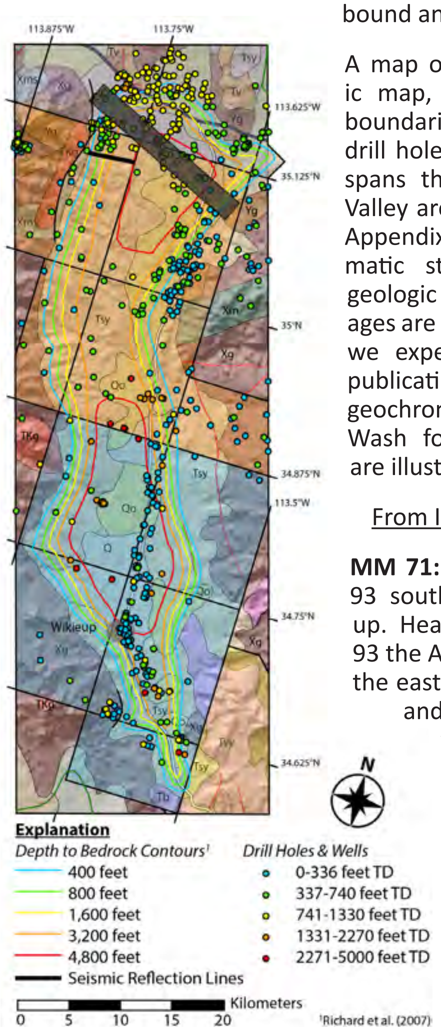


Figure 1. General location map along Big Sandy Valley and legend.

A map of the statewide geologic map, 7.5-minute quadrangle boundaries, depth-to-bedrock, drill holes and seismic lines that spans the length of Big Sandy Valley are shown in Figure 1 and Appendix 1. A generalized schematic stratigraphic column of geologic formations and relative ages are shown in Figure 2, which we expect to revise in future publications. A summary of new geochronologic ages for the Tule Wash formation, and pending, are illustrated in Appendix 4.

From Interstate 40 & Hwy 93

MM 71: Exit I-40 onto US Hwy 93 southbound towards Wikieup. Heading south on US Hwy 93 the Aquarius Mountains form the eastern margin of the basin, and the Hualapai Mountains form the western boundary. The highway curves the next couple of miles on a low-relief piedmont sourced from the Hualapai Mountains, moderately dissected into older fanglomerate deposits. The valley axis is defined by an unnamed wash.

To the east, Tin Mountain forms a prominent peak immediately north of I-40 as the highway ascends east into upper Knight Creek watershed between Cottonwood Mountains to the north and Aquarius Mountains to the south. A prominent light gray, moderately dissected, alluvial fan emanates from the watershed and is equivalent to the Big Sandy Formation in age and morphology.

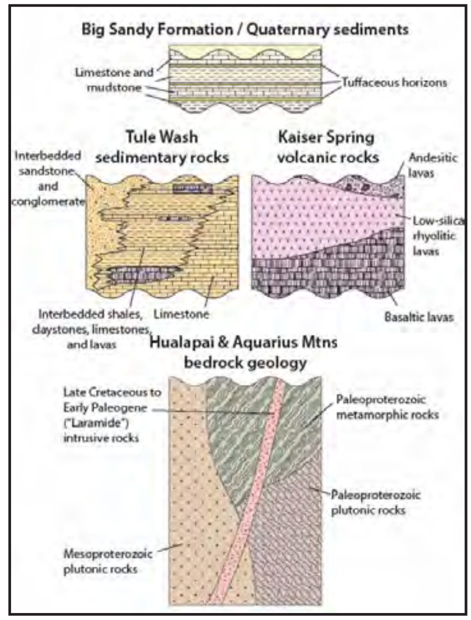


Figure 2. Schematic Stratigraphic Column: Bedrock geology synthesized from Meazell (2014), Tule Wash from Worley (1979) and Scarborough and Wilt (1979), Kaiser Spring from Moyer and Esperança (1989), and Big Sandy from Sheppard and Gude (1972) and MacFadden et al. (1979).

The Hualapai Mountains are composed of Proterozoic igneous and metamorphic rocks and intruded by multiple late Cretaceous-early Paleogene (Laramide) porphyry stocks. The Aquarius Mountains have Proterozoic rocks assemblages similar to the Hualapai Mountains but are intruded by sparse Laramide and Neogene dikes.

Depth to crystalline bedrock (i.e. thickness of basin fill) in this part of the basin is about 4,000-5,000 ft deep, based on gravity data (Oppenheimer and Sumner, 1980; Richard et al., 2007) (Figure 1); however, this model is outdated and is currently being revised to account for bedrock inliers and more recent seismic, well and exploratory drillholes.

MM 94.5: Crossing McGarrys Wash as US Hwy 93 straightens into a north-south drive through the axis of the basin.

MM 95.7: Crossing old highway 193 (west) and Hackberry Rd (east).

MM 96.1: Crossing Bottleneck Wash.

MM 97.1: Roadcut through muddy and sandy lithofacies of the Big Sandy Formation, here capped by fluvial gravels from the ancestral Knight Creek axial wash (about 80 m or 260 ft above the modern creek). Modern Knight Creek appears to be superimposed over older basin fill and bedrock further east, forming part of a young and developing, narrow canyon with a meander shape. The divide for this subbasin was likely a couple miles to the south, formed by a fan complex (bajada) emanating from the Hualapai Mountains around modern day Antelope Wash.

MM 97.3: Passing Breccia Dr. on west (right) side of highway.

MM 97.5: Crossing modern Kabba Wash. The previous 0.4 mi were two sluggish valleys filled with Holocene sediment, which are abandoned strands of two former paths of Kabba Washs, most likely pirated by drainages with shorter and lower paths to Knight Creek.

MM 98.1: Passing exit to an unnamed road east (left) that provides access to Bear Road, a north-south road along the west bank of Knight Creek.

MM 100: Entering floodplain of Knight Creek and confluence with Wheeler Wash. Exposures along roadcuts and in the mouth of Wheeler Wash are subhorizontal alluvial fanglomerate lithofacies and sandy lithofacies of the Big Sandy Formation. Paleocurrents from clast imbrication point to the north and northeast towards fine-grained facies, indicating a small, closed basin at this elevation during Big Sandy deposition, informally referred to as "Round Valley" subbasin.

MM 100.8: Passing exit to Windmill Ranch, a small ranching community developed since the early 1900s. South of Windmill Ranch and east of the highway, Knight Creek is incised in older, east-tilted (15-20 degrees), and north-imbricated conglomerate mapped as the Tule Wash formation (Thompson et al., 2024).

East of Knight Creek is a tilt block of conglomerate, sandstone, mudstone and limestone/tufa lithofacies of the Tule Wash formation (Figure 3).

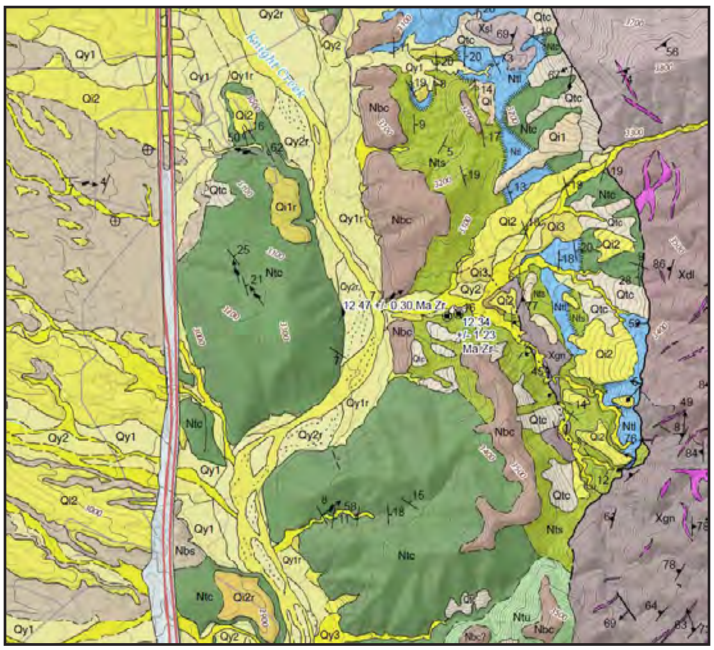


Figure 3. Geologic map from the Bottleneck Wash 7.5-min quadrangle (Thompson et al., 2024) east of Hwy 93).

This sequence is also tilted easterly against a west-dipping normal fault with at least several hundred meters displacement. Three ash layers interbedded with sandstone yielded U-Pb single-grain zircon ages of 11.21 ± 0.67 Ma (not plotted in Figure), 12.06 ± 0.73 Ma, and 11.63 ± 0.60 Ma (Appendix 4). This sequence is interpreted to represent part of a small subbasin of the Tule Wash formation, similar to the "Round Valley" Big Sandy subbasin.

Notice in Figure 3 that the younger Big Sandy Fm. conglomerate (unit Nbc) cuts across the Tule Wash units (Ntc/Nts); this contact dips into the subsurface beneath Knight Creek, highlighting the erosional paleotopography between the two formations.

MM 102.2: Crossing Antelope Wash. West of the highway, the Big Sandy Fm. paleovalley is present and estimated to be about 100-150 m thick. East of the highway are large boulders mantling slopes that overlie east-tilted fanglomerate of the Tule Wash beds (Ntc) – the boulders are sourced from the Hualapai Mountains and form a lag on these slopes.

MM 102.8: Crossing the from the Bottleneck 7.5-minute quadrangle (north) into the Pilgrim Wash quadrangle (south).

MM 103.4: Crossing over Moss Wash. The Big Sandy paleovalley remains west of the highway; however, the polarity of tilting of the Tule Wash beds changes from east-tilted to west-tilted. The relative age of tilting associated with faults to the east and west, if different, remains unclear.

MM 104: Not visible from the highway, located along the west side Knight Creek, are rock-avalanche deposits dominated by angular boulder and cobble clasts of the Hualapai-sourced Wheeler porphyry, indicating the axis of the depositional basin during Tule Wash time was east of the modern river.

MM 105: Crossing an unnamed wash that was superimposed over buried Tule Wash conglomerate when an older Knight Creek was about 140 m higher than the present. A major west-dipping normal fault juxtaposing Tule Wash conglomerate against Proterozoic rocks is exposed across this wash on the east side of Knight Creek where Hackberry Spring emerges (Figure 4).

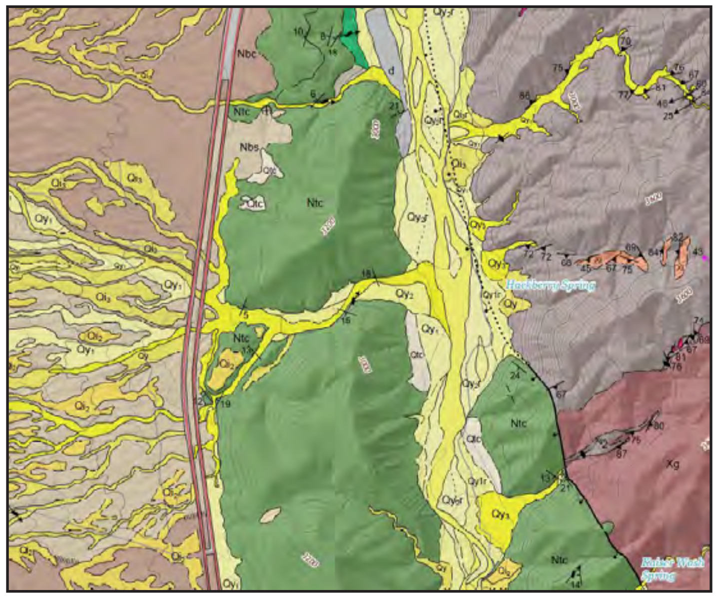


Figure 4. Geologic map snippet of Knight Creek Canyon along Hwy 93).

