Table of Contents

Acknowledgements

Much of this document is based on a website prepared by Anne Egger (http://pangea.stanford.edu/groups/warners/) as part of an outreach effort related to Stanford University research efforts in the Warner Mountains and Surprise Valley. The reader is directed there for more detailed information about the geology and geophysics of the area, as well as for references to the related published literature.

Figure on Title Page. View southeast across Surprise Valley to the steep range front on the east side of the Warner Mountains.

The steep range front is indicative of young uplift--the mountains rising faster than erosion can remove them. Snow cover picks out the westward dips of dark Tertiary sedimentary and volcanic layers. The smooth flat-topped slope in lower right is the deposit of a delta in glacial Lake Surprise, which, at the height of the last glaciation about 20,000 years ago, filled the valley to a depth of 500'. Photo courtesy of Surprise Valley Chamber of Commerce.

GEOLOGIC SETTING

The Great Basin and the Basin and Range Province

The Warner Mountains and Surprise Valley lie at the western edge of the Great Basin (Figures 1 and 2), an area drained by rivers and streams that flow to local sinks, rather than by integrated river systems that ultimately flow to the sea. These isolated hydrologic basins are associated with the corrugated topography of the Basin and Range province (Figure 3). This topography is the result of stretching and extension of the western part of the North American tectonic plate in the last 40 million years.

During extension, the upper brittle part of the crust breaks along faults (Figure 4), forming alternating basins and ranges, and the deeper, hotter levels of the continental crust stretch like taffy. Sediments eroded from the ranges end up in the basins. In Surprise Valley these sediments are as much as 7,000' deep. The gravelly and sandy layers of the basin fills serve as the aquifers in the Basin and Range Province (Figure 5).

Seismic study across the Warner Range and Surprise Valley

We know the thickness of the crust in the northwest corner of the Basin and Range because a geophysical survey conducted by geophysicists and geologists from Stanford University and the U.S. Geological Survey in 2004 passed through the area (Figures 6 and 7). Small explosions were set off to send seismic waves through the ground. A more detailed study of Surprise Valley itself was undertaken using a trunk-mounted thumper, dubbed T-Rex (Figure 6), as another method of sending seismic waves through the earth.

By measuring the time it takes for the seismic waves to travel through the earth, bounce off the boundary between the crust and the mantle below, and return to the surface, one can calculate the thickness of the crust. Beneath Alturas, the crust is the typical thickness in northern California, about 37 kilometers (= 22 miles). It starts to thin beneath Surprise Valley, and beneath the Black Rock Desert (Figure 6) it is 31 km thick, about 20% thinner than normal.

Even though the crust has been stretched and thinned, the Great Basin is not topographically low; most of it is above 4,000' in elevation (Figure 3). This means that the thin crust must be buoyed up by hot mantle below. That anomalously hot mantle gives rise to young volcanic rocks and to higher-than-average temperatures in the crust.

Active faulting in Surprise Valley and earthquake hazards

A puzzling aspect of the geology of the Warner Mountains and Surprise Valley is that, despite the very steep range front (cover photo), suggesting youthful uplift, and obvious faults cutting young deposits on the west side of the valley (Figure 8), the area is seismically quiet. In order to determine how often there are large earthquakes in the area, geologists from the U.S. Geological Survey dug a trench in 2005 across one of the young faults that cuts the alluvial fan near the range front north of Cedarville (Figures 8 and 9). By obtaining dates on sediment layers offset by the fault where it is exposed in the trench wall, they determined that the last big earthquake in the area took place about 200 years ago.

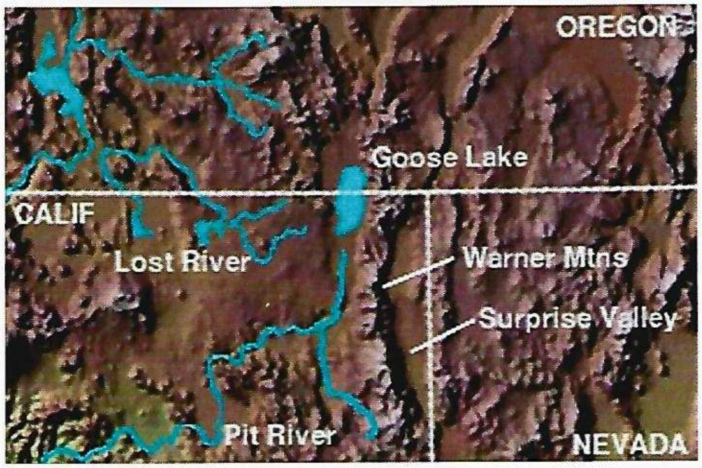

Figure 1. Relief map showing the Warner Mountains and Surprise Valley.
The Pit River drains into the Sacramento Valley. East of the Warner Mountains, each valley has its own separate drainage system for surface water, though, depending on the geology, groundwater can flow between the basins. From http://upload.wikimedia.org/wikipedia/en/e/ea/Wpdms_shdrlfi020l_warner_mountains.jpg.

