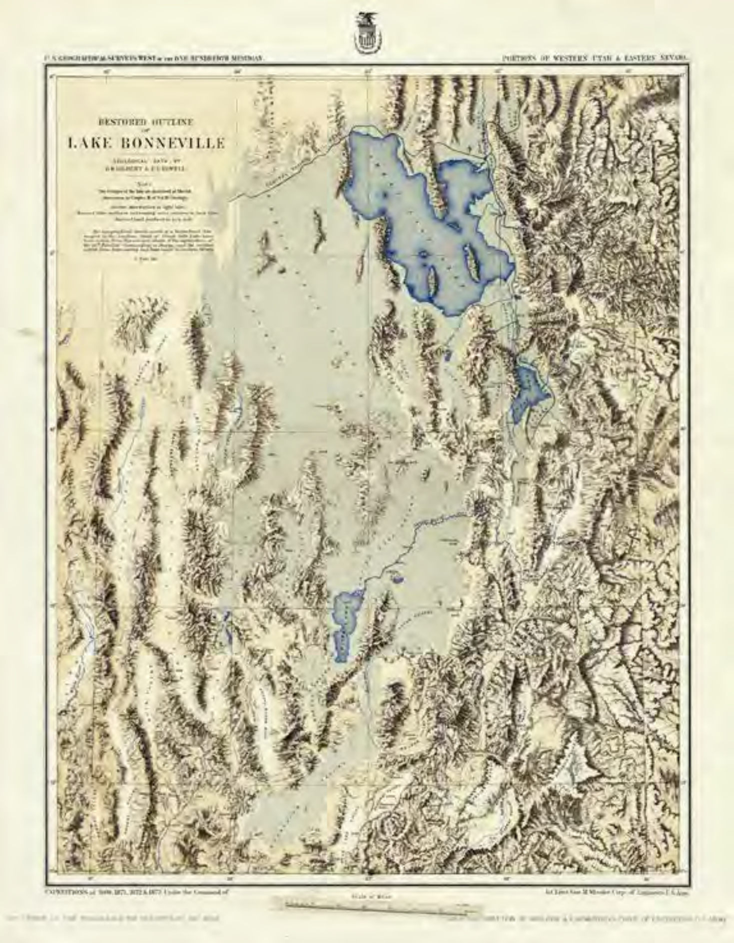
GEOLOGY OF THE INTERMOUNTAIN WEST
an open-access journal of the Utah Geological Association
Volume 4 *2017*

SHORELINES AND VERTEBRATE FAUNA OF PLEISTOCENE LAKE BONNEVILLE, UTAH, IDAHO, AND NEVADA

Mark Milligan and H. Gregory McDonald



A Field Guide Prepared For
SOCIETY OF VERTEBRATE PALEONTOLOGY
Annual Meeting, October 26 – 29, 2016
Grand America Hotel
Salt Lake City, Utah, USA

GEOLOGY OF THE INTERMOUNTAIN WEST

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Volume 4 **2017**

Editors

Society of Vertebrate Paleontology Editors

Production

Cover Design and Desktop Publishing
Douglas A. Sprinkel

Cover

Restored outline of Lake Bonneville. Geological data by G.K. Gilbert and E.E. Howell. Lithography by J. Bien. Dated 1876. From, "Topographical Atlas Projected to Illustrate United States Geographical Surveys West of The 100th Meridian," a collection of 135 topographical and geological atlas sheets, 1876 to 1881. Downloaded from the David Rumsey Map Collection, www.davidrumsey.com. Ancient lake surface in light blue. Present (1876) lake surfaces and running water courses in dark blue. Ancient land surface in dark drab. Thought to be the oldest published map of Lake Bonneville, this 1876 map does not show the full extent of the lake as depicted in Gilbert's 1890 monograph.

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Shorelines and Vertebrate Fauna of Pleistocene Lake Bonneville, Utah, Idaho, and Nevada

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ABSTRACT

Pleistocene Lake Bonneville created many classic examples of lacustrine shoreline landforms, which preserve a wide variety of vertebrate fossils. This field guide provides a review of the published literature for a sampling of the lake's world-class localities. This guide also provides a brief overview of modern Great Salt Lake and its microbialites recently exposed by near-record low lake levels. Stops include G.K. Gilbert Geologic View Park, Draper spit, Steep Mountain beach, Point of the Mountain spit, American Fork delta, Stockton Bar, and Great Salt Lake State Park.

INTRODUCTION TO LAKE BONNEVILLE AND THE BONNEVILLE BASIN

The following section is modified from Godsey and others, 2005a.

Lake Bonneville was a large pluvial lake that occupied the eastern Great Basin during latest Pleistocene marine Oxygen Isotope Stage (MIS) 2, from approximately 30 to 13 cal ka (figure 1) (Gilbert, 1890; Oviatt, 2015). This region is part of the Basin and Range Province that developed in response to east-west crustal extension beginning ca. 20 Ma. Normal faulting and subsidence caused the formation of basins separated by uplifted fault blocks. The most significant subsidence occurred at the eastern margin of the Basin and Range Province, and it is here that the Bonneville basin formed. Extension continues to modify the landscape in the Basin and Range today.

The Bonneville basin has been a region of internal drainage for the past 15 m.y. and lakes of varying sizes have occupied part of the basin throughout most of this

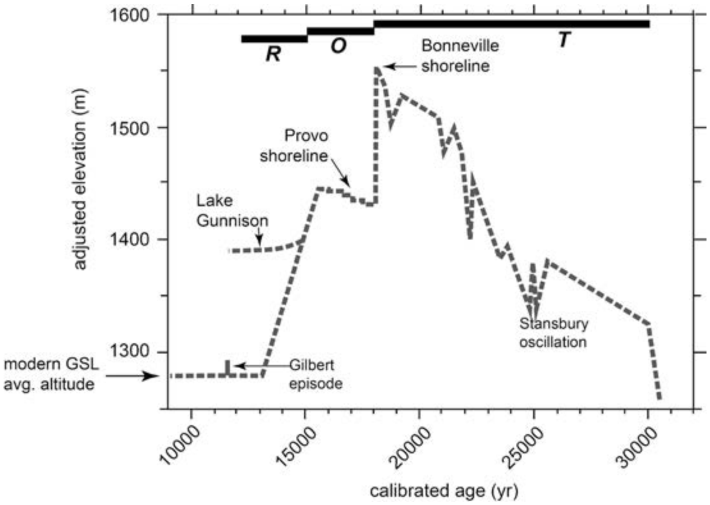


Figure 1. Simplified hydrograph of Lake Bonneville. Altitudes adjusted for isostatic rebound. Bars at top show transgressive (T), overflowing (O), and regressive (R) phases. Modern Great Salt Lake (GSL) average altitude is 1280 m. Lake Gunnison is an isolated lake in the Sevier sub-basin that formed with the regression of Lake Bonneville. Figure courtesy of Jack Oviatt (Kansas State Univeristy).

Citation for this article.
Milligan, M., and McDonald, H.G., 2017, Shorelines and vertebrate fauna of Pleistocene Lake Bonneville, Utah, Idaho, and Nevada: Geology of the Intermountain West, v. 4, p. 181–214.

time (Currey and others, 1984). Researchers have produced evidence that at least four deep-lake cycles have occurred in the Bonneville basin over the past 780,000 years, the Bonneville lake cycle being the youngest of these (Oviatt and others, 1999).

Lake Bonneville began to form ca. 30 ka when colder and/or wetter climate conditions during the Last Glacial Maximum caused it to rise (Oviatt, 2015). The timing and/or the rapidity of the rise may have been influenced by diversion of the upper Bear River into the Bonneville basin ca. 30 ka (Reheis and others, 2014), although Pederson and others (2016) report evidence that the river diversion occurred about 50 ka. The transgression continued until ca. 25 ka when changing climate conditions caused the lake to undergo a slight regression (Oviatt, 2015). For nearly 3000 yr, the level of the lake oscillated through a vertical range of about 50 m near 1370 m above sea level (masl), forming the Stansbury shoreline, and then began to rise again. By ca. 18 ka, the lake had reached the level of the topographic divide near Zenda, Idaho (figure 2), and began to overflow. This marks the beginning of the open-basin phase of the lake and the formation of the Bonneville shoreline (figure 1).

When the lake became very deep and heavy in the center of the basin, transgression was enhanced by hydro-isostatic subsidence. However, the primary driver of transgression was a change in water budget caused by climate change in the basin. Water inputs from precipitation, groundwater, and runoff became much greater than outputs by evaporation and groundwater. At 18 ka Lake Bonneville was over 300 m deep and covered an area of ~51,000 km^2 (Oviatt and Miller, 1997). Rivers emanating from the high mountains to the east provided large amounts of clastic material that was deposited in deltas along the mountain fronts (Lemons and others, 1996). Spits, barriers, bars, and beaches were supplied sediment by alluvium and weathered bedrock in regions with little riverine input. Muds and marls were deposited in more distal, offshore locations (Oviatt and Miller, 1997).

Catastrophic failure of the alluvial-fan dam (the alluvial-fan deposits overlie tuffaceous sediments of the Neogene Salt Lake Formation) at the Zenda (figure 2) threshold in southern Idaho ca. 18 ka caused a massive flooding of lake waters into the Snake River drainage (Gilbert, 1890). There is insufficient resolution to determine how long the lake remained at the threshold before failure, although it is likely the overflow period was

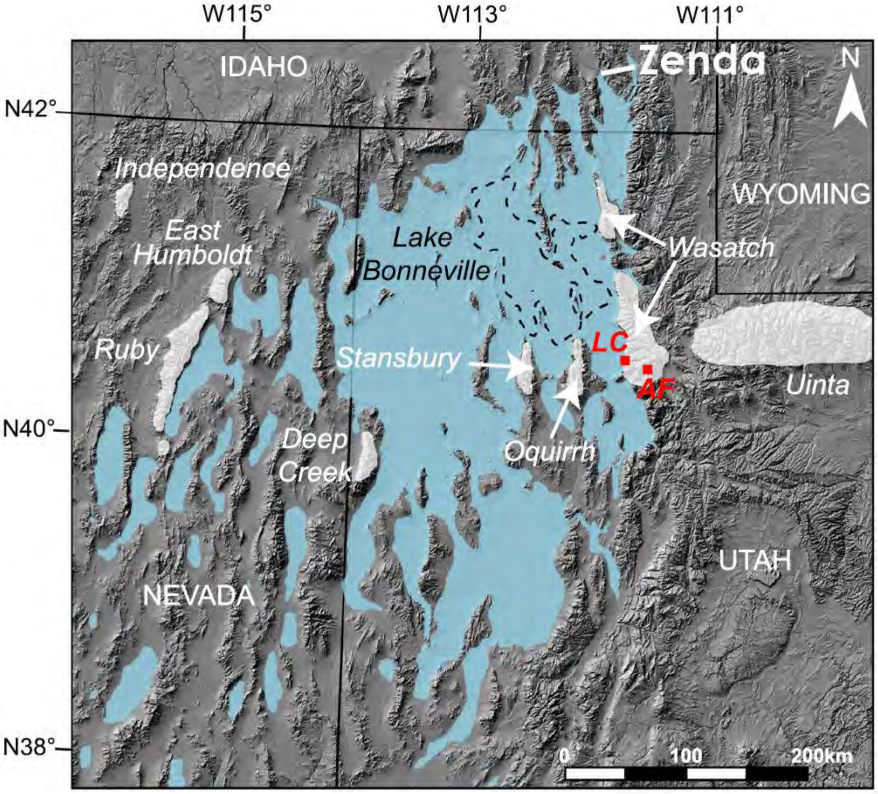


Figure 2. Shaded-relief map showing the extent of Lake Bonneville and other Great Basin lakes (blue) and select mountain ranges with valley glaciers (white) during the latest Pleistocene. Dashed line delineates Great Salt Lake. Red boxes indicate the locations, Little Cottonwood (LC) and American Fork (AF) Canyons, of study areas for 10Be cosmogenic surface-exposure dating of erratic boulders atop moraines by Laabs and others (2011) and Laabs and Munroe (2016). Modified from Laabs and others (2011).

very short (Oviatt, 2015; Oviatt and Jewell, 2016). This event, called the Bonneville flood, caused a drop in the lake level of at least 125 m (Miller and others, 2013) and is believed to have occurred in less than one year's time (Malde, 1968; O'Connor, 1993, 2016). Headward erosion by flood waters shifted the drainage divide to the southeast ~3.2 km to near Red Rock Pass, Idaho (Currey, 1982). The lake re-stabilized at the new threshold, probably on massive landslide deposits, and the Provo shoreline began to form (figure 1; Gilbert, 1890; Miller, 2016).

The lake oscillated at or near the level of the Red Rock Pass outlet until a change in climate conditions permanently drove the lake below the threshold, starting ca. 15 ka (Godsey and others, 2011; Oviatt, 2015). By ca. 13 ka, the lake had reached levels comparable to modern Great Salt Lake (Oviatt, 2015). This marks the end of the Bonneville lake cycle and the beginning of its successor, Great Salt Lake. The lake appears to have risen again briefly ca. 11.6 ka during the Gilbert episode (Oviatt and others, 2005; Oviatt, 2014), but the existence and extent of a Gilbert shoreline is suspect and the subject of ongoing investigations (Oviatt, 2014).

The mass of Lake Bonneville's water weighed down and isostatically depressed the Earth's crust. With the demise of the lake the crust rebounded to its original elevation, thus elevating and distorting the originally horizontal shorelines (Gilbert, 1890; Adams and Bills, 2016). The greatest rebound, up to 74 m, was at the deepest part of the basin on the west side of Great Salt Lake (Currey, 1990).

CLIMATE AND GLACIATION

Though permanent diversion of the upper Bear River into the Bonneville basin may have influenced the timing and/or the rapidity of the rise of Lake Bonneville (Reheis and others, 2014), the climatic variables of evaporation and precipitation subsequently controlled lake level and glacial extent in the Bonneville basin (Laabs and Munroe, 2016). The importance of temperature vs. precipitation in controlling lake and glacier mass balance has been controversial (Laabs and others, 2011; Reheis and others, 2014). Some studies suggest a cold and dry climate in the interior western U.S. during MIS 2 (e.g., Porter and others, 1983; Kaufman, 2003). Other studies suggest increased precipitation drove lake and glacier expansions (e.g., Benson and Thompson, 1987).

