The Making of a Perfect Racetrack at the Bonneville Salt Flats

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THE STORY OF THE SALT

It is a unique experience being out on the salt at the Bonneville Salt Flats. The sun seems a bit too bright as light reflects off the cubic halite crystals that cover the stark saline ground (Figure 1). There is a sense of isolation and vastness with the curvature of the earth visible on the horizon. There is a profound silence. The only sound on some hot, dry days is the crackling of halite crystals as they precipitate from shallow brines. Void of any macro flora or fauna, the salt flat ecosystem is only apparent in thin layers of bright green or pink halite below the surface, or the insects that are trapped in the growing salt. Wagon tracks left when the ill-fated Donner Party became bogged in the sediment in 1846 reportedly remained visible in the salt for over 90 years; a vivid reminder of the dangers of this harsh landscape. Car tire tracks have long since replaced wagon tracks. Each year in the late summer, when the salt crust permits, the silence of the salt explodes with the roars of racing motors. Land speed records were set on the Bonneville Salt Flats through the 20th century; it is a landscape intricately linked with U.S. car culture. The final season of Mad Men shows the protagonist, Don Draper, speeding recklessly through the night across the salt flats: a symbol of his fragile freedom and the endless possibility of the West. The landscape has called dreamers and innovators, daring them to push the limits of human speed.

The geology of the Bonneville Salt Flats tells a story of landscape change on a range of temporal scales—from tectonic processes over millennia to seasonal fluctuations to even shorter timescale events that change the surface with a single storm event or week of sunshine. Humans have come to value this relict landscape, but the Bonneville Salt Flats is an active and dynamic system, changing continuously in response to rain, wind, evaporation, and groundwater flux. These are all factors over which humans have little direct control. The impacts of long term, natural, geological processes morph together with landscape responses to human presence— a century of racing, mining, and recreation; and now, additionally, mitigation and adaptation of diverse stakeholder communities reacting to the ever-changing conditions.

The Bonneville Salt Flats (BSF) is a perennial salt pan that spans over ~75 km^2 adjacent to the Utah–Nevada border (Figure 2). The extension of the Basin and Range lays the tectonic framework for the development of interbasinal playas, like the Bonneville Salt Flats, where groundwater flowpaths focus discharge and concentrate solutes in springs rimming playa boundaries (Gardner and Heilweil, 2014). On glacial-interglacial time scales, the impact of Pleistocene Lake Bonneville and a cold and wet climate regime are evidenced by a series of tufa-traced shorelines stepping down the southeast face of the Silver Island Mountains, bounding the salt flats to the northwest, and by the vast lacustrine playa surface that blankets the Great Salt Lake Desert. The Great Salt Lake and BSF are both remnants of Pleistocene Lake Bonneville which drained at the end of the last glacial maximum and desiccated over the last ~13,000 years (Oviatt, 2015). As regional climate warmed and dried through the Holocene, the pluvial lakes of the Pleistocene glaciations disappeared, leaving both a sedimentary and hydrological footprint, as much of the groundwater in the Basin and Range is dated to ~20 ka— Bonneville water (Gardner and Heilweil, 2014). Isostatic rebound of the Bonneville lake basin (Crittenden, 1963; Oviatt, 2015) and hypothesized neotectonic faulting along the northwestern edge of the salt flats moved the West Desert's low point from further east to the western edge of the basin at the modern BSF, where a wedge of salts concentrated and precipitated over thousands of years. On human time scales, cycles of flooding, drying, and automobile racing punctuate the seasonal transitions in the landscape. This combination of geologic and hydrologic circumstances led to a thin (<2 m) accumulation of saline chemical sediments in the westernmost surface of the Great

Figure 1: The halite surface of the Bonneville Salt Flats in August of 2013 (photo credit: B.B. Bowen).

Salt Lake Desert— the Bonneville Salt Flats— the "fastest place on Earth."