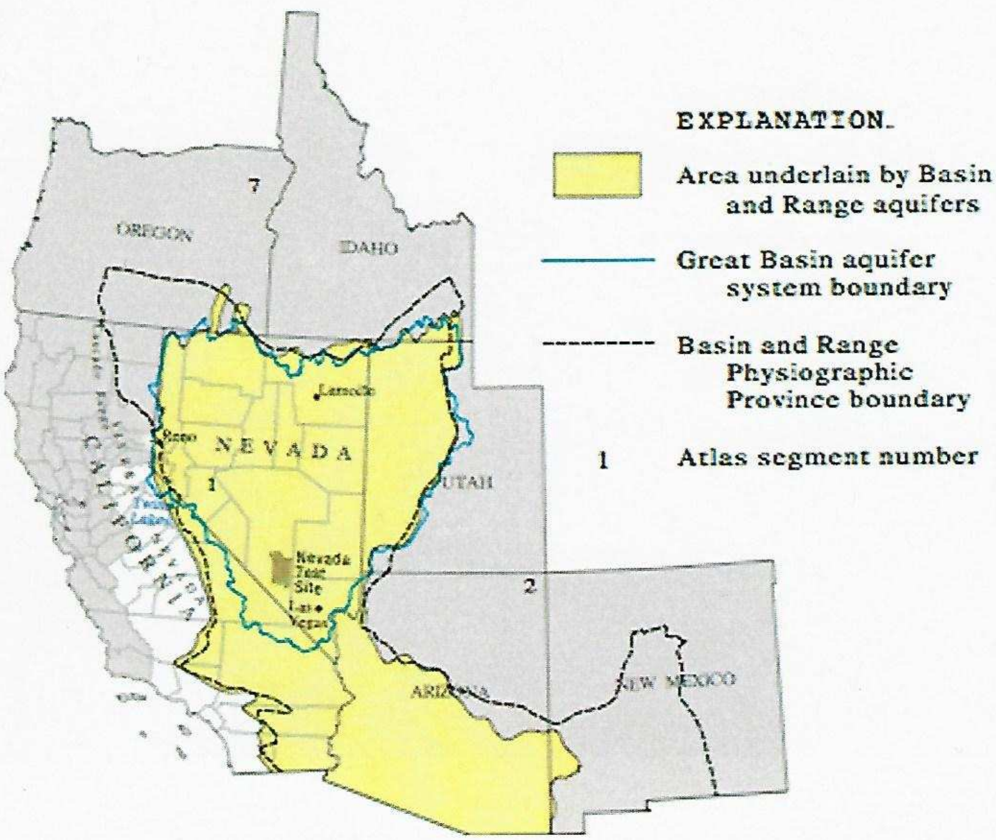

Figure 2. Location map of hydrologic Great Basin and the geological province called the Basin and Range.
The Great Basin, an area of internal drainage, is located entirely within the fault-bounded Basin and Range province, which extends into northern Mexico. Most of the active faulting and seismicity in the Basin and Range province occurs along its western boundary in California and along the eastern margin in Utah. From http://capp.water.usgs.gov/gwa/ch_b/gif/b016.gif.

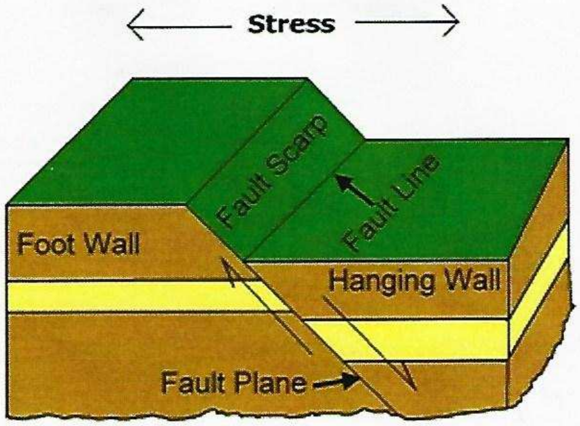

Figure 4. Diagramatic representation of a normal fault.
Normal faults are common in regions of the crust undergoing extension, and they are the faults that control the topography in the Basin and Range province. From http://www.uwsp.edu/geo/faculty/ritter/images/lithosphere/tectonics/normal_fault_labelled_diagram.jpg.