The long-held idea that glacial maxima predated lake-level highstand (e.g., Madsen and Currey, 1979) favored a wetter and warmer scenario. However, Godsey and others (2005b) describe glacial till stratigraphically above and below Bonneville shoreline deposits. Furthermore, Laabs and Munroe (2016) used ^{10}Be cosmogenic surface-exposure dating of erratic boulders to determine that terminal moraines in the Bonneville basin were occupied near the time of the Bonneville highstand at 18 ka and subsequently abandoned while the lake continued to overflow at the Provo threshold.

Thus, the climate favored simultaneous lake transgression and glacial advance until ca. 18 ka. The apparent start of ice retreat while the lake still overflowed suggests that sometime after 18 ka the climate warmed but precipitation remained high enough to sustain a positive water budget for the lake until retreat from the Provo shoreline at ca. 15 ka (Laabs and Munroe, 2016).

THE PLEISTOCENE AND HOLOCENE VERTEBRATE FAUNA OF LAKE BONNEVILLE

In Gilbert's 1890 monograph on the geology of Lake Bonneville, it only briefly mentions vertebrate remains as some "elephantine bones and ivory" recovered from a "post-Bonneville" marsh east of Utah Lake. However, Pleistocene vertebrate remains associated with the lake deposits were being discovered in the area during the earliest studies of the lake (Chadbourne, 1871) and the recovery of vertebrate fossils from Lake Bonneville sediments and sediments in caves in the Bonneville basin continues to the present (figure 3).

Our knowledge of the Pleistocene vertebrate fauna associated with Lake Bonneville is based on numerous localities in the lake basin. Jefferson and others (1994) listed 18 localities in Salt Lake County, three in Davis County, and one each in Box Elder and Weber Counties. Most of our knowledge of the fauna has occurred recently (Stokes and others, 1964; Smith and others, 1968; Nelson and Madsen, 1978, 1980, 1983, 1986, 1987; Miller, 1982, 2002; Feduccia and Oviatt, 1986; Gillette and Miller, 1999; Schmitt and Lupo, 2016). Based on the

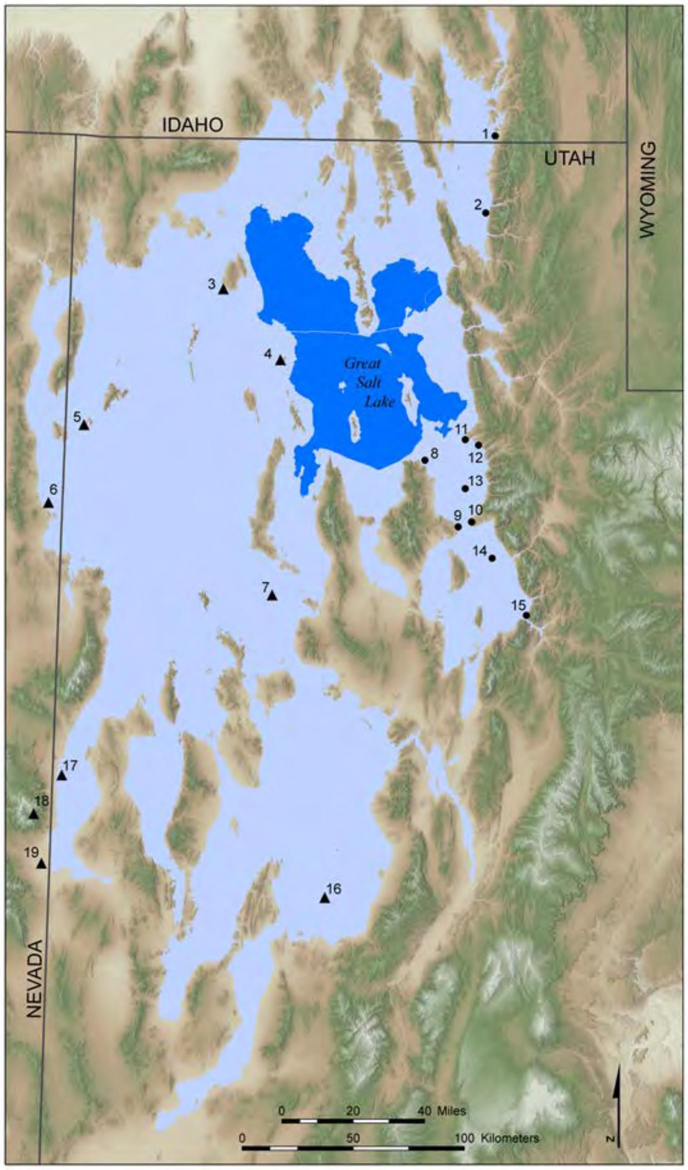


Figure 3. The Bonneville basin showing locations of selected paleontological and archaeological sites with vertebrate remains. Circles are open air sites and triangles are cave or rock-shelter sites: (1) Franklin Peccary Site, (2) Logan Cemetery, (3) Hogup Cave, (4) Homestead Cave, (5) Danger Cave, (6) Bonneville Estates Rock Shelter, (7) Camels Back Cave, (8) Lark, (9) Jordan Narrows, (10) Point of the Mountain Sloth Site, (11) Monroc Gravel Pit, (12) Huntsman, (13) Sandy Mammoth, (14) Orem Sloth Site, (15) Spanish Fork, (16) Tabernacle Crater Camel Site, (17) Crystal Ball Cave, (18) Smith Creek Cave and Cathedral Cave, and (19) Snake Creek Burial Cave. Modified from Schmitt and Lupo (2016).

location, elevations, and the physical stratigraphy of the various sites, the majority of the fauna associated with Lake Bonneville gravel deposits comes from sediments deposited at or near the Bonneville and Provo shorelines (Nelson and Madsen, 1987; McDonald and others, 2001).

After dropping from the Bonneville to Provo level, the lake occupied the Provo shoreline for about 3000 years. The Provo shoreline is formed by a complex of several coalescing coastal landforms, many of which form a pattern of distinctive beach ridges that can be identified throughout the basin (Burr and Currey, 1988; Godsey and others, 2005a; Miller and others, 2013; Miller, 2016). Radiocarbon ages of sediments associated with the Provo shoreline indicate that Lake Bonneville dropped rapidly from the Provo shoreline at about 12,600 ^{14}C yr B.P. (15,000 cal yr B.P.). The rapid lowering of the lake level from the Provo shoreline correlates with the decline of Lakes Lahontan in Nevada and Estancia in New Mexico, and with the onset of the Bølling–Allerød warming event (Godsey and others, 2011). The earliest report of Pleistocene vertebrates from deposits associated with Lake Bonneville was by King (1878) who noted that "the latest subaerial gravels [i.e., Provo shoreline] yielded a skull of *Bison latifrons* and fragments of bones, supposed to be a "reindeer." Unfortunately the location where the specimens were found is unknown as is the current location, and it is not known if they were even collected. *Bison antiquus* is also present and has been recovered from gravel pits along the eastern shoreline of the lake (figure 4B).

The deposits associated with the Provo shoreline span the time interval when the climate in the Great Basin was transitioning from the colder, wetter conditions of the Last Glacial Maximum to the warmer, drier conditions of the late Pleistocene and early Holocene (Godsey and others, 2011). The expansion and contractions of lake levels in the Great Basin during the late Pleistocene to Holocene transition have been linked to position of the jet stream as it was deflected around the North American ice sheets (Kutzbach, 1987). In general, pluvial lakes at lower latitudes (ca. 32°–35° N), such as Lake Estancia in New Mexico, reached their highstand when the continental ice sheets had reached their maximum extent about 15,000 ^{14}C years ago (Garcia and Stokes, 2006). In contrast, lakes at higher latitudes (ca. 38°–40° N), such as Bonneville and Lahontan, experienced their

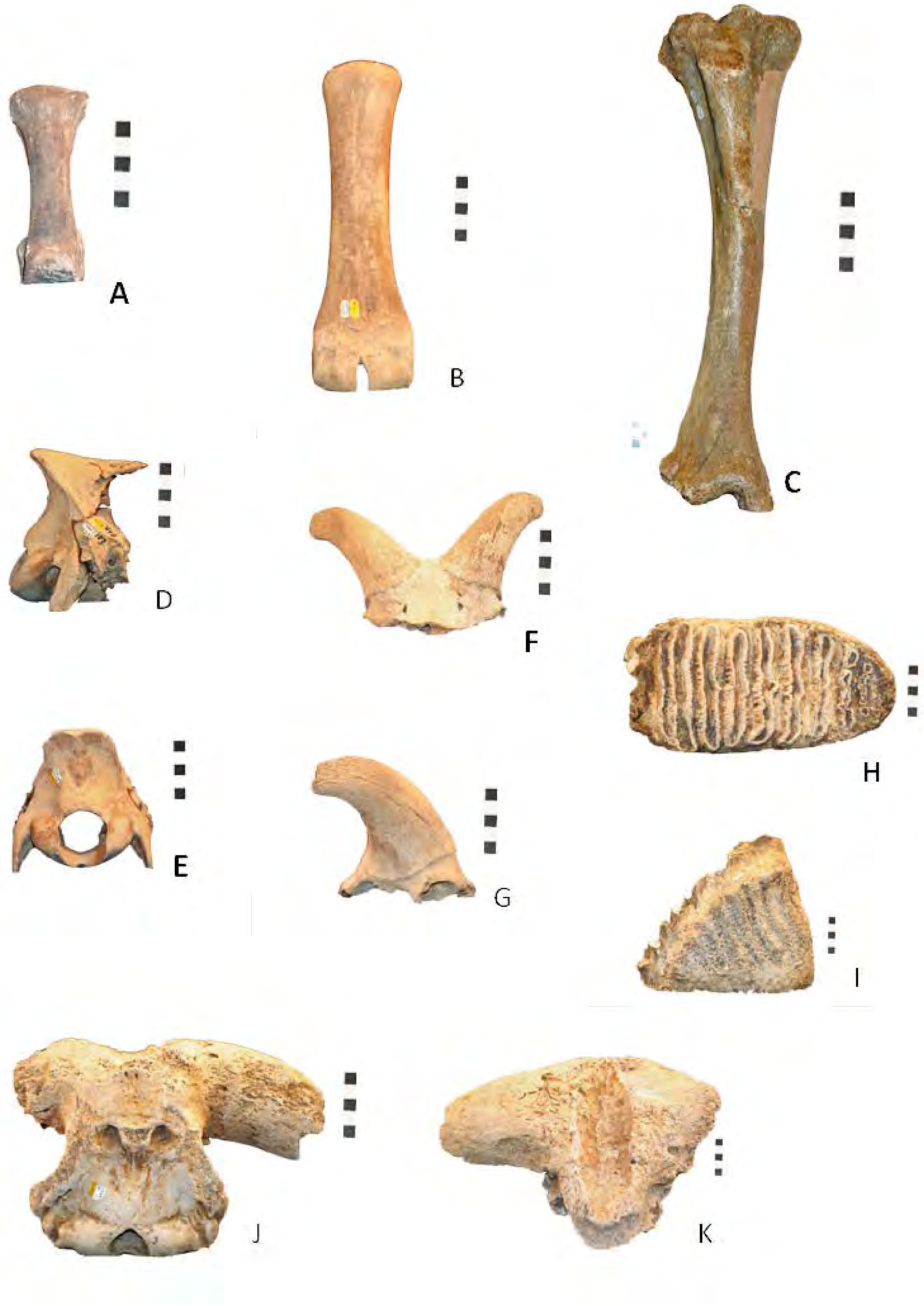


Figure 4. Pleistocene vertebrate fossils from gravel pits on the east side of Lake Bonneville. (A) *Camelops hesternus*, proximal phalanx, anterior view. (B) *Bison antiquus* metacarpal, anterior view. (C) *Arctodus simus* right tibia, anterior view. (D and E) *Equus* sp. braincase, right lateral, posterior view. (F and G) *Ovis canadensis* braincase, anterior and right lateral view. (H and I) *Mammuthus columbi* right upper molar, occlusal, lateral view. (J and K) *Bootherium bombifrons* (male) braincase, posterior and dorsal view. All specimens in the Natural History Museum of Utah. Scale is 5 cm.

highstands slightly later (ca. 14,500–13,500 ^{14}C yr B.P.) following the retreat of the ice sheets northward (Adams and Wesnousky, 1998; Benson and others, 1990; Garcia and Stokes, 2006). As the ice sheets continued to retreat, storm tracks also shifted northward, resulting in reduced annual precipitation and a lowering of water levels in pluvial lakes in the region.

The development of a clear record of changes in the lake-level within the Bonneville basin is critical for examining regional climate patterns and the degree of synchronicity in the highstands in the numerous pluvial lakes across the western United States during the Last Glacial Maximum (Benson and others, 1990; Adams and Wesnousky, 1998; Benson, 1999; Licciardi, 2001; Garcia and Stokes, 2006; Broecker and others, 2009). A better understanding of the climatic conditions that determined lake levels also provides a framework for understanding how the Pleistocene fauna of the region was impacted by climatic and environmental change since changes in precipitation not only impacted lake levels but vegetation as well.

Multiple caves (e.g., Homestead Cave and Cathedral Cave in Utah, and Danger Cave and Smith Creek Cave in Nevada) are associated with Lake Bonneville that after becoming exposed with the lowering of lake level accumulated small vertebrate remains. Sediments in Homestead Cave have been dated from 11,270 ± 135 to 1020 ± 40 ^{14}C yr B.P. (Broughton, 2000). Radiocarbon dates for Cathedral Cave range from 15,310 ± 60 to 740 ± 40 ^{14}C yr B.P. (Madsen, 2000). Whereas the fauna recovered from both caves spanned the Pleistocene-Holocene transition no extinct species were recovered from either cave.

