Guide for the Earth Science Week Field Trip, October 13, 2018

Nevada Bureau of Mines and Geology

Educational Series E-63

Sparkling or Still?
A Tour of Geology from Soda Lakes to Stillwater Marsh, Nevada

Soda Lake

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2018

Logistics

The field trip starts and ends at the Great Basin Science Sample and Records Library / Publication Sales and & Information Office, which we will refer to as the ***Gold Building*** throughout this guidebook. To get to the Gold Building from downtown Reno, take US-395 North to Exit 71 for Dandini Blvd. Follow Dandini Blvd. east, veer right onto Raggio Pkwy, and the Gold Building will be on your left. The address is **2175 Raggio Parkway, Reno, NV 89512**.

Please plan to arrive at the Gold Building parking lot by **8:00 am.** Following some introductory comments, route plans, and discussion, we will start driving by **8:30 am**. The Gold Building has a free parking lot, and we encourage field trip participants to carpool and/or leave extra cars in the parking lot. Although the roads are passable without four-wheel drive, several roads may be more easily navigated with higher clearance vehicles.

Road Log mileage may vary depending on tire size and other factors and should be considered approximate. GPS coordinates are provided for each of the stop localities in the WGS 84 coordinate system. Please bring a pack lunch, water, sturdy shoes, jacket, camera, and a smile.

Introduction

This field trip will take us on a diverse tour of the geological sights around Fallon, NV (figure 1), which involve active faulting, recent volcanism, ancient lakes, geologic engineering projects for flood diversion, and even geothermal energy. We will first drive to look at active normal faulting along Rainbow Mountain, east of Fallon, before observing the Salt Wells geothermal field. We will have a rockhounding lunch stop where we will look for the beautiful Nevada "wonderstone."

After lunch, we will examine and discuss the "Big Dig", which was an impressive flood diversion project that mitigates potentially damaging flooding of the Carson River. Our last two stops will involve two relatively young volcanoes. "Young" in this case partly means in geologic terms. Rattlesnake Hill, a prominent landmark on the northeast side of Fallon, is a basaltic cinder cone and lava flow complex that is probably a little less than 1 million years old. However, Soda Lakes, a basalt "maar" (learn what this is in the stop description) may be only 1,500 years old and definitely no more than 10,000 years old. Early Native Americans were around at either time and may have witnessed the Soda Lakes eruptions. Rattlesnake Hill and Soda Lakes are two different kinds of basaltic eruptions that result from their different interaction with ground and surface water present at the time.

An important and significant aspect of the geology of Lahontan Valley that we will see today are the remnants of a large pluvial lake that covered much of western Nevada, including all of Lahontan Valley, during each of the Pleistocene glacial cycles or ice ages (figure 7). This lake is called Lake Lahontan by geologists and is distinct from Lahontan Reservoir. At Lake Lahontan's highest water level of about 1,332 m (4,369 ft), roughly 15,700 years ago, it extended from Honey Lake in California across the Black Rock Desert to the valleys north of Winnemucca and south across Fallon to Walker Lake (figure 7). The mountains around Fallon were islands in the lake (figure 8). As the climate warmed and glaciation waned, the lake level fluctuated and Lahontan Valley dried out. Only Pyramid and Walker Lakes remain. The last significant highstand around Fallon was about 7,700 years ago (Adams, 2016). Native Americans lived along the lake shores, for example, at Grimes Point. The evidence of Lake Lahontan can be seen all around Fallon during our trip today. In particular, horizontal shorelines and bars punctuate the hillsides, fine-grained, commonly banded and light-colored lake sediments were deposited, and flat-floored valleys and terraces were formed.

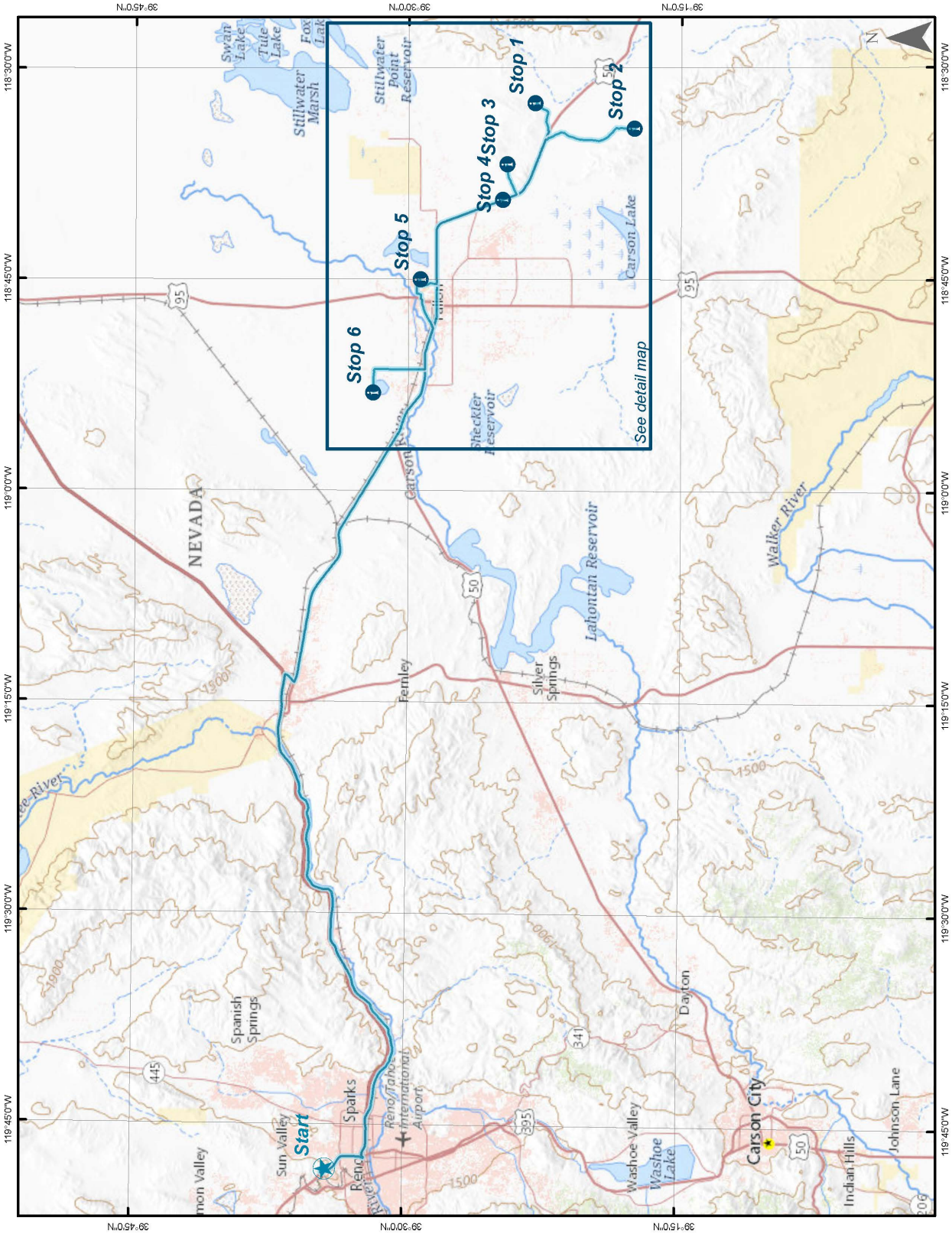

Figure 1A. Overview map showing the starting point and locations that will be visited throughout the trip. See figure 1B for detailed location map.

Figure 1B. Detailed map showing locations of the six stops that we will be making around the Fallon area.

Approximate Schedule

8:00 am – Meet at the Gold Building

8:30 am – Depart

10:00 am – Stop 1: Rainbow Mountain scarp stop

11:00 am – Depart Rainbow Mountain

11:20 am – Stop 2: Salt Wells geothermal field

12:15 pm – Depart Salt Wells

12:45 pm – Stop 3: "Wonderstone" site and lunch stop

1:45 pm – Depart

2:00 pm – Stop 4: Big Dig site

2:45 pm – Depart Big Dig site

3:15 pm – Stop 5: Rattlesnake Hill

4:15 pm – Depart Rattlesnake Hill

4:45 pm – Stop 6: Soda Lakes

Return to Reno at your own pace, or follow the caravan back.

Road Log (see figure 1 above)

Start of trip is the Gold Building (GPS coordinate: 39.57175604°, -119.802847°; WGS 84)

ZERO miles at the Gold Building.

0.0 – Turn right onto Raggio Pkwy, then turn left onto Dandini Blvd., and at 0.5 miles turn left onto US-395 South.

3.3 – Take Exit 40 and merge onto I-80 East.

7.1 – To the left (north of I-80) is Spark's Marina, which was formally known as the Helm's gravel pit. This quarry provided rock for nearby construction and road projects since 1968, but it was flooded in the "New Year's flood" of 1997. Since then, it has remained a public marina and swimming hole.

8.8 – Just crossed the Vista fault, which bounds the eastside of the Truckee Meadows.

9.2 – Entering Truckee River Canyon. The river has deeply incised through the Virginia and Pah Rah Ranges exposing the bedrock geology.

12.7 – ~1.4-Ma McClellan Peak basalt flows are visible capping the ridges to the south.

16.8 – Most of the hills on the horizon are older volcanic rocks, ~10 Ma +

18.8 – Visible on the right is the Frank A. Tracy Generating Station, a natural gas power plant.

21.1 – White sediments in cut south of road are Lake Lahontan sediments.

24.9 – The Derby Dam, south of the highway, diverts water to an irrigation ditch for Lahontan Valley.

26.9 – White cliffs south of the highway are ~10 million year old diatomaceous sediments with fish fossils (see NBMG E-40).

29.9 – Mix of older Oligocene (~25–30 million year old) ash-flow tuffs (colorful rocks) with white Lake Lahontan sediments on north side of the road.