Saturday Camp at northbound MM 105: Going northbound on Hwy 93, exit right (east) immediately after mile marker 105 onto a gravel road. Continue north on this road about 100 ft to an unlocked gate (please close gate behind you) and proceed east down the wash for 1.0 mile to an opening in Knight Creek. Camping is primitive and dispersed and is on State Land. Note from here to the nearest gas stations in Wikieup is about 25 minutes.

MM 105.9: Passing Blake Ranch Rd (County Highway 129) turnoff on west side of highway. This scenic road crosses high, dissected topography with over 1,000 ft of relief in many places and connects to I-40 at the Loves gas station. Notice the lag of large boulders east of the highway – part of the debris-flow conglomerates in the Tule Wash conglomerate beds (Ntc).

MM 107.4: Passing turnoff east to the Upper Trout Creek Road. This road also connects back to highway 93 a few miles south and provides access to the confluence of Knight Creek and Trout Creek, where Big Sandy River begins. Nearly flat-lying, south-imbricated Big Sandy conglomerate (Nbc) is exposed in roadcuts along Hwy 93 for the next mile.

<u>Stop 0 – Meet and Field Trip Start (~30 minutes)</u>
<u>(34.923°, -113.668°)</u>

Exit US Hwy 93 at MM 108.5, Cane Springs Ranch Road and head west. This is private property so please drive slowly 0.42 mile west to an opening near a few structures and turn sharp left; proceed 0.1 mi across Cane Springs Wash and stay to right and proceed an-other 0.1 mile to a corral opening where we will gather and start the field trip. We will then carpool into as few vehicles as possible to access stops 1 and 2.

Stop 1: Cane Springs Wash (~2 hours) (34.940°, -113.708°)

Proceed west past corral gate 0.5 mile to Pilgrim Wash and at the junction turn right (north) and drive along the south bank of Cane Springs Wash. Proceed for 2.1 miles to Stop 1 (Figure 5). Here we will look at conglomerates and breccia of the Tule Wash formation, Big Sandy Formation fanglomerate, and overall structure and location of basin fill in this part of the basin.

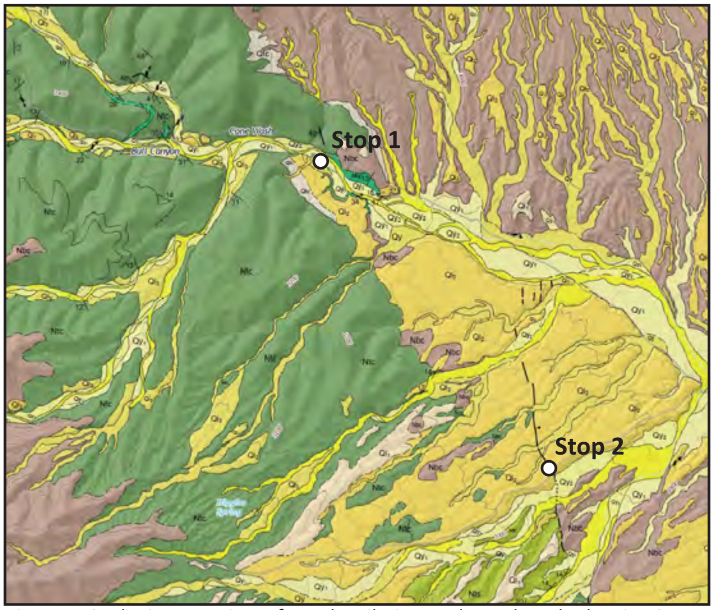


Figure 5. Geologic map snippet from the Pilgrim Wash quadrangle showing Stops 1 and 2.

To Stop 2: We will proceed up the road to a turnaround spot and head back to the Cane Springs and Pilgrim Wash T-junction. Turn right and head southwest 0.9 miles to an abrupt topographic bench about 2 meters high. We will stop here and discuss the fault, its characteristics, and age. Stop 2 is shown in Figure 5, and an aerial drone view is shown in Figure 6.

Stop 2: Hualapai Mountains Quaternary Fault Zone (~1 hour) (34.919°, -113.690°)

At this relatively accessible location we will consider newly discovered evidence for Quaternary activity on the Hualapai Mountains fault zone. Pliocene to Quaternary activity was suspected in this area in the early 1980s, but no definitive evidence was documented at that time (the Hualapai Mountains fault zone of Menges and Pearthree, 1983). Reconnaissance evaluation of modern aerial photography in preparation for detailed mapping efforts in Big Sandy identified several areas where it appeared likely that middle to late Quaternary alluvial fan deposits were displaced. Field reconnaissance and detailed mapping found clear evidence of Quaternary displacement in several areas, including the area of Stop 2.

The predominant deposits around Stop 2 are middle to late Pleistocene alluvial fan deposits, labeled Qi2 on our maps. Deposits of this age are widespread throughout Big Sandy Valley, forming extensive relict alluvial fans and stream terraces; we estimate the age of Qi2 deposits and surfaces based on fairly strong, reddish brown clay soil development (moderate to strong argillic horizons) and their positions in the landscape many meters higher than modern washes. Qi2 surfaces typically are moderately dissected, with some fairly extensive planar surface remnants but plenty of post-depositional erosion.

Evidence of young fault activity here is displacement of the Qi2 surface down to the east, forming a 5-10-m-high, east-facing fault scarp that trends essentially perpendicular to all of the drainages that cross it. In addition, the extent of erosion into Qi2 deposits is greater in the upthrown block west of the fault zone. Similar fault scarps exist on Qi2 deposits 1 km south and 8 km north of this site; Qi2 alluvial surfaces are displaced 3-5 m vertically. Near the southern end of the fault zone, 5 km south of this site, a late Pleistocene Qi3 surface appears to be displaced down to the east by 1-2 m. Much higher possible fault scarps formed on Big Sandy Formation alluvial fan deposits are found at locations between the more obvious Quaternary offsets. We have not found any fault exposures in this immediate vicinity but minor normal faults are exposed along this trend in older, more dissected deposits to the south and north.

Based on these observations, we conclude that there is strong evidence of Quaternary activity on the Hualapai Mountains faults zone. Based on displacement of one Qi3 alluvial fan, the most recent surface displacement likely occurred in the late Quaternary. Greater displacement of Qi2 fans and older deposits indicates recurrent fault movement throughout the Quaternary. Although evidence of surface displacement cannot be confidently identified in more dissected landscapes, locations with clear evidence of Quaternary displacement extend for about 15 km subparallel to the Hualapai Mountain front. We infer that these sites record evidence of sizable paleoearthquakes generated by fault ruptures of 15+ km length.

Return to corral gate and highway. Turn right and proceed south along US Hwy 93 towards our next stop.

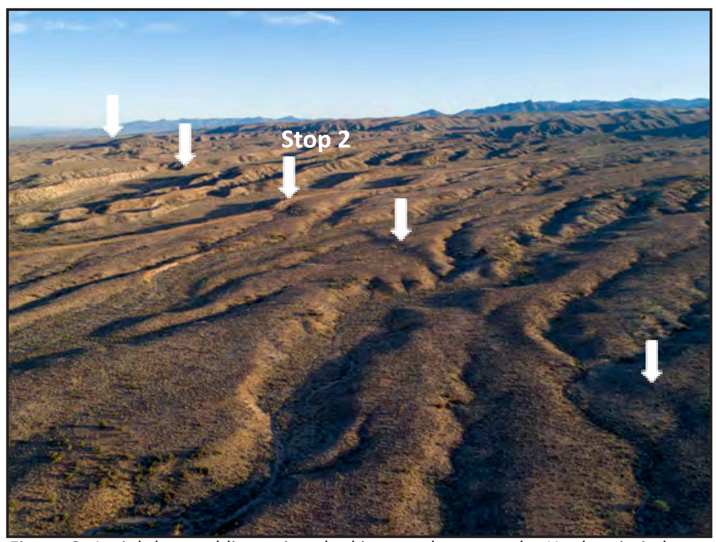


Figure 6. Aerial drone oblique view, looking southwest at the Hualapai piedmont and the "Hualapai Mountains fault". Pilgrim Wash is the larger wash in near center-left. The fault scarp is shown with white arrows. Jeep for scale at middle arrow and location of Stop 2.

MM 110.5: Exit east onto Lower Trout Creek Rd. This section of the road log will follow the east side of the river along Back Rd or Lower Trout Rd. To continue south on Hwy 93, go to the following section "US Hwy 93 southbound continued from MM 110.5"

East side of Big Sandy River via Back Rd/Lower Trout Creek Rd to Pump Station Road (17.3 miles)

Set trip meter to zero. This section of the road log is for the geology along the east side of Big Sandy River and access to Stops 3 and 4. After Stop 4 to upper Burro Wash, we'll exit south to Pumphouse Road onto US Hwy 93 and head back north to camp in Knight Creek.

Mile 0.0: Follow dirt road east 0.8 mile and turn left on Lower Trout Creek Rd. Proceed 1.5 mile to junction with South Upper Trout Creek Rd.

Mile 2.3: Turn right on Trout Creek Road. This surface is a late Pleistocene river terrace (Qi3r) with moderate argillic soil development. The terrace is several meters thick and overlies unmappable Tule Wash formation redbed lithofacies at the end of the roadcut before entering the river.

Mile 2.4: Crossing Big Sandy River. The first part of the floodplain is marked by early Holocene river deposits that exhibit classic gravel bar and sand swale topography with mature creosote, acacia, mesquite, and some juvenile to mature tamarisk, palo verde, yucca, cholla, and desert broom with light to moderate soil development. After crossing the active river channel, notice the coarse river cobbles on the left. These are an older Pleistocene river fill deposit (Qi2r) that was cut down to near, or in some cases, below the modern channel. Following aggradation of the river deposit, the adjacent wash deposits local tributary alluvium (Qi2) on Qi2r.

Mile 3.0: Turn right on Back Road (County Rd 159). Proceed 0.4 mile to Stop 3 at Mile 3.4.

Stop 3: Tule Wash formation lithofacies on Back Road (~1 hour) (34.893°, -113.616°)

Here we will look at the Tule Wash conglomerate lithofacies and structures exposed in a roadcut. Refer to Figure 7 for a reference to geologic units and structure symbols. We'll compare clast lithologies seen in Stop 1 and discuss and compare their provenance. Faults and slickenlines are also present. Using the geologic maps, we'll also discuss map units, structure, paleocurrents and other mapping patterns on the east side of the basin.

Some questions we will explore: What do the subfacies in the Tule Wash tell us about paleodepositional constraints? How does the structure and relative timing of deformation of these beds relate to structures west of here? What is the source of oxide mineralization in the redbed lithofacies? What does the overlying Big Sandy Formation tell us about the timing of deformation and erosion in the basin?