The composite fauna which is derived from multiple sites spanning thousands of years is highly biased toward larger taxa; 15 mammals, two birds, and six fish are reported by Nelson and Madsen (1987). Since then the megafauna has been expanded by the discovery of two separate finds of the Jefferson ground sloth, *Megalonyx jeffersonii* (Gillette and others, 1999; McDonald and others, 2001). Whereas some specimens can be placed within a chronology based on where they were collected, the vertebrae faunal record is not sufficiently robust or has a tight enough chronology at this time to actually document any faunal change in response to climatic change. Few of the older specimens have been radiocarbon dated, and in many cases the quality of preservation of many specimens does not permit a radiocarbon date. Schmitt and Lupo (2016, table 13.1) provide a list of the extinct Pleistocene mammals of the Bonneville basin, although some of the taxa were recovered from localities adjacent to the basin and not the basin proper. A composite list of taxa from sites directly associated with Lake Bonneville appears in table 1.

A muskox skull was among the first vertebrate fossils to be described from the Bonneville basin (Chadbourne, 1871). Nelson and Madsen (1987) recognized two taxa of musk ox, *Bootherium bombifrons* and *Symbos cavifrons*, from the Bonneville basin but these two taxa are now considered male (*Symbos*) and female (*Bootherium*) of the same species (McDonald and Ray, 1989), so one extinct species of muskox, *Bootherium bombifrons*, is now recognized from the late Pleistocene in North America, along with the extant muskox, *Ovibos moshatus*. Nelson and Madsen (1987) reported four skulls of the female have been recovered and 21 skulls of the male along with some post-cranial material. Gillette and Miller (1999) reported a partial skeleton found during construction of the Huntsman Chemical Corporation headquarters in Salt Lake City, another skull from the Staker gravel pit, an ear region and vertebrae from a gravel pit owned by the Kennecott Copper Company in Salt Lake County, a skull from Spanish Fork in Utah County, and post-cranial bones from the same gravel pit at Point of the Mountain that produced a ground sloth. The predominance of male skulls has been noted elsewhere (McDonald and Ray, 1989) and has been explained as reflecting the more robust build of the male skull which favors its preservation (figures 4J and 4K). Nelson and Madsen (1987) observed that skulls are readily noticed by machinery operators in the gravel pits so have a better chance of being collected. The sample of skulls of *Bootherium* from the Bonneville basin is one of the largest samples for the species and one of the few places where both skull morphs have been found.

As is common in the western United States, mammoth, as represented by *Mammuthus columbi* (figures 4H and 4I), is more common than mastodon, *Mammut americanum*, and this is also true for the Bonneville ba-

Table 1. Late Pleistocene and early Holocene vertebrate taxa associated with Lake Bonneville. Compiled from Nelson and Madsen (1987), Gillette and others (1999), Broughton (2000), Grayson (2000), and Broughton and others (2000), Livingston (2000), McDonald and others (2001), Schmitt and Lupo (2016), and Wolfe and Broughton and Smith (2016). * = extinct taxa.

Class Osteichthyes
- *Gila atraria*
- *Richardsonius balteatus*
- *Catostomus ardens*
- *Catostomus discobolus*
- *Panosteus virescens*
- *Chasmistes* cf. *liorus*
- cf. *Salvelinus confluentus*
- *Oncorhynchus clarki*

(also reported as *Salmo clarki*)
- *Prosopium gemmifer*
- *Prosopium spilonotus*
- *Prosopium abyssicola*
- *Cottus bairdi*
- *Cottus extensus*

Class Aves
- *Podilymbus podiceps*
- *Podiceps* sp.
- *Aechmophorus occidentalis*
- *Phalacrocorax auritus*
- (reported as *P. macropus*)
- *Branta* sp.
- *Anas* sp.
- *Athya* sp.
- *Bucephala albeola*
- *Bucephala clangula*
- *Oxyura jamaicensis*
- *Cygnus buccinator*
- *Circus cyanus*
- *Accipiter striatus*
- *Buteo* sp.
- *Falco sparverius*
- *Falco columbiarius*
- *Falco* cf. *mexicanus*
- Phasianidae
- *Rallus limnicola*
- *Porzana carolina*
- *Porphyra/Gallinula/Fulica*
- *Recurvirostra americana*
- *Phalaropus* sp.
- *Larus* sp.
- *Zenaida macroura*
- *Coccyzus americanus*
- *Tyto alba*
- *Otus* sp.
- *Bubo virginianus*
- *Glaucidium gnoma*
- *Athene cunicularius*
- *Asio* sp.
- *Ageolius acadicus*
- *Chordeiles* cf. *acutipennis*
- *Phalaenontilus nuttallii*
- *Melanerpes lewis*
- *Sphyrivicus* sp.
- *Picoides* sp.
- *Colantes auratus*
- *Tyrannus verticalis*
- *Eremophilia alpestris*
- cf. *Stelgidopteryx serripennis*
- *Cyanocetta stelleri*
- *Aphelocoma coerulescens*
- *Pica pica*
- Troglodytidae
- *Myadestes townsendi*
- *Turdus migratorius*
- *Oreoscoptes montanus*
- *Bombycilla garrulous*
- *B.* cf. *cedrorum*
- *Lanius ludoviciana*
- *Piranga ludociviana*
- *Pheuticus* cf. *melanocephalus*
- *Piplio* cf. *chlorurus*
- *Piplio* cf. *erythrophthalmus*
- *Agelaius phoeniceus*
- *Sturnella neglecta*
- *Xanthocephalus xanthocephalus*
- Fringillidae
- *Carpodacus mexicanus*
- *Carduelis tristis*
- *Coccothraustes vespertinus*

Class Mammalia
- *Megalonyx jeffersonii* *
- *Brachylagus idahoensis*
- *Lepus californicus*
- *Lepus townsendii*
- *Sylvilagus* cf. *audubonii*
- *Sylvilagus cf. nuttallii*
- *Ammospermophilus lecurus*
- *Tamias minimus*
- *Marmota flaviventris*
- *Spermophilus mollis*
- *Thomomys bottae*
- *Thomomys talpoides*
- *Chaetodipus formosus*
- *Dipodomys microps*
- *Dipodomys ordii*
- *Microdipodops megacephalus*
- *Perognathus longimembris*
- *Perognathus parvus*
- *Lemmiscus curtatus*
- *Microtus* sp.
- *Neotoma cinerea*
- *Neotoma lepida*
- *Ondatra zibethicus*
- *Onychomys leucogaster*
- *Peromyscus* sp.
- *Pitymys* sp.
- *Reithrodontomys megalotis*
- *Vulpes vulpes*
- *Vulpes velox*
- *Canis latrans*
- *Canis lupus*
- *Arctodus simus* *
- *Ursus americanus*
- *Lynx rufus*
- *Mustela erminea*
- *Mustela frenata*
- *Mustela vison*
- *Spilogale putorius*
- *Taxidea taxus*
- *Equus* sp.
- *Platygonus compressus* *
- *Camelops hesternus* *
- *Odocoileus hemionus*
- *Navahoceros* cf. *fricki* *
- *Antilocapra americana*
- *Ovis canadensis*
- *Bison* cf. *antiquus* *
- *Bootherium bombifrons*
- (including *Symbos cavifrons*) *
- *Mammut americanum* *
- *Mammuthus columbi* *

sin with 17 documented records of mammoth and only one record of mastodon (Nelson and Madsen, 1987; Larson, 1999). This may simply reflect differences in preferred habitat with mastodons more closely associated with coniferous forests that would have been present at higher elevations in the Wasatch Range outside the lake basin (Miller, 1987), while the mammoths would have grazed in the more open grassland habitat at lower elevations. The recovery of a mammoth from a gravel pit near Newcastle in the Escalante Valley, Iron County, is the southernmost record of this taxon associated with Lake Bonneville (Larson, 1999). The specimen was recovered from an alluvial-fan complex and was radiocarbon dated at 28,670 ± 260 ^{14}C yr B.P., which predates the lake's highstand in that valley 12,000 years later. However, while the southern edge of Lake Bonneville did extend into the northern part of the Escalante Valley (Currey, 1982) the lake did not extend as far south as the site where the mammoth was found.

Another taxon associated with Lake Bonneville that is relatively rare in the western United States is the flat-headed peccary, *Platygonus compressus* (McDonald, 2002). The single record, consisting of most of the skeleton of one individual comes from the Cache Valley. The specimen was radiocarbon dated at 11,340 $\pm$ 50 ^{14}C yr B.P. and indicates the floor of the valley was inhabited by terrestrial fauna relatively soon after the flood and drop in lake level. The extinct camel, *Camelops*, which is uncommon, has been referred to *C. hesternus*, primarily based on size (figure 4A). Mule deer, *Odocoileus hemionous*, is known only from a humerus and femur recovered the same gravel pit. Horse, currently not referred to species, is also present but also uncommon (figures 4D and 4E).

Among the most common species recovered from sediments associated with Lake Bonneville is the mountain or bighorn sheep, *Ovis canadensis* (Stokes and Condie, 1961; Stokes, 1966). This species is represented by a least two dozen individuals but is a highly-biased sample. The mountain sheep is primarily represented by crania (figures 4F and 4G) or horn cores of adult males. Skulls of females and juveniles have not been recovered and only a very few post-cranial bones have been found. Stokes (cited in Nelson and Madsen, 1987) suggested that the large sinuses in the male skulls and horns allowed them to partially float and thus be transported. As noted by Nelson and Madsen (1987) almost all the specimens show abraded surfaces suggestive of being rolled on the beach prior to burial. Unfortunately, the way most vertebrate specimens associated with Lake Bonneville are recovered during commercial gravel and sand quarrying has precluded the recovery of any good taphonomic data. The sample is highly biased towards larger specimens that are more easily noticed and no longer in situ. Consequently most finds are of single bones, although a few associated bones of an individual are occasionally found, such as the short-faced bear which includes a partial vertebral column of posterior thoracic to sacral vertebrae, pelvis, and bones of the hind limbs (Nelson and Madsen, 1983).

As expected only a few carnivores have been recovered from the gravel deposits. These include two extant canids, *Vulpes vulpes* and *Canis lupus*, and two bears, the extant *Ursus americanus* and extinct *Arctodus simus* (Nelson and Madsen, 1983, 1986, 1987) (figure 4C). The *Arctodus* is one of two records of this taxon in Utah; the other is from the Huntington Dam Mammoth Site in the Wasatch Plateau south of the Bonneville basin (Gillette and Madsen, 1992).

The only partial skeletons recovered to date are from the short-faced bear, *Arctodus,* and the sloth, *Megalonyx*. Unlike most of the other taxa, which are from deposits associated with the Bonneville shoreline, the two sloth records are from the Provo level. Also, both sloth specimens come from the south end of the basin from Point of the Mountain and Orem, and both were recovered in situ. The sedimentologic and taphonomic data for the Point of the Mountain specimen suggest that the sloth carcass may have washed into Lake Bonneville relatively intact. The carcass was transported some distance along the Wasatch Front by longshore drift. As the carcass was transported toward Point of the Mountain, it made its way to the edge of the wave-built terrace of a large spit. The spit would have been migrating to the west, but the longshore current and direction of the spit would have produced foreset beds oriented to the northwest. The carcass eventually fell off the wave-built terrace of the spit and settled into deeper water (approximately 10 m) that had been receiving only suspended-load, hemipelagic sediments. Eventually, foreset lamination from spit progradation buried the carcass, thus preventing scavenging and disassociation of the skeleton (McDonald and others, 2001). The sand and gravel in which the Orem skeleton was buried are either deltaic deposits of the Provo phase of the Bonneville lake cycle or stream alluvium related to the Provo phase of the Bonneville lake cycle (Machette, 1992). The skeleton was in coarse, ungraded and unbedded gravel, but with slight imbrication of the gravel clasts immediately adjacent to the bones that suggested high-energy fluvial sedimentation.

Virtually all of the small mammal remains associated with Lake Bonneville have been recovered from cave deposits. Most of these accumulations appear to be the result of foraging by owls. The small mammal remains from Homestead Cave have been intensively studied (Grayson, 2000) based on 183,798 identified bones and teeth. This documentation of the changing proportions of species pairs and species replacement in succeeding strata indicates major shifts in the climate and consequently the vegetation (Grayson, 2000). Two species of *Dipodomys* are present, *D. microps* and *D. ordii*. *D. microps*, the chisel-tooth kangaroo rat, which uses its lower incisors to shave off the outer hypersaline tissue from the leaves of *Atriplex* sp. in order to access the palatable inner tissue, whereas *D. ordii* is a granivore that is usually associated with sagebrush habitat, so there is minimal overlap in the distribution of the two species. The increase in the number of specimens of *D. microps* and decline of *D. ordii* in the stratigraphic sequence suggests the progressive replacement of sagebrush-dominated habitat by shadscale-dominated habitat through the Holocene. A similar pattern is demonstrated by the changes in abundance of *Microtis* and *Lemmiscus*. *Microtis* utilizes grassland habitat whereas *Lemmiscus* prefers habitat dominated by sagebrush, usually *Artemisia tridentata*. *Microtis* is common in the late Pleistocene and early Holocene sediments at Homestead Cave but decreases in number after 8.3 ka and is uncommon after 7 ka, and is replaced by *Lemmiscus* as the common vole. Also, around 8.3 ka, *Neotoma lepida* replaces *N. cinerea* in the fauna. A similar pattern is seen in the pocket mice, *Perognathus*, with *P. parvus* common in the late Pleistocene and then replaced by *P. longimembris*. *P. parvus* in the Great Basin today is found at higher elevations indicating a preference for cooler temperatures whereas *P. longimembris* tends to be found at lower elevations with higher temperatures. Likewise, the pocket gopher, *Thomomys talpoides*, is found at higher elevations and mountain valleys in Utah today while *T. bottae* lives in the lower valleys. At Homestead Cave, *T. talpoides* is present only in the late Pleistocene and is replaced by *T. bottae*, indicating a transition from cooler to warmer temperatures. The yellow-bellied marmot, *Marmota flaviventris*, lives at higher elevations in the southern part of its range and at lower elevations in the more northern parts of its range, reflecting its sensitivity to warmer temperatures. At Homestead Cave, it is more common in the lower late Pleistocene strata and appears to have disappeared from the area around 8 ka so its disappearance may be indicative of warming temperatures.

Most bird remains associated with Lake Bonneville consist of isolated finds and the only known avifaunas are from cave deposits, like those of Homestead Cave. The avifaunal assemblage from Homestead Cave consists of 6000 specimens representing 75 species from 26 families (Livingston, 2000). The avifauna includes not only taxa that would be expected to be associated with a lake—divers, specialized fishers, waterfowl, shorebirds and marshbirds—but also upland game birds, woodpeckers, and perching birds. The diurnal predators like hawks and falcons, and nocturnal predators, owls, are believed to have been the primary contributors to the fauna in the cave.