37.6 – Take Exit 48 toward Fallon, Ely south through suburban Fernley to a roundabout.

38.8 – Go 270° around roundabout (effectively turning left) to Alternate Highway 50 toward Fallon.

46.9 – Patua Geothermal power plant, left of road; note the cooling towers and pipelines.

49.2 – Hazen, and the opening of Lahontan Valley; the big flat expanse is filled with sediments that accumulated in Lake Lahontan.

54.4 – The little hills to the south of the road are sand dunes.

66.3 – Fox Peak gas station and convenience store; this is where some participants starting in Fallon will start the field trip.

67.0 – Rio Vista Blvd to Rattlesnake Hill (we will turn here later for stop 5).

75.4 – We just crossed the "Big Dig" flood mitigation canal (we will stop here later for stop 4).

76.3 – Grimes Point archaeological site with restrooms; note the shorelines on the hill north of the road.

80.9 – Turn left here onto dirt road heading north. Be careful and signal well in advance.

83.3 – **Stop 1 (GPS coordinate: 39.385232°, -118.542231°): Rainbow Mountain scarp** Please park on the right side of this road. We will walk across to the west to view the Rainbow Mountain fault scarp. Afterwards, head back the way you came toward Highway 50.

86.0 – Turn right (west) back onto Highway 50.

86.6 – Turn left (south) onto Salt Wells Road (road sign).

89.0 – Take left at fork in road, following more main road.

91.7 – Follow rightward bend in the road.

91.9 – Veer right, driving straight, onto side road.

92.2 – **Stop 2 (GPS coordinate: 39.305360°, -118.575089°): Salt Wells geothermal field** Park anywhere around the well head. Note Sand Mountain—the big sand dune—to the east, in the distance, across Sixmile flat. Afterwards, head back the way you came toward Highway 50.

97.8 – Turn left (west) onto Highway 50.

101.9 – Turn right into Grimes Point. There are restrooms here, if needed, and you can catch up with the group down the road.

104.0 – **Stop 3 (GPS coordinate: 39.410362°, -118.61466°): "Wonderstone" site and lunch** At the fork in the road, park anywhere. This will be our lunch stop, so feel free to explore looking for "wonderstone" rocks. Afterwards, head back the way you came toward Highway 50.

106.1 – Turn right (west) onto Highway 50.

106.9 – Turn right off highway onto dirt road; turn is just before highway goes over the "Bid Dig" canal.

107.0 – **Stop 4 (GPS coordinate: 39.413735°, -118.654949°): "Big Dig" site** Park anywhere here. Afterwards, head back to Highway 50.

107.1 – Turn right (west) onto Highway 50.

115.6 – Turn right (north) onto Rio Vista Blvd.

116.1 – Bear right after crossing small bridge to head up Rattlesnake Hill.

116.5 – Turn left onto gravel road toward Rattlesnake Raceway.

116.7 – Turn left onto road going up hill; there are many road options that go up the hill here.

117.0 – **Stop 5 (GPS coordinate: 39.487565°, -118.751334°): Rattlesnake Hill** Park anywhere here. Afterwards, head back down hill to Highway 50.

118.3 – Turn right (west) onto Highway 50.

124.0 – Turn right (north) onto Soda Lakes Road.

126.1 – Turn left onto Cox Road.

127.0 – Turn right onto gravel road up toward rim of Soda Lake.

127.5 – **Stop 6 (GPS coordinate: 39.520647°, -118.873475°): Soda Lake, south rim** Park anywhere here. Afterwards, head back down to Highway 50. This is the last formal stop of the field trip.

Head back toward Highway 50 by driving south toward Cox Road, turning left (east) onto Cox Road, and then right onto Soda Lakes Road. Once you reach Highway 50, turning right (west) will take you back toward Reno.

Field Stop Descriptions

Stop 1. Rainbow Mountain fault scarp and ancient shorelines

The 1954 central Nevada earthquake sequence was a remarkable series of events. Five surface faulting earthquakes of magnitude 6.1 to 7.1 occurred over a six-month period. Within these, four were double events, a magnitude 6.2 earthquake followed 11 hours later by a magnitude 6.1 event, and a magnitude 7.1 earthquake followed four minutes and 20 seconds later by a magnitude 6.9 event. Over seven different faults displayed surface rupture from earthquakes during this sequence, totaling over 182 km (113 miles) of surface rupture. Vertical ground offsets as much as 2.8 to 3.8 m (9 to 12 ft) were observed with this sequence of earthquakes. The major earthquakes were felt throughout most of Nevada and significant damage occurred in the Fallon area.

Today we will visit the location of the surface rupture for the first event: the July 6th Rainbow Mountain earthquake. Figure 2 shows the Modified Mercalli Intensity map of this event. Different intensities (Roman numerals) represent different levels of shaking. Reno is on the western edge of the Intensity VI area. Minor impacts resulted from this level of shaking, such as cracked plaster and contents being shifted or thrown to the floor. All people generally felt the earthquake, being awakened if asleep, and several folks were frightened from the temblor. Reno is about 108 km (67 miles) from the surface rupture of this event, which is stop 1.

The Rainbow Mountain fault has been studied by several people through the years. Don Tocher (U.C. Berkeley) mapped and described the ground ruptures immediately after the July and August 1954 events. More recently, John Caskey and Steve Wesnousky from the UNR Center for Neotectonic Studies, and John Bell and Alan Ramelli from the NBMG revisited and measured these surface ruptures and dug trenches across the Rainbow Mountain fault to determine its paleoearthquake (past earthquakes) history. Fault rupture and paleoearthquake information presented below are based on Tocher (1956) and Caskey et al. (2004).

The first of the major 1954 earthquakes was at 4:13 am on July 6th. It was a magnitude 6.2 earthquake that occurred on this fault along the eastern base of Rainbow Mountain. The earthquake broke the surface, although it seems incomplete and underrepresentative in many places of what must have happened in the subsurface. The right-normal oblique-slip earthquake rupture was about 20 km (12 miles)

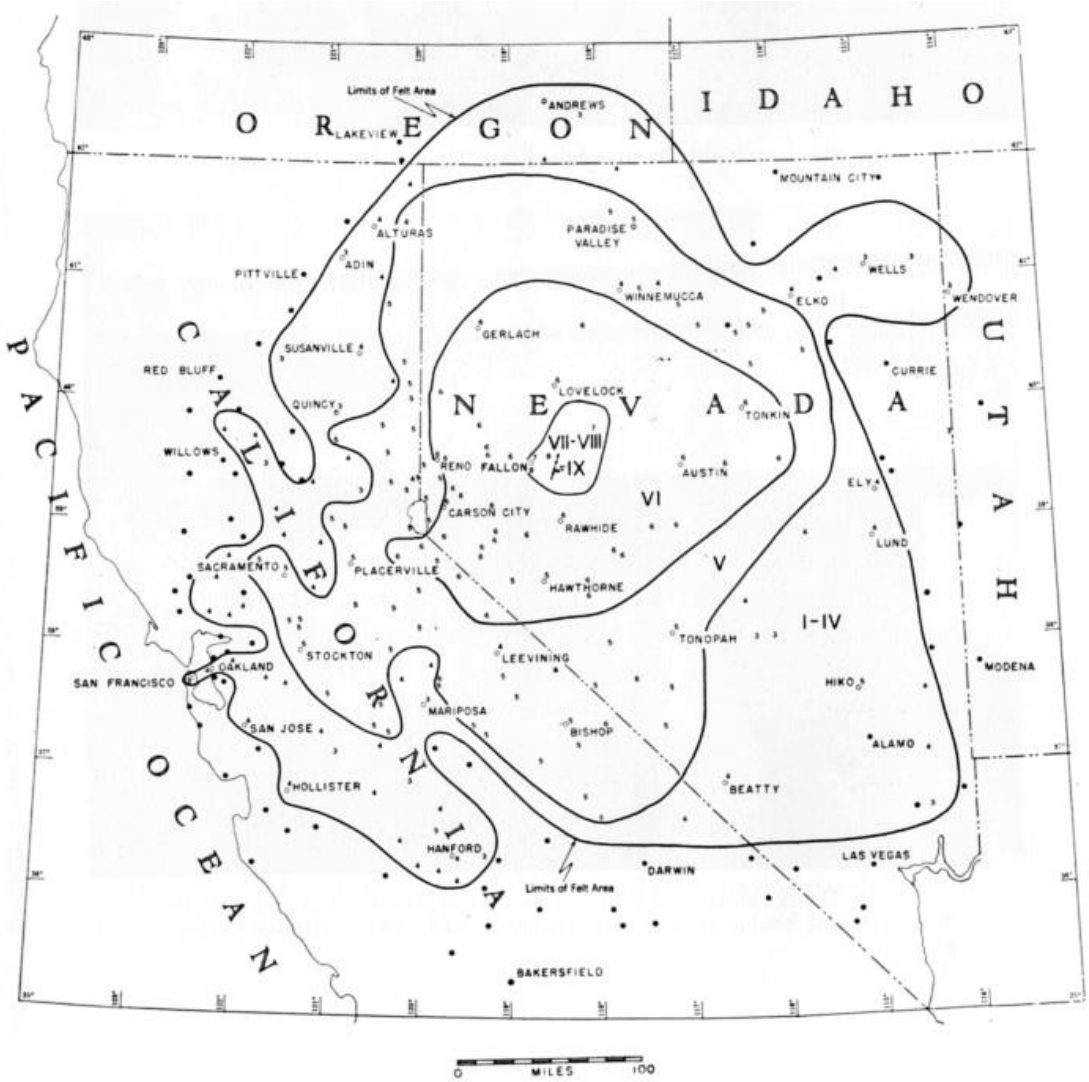

Figure 2. Modified Mercalli Intensity map of the July 6, 1954 earthquake showing the locations of the returned questionnaires (black dots) and approximate contours of the different assigned intensities. The most damaging effects from this earthquake were confined to Lahontan Valley. The outer felt contours (I-IV) were likely limited because this was an early-morning earthquake when many people were still asleep. Intensity IX is the surface rupture, VII-VIII is where buildings and chimneys were damaged, VI has cracked walls and frightened people, V is felt by most all and people awakened from sleep, I-IV is felt by some. Map: Murphy and Cloud (1956).

long and was mapped by Tocher (1956) from Highway 50 northward along Rainbow Mountain and into the southern Carson Sink. Hinz et al. (2011) extended the 1954 ruptures along the Rainbow Mountain fault about 2 km (1.2 miles) south of Highway 50. Caskey et al. (2004) measured offsets along the rupture and found the largest vertical offset was 35 cm (14 in).

