Great Salt Lake Desert Landscape Change Over Multiple Temporal Scales—A Field Trip Guide Covering the Bonneville Salt Flats and Knolls Sand Dunes

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TRIP OVERVIEW

This one-day (~260-mile) field trip guide provides an overview of the late Pleistocene to Holocene history of the Great Salt Lake Desert. Stops include Knolls Sand Dunes and areas on or surrounding the Bonneville Salt Flats, such as Juke Box trench, the Bonneville Salt Flats International Speedway, and the saline pan center and edge (Figure 1). We cover the post-Lake Bonneville geomorphic evolution of the Great Salt Lake Desert including changes in land cover over the past century. The Great Salt Lake Desert area provides unique access to saline landscape features including gypsum dunes and a perennial saline pan. We discuss the origin of these features and how they fit within the area's broader geologic context. The accessibility of sites discussed here depends on surface conditions. In general, late summer to early fall is the most opportune time to visit this area. *Vehicular travel to any of the off-road sites is discouraged when there is standing water or high near-surface moisture (wet mud with little traction). Surface conditions can change rapidly, and we recommend researching current conditions before initiating this trip. This desert is hot and dry during the summer and there is no shade and limited access to water; please plan accordingly.*

Past and current Great Salt Lake Desert depositional changes provide an analog for the modern Great Salt Lake with changing water availability, potential dust production, competing priorities, and rapidly changing land cover. The information presented here impacts understanding natural and geologic heritage, changing management strategies, and landscape dynamism over multiple spatial and temporal scales.

DEPOSITIONAL AND EROSIONAL HISTORY

This trip features a landscape in the heart of the Great Basin, the Bonneville basin in northwestern Utah, which includes classic examples of Basin and Range topography. While traveling between Salt Lake City and the Great Salt Lake Desert, we will cross several mountain ranges that have excellent fault-block tilting and Lake Bonneville shoreline exposures. The Bonneville Salt Flats and Knolls dune field areas are bounded by grabens with <300 ft of deposition in the past 600,000 to 800,000 years (Shuey, 1971). The Bonneville Salt Flats is located within the Wendover Graben; this area has >1000 ft of laminated carbonate muds and gypsum beds that are underlain by conglomerates (Stephens, 1974; Bernau and others, 2023b). The Wendover and other nearby grabens began forming in the Miocene (Miller and others, 2021). Although faulting and seismic activity are thought to have largely ceased in this area, we discuss evidence for late Pleistocene to Holocene fault movement and soft sediment deformation features (the cause of these features, whether seismicity, decompression dewatering, or compaction, is unknown). In addition to this field trip guide, several maps provide more insights into the geologic history of this area (Cook and others, 1964; Doelling, 1964; Stifel, 1964; Doelling and others, 1994; Clark and others, 2020; Bernau and others, 2023; Clark and others, in progress).

Late Pleistocene to Holocene Geological Record

Late Pleistocene Lake Bonneville provides the geologic backdrop for this trip. Based on radiocarbon dating, Lake Bonneville was persistent between 30,000 and 13,000 calibrated radiocarbon years before present (cal yr B.P.) (Figure 2) (Oviatt, 2015). At its peak, it was almost as big as Lake Michigan and extended over one-third of the state of Utah. Lake Bonneville extended from the Wasatch Range to the Utah-Nevada state line area and from Soda Springs in

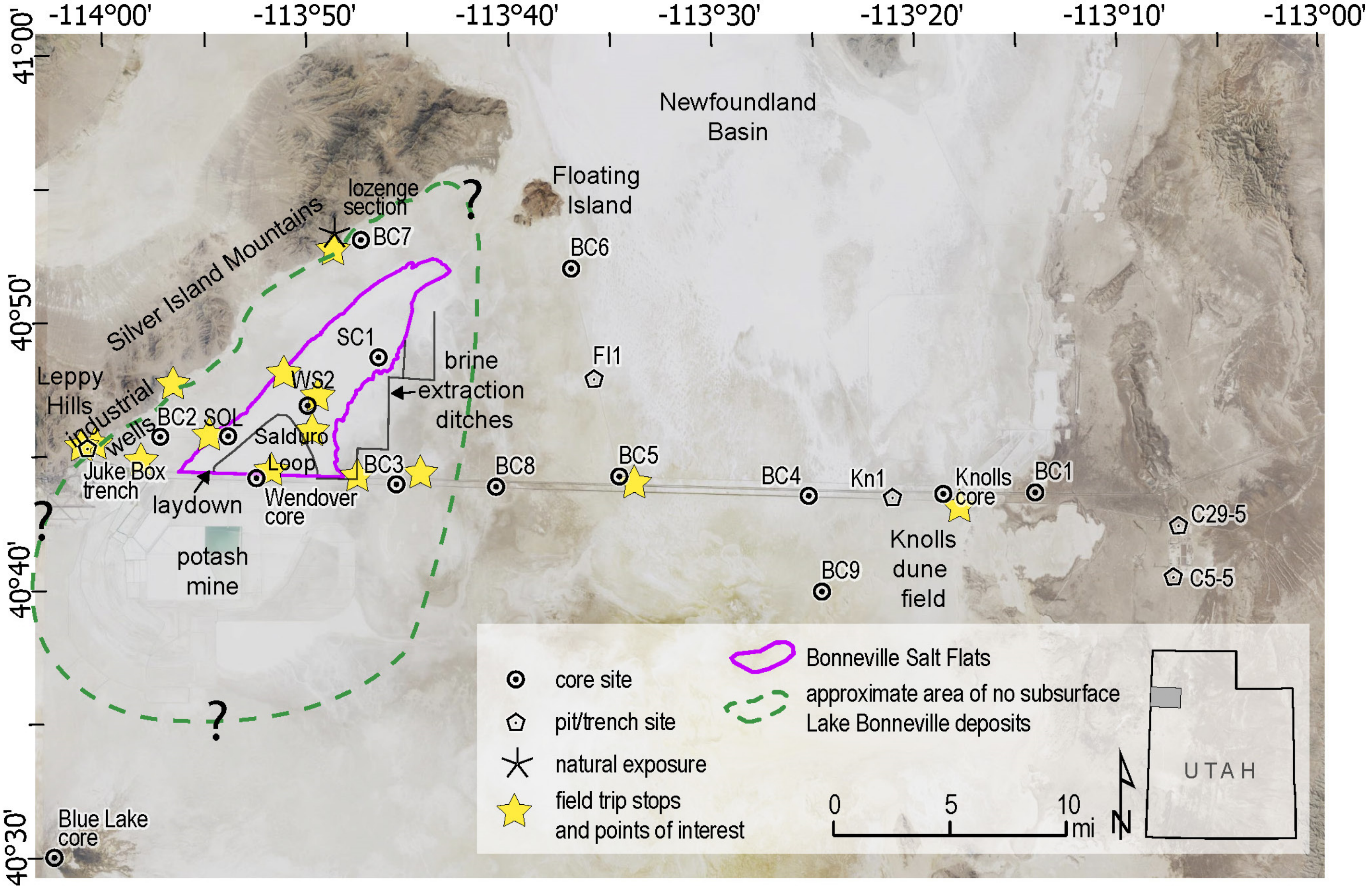


Figure 1. *Field trip area overview. Yellow stars denote field trip stops and points of interest. Other symbols denote sites used to interpret the Great Salt Lake Desert depositional record in Figure 3. Figure modified from Clark and others (in progress). Basemap imagery from Earthstar Geographics.*

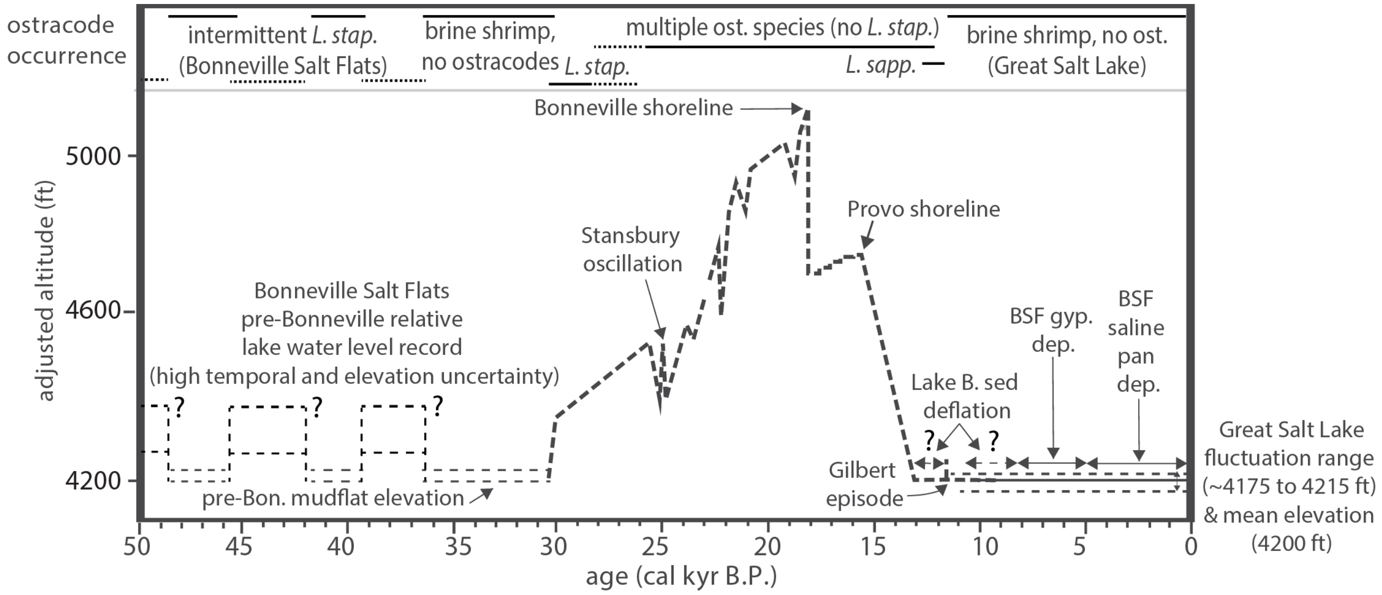


Figure 2. *Lake Bonneville hydrograph with depositional history from Bonneville Salt Flats cores added. Modified from Oviatt (2015).*

southern Idaho south to Parowan, Utah (making it nearly twice as long as it was wide) (Gilbert, 1890). In addition to its shorelines, Lake Bonneville left a regular stratigraphic succession of marl across its basin (~1–6 ft thick in most areas).

Erosion of the Great Salt Lake Desert

The Great Salt Lake and Bonneville Salt Flats have long been considered saline remnants of Lake Bonneville (Eardley, 1962). Analysis of Great Salt Lake Desert shallow cores, pits, trenches, and other exposures indicates that story is more complicated (Oviatt and others, 2020; Bernau, 2022; Bernau and others, 2023b; Clark and others, in progress). The Bonneville Salt Flats, rather than forming from Lake Bonneville's remnant waters, began forming at ~8,000 cal yr B.P., about 5,000 years after Lake Bonneville's final retreat to modern Great Salt Lake levels. After Lake Bonneville desiccated, an estimated 3–6 ft of Lake Bonneville sediments were deflated (eroded by wind) from the area surrounding the site of the modern Bonneville Salt Flats. This past deflation provides an analog for potential Great Salt Lake sediment deflation that may occur if its water levels continue to decline.