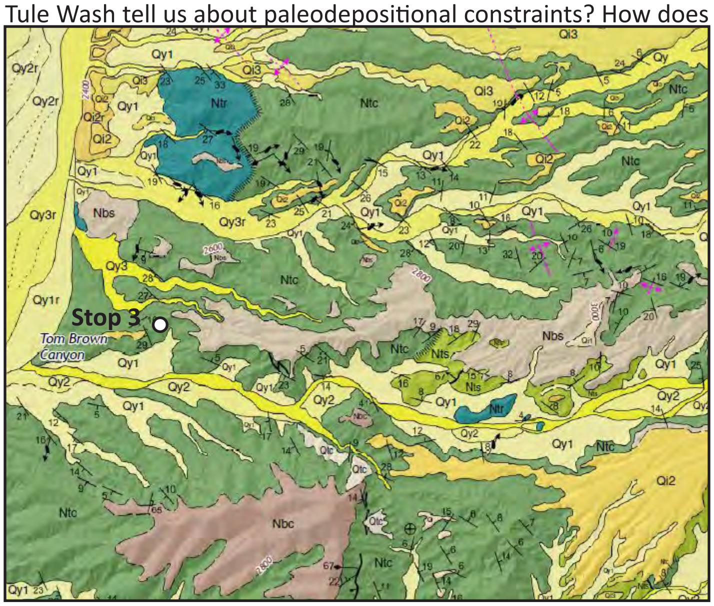


Figure 7. Geologic map snippet from the southern Tom Brown Canyon quadrangle (Johnson et al., 2024). Though the road is too faint to see, Stop 3 is plotted for reference.

Next, we will follow the road log south on Back Road to Stop 4 in upper Burro Wash.

Mile 3.7: Crossing Tom Brown Canyon. Notice tilted strata of the Tule Wash formation up canyon, capped by a younger unit, a sandy lithofacies (Nbs) of the Big Sandy Fm. This contact is 100 ft lower than the same contact crudely exposed south of the wash (Nbc on Ntc). The relative age of Nbc and Nbs are unknown but we hypothesize that the lower Nbs filled in erosional paleotopography cut into the Tule Wash formation first and continued to significantly aggrade throughout the basin to higher elevations, which Nbc fanglomerate represents.

Mile 5.1: Passing road on left to the Big Sandy Shooting Range, recently ranked as the largest machinegun range in the US.

Mile 5.6: Passing exposures of east-tilted Tule Wash beds and entering Pearson Falls Wash.

Mile 6.9: Passing Carpenter Ranch Road on right; this crosses Big Sandy River and leads back to Hwy 93. Near this mile mark, the Big Sandy and Tule Wash formations are difficult to distinguish due to ubiquitous talus and colluvium mantling the slopes; however, the angular unconformity can be mapped and dips steeply to the west and into the subsurface here similar to relationships seen around Stop 3 and throughout the basin on both sides of the valley.

Mile 7.9: Passing unmarked road on right that crosses Big Sandy River back to Hwy 93. Continue south on Back Road.

Mile 8.5-9.5: As we drive through the sandy lithofacies of the Tule Wash formation, the Big Sandy fanglomerate forms prominent cliffs overlying tilted Tule Wash beds seen higher up in the piedmont (Figure 8). Big Sandy Fm. fanglomerate is part of a large alluvial fan remnant from Pearson Falls Wash. In the middle-ground, debris-flow conglomerate beds form more resistant olive gray ridges with interbeds of softer sandstone. Though exposures are poor, some of these conglomerate beds are suspected to be related to or are inherently rock-avalanche deposits in the Tule Wash formation.

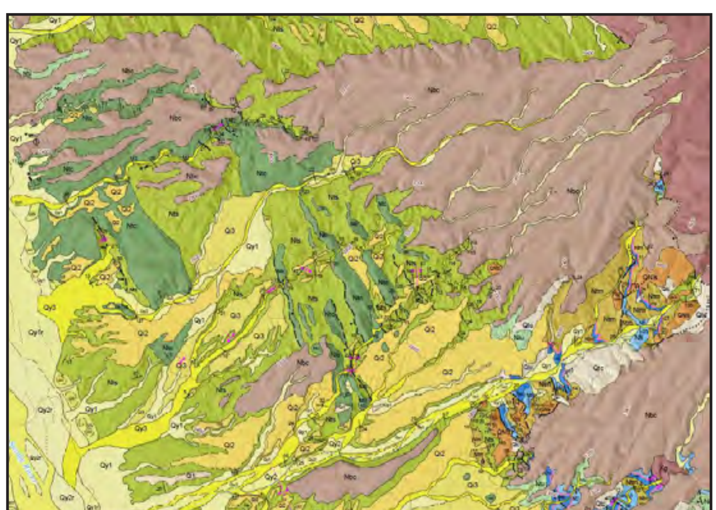


Figure 8. Snippet taken from the geologic map of the Tule Wash Quadrangle (Gootee & Johnson , 2023). Notice the Big Sandy fanglomerate (unit Nbc) overlying Tule Wash strata tilted east against Aquarius Mountain crystalline rocks.

Mile 10.1: Crossing Tule Wash, the locality namesake for the Tule Wash formation. A generalized cross section by Scarborough and Wilt (1979) is colorized in Figure 9.

Mile 10.7: Crossing Big Wash. The upper parts of this wash offer excellent exposures of the Tule Wash formation, though road travel is slow and challenging. A snippet from the Tule Wash Quadrangle geologic map is shown in Figure 10.

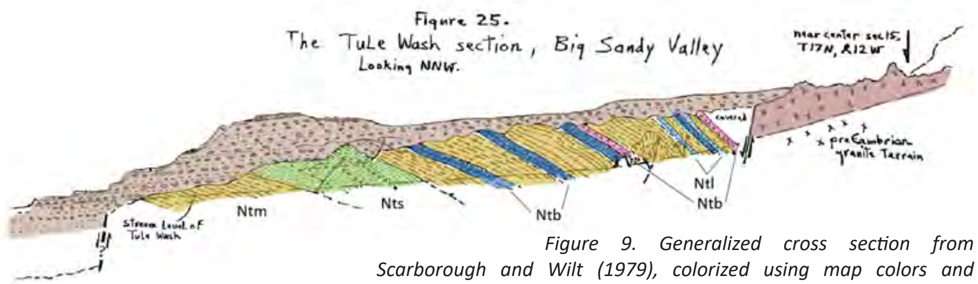
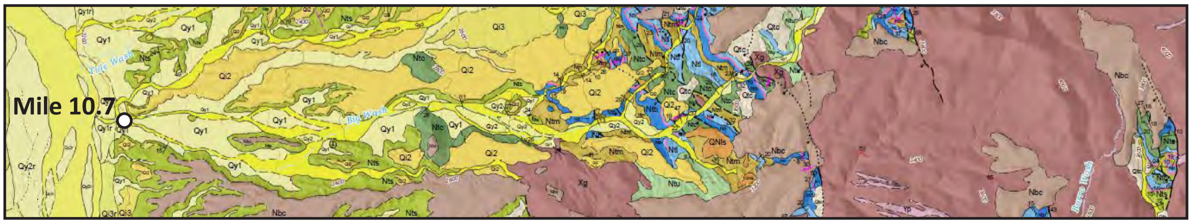


Figure 9. Generalized cross section from Scarborough and Wilt (1979), colorized using map colors and units from recent geologic mapping. There are many faults in the sequence that repeat Tule Wash stratigraphy. Interbedded rock avalanche deposits and debris-flow conglomerates are also not accounted for.

Figure 10. Map view of Big Wash, Tule Wash formation lithofacies, Big Sandy Fm., and Proterozoic rocks mantled by Tule Wash formation in the Aquarius Mountains.



Mile 12.8: Crossing the mouth of Burro Wash. This wash offers a variety of geologic features that almost made it into the field trip, however, the wash was recently blocked off by flooding and not accessible on this trip. Figure 11 is a snippet from the Tule Wash quadrangle of Burro Wash. A few points are worth summarizing the geology of lower Burro Wash:

- Unlike sections north of this wash, the entire exposed section of Tule Wash beds are east-tilted toward a west-dipping range-bounding fault, except near the fault where beds are dragged and dip westerly. Anticlines and synclines are common.
- Near the main fault, east-tilted sandstone lithofacies has several debris-flow conglomerates and possibly rock-avalanche or sturzstrom deposits (shown on the cover and Figure 11). Beneath one such deposit, a vitric ash up to 6 m thick is also incorporated into the sturzstrom-like deposit. This ash yielded zircons with a U-Pb age of 10.4 ± 0.2 Ma (Appendix 4).
- The rock avalanche deposits are mud and sand-supported with boulders up to 10 m long, weathering into soft slopes with structureless bedding and occasionally visible recumbent folds (shown as orange marker beds on map). Avalanche beds are up to 10 m thick, overlain and underlain by para-planar, tabular sand beds. Directional indicators (fold asymmetry, fold axes, and shear planes) indicate a westerly source, and the deposits contain porphyry clasts resembling rocks present in the Hualapai Mountains but not the Aquarius Mountains (Figure 12). These observations suggest a highly asymmetric valley axis along the eastern side of the basin.
- An angular unconformity between tilted Tule Wash beds and overlying Big Sandy Fm. fanglomerate (unit Nbc) is present everywhere exposed. This contact dips into the subsurface about 0.25 mile from Back Rd. and probably represents early Big Sandy basin-filling.
- One early Pleistocene river terrace (Qi1r) is exposed at the top of a hill near the mouth of the wash on the north side, about 70 m (230 ft) above the modern river floodplain; age unknown.

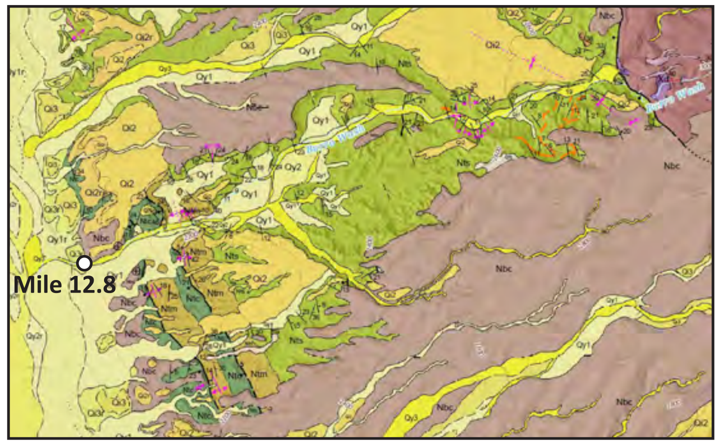


Figure 11. Geologic map snippet of lower Burro Wash. Upper Burro Wash (not shown) is in our next Stop 4.

Mile 14.3: Turn left on unmarked dirt road towards upper Burro Wash. Bull Canyon will be visible along the south side of road. **Reset odometer to zero.**

Figure 12. Aerial drone view of Tule Wash sandstone beds (Tts/Nts) with interbedded rock-avalanche deposits (Ttx/Nts). Note Jeep center-right for scale.

Mile 3.4: Exit left on small dirt road and descend into the south fork of upper Burro Wash. See Figure 13 for the geologic units we will encounter on the way to Stop 4. At mile 3.8 you will cross the south fork of Burro Wash, where the road ascends across weathered Proterozoic rocks (unit Xg) into overlying Big Sandy conglomerate (unit Nbc). The angular unconformity is seen to your right, where Big Sandy conglomerate overlies an east-dipping ledge of Tule Wash limestone (unit Ntl) ~50 m upstream (Figure 14). The nonconformity between the Proterozoic rocks and Tule Wash formation is covered by colluvium here. Proceed 1.3 miles to Stop 4 (mile 5.1) to the north fork of Burro Wash.