Eleven hours after the magnitude 6.2 event, the second major earthquake (magnitude 6.1) occurred on the Fourmile Flat fault, about 10 km (6 miles) southeast of stop 1. A cloud of dust was seen rising from Fourmile Flat following this event. The Nevada Highway Patrol reported at 3:09 pm that Highway 50 was damaged by the earthquake where the fault crosses the road. Caskey et al. (2004) mapped discontinuous surface ruptures over a distance of 6.5 km (4 miles) along the Fourmile Flat fault, and measured a maximum vertical offset of 30 cm (12 in).

Forty-nine days passed following these events along with many aftershocks, but things appeared to be calming down before another major earthquake, a magnitude 6.8, occurred along the Rainbow Mountain fault at 10:51 p.m. on August 21. The earthquake nucleated downdip on the fault near stop 1 and mostly ruptured to the north, into the southern Carson Sink for a total of 53 km (33 miles) (Caskey et al., 2004). This rupture overlapped with the ruptures from the first earthquake for over 12 km (7.5 miles). The largest vertical offset was 80 cm (31 in) and the largest right-lateral offset was 1 m (3.2 ft) (Caskey et al., 2004). The impact of these earthquakes on Fallon and other places will be discussed at the Rattlesnake Hill overview stop.

The final episode in this earthquake sequence was a pair of large earthquakes that were located one and two valleys to the east of stop 1. The first of these was the magnitude 7.1 Fairview Peak earthquake that occurred at 3:07 am on December 16, followed by the magnitude 6.9 Dixie Valley earthquake, which occurred four minutes and 20 seconds later. The first event was a right-normal oblique slip earthquake and the second was a normal dip-slip event, with maximum vertical offsets of 2.7 to 3.7 m (9 to 12 ft). Surface ruptures from these events are shown in figure 3. The offset of the Fairview Peak event can be viewed about nine miles south of Highway 50 at a viewing area on the eastern side of Fairview Peak.

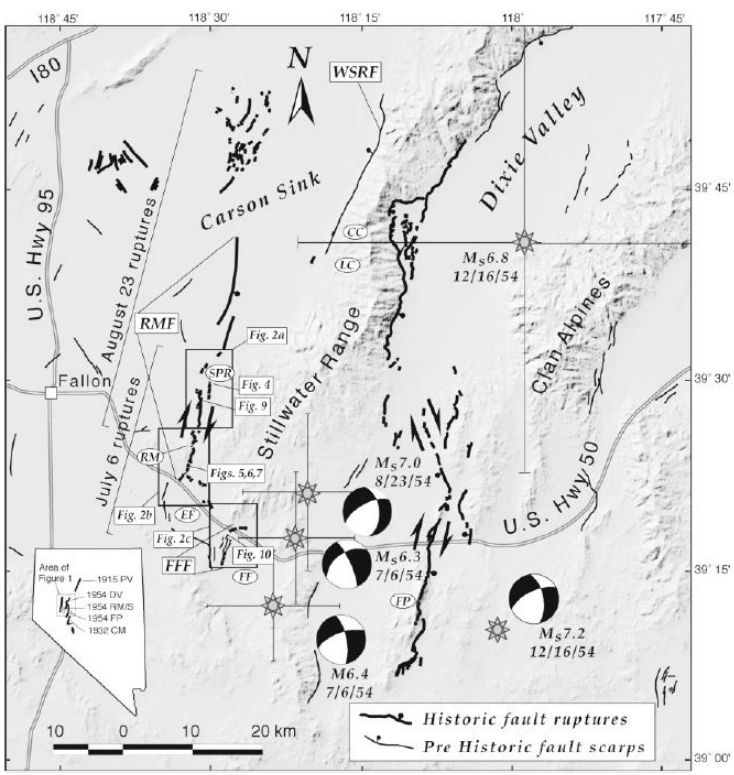

Figure 3. Location of earthquakes and fault ruptures observed in the 1954 earthquake sequence. From Caskey et al. (2004).

Caskey et al. (2004) trenched the Rainbow Mountain fault near stop 1 and examined a stream cut on the Fourmile Flat fault to determine the recent paleoearthquake histories of these faults. If geologists know how often earthquakes occur along faults and their size, they can then characterize its earthquake hazard. Caskey et al. (2004) used radiocarbon dates, volcanic tephra ages, and the pluvial lake history to constrain the

events they were able to identify in these exposures. Figure 4 shows the central portion of a trench log from Caskey et al. (2004)'s northern trench on the Rainbow Mountain fault. The trench shows a small 30 cm (12 inch) high eroded fault scarp from the 1954 break. Below this is a thin distinct reddish mud layer labeled "Qsc" that is offset 1.8 m (5.9 ft) vertically across the fault. This offset is from the 1954 event and an older earthquake. This older event had 1.5 m (4.9 ft) of vertical offset. The easternmost fault trace in the figure offsets a unit labeled "Qsc1a" in a reverse sense, but only cracks the previously mentioned thin

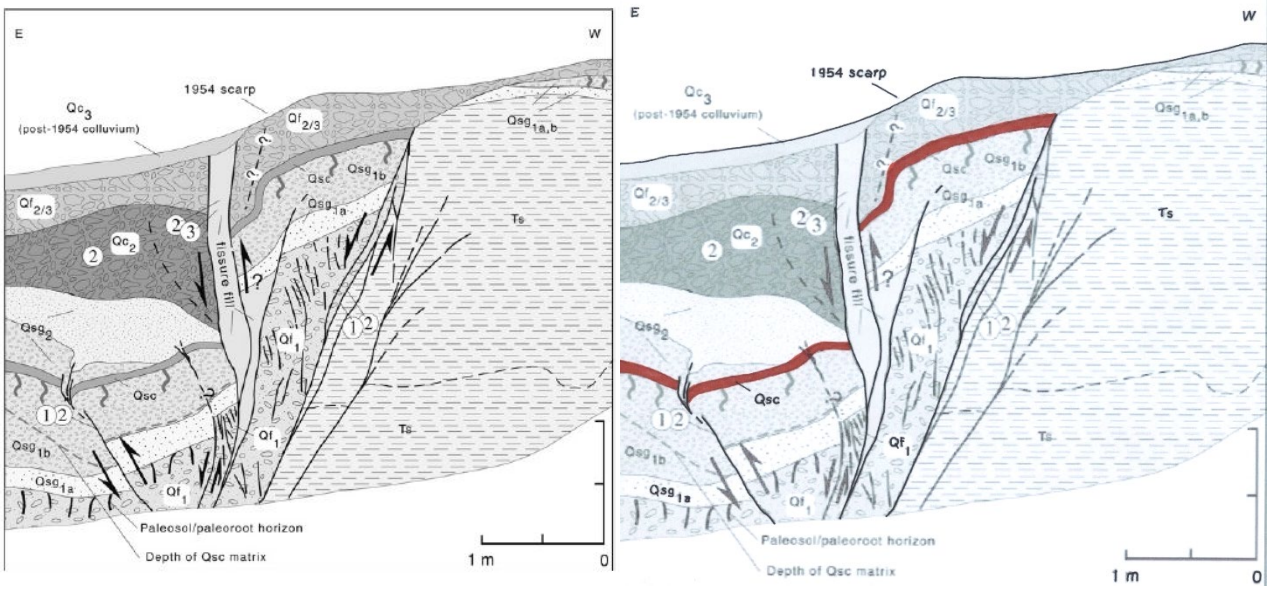

Figure 4. Central portion of a trench log on the Rainbow Mountain fault (Caskey et al. 2004).

red layer ("Qsc"); this is evidence the oldest event exposed. This event is thought by Caskey et al. (2004) to have a similar vertical offset as the second event, 1 to 1.5 m (~3 to 5 ft). This location described above is slightly north of where we are stopping today, and describes what the scarps looked like immediately following the earthquake. What we will see today are the eroded remnants of the fault scarp.

Caskey et al. (2004) presented the results of their paleoearthquake study in figure 6. This diagram shows three earthquakes each on the Rainbow Mountain and the Fourmile Flat faults. Also shown are various age constraints for these events. The youngest paleoearthquake (<1,500 years) on the Fourmile Flat fault was a relatively isolated event. The next oldest event on the Fourmile Flat fault occurred during the mid-Holocene and overlaps in time with the middle event shown on the Rainbow Mountain fault. It is possible that something similar to the 1954 earthquake sequence occurred then, but there are other possibilities as well. The surface offset on the middle event on the Rainbow Mountain fault was five times the offset in 1954, indicating this was likely a significantly larger event than the July 6, 1954 earthquake, perhaps even larger than the August 21 Stillwater earthquake. A latest Pleistocene to early Holocene event was recognized on the Rainbow Mountain fault.