The Great Salt Lake Desert depositional record along Interstate Highway 80 (I-80) is summarized in Figure 3 (Louderback and Rhode, 2009; Oviatt and others, 2018; Oviatt and others, 2020; Bernau, 2022). Surprisingly, because of the deflation of Lake Bonneville sediments, the Bonneville Salt Flats—a Great Salt Lake Desert depositional area with up to 5 ft of Holocene deposition—has a less complete geologic record than the adjoining mudflat, which has had little, if any Holocene deposition but has retained all to some of the Lake Bonneville marl deposits. This depositional difference highlights the potential for topographic lows in arid climates to have less complete geologic records, making this an important consideration when planning and interpreting investigations of paleoenvironmental records.

Research on modern deflation at Owens Lake, California, provides a model that explains observed Great Salt Lake Desert deflationary patterns (Figure 4) (Reynolds and others, 2007). Deflation in arid settings is strongly influenced by groundwater level and salinity. Playas become deflationary surfaces when groundwater levels fall far below the surface (Rosen, 1994). This fact alone, however, does not explain observed deflationary patterns. The Bonneville Salt Flats, as a regional topographic low, should have higher groundwater levels than adjoining Great Salt Lake Desert basin floor areas, which do not have the same degree of deflation. Salinity explains this apparent contradiction. The Bonneville Salt Flats area would have had higher groundwater salinity as water flowed in and evapoconcentrated from surface waters

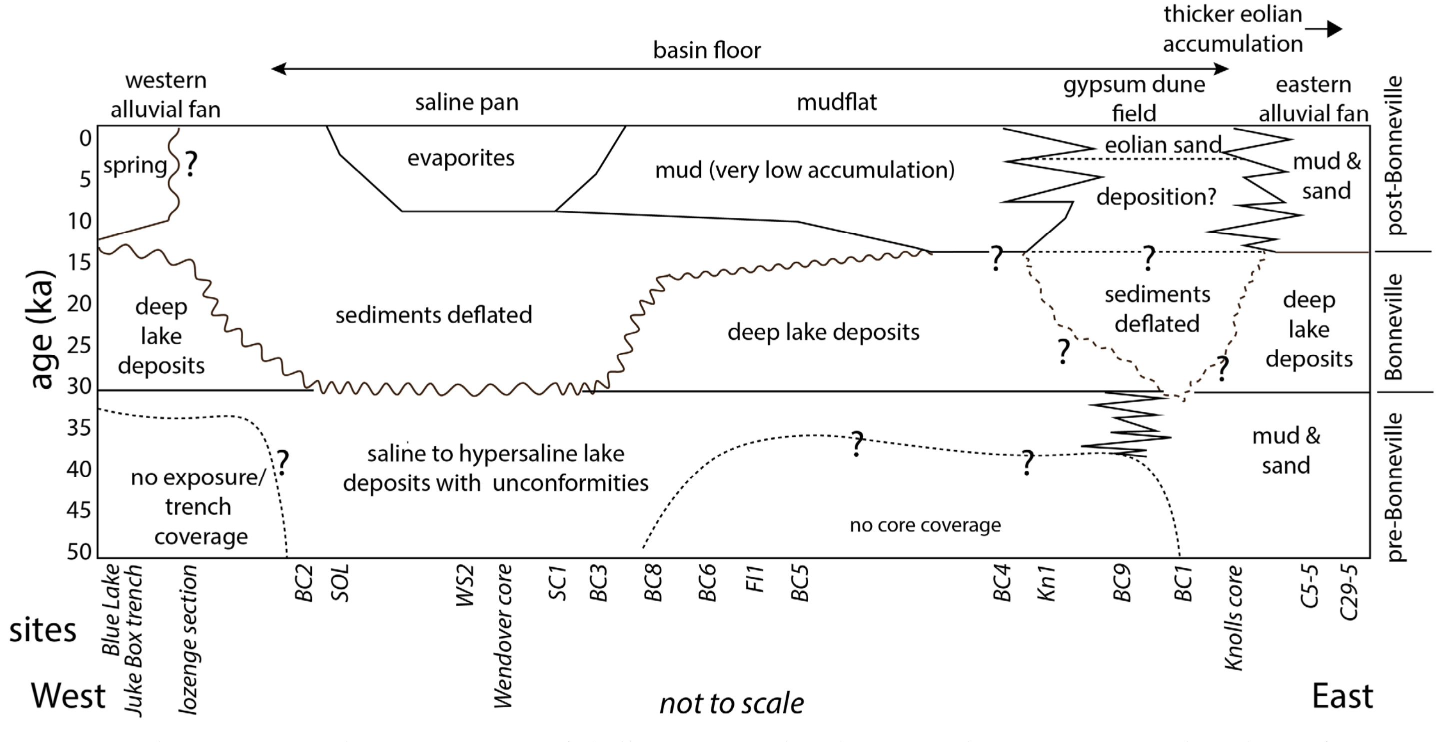


Figure 3. Chronostratigraphic cross section of shallow Great Salt Lake Desert deposits. Figure is based on information from Great Salt Lake Desert core and pit sites shown in Figure 1 (Louderback and Rhode, 2009; Oviatt and others, 2018; Oviatt and others, 2020; Bernau, 2022) and the information supporting this figure is described in Bernau and others, 2023b.

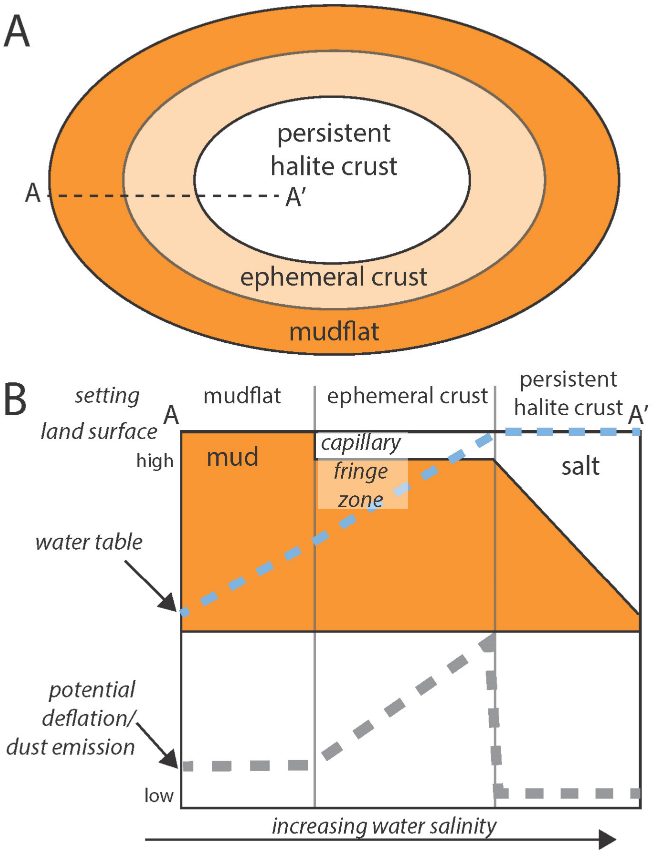


Figure 4. *Deflation model for the Great Salt Lake Desert, modified from Reynolds and others (2007). (A) The saline pan and surrounding area. (B) Cross section A - A' shows deflation is highest in the area immediately adjacent to the persistent halite crust (Figure from Bernau and others, 2023b).*

or groundwaters. Surficial salts, depending on their thickness and composition, greatly alter a surface's erodibility. Thick salt layers crystallized from standing water are very resistant to erosion. Ephemeral crusts created from groundwater evaporation, however, are highly unstable; they easily break up and act as abrasives. Similarly, displacive evaporite growth, commonly gypsum, may alter the properties of near-surface mud. Areas with minor salinity (groundwater table so low that the capillary fringe is below the surface, or they have continuous freshwater input) can form relatively stable surfaces that limit deflation.

Using the model in Figure 4, it is likely that before saline pan formation at the Bonneville Salt Flats that this area had an ephemeral crust that accelerated deflation, enabling Lake Bonneville sediments to be locally removed. As climate shifted at ~8,000 cal yr B.P., gypsum sands began accumulating at the saline pan, limiting deflation. Finally, saline pan deposition with bedded halite deposits began to accumulate around 5,500 cal yr B.P. as the climate became cooler and wetter (Bernau, 2022). These cooler and wetter conditions enabled more surface water, and potentially, groundwater, to flow into the saline pan and for deeper and longer-lived surface ponding to occur. Thicker, bedded halite deposits, like the halite layers seen at the modern surface of the Bonneville Salt Flats were then able to form.

FIELD TRIP ROAD LOG

Begin by driving west along I-80 from Salt Lake City for ~80 miles to Exit 41 (Knolls). You will pass through several mountain ranges and basins of the eastern Basin and Range physiographic province. The Great Salt Lake Desert, because of its remoteness, hosts hazardous waste facilities and military testing. Much of the Great Salt Lake Desert hass limited to public access due to military testing and training activities. Near Aragonite, as you enter the Great Salt Lake Desert (near Exit 49), smokestacks from a hazardous waste incineration plant to the south become visible. A low-level nuclear and mixed waste landfill is west of this facility near Clive (Exit 49). A hazardous waste landfill is also located northwest of the Clive exit.

Knolls Sand Dunes

Take Exit 41, drive to the south, and follow the road as it bends west. After ~1 mile, you will be in the dunes (40.7244° N, 113.2821° W; all coordinates in WGS84 datum). Several places on the side of the road provide some distance from the road and are safer than the road for parking. This road can be busy with ATVs and UTVs, particularly on weekends.

Site Description

The Knolls dune field and other Great Salt Lake Desert gypsum dunes have been investigated since the 1950s (Jones, 1953; Eardley, 1962; Dean, 1978; Jewell and Nicoll, 2011; Boden, 2016; Fitzgerald, 2019). These dunes and salt pans are considered excellent analogs for aspects of the Martian landscape and may help us better understand Mars' surface evolution and past potential for the existence and preservation of life (Benison and Karmanocky, 2014). Gypsum dunes have low preservation potential. Most documented gypsum dunes are less than a few tens of thousands of years old (Warren, 2006).