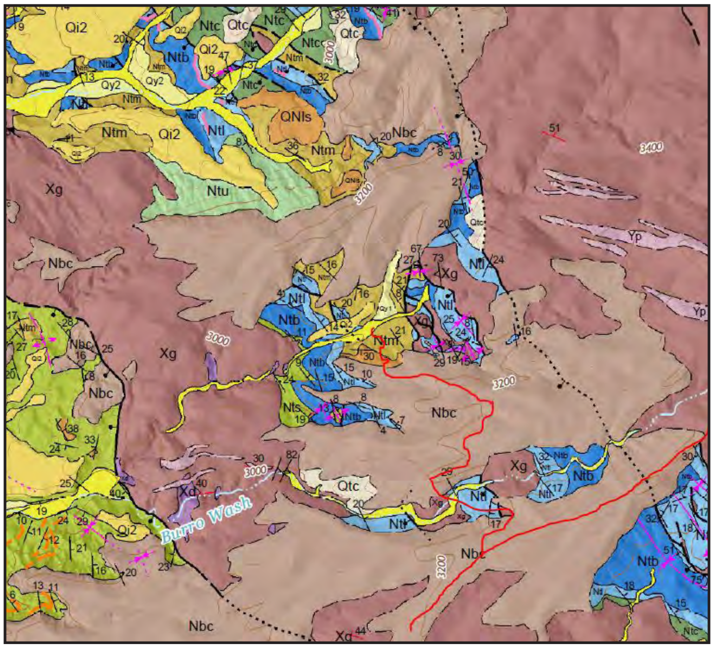


Figure 13. Geologic map snippet from the Tule Wash quadrangle (Gootee and Johnson, 2023) highlighting the road (red line) to Stop 4.

Stop 4: Upper Burro Wash Geology (2 hours) (34.802°, -113.552°)

The Tule Wash formation is exposed in a series of east-tilted fault blocks along the north fork of Burro Wash. We will walk through a well-exposed section of the lower part of the succession in the western fault blocks. Proceed downstream 400 m from the road to a side canyon on the north side of the wash. Continue up this side canyon to the unconformity at the base of the Tule Wash formation, where Proterozoic granite, diorite, and pegmatite are overlain by conglomerate and sandstone 2-4 m thick (unit Nts). The sandstone is overlain by basalt (Ntb), approximately 55 m thick. We can briefly discuss how textures in the basalt may have formed in subaqueous lava flows. Continue up section to exposures of the limestone lithofacies (unit Ntl). This unit, about 20 m thick here, consists of thin- to medium-bedded white limestone with interbeds of olive-gray sandstone and intervals of thinly interbedded limestone, pink mudstone, and gray shaly mudstone. In some sections, pisolite beds and tepee structures are observed; none were noted here, but look out for those features. The limestone is overlain by mudstone lithofacies (unit Ntm; Figure 15), which is characterized by poorly indurated yellow-tan, orange, and light green-gray mudstone, commonly with selenite gypsum seams (Figure 16) and thin interbeds of fine-grained sandstone. Some intervals contain gray crystalline limestone. Worley (1979) interpreted the limestone and mudstone as representing shallow lacustrine and playa environments, respectively. There is an excellent exposure of the mudstone lithofacies near where the vehicles are parked, so we will return there rather than continuing up this canyon section.

After observing gypsiferous mudstone outcrops near the road, proceed back to vehicles and return 5.1 miles to Back Road.


Figure 14. Angular unconformity in upper Burro Wash, east-tilted Tule Wash limestone overlain by Big Sandy conglomerate.


Figure 15. Limestone lithofacies (right, white to pinkish) overlain by orange to yellow-tan poorly indurated mudstone. North fork of Burro Wash, looking east.


Figure 16. Tule Wash mudstone lithofacies with concordant selenite gypsum layers.

Mile 0.0: At Back Road intersection, reset the odometer to zero and turn left (south).

Mile 0.6 to 1.5: Crossing Bull Canyon Wash. Over the next ~1 mile on the east of the road are badland bluffs of olive gray, muddy and tan sandy lithofacies of the Big Sandy Formation. These facies represent the uppermost mixed lacustrine and playa depocenter of the basin floor exposed at this elevation. The muddy and sandy lithofacies are generally intermixed and transition east into conglomeratic lithofacies over 1 km. Big Sandy Fm. deposits are flat lying to very gently dipping westerly. The Tule Wash units are buried in the subsurface but are exposed further south in the Wikieup quadrangle.

Mile 1.8: Turn right on Pump Station Rd. and proceed west 1.4 mile to US Hwy 93. Turn left if going to Wikieup and right to head to camp at Knight Creek.

US Hwy 93 southbound continued from MM 110.5

MM 110.5: Continue south from the road log section "From I-40 & Hwy 93" at MM 110.5.

MM 113.5-115: The highway crosses well-rounded hills of sand and fine gravel of the Big Sandy Formation sandy lithofacies, mostly seen on the west side of the highway. One limestone bed found interbedded with sandy beds indicates the expansion of the Big Sandy lake further south up into this area. The muddy lithofacies is not exposed in this part of the basin which may suggest pulses of siliciclastic fine-grained sediment were located further south in deeper water.

MM 115.7: Crossing Deluge Wash, a major wash that cuts across the late Cretaceous Diamond Joe composite pluton, Proterozoic bedrock, Tule Wash and Big Sandy basin fill deposits, and Pleistocene fans (Figure 17). The Big Sandy conglomerate lithofacies (Nbc) is prominent and fills eroded Tule Wash formation in this part of the basin. A sandy facies (Nbs) is present near the mouth of Deluge Wash including several thin limestone beds near the paleo-axis of the Big Sandy depocenter. Near the upper end of a thick Qi2 fan deposit on the south side of Deluge Wash, Qi2 alluvium is 30 m (100 ft) thick. One exposure of this unusually thick deposit was sampled for cosmogenic burial dating and infrared stimulated luminescence of feldspar (IRSL) dating to capture the age and accumulation rates of Qi2 here, but also as a proxy to other thick Qi2 deposits seen throughout the valley.

NOTE: The Diamond Joe pluton, discussed below, is not visited on this trip. Access is, in general, quite poor, with the road/jeep trail along Deluge Wash presently only accessible via foot from a mile west where Crow Canyon joins Deluge Wash to the Leviathan vein. While an ATV could potentially make it along the southern Deluge Road road/jeep trail, most vehicles will become stranded. The road to the north of Crow Canyon, splitting off from US-93 and passes the "Water Tanks" marked in the SW1/4 of Section 17 of T17N R13W, is easily drivable to the eastern margin of the pluton and can be driven around the pluton to approach from the west, where the road is in general in good repair (as of April 2023). However, local rock falls have occurred onto the road that make passage challenging. Hopefully the road will receive attention and maintenance in the future to increase access to this remarkable field site.

The Diamond Joe pluton, not visited in this trip, consists of three major phases: an outer equigranular granodiorite, an intermediate porphyritic quartz monzonite, and an inner quartz monzonite porphyry (Gerla, 1983; Thompson et al., 2023). Loghry (1973, in AZGS Mining Data, 2014a) referred to these phases as the Leviathan biotite granodiorite (equivalent to equigranular granodiorite), Hamme quartz monzonite (equivalent to porphyritic quartz monzonite), and the coarse porphyry (quartz monzonite porphyry). Additional volumetrically minor phases include quartz porphyry, granite, and rare porphyritic dacite-latite (Gerla, 1983). The outer equigranular granodiorite phase has previously reported U-Pb zircon ages of 72.1 ± 0.6 Ma and 72.8 ± 3.2 Ma by, respectively Greig (2021) and Chapman et al. (2017). Mid-Cenozoic lamprophyre dikes cut the Diamond Joe stock.

The Gunsight fault has a strike of 145° and dips SW with an estimated throw of 340-525 m (Gerla, 1983). Unaltered gouge suggest the fault is post-mineral. The principal vein systems in the pluton are the Leviathan vein and Silvertrails vein (respectively trending 055° and 065°) which are up to ~10 m in thickness.

Gerla (1983) describes two broad patterns of alteration mineral zonation, generally interpreted as an early high-temperature alteration and later lower-temperature alteration, with quartz+pyrite or iron oxide typically associated with each alteration assemblage. The first pattern is generally concentric and zoning out from the center with K-feldspar, K-feldspar+muscovite, K-feldspar+muscovite+chlorite, albite+muscovite+chlorite, and albite+chlorite+epidote. The second alteration event produced superposed sericite+K-feldspar,argillic, and carbonate alteration. Particularly noteworthy is the abundant coarse muscovite, also called greisen, alteration present throughout the Diamond Joe pluton. Runyon et al. (2019, Table 1) summarizes the diversity of coarse muscovite veins in the Diamond Joe pluton from dominantly muscovite with muscovite envelopes veins, K-feldspar+muscovite+quartz+fluorite+calcite, quartz+muscovite+K-feldspar(±chalcopyrite+molybdenite), quartz-pyrite veins with muscovite+K-feldspar envelopes. Sulfide mineralization is dominantly restricted to an arcuate zone in the hanging wall (southwestern) block of the Gunsight fault (AZGS Mining Data, 2014b).

The presence of abundant coarse muscovite alteration is suggestive of the modern exposures at Diamond Joe are representative of the root zones of a porphyry system. Bell Copper is currently exploring and drilling at their Big Sandy porphyry prospect to the ENE of Diamond Joe that is inferred to be the top of the Diamond Joe pluton. U-Pb zircon dating of a granodiorite (74.2 ± 1 Ma) intercepted in drill core overlaps with the Chapman et al. (2017) date. Drill hole BS-1 largely encountered propylitic alteration and BS-2 (while largely in Proterozoic bedrock) encountered propylitic alteration with a few meters of leached capping and supergene enrichment. Drill hole BS-3 encountered 111 m of leached capping above a 200-m interval of supergene chalcocite with an average grade of 0.42 % Cu and 2.4 g Ag/tonne. Below the supergene enrichment blanket, BS-3 intercepted a further 524 m dominated by pyrite (averaging 10 wt. %) with minor chalcopyrite (20:1 pyrite:chalcopyrite), tennantite, sphalerite, and trace molybdenite. This interval averaged 0.16 % Cu and 2.2 g Ag/tonne (Bell Copper, 2024). Drilling of BS-4 is ongoing.

MM 116.6: Passing turnoff west to well-travelled dirt road up south side of Deluge Wash. The exit to the east is a short loop

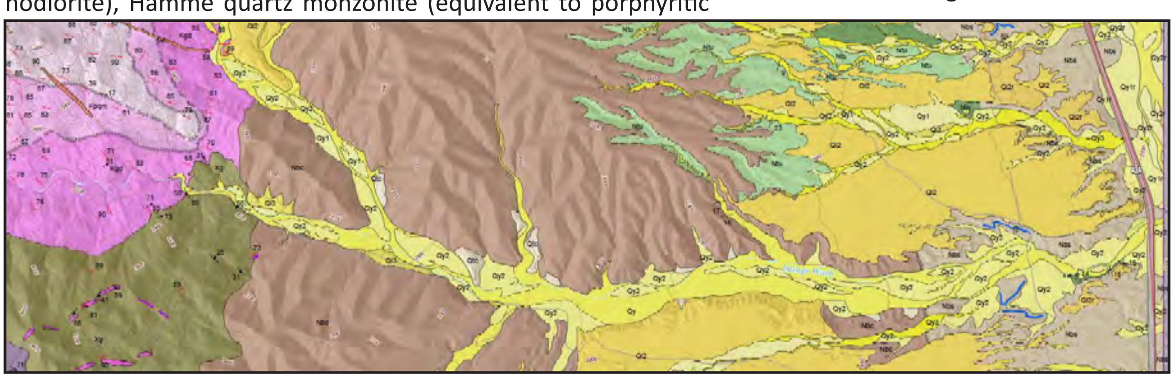


Figure 17. Geologic map snippet from the Gunsight 7.5-min quadrangle (Thompson et al., 2023). Big Sandy Formation sandy lithofacies (Nbs), conglomeratic lithofacies (Nbc) and undivided Tule Wash formation (Ntu) are basin fill units shown. The blue line are interbedded limestone beds.

through old Hwy 93 and offers nice roadcut exposures across Qi2r Big Sandy river deposits overlying basin fill (Nbs).