Figure 5. Surface ruptures from the July 6, 1954 earthquake events. From Tocher (1956)

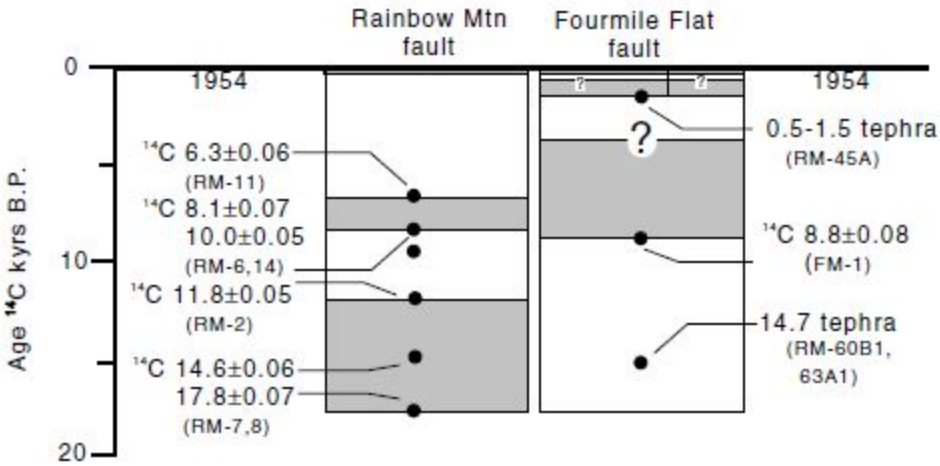

Figure 6. The 1954 event and paleoearthquakes occurring on the Rainbow Mountain and Fourmile Flat faults (Caskey et al. 2004). The shaded gray areas are the bracketed ages of paleo-earthquakes and the heavy line at the top of the graphic represents the 1954 events.

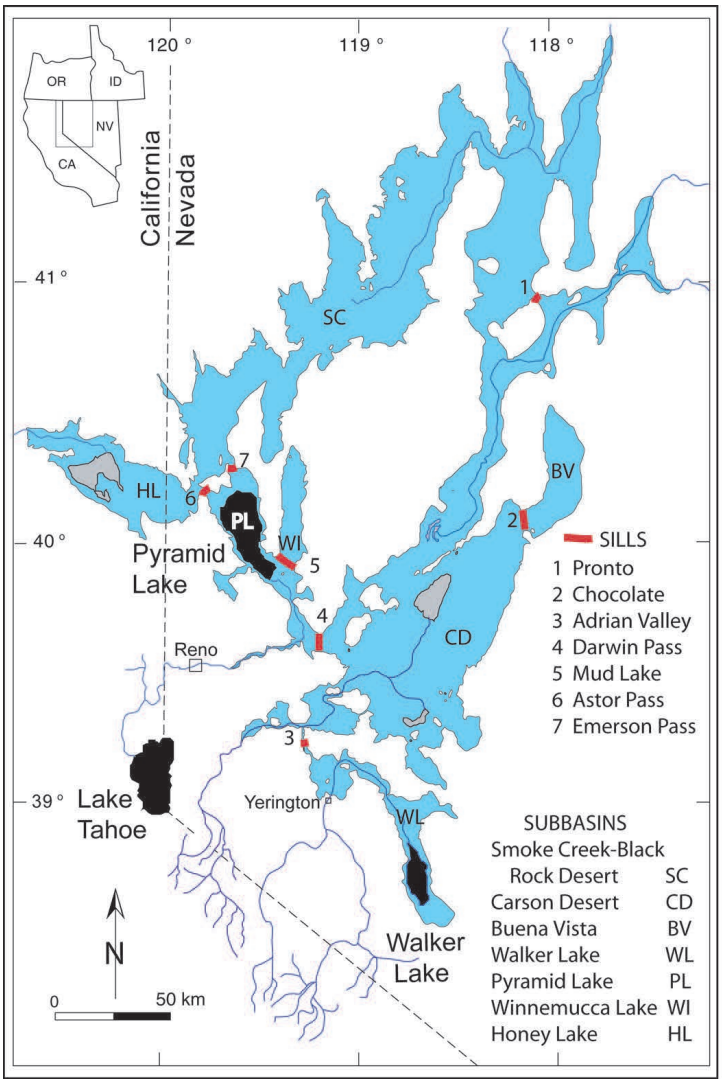

Figure 7. Extent of Pleistocene Lake Lahontan at its highstand about 15,000 years ago, from Benson (2004). At that time and several times earlier during the Pleistocene Epoch, Lake Lahontan covered many of the valleys in western Nevada and eastern California and connected what are now Lahontan, Pyramid, Honey, Carson, and Walker lakes. Black areas show existing lakes, and gray areas show ephemeral lakes and sinks. Red lines indicate overflow points (sills) between subbasins. All of our stops were underwater at the time, and only the higher hills and mountains around Lahontan Valley were islands in Lake Lahontan (figure 8).

Latest Pleistocene Lake Lahontan once filled many of the valleys in western Nevada. The lake reached a highest stand (elevation 1,332 m; 4,369 ft) at about 15,700 years ago. A depiction of what this highstand would have been like locally is shown in figure 8. Only the uppermost part of Rainbow Mountain was above water during this highstand. Lake levels in this closed basin fluctuated through time (see table). As the lake level filled and lowered, it formed shoreline terraces, bars, and deposits on the sides of Rainbow Mountain. Lake deposits are an important part of the surficial geology in this region as these features have been used as datum for constructing the paleoearthquake history of local faults.

Approximate Ages and Heights of High Lake Stands in Lahontan Valley*

Age	Elevation	Comment
25-30 ka		early Sehoo lake
15.7 ka	1,332 m; 4,369 ft	Sehoo highstand
<11.3 ka	1,228 m; 4,028 ft	late Sehoo lake

* Compiled from Morrison (1991), Caskey et al. (2004), and Adams (2016).

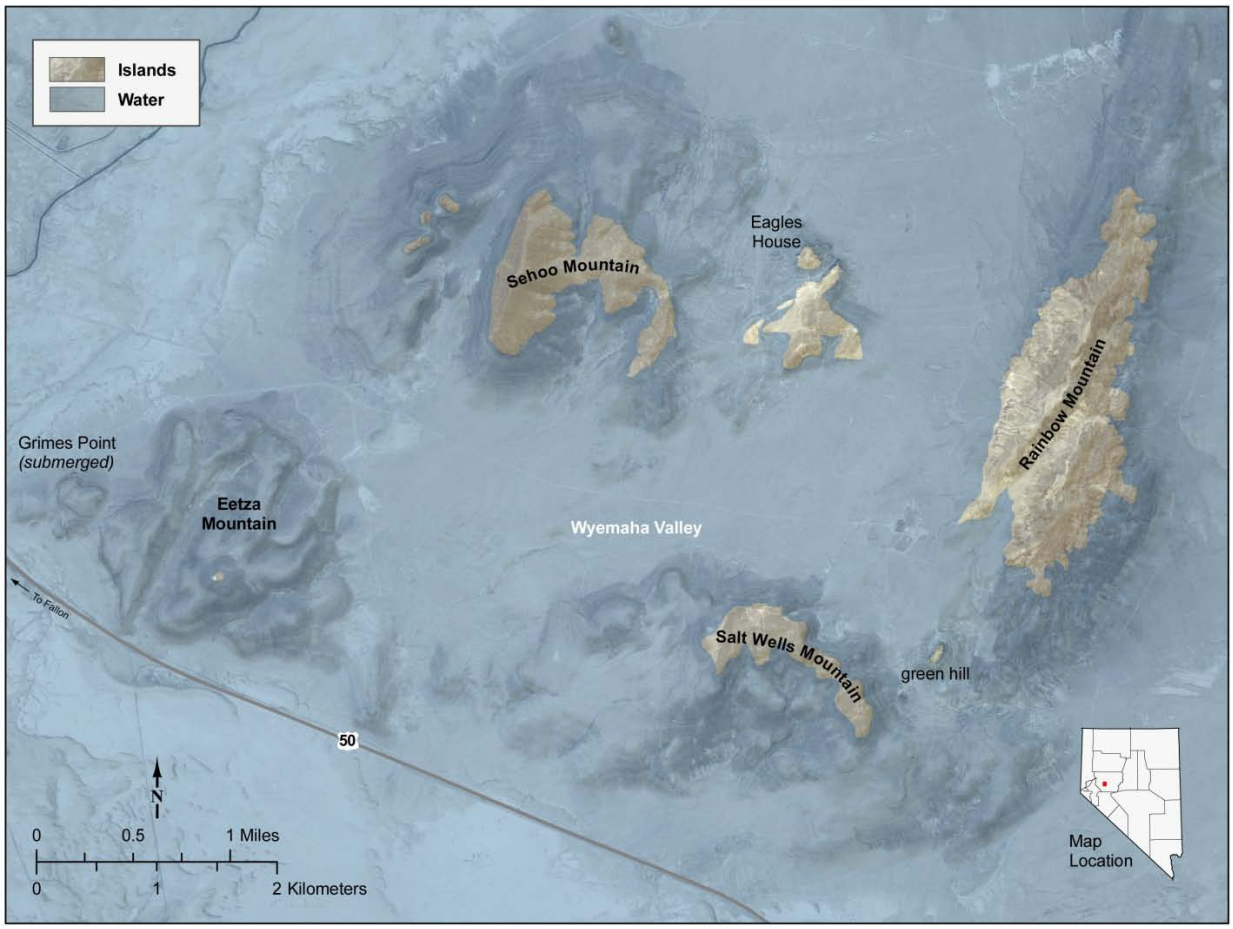

Figure 8. Islands in Pleistocene Lake Lahontan approximately 15,000 years ago, when the lake was at an elevation of approximately 1,332 m (4,369 ft). Cartography by Matthew T. Richardson on base map from the U.S. Geological Survey (LaPointe et al., 2011).