Gypsum dunes on the eastern side of the Great Salt Lake Desert are concentrated along a change in slope (Doelling, 1964). Dunes consist of predominantly medium- to very fine sand (Figure 5) and may

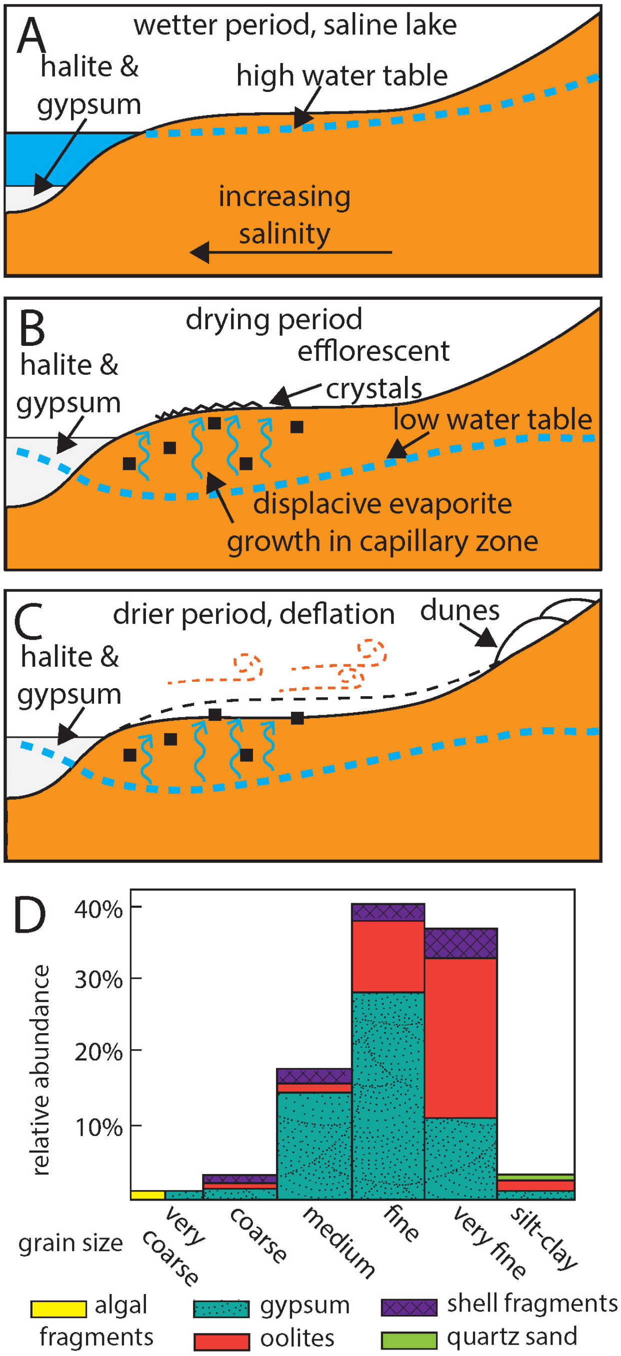


Figure 5. *Schematic model for gypsum dune origin (A to C) and grain size composition of dunes at Knolls (D). (A to C) is based on Bowler (1986) and (D) is modified from Jones (1953).*

be >30 ft high (Boden, 2016). Most grains are gypsum (up to 60%), with oolites being the second most common grain. Trace shell fragments (predominantly ostracodes), algal fragments, and quartz sand also occur (Jones, 1953). Quartz and oolitic dunes occur in other Great Salt Lake Desert areas (Dean, 1978). In addition to these eastern gypsum dunes, there are several smaller dune areas to the west, approaching the Bonneville Salt Flats (Boden, 2016).

Gypsum dunes are evidence of a drying saline landscape. Gypsum forms in arid environments 1) as bottom growth crystals at the bottom of a shallow saline lake, or 2) displacively in subsurface sediments from the evaporation of groundwaters. Great Salt Lake Desert gypsum dunes are thought to mostly originate from displacive growths. Drying conditions and falling groundwater levels enable gypsum crystals to be transported (Figure 5). Deflation of fine-grained sediments exposes displacive crystals which then are redistributed by wind and accumulate downwind along changes in slope. In the modern Great Salt Lake Desert, predominant winds are from the west/southwest (Jewell and Nicoll, 2011). Dunes are stabilized by vadose zone moisture (wetter conditions), when available, or vegetation, or they stabilize where prevailing winds meet.

Analyses of cores reveals that Lake Bonneville sediments were partially to fully deflated at and near Knolls (Eardley, 1962; Oviatt and others, 2020). Similarly, Lake Bonneville marl has been truncated in the area to the west of Knolls, indicating deflation was concentrated here (relative to the mudflats to the west) before gypsum deposition. Optically stimulated luminescence dating of gypsum crystals (an atypical material for this technique) suggested that gypsum dune formation has been constant since >2,300 yr B.P. and is ongoing (Fitzgerald, 2019). Gypsum was deposited at the Bonneville Salt Flats between 3,500 and 1,700 cal yr B.P. (Bernau, 2022). Analyses of aerial photography from the years 1953, 1972, and 2015 indicate that many dunes in the Knolls area are still active, with some dunes moving by several miles in that period (Fitzgerald, 2019). Similarly, our observations of sediment caught by a snow fence running parallel to old Highway 40 (south of I-80) indicate Great Salt Lake Desert deflation is still actively occurring. Sediments stopped by the snow fence consisted of mud, gypsum crystals, and carbonate lumps.

Transit To Juke Box Trench

Return to I-80 and continue west for 37 miles to Exit 4. The interstate mile markers below note areas of interest along this route.

Mile Marker 25

The unimproved road leading to the northwest from here connects to Floating Island. Floating Island's name stems from the mirage that occurs on hot days, creating an illusion that the small mountain is suspended or floating in the air. *Note: Traversing the Floating Island Dike Road is only advisable with a heavy-duty high-clearance vehicle.* This elevated road on an earthen dike was constructed to limit the extent of the West Pond, a large lake created in the Great Salt Lake Desert by the West Desert Pumping Project in the 1980s (Wold and Waddell, 1994; Kohler, 2002). During this wet period, rising Great Sale Lake levels had the potential to flood infrastructure, commercial facilities, and homes. To address this, large pumps ~11 miles west of Lakeside, Utah, were constructed and used to pump Great Sale Lake water into the Great Salt Lake Desert, specifically the Newfoundland Evaporation Basin (the area directly to the north and east of mile marker 25) (Figure 1). When pumped waters evaporated, they created a saline pan that exceeds the modern Bonneville Salt Flats in extent. Over time the saline pan has decreased in size (Radwin and Bowen, 2021). Due to the absence of a saline pan in the Newfoundland Basin before the pumping project, it is unlikely that the hydrological conditions in the area would naturally support the long-term persistence of a saline pan.

Mile Marker 15

Analyses of aerial imagery and past reports of the Bonneville Salt Flats' extent indicate that the Bonneville Salt Flats' surface halite once extended to this location (Nolan, 1927). The past thickness of halite between mile markers 15 and 13, however, was thin (<1 inch).

Mile Marker 13.5

The ditch (which has adjoining tailings berms) stretching to the north is used to collect briny groundwater for potash production. The ditch extends under the highway and to the south where it connects to large evaporation ponds used to concentrate brine at the potash mine. These evaporation ponds are a local source of gypsum sand in the Great Salt Lake Desert. There is another set of berms between this and the next stop; they are from a brine collection ditch that has been inactive since the 1960s (the Salduro Loop).

Note: The ditches are located on private property and a fence along the road limits the pull-over area, ***do not stop here or enter the ditches****.*

Mile Marker 10

Many people know the Bonneville Salt Flats from the I-80 rest stop. This stop has public restrooms and is the best place to explore the Bonneville Salt Flats' surface morphology for salt polygons. More discussion of salt polygons is available under the Bonneville Salt Flats surface morphology section of this guide.

Exit 4

Take Exit 4. Near Exit 4, there is a gas station with public restrooms, the remaining stops do not have any facilities. This stop is also an option to refuel before continuing or returning to Salt Lake City. Continue north on Leppy Pass Road for ~0.2 miles and take a left onto the paved I-80 frontage road. Continue on the I-80 frontage road for 1.4 miles until the road reaches a T intersection. Take a right. Continue for 0.8 miles towards the alluvial fan until there is another T in the road, take a left and continue for ~200 ft, and park. Walk to Juke Box trench (40.7549° N, 114.0102° W) (elevation ~4255 ft) ~150 ft southeast of here.

Please be aware that the roads beyond the I-80 frontage road are not regularly maintained. In the event of recent precipitation or insufficient evaporation to dry the surface, these roads can become impassable. Exercise caution and consider the weather conditions before venturing onto these roads. Under sustained dry conditions, all sites described in the rest of this guide are accessible in 2-wheel-drive vehicles with standard clearance. Accessibility is markedly reduced under wet conditions. ***Proceed with caution.***

Juke Box Trench

Juke Box trench is located at the site of a past spring. Because of the archeological significance of this area (see discussion of Juke Box Cave and Danger Cave), a trench was excavated and investigated by archeologist David Madsen and colleagues in the 1980s. It was enlarged in 2009 and revisited for paleoenvironmental interpretation (Oviatt and others, 2018).

This stop has an excellent example of pre-Bonneville, Lake Bonneville, and post-Bonneville deposits. The depositional section is (1) base: pre-Bonneville oolitic sand and carbonate-cemented gravel and sand; (2) Lake Bonneville offshore fine-grained sediments (marl); (3) an unconformity that cuts the Bonneville section; (4) a gravel lens at the base of the post-Bonneville sequence (possibly deposited during the Gilbert episode); and (5) Holocene wetland deposits.

Depositional record

Three main strata in Lake Bonneville marl correspond to different stages in the lake's levels. During the lake's rising (transgressive) stage, it left laminated marls (Figure 6). The laminae are interpreted as evi-