The three most common families of birds from Homestead Cave are the Podicipedidae (grebes) at 30% of the total assemblage, Anatidae (ducks) at 15% of the assemblage, and Alaudidae (larks) at 20% of the assemblage. The presence of the two aquatic families is expected given the cave's association with the lake. In fact, the two lowest strata in the cave, when the lake level was still relatively high, are dominated by waterfowl in terms of both the number of taxa, and percentage of bones from waterfowl recovered. Larks do not become common until the upper stratigraphic levels, reflecting the lower lake level and presence of more open habitat. Missing from the avifauna are larger taxa like loons, pelicans, swans, cranes, and herons that are all larger than the predatory birds in the fauna. Cormorants and mergansers, which are obligate piscivores, are restricted to the lower levels of Homestead Cave and disappear early, likely reflecting the loss of a food source with lower lake levels and increased salinity.

While fish do not live in Great Salt Lake today, fresher water during the Bonneville lake cycle supported a variety of fish (Broughton and Smith, 2016). Broughton and Smith (2016) described 10 primary localities in the Bonneville basin that produced fish remains: six are open-air sites and four are caves. Broughton and Smith (2016) documented 13 species of fish represented by fossils, out of the 21 species present in the extant fauna (table 1). The fish found in Lake Bonneville sediments account for three of the four endemic and five of the nine native species in modern Bear Lake (figure 3).

Homestead Cave is in the Lakeside Mountains (figure 3). The opening of the cave at 1406 m is between the Provo and Stansbury shorelines. The Pleistocene fauna recovered included 11 species of freshwater fish concentrated in the lowest stratum of the deposits and 11 freshwater species from sediments that accumulated in the cave after 11,200 ^{14}C yr B.P. Eight of the species occur in Bear Lake. The fish remains are thought to have been caught by owls (Broughton, 2000; Broughton and others, 2000). Analysis of the ^{87}Sr/^{86}Sr values of the fish bone from the lowest stratum of the cave suggests they grew near the terminal Pleistocene Gilbert shoreline. A decrease in fish size and an increase in species tolerant of higher salinities or temperatures in the lowest deposits suggest multiple die-offs associated with declining lake levels. An initial, catastrophic, post-Provo die-off occurred at 11,300 –11,200 ^{14}C yr B.P. (~ 13.2 to 13.1 cal ka) and was followed by at least one rebound or recolonization of fish populations. Around 3.7 cal ka there was a highstand of the lake and this is reflected in a peak in the frequency of bones of *Gila atraria* (Utah chub) in the cave sediments. Despite this rebound fish were gone from Lake Bonneville sometime before 10,400 ^{14}C yr B.P. Cathedral Cave which is close to Homestead Cave has a distinctively different fish fauna that consists exclusively of sculpin. As sculpins prefer cold deep water their presence in the cave sediments is attributed to accumulating during a deep-water phase, ca. 100–200 m of Lake Bonneville when the lake was at either the Bonneville or Provo level. Strata above the level with the sculpins had a radiocarbon age of 15,310 ± 60 ^{14}C yr B.P. (Broughton and Smith, 2016).

ROAD GUIDE

The road guide begins at the Grand America Hotel in Salt Lake City (figure 5). The route heads south to the G.K. Gilbert Geologic View Park, the Draper spit, Steep Mountain shorelines, the Point of the Mountain spit, and the American Fork delta. The route then heads west to the Stockton Bar, north to Great Salt Lake, and east to return to Grand America.

Mileage (mi) Interval / Cumulative	**Description**
0.0 / 0.0	Grand America Hotel's porte cochere entrance at approximately 60 East 600 South Street, Salt Lake City (figure 5). Turn left out of porte cochere and proceed several hundred feet to State Street.
0.0 / 0.0	Turn right onto State Street.
0.6 / 0.6	Turn right onto 900 South and proceed west.
0.3 / 0.9	Turn left onto West Temple and merge onto the Interstate 80 (I-80) East ramp to Cheyenne.
2.5 / 3.4	Merge onto I-80 East.
4.6 / 8.0	Take exit 128 for I-215 South.
6.3 / 14.3	Take exit 6 for 6200 South and turn left, proceeding east.
0.8 / 15.1	6200 South curves right (south) and becomes Wasatch Boulevard.
3.2 / 18.3	Bear right at signal to continue on Wasatch Boulevard.
1.1 / 19.4	Turn right onto Little Cottonwood Road at signal.
0.1 / 19.5	To **Stop 1**. Pull into dirt parking area on right at 3345 East Little Cottonwood Road, Sandy.

Stop 1
G.K. Gilbert Geologic View Park

Located near the mouth of Little Cottonwood Canyon, this geologic park showcases multiple geomorphic and geologic features and has long been a destination for field trips. The park was dedicated in 2008 and in-

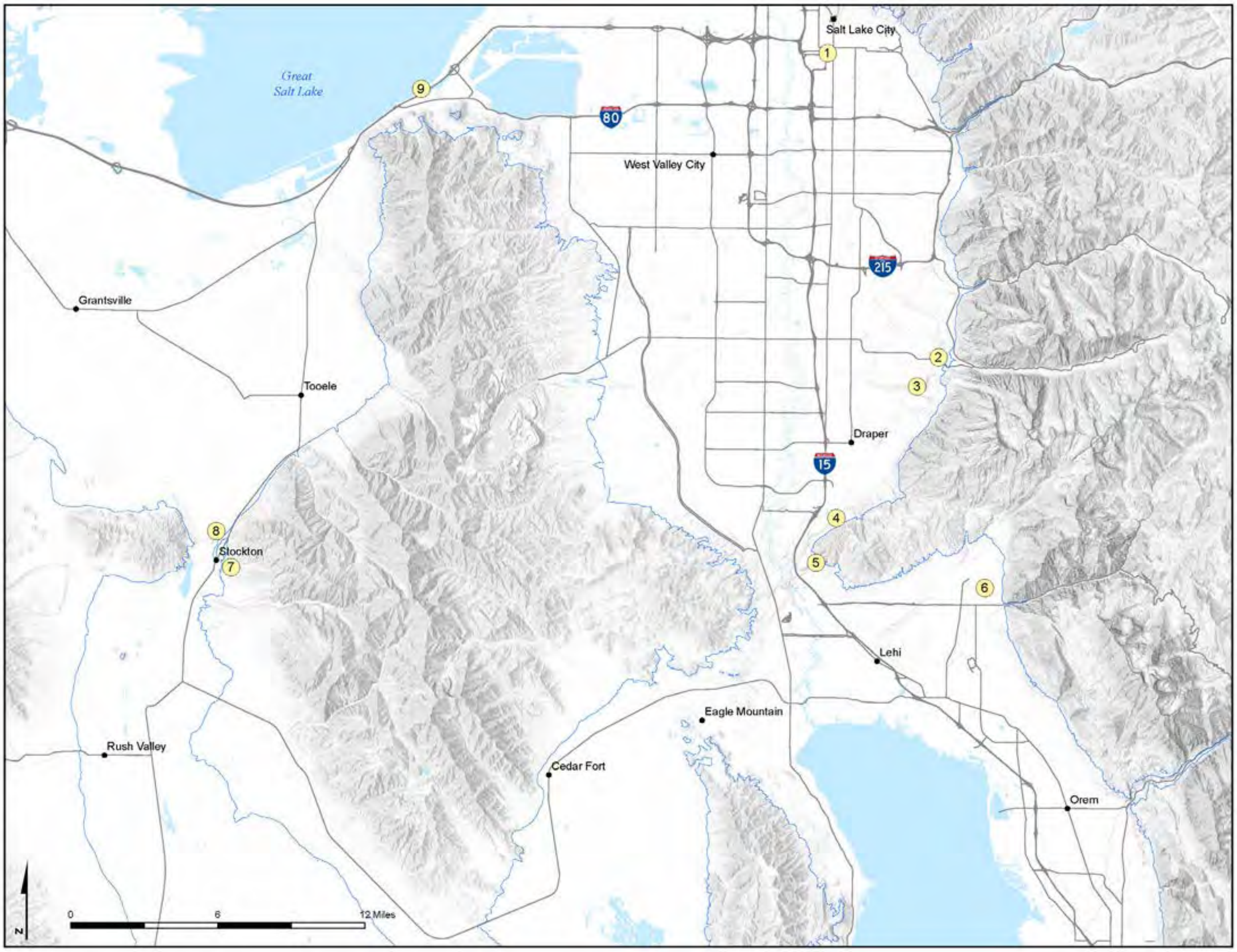


Figure 5. Field trip stops. The blue line is the 5200-foot-elevation contour, which approximates the Bonneville shoreline (not adjusted for isostatic rebound).

cludes five non-technical interpretive signs with information about bedrock geology, mining and quarrying activity, the Wasatch fault, Lake Bonneville, and glaciation (figure 6).

Three bedrock formations are visible from the park: (1) Early Proterozoic Little Willow Formation, (2) Late Proterozoic Big Cottonwood Formation, and (3) Oligocene Little Cottonwood stock (Eldredge, 2008). Contorted quartz schist and gneiss primarily comprise the Little Willow Formation. Alternating shale and quartzite originally deposited in a tidal/shoreline environment generally comprise the Big Cottonwood Formation. Quartz monzonite comprises the bulk of the Little Cottonwood stock.

Gold was mined from the Little Willow Formation more than a century ago, and mine dumps are evident near the north side of the canyon mouth (Eldredge, 2008). "Granite" (quartz monzonite) has been quarried from the Temple Quarry, located just out of view in the lower canyon. This stone was used to construct the Church of Jesus Christ of Latter-day Saints' Salt Lake Temple and other prominent buildings in Salt Lake City and has been quarried intermittently since the 1860s.

Formed by repeated earthquakes and reaching more

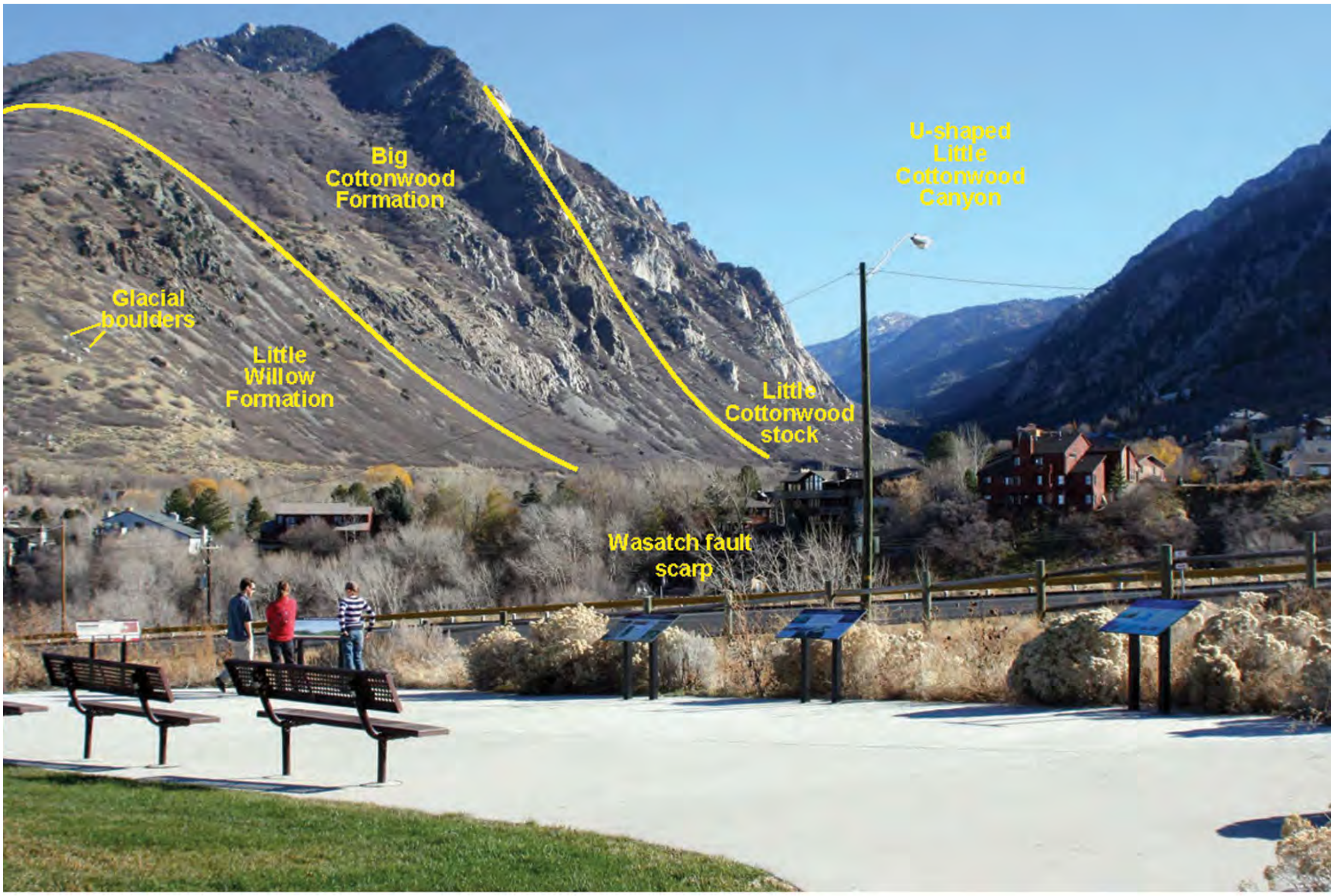


Figure 6. Annotated view to the northeast from the G.K. Gilbert Geologic View Park.

than 30 m high, the scarps visible here on the Salt Lake City segment are some of the largest of the Wasatch fault zone (figure 7). The Wasatch fault zone is an approximately 370-km-long, 10-segmented normal fault system that forms the Wasatch Front and the eastern boundary of the Basin and Range Province (Machette and others, 1992). Faulting began approximately 18 Ma (Parry and Bruhn, 1987) and vertical slip rates have apparently varied through time. Long-term slip rates are about 0.7 mm/yr since ca. 18 Ma (Parry and Bruhn, 1987), 0.2–0.4 mm/yr since 5 Ma (Armstrong and others, 2004), and 0.5–1.0 mm/yr since 0.4–0.8 Ma (Mayo and others, 2009). Displaced latest Pleistocene shorelines and fans yield vertical slip rates of approximately 0.1–0.3 mm/yr (Machette and others, 1992). Post-Provo level paleoseismic trenching data yield slip rates of approximately 1–2 mm/yr (e.g., Machette and others, 1992; Lund, 2005; DuRoss and others, 2016). Modern geodetic horizontal extension across the fault zone is ~1.6–3.2 mm/yr (Chang and others, 2006; Kreemer and others, 2010).