Just north of Interstate-80 (I-80), BSF is the home of the Bonneville Speedway, a landmark on the U.S. National Register of Historic Places and an Area of Critical Environmental Concern, where ground speed records have been set for over 100 years. The salt-paved landscape of BSF provides a rare resource for the state of Utah and the international motorsports community— an iconic frontier destination for land speed racing. Top ground speeds at BSF steadily increased through the 20th century, topping 600 miles per hour and establishing a multi-generational racing community that is passionate about the salt and reliant upon a stable surface halite (NaCl) crust that must be several centimeters thick for their sport (Figure 3). During most late summers, the hard, seasonally repaved halite surface, level ground, consistent texture, moisture content, and extensive area of BSF provide an ideal playground for speed enthusiasts, bringing many different types and classes of vehicles to test their speed at Bonneville (Noeth, 2002). The high albedo and shallow water table provide a moist surface that keeps tires cool. Through the mid-century, BSF had the long, straight, and uninterrupted distance racers need for both the "go" (acceleration) and the "woah" (slowing down). However, geology does not mandate that there always be a hard, stable halite surface that covers the >13 miles needed for high speed racing, and the racers have struggled in recent years to find stable salt over the continuous distances needed for setting high speed records. In 2014 and 2015 the international "Speed Week" and "World of Speed" events, historic and cultural landmarks for Bonneville racing, were cancelled due to unsuitable and unsafe racing conditions. In 2014 water covered the surface year-round. The following year, the uppermost halite crust was thin and exposed the underlying clay-rich gypsum beds. It was slick as snot and unsuitable for racing. But in 2016 and 2017, the halite crust was strong and racing enthusiasts brought record numbers of speedsters to the West Desert. In the summer of 2017, the Bureau of Land Management reported over 30,000 visitors to the salt. The "bad years" of 2014 and 2015 were not the first time the racing has been cancelled. Racing cancellations during the El Nino of 1982-1983 and again in 1993-1994 due to flooding suggest