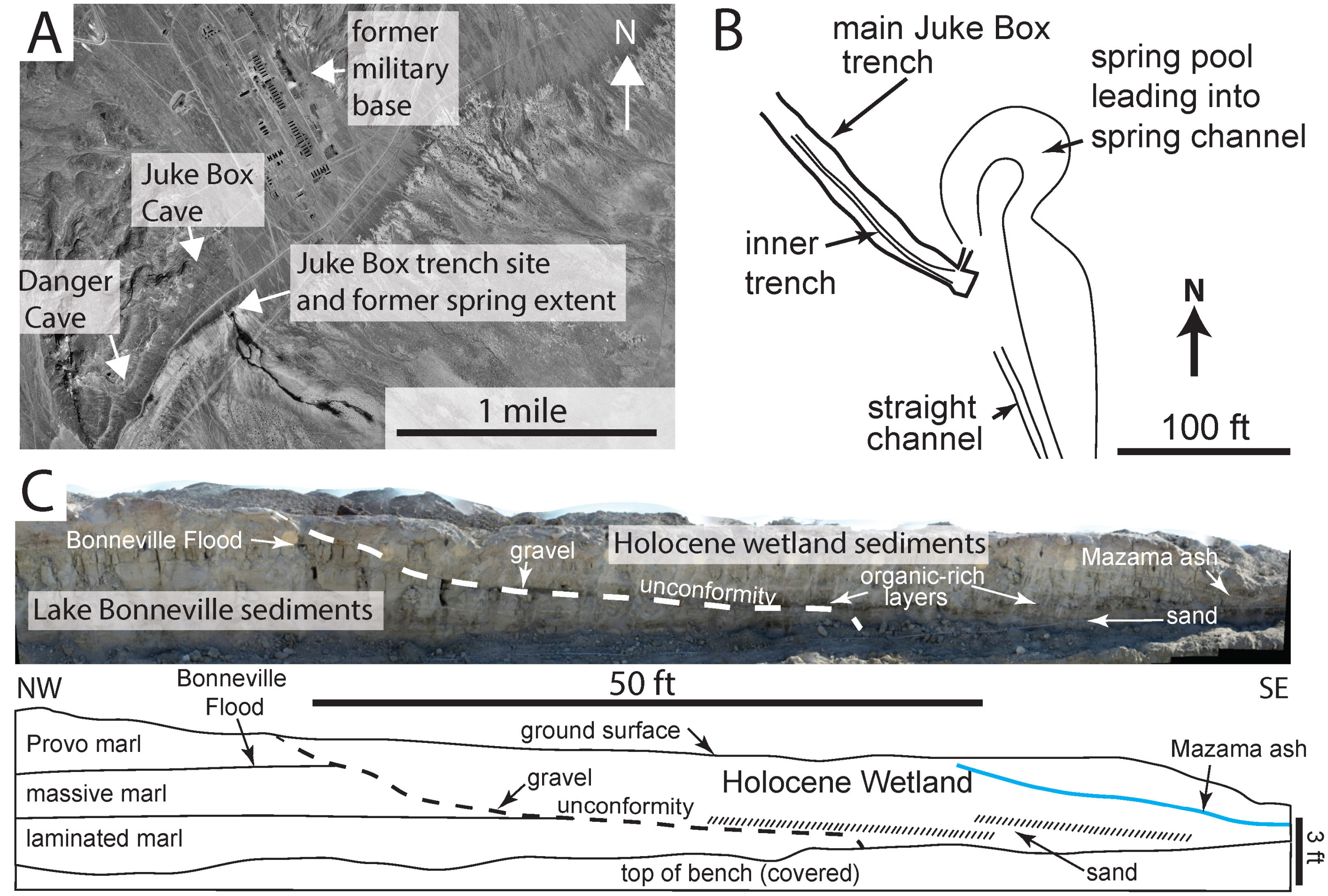


Figure 6. *Overview of Juke Box trench. (A) 1946 aerial imagery overview of the area. Danger and Juke Box caves, former military base, and past extent of spring noted. (B) Map overview of Juke Box trench. (C) Juke Box trench sediments. Note lateral change in deposition locally with little to no Holocene deposition and Lake Bonneville (Provo marl, massive marl, and laminated marl) sediments being preserved to the northwest (coincident with a notable change in surface morphology), and deflated area covered by Holocene wetland sediments. This wetland was active as recently as 1946. (B and C) modified from Oviatt and others (2018).*

dence of little bioturbation and more-rapid deposition. As Lake Bonneville approached its maximum size and formed the Bonneville level shoreline, a more massive (layerless) marl was deposited. This layer is interpreted as originating from slower depositional rates and more bioturbation. The top of this interval is denoted by a sharp change in lithology associated with the Bonneville flood. As the lake decreased in size, the color of the marl changed, reflecting changes in mineralogy associated with the evapoconcentration of lake waters (Provo level and post-Provo). Across these stages, ostracode species also change, creating a regular sequence that can be used to aid stratigraphic interpretation (Figure 2) (Oviatt, 2015, 2017).

Based on radiocarbon dating, deflation (wind erosion) of Lake Bonneville sediments occurred between the terminal desiccation of Lake Bonneville (~13,000 cal yr B.P.) and the Gilbert episode (~11,600 cal yr B.P.) (Oviatt and others, 2018). Radiocarbon dating and tephra indicate sustained wetland deposition since ~10,500 cal yr B.P. A significant stratigraphic marker in these deposits is the Mazama ash (7,600 yr B.P.), which was deposited during the last significant eruption of the volcano at Crater Lake National Park in Oregon.

Juke Box Cave and Danger Cave (Optional Stop)

This optional stop is located to the west of Juke Box trench. Juke Box Cave and nearby Danger Cave are important archeological sites. Furthermore, the vista from Juke Box Cave's entrance provides an excellent overview of the area.

Continue along the road from where you parked for ~150 ft, take the road to the right and head up the alluvial fan until you reach a large turnaround area, and park there. From here the road extends up to Juke Box Cave (40.7570° N, 114.0130° W) (elevation ~4446 ft). This is a short, but steep, hike. To reach Danger Cave (40.7490° N, 114.0182° W) continue ~0.6 mi southwest along the dirt road from where you parked. A short path leads to the gated cave entrance.

Archeological Significance

Juke Box Cave is believed to have acquired its name because during World War II soldiers from the nearby military barracks (Figure 6A) used the cave to socialize and even went so far as to construct concrete dance floor in its confines. Danger Cave holds the distinction of being Utah's first State Monument. It also holds a place on the National Register of Historic Places and is recognized as a National Historic Landmark. Major excavations were conducted at Juke Box and Danger caves in the 1940s and 1950s by University of Utah researchers (Jennings and others, 1956). Since then, intermittent work has been conducted on the caves, taking advantage of new archaeological techniques as they have become available (Madsen, 2014). The initial excavation of Danger Cave was important in helping establish the utility of radiocarbon dating as a valid chronological tool when it proved to be one of the oldest archeological sites in North America known at the time.

These caves were occupied repeatedly by indigenous people between about 12,500 cal yr B.P. to historic times (Jennings and others, 1956; Madsen and Rhode 1990; Rhode and Madsen, 1998; Rhode and others, 2005; Rhode and others, 2006; Goebbel and others, 2007). Early people were present here intermittently from ~12,500 to 8,000 cal yr B.P. This area was later used by Desert Archaic people (~1,500 cal yr B.P.), the Fremont (~1,500 to 700 cal yr B.P.), and proto-historic Shoshonean groups (~700 cal yr B.P. – present). The extremely good preservation in the dry caves, coupled with their detailed stratigraphy, has provided some of the best evidence of prehistoric lifeways of Great Basin peoples, as well as records of ecosystem change and paleoclimate. Textiles, baskets, pottery, animal bones, plant remains, weapons, chipped stones, coprolites, quids (chewed bits of fibrous food), arrowheads, and leather scraps have all been found in the caves.

Paleoenvironmental Record

Juke Box Cave is located near the Stansbury shoreline and Stansbury shoreline tufas are visible near the cave's entrance. Plant and animal remains left by the cave's inhabitants record changes in the surrounding environments, including the Juke Box spring marshland that existed below the cave and nearby desert and mountain ecosystems. Additional paleoenvironmental information from pollen analyzed from cores taken in the marsh and from woodrat nests found in nearby caves containing well-preserved plants, insects, and vertebrate remains supplement the cave records (Rhode and Madsen, 1998; Madsen and others, 2001). These woodrat "middens" can be preserved for tens of thousands of years, providing ecological snapshots of the past, making them invaluable paleoenvironmental tools.

Bonneville Salt Flats

Return to the I-80 frontage road and continue for 1.4 miles until you reach Leppy Pass Road. Take a left. Continue for 5 miles (at the bend in the road, turn right/east towards the Bonneville Salt Flats). At the end of the pavement, there is a large turn-around area. Park here (40.7625° N, 113.8958° W). Depending on events and surface conditions you may be able to access the salt crust (stops in these areas are described in the geomorphology section below).

Access to Bonneville Salt Flats crust is limited seasonally by surface flooding. In general, if there is surface moisture at the end of the access road, stay off the salt flats. Ignoring this guideline may rip up and damage the crust for years to come (Figure 7). In addition, the salt can be thin. It is easy to get stuck in the underlying mud and it is expensive and damaging to be towed out. Only drive on the salt when it is dry and when your tires do not leave a track. Furthermore, access is limited during events such as Speed Week. The Bonneville Salt Flats is on public land managed by the Bureau of Land Management. A schedule of Bonneville Salt Flats events is available at https://www.blm.gov/visit/bonneville-salt-flats.

When on the salt flats, be careful to watch out for cross-traffic. ***Fatal crashes have happened here before****. Also, be aware of the state of the crust. If your vehicle is leaving tracks, keep momentum, turn around, and return to the stable crust!*

The vast expansive landscape of the Bonneville Salt Flats is treasured for different uses by many groups of people. The brines underlying the saline pan are enriched in potassium and have been mined continuously since 1939 (Bingham, 1980). The landscape is valued by tourists and artists for its sharp contrasts and stark beauty (Zajchowski and others, 2020; Bowen and Wischer, 2023). The hard flat surface is treasured by the vehicular land-speed racing community for its flatness, mechanical properties, and length (Francisco, 1965). Social and physical scientists also value this landscape, which provides an example of saline processes influenced by human action

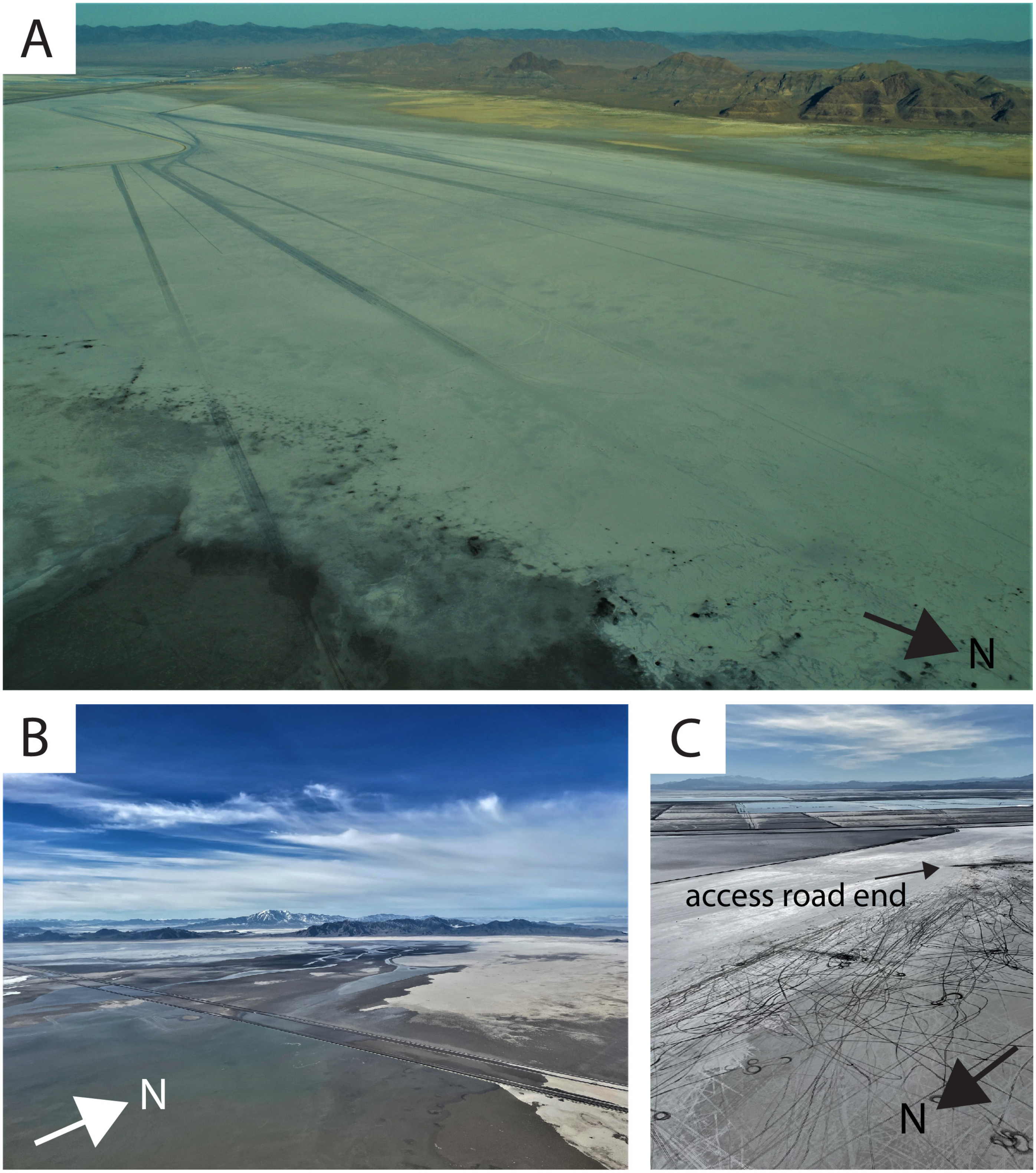


Figure 7. *Aerial imagery of the Bonneville Salt Flats. (A) Racetracks and view of Silver Island Mountains. (B) Water input from south of Interstate 80. (C) Car tracks left near the end of the access road, view of potash mine to the south. Note that tracks are more evident to the west, towards the edge of the saline pan where the crust is thinner. North arrows added to show orientation. Images taken with pilot Dr. Gabe Bowen on (A) August 17, 2019, (B) February 19, 2023, and (C) October 30, 2022. These and other Bonneville Salt Flats aerial imagery available at: https://geodata.geology.utah.gov/pages/search.php?search=%21collection129324.*