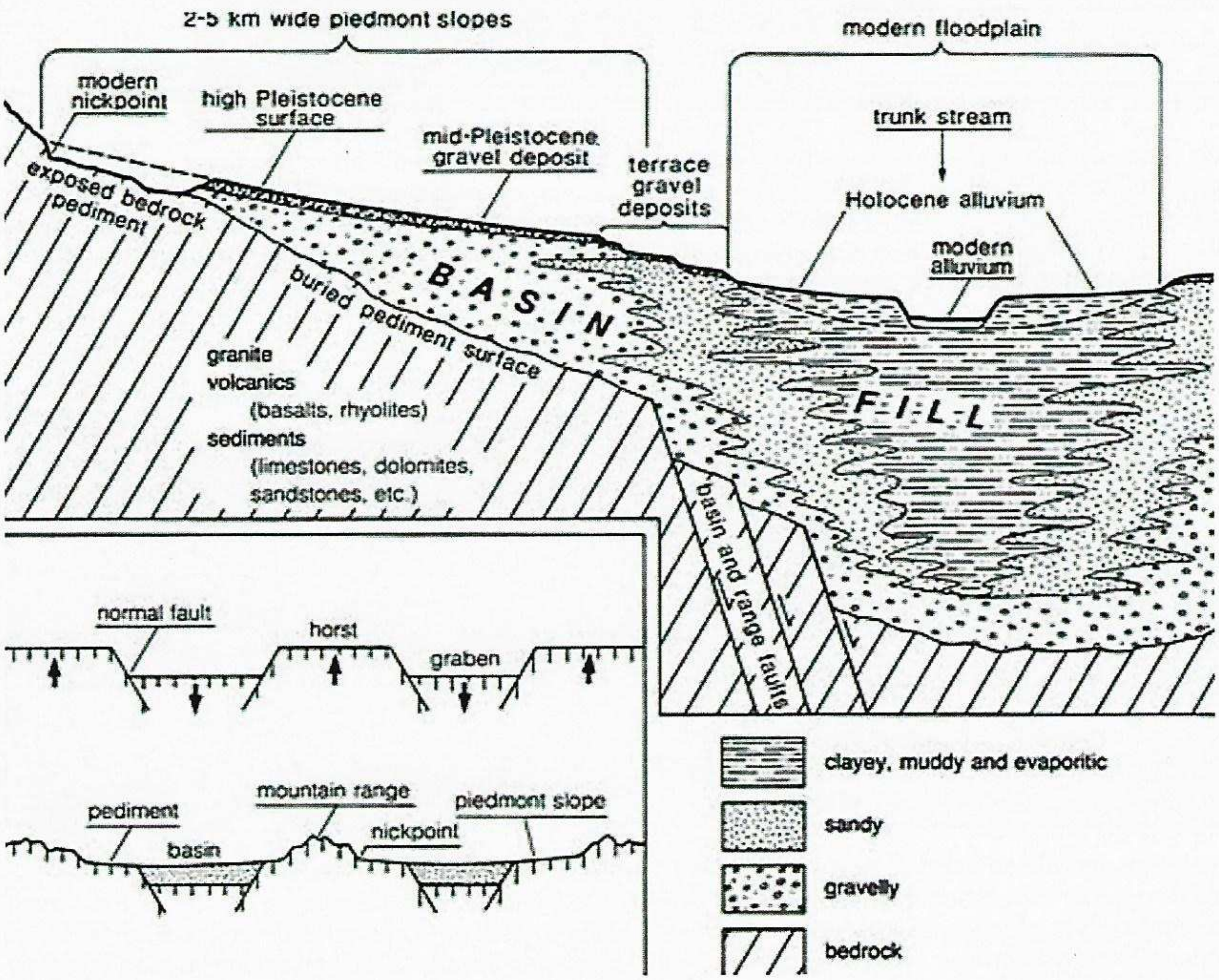

Figure 5. Diagramatic cross section of a normal-fault-bounded valley in the Basin and Range province.
From http://southwest.library.arizona.edu/azso/fig021.jpg.