The park is located above the elevation of the Bonneville shoreline and lake features are not visible. The park rests on glacial till and would have been covered by glacial ice near the time of the Bonneville highstand at 18 ka (Laabs and Munroe, 2016). Glacial features visible from the park include the classic U-shaped valley of Little Cottonwood Canyon, moraines, and scattered glacial boulders. This is one of only a few localities in the world where mid-latitude alpine glaciers entered lakes during the Last Glacial Maximum. As discussed in the Climate and Glaciation section above, Laabs and Munroe (2016) dated erratic boulders found both on the north side of the canyon mouth and on top of the moraine crest visible to the south, which yielded

Figure 7. View to the southeast from the G.K. Gilbert Geologic View Park. Prominent ridge at center is a left lateral glacial moraine that is offset by two prominent west-facing Wasatch fault scarps (yellow lines).

a cosmogenic exposure age of ca. 18 ka (figures 6 and 7).

Continue road guide.

0.0 / 19.5 Turn left out of parking area onto Little Cottonwood Road.
0.1 / 19.6 Turn right onto Wasatch Boulevard and proceed southwest on Wasatch Boulevard.
4.4 / 24.0 Turn left onto 1700 East and proceed south.
0.7 / 24.7 1700 East curves right (west) and becomes Draper Parkway.
0.4 / 25.1 To **Stop 2** at 1360 East Draper Parkway, Draper.

Stop 2
Walmart Neighborhood Market

This is intended as a restroom stop, but the parking lot provides distal views to the south of Steep Mountain (figure 8) and the entire north flank of the Traverse Mountains (see Stop 3). This store and parking lot are on the south flank of the Draper spit. The bare slope across the road to the north was the headwall of a now reclaimed gravel pit. The sand and gravel that comprise the spit were presumably sourced from Little Cottonwood and Big Cottonwood Canyons to the north. The elevation of the parking lot is below the Provo shoreline at approximately 1420 m.

Continue road guide.

0.0 / 25.1 Turn left out of parking lot onto Draper Parkway and proceed west.
0.2 / 25.3 Turn left onto 1300 East at signal.
0.2 / 25.5 Proceed through traffic circle and continue on 1300 East.
1.6 / 27.1 Turn right onto Highland Drive and proceed southwest.
2.2 / 29.3 To **Stop 3**. Pull off on the right shoulder south of intersection of Highland Drive and Bangerter Parkway-Traverse Ridge Road (approximately 155 East Highland Drive, Draper).

Stop 3
View of Steep Mountain

The Traverse Mountains are an east-west trending range in an area dominated by north-south trending ranges. They extend between the Wasatch Range to the

Figure 8. Aerial view (toward west) of the prominent Bonneville- and Provo-level shorelines at Steep Mountain on the north side of the Traverse Mountains. Photo courtesy of Mark Bennett (unaffiliated).

east and the Oquirrh Mountains to the west, and have a gap cut by the Jordan River. Additionally, the Traverse Mountains lie at the boundary between two segments of the Wasatch fault, the Salt Lake City segment to the north and the Provo segment to the south.

The location and orientation of the Traverse Mountains is thought to be due to an ancient crustal structure that predates the crustal extension that created the modern landscape. The east-west orientation of these mountains subjected their north flank to intense waves generated across a 200-km-long, unimpeded stretch of Lake Bonneville that once extended to the north (Schofield and others, 2004).

The north-facing Steep Mountain part of the Traverse Mountains is composed of highly fractured quartzite of the Pennsylvanian Oquirrh Group (figure 9). This quartzite was readily pulverized by waves, creating an enormous supply of sand and gravel. Beneath the steep face of bedrock lies the Steep Mountain beach complex, a broad Bonneville-level depositional platform consisting of sediment deposited offshore as the lake transgressed to its highstand (Oviatt and Jewell, 2016). The sediment-to-bedrock contact below this platform is evidenced by a change in vegetation on the slope above the Provo shoreline. The sand and gravel of the upper half of this slope is dominated by shrubby vegetation, the bedrock of the lower half by grasses (figure 8). While substantial amounts of sand and gravel remained in the Steep Mountain beach complex, strong longshore currents traveling west and south through the Jordan River Narrows transported much of the material, redepositing it in the Point of the Mountain spit (Schofield and others, 2004).

Previous workers (e.g., Shelton, 1966) have cited this location as a prominent example of a Bonneville shoreline erosional platform, presumably developed during a prolonged period (hundreds of years or more) of open basin overflow at the Bonneville highstand. However, Oviatt and Jewell's (2016) recognition of a depositional platform deposited during lake transgression shows that there is no evidence for such a period of prolonged overflow at this location. This interpretation coupled with consistent evidence from other locations suggests that the lake transgressed to the Bonneville shoreline and then overflowed only briefly before the Bonneville flood, a return to Gilbert's original 1890 hypothesis.

Continue road guide.

0.0 / 29.3	Continue southwest on Highland Drive.
0.6 / 29.9	Turn left onto Minuteman Drive and proceed south. Note, Minuteman Drive becomes Frontage Road.
2.7 / 32.6	Turn left onto Flight Park Road and proceed east.
0.9 / 33.5	Flight Park Road curves left and loops around to the west.
0.6 / 34.1	To **Stop 4**. Stop at end of Flight Park Road.

Stop 4
Flight Park State Recreation Area, Utah County

The Point of the Mountain spit and adjacent Steep Mountain beach are two of the largest and most spectacular shoreline features of the Bonneville basin. As with all prominent shoreline features in the Bonneville basin, G.K. Gilbert (1890) was the first to document this spit complex (figure 10). The gross shape of the spit is that of

Figure 9. Prominent Bonneville bench and Provo-level shoreline at Steep Mountain, on the north side of the Traverse Mountains.

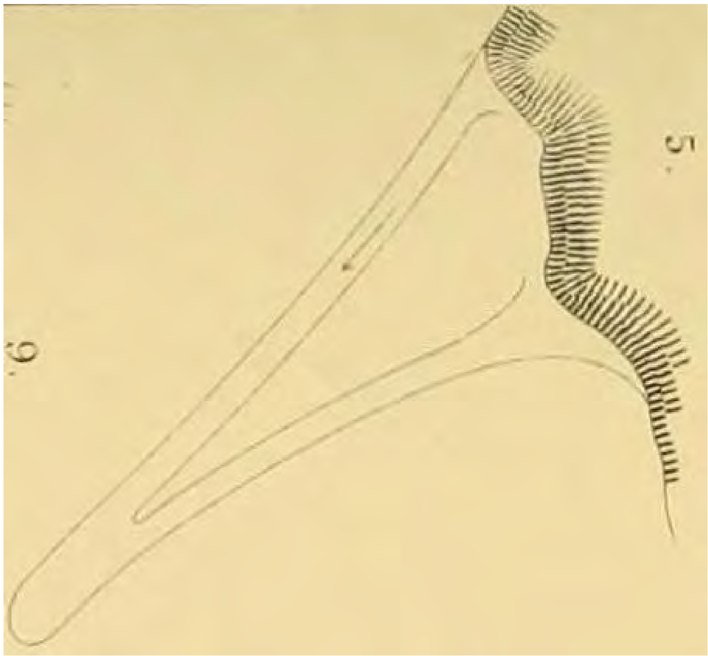


Figure 10. Point of the Mountain "V-shaped embankment" (spit). North is toward top of page. From Gilbert (1890, plate 7).

a V-shaped embankment anchored laterally to bedrock, but in reality it is a complex feature that formed not only during the Bonneville lake cycle but also during known older lake cycles (Schofield and others, 2004).

Based on clast lithology and geomorphic analysis of multiple shoreline features at and adjacent to Point of the Mountain, Schofield and others (2004) determined that the Point of the Mountain spit formed as a result of the highly fractured bedrock of Steep Mountain being exposed to wave trains that approached from the north-northwest causing north-to-south longshore sediment transport (figure 11). Shoreline development and sediment transport on the southern portion of the spit were minimal. A predominant northerly wind direction during the Pleistocene matches modern winter storms that tend to come from the northwest, though southern winds from prefrontal lows can also be significant.

Point of the Mountain has been extensively mined for aggregate (figures 12 and 13). The total amount of sand, gravel, and rock removed is unknown, but according to Utah Division of Oil, Gas and Mining documents, roughly 25 million tons was mined just from 2009 to 2014. Just east and uphill from this stop a mine is permitted with a 5 to 22 year life expectancy and an estimated 2 million tons of mostly bedrock material removed per year.

Continue road guide.

0.0 / 34.1 Return back down Flight Park Road to Frontage Road.

1.5 / 35.6 Turn left onto Frontage Road. Note, Frontage Road becomes Digital Drive. Proceed east and then south.

2.1 / 37.7 Turn left onto Timpanogos Highway

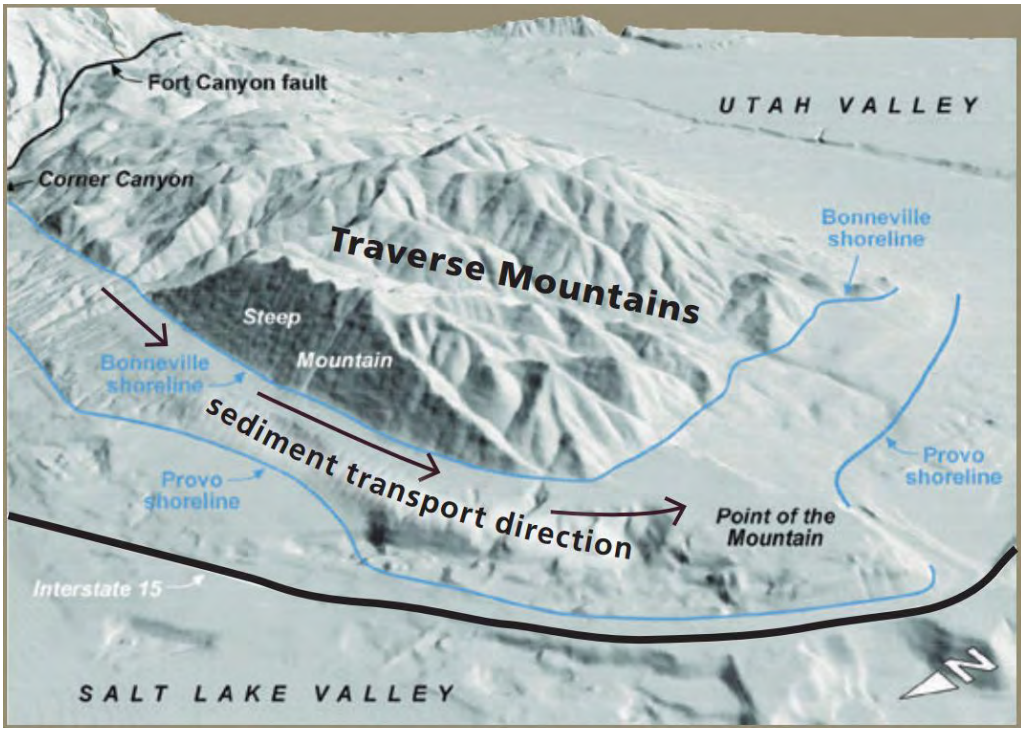


Figure 11. Shaded-relief image of the Traverse Mountains. Image is approximately 5 km across.

Figure 12. View of the north side of the Traverse Mountains. Photo shows Point of the Mountain before any significant mining activity; date unknown. Figure modified from Shelton (2004).

Figure 13. Mining has removed much of the Pleistocene sediments and some of the bedrock at Point of the Mountain. Top photos 1993 (left) and 2015 (right) Google Earth imagery. Bottom photo of gravel pit shows view to the north from Flight Park State Recreation Area in Utah County. Google Earth imagery © 2015 Google Inc.; top left image—U.S. Geological Survey and top right image–Landsat.

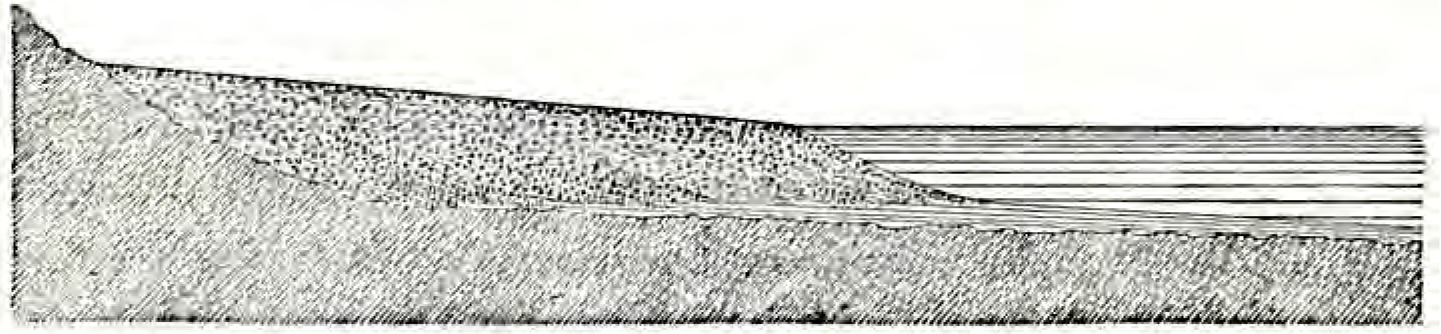
State Road (SR) 92 and proceed east.
6.0 / 43.7 Turn left onto North County Boulevard (4800 West) and proceed north.
0.2 / 43.9 Turn right onto 11200 North and proceed east to end of road.
0.3 / 44.2 To **Stop 5**, 4560 West 11200 North, Highland City.