(e.g., Christiansen, 1963; Zajchowski and others, 2020). Here, we describe a century of changes at the Bonneville Salt Flats and provide context for these changes through the window of the Bonneville Salt Flats' depositional history. We then describe the surface expression of the crust and how it varies spatially and temporally.

Recent change

The Bonneville Salt Flats' recent history is characterized by changes in salt crust area and thickness (Figure 8). Furthermore, the geochemistry of Bonneville Salt Flats brines has changed over time in response to changing management (Bernau and others, 2023a, this volume). Anthropogenic activities during this period are strong contributors to this change. The saline pan has been dissected by industrial activity and an interstate highway, and its waters have been collected for mineral production. These changes have upset and limited the ability of multiple stakeholders to use the site, spurring several salt crust thickness studies, research, and lobbying for action (Francisco, 1965; Kipnis and Bowen, 2018).

For a quarter century, restoration efforts at the Bonneville Salt Flats have focused on a brine "laydown" program. To the north of Juke Box trench, there are alluvial-fan aquifer production wells. These brackish water wells are used to provide the potash mine with water for its operations. They have also been used to supply water for the laydown program since 1997. The laydown uses alluvial-fan water to dissolve waste halite from mine operations, the resulting brine then floods the Bonneville Salt Flats' surface. This project has not had anticipated results, and the crust has continued to decrease in area and thickness (Figure 8B and D) (White, 2004; Bowen and others, 2017; Kipnis and Bowen, 2018).

Alluvial-fan aquifer extraction may be exacerbating long-term crust declines (Bernau and others, 2023a, this volume). Since the onset of the laydown, groundwater levels in the alluvial fan have steadily fallen, leading hydraulic gradients to reverse; instead of water flowing towards the saline pan as it used to, it now flows away from the saline pan. This is evidenced by the salinity of the waters the wells now produce–they used to be fresh, but several wells now produce brine that is saltier than the ocean (Bernau and others, 2023a, this volume). A portion of this water likely comes from groundwaters underlying the saline pan. Dewatering from lowering alluvial-fan water levels (from surface to ~50 ft below the surface in 2021) has created >3-ft-wide desiccation fractures in areas near the mountain front (Mason and Kipp, 1998).

Depositional history

The depositional history of the Bonneville Salt Flats' site provides insights and perspective on modern change. Before Lake Bonneville, there were intermittent shallow saline lakes similar to the modern Great Sale Lake (>45,000 to >28,000 cal yr B.P.) (Figure 2; Bernau, 2022). These lake deposits have small faults and soft sediment deformation features, suggesting past seismic activity; an alternative interpretation of these features is that they are dewatering structures that developed as lake levels fell, and water was released from sediments as the overlying pressure of lake waters was removed. A fault with ~1.5 ft of Holocene offset along the southeastern Silver Island Mountains in a former spring area suggests that seismic activity may be ongoing (Hecker, 1993; Madsen, D., personal communication, 2022) (further investigation and interpretation of these sediments is needed). From the Bonneville Salt Flats you can see shorelines left by Lake Bonneville on the Silver Island Mountains and the Leppy Hills (Figure 7A).

The Bonneville Salt Flats salt crust consists of layers of gypsum sand and halite crystals. The gypsum sand becomes coarser with increasing depth, indicating the displacive growth of crystals after deposition (Bowen and others, 2018; Bernau and Bowen, 2021). Bonneville Salt Flats' gypsum deposition began at ~8,000 cal yr B.P. (Bernau, 2022). The origin of the gypsum sand is likely in-situ growth, which is seen in some modern sediments. Some grains may originate from displacive crystals that were later reworked with deflation. Radiocarbon dating of pollen, and similarly sized material from bedded Bonneville Salt Flats evaporites, indicates that the Bonneville Salt Flats is much younger than previously thought. The Bonneville Salt Flats likely resembled today's saline pan by 5,500 cal yr B.P., not immediately after Lake Bonneville (13,000 to 11,000 cal yr B.P.), as was previously thought. This new evidence indicates the saline pan may be a much more ephemeral feature than assumed. Similarly, the Bonneville Salt Flats' depositional history with respect to regional changes in climate indicates that halite is deposited under wetter conditions whereas gypsum is deposited under drier conditions. Recent records suggest this region is becoming drier (Williams and others, 2022), making the Bonneville Salt Flats likely to shift towards more gypsum accumulation even in the absence of direct anthropogenic alteration.

Crust surface morphology

You can view a timeline of surface conditions from this location in photos collected by citizen scien-

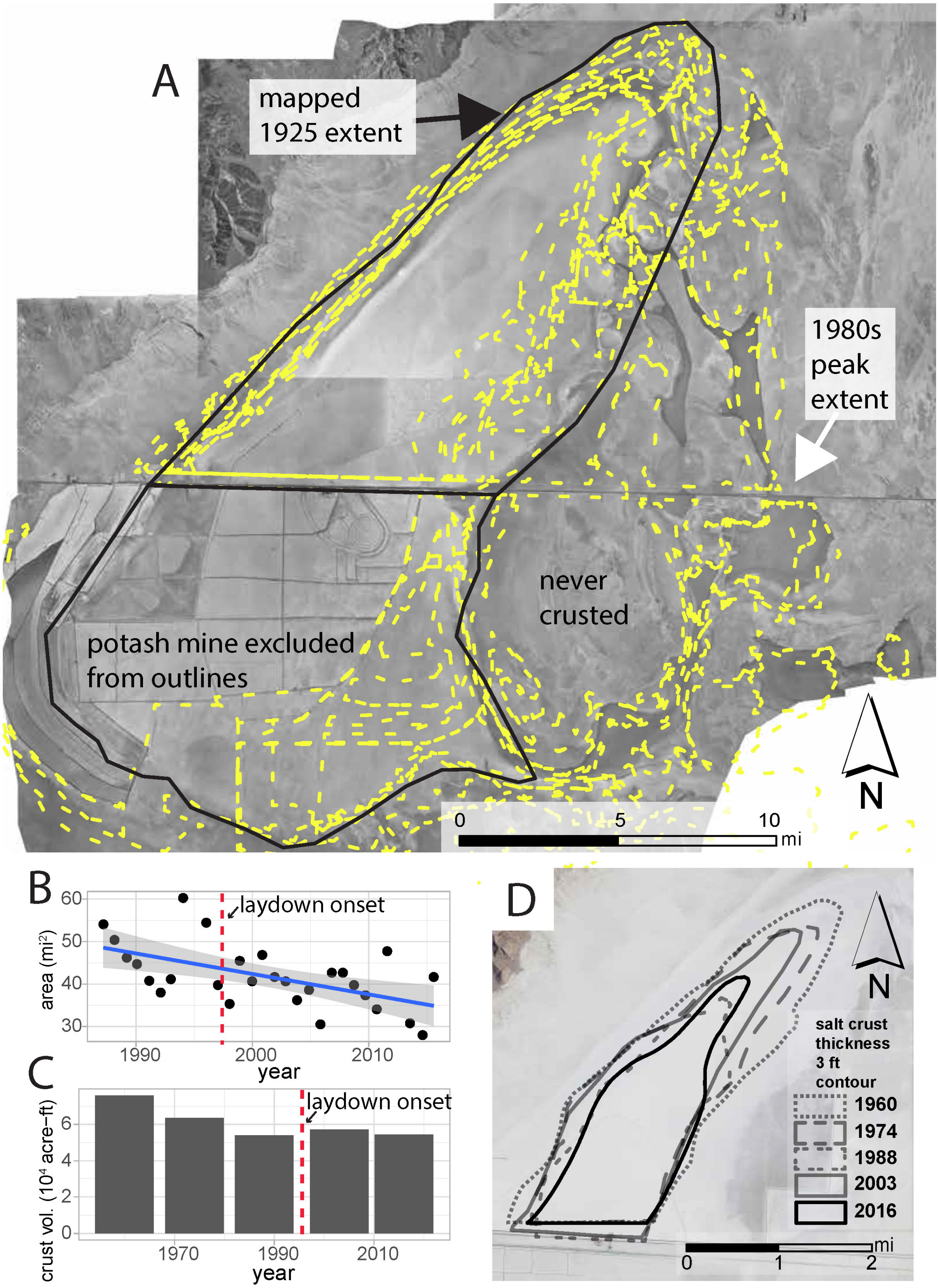


Figure 8. *Overview of change at the Bonneville Salt Flats. (A) Photomosaic of 1953 aerial imagery giving an overview of the Bonneville Salt Flats. Dashed yellow lines show the extent of surface halite from aerial imagery and black outline shows the oldest mapped extent of surface halite (Nolan, 1927). Aerial imagery is available in non-photomosaic form at https://imagery.geology.utah.gov/pages/home.php and in photomosaic form at https://geodata.geology.utah.gov/pages/search.php?search=%21collection129324. (B) A consistent long-term trend of declining saline extent is evident in analyzed Landsat data mapping the areal extent of end-desiccation surface halite over the Bonneville Salt Flats area north of I-80 (Bowen and others, 2017). (C) Recalculated (to adjust for differences in methodology) crust volume across salt crust thickness studies (1960 to 2016) (Kipnis and Bowen, 2018). (D) Change in the area of 3 ft crust thickness contour at the Bonneville Salt Flats across studies (modified from Kipnis and Bowen, 2018).*

tists here: https://www.chronolog.io/site/BSF101. These images highlight how variable the surface of the crust can be seasonally, or from week to week. Less than 1 cm of precipitation has led to >20 cm of flooding at this location. Heavy summer precipitation can rapidly alter conditions and event plans. Storms and deteriorating crust conditions led to the cancellation of racing events in 1993, 1994, 2014, 2015, and 2022 (Kipnis and Bowen, 2018).