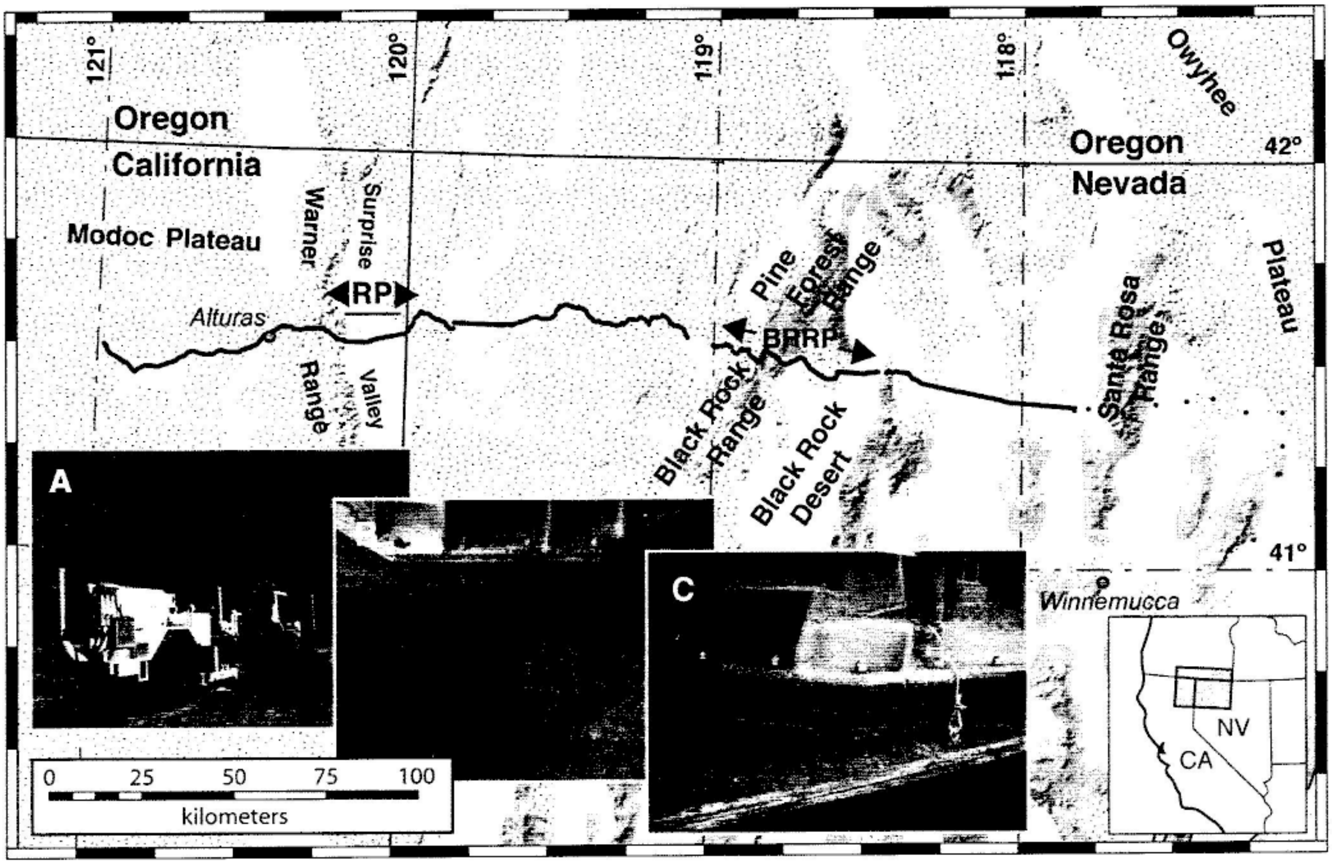

Figure 6. 2004 seismic survey across the northwesternmost Basin and Range province.
Light gray: Quaternary deposits. Stippled area: Tertiary volcanic and sedimentary units. Dark gray: Paleozoic and Mesozoic igneous and metamorphic rocks. Black circles and solid line: 2004 Stanford seismic survey line. Inset photos: (A) T-Rex in the Black Rock Range; (B) indentation in road surface by T-Rex (pen for scale); (C) plywood pad added to baseplate to protect paved road surfaces. From Lerch et al. (2008).

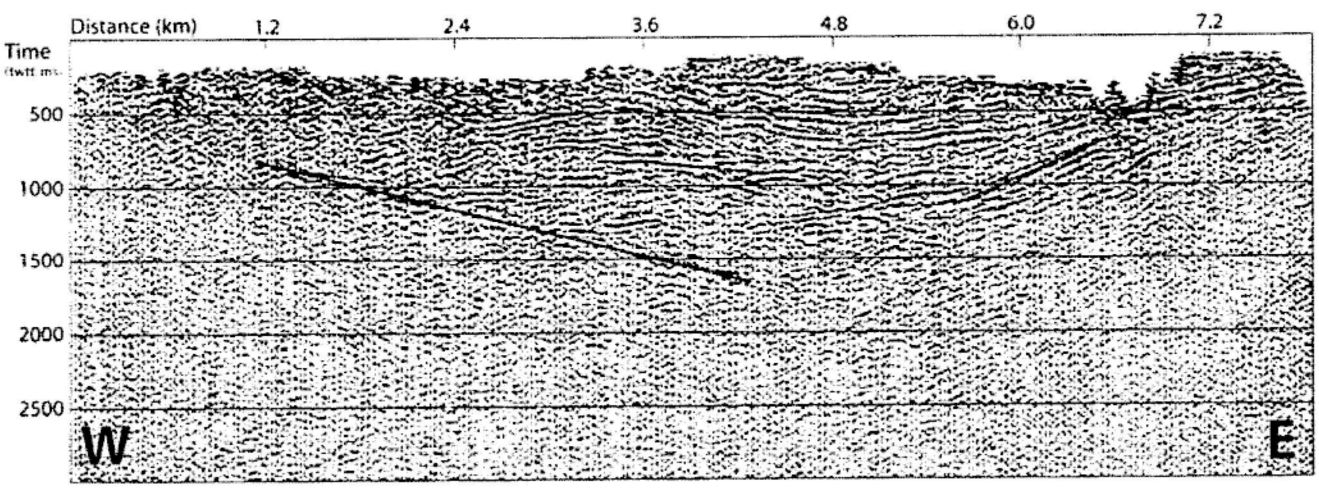

Figure 7. Seismic cross section across Surprise Valley based on 2004 seismic experiment.
The dark bands are rock formations or faults that reflected the seismic waves strongly. The red line is drawn along a reflector that probably represents the normal fault that bounds the eastern side of the Warner Range as is occurs in the subsurface. The blue line probably represents the continuation underground of the tilted basalt lava flows that are exposed on the eastern side of Surprise Valley. The flatter reflectors in the central portion of the image are probably lake sediments that have filled the Surprise Valley over the past few million years. From http://pangea.stanford.edu/groups/warners/seismic.html.

Geologic History

This corner of the northwest Great Basin is geologically relatively poorly understood. During the 1950s through 1970s, reconnaissance mapping was undertaken by the U.S. Geological Survey to assess the mineral and geothermal potential of the area. Unraveling the geologic history in light of a more modern understanding of plate tectonics and with more advanced geophysical and geochronological techniques is the subject of active research by groups at several universities and at the U.S. Geological Survey and the Nevada Bureau of Mines. As a result, what follows is only a preliminary account, based on our current knowledge, and is likely to change as more field and laboratory data are acquired.

If you drove over the Warner Range from Alturas to Cedarville, you may have noticed as you drove across Cedar Pass that the rock layers tilt westward at about 30 degrees (Figure 10). The blocks that make up the ranges in the Basin and Range Province are typically tilted as they slide along normal faults during extension. This tilting allows one to see deeper levels in the rocks layers. As one drives from Alturas to Cedarville one passes progressively from rocks only a few million years old to the oldest exposed rocks in the area, which are only about 35 million years old. On the geologic scale of time, the rocks and the landscape of the Warner Range and Surprise Valley are young.