MM 188 to MM 120: Passing Gunsight Canyon. The highway passes through small exposures and rounded fan remnants of latest Pleistocene age that cap Big Sandy Fm. sandy lithofacies (Nbs).

MM 120.3: Passing Tompkins Canyon wash.

MM 121.3: We will pass the exit to Pump Station Road and proceed to Chevron or Mobile gas stations in Wikieup for a short pit stop, gas if needed, and carpool to Stop 5. We will then return to this mile marker and follow instructions for the next segment of the road log “Pump Station Road to Stop 5”.

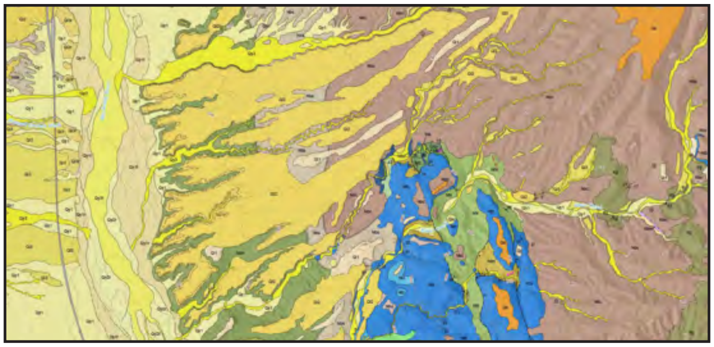


Figure 18. Geologic map snippet from northern part of the Wikieup quadrangle (Ferguson et al., 2023) showing the locations of mile marks and Stop 5.

Pump Station Road & East Loop to Stops 5 and 6

MM 121.3 – Mile 0.0: Turn onto Pump Station Road. Reset the odometer to zero. Head east 1.25 mile, across Big Sandy River, to Back Road/Lower Trout Road.

Mile 1.25: Turn right on Back Road/Lower Trout Road and immediately cross Boner Wash. The road will ascend onto a broad, planar alluvial fan remnant mapped as a middle to late Pleistocene surface (Qi2). A moderate to strong argillic soil development is typical of this age landform. Qi2 surfaces are the large fan-shaped polygons on the left, center-top of Figure 18.

Mile 3.0: crossing gully cut into sandy lithofacies of Big Sandy Formation. The axis of basin fill deposition at this time was about a km to the west, though this margin was close to the nearshore or waterline, indicated by occasional freshwater limestone beds that punctuate this facies.

Mile 3.2: Immediately east of the road is a high fan surface remnant (Qi1) about 40 m (130 ft) above the road, and 130 m (420 ft) above the modern river (Figure 18). The age of this surface is unknown, older than the highest fan (Qo), but younger than Qi2. Further east is a rare, preserved high fan remnant (Qo) that likely represents the maximum basin highstand of the Big Sandy Formation, standing at 1,030 m-elevation, over 430 m (1,400 ft) above the modern river. Age constraints on both bracketing units are forthcoming.

Mile 4.2: The road suddenly descends off the Qi2 fan into the muddy lithofacies of the Big Sandy Fm. Notice the rich, olive-gray mud and clay below capping Qi2 alluvial gravels.

Mile 4.9: Turnoff to smaller dirt road to east (left) and proceed 0.4 mile to an unnamed wash. We’ll park, put up some maps, and walk over to outcrops at Stop 5.

Stop 5 Big Sandy Formation Type Locality (2 hours)
(34.706°, -113.579°)

From the parking spot we will hike up to an eroded badland of muddy lithofacies of the Big Sandy Formation, the type locality. We will discuss the work of Sheppard and Gude (1972), geochronology, and sedimentary textures/structures.

Figure 19. Soft-sediment deformation in the muddy lithofacies of Big Sandy Formation at the type locality.

The Big Sandy Formation was formally described by Sheppard and Gude (1972) as consisting chiefly of lacustrine deposits occupying an area of approximately 70 km2 in southern Big Sandy Valley. They defined the Big Sandy Formation as lacustrine facies consisting of mudstone, with silt and sand components. They recognized a marginal conglomerate lithofacies that laterally grades into the lacustrine facies but did not include the coarse-grained facies as part of the formation definition or extent.

Geochronologic work to constrain the upper and lower ages of the Big Sandy Formation is ongoing. Basaltic dikes that intrude and are interbedded with conglomerate lithofacies at stratigraphically and topographically high levels southwest of Wikieup are consistent with a latest Miocene age between 5.9 and 5.5 Ma for deposition (Macfadden et al., 1979; Wilshire, 1990; this mapping), but the upper and lower ages of the formation remain unknown.

Based on our mapping of lithofacies equivalent to the Big Sandy Formation in the Wikieup quadrangle and farther north, the southern Big Sandy valley was a terminal closed-basin depocenter for primarily fine-grained siliciclastic deposition in a shallow, groundwater-fed alkaline lake, punctuated by shallow lacustrine carbonate deposition. Sediment and water were locally supplied from the Hualapai Mountains, Aquarius Mountains, and the Poachie Range, and from ancestral drainages supplied from roughly the area near the confluence of Knight Creek, Cane Springs Wash and Trout Creek. Sediment of the Big Sandy Formation in the southern depocenter aggraded up to a maximum-filling surface before spilling across a bedrock sill further south, integrating Big Sandy and Greenwood valleys that resulted in the formation of the Big Sandy River. Incision of the Big Sandy River into fine-grained Big Sandy Formation deposits resulted in a series of off-lapping or prograding alluvial fans that tracked basin incision during the Pliocene and Quaternary.

At Stop 5, the primary bedforms in mud and clay beds are generally laminated-planar, but are often deformed by soft-sediment deformation (tee-pee, dissolution-collapse) subsequently overlain by non-deformed bedding (Figure 19). Silica and carbonate cement are secondary. Mineralization in this lithofacies has been explored for lithium, uranium and other heavy elements (Hawkstone Mining, 2019; Scarborough and Wilt, 1979; Granger and Raup, 1962) which lies within the Nbm map unit (not differentiated).

Hike back to vehicles and proceed back to Lower Trout Rd/Back Rd.

Mile 4.9 (cont’d): We will resume travel south on Back Rd to Hwy

93 and towards Stop 6. Notice south of this point high, rounded gravels (map unit Qi1r, capped by Qi1).

Mile 6.4: Passing the entrance to Cofer Hot Springs, a privately owned site. The road we're on also appears to change from Lower Trout Road/Back Road to Cholla Canyon Ranch Road. The springs are a sacred site to the Hualapai Tribe, also known as Ha' Kamwe'. Extensive riparian and palm trees are found around the spring.

Figure 20. Primary textured vugular limestone typical of the limestone lithofacies of Big Sandy Formation. This lithofacies is probably associated with groundwater-fed springs, though other textures indicat precipitation from an ephemeral-perrenial alkaline lake and are especially prevalent in bedrock reaches sheltered from sediment input from tributaries.

Figure 21. Bedded limestone east of Wikieup draped on rhyolite breccia interpreted to be a rock-avalanche breccia associated with the Tule Wash sequence.

The spring is artesian fed, thought the source of the groundwater is unclear. No faults that cut across Big Sandy deposits were identified through mapping. The spring chemistry is sodium-mixed, slightly alkaline, with a temperature of about 34oC (93oF), with elevated Arsenic (0.15 mg/L) and Fluoride (4.25 mg/L), and 800 mg/L Total Dissolved Solids (Towne, 2009). The estimated artesian discharge is 290 acre-ft/year (~10,800 gallons per minute).

Mile 7.0: Crossing Bitter Creek. This creek and unnamed creeks immediately south offer excellent exposures of the carbonate/ limestone lithofacies of Big Sandy Fm., which lapped up on older, eroded rocks equivalent to the Tule Wash formation. See Figures 20 and 21 of this facies.

Mile 8.7: End of loop County Rd. 159 with US Hwy 93 at MM 127.4. Turn left and proceed south towards Stop 6.

MM 128.7: Exit south on South East Street. Set odometer to zero.

Mile 0.0: Drive southwest on S. East St.. At 0.1 mile you will drive over a fresh alluvial fan emanating from Gray Wash into Big Sandy River.

Mile 0.45: Leaving Big Sandy River floodplain into an active wash cut into a Holocene alluvial fan; proceed straight into wash. Notice the red-brown rocks to the right and along the north side of

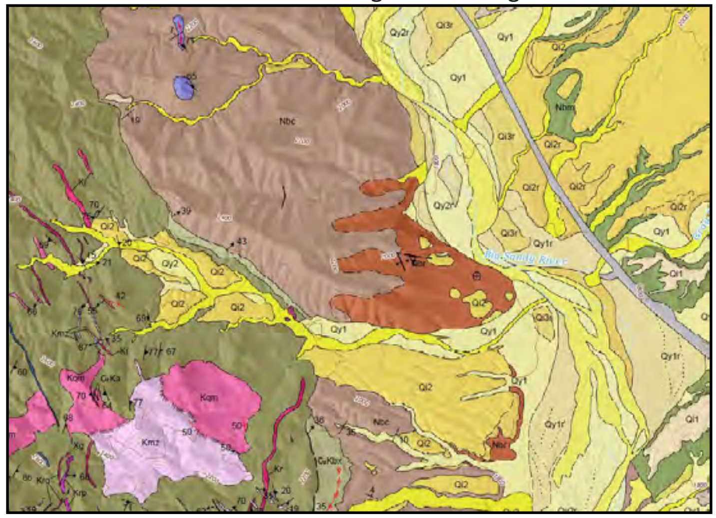


Figure 22. Geologic map snippet from western Wikieup geologic map (Ferguson et al., 2023) to Stop 6.

the unnamed wash (Figure 22). These redbeds are equivalent to the conglomeratic lithofacies of the Big Sandy Formation. Oxidation of this lithofacies grades from strong, well-cemented and indurated along the river, to a gradation into unoxidized deposits further up stratigraphic section. North along S. East St. are metate grinding pits and other archaeological remnants from ancestral inhabitants of the valley.

Mile 0.8: Exit wash onto dirt road on south side of wash. This is a late Pleistocene fan remnant, unit Qi3.

Mile 1.5: Turn right at fork in road and proceed into the wash a short distance to an exposure of rhyolite bedrock in the wash. This is Stop 6.

<u>Stop 6: Silicified Breccia: Hualapai Low-Angle Fault(?)</u>
<u>(34.640°, -113.593°)</u>

The silicified breccia occurs in the area around the Wikieup porphyry prospect, where the unit outcrops along the contact between the Proterzoic granite and gneiss (Xg) and conglomeratic facies of the Big Sandy Formation (Nbc). The silicified breccia varies in thickness from 30-100 meters along its northern exposure and up to 330 meters along its southern exposure. The upper contact, in proximity to the Big Sandy Formation (Nbc), is typically stained dark brown to red brown due to oxidation, and has local exposures where a weak linear fabric, interpreted here as dip-slip fault striae, are present. The silicified breccia has subangular to subrounded clasts (and lesser angular clasts) of all Proterozoic rock types, and many small clasts that are highly silicified preventing definitive identification of the protolith (but potentially Cretaceous intrusive rocks). Petrographic examination shows intense silicification with the smaller clasts replaced by fine-grained quartz. Rare feldspar grains display clear evidence for partial replacement by quartz along their margins. Where mafic minerals were present, they have been completely replaced by chlorite.