Stop 5
American Fork Delta

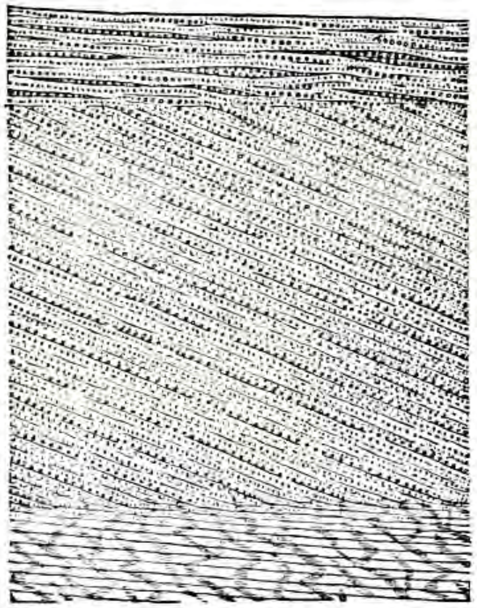
The following section is modified from Godsey and others, 2005a.

The American Fork delta is a classic Gilbert-type delta. Gilbert's 1890 study of Pleistocene Lake Bonneville was the first detailed geomorphic and stratigraphic study of gravelly deltas. Gilbert is reported to have visited all of the lake's deltas; however, only two locations were discussed in detail, the Bonneville-level delta at American Fork and the Provo-level Logan River delta (located in Cache Valley, northeastern Utah). From these observations of the lake's coarse-grained deltas, Gilbert developed the topset-foreset-bottomset model (figure 14). However, gravel-pit exposures show that one of Gilbert's original study localities, the Bonneville-level delta at American Fork, is composed almost entirely of subhorizontal gravel (topsets). Taking advantage of such gravel-pit exposures not available to Gilbert, this model can be refined to show two end member deltas: (1) topset-dominated deltas deposited during the Bonneville transgression, and (2) foreset-dominated deltas deposited at the Provo shoreline and during the Provo regression (figures 15 and 16) (Milligan and Chan, 1998). Other gravel-pit exposures at the Bonneville level of the Big Cottonwood Canyon and American Fork deltas displayed a predominance of horizontally stratified gravel that comprises the topset-dominated delta system. Other gravel-pit exposures at the Provo level of the Big Cottonwood Canyon and Brigham City deltas displayed a predominance of steeply dipping gravel that comprises the foreset-dominated delta systems.

Three key factors contribute to the development and depositional styles of these Wasatch Front Gilbert deltas: active tectonism, rapid lake-level fluctuation, and drainage basin deglaciation. Slip on the Wasatch fault zone produced the steep drainage basins responsible for the overall coarse-grained nature of these Gilbert deltas.



—Section of a Delta.



—Vertical section in a Delta, showing the typical succession of strata.

Figure 14. Gilbert's classic topset-foreset-bottomset model of coarse-grained deltas (from Gilbert, 1890).

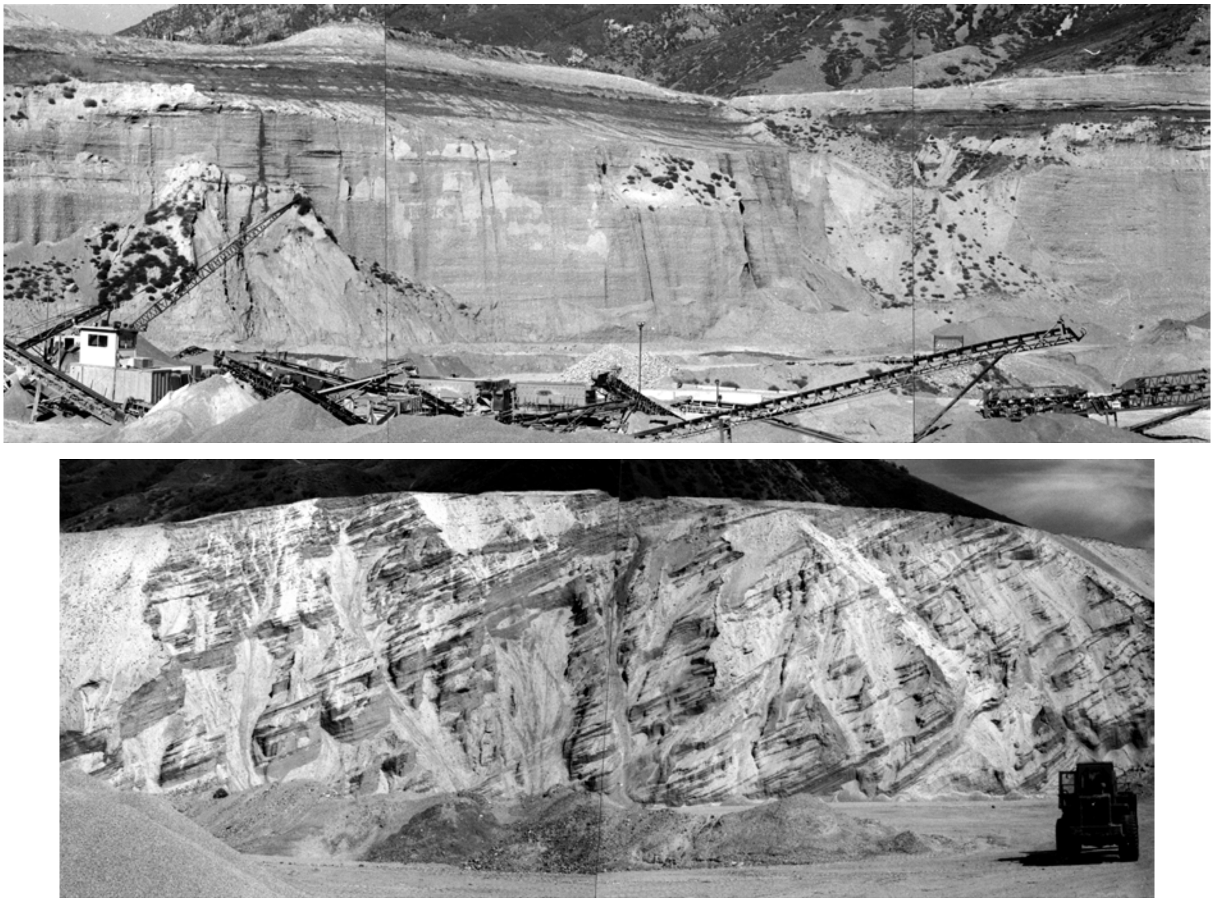


Figure 15. Top photo shows the horizontal gravel of topset-dominated at the Bonneville level (late-transgressive-phase), American Fork delta, ca. 1993. Bottom photo shows the steeply dipping gravel of a foreset-dominated delta, Provo level at Brigham City, ca. 1993.

However, slip rates of 0.76–1.5 mm/yr, the average for the last 15 kyr in study areas (Machette, 1988; Schwartz and Lund, 1988; Personius and Scott, 1992), are overprinted by lake-level change that can exceed 80 mm/yr (long-term post-Provo regression rate) or even 125 m/yr for the nearly instantaneous Bonneville flood event.

Drainage basin deglaciation and the release of glacial outwash played a role in sediment supply and, thus, the distribution of facies found at some localities. The effects of deglaciation are best seen at Big Cottonwood Canyon (about 5 km north of Stop 1), where glaciers neared the Bonneville shoreline producing topsets of subaerial glacial outwash. Evidence for glaciation (e.g., moraines and striations) is also found in the upper reaches of the American Fork drainage basin (Laabs and others, 2011).

Facies distributions were most strongly influenced by lake level fluctuation, which largely controls accommodation space and sediment supply. Topset-dominated deltas formed with increasing water depth created by climate-driven transgression to the Bonneville shoreline. Foreset-dominated deltas formed with decreasing water depth. Catastrophic lake-level drop due to the Bonneville flood and the subsequent climate-driven Provo regression not only greatly reduced accommodation space, but also provided abundant sediment supply by exposing unlithified Bonneville-level deltaic sediments for reworking.

The Bonneville-level American Fork delta seen at this stop exemplifies a topset-dominated system that displays a classic "Δ" shape in plan view. These gravel topset deposits consist of horizontal clast-supported pebble and cobble gravel with lenses of silty sand deposited during the Bonneville transgression and brief highstand.

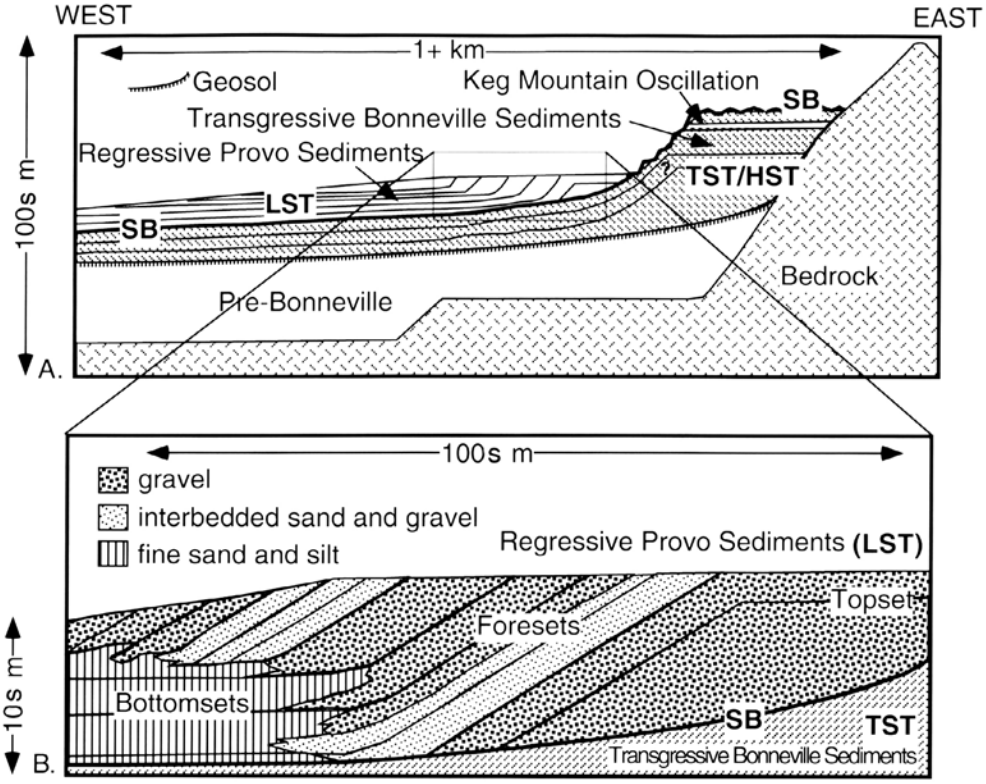


Figure 16. Schematic representation of American Fork's topset-dominated delta (area above "TST/HST" on top figure) deposited during the Bonneville transgression and brief highstand, and Brigham City's foreset-dominated delta (lower figure) deposited at the Provo shoreline and during the Provo regression. Sequence stratigraphy terms: SB = sequence boundary, LST = lowstand systems tract, TST = transgressive systems tract, HST = highstand systems tract. From Milligan and Chan (1998).

Near the top of the delta (dark band in top photo of figure 15) is an intervening 9-m section of sandy clay and coarse-grained to very coarse grained sand with granules and oblate pebbles. Sedimentary structures include wave ripples and tabular cross-bedding. The cross-bedding suggests a southerly flow direction (parallel to the shoreline) and is likely to have been created by littoral currents. The presence of oblate pebbles and symmetric ripples suggest shallow-water, wave-influenced deposition in a delta-front beach environment.

The occurrence of this fine-grained beach facies amidst coarse-grained delta topsets may be attributed to a downward lake-level oscillation (Machette, 1988). The drop in lake level during this oscillation (figure 1) probably caused the American Fork River to incise a channel through the delta, thus transferring the river deposition westward into the basin (figure 17). This river channel (until filled) would have cut off the coarse-grained sediment supply (during the oscillation rise and final transgression to the Bonneville shoreline), allowing the accumulation of the finer-grained beach and delta-front sands.

Continue road guide.

0.0 / 44.2	Return on 11200 North to 4800 West (North County Boulevard).
0.3 / 44.5	Turn left onto 4800 West and proceed south.
0.2 / 44.7	Turn right onto SR 92 and proceed west.
5.0 / 49.7	Turn left onto 1200 West and proceed south.
1.4 / 51.1	1200 West curves right and becomes SR 85, proceed west.
2.8 / 53.9	Turn left onto Redwood Road and proceed south.
1.8 / 55.7	Turn right onto SR 73 and proceed west.
0.9 / 56.6	Turn right to stay on SR 73 and continue west.
35.7 / 92.3	Turn right onto SR 36 towards Stockton and Tooele and proceed north.
5.2 / 97.5	Turn right onto Silver Avenue (look for Sinclair Station on the corner) and proceed east.
0.2 / 97.7	Silver Avenue curves right and becomes Copper Street. Proceed south.
0.2 / 97.9	Turn right onto Roger Street and proceed west.
0.1 / 98.0	To **Stop 6**.

Figure 17. Aerial view of the Bonneville-level (late-transgressive-phase) American Fork delta ca. 1970. Note incision by the modern American Fork river channel. Photo from Utah Geological Survey aerial image collection.

Stop 6
Alex Baker Baseball Park
(382 South Roger Street, Stockton)

This was the planned lunch stop. The south side of the Stockton Bar and spit complex can be viewed from here. See Stop 7 for a complete description.

Continue guide.

0.5 / 98.6	Return to SR 36, turn right, and proceed north.
1.9 / 100.5	Turn left onto entrance road for Bauer Pit and park.
0.0 / 100.5	To **Stop 7** at the Bauer Pit entrance road.

Stop 7
Stockton Bar Overview, Tooele County

The following section is modified from Godsey and others, 2005a.

General Description

The Stockton Bar is enormous and perhaps the most impressive geomorphic feature found in the Bonneville basin. G.K. Gilbert first documented this area in the 1890 monograph (figures 18 and 19).

Stockton Bar consists of a series of spits, barriers, and beach ridges in the valley between the Stansbury and Oquirrh Mountains. The bar and spit complex ultimately isolated lake waters in Rush Valley to the south from the main body of Lake Bonneville (Gilbert, 1890; Gilluly, 1929; Burr and Currey, 1988). How the barrier bar and spit complex grew and evolved has still not been satisfactorily resolved (C.G. Oviatt, Kansas State University, written communication, 2016). Complex surface geomorphology and internal stratigraphy has led to various interpretations of its development.