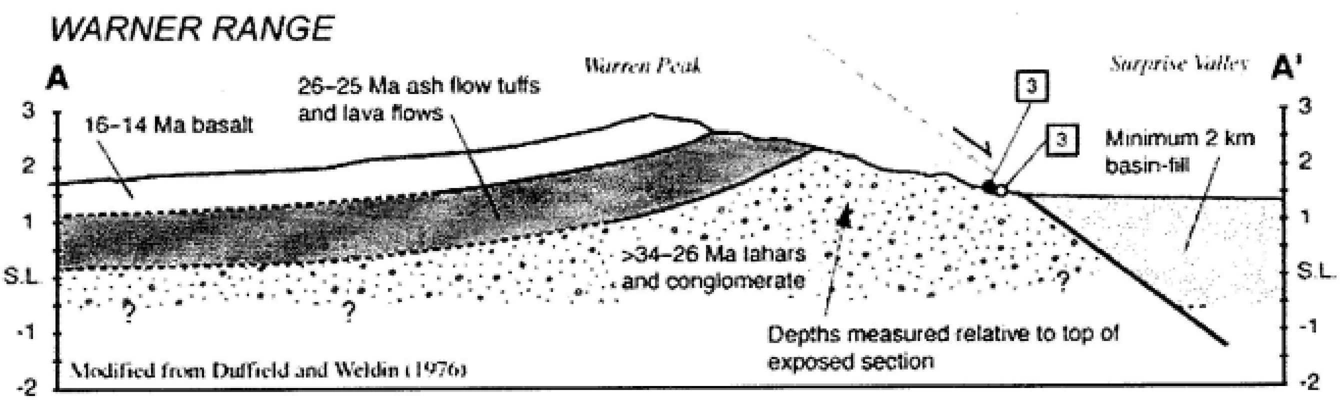

Figure 10. Simplified west-east geologic cross section across the Warner Range and part of Surprise Valley.
Elevation above and below sea level given in kilometers. There has been at least 6 km (about 3.5 miles) of offset along the Surprise Valley fault zone. The timing of the uplift of the Warner Range is poorly known, but a major part of it started about 4 million years ago. From Colgan et al. (2006).

The oldest rocks exposed are stream sediments and volcanic mudflows derived from a distant andesite volcano (similar to modern-day Mt. Shasta or Mt. Rainier). Eventually, magma was venting in or near the Warner Range, as lava flows overlie the sediments. The remains of a volcano can be seen on the east side of Surprise Valley, making up a high point on the Hays Canyon Range. It is the gutted remnants of a small, 26-million-year-old, basaltic andesite volcano, exposed by faults that bound the valley.

Of similar age to the Hays Canyon volcano is a rhyolite ignimbrite that is exposed to its north. The product of a hot avalanche of pumice, ash, and gases, it engulfed a forest of Metasequoia trees, whose petrified remnants now stand in mute testimony to a time when this area was much more lush[1]. Hot vapors rising through the ignimbrite precipitated minerals that tint it pink or salmon and that cement the pumice and ash together. Along Hwy 299/Rd 8a near Fortynine Mountain and along the road on the west side of Long Valley, near Vya (see map on back cover), the ignimbrite erodes into picturesque tepee-shaped "hoodoos".

The basalt and andesite lava flows and rhyolite ignimbrite dammed the drainages, forming lakes. The fine-grained sediments that accumulated in these lakes contain fossil impressions of leaves and fish.

Flowing over the rhyolite ignimbrite and around Hays Canyon volcano and the sediments that overlie them are younger basalt lava flows about 16 million years in age. Basalt lava flows of the same age cap what appears to be a correlative geologic section in the highest part of the Warner Mountains. Dark-colored vertical dikes that are the feeders for these lavas cut the light-colored ignimbrite and ashy sediments. A striking example of one of these dikes is exposed on the south side of Hwy 299/Rd 8a near Fortynine Mountain.

The period 17 to 15 million years ago was one of enormous volcanic activity in what is now the northwestern Great Basin and the Columbia River basin. Voluminous black basalt lavas flooded the landscape, locally forming thick sequences like those seen in the Columbia River gorge and in Oregon at Steens Mountain and Abert Rim[2]. At the latitude of Surprise Valley, these basalt flows are near their southern limit. Instead, in northwest Nevada, rhyolite eruptions so large that the roofs of their magma chambers collapsed to form four calderas, blanketed the landscape. These huge outpourings of basalt and rhyolite magma mark the first outbursts from the "hot spot" that now gives rise to the young volcanism and spectacular hot springs at Yellowstone National Park.

Younger basaltic lavas, as young as 3 million years old, outcrop on the northeast side of Surprise Valley. They are cut by obvious normal faults, which drop them down into the valley, indicating that the Basin-and-Range topography continues to develop.

The timing of uplift of the Warner Mountains is poorly known. It appears that the present range began to form about 4 million years ago, but there might also have been faulting and tilting between 26 and 16 million years ago. The steep eastern range front and the presence of fault scarps in young valley sediments indicate that uplift is ongoing.