Along the northern exposure, the upper surface dips 39-50°NE. The lower contact, in proximity to the Proterozoic granite and gneiss, dips 36°NE and 35°SE along the southern exposure. This change in dip direction is interpreted to the silicified breccia representing a fault that forms a salient around the Wikieup porphyry prospect, similar to how it was originally described by Hansen (1977) as a "silicified gouge zone." The difference between Hansen (1977)'s interpretation and that of the authors here is that we do not attribute the fault to accommodating the emplacement of the Wikieup stock as it is not in contact with the stock anywhere. Instead, we interpret this fault, preserved as silicified breccia, to be pre-Big Sandy Formation. The Big Sandy Formation does not appear anywhere to be faulted or silicified, suggesting that the silicification was syn- or post-deformation, and the Big Sandy Formation was later deposited against the silicified fault.

This fault could be the along-strike continuation of the Hualapai low-angle normal fault. Presently, that fault is best documented by seismic reflection (Pastor, 2013) run by Bell Copper in ~2007. Mapping in the Dean Peak 7.5' quadrangle (Garcia et al., 2024) did not reveal surface exposures of the fault, but suggest the fault is located near the contact between bedrock and basin-fill conglomerates. However, the young and generally undeformed Big Sandy Formation in many places covers the contact between bedrock and the deformed Tule Wash beds. Mineral exploration of the Perseverance and Big Sandy porphyry prospects as the top of the, respectively, Wheeler Wash and Diamond Joe plutons is suggestive the fault continues southward, with one possibility being that this outcrop could be the along-strike continuation of the Hualapai low-angle normal fault. See Appendices 2 and 3 for more detail about the Wheeler Wash and Diamond Joe plutons, respectively. The difference in dip between the fault as suggested by seismic reflection and in outcrop could be explained by a decrease in displacement toward the Wikieup prospect, with normal fault-related tilting decreasing towards fault tips. Alternatively, this could be an unrelated structure.

Return back to vehicles and head back to the junction on west side of Big Sandy River. To get back to Wikieup there are two options:

1.) Head straight to Hwy 93, turn right and go east 1.3 miles to a turnaround, then back west about 6 miles on Hwy 93 to Wikieup.

2.) The road to the left (north) leads 2.5 miles north back to Hwy 93 where you can cross the southbound lane and drive 2.8 miles back to Wikieup. On this route, 1.4 miles into the drive you can see a basalt plug up the unnamed wash that crosscuts Big Sandy conglomerate (see purple unit Nbb cutting Nbc in Figure 22). The plug also turns into a flow on Nbc where the flow is capped in other places by more conglomerate; thus interbedded with some of the highest Big Sandy Fm. Deposits, representing the latest or maximum depositional age of the formation. The flow was previously K-Ar dated to ~5.3 Ma by Wilshire (1990). We redated the flow via 40Ar/39Ar from groundmass concentrate and yielded a date of 5.23 ± 0.11 Ma.

Figure 23. An iconic artwork and entrance to Wikieup. Apparently, this was built in the 1990's by a couple from Michigan who no longer reside in the valley.

US Hwy 93 Southbound cont'd: Pump Station Rd to Burro Creek

MM 121.3: Passing Pump Station Road.

MM 121.5: Crossing over Natural Corrals Wash. Camping and excellent views are accessible up this wash. The Big Sandy Formation is exposed throughout the wash, conglomerate and sandy lithofacies, with rare carbonate beds.

MM 122.7: Notice a welcoming iconic homespun rocket art with Snoopy, Woodstock, and Spike on the right (Figure 23). Entering northern Wikieup.

MM 123.7: Passing County Rd 123 or Chicken Springs Road on right (west). This road connects to Dutch Flat and Alamo Lake.

MM 123.8: Chevron gas station and potential carpool site 1 of 2. The second carpool option is a Mobile station also on the west side 0.2 miles south.

MM 125.9: Crossing over Bronco Creek, a seemingly small creek with a moderate ~50 km2 watershed. This creek experienced an extreme flood on August 19, 1971 (House and Pearthree, 1995). Waves were splashing over the highway bridge (the current southbound bridge) but it survived the flood. In the vicinity of upper Burro Creek, the Proterozoic Burch Peak Batholith is extensive and is crosscut by numerous diabase, leucogranite, pegmatite, and Laramide rhyolite, monzonite and quartz-monzonite dikes.

MM 126.5 to 127.2: Crossing Big Sandy River.

MM 127.4: Passing exit to County Road 159 (Cholla Canyon Ranch Road/Back Road/Lower Trout Creek Road) that follows the east side of the river up to Knight and Trout Creeks.

MM 127.7: Crossing over Sycamore Creek.

MM 128.3: Passing dirt road on right (north side). The high Qi2 fan to the right was the site for multiple test holes and wells drilled around 2000 for the Caithness Big Sandy project that evaluated a site for a future natural gas-fired generating station. Ultimately, the site was rejected. Surficial geology combined with well data was used to construct a NE-SW cross section through here, shown in Figure 24. One of the findings of the study revealed a lower aquifer below the Big Sandy lake beds with artesian conditions similar to Cofer Hot Springs. These lower beds are interpreted to be equivalent to the Tule Wash formation beds, and the westernmost part of the Kaiser Spring volcanic field.

MM 128.6: Crossing over Gray Wash. And access to Banegas Crossing and South East Street on south side of highway only (no access from northbound traffic).

MM 128.8: Two excellent exposures of the muddy and sandy lithofacies of Big Sandy Formation in roadcuts on north side of highway. Mid-Pleistocene alluvium cut and fills the top of the roadcut.

MM 129.2: On the left (north) is a brief view into badland topography associated with muddy and sandy lithofacies of Big Sandy Fm., capped by middle and late Quaternary alluvial terraces.

MM 129.5: Spectacular roadcuts through more muddy and sandy lithofacies of the Big Sandy Fm. Two generations of Qi2 are cut into the upper part of basin fill. Samples from the muddy lithofacies were sieved and analyzed for microfauna, pollen, microcarbon; however, did not yield any results. Multiple samples in these facies have been analyzed with similar results. Nearby chert beds are also common, found in both muddy and limestone facies. The favored interpretation based on work done to date is that the Big

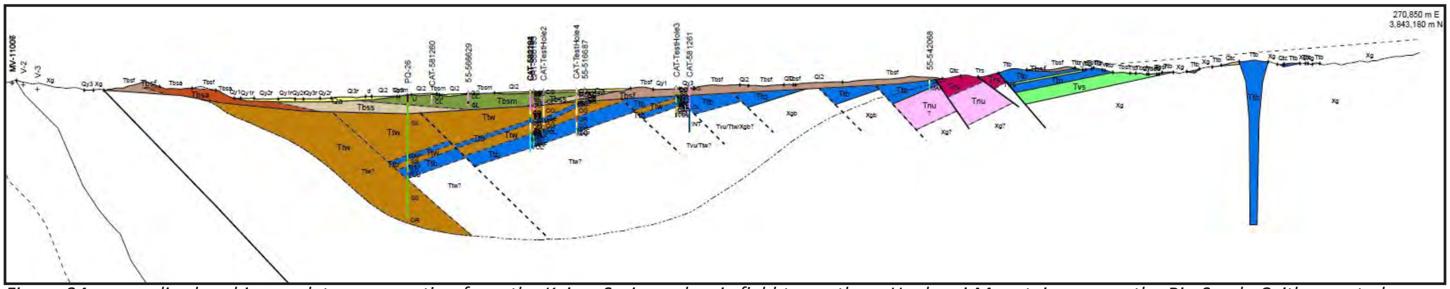


Figure 24. generalized and incomplete cross section from the Kaiser Spring volcanic field to southern Hualapai Mountains across the Big Sandy Caithness study area, combining surface mapping with subsurface well log data.

Sandy paleolake had moderate to high alkaline water with occasional freshwater incursions (Cohen, Quade and Bright, personal communication, 2021-2024).

MM 130.1: passing dirt road on north side of highway that provides access to numerous areas on mixed private and BLM land.

MM 131.7: Crossing Box Canyon where horizontal strata of carbonate-cemented sand with limestone interbeds are exposed in the canyon walls. South of US Hwy 93 these lithofacies contain numerous megafauna excavated in a few quarries.

MM 132.1: Crossing turnoff to Burro Creek Crossing Rd to the north, and Signal Road (Road 137) to the south. Signal Road also leads to Camp option #3 in Box Canyon Wash. Signal Road leads to Alamo Lake and the lower Colorado River corridor near Parker, AZ.

MM 133.5: Around this mile mark, Big Sandy fanglomerate deposits overlie bimodal volcanics to the south that are mantled on Proterozoic bedrock of the Poachie Range. Basalt flows in this area have been 40Ar/39Ar dated to 10.34 ± 0.08 and 10.11 ± 0.09 Ma, though their relationship to the Kaiser Spring volcanic field north and east is unclear. The Big Sandy Formation muddy and conglomerate facies unconformably onlap these rocks, suggesting that the basalt and rhyolite are probably related to deposition and/or erosion of the Tule Wash formation in this part of the basin.

MM 134.5 and 134.7: roadcuts through Big Sandy Formation, fanglomerate lithofacies. Multiple small faults and soil horizons are visible, shown in Figure 25.

MM 135.2: Crossing Kaiser Springs Wash and prominent bridges.

MM 138.6: A thin basalt flow caps tuff and volcaniclastic beds. The age of the flow is not yet dated, though it is one of the youngest flows in the volcanic field. Overlying this flow are remnants of basin-fill deposits to the south and east, dissected by Burro Creek and a major tributary south of US Hwy 93, Black Canyon. Burro Creek likely integrated across western Kaiser Spring volcanic rocks and the Poachie Range via aggradational piracy or spillover sometime after 5 Ma.

Figure 26. Aerial drone view looking north at US Hwy 93 bridge over Burro Creek towards the Kaiser Springs volcanic field. Elephant Mountain is visible on the horizon-left.

Figure 25. roadcut exposures along US Hwy 93 annotated to show faulted strata (black lines) and soil horizons (yellow lines).

MM 138.85: Driving on northbound Burro Creek bridge crossing over Burro Creek, 388 ft below (118 m) (Figure 26). Both bridges are two of the southwestern United States' longest arch spans. The original silver colored two-lane truss arch (now the southbound lane) was built in 1966 by the American Bridge Company and spans 680 feet between hinges, anchored in basalt flows. In 2005, a second span was built parallel to the original Burro Creek bridge for the northbound lane. The bridge is a favorite of Phoenix-area BASE jumpers.

Burro Creek Campground can be seen south of the bridge. Burro Creek cuts through the western Kaiser Spring volcanic field (Moyer, 1990; Thompson et al., 2023), a mid-Miocene bi-modal volcanic field that erupted during the Neogene (Miocene to early Pliocene) onto an erosional surface across Proterozoic metamorphic and igneous rocks.