Stop 2. Salt Wells geothermal plant

Nevada has more geothermal resources than any other state. Nevada currently hosts ~25 geothermal power plants, which have a collective capacity of ~700 megawatts (MW). One MW is enough to power about 1,000 homes. Geothermal systems require heat and relatively high rates of fluid flow through fractured rocks. Most of the geothermal systems in this region occur along relatively young faults, which have been active in approximately the past one million years. Research shows that certain types of fault

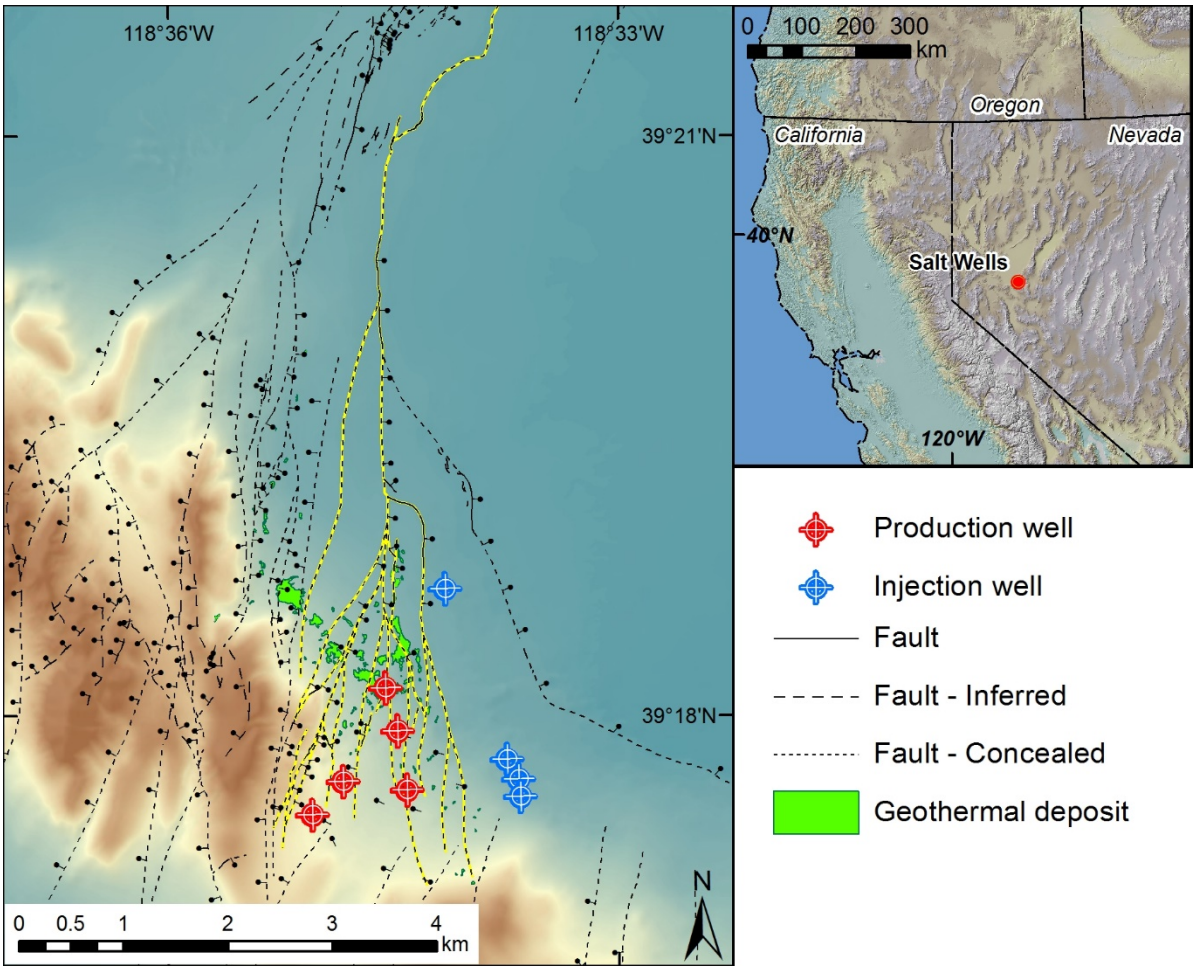

Figure 9. Map of faults and geothermal features and wells in the Salt Wells area (modified from Siler et al., 2018). Strands of the Rainbow Mountain fault are highlighted in yellow. Note that this fault breaks into multiple strands as it terminates southward in the vicinity of the geothermal field, which is marked by the geothermal deposits and production wells.

patterns, such as fault intersections, fault terminations, and steps between major faults, are particularly conducive to geothermal activity (Faulds et al., 2011; Faulds and Hinz, 2015).

The Salt Wells geothermal field occupies the west-southwest margin of the Salt Wells basin (figure 9) ~20 km (12.4 miles) southeast of Fallon. ENEL operates a 14 MW binary power plant (figure 10) that taps a shallow geothermal reservoir with an estimated temperature of ~145°C (293°F). Binary power plants are "closed-loop systems": geothermal fluids are pumped out of the ground, into a heat exchanger that heats a separate fluid, which is used to spin turbines and generate electricity. The geothermal fluids are then reinjected into the reservoir where they heat up, continuing the cycle. Nothing, except water vapor is emitted into the atmosphere in a binary system (US Department of Energy: https://www.energy.gov/eere/geothermal/electricity-generation). Geothermometry (an estimate of temperature of fluids at depth) suggests that a deeper reservoir may exist at temperatures of 180–190°C (356–374°F). This area lies near the intersection of the Walker Lane belt of right-lateral strike-slip fault systems and the central Nevada seismic belt, where several historic 6.0 to 7.0 magnitude normal and normal-dextral earthquakes have occurred (Caskey et al., 2004), which were discussed at stop 1. The

stratigraphy at Salt Wells consists of ~16 to 12 million old lavas and lesser interbedded sedimentary rock. Well data suggest that the basalt exceeds 400 m (1,312 ft) in thickness. The basalt overlies ~100–200 million year old granitic and metamorphic basement rock. The basalts are overlain by recent alluvial fans and lacustrine deposits associated with Pleistocene Lake Lahontan. Gently to moderately tilted fault blocks bounded by northerly striking normal fault zones characterize the structural framework of the Salt Wells area (Hinz et al., 2011).

Figure 10. View looking northeast at the 14 MW Salt Wells geothermal power plant. Note the large sand dune at Sand Mountain in the background.

The Salt Wells geothermal field appears to be localized along the steeply east-dipping Rainbow Mountain fault zone as it loses displacement southward, breaks into several splays (i.e., horsetails), and intersects several other faults (figure 9; Hinz et al., 2014). The fault in this area is marked by several recent fault scarps cutting Pleistocene silicified sand deposits. Temperature gradient drilling has defined a large, 12-km-long (7.5 miles) heat flow anomaly essentially along the southern end of the Rainbow Mountain fault zone at the Salt Wells geothermal system. The increased fracture density generated by the multiple intersecting faults probably produced greater permeability in the area, which has in turn provided convenient channelways for the hot fluids circulating upward from great depths.

Figure 11. Silicified sands deposited on the shoreline of ancient Lake Lahontan. This sandstone rock was probably deposited about 15,000 years ago and has since been cemented by silica derived from geothermal fluids.

At this stop, we will visit an old shoreline of Lake Lahontan, where sands have been cemented by silica (figure 11) derived from the geothermal fluids. The silica, which is present as opal (some replacing possible plant stems), chalcedony, and fine quartz, has indurated the sands, helping to preserve them from erosion by the wind and rain. Silicified sands like these can be good indicators of geothermal systems hidden at depth, because silica precipitates as the water cools. It is estimated that ~3/4 of Nevada's geothermal systems are blind or hidden beneath the surface, with no surface hot springs or steam vents. Thus, indicators of past geothermal activity like these

silicified sands can be utilized in exploration to discover new geothermal resources. We will also view and discuss geothermal wells and the Salt Wells power plant at this stop (figure 10).

Stop 3: "Wonderstone" site (lunch stop)

Throughout the day you may have noticed hillsides where Lake Lahontan's waves incised horizontal lines that represent its former shorelines (figure 7 and 8). Near Grimes Point, the observed shorelines were carved between 13,000 and 11,000 years ago. During this period, beach gravels were also deposited, such as the gravels we will look at on this rockhounding lunch stop. One of these rock types is informally known as "Nevada wonderstone" (figure 12), which gained its beautiful form over a long geologic history. The rock is actually a rhyolite air-fall tuff ejected from a volcano about 12 million years ago. Outcrops of this rhyolite tuff were altered by hot waters that deposited pyrite (FeS_2) and quartz (SiO_2) in the rock. These hydrothermal fluids would have been similar to waters in modern hot springs, which are common in present-day Nevada. These hot waters are used by geothermal power plants across the state to produce electricity, such as the Salt Wells plant we looked at earlier.

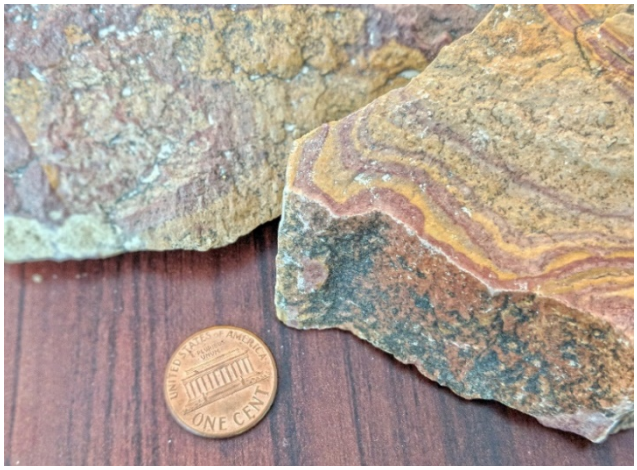

Figure 12. Nevada wonderstone.