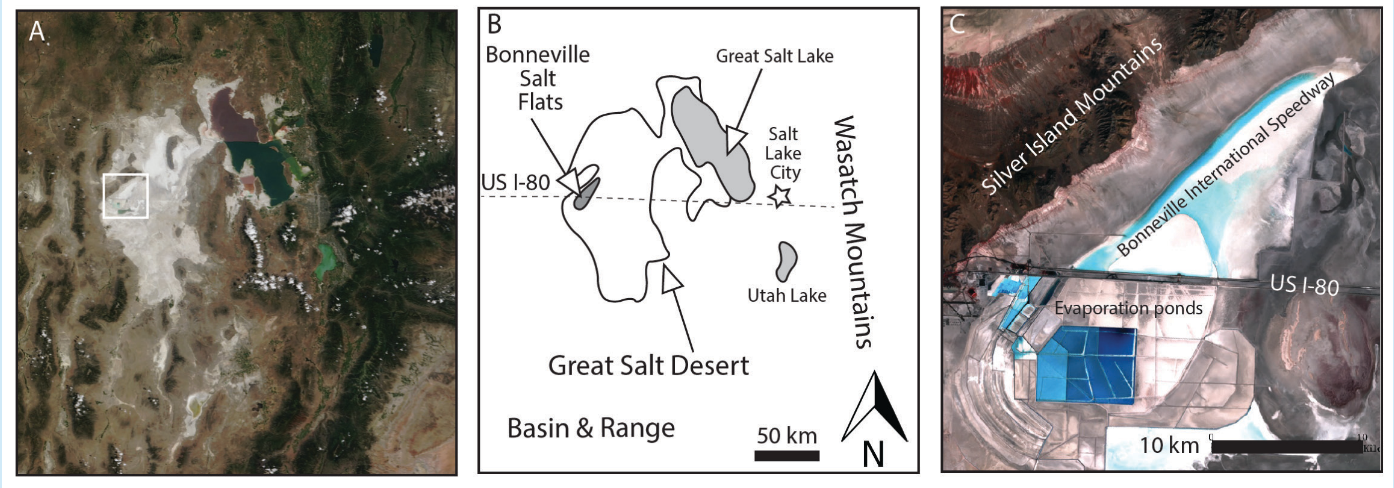

Figure 2: A) MODIS satellite image (July 25, 2011) of the Bonneville basin and the West Desert of Utah with location of C shown by box; B) schematic map of area shown in A highlighting key features; C) False color (infrared to highlight water on surface in blue) Landsat satellite image from June 22, 2015 of the BSF playa located at 40°47’00” North, 113°50’00” West. Surface water commonly accumulates along a regional low bounding the northwest edge of the salt flat, adjacent to the Bonneville International Speedway.

Figure 3: Historic photos of BSF: waterlogged in 1937 (left) and starting lineup in 1966 (right) (photos provided by Louise Noeth).

that quasi-decadal cycles of seasonal precipitation may lead to poor salt crust conditions and cancellations. Perceptions of a diminishing salt crust have resulted in long term efforts within the racing community to "Save the Salt" with discussions about increased infrastructure and implementation of experimental solute transfers in an attempt to grow the surface salt crust.

South of I-80, the salt flats morph into organized patterns of solar evaporation ponds (Figure 4). Groundwater brines from below BSF have provided a rich source of potash (KCl) and saline resources have been harvested from this system for more than 100 years (Nolan, 1928). The potash is sold as a nutrient additive for fertilizers that have played a major role in allowing the agricultural industry to double global food production over the last fifty years (Johnston, 2002). More than 100 miles of collection ditches that re-route groundwater to the evaporation ponds outline the perimeter of the salt crust system. It is difficult to track the total amount of salt that has been extracted from BSF due to the changing of operators over the century. Current operators report that between 1998 and 2015, approximately 6 million tons of NaCl and 137,000 tons of KCl were harvested from the northern leases, which include BSF and the surrounding areas north of I-80. Over that same period, approximately 11 million tons of NaCl and 128,000 tons of KCl have been *returned* to the surface of BSF as brine through the Salt Laydown Project in an effort to slow or perhaps reverse depletion of the salt crust (White, 2004). Although more solutes have been laid down than extracted through mine-related processes over the last 20 years, the mitigation efforts have not yielded the intended results of growing the surface salt crust. It is possible that the addition of saline brine to the northern region has helped to maintain saturation levels in the shallow brine aquifer. Ongoing research seeks to test the specific impacts of both the extraction and mitigation efforts on the saline strata.

Data-driven management of this valued landscape requires an understanding of the sedimentary history of BSF and active sedimentological processes impacting