END ROAD LOG

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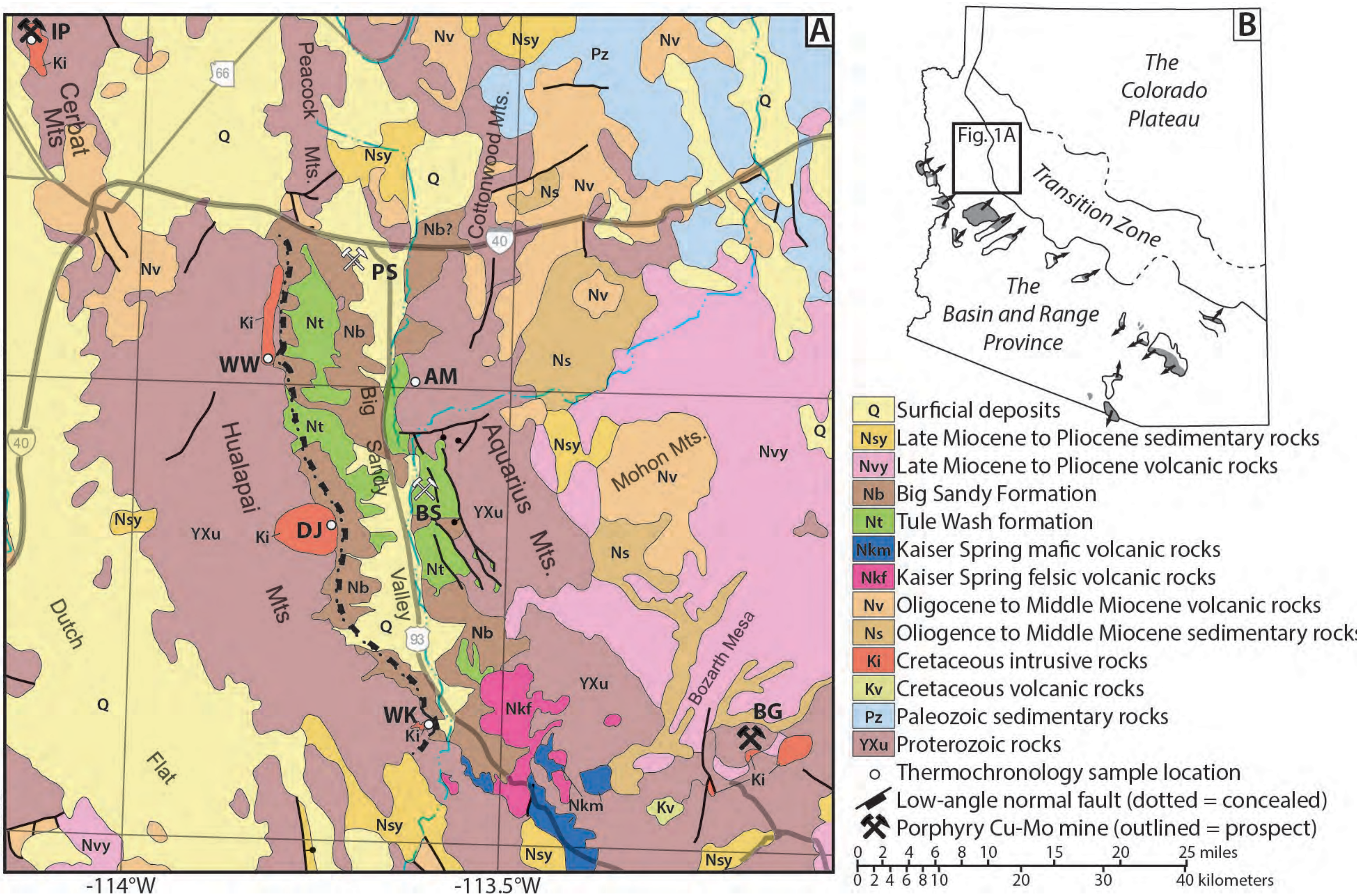
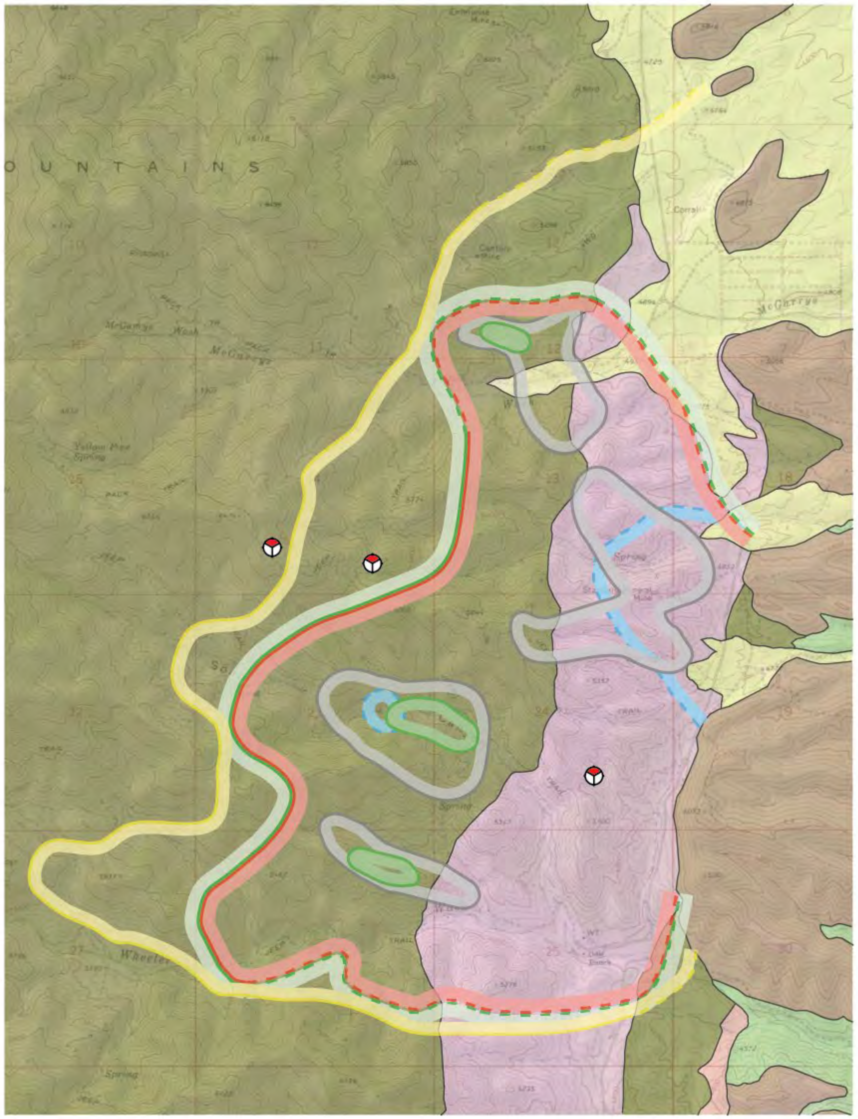
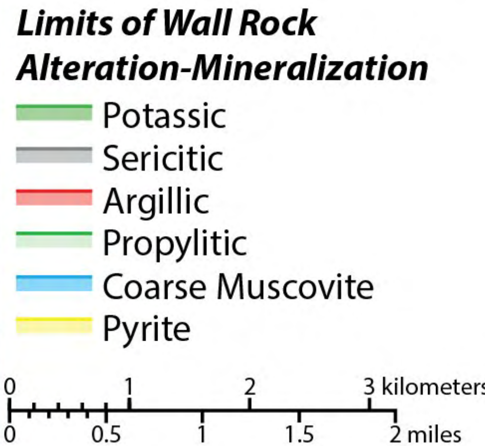
Appendix 1 – Simplified Geologic Map of Big Sandy Valley



Simplified from Richard et al., 2000 with modifications from recent geologic mapping.



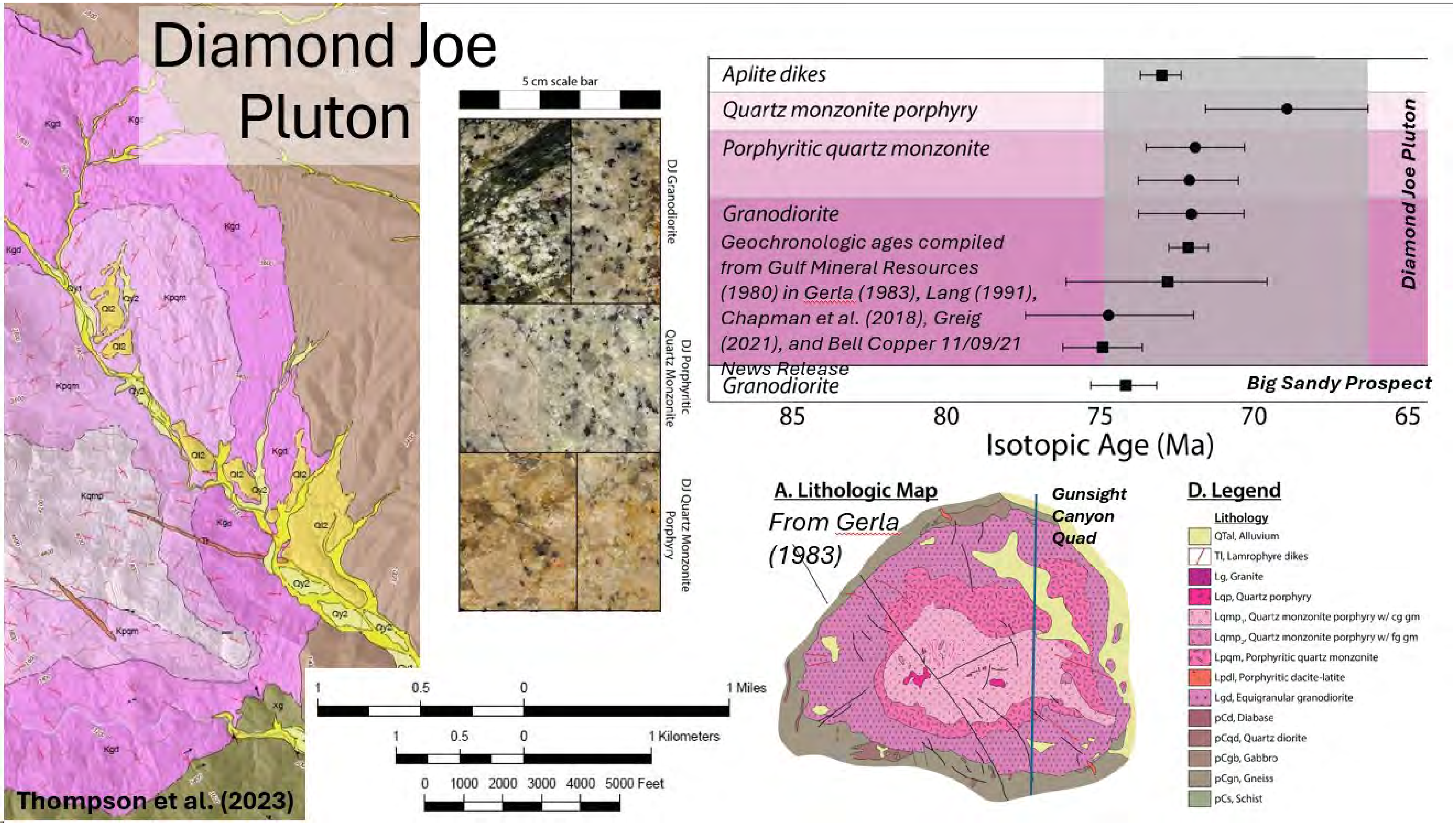


Geology from Garcia et al. (2024) and Pastor (2013)