Slabs of basaltic lava sitting on top of weak, ashy sediments, all cut by faults, is a geologic recipe for failure. Giant landslides have taken huge scallops out of the sides of the mountain ranges, and deposited jumbles of debris at their bases. One such landslide can be seen in the Hays Canyon Range on the east side of Surprise Valley, just south of where Hwy 299 crosses the valley.

---

[1] Modern Metasequoia trees, the deciduous "Dawn Redwood", live where annual precipitation exceeds 3' (compared to the 13" in modern-day Surprise Valley). Petrified Metasequoia is the state fossil of Oregon.

[2] Locally, large crystals of plagioclase in these basalts have a distinctive shimmer, making them "Oregon Sunstone", the state gemstone of Oregon.

Earth Resources

Hot springs and geothermal resources

The thin crust with anomalously hot mantle below creates higher-than-average temperatures in the crust of the Great Basin (Figure 11). Groundwater that circulates deeply is heated, and, becoming buoyant, rises. Typically it is channeled upward along fault zones to emerge at the surface as hot springs (Figure 12).

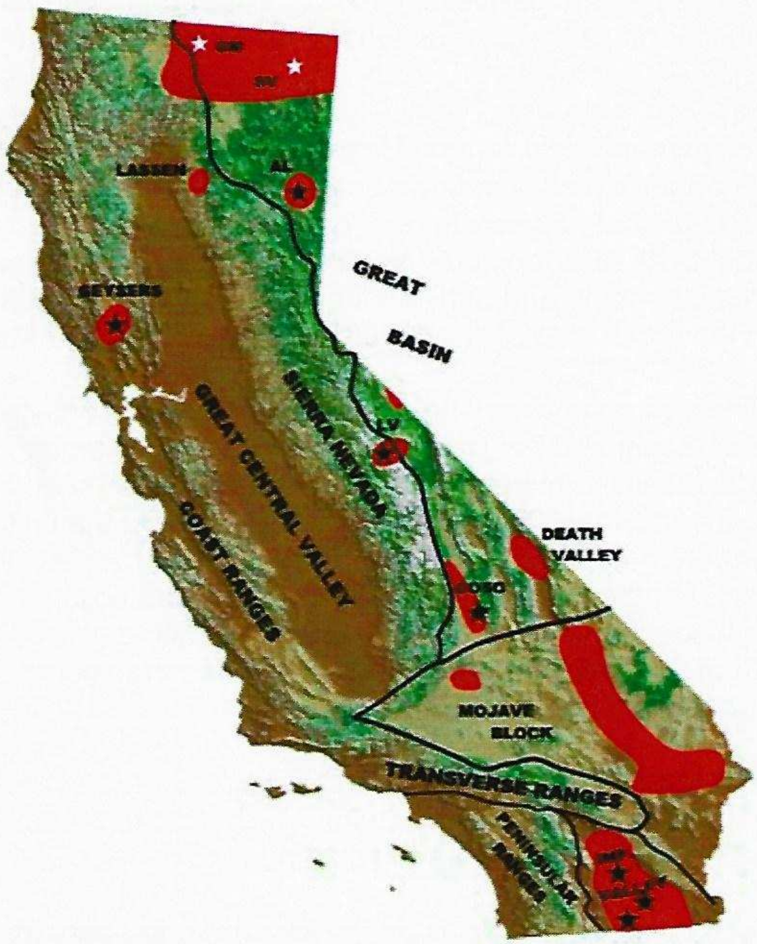

Figure 10. Shaded relief map of California showing areas with geothermal development and potential.

Areas of elevated heat flow (>100 mW m-2) shown in red, including Surprise Valley (SV), are the most favorable locations for geothermal prospecting. Locations of geothermal power plants shown with black stars. (From Sass and Priest, U.S. Geological Survey Open-File Report 02-132.)

Surprise Valley is host to many hot springs and a known geothermal resource area. On cold mornings, steam can be seen rising from the hot water at The Surprise Valley Resort and Spa (Figure 13), just south of the Highway 299 crossing Surprise Valley. Further north, a line of hot springs marks out one of the faults bounding the east side of the valley (see map on back cover). The largest group of hot springs lies just north of Lake City along the fault bounding the west side of the valley (Figure 14). More than one hundred hot water orifices, a few of them with boiling water, and a winter snowmelt area mark out a 1.5-mile-long area of extraordinarily high heat flow.

Figure 13. Surprise Valley Hot Springs Resort and Spa.
Photo courtesy http://www.surprisevalleyhotsprings.com/brochure.html.

One night in 1951, steam explosions burst through a cow pasture, shooting hot mud nearly 1,000' into the air (Figure 15). The attention this event garnered resulted in the Lake City area being one of the first geothermal systems in the Great Basin to be explored and drilled, starting in 1959.

The waters are Na-Cl-SO_4-type thermal waters with compositions indicative of reservoir temperatures of about 200°C. A productive well was drilled in 1973, but interest waned due to the relatively modest down-hole temperatures of 180°C (about 350°F) and the remote location. The hot water so far encountered on drilling is marginal for use in generating electrical power, but it is well suited to direct use, such as aquaculture and space heating (Figure 16). As oil prices have risen in the last few years, the area is once again being evaluated and drilled.