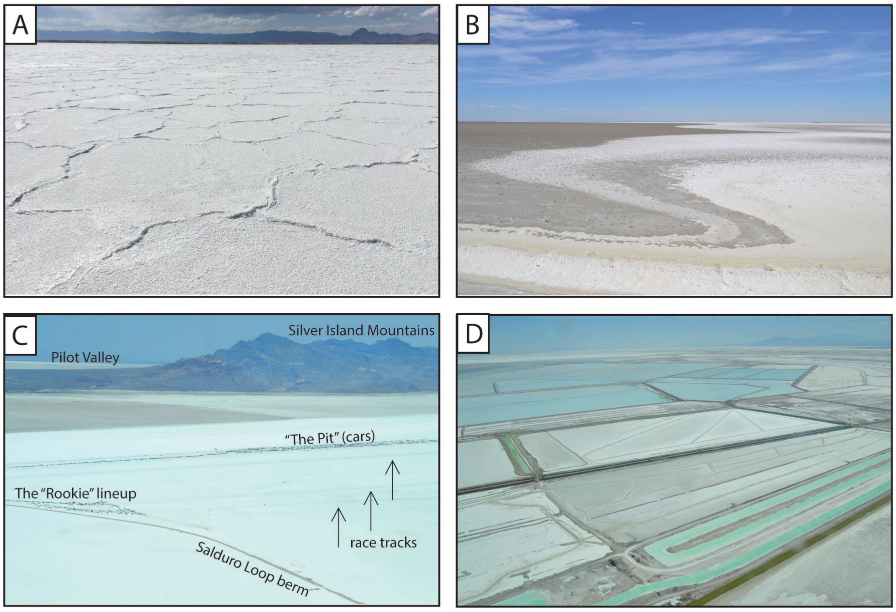

Figure 4: Photos of BSF. A) Desiccated halite surface with polygonal pressure ridges, Bonneville Salt Flats, September 2016; B) the edge of the salt on the northwestern boundary showing a thin veneer of surface halite and an uneven boundary of the salt crust surface, September 2016; C) aerial view of BSF looking NW during Speed Week in 2017 showing extent of activities along the salt crust during racing events; the edge of the salt crust, Silver Island Mountains with Pilot Valley in the distance (note berm of Salduro Loop, cars at rookie track near the berm, and lineup of the "pit" along the international speedway track); D) aerial view of mining evaporation ponds looking south of I-80 and BSF.

the salt crust. How thick and stable are the surface halite beds that make the Bonneville Salt Flats ideal for a race track? What kinds of landscape changes and processes will impact the potential to use BSF as a racetrack, and what is the legacy on the landscape of this unique history of land use?

THE SEDIMENTS OF THE BONNEVILLE SALT FLATS

Ongoing interdisciplinary research on the dynamics of BSF allows for new insights into the sedimentary architecture of this landscape and allows for evaluation specifically of the thickness, continuity, and vulnerability of the halite surface crust that makes up the race track of the BSF "International Speedway". In the Fall of 2016, sixty-nine shallow (up to ~2m deep) sediment cores were collected as a part of the BLM-required "Salt Crust Thickness Study" (US BLM, 2012; Bowen et al., in press) (Figure 5). These windows into the subsurface provide new detailed insights into the composition and the spatial heterogeneity of the saline evaporite strata that cap the larger regional Bonneville basin lacustrine deposits. These new subsurface data allow for comparisons with historic measurements of the BSF strata that have been made on decadal time scales since 1960 (White and Terrazas, 2006; Bowen et al., in press; Kipnis and Bowen, in press). Evaluation of changes in sedimentary architecture through time helps to constrain the processes that are impacting the landscape. Assuming that methods through time are comparable, these data show that the total volume of salt is not currently changing significantly, but may have experienced nearly 30% loss of volume through the 2nd half of the 20th century. The spatial patterns of both halite loss and gypsum accumulation are not consistent through time. Salt loss in the 1960s and 1970s was focused on the central thickest part of the salt crust, while more recent decreases are greatest along the northwest margin, where land speed racing and seasonal ponding are most concentrated (Kipnis and Bowen, in press).

The sediments at BSF consist of a variety of saline facies including the uppermost bedded halite (the racing surface), subsurface coarse porous halite, and a range of interbedded gypsum sand units that generally fine upward (Figure 6). The subsurface saline sediments are

