The Holocene Great Salt Lake and Pleistocene Lake Bonneville System: Conserving our Geoheritage for Future Generations

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ABSTRACT

The modern (Holocene-age) Great Salt Lake (GSL) and Pleistocene Lake Bonneville of the Bonneville Basin (BB) together make a geosite (GSL-BB system) of exceptional scientific, cultural, aesthetic, and societal value. GSL is the largest saline lake in the Western Hemisphere and a sensitive recorder of climate. For millennia, this distinctive salty water body has been a dynamic and complex natural ecosystem, including an important waterway for birds and other wildlife and an archive of environmental change and history. Lake Bonneville is a seminal part of the history of science in the United States through the work of G.K. Gilbert, who in the 1870s and 1880s developed both critical scientific concepts (e.g., isostasy) and methods (e.g., multiple working hypotheses), which are still employed today. GSL is a major tourist attraction, an economic driver, and a place of scientific exploration. Yet today, the GSL is in grave danger of near total desiccation due to a combination of factors: human removal of waters that would normally replenish the lake, climate change, and other environmental pressures. Over the past few decades there has been a growing international movement to recognize and respect our geoheritage, by raising visibility and protection of high-priority geosites. The GSL-BB system is a geoheritage site that urgently needs our protection.

GEOHERITAGE CONCEPT

An International Movement

Over several decades, a growing international geoconservation movement recognizes that exceptional geological sites need to be protected and managed as part of our geoheritage. The Geological Society of America Position Statement (Geological Society of America, 2022) defines geoheritage sites as areas with geologic features of significant scientific, educational, cultural, and/or aesthetic value. These sites are key to advancing knowledge and support the broad understanding of the environment, its geodiversity and biodiversity, and the factors that influence climate change (see America's Geoheritage II workshop proceedings, 2021 https://nap.edu/26316). Although biodiversity is notably visible to the public, the geologic setting – its geodiversity and the convergence of geographic to environmental conditions – commonly form the underpinnings and context for biodiversity. The extensive and rapidly expanding body of literature on geoheritage is too extensive to detail here (e.g., see summaries of Brilha, 2015, 2018; Reynard and Brilha, 2018; Brilha and others, 2018).

The United States is endowed with many sites that embody a rich geoheritage. The U.S. and State Park systems have had an important impact on the conservation movement, but there has been growing recognition for more coordinated global recognition of natural sites. Thus, geoheritage calls for global communication and cooperation, and provides the context that covers much of the science and education related to important geosites, while also embracing ethics, outreach, inclusivity, protection, and management. Geoheritage also relies on modern technology to understand and model how natural systems are impacted. As Earth scientists, we understand Earth systems, with their change and interrelationships, and feedbacks in time and space. We must be caretakers and advocates for GSL, as we have both the knowledge and responsibility to help balance nature and societal needs.

Geosite Locality

In the Basin and Range province, ancient Lake Bonneville (Figure 1A) covered much of western Utah during the last glacial maximum. The modern GSL (Figs. 1B, C) is the recent version of the closed-basin GSL-BB system, which, during the past few million years, has been dominated by various saline to hypersaline lakes similar to Holocene GSL. Between 30,000 and 13,000 yr BP the lake system was deeper and more extensive (Lake Bonneville) and was dominated by freshwater (Figure 1D, Currey and others, 1984). There is much interest in the GSL as shown by the considerable literature covering more than a century, including this volume (also see Gilbert, 1886, 1890; Oviatt and Shroder, 2016a). The significant runoff that resulted from the wet winter of 2022-2023, does not significantly ameliorate the long -term decline in water level of the GSL.

For centuries, GSL has been the largest saline lake in the Western Hemisphere, recording a history of change (Madsen, B.D., 1989; Gwynn, 2002a). But now in the Anthropocene, drying of GSL (Figs. 1B, C) and the probability of it disappearing, leaving behind a bowl of toxic dust with a few pools of salty water, has understandably raised alarm (e.g., Flavelle, 2022). With growing pressures of urbanization in Utah, the geologic features in Antelope Island State Park in Davis County, Utah, provides one of the few sites left to easily access the GSL and see the context of its history over millennia, including the cyclic rises and falls of GSL and Lake Bonneville. This paper focuses on the broad spectrum and overview of geoheritage values and why it is important to protect the GSL.