Subsequent rainwater penetrated the rock to oxidize the pyrite, forming parallel bands of red hematite (Fe_2O_3) and orange and brown goethite ($FeO(OH)$), which are known as **Liesegang bands**. Erosion broke pieces of the rock from its outcrop, and streams carried pebbles to the shores of ancient Lake Lahontan, where wave action rolled and tumbled the pebbles until they acquired smooth shiny surfaces.

Take some time to find the perfect specimen. Other volcanic rocks also comprise the gravels, but do not have the colorful banding, and lower silica content is not conducive to achieving such a high luster when tumbled.

Stop 4. "Big Dig" Flood Project in Lahontan Valley

In early 2017, flooding occurred along the Carson River in Carson City, but flood waters downstream were largely held in Lahontan Reservoir, with only minor flooding occurring in Fallon. Snow in the Sierra Nevada Mountains was heavy that year with a 250% of average annual precipitation in the Carson River Watershed. Churchill County, Fallon, the Truckee-Carson Irrigation District, the U.S. Bureau of Reclamation, and several state agencies recognized the implications of a heavy snow pack in the Carson River watershed on the community of Fallon.

The lower part of the Carson River system consists of Lahontan Reservoir and the Carson River discharge into Lahontan Valley. Downstream of the reservoir, the Carson River splits: some flow is directed north towards Carson Sink while the rest travels southeast towards Carson Lake. As Carson Lake fills, it begins to flood the southern parts of Fallon. Another major sink in Lahontan Valley is the Stillwater Point Reservoir area, which is about 27 km (17 miles) northeast of Carson Lake and east-northeast of Fallon.

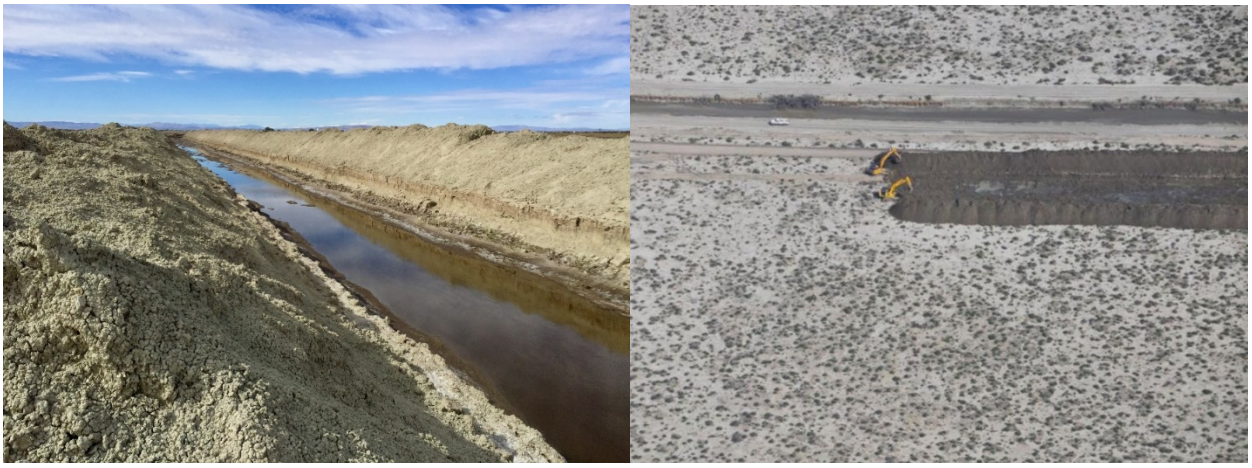

Figure 13. A portion of the completed "Big Dig" (left). Excavators digging the Big Dig. Image provided by Mike Heidemann, Churchill County Emergency Management (right).

Aware that flooding in Fallon was imminent during the 2017 spring and summer snow melt, a series of 13 projects were completed to avert this flooding. Some of these were direct mitigation projects while others were to accommodate these mitigation projects. For example, vegetation was removed from the Carson River downstream of Lahontan Dam, increasing flow capacity from about 1,000 cubic feet per second (cfs) to an estimated 3,000 cfs. A weir was installed at the V Canal intersection with the Carson River to allow flood waters to be diverted towards Carson Lake. New, larger culverts were installed where the flood waters would pass beneath U.S. Highways 95 and 50. Gas and fiber optic lines were moved and buried so as to cross below the flood trench. To keep Carson Lake from flooding south Fallon, workers dug a trench to connect existing agricultural canals and divert water to the Stillwater Point Reservoir. This project became known as the "Big Dig" and is our focus at this stop.

The Big Dig is a 27 km (17 mile) waterway connection from Carson Lake to Stillwater Point Reservoir. Existing agricultural canals were connected with 9.7 km (6 miles) of new trench to complete the project. The waterway is as little as 1.8 m wide (6 ft) and ranges from 1.8 to 8 m (6 to 27 ft) deep. The project involved 40 workers and a volunteer farmer's brigade. The project was completed in about 6 weeks of 24/7 work, or with about 20,000 hours of manpower. It involved 10 large excavators, 2 bulldozers, 8 scrapers, and 2 blades. In total, about 1.9 million cubic meters (~2.5 million cubic yards) were estimated to have been moved to dig the trench. It is estimated that the combined projects passed 1.2 cubic kilometers (1,000,000 acre-feet) of high water in 2017;

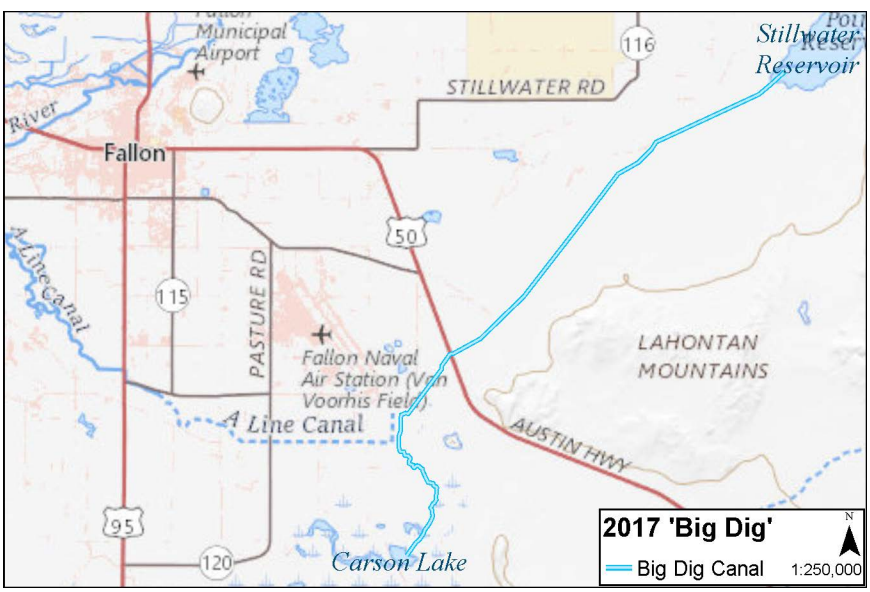

Figure 14. Map showing the extent of the completed "Big Dig" canal from Carson Lake in the south, to Stillwater Reservoir in the northeastern portion of the map.

that is 3 times the capacity of Lake Lahontan – enough water to cover the entire state of Rhode Island with .3 m (1 ft) of water.

Stop 5. Rattlesnake Hill

Our next stop is at Rattlesnake Hill, which is one of three basalt volcanoes that are 1 million years old and younger in Lahontan Valley. The valley during this time was much like it is today, a wide, flat basin, but the basin was occupied by huge lakes periodically during much of the Pleistocene glacial cycles or ice ages (figures 7 and 8). The kind of volcano that is present at Rattlesnake Hill, which is probably about 900,000 years old, tells us that the area was not a lake at that time. Rattlesnake Hill is a deeply eroded cinder cone and lava flow complex; its origin as a cinder cone is shown by the volcaniclastic basalt textures that we will see around the top of the hill, especially in an abandoned quarry near the giant cross. Remnants of the lava flow are found around its southeast edge, and massive basalt, possibly a dike, underlies the cross. The original cinder cone may have risen several hundred feet above the top of Rattlesnake Hill. Basalt magma ultimately comes from the Earth's mantle, which is generally very hot – 1,000°C (1,800°F) – and reacts explosively when it reaches surface or ground water near the Earth's surface. Cinder cones form when relatively little surface or groundwater is available to generate highly explosive eruptions, which indicate a lake was not present when Rattlesnake Hill erupted. Eruptions at cinder cones commonly start with moderately explosive "cinder" eruptions that result from interaction with however much water is available. Once that water is exhausted – boiled away by the hot magma, explosive eruptions end, and the basalt magma can rise to erupt as lava. The recent eruptions in Hawaii were of lava flows fed by basalt fire fountains that underwent almost no interaction with groundwater. Although spectacular, these were not as explosive as the cinder cone here or the maar at Soda Lakes, so the eruptions actually did less damage than if they had exploded through significant water.

Rattlesnake Hill is largely covered by very intricate tufa deposits that hide much of the basaltic rock that formed the volcano (figure 15). The presence of this tufa shows that Rattlesnake Hill was underwater during much of the Pleistocene, but only after the volcano became extinct.

Tufa:

Figure 15. What's a one-fa plus a one-fa? It's a tufa! Tufa covered pebbles and cobbles can be seen in the images above. We will see several occurrences of this type of tufa on this tour.

Tufa is composed of calcite (calcium carbonate, $CaCO_3$) and forms when freshwater springs come in contact with relatively alkaline lake waters. The interaction causes the precipitation of calcite, which goes on to coat existing rocks, form towers, and other interesting features. Tufa can only form below the water surface, so everywhere you see tufa on this trip, remember that it was once under water. Tufa forms in several locations throughout the Great Basin including Mono Lake, Pyramid Lake, and throughout the Lahontan Valley.