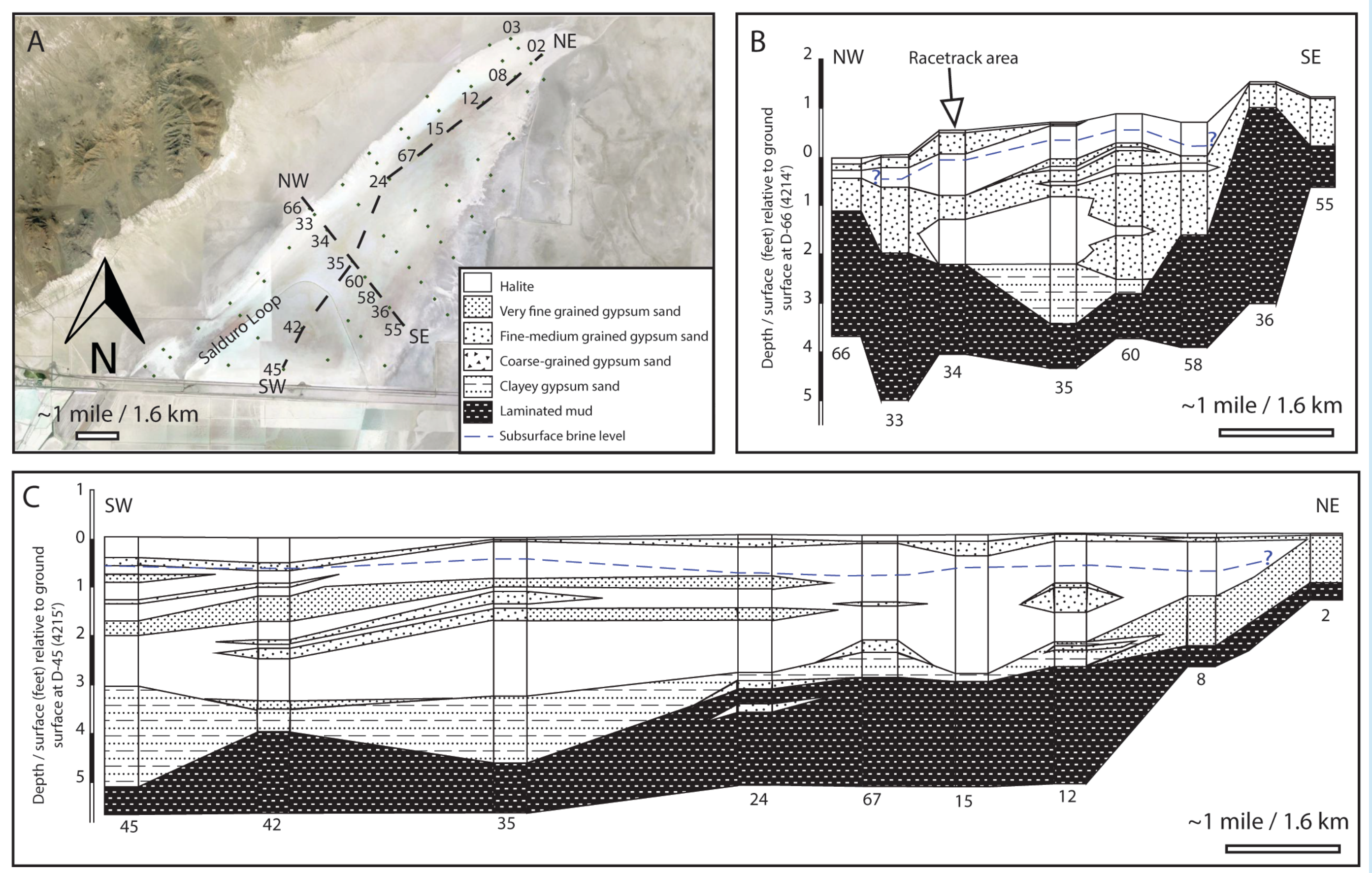

Figure 5: Interpretation of sedimentary architecture of Bonneville Salt Flats surface saline sediments from cores collected in September 2016. A) Aerial photo (NAIP) of BSF with location of Salt Crust Thickness Study core sites and location of cross sections from the NW to SE (B) and from the SW to NE (C). Numbers indicate core names (also shown at base of stratigraphic columns in B and C). B) Schematic illustration of sedimentary facies in cores and interpretation of stratigraphy across the salt crust, general location of racetrack ("Bonneville International Speedway") indicated. C) Schematic illustration of sedimentary facies in cores and interpretation of stratigraphy along the length of the salt crust from I-80 to the northeastern boundary of the salt crust. Depth of shallow brine aquifer surface at the time of coring (September 2016) indicated with blue dashed line.