Gilbert (1890) recognized a series of seven sequential "beds" between the Oquirrh Mountains and South Mountain that was correctly interpreted as building during the lake's rise to the Bonneville level and creating the Stockton Bar (figure 18). Gilbert also recognized that the Stockton spit complex and an unnamed spit on the west side of Stockton Bar superseded this barrier bar series. Furthermore, Gilbert recognized that buried stratigraphy might further refine or reinterpret the simple depositional history.

Based on detailed study of surface geomorphology, Burr and Currey (1988) show transgressive-age shorelines (T on figure 20) to the north and south of the main bar, and a series of shorelines (B1, B3, B5, B6, B8 on figure 20) formed during a prolonged period of overflow at the Zenda threshold. However, there is no independent evidence of prolonged overflow at the Bonneville highstand (C.G. Oviatt, Kansas State University, written communication, 2016).

Based on ground-penetrating radar, Smith and others (2003) believed the barrier bar formed first by vertical accretion during slow transgression due to climate or basin subsidence, followed by the continued transgression and a reorientation of longshore transport that

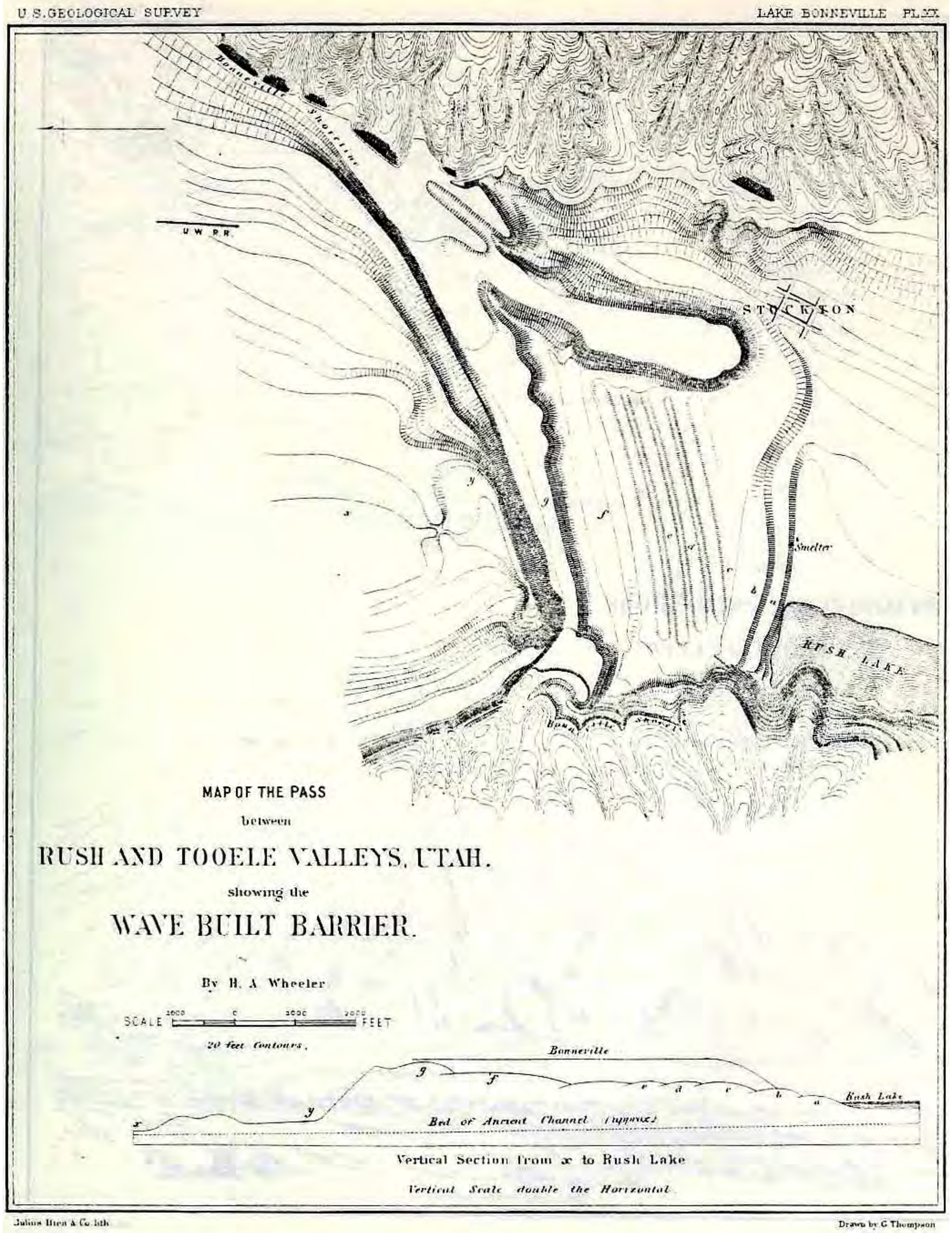


Figure 18. G.K. Gilbert recognized a series of seven sequential "beds," labeled a–g, deposited during the lake's rise to the Bonneville level. Gilbert also postulated that the Stockton spit complex and an unnamed hook-shaped spit on the west side of Stockton Bar superseded this barrier bar series. Map of Stockton Bar by H.A. Wheeler as illustrated in Lake Bonneville, U.S. Geological Survey Monograph 1, by G.K. Gilbert (1890).

Figure 19. Top image, "The Great Bar at Stockton, Utah" as illustrated in Lake Bonneville, U.S. Geological Survey Monograph 1, by G.K. Gilbert (1890). The name has subsequently been shortened to Stockton Bar. Bottom image shows a similar but recent perspective of the Stockton Bar. Photo courtesy of Holly Godsey (University of Utah).

created Stockton spit, and a final rise that again reoriented longshore transport and created the smaller upper spit (figure 21). These various interpretations are likely to be refined by future work.

The Stockton Bar as a Geoantiquity

Concerned scientists have been involved in research to document and preserve important landforms, named *geoantiquities* or *geosites*, related to Lake Bonneville and Pleistocene Earth surface processes (Chan and others, 2003; Chan and Godsey, 2016). Sediments that make up Lake Bonneville landforms are typically well rounded, well sorted, and unconsolidated, making them prime aggregate material and targets for quarrying operations. The Stockton Bar tops the list of important geoantiquities, not only because of its scientific and educational merit, but also because of its historical, aesthetic, and recreational value. The bar has been a site of mining activity for at least 60 years, but excavation efforts have increased steadily with the growing aggregate needs of neighboring urban communities.

After many public speeches, field trips, community education campaigns, and partnerships with various conservation organizations, the struggle for preservation of the Stockton Bar has met with mixed but generally positive results. A landfill and a tailings pond exist on the north side of the bar, homes have been developed on the transgressive shorelines to the south, and mining still threatens to remove deposits on the east side of the bar. However, multiple attempts for new mining permits have been stalled.

Efforts to protect the bar began in earnest in 1999 with a permit request to remove 400,000 tons of sand and gravel. Due to extensive efforts by local citizens and scientists, the Tooele County planning commission did not issue the permit. In 2009, an uprising of local citizens supported by scientists prevented rezoning that would have allowed increased mining. Again in 2015, under pressure from local citizens and nationally and internationally renowned scientists, the Tooele County planning commission rejected a rezoning request by an aggregate mining company.

Perhaps most significantly, the Tooele County General Plan Update 2016 includes language that recognizes the Stockton Bar as "perhaps the most important natural feature in the area," the mining of which would be "an incalculable loss," and recommends modifying County Code "to ensure the Stockton Bar and other irreplaceable natural features are preserved and protected in perpetuity." While encouraging for preservationists, the landownership of Stockton Bar remains private and thus protection is uncertain. Continue north on SR 36.

Continue road guide.
16.2 / 116.7 Take the I-80 eastbound ramp.
5.4 / 122.1 Take exit 104 for SR 202.

Figure 20. Based on detailed study of surface geomorphology, Burr and Currey (1988) show transgressive-age shorelines (T) to the north and south of the main bar, and a series of shorelines (B1, B3, B5, B6, B8) that formed during a prolonged period of overflow at the Zenda threshold. However, there is no independent evidence of prolonged overflow at the Bonneville highstand (C.G. Oviatt, Kansas State University, written communication, 2016). Rp and Rg demark Rush Valley Provo- and Gilbert-age shorelines. Modified from Burr and Currey (1988).

0.5 / 122.6 Turn left onto SR 202 and proceed northwest.
0.3 / 122.9 Turn left onto frontage road and proceed southwest towards Great Salt Lake State Park.
2.0 / 124.9 To **Stop 8** at the Great Salt Lake Marina, 1075 South 13312 West, Magna.

Stop 8
Great Salt Lake State Park Marina

Although Great Salt Lake is but a small remnant of Lake Bonneville, it has the largest surface area of any natural lake west of the Mississippi River. As a terminal lake with no outlet, its level is in constant flux (figures 22 and 23). In Holocene time its level has fluctuated less than 15 m. In the roughly 170-year historic period the lake has fluctuated about 6 m, responding primarily to changes in precipitation and consumptive use of fresh water in the basin. Construction of causeways and dikes has divided the lake into four major parts (north arm, south arm, Bear River Bay, and Farmington Bay) with

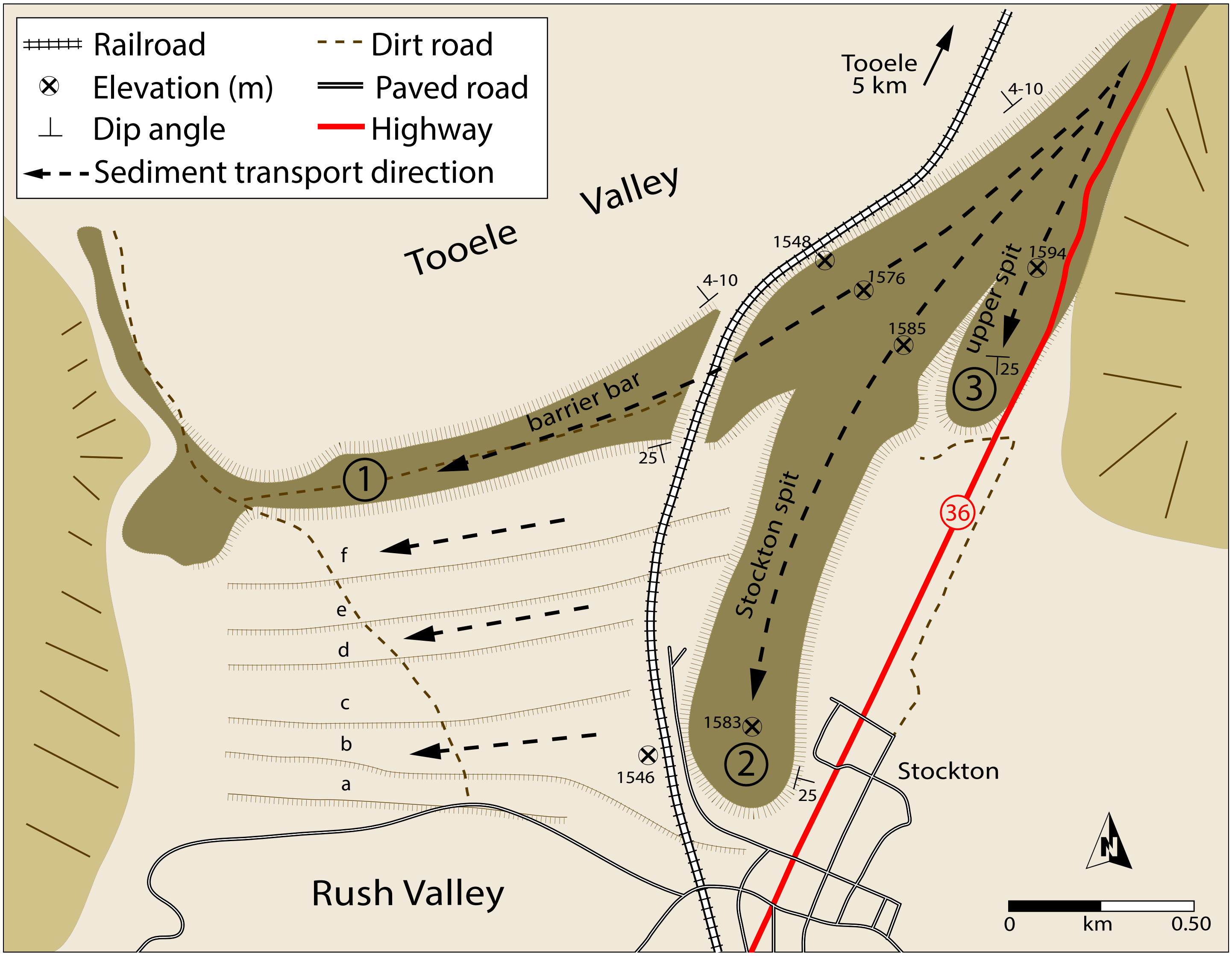


Figure 21. Smith and others (2003) used ground-penetrating radar to develop a depositional model of the Stockton Bar complex that suggests the barrier bar portion (1) formed first during slow transgression, followed by continued transgression and a reorientation of longshore currents that deposited the Stockton spit (2), and a final rise that again reoriented currents and deposited the smaller upper spit (3). Modified from Smith and others (2003).

different levels and salinities (figure 24).

The lake is a major source of mineral resources, supports a multi-million dollar brine shrimp industry, is a globally important migratory bird site, and much more. Entire books are dedicated to Great Salt Lake (e.g., Gwynn, 2002). This field trip guide will not attempt to touch upon this wealth of information but will give a brief overview of microbialites recently exposed by near-record low lake levels.

General Characteristics of Great Salt Lake

(Gywnn, 1996 and modified from Vanden Berg and others, 2015)

- 33rd largest lake in the world (largest fresh or saltwater lake in the United States after the Great Lakes)
- Averages 121 km long by 56 km wide.
- Surface elevation: historical average (since 1847) ~1280 m (4200 ft) covering 4185 km^2, historical high 1283.77 m (4211.85 ft) in 1986 and 1987, historical low 1277.52 m (4191.35 ft) in 1963.