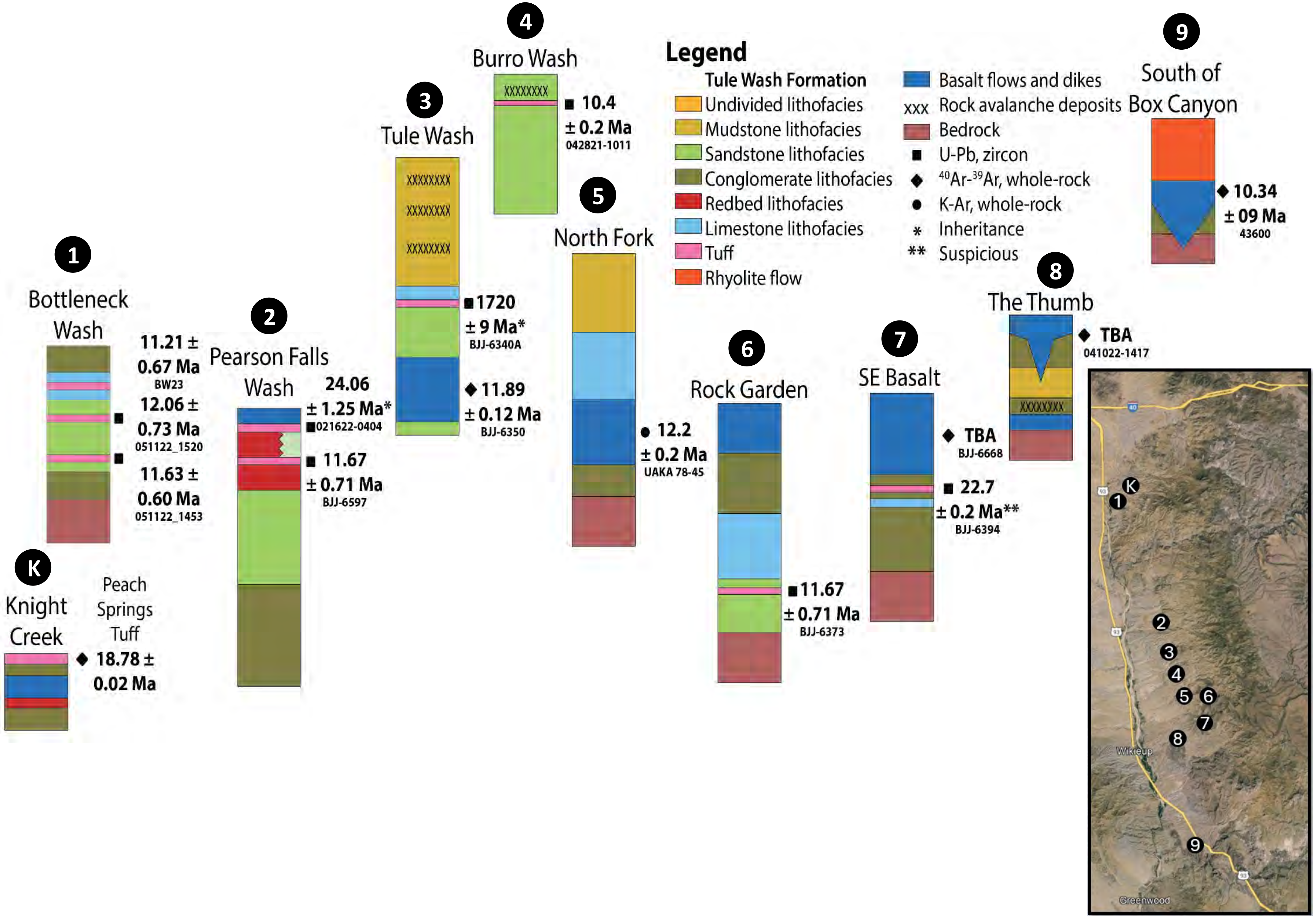
Alteration-mineralization from Vuich (1974), Pastor (2013), Bain (2015), and Garcia et al. (2024) mapping

- Biotite-bearing quartz monzonite to granodiorite
  - 71.9 ± 0.8 Ma (Greig, 2021)
- Large alteration footprint in northern Hualapai Mountains
- Bell Copper / Cordoba Minerals exploring for faulted top of system
  - Perseverance

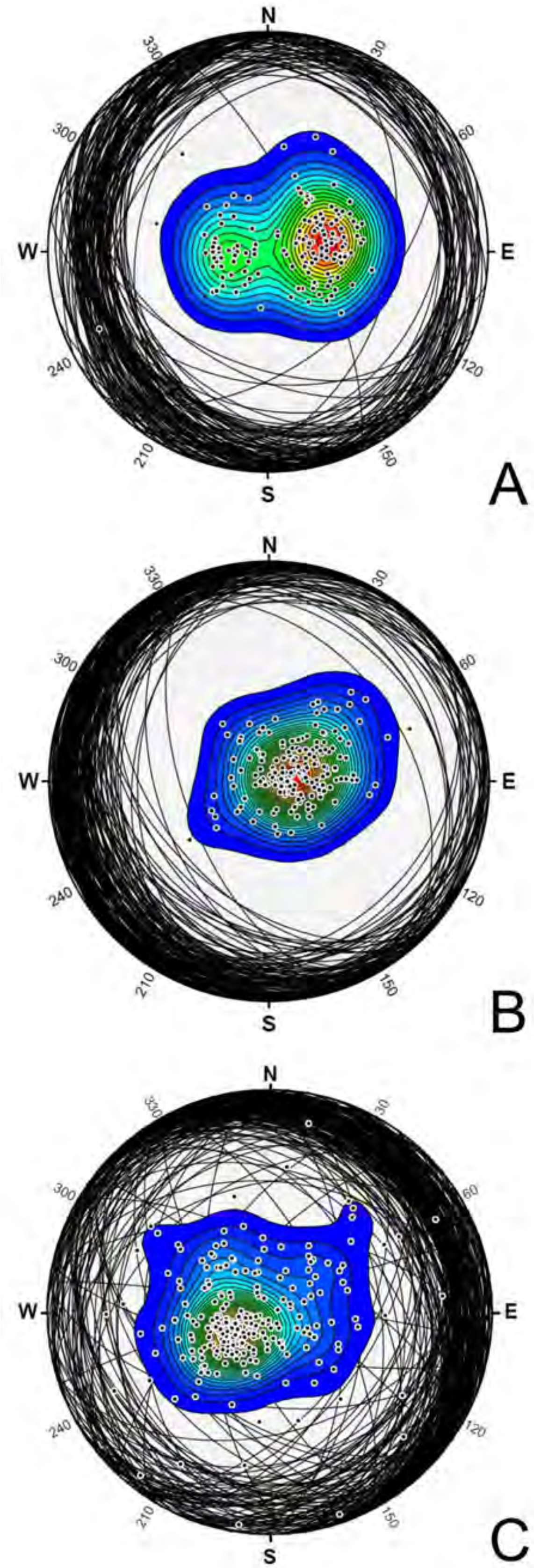
Appendix 3 – Diamond Joe Pluton



Appendix 4 – Geochronology of Tule Wash formation



Appendix 5 - Sterographic projections of bedding in Tule Wash formation



Equal-area projections of bedding attitudes of the Tule Wash formation, shown as both planes and poles. (A) Bottleneck Wash and Dean Peak quadrangles (n=156, mean 165/10), (B) Pilgrim Wash and Hibernia Peak quadrangles (n=198, mean 161/11), (C) Tule Wash quadrangle (n=628, mean 341/08). Plots were generated using Stereonet software v. 11.5.1 (Allmendinger et al., 2012; Cardozo and Allmendinger, 2013). Mean bedding orientations, given as strike/dip, correspond to Fisher mean vectors calculated from poles to bedding.

Appendix 6 – Magnetostratigraphy of Big Sandy Formation (Macfadden et al., 1979)

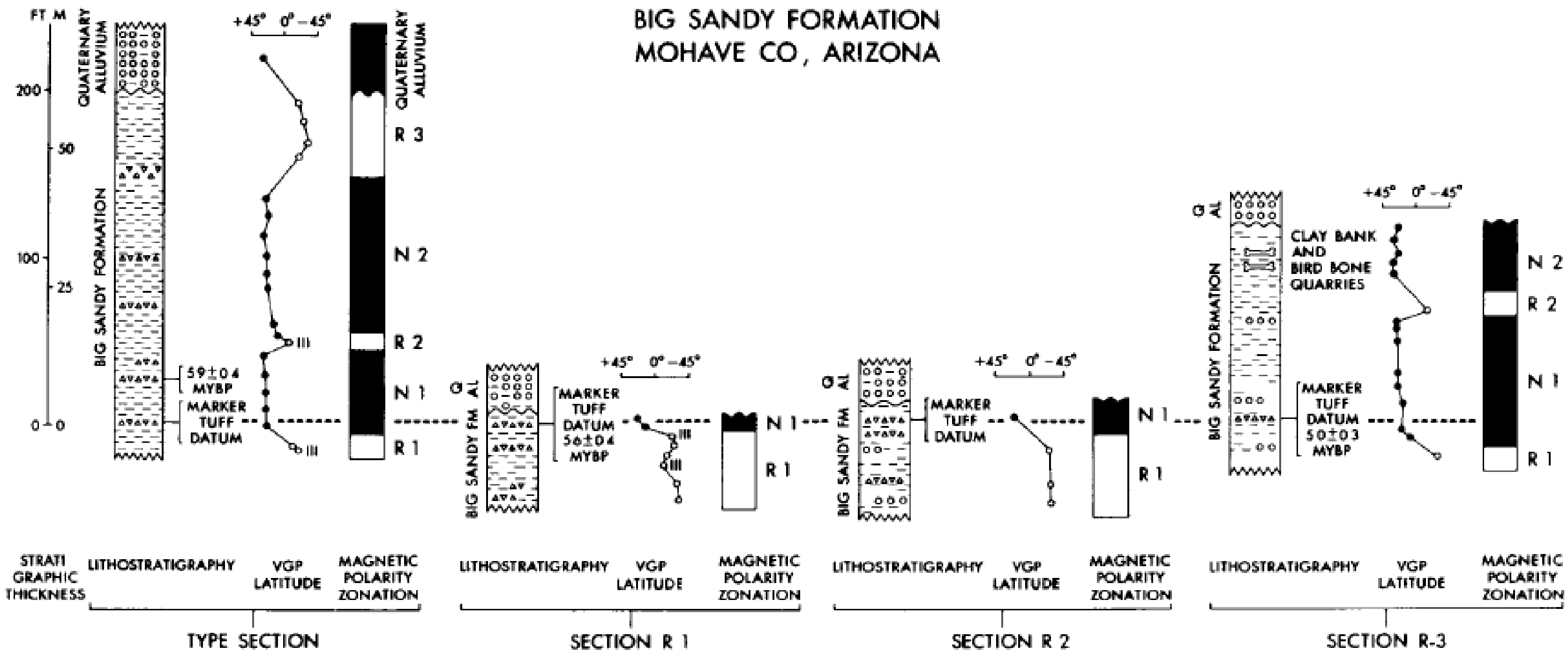


Fig 5 Lithostratigraphy, biostratigraphy, fission-track dates, and magnetic polarity zonation for the type section and reference sections R-1, R-2, and R-3 of the Big Sandy Formation The base of the marker tuff datum is used to correlate among the four sections For the site VGP (virtual geomagnetic pole) latitudes, normal and reversed polarities are represented respectively by black and white circles The four class III sites are indicated by "III" in VGP latitude columns For the magnetic polarity zonations, black and white represent respectively normal and reversed polarities All polarity boundaries are interpreted to lie midway between superposed sites of opposite polarities