impacted by diagenetic processes including displacive halite growth, halite dissolution, and the formation of biofilms. The uppermost halite crust, composed of massive crystals, ranging in size from 10s of microns to ~2 cm, expands as the halite desiccates, creating pressure ridges at the boundaries of the polygonal desiccation fractures that may produce pathways for additional evaporation. The footprint of the total halite surface area at BSF ranges from <80 km^2 to over 160 km^2, can change on short (weekly, monthly, annual) time scales. While there is considerable seasonal and annual variability, the areal extent has generally decreased over the last three decades (Bowen et al., 2017). Underlying the surface halite crust are alternating discontinuous layers of laminated gypsiferous sand, aragonitic carbonate, and halite with diverse textures (e.g., bedded, porous, blocky) (Turk et al., 1973; Lines, 1979). The base of the salt crust is defined as the abrupt transition from saline sediments to dark, laminated, clay-rich deposits interpreted as regionally continuous sediments associated with Lake Bonneville (Oviatt, 2015). The specific time-constrained depositional history recorded by these laminated sediments is a topic of ongoing research. The sediment succession is present in the modern surface environment around BSF; clay rich gypsum sands and carbonate pelloid muds surround the central zone where the halite crust occurs. In many areas, the halite crust consists of only a surface veneer.

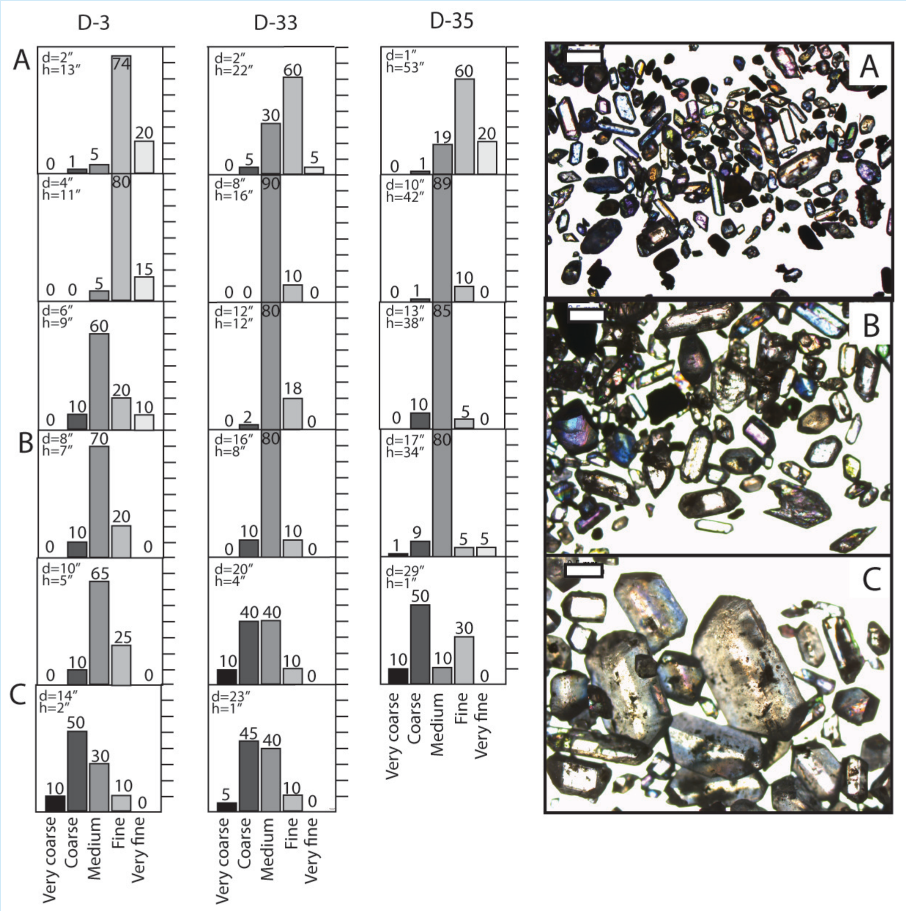

Figure 6: Stratigraphic patterns in grain sizes of gypsum from three BSF cores. Drill site locations shown in Fig. 5A. Drill site 33 stratigraphic data shown in Fig. 5B, and drill site 35 stratigraphic data shown in Fig. 5B and 5C). d=depth from surface and h=height from contact with laminated mud. In general, areas with abundant interbedded gypsum strata show a fining-upward trend with larger euhedral crystals in the lower gypsum units and smaller grain sizes in the uppermost beds. Micrographs A-C show examples from site D-3 with specific stratigraphic location noted on left. All scale bars in upper left corner of micrographs are 0.5 mm in length.