GEOHERITAGE VALUES

Cultural and Historical Value

The GSL-BB system has significant cultural as well as historical value because of the role that the landscape played for indigenous peoples as well as in the subsequent exploration of the west by European Americans. Humans have occupied the Great Basin for thousands of years. Native American tribes that have lived in the GSL region, and that are still an important presence, include the Western Shoshone, Goshute, Ute, Paiute, and Washoe peoples (National Park Service, 2015). The landscape was a vital resource where native people hunted and gathered for sustenance, and the GSL watershed provided an exceptional bounty (e.g., Madsen, D.B, 1989). Today many tribal descendants feel an important connection to the land, particularly where open spaces retain much of their original, natural expression.

In the 19th century with expansion and exploration of the west by European Americans (e.g., Stegner, 1954), early scientific studies included the documentation of Lake Bonneville, based on studies of its shorelines, deltas, and sediments by renowned American geologist G. K. Gilbert (1886, 1890). His careful studies on foot and horseback allowed him to deduce that valley floors were previously covered by water and the isolated mountain ranges had been islands and peninsulas in a Pleistocene water body he named "Lake Bonneville." Gilbert used the Bonneville basin to investigate the idea of isostasy (equilibrium adjustments of Earth's crust to changing distributions of weight at the surface, in this case the growth and eventual loss of the water load of Lake Bonneville). Individual shorelines of Lake Bonneville vary in elevation with the highest elevations occurring where the lake was deepest (the weight of the water in the lake depressed the underlying crust, and when the water evaporated, the crust rebounded). This work was the case example for Gilbert to illustrate the methodology of multiple working hypotheses to overcome bias in human reasoning (Gilbert, 1886). His recognition of the dynamic equilibrium of landforms and his correlation of shoreline elevations was seminal to understanding the complex interplay of isostasy and basin tectonics. Gilbert identified and quantified evidence of shoreline superelevation and effects of fetch on shoreline elevations of GSL and Lake Bonneville. Because of Gilbert's work, the GSL-BB system represents a seminal part of the history of science in America.

Gilbert used his experiences in this basin to understand distinctive shoreline barriers, terraces, and spits, and he chronicled the causal changes in hydrology based on rises and falls of Lake Bonneville and the highstands of GSL during the 1870s compared to falling levels of GSL during the 1880s. Remarkably, Gilbert's seminal work has been an inspiration to people all over the world who have studied the history of closed-basin lakes. To be able to retrace Gilbert's thoughts and walk in his footsteps has deep meaning for those who value historical significance. Many Bonneville shorelines are now being rapidly lost or covered due to urbanization, but Antelope Island State Park preserves near-pristine records of these ancient shorelines.

Scientific and Educational Value

The GSL-BB system encompasses a rich geoheritage (Figure 2) and contains many classic textbook geologic features and landscapes, that are significant to both education and research. Much of the specific science is detailed in other papers of this volume.

Geomorphology and Ice Age History

The geoheritage value of the Bonneville basin's prominent ice-age landforms is explained in more detail in other publications (Chan and Currey 2001;