The surface expression of evaporites at the Bonneville Salt Flats is dynamic and changes in response to cycles of flooding, evapoconcentration, and desiccation (Figure 9) (Lowenstein and Hardie, 1985; Bernau and Bowen, 2021). During the flooding stage, rainfall contributes to the full or partial dissolution of halite (Figure 9). This is apparent in dissolution pits that expose darker, gypsum and microbial-rich mud that underlies surface halite layers (Figure 10A1 and A2). During the evaporation stage, salt crystals begin to crystallize on the surface of the brine as rafts or at the sediment-water interface as bottom-growth crystals (Figure 10B1 and B2). One unique feature at the Bonneville Salt Flats is salt blisters (Figure 10B3), these may form from the remobilization of trapped air under a crust after flooding. Most people know the Bonneville Salt Flats from its appearance during the desiccation stage. The crust is in this stage when surface water is completely removed by evaporation. Many surface morphologies form during this period, with the most rapid growth occurring immediately after the surface enters the desiccation stage when near-surface pores are larger (not filled by crystal growth) and contain water. One diagnostic feature of this period is efflorescent (or popcorn) halite (Figure 10C). These aptly named crystals effloresce, or bloom, from the ground.

During the desiccation stage, efflorescent growth causes the crust's morphology to change. On the salt flats, we will cover the transition from the thin-crusted, pressure-buckled crust at the western edge of the Bonneville Salt Flats to the smooth-crusted transitional zone near the raceway and weather station (Figure 11). Finally, we will move towards the Salduro Loop, an area covered by polygonal crust. The surface expression of the crust is influenced by its thickness and history (Figures 11E, 12, and 13). For more information about the surface expression of halite crusts and other surface features in similar settings see Christiansen (1963), Lines (1979), Goodall and others (2000), Wang and others (2014), El-Maarry and others (2015), Nield and others (2015), Milewski and others (2017), Lasser and others (2020), Bernau and Bowen (2021), and Zhang and others (2021).

Buckled crust

Our first stop on the Bonneville Salt Flats' crust occurs on its western edge. Drive onto the saline pan and follow the main traffic area (salt crust is smoother) to the northeast for 4.5 miles (40.8054° N, 113.8309° W). Then turn west towards the Silver Island Mountains and continue until you see buckled crust (Figure 11A).

Note: If you approach this area in the mid-summer or early fall and there has not been a recent flooding event you will see pressure-buckled crust. You may opt to stop and walk to this area if the surface is becoming less stable and you are beginning to create tracks. ***Avoid getting stuck – turn around if the surface is unstable!***

The buckled crust is underlain by a thin layer of gypsum sand over carbonate mud. It is located near the salt-flat to mudflat transition, so wind-blown sediment may easily accumulate on these buckles. The buckled morphology forms as the crust bends to accommodate increases in crust volume. As the crust buckles it may transport sediment on its underside as well as sediments deposited by wind on its surface to-

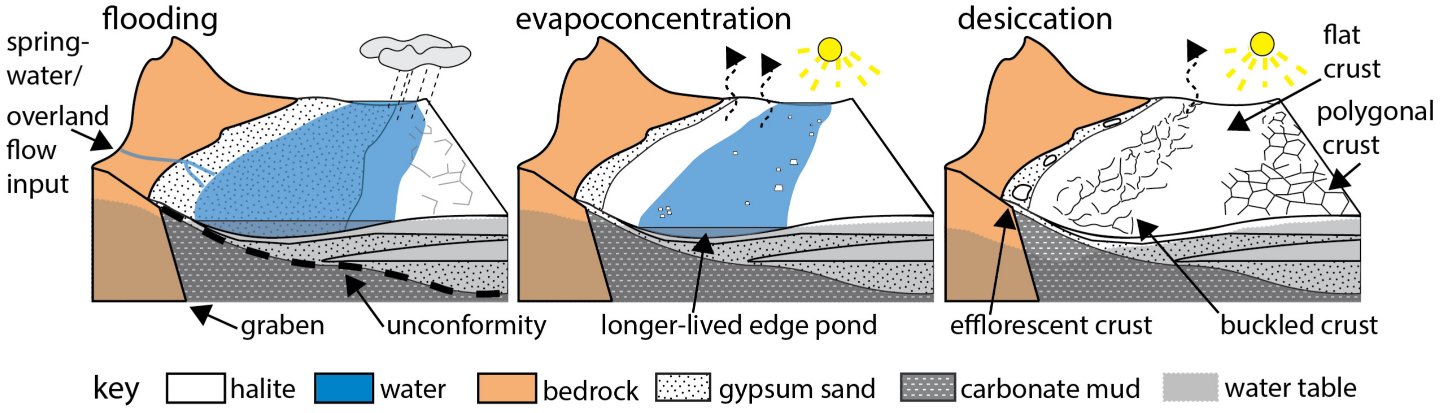


Figure 9. *Flooding, evapoconcentration, and desiccation periods at the Bonneville Salt Flats (modified from Bernau and Bowen, 2021).*

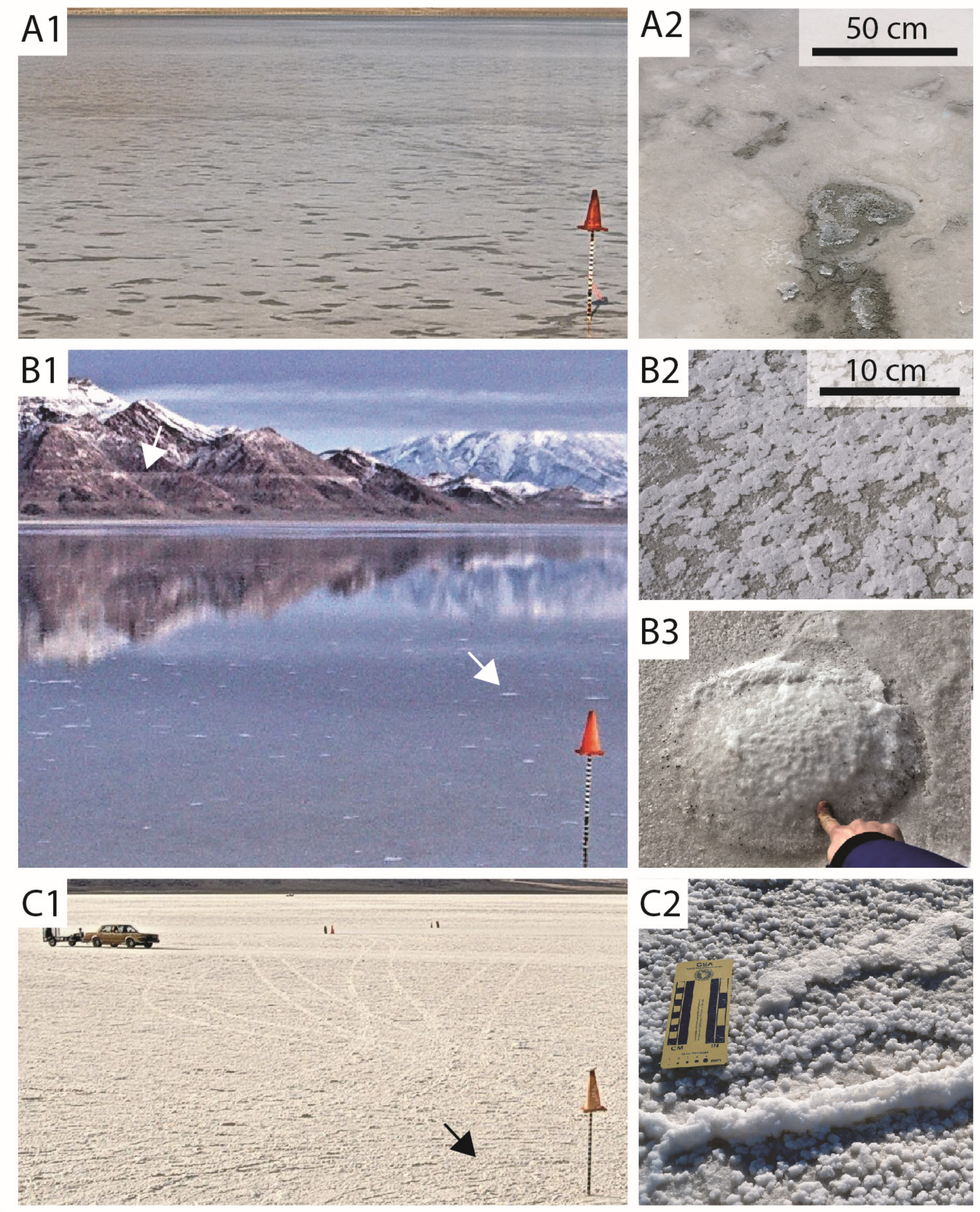


Figure 10. *Surficial expression of the Bonneville Salt Flats across flooding, evaporation, and desiccation periods (modified from Bernau and Bowen, 2021). (A) Flooding features include halite-undersaturated brine and partial (dissolution pits [A2]) to full dissolution of the surface crust. (B) Evaporation stage, where halite crystalizes on the water surface as rafts (white arrow) (B1 and B2). (B1) View to west of prominent Lake Bonneville shorelines looking west. (B3) Halite blister feature where halite has bulged up after flooding. This feature is surrounded by insects, which accumulated at the water level line and bottom-growth halite. Halite blisters often occur in the southern racetrack area in the autumn after the surface has desiccated after flooding. Blisters are shown forming in Figure 11. (C) As the surface shifts from the flooding to the desiccation period efflorescent (or popcorn) halite (black arrow) (C2) forms.*