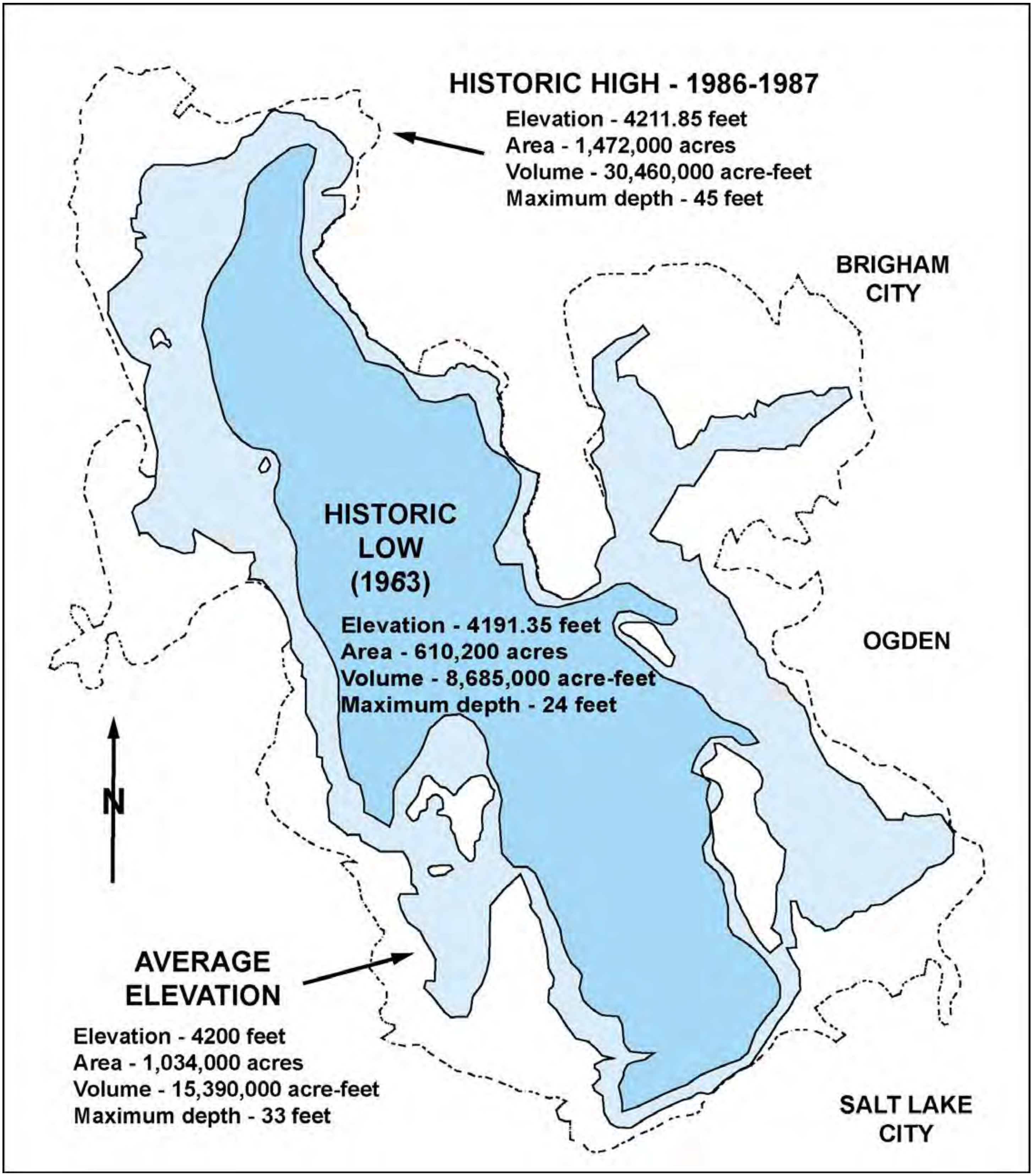


Figure 22. Areal extent, elevation, volume, and maximum depth of Great Salt Lake at historic high, average, and historic low-water levels. From Gwynn (1996).

- Lake-level fluctuations: 0.3-0.6 m (1-2 ft) annually on average.
- Maximum depth at average elevation (1280 m [4200 ft]): ~10 m (33 ft).
- Volume: 19 km^3.
- Salinity: south arm = 5-22% (highly dependent on lake level and location), north arm = 24–26% (near or at salt-saturation point).
- Average chemical composition: chloride = 56%, sodium = 32%, sulfate = 7.0%, magnesium = 3.3%, potassium = 2.1%, calcium = 0.2%.
- Estimated reduction of lake level due to consumptive uses: 3.4 m (11 ft) (Wurtsbaugh and others, 2016).
- Estimated south arm lake-level drop due to a 55 m long Union Pacific causeway breach: ~0.5 m (1.5 ft). Breach made on December 1, 2016.
- Lake levels for October 2016: south arm = ~1277.8 m (4192.3 ft), north arm = ~1276.8 m (4189.1 ft), maximum water depth ~7.7 m (25 ft).

Fish

At its historic high level in 1986 the lake's south arm salinity dropped below 6%. This was low enough for a breeding population of brackish-water killifish (*Lucania parva*) to enter the lake from a formerly isolated spring located on the south shore (Stephens, 1990). With the subsequent lake-level drop the killifish were gone by the following spring.

Microbialites

An unforeseen benefit of the otherwise problematic recent low lake levels is the exposure of incredible expanses of microbialites (figure 25). Microbialites are organic sedimentary deposits formed when microbial communities (cyanobacteria) trap and bind sediment and/or form the locus of mineral precipitation, principally calcium carbonate (Burne and Moore, 1987). More commonly known stromatolites are a type of mi-

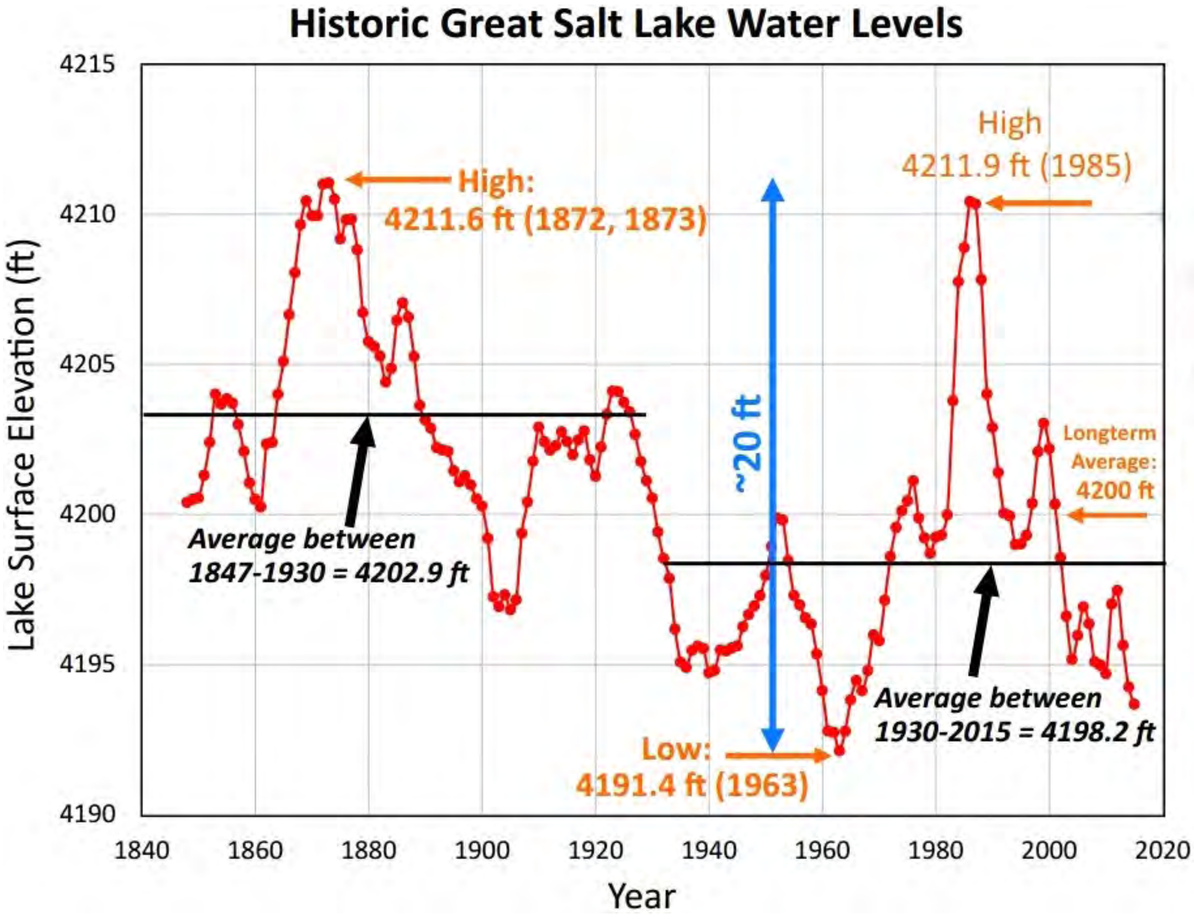


Figure 23. Great Salt Lake hydrograph (from Vanden Berg and others, 2015).

Figure 24. Google Earth image of Great Salt Lake. Image dates range from August 16, 2014 to July, 8, 2016. Google Earth imagery © 2015 Google Inc.

crobialite that exhibit internal lamination. The microbialites of Great Salt Lake do not typically show internal lamination but a thrombolitic (clotted) fabric (figure 26) (Chidsey and others, 2015).

Microbialites develop in mats, typically composed of bacteria, fungi, protozoans, or algae. Lindsay and others (2016) have used DNA sequencing to determine the abundance of bacteria, archaea, and eukarya in Great Salt Lake microbialities (figure 27). Their results show south arm of Great Salt Lake microbialites contain an abundance of photoautotrophic taxa that may drive carbonate precipitation and thus suggest the microbialites are still actively growing.

Figure 25. Microbialites northeast of Stansbury Island, south arm Great Salt Lake. The large bioherm (lower left) has an approximate 3 m diameter. The green-brown color on the microbialites is due to a covering of cyanobacteria. The lighter area is dead and bleached due to exposure. Photo courtesy of Michael Vanden Berg, Utah Geological Survey. Photo date November 4, 2015.

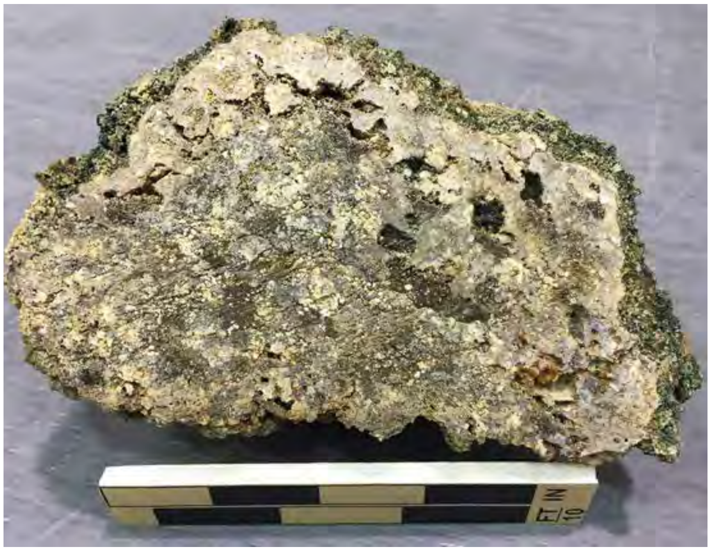


Figure 26. A sliced microbialite from south arm of Great Salt Lake. Photo courtesy of Michael Vanden Berg, Utah Geological Survey.

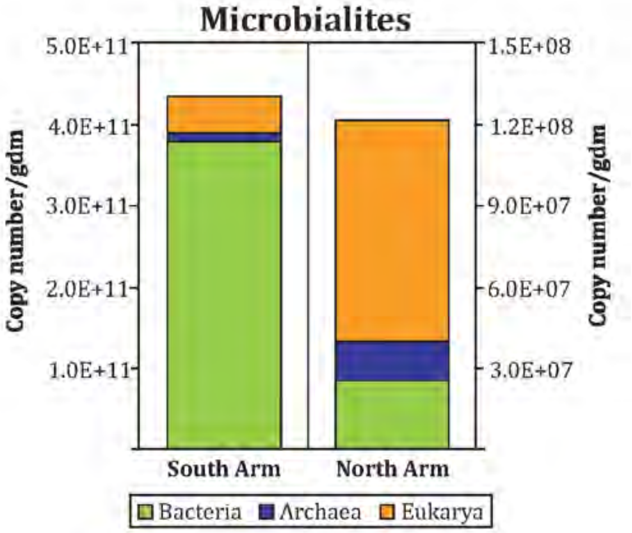


Figure 27. Relative abundances of archaeal, bacterial, and eukaryl rRNA genes in south and north arms of Great Salt Lake. Modified from Lindsay and others (2016).

Continue road guide.

2.8 / 127.7 Return to I-80 eastbound ramp and proceed east towards Salt Lake City.

14.7 / 142.4 Take exit 121 for 600 South and proceed east on 600 South.

1.6 / 144.0 Turn left onto State Street and proceed north.

0.2 / 144.2 Return to Grand America Hotel.

END OF ROAD LOG.

ACKNOWLEDGMENTS

No new work is presented in this geologic road guide. It is merely a compilation of previously published work. As such, we acknowledge the authors of our main sources of information: Don Currey (University ofUtah), Holly Godsey (University of Utah), Benjamin Laabs (North Dakota State uinversity), Jack Oviatt (Kansas State University), Marith Reheis (U.S. Geological Survey), Ian Schofield (Loughlin Water Associates), and Michael Vanden Berg (Utah Geological Survey). A new comprehensive book, *Lake Bonneville, A Scientific Update* (edited by Oviatt and Shroder, 2016) necessitated updates to the original manuscript. We would also like to acknowledge and thank Jack Oviatt for his extremely helpful review of this manuscript. We thank the Vertebrate Paleontology Department of the Natural History Museum of Utah for permission to photograph the fossil specimens in their collection illustrated in figure 4.

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