The tufa formations and shapes observed at Rattlesnake Hill are very similar to some of those that can be seen to the north at Pyramid Lake. The distribution of tufa formations allows geologists to extrapolate past lake levels and relative timing of highstands in the region (Benson, 2004). Figure 15 shows boulders and stones that were covered by thick layers of tufa. This type of tufa deposition suggests a near-shore, shallow-water depositional environment (Benson, 2004).

1954 Earthquake Damage:
We talked about the July 6th and August 21st earthquakes along the Rainbow Mountain fault, off to the east. From this vantage point, we can see the Naval Air Station and Fallon, where some of the most severe injuries and damage occurred. Most of the reported injuries from the earthquake were at the Fallon Naval Station, where 12 men were injured when lockers toppled onto the bunks they were sleeping in (The Fallon Standard 7/7/1954); the worst of these injuries were a fractured leg and a fractured foot. One woman in the Stillwater District was badly burned on her face and side as she "attempted to turn off a gas tank which had been shaken loose and from which gas was escaping" (The Fallon Eagle 6/10/1954). The earthquake damaged many homes and buildings in Fallon, caused several chimney failures, threw around and damaged contents, damaged several roads, severely damaged canal and irrigation systems, and temporarily cut electric power and telephone communications (The Fallon Standard 7/7/1954; Murphy and Cloud, 1956). Visible damage was initially reported to over 23 buildings (out of about 50) in the business district of Fallon (The Fallon Standard 7/7/1954 and 8/11/1954; Murphy and Cloud, 1956).

Fallon Buildings that were Damaged or Closed by the July 6, 1954 Earthquake

Allen Hotel
Bank Club
Baptist Church
Christian Science Church
Churchill County Telephone Building
Esquire Club
Fallon Fraternal Hall
Fallon Standard building
Frazzini Furniture Co.
Glad Shop
I.H. Kent Co. Store
Neil Farrell's building
Old Bank Building
Old Fallon Meat Market
Overland Hotel
Palace Club
Taggery
Sportcenter
Sprouse Reitz Store
Standard Printing
West End School
Western Hotel
Woodliff Building

In communities surrounding Fallon namely, Stillwater, Lone Tree, and the Fallon Paiute-Shoshone Reservation, there was severe liquefaction damage in addition to the shaking effects. It was estimated that 300 to 400 farms were affected by the earthquake and "require varied amounts of releveling, minor ditch construction, or other repairs" (The Fallon Standard 7/14/1954). Paved roads were "settled, cracked, and buckled in several places" around Fallon, Stillwater, and Lone Tree (Murphy and Cloud, 1956).

The July 6, 1954 earthquake caused severe damage to the irrigation system known as the *Truckee Carson Irrigation District* and the *Newlands Project*. Damage to the canals was especially extensive in the Lone Tree and Stillwater areas (Steinbruggie and Moran, 1956). The main cause of the damage was shaking-induced liquefaction, shaking-induced settlement of earthen structures, and subsequent erosion from escaping water. Steinbrugge and Moran (1956) state "in the Lone Tree and Stillwater areas, canal banks settled from 0.3 to 1 m (1 to 3 ft) at the same time the bottoms of the canals were raised from 0.3 to 0.6 m (1 to 2 ft), and in the extreme case the bottom of a drain ditch was forced up approximately 1.5 to 1.8 m (5 to 6 ft)." The extensive damage to the irrigation system prompted the first federally declared disaster for Nevada and was the first disaster declaration for an earthquake in the United States (U.S. Disaster Recommendation DR-19).

Figure 16. Earthquake-induced liquefaction caused the bottom of the irrigation canal to rise and fill it (note the numerous sand volcanoes in the risen fill). From Steinbrugge and Moran (1956).

Another major earthquake (magnitude 6.8) in the Fallon area occurred on August 23, 1954, six weeks after the Rainbow Mountain earthquake, and just as many of the repairs to damaged buildings and infrastructure from the July earthquake were being wrapped up. In Fallon, "people reported that it was very difficult to maintain balance and walk" when the earthquake occurred at about 10:45 p.m. on a Monday night (Murphy and Cloud, 1956). People again swarmed out into the streets during and immediately following the event (The Fallon Standard 8/25/1954). There was only one injury reported from the August earthquake; this occurred at Stillwater, where "Martin Dodge cut one foot severely on broken glass" (The Fallon Standard 9/1/1954).

The Stillwater earthquake caused additional building damage in Fallon, but the strongest shaking was closer to the earthquake to the northeast of Fallon, in Stillwater and at the Fallon Paiute-Shoshone Tribe Reservation. The Table lists buildings that were reported to have been damaged by the August 23 earthquake. All but one building that had been repaired from the July earthquake survived the second earthquake, proving that the repairs were largely effective (The Fallon Standard 9/8/1954).

Buildings Damaged by the August 23, 1954 Earthquake

Bank Club	Old Post Office Building
Fallon City Hall tower	Powell Building
Fallon Theater	Stillwater School
Kent Store	West End School
Lone Tree School	Williams Building
Oates Park School	

Figure 17. Top: Section of upper wall on the Bank Club that fell into the adjacent Glad Shop. Photograph was taken by Laura E. Mills and is from Steinbrugge and Moran (1956). Right: Damage to the Glad Shop from the impact of adobe bricks failing from the adjacent wall. Photograph was taken by Laura E. Mills and is from Steinbrugge and Moran (1956).

The damage to the irrigation system was similar to the July 3 earthquake with "a large part of the emergency work … completely obliterated by the shock" (Murphy and Cloud, 1956). The only upside to the situation was that the manpower and equipment required to fix the canal system were on site. Additional Federal emergency funding was dedicated to restoring the irrigation system from this second damaging earthquake.

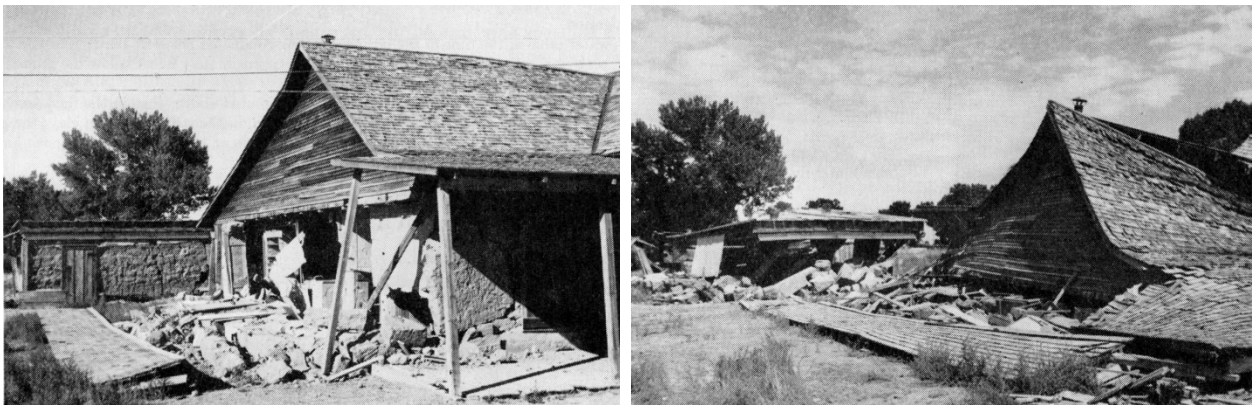

Figure 18. Damage from the July 6, 1954 earthquake to what has been called one of the oldest buildings in the area, an adobe house near Stillwater (Steinbrugge and Moran, 1956). The east and west walls have fallen out from the earthquake. Note the shed in the back on the left that is cracked, but still standing (left). Damage from the August 23, 1954 earthquake to the same two buildings (Steinbrugge and Moran, 1956). The house has completely collapsed and the shed has mostly collapsed (right).

Stop 6. Soda Lake

Figure 19. Soda Lake from the edge of the crater.

Soda Lake and Little Soda Lake are the two youngest volcanoes in Nevada and, at possibly only 1,500 years old (see next paragraph), some of the youngest volcanoes in the region that includes the Mammoth – Long Valley – Mono Lake area of volcanoes (some of which are only about 600 years old). Soda Lakes are younger than the sediments that were deposited in the youngest version of Lake Lahontan. Geologists call these types of volcanoes *maars* (pronounced "Mars"), or tuff rings. After this stop you can say that you "have been to maars." The maars are broad, low-relief, nearly circular volcanic craters. Maars and tuff rings have low volcanic rims and crater floors that are below ground level at the time of formation; Soda Lake is about 64 m (210 feet), so its floor is far below the surrounding ground level. They formed when basalt magma rose close to the surface, boiled the groundwater, and caused an intensely explosive eruption of magma through the wet sediments of Lahontan Valley. You can find telltale “basaltic bombs” around the margins of the craters, which formed when basalt magma was blown into the air and cooled – solidified before reaching the ground (figure 20). None of these bombs are particularly spectacular looking, so figure 21 shows a “spindle” bomb from a young basalt volcanic field in Durango, Mexico. Look for small crystals of plagioclase feldspar (clear to white), olivine or peridot (green) or pyroxene (brownish black) in these dark vesicular volcanic rocks (figure 20). The explosive eruption also allowed basalt to pick up fragments of country rock from the pathway it took to reach the surface. For example, basalt at Soda Lakes has pieces of granite that came from depths of 1 km (0.6 miles) or more below the surface; the nearest granite at the surface is 35 to 50 km (22 to 31 miles) away in the mountain ranges that surround Lahontan Valley. Explosive basalt eruptions help geologists learn about what is otherwise hidden below surface.