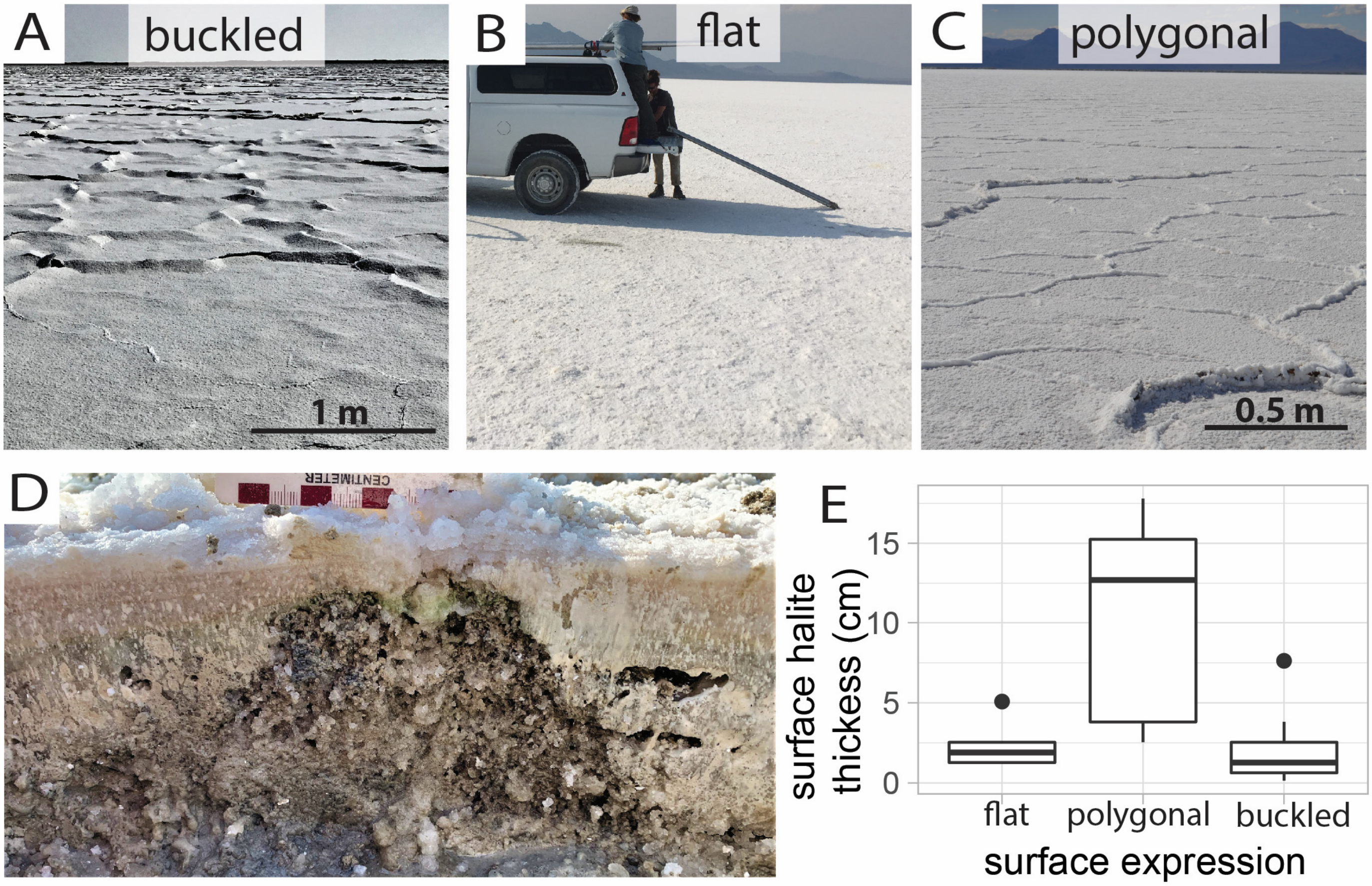


Figure 11. *Surface and subsurface expression of halite crust (modified from Bernau and Bowen, 2021). Surficial halite can vary widely, but generally is (A) buckled, (B) flat, or (C) polygonal. (D) Cross section across a polygon similar to that shown in (C). (E) Surface expression of halite crust in relation to surface halite thickness. Pressure buckles consistently occur near saline pan's edges. Flat areas coincide with southern and central racetrack areas where seasonal ponding is persistent (Bowen and others, 2017; Craft and Horel, 2019). The polygonal crust is concentrated within and to the northeast of the Salduro Loop.*

ward the area of buckling. This may lead to the formation of a small detrital sediment ridge; this ridge creates a preferred area for buckling to occur in the future because crusts deposited over the ridge will be thinner and easier to break, creating a feedback loop for buckling to regularly occur in the same area and for more sediment to accumulate at the same spot (Figure 12 left) (Lokier and Steuber, 2009; Lokier, 2012). Observations of other areas of the saline pan indicate that the surface expression of buckling can be highly variable in height, spacing, and shape (polygonal vs. orthogonal), potentially depending on the thickness of surface halite, mineralogy, and other factors (for example, buckles often form where car tracks have created a preferential break point).

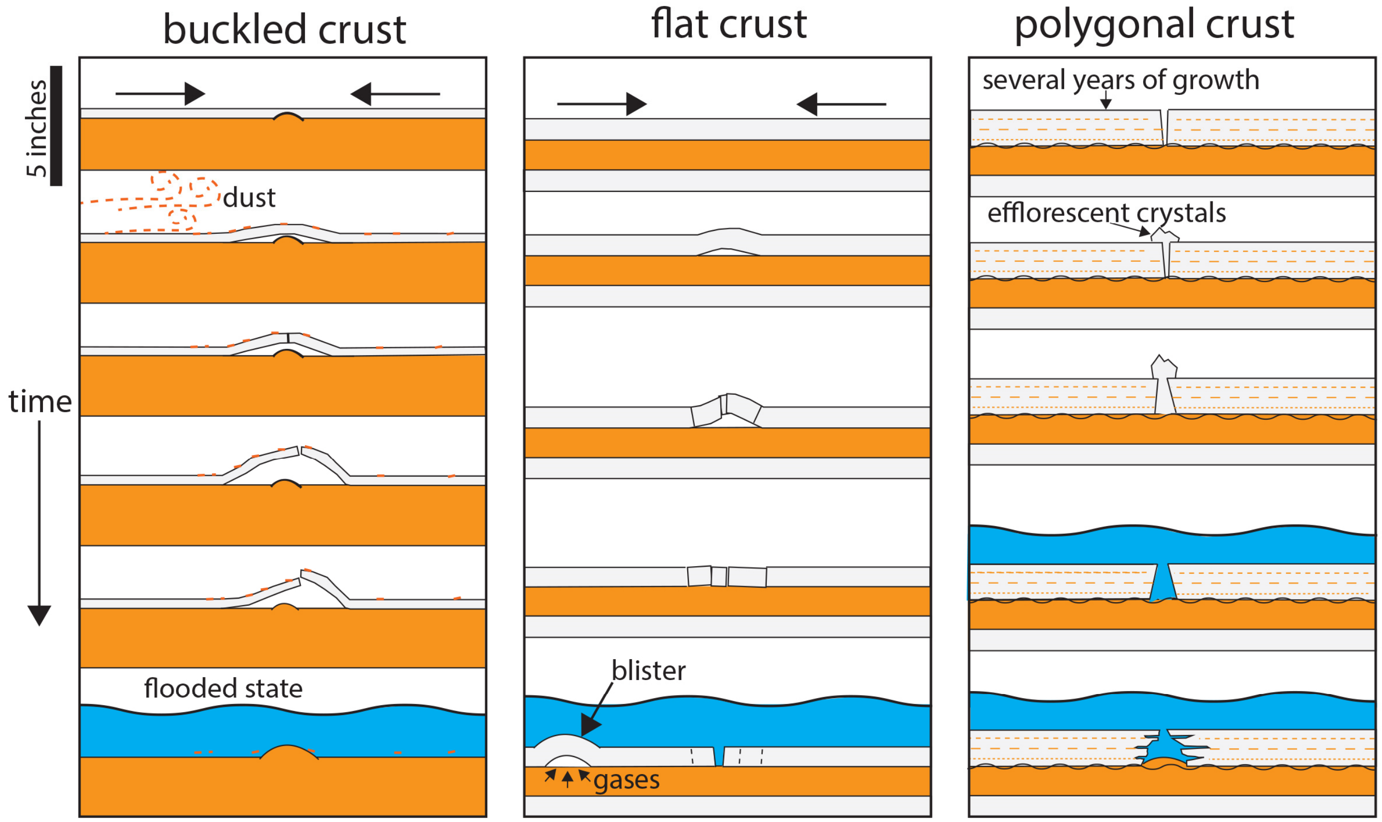
Flat crust

Our next stop is near the center of the Bonneville Salt Flats at the BFLAT weather station. Drive south for ~1.5 miles (40.7846° N, 113.8297° W). The weather station should become visible as you near it; it has a chain link fence surrounding it.

Note: Watch for cross traffic, this route cuts across several racetracks and high traffic areas.

You may notice as you travel towards the saline pan center that the crust's morphology changes and is generally flatter. In areas where the racetrack has been prepped even efflorescent crystals become subdued. The racetrack is prepared by dragging heavy steel beams behind a vehicle to crush and homogenize the crust (Morgan, 1985). If the crust is too thin or if conditions are too moist, preparing the racetrack can rip the crust, degrading its quality and limiting the ability to safely race.

In addition to racetrack preparation, regular flooding of this area (a seasonal pond is concentrated on the Bonneville Salt Flats' western edge, a topographic low point) and salt crust thickness likely contribute to its flatness. Seasonal flooding at the Bonneville Salt Flats is one of the features that makes it so ideal for land-speed racing. Flooding removes any buckles in the crust and redistributes sediment, and when the pond desiccates it leaves a new flat crust. Areas that



crust edge, thin salt, crystallized annually

between edge and center, thicker crust, possible annual dissolution

center of crust, thickest crust, partially dissolved annually, underlain by deeper halite layers

Figure 12. *Schematic of processes leading to the formation of different surface morphologies. The upper (first) section shows the surface at beginning of the desiccation stage. (Left) Formation of buckled crust, which typically occurs in thin salt at saline pan edge. Note the accumulation of sediment at the buckle location as halite crust expands with efflorescent growth (modified from Lokier, 2012; Lokier and Steuber, 2009). (Center) Formation of flat crust and blisters. The flat crust is generally thicker, limiting its ability to buckle or reach heights seen in thinner crust areas. Blisters are thought to form after flat areas flood, the lack of surface buckles and breaks in these areas limit off-gassing, enabling trapped gases to move laterally, accumulate, and bubble up in an area, deforming the crust in the process (based on the description in Bernau and Bowen [2021] and similar to microbial mat gas domes in other settings [Goodall and others, 2000; Noffke and others, 2002]). (Right) Polygonal crust development occurs in areas where halite crust is persistent across flooding events; although a contractional origin of polygons has been proposed, the features at the Bonneville Salt Flats may be explained by repeated cycles of flooding with preferred dissolution occurring along polygonal edges (either pre-existing or formed by buckling). The gaps then become preferred areas of dissolution (see Figure 11D and Bernau and Bowen [2021] for further reference). Note that under extended flooding periods, the surface halite can completely dissolve near the Bonneville Salt Flats' center; during these periods, remnant gypsum becomes rippled from wave action.*

flood less frequently, such as Death Valley and Salar de Atacama, can have rough surfaces that develop as the crust deforms during the desiccation stage (Bobst and others, 2001). The crust in this flat area is generally thicker than the buckled crust area. A thicker crust may be harder to buckle because of its mechanical properties. Similarly, the thicker crust has more pore space that efflorescent crystals could develop within, vertically distributing crystal growth and reducing lateral deformational pressures (Figures 11E and 12 center).

The site of the BFLAT weather station (operated by the Utah Geological Survey after 2021 and by the University of Utah from 2016 to 2021) highlights some of the long-term research performed on the Bonneville Salt Flats. The weather station measures precipitation and evaporation, enabling researchers to understand how water is moving in and out of the crust. It also collects time-lapse images and logs data every 5 minutes, enabling anyone to see current surface conditions on the saline pan (https://meso1.chpc.utah.edu/station_cameras/bflat_cam/bflat_cam_current.jpg). Similarly, several groundwater monitoring wells with multiple depths are present here. These wells are used to understand how groundwater levels change in response to climate and human actions. They also enable researchers to determine if shallow groundwater at the saline pan is moving up to moving up to feed the crust or if it is moving down and removing salts from the saline pan.