In 1984 a geothermal space-heating system was installed in Cedarville. Water at about 128°F (50°C) is pumped from two wells in excess of 1000' deep, and is circulated to the high school, elementary school, and the hospital and clinic. Similar systems have been installed by the Paiute tribe at the Fort Bidwell Reservation north of Lake City (see map on back cover). The high school in Alturas is heated with geothermal fluids, and an aquaculture operation in Canby, about 40 miles west of Cedarville on Highway 299, uses the warm water to grow tilapia (Figure 16).

Mineral deposits

The Basin and Range Province is the focus of most of the current mineral exploration in the United States. The ore deposits owe their existence to geothermal systems that result from thin, hot crust and the heat provided by magmas associated with volcanism of the last 40 million years. The deep hot fluids dissolve metals from rocks, flow upward along the zones of weakness provided by faults, and precipitate ore minerals on boiling or cooling near the surface. The Lake City geothermal system is a gold deposit in the making; fossil geothermal systems are the source of many of the gold deposits that are unusually abundant in Nevada.

The High Grade gold district in the Warner Range north of Fort Bidwell was active fitfully in the 1920s to 1940s, but was more the product of local boosterism than of major mineralization. From 1986 to 1993, Cedarville experienced a boomlet while the Hog Ranch gold mine, some 50 miles to the southeast, was being actively mined.

With the price of all commodities rising, and the need to expand energy sources other than fossil fuels, exploration in the northwestern Great Basin is likely to increase in the future. In addition to hosting gold deposits, the 15- to 16-million-year-old calderas are a source of mercury, uranium, gallium, and lithium. The volcanic rocks of the area have unusually high concentrations of these elements, which were leached out of the volcanic ash when it fell into lakes. The lake deposits of the 15-million-year-old caldera near McDermitt, Nevada (about 80 miles east of Cedarville) was mined for mercury from 1907 until 1990, when the mine closed due to low demand. The area is now being actively drilled for uranium, motivated by the approximately five-fold increase in the price in uranium over the last five years. It is also being explored for gallium, an essential component in semiconductors. The development in the next few years of improved lithium batteries to power electric vehicles may increase interest in the northwest corner of Nevada, because the volcanic rocks there contain one of the largest lithium resources in the world.

Petrified wood and fire opal

The volcanic ash associated with the calderas is also rich in silica. Groundwater leaches the silica and then precipitates it in the pores of twigs, leaves, and logs, petrifying them and locally producing fire opal. The excellent preservation of the woody structures by hard silica makes it possible to identify the petrified plants, which provide valuable information about past climate. For example, in the mountain range on the east side of Surprise Valley there are petrified stumps up to 4' in diameter of Metasequoia (Dawn Redwood) encased in a 26-million-year-old ignimbrite. The Metasequoia is suited to wet temperate climates, indicating that conditions were much less arid in the distant past.

WATER IN A LAND OF LITTLE RAIN

The author Mary Austin referred to the Great Basin as "The Land of Little Rain." Storms lose their moisture passing over the Klamath Mountains, the Cascades, and finally the Warner Mountains, making Surprise Valley indeed a land of little rain. The average annual precipitation for the last 60 years has been just less than 13".

Glacial Lake Surprise: Ancient lake shorelines and delta deposits

Little precipitation combined with high rates of evaporation result in Surprise Valley containing shallow, salty, playa lakes. But it hasn't always been so. During the last glaciation, peaking about 20,000 years ago, a freshwater lake some 500' deep filled the basin (Figure 17). Cooler temperatures led to less evaporation, so water reaching the lake remained there.