The Soda Lakes maars show no evidence of shorelines around their outside edges, which indicate they formed after the youngest highstand of Lake Lahontan that occurred during the early Holocene. The elevation of this highstand was 1,228 m (4,028 feet) and would have reached the lower flanks of Soda Lake; the rim of Soda Lake is about 1,250 m (4,100 feet). The absence of shoreline features against the volcano strongly suggests that the volcano came later. An attempt was made to determine Soda Lakes absolute age by a particularly obscure method that involves cosmic rays striking the little olivine grains. The attempt was unsuccessful, but the geologist who did the work suggest that Soda Lakes could be as young as 1,500 years. This speculation is not published, and nobody is sure what anybody really said, so in the geologic world, this “date” is known as a “rumorchron”. Regardless, humans have lived around Lake Lahontan at least since 10,000 years ago, so someone probably witnessed the eruption.

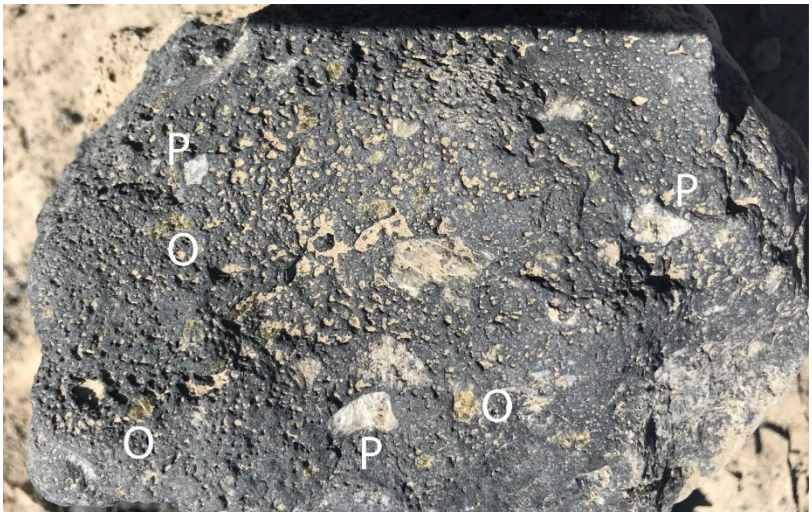

Figure 20. Basalt bomb at Soda Lakes containing clear-white grains of plagioclase feldspar (P) and green olivine (O). Rock is about 13 cm (~5 inches) long.

Along the northwest shore of Soda Lake are some small white dots, which, to some old people's eyes, might have been pelicans. Actually, the dots are a series of tufa mounds (Rosen et al., 2004), much smaller than but similar to the famous Pyramid of Pyramid Lake. The tufa mounds are as much as 3 m (~10 ft) tall and 5 m (~16 ft) across at the base. They are precipitating from cold groundwater discharging at the top of the mounds. Rosen et al. (2004) point out that the tufa mounds only grow in water and that, prior to the beginning of irrigation in 1907 (the Newlands Project), the water level in Soda Lakes was 18 m (~60 ft) below where it is now. That means the mounds only started growing after 1907 and have grown very rapidly in the last 111 years.

Soda Lake owes its name to its very alkaline and saline water. The present-day lake is stratified. Water above a depth of about 35 m has about 26,000 mg/liter, and deeper water has about 87,600 mg/liter (Kharaka et al., 1984), which is about 2.5 times as saline as sea water (35,000 mg/liter). The pH is about 9.7 throughout. Before inflow of irrigation water, the lake was not stratified and even more saline, with a total dissolved solids of about 146,000 mg/liter (Kharaka et al., 1984). Soda Lake and its value as a potential source of soda ash and potash were recognized in the 1800s (King, 1878; Russell, 1885).

Figure 21. Volcanic bomb from Durango, Mexico, showing classic aerodynamic bomb morphology. Specimen collected by Chris Henry, photo by Jack Hursh, NBMG.

Soda Lakes are the most recent of several basalt eruptions that occurred in Lahontan Valley in the last 1 million years. The volcanoes of Upsal Hogbacks, about 15 km (9 miles) north-northeast of Soda Lakes, also resulted from small basaltic eruptions that explosively boiled ground and surface water. Upsal Hogbacks consists of two centers, a northern center with one tuff cone and a southern with three tuff cones (Anderson, 2014). The best estimate of the age of Upsal Hogbacks is between about 25,000 and 11,000 years. Ancient Lake Lahontan was a deep lake at the time, with a lake level as high as 1,332 to 1,336 m (4,369 to 4,383 ft), and the highest preserved part of Upsal Hogbacks today is about

1,259 m (4,130 ft). Therefore, the basalt magma came up through both ground and abundant surface water, which is shown by the type of volcano at Upsal Hogback. Tuff cones have higher volcanic rims than tuff rings (maars) and shallower crater floors, generally not below the ground level at the time. Tuff cones generally form where magma interacts with a lot more water than tuff rings, for example, Lake Lahontan. Lake Lahontan covered Upsal Hogbacks after the eruptions, as shown by erosion of the upper parts of the volcanoes, by the presence of tufa across the top, and abundant shorelines developed around its edge.

The Soda Lakes Conservation and Resource Area is part of Churchill County's Parks and Recreation Department and open to the public. You can come back to circumnavigate Soda Lake, ride your 4-wheel drive truck, ATV, or motorcycle, look at the waterfowl, or collect more basalt and olivine. Please remember to respect the natural area by sticking to existing vehicle tracks and picking up after yourself.

References

Adams, K.D., 2016, Lake-level, lake-surface area, and lake-volume changes at Pyramid Lake, NV over the last 16 cal ka: Geological Society of America Abstracts with Programs, 48, (7), doi: 10.1130/abs/2016AM-281049

Anderson, E., 2014, Physical volcanology and geochemistry of Upsal Hogback volcano, Fallon, Nevada, USA: M.S. Thesis, Carleton University, Ottawa, Ontario, 254 p.

Benson, L., 2004, The tufas of Pyramid Lake, Nevada: U.S. Geological Survey Circular 1267, 14 p.

Caskey, S.J., Bell, J.W., Ramelli, A.R., and Wesnousky, S.G., 2004, Historical surface faulting and paleoseismicity in the area of the 1954 Rainbow Mountain–Stillwater earthquake sequence, central Nevada: Bulletin of the Seismological Society of America, v. 94, no. 4, p. 1255–1275.

Faulds, J.E., Coolbaugh, M.F., Hinz, N.H., Cashman, P.H., and Kratt, C., Dering, G., Edwards, J., Mayhew, B., and McLachlan, H., 2011, Assessment of favorable structural settings of geothermal systems in the Great Basin, western USA: Geothermal Resources Council Transactions, v. 35, p. 777–784.

Faulds, J.E., and Hinz, N.H., 2015, Favorable tectonic and structural settings of geothermal systems in the Great Basin region, western USA—proxies for discovering blind geothermal systems: Proceedings World Geothermal Congress, Melbourne, Australia, 19–25 April 2015, 6 p.

Hinz, N.H., Faulds, J.E., and Bell, J.W., 2011, Preliminary geologic map of the Bunejug Mountains quadrangle, Churchill County, Nevada: Nevada Bureau of Mines and Geology Open-File Report 11-9, scale 1:24,000.

Hinz, N.H., Faulds, J.E., and Coolbaugh, M.F., 2014, Association of fault terminations with fluid flow in the Salt Wells geothermal field, Nevada, USA: Geothermal Resources Council Transactions, v. 38, p. 3–9.

King, C., 1878, Report of the geological exploration of the 40th parallel, volume 1, Systematic Geology: Professional Papers of the Engineer Department, U.S. Army, No. 18, 803 p.

Kharaka, Y.F., Robinson, S.W., Law, L.M., and Carothers, W.W., 1984, Hydrogeochemistry of Big Soda Lake, Nevada—an alkaline meromictic desert lake: Geochimica et Cosmochimica Acta, v. 48, p. 823–835.

LaPointe, D.D., Price, J.G., Davis, D.A., and dePolo, C.M., 2011, "Life's a beach"—in search of ancient shorelines and volcanoes in the Grimes Point and Lahontan Mountains area (Guide for the Earth Science Week field trip, October 15 or 16, 2011)—Nevada Bureau of Mines and Geology Educational Series 51, p. 12.

Morrison, R.B., 1991, Quaternary stratigraphic, hydrologic, and climatic history of the Great Basin, with emphasis on Lake Lahontan, Bonneville, and Tecopa, *in* Quaternary nonglacial geology—conterminous U.S., R. B. Morrison, editor, Geology of North America, Vol. K-2, Geological Society of America, Boulder, Colorado, p. 283–320.

Murphy, L.M., and Cloud, W.K., 1956, United States earthquakes 1954: U.S. Department of Commerce, Coast and Geodetic Survey Serial No. 793, 110 p.

Rosen, M.R., Arehart, G.B., and Lico, M.S., 2004, Exceptionally fast growth rate of <100-yr-old tufa, Big Soda Lake, Nevada—implications for using tufa as a paleoclimate proxy: Geology, v. 32, p. 409–412.

Russell, I.C., 1885, Geologic history of Lake Lahontan, a Quaternary lake of northwestern Nevada: U.S. Geological Survey Monograph 11, 288 p.

Siler, D.L., Hinz, N.H., and Faulds, J.E., 2018, Stress concentrations at structural discontinuities in active fault zones in the western United States—implications for permeability and fluid flow in

geothermal fields: Geological Society of America Bulletin, v. 130, no. 7-8, p. 1273–1288; https://doi.org/10.1130/B31729.1.

Steinbrugge, K.V. and Moran, D.F., 1956, Damage caused by the earthquakes of July 6 and August 23, 1954: Bulletin of the Seismological Society of America, v. 46, p. 15–33.

Tocher, D., 1956, Movement on the Rainbow Mountain fault: Bulletin of the Seismological Society of America v. 46, no. 1, p. 10–14.

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