Polygonal crust

Our final stop on the Bonneville Salt Flats' crust visits the polygonal crust. Head 1 mile south from BFLAT towards the berm of the Salduro Loop (40.7700° N, 113.8283° W). The Salduro Loop was a brine collection ditch. The crust next to it can be soft, in some areas inside the loop you can see where the ditch filled in with halite by identifying deep brine-filled holes in the salt. *To minimize the chances of getting stuck, do not drive within 100 ft of the loop. Furthermore, the salt where the ditch has filled in with halite may be fragile and could collapse beneath you, step with care*!

This site has some of the thickest surface crust at the Bonneville Salt Flats. It also has a distinctive polygonal fracture system. The polygons are highlighted by vertical ridges of efflorescent halite. The efflorescent halite is very porous and dissolves during flooding, inverting the local topography (leaving a crack where a ridge once was). This crust is persistent across multiple flooding events. Under extended flooding periods, the surface halite can completely dissolve near the saline pan's center and remnant gypsum becomes rippled. Although a contractional origin of salt polygons has been proposed (Tucker, 1981), the features at the Bonneville Salt Flats can be explained by repeated cycles of flooding with preferred dissolution occurring along polygonal edges (either pre-existing or formed by buckling) and the growth of efflorescent salt at the surface (Bernau and Bowen, 2021) (Figures 11D and 12 right).

The polygonal geometries at the Bonneville Salt Flats occur at multiple scales, ranging from less than a meter to over 300 meters across. The multiple scales of polygons can be seen in person, in aerial imagery (Figure 13), and, at the largest scale, in multispectral satellite (resolution up to ~100 ft/pixel) spectral index images. Using different methods and examining polygons at a much smaller scale, Lasser and others (2020) present evidence for convection occurring beneath polygonal crusts, indicating a strong relationship between the surface expression of saline pans and groundwater movement beneath them.

You may now enjoy exploring the rest of the Bonneville Salt Flats' crust or return to Salt Lake City. To return to the access road head west and follow the Salduro Loop berm (~4 miles), then return west towards the access road which will become be visible (40.7625° N, 113.8958° W).

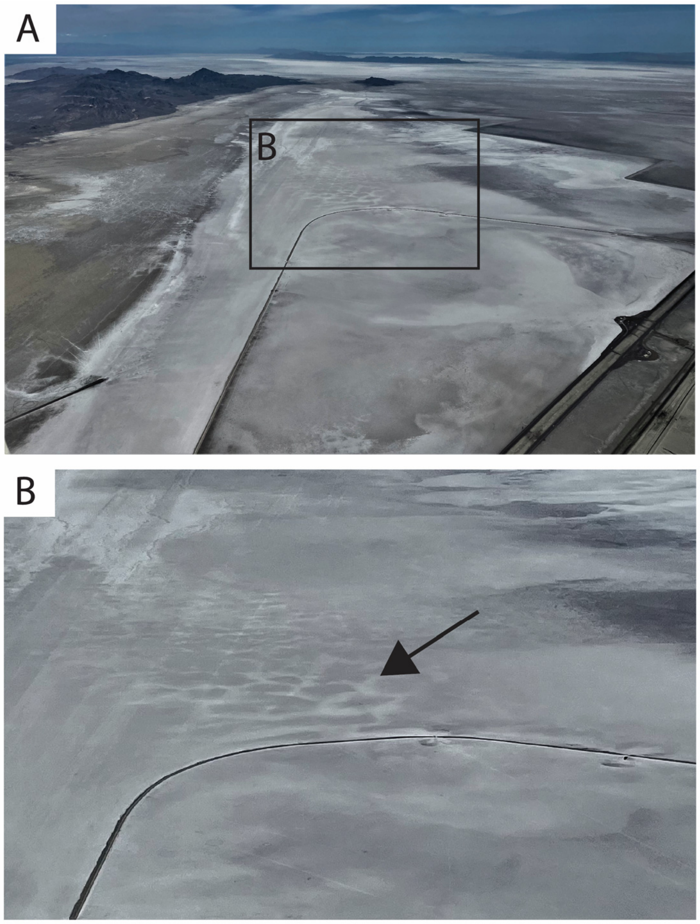


Figure 13. *Aerial imagery of the Bonneville Salt Flats on June 9, 2022. (A) View looking north. (B) Large polygonal features (black arrow). Images taken with pilot Dr. Gabe Bowen.*

Silver Island Mountains Access Road (Optional Extension)

The Silver Island Mountains access road provides another great perspective on this area, specifically on the contact between deflated and non-deflated surfaces. To access it, go west from the end of the access road for 3.8 miles. At the T in the road, go right. Continue for 0.8 miles and take a slight right onto Silver Island Road (unmarked) and continue north for ~14.5 miles (40.8926° N, 113.7978° W). *Note: This road is periodically maintained and may have heavily rutted or muddy areas that require a high clearance vehicle.*

The exposed gravel bar here is enhanced by erosion; it is known as the lozenge section and highlights the sharp contact between preserved and deflated areas. The lozenge section is capped by Lake Bonneville's late-regressive-phase well-rounded gravels. Lake Bonneville sediments are likely preserved here because the gravels limited deflation (Figure 14A). Below the gravels are reddish, silty, sandy beds that

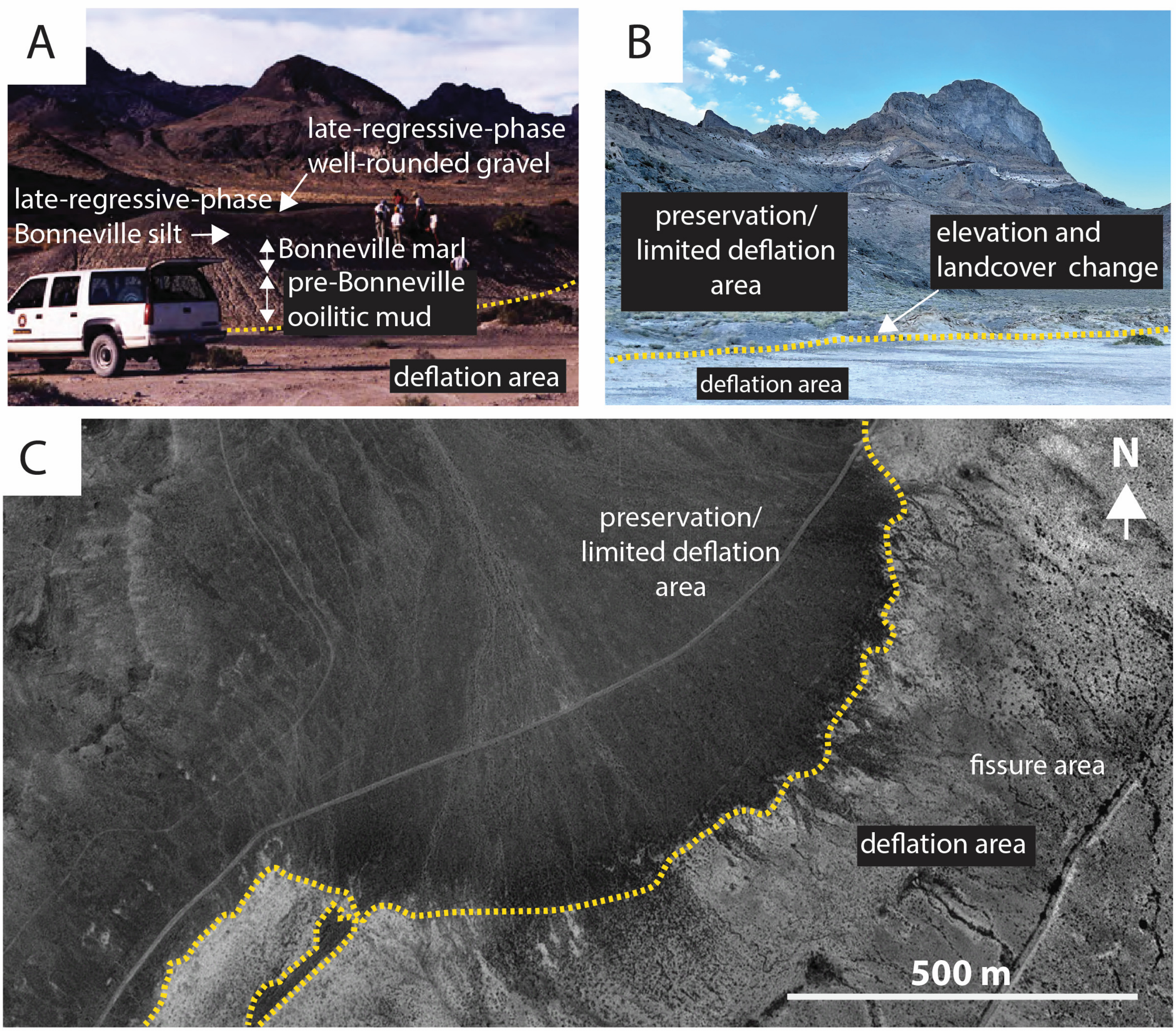


Figure 14. *Edge of deflation along the Silver Island Mountains' alluvial-fan edge. (A) The lozenge section (image modified from Munroe and others [2015] and site further described in Oviatt and others [2020]). (B and C) Preservation and deflation areas are delineated by changes in elevation and land cover. Note that the preservation of Lake Bonneville sediments delineated by surface cover is also evident at Juke Box trench (Figure 6). (C) is a USGS National Aerial Photography Program (NAPP) photo from July 1997. Dashed yellow line delineates between the areas of preservation (alluvium and gravel bars) and deflation.*

overlie Lake Bonneville and underlying pre-Lake Bonneville sediments. The eroded mudflat is to the east and the alluvial-fan deposits, which have limited erosion, are to the west (Figure 14B).

If you continue northeast on this road, you will see similar erosional features and will reach a road that connects with Floating Island (40.9295° N, 113.7189° W). Turn around and retrace your route. The final stop is an alluvial fan that demonstrates the erosional contact between deflated and preserved Lake Bonneville sediments. This stop coincides with the furthest northern extent of groundwater extraction, a now-dormant spring, and desiccation fissures. Return south along Silver Island Road for 11 miles. Stop just after the promontory (40.7960° N, 113.9395° W).

To the east of this area is a former spring (40.7947° N, 113.9325° W). The eastern linear feature is a now inactive freshwater collection ditch for the northernmost extent of now inactive brackish water production wells (Figure 12C). The mudflat area between the former collection ditch and the alluvial fan has many large, deep (several feet) desiccation fissures (Mason and Kipp, 1998). *There are no trails here so choose your steps carefully.*

Directions Back To Salt Lake City

Return to I-80 and head east (~120 miles). If you drove on the salt flats you may wish to wash your vehicle in Wendover or back in Salt Lake City. Salt accumulation depends on surface conditions; for example, salt may more easily accumulate on your vehicle if the Bonneville Salt Flats has flooded recently or if groundwater levels are near the surface, as they are in the mid-summer (Bernau, 2022). The crust is driest in the fall to winter, when groundwater levels decline if there has been no precipitation (salt accumulation on your vehicle will be lower under these conditions). Salt will cake onto the surface and get onto ledges and crannies beneath a vehicle. We recommend using a self-service carwash (with hot water if possible) to ensure salt has been removed and to limit potential corrosion.

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