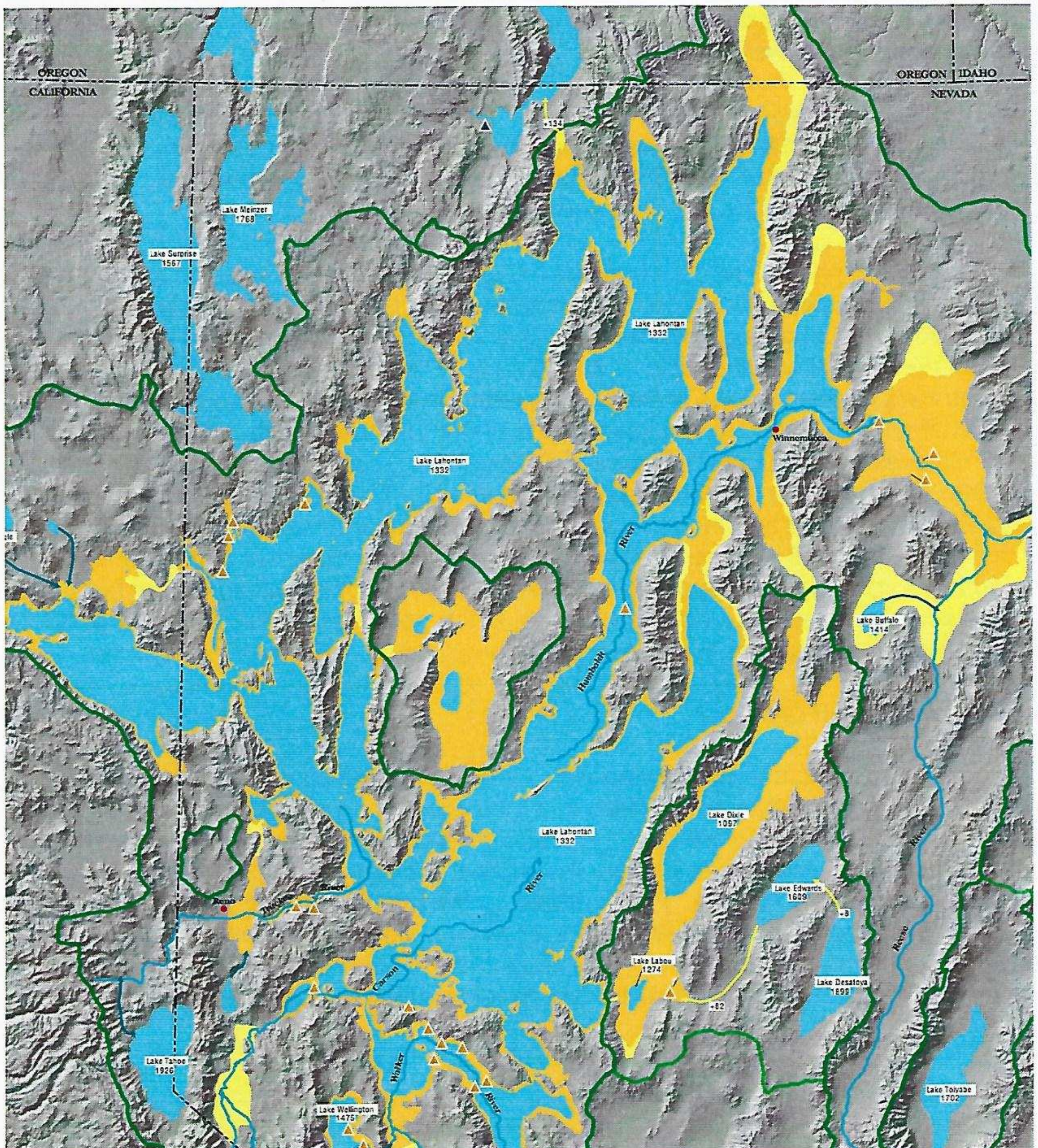

Figure 17. Lakes in the northwest Great Basin during the last glacial maximum ~20,000 years ago. Glacial Lake Surprise is in the upper left corner. Compare it in size to Lake Tahoe, in the lower left corner. Both are dwarfed by huge Lake Lahontan, the only remnant of which is modern-day Pyramid Lake to the northeast of Reno. From Reheis (1999) U.S. Geological Survey MAP MF-2323.

When the sun angle is low, you can see the ancient shorelines of Lake Surprise as a series of benches looking like bathtub rings on the east side of the valley. Each bench marks where the lake level stabilized for some time, and shoreline waves eroded a beach.

Other evidence for the high lake levels are the flat-topped deposits of deltas that formed where ancient streams spilled out of the Warner Mountains into Lake Surprise (photo on cover). The decrease in velocity as the water entered the lake caused all the debris the stream was carrying to be sedimented out near the canyon mouth. The resulting sand and gravel layers that form the delta deposits are locally quarried for road paving material.

Today, the only remnants of Lake Surprise are three shallow alkali lakes (see map on back cover), and the water stockpiled as groundwater from the glacial times. Although the shallow levels of the valley aquifers are recharged annually by rainfall and by snowmelt that soaks into the surrounding mountains, pumping the valley's groundwater is, to some extent, "mining" glacial water that will not be replenished during this warmer interval.

Water shaping the desert landscape: flash floods, debris flows, and alluvial fans

One of the ironies of the high desert of the Great Basin is that even though water is scarce, it is still a major force in shaping the landscape. Unlike in more temperate lands, streams in the desert get smaller as they go downstream, losing water to the porous bed below, and they often flow for only part of the year. They are ephemeral, flowing only in winter or in the spring and early summer when they have snowmelt to carry.

Although the volumes of water they carry are small, ephemeral streams have steep gradients that allow them to transport great volumes of debris, even large boulders and fallen trees. And there are times when they have a lot of work to do. Thunderstorms can park themselves in one spot in the mountains, splashing down inches of rain in short bursts. Once the ground is saturated, the rainwater mixes with debris and makes a slurry, which slides down the streambed, picking up momentum and incorporating more debris as it flows. At the canyon mouth, the gradient lessens and the "flash flood" slows and deposits its load of debris. A stream may see a large debris flow only once a decade, but over the course of geologic time, the debris flows construct a large fan of debris emanating from the canyon mouth (Figure 18).

These alluvial fans flanking the fault-bounded ranges are a characteristic landform of the Basin and Range province. Cedarville and the smaller community to the north, Lake City, are sited on alluvial fans. In the winter of 1996, twice the normal amount of snow had fallen by December. Then days of unusually warm rain melted the snowfall and swelled Mill Creek and Powley Creek, which flowed through the Parman Ranch watering its cattle pasturelands. On New Year's Eve, Mill Creek overflowed and sent cobble-filled debris flows through the streets of Lake City. The rocks in Powley Creek were no match for the torrent, having been weakened long ago by acidic gases from hot springs, and they were scoured away to form huge debris flows full of tractor-sized boulders and old-growth logs that swept over the alluvial fan, carrying away the Parman home and several outbuildings. The crushed remains of those buildings, visible from the County Road 1 just north of Lake City, are an instructive reminder that, in this land of little rain, water is still a powerful force.