The details of the specific environmental history represented by the evaporite sediments at BSF are not entirely clear, but basic observations about the character and distribution of the saline sediments and active surface processes give some important clues. The shallow brine aquifer at BSF is a Na-Cl dominated system that is not currently saturated with respect to Ca and SO$_4$, but the presence of abundant gypsum within the sediments shows that, at times in the past, a gypsum-precipitating system existed. Interestingly, the relative concentration of sulfur and level of gypsum saturation is one of the primary differences between the chemistry of the current Great Salt Lake system and BSF with greater sulfate amounts in the Great Salt Lake system suggesting differential brine evolutionary paths once the two bodies were separated (Kohler and White, 2004). The euhedral grains of gypsum suggest displacive growth either at the sediment-water interface or within saturated pore space of unconsolidated sediment. The fining upward sequence suggests that the primary growth phase occurred during the initiation of BSF evaporite deposition, and that grains have been reworked through geologic time making smaller and more rounded sand grains. Some of the smaller grains are quite angular, suggesting that these may also include diagenetic gypsum crystals that have not been transported very far. Alternatively, a decrease in gypsum saturation may be responsible for a change in crystal size through time.

One interpretation is that spring deposits focused gypsum-saturated brines, causing localized interbedded gypsum units seen within bedded halite deposits at BSF (Figure 5C). Springs are dispersed along the perimeter of the Bonneville basin today, and Holocene spring deposits have been described on the western edge of the BSF playa at the base of the Silver Island Mountains in Jukebox trench (Oviatt et al., in press). Gypsum sand is ubiquitous across the West Desert (Eardley, 1962).

Figure 7: Photos from the time-lapse camera on the BSF BFLAT Mesowest weather station on September 18, 2017 (left) and four days later on September 22, 2017 (right) showing the rapid transition from desiccation to flooding (http://mesowest.utah.edu/cgi-bin/droman/meso_base_dyn.cgi?stn=BFLAT).

Semi-lithified gypsum dunes ramp up against Paleozoic carbonate horsts, and active gypsum and carbonate pelloid dunes accumulate along the vegetated edges of the salt flats and the speedway access road. These dunes are evidence of active and relict eolian processes. Simple dust traps installed in 2016 have confirmed active eolian deposition on this surface, with rates ranging from 0.01 – 9.06 mg/day (Stinson et al., 2016).

A new, state-of-the-art weather station was installed in September 2016 to investigate how the salt crust environment changes through time. The surface processes that impact BSF are closely tied to the hydrology and water budget, and understanding of those fluxes requires measurements of the energy budget, quantified now by the weather station. The weather station includes a fixed camera that takes a photo every five minutes, allowing for new observations of how the landscape changes on human time scales (Figure 7). These data are facilitating quantification of the energy and water budget on the salt flats, variations over daily, seasonal, and annual time scales, and the dynamics of roving hypersaline lakes (or seiches) that move across the salt crust surface in response to precipitation events, wind, and changes in atmospheric pressure. They show the timescales of crust surface change and the footprint of the racetrack in the distance. Longer term observations from this site will advance research on the environmental parameters and processes that influence salt growth, dissolution, eolian processes, and groundwater hydrology and geochemistry.

GEO-MICRO-BIO-HYDRO-ANTHROPOLOGICAL SYSTEMS

BSF system is generally void of macroscopic life or ecological processes, with the most obvious life form being the recreating humans. The boundary of the salt flats is dominated by salt-tolerant shrubs and insects that occasionally swarm onto the flats and become trapped in the growing salt. However, as has been seen in essentially all water-bearing environments on Earth, even the most extreme chemistries host microbial life (Harrison et al., 2013; Cowen et al., 2015) and BSF is no exception. Bright-field microscopy of salt samples from BSF revealed rods, cocci, and pleomorphic cell shapes, some of which appear to be motile. DNA sequences from a subset of isolates indicate that at least four genera of halophiles inhabit BSF (*Haloarcula, Halorubrum, Alkalibacillus,* and *Halobacillus*), consistent with genera that inhabit other hypersaline environments. Microbial communities present in any environment contribute to the ecology of the entire system in critical ways by cycling elements, providing a biological foundation upon which other organisms can establish themselves, and altering the chemistry of the fluid-sediment system on both a micro and macro scale. In environments considered "extreme" by human standards such as BSF, microbes are commonly the only life forms that can survive. Many extremophilic organisms have evolved unique attributes, strategies, and biochemistries that enable them to eke out a living where most other organisms cannot. Such is the case for extreme hypersaline ecosystems that select for organisms not only capable of tolerating high salt concentrations, but those that actually require high salt for growth (Litchfield and Gillevet, 2002). Little is known about the microbial link to hypersaline geochemical systems, how microbes survive in the relatively nutrient poor ecosystems within the salt and sediments, and how they vary through evaporite stratigraphic architecture (e.g., Lowenstein, 2012; Ferris et al., 1991).

Recent results from genome and isolate studies and from saline soils surrounding BSF indicate the importance of microbe-related biogeochemical processes in this environment. Isolates show an unexpected potential to oxidize atmospheric and sub-atmospheric carbon monoxide (CO) and CO oxidation coupled to nitrate reduction (King, 2015). Other electron acceptors may also support CO oxidation. These results indicate that at least some extremely halophilic euryarchaeotes participate in the biogeochemical cycling of CO and use it for energy metabolism to support their populations in situ, just as their salt-sensitive counterparts in non-saline soils do. Ongoing research at BSF will further constrain the ecological diversity, spatial context, and biogeochemical implications of the microorganisms in this environment. The role of microbial communities in mediating biogeochemical cycling has important implications for the processes that impact BSF, and is also significant for advancing understanding of astrobiological potential in extraterrestrial extreme environments on other salty planets and moons.

In addition to evaluating the sedimentary record, hydrological processes, and geobiology at BSF, research includes analysis of the role of life on this landscape– from geomicrobiological processes to evaluation of the human social systems impacting BSF. There are numerous stakeholders with vested interest in the state of BSF. There is active engagement from the mining industry, the racing community, scientists/researchers, government agencies, nearby residents, the global public, and users such as rocket clubs, artists, photographers, the film industry, and general recreationists. These many and diverse stakeholder groups have unique histories, perspectives, interests, and perceptions that shape their beliefs about what processes are driving changes in the BSF environment and what should be done to address those changes. Yet, little is known about how their uses impact this unique ecosystem.

HUMANS AS AGENTS OF SEDIMENTARY PROCESSES

The Bonneville Salt Flats is a landscape where the long and short-range timescales of geologic and human processes collide. The slow geologic dynamics that shape the changing sedimentary system overlap with human interests in use of the salty surface for a speedway. A major transcontinental highway dissects the playa system, and mine pumping, extraction, and recycling of brine impacts both water and solutes from near-surface and regional groundwater. (Mason and Kipp, 1998; White, 2004). The timing, volume, and concentrations of brine flow, either by human use or natural and human-engineered processes, needs further exploration in understanding observed changes to the salt crust sediments. While geologic processes dominated this depositional system in the past (Lines, 1979), current human-related uses impact fluxes in solutes and water as well as surface texture and morphology (Jewell et al., 2016). They play a significant role in how the landscape now changes. Ongoing research will help to quantify the relative roles of human-dominated compared with geologic processes in shaping the salt flats and determining its future as a racer's paradise.

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