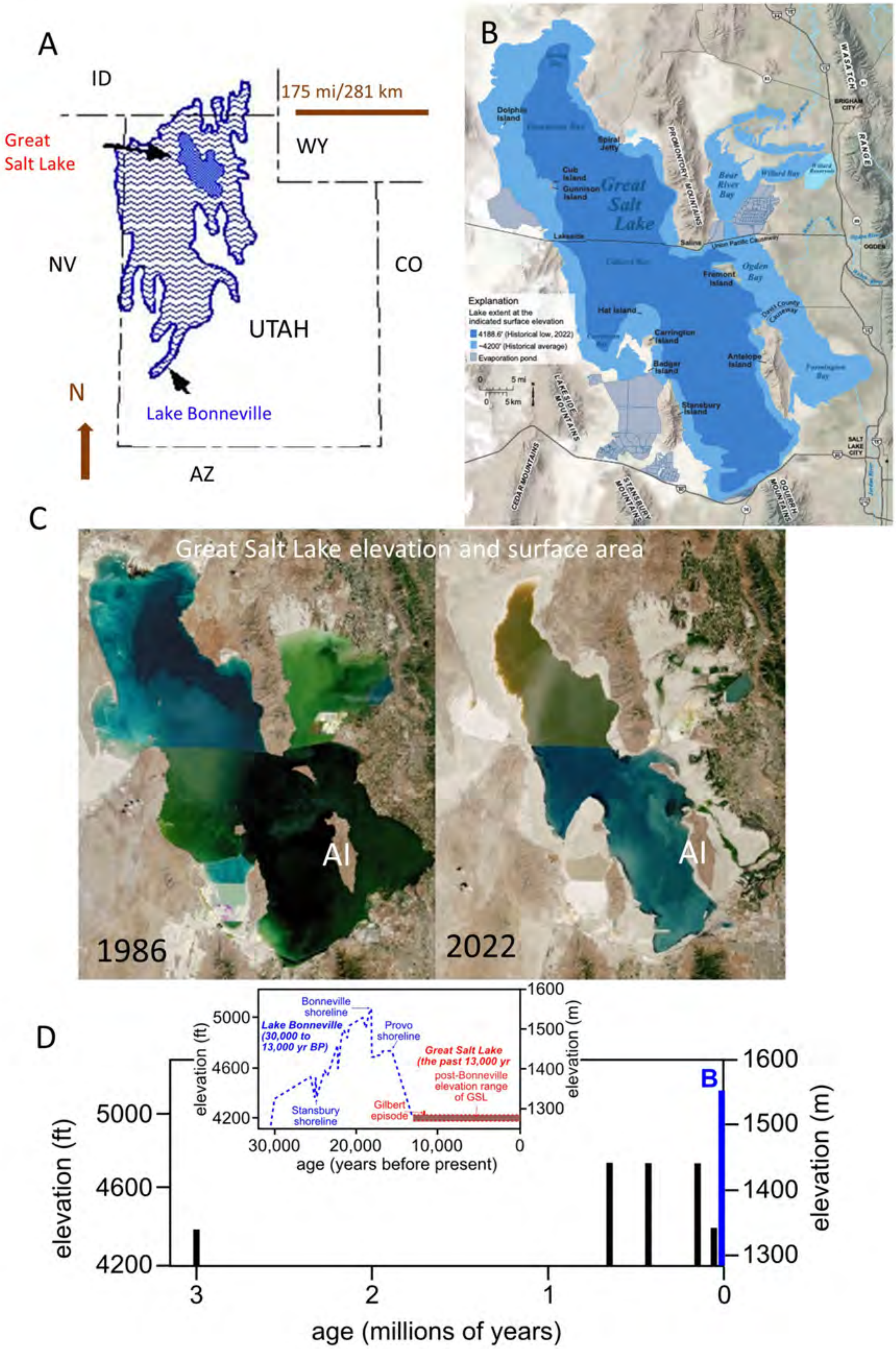

Figure 1. *The GSL-BB system. A. Location of GSL and Lake Bonneville in western Utah. B. Overview map of GSL showing the historic average elevation, and the new 2022 historic low (Figure from Clark and Baxter, 2023.) C. Corresponding Landsat satellite imagery of GSL elevations showing the record high of GSL in 1986 at left vs. historic low in 2022. AI = Antelope Island. Images (Images are public domain.) D. Known Bonneville basin lake cycles. The blue line labeled B in the main graph marks the Bonneville deep-lake cycle. Vertical black bars represent older deep-lake cycles. The base of the main graph is the elevation of modern GSL. Inset shows the shoreline history of Lake Bonneville (blue) and GSL (red) with named shorelines (also see Figure 3). (Inset figure from Oviatt and Shroder, 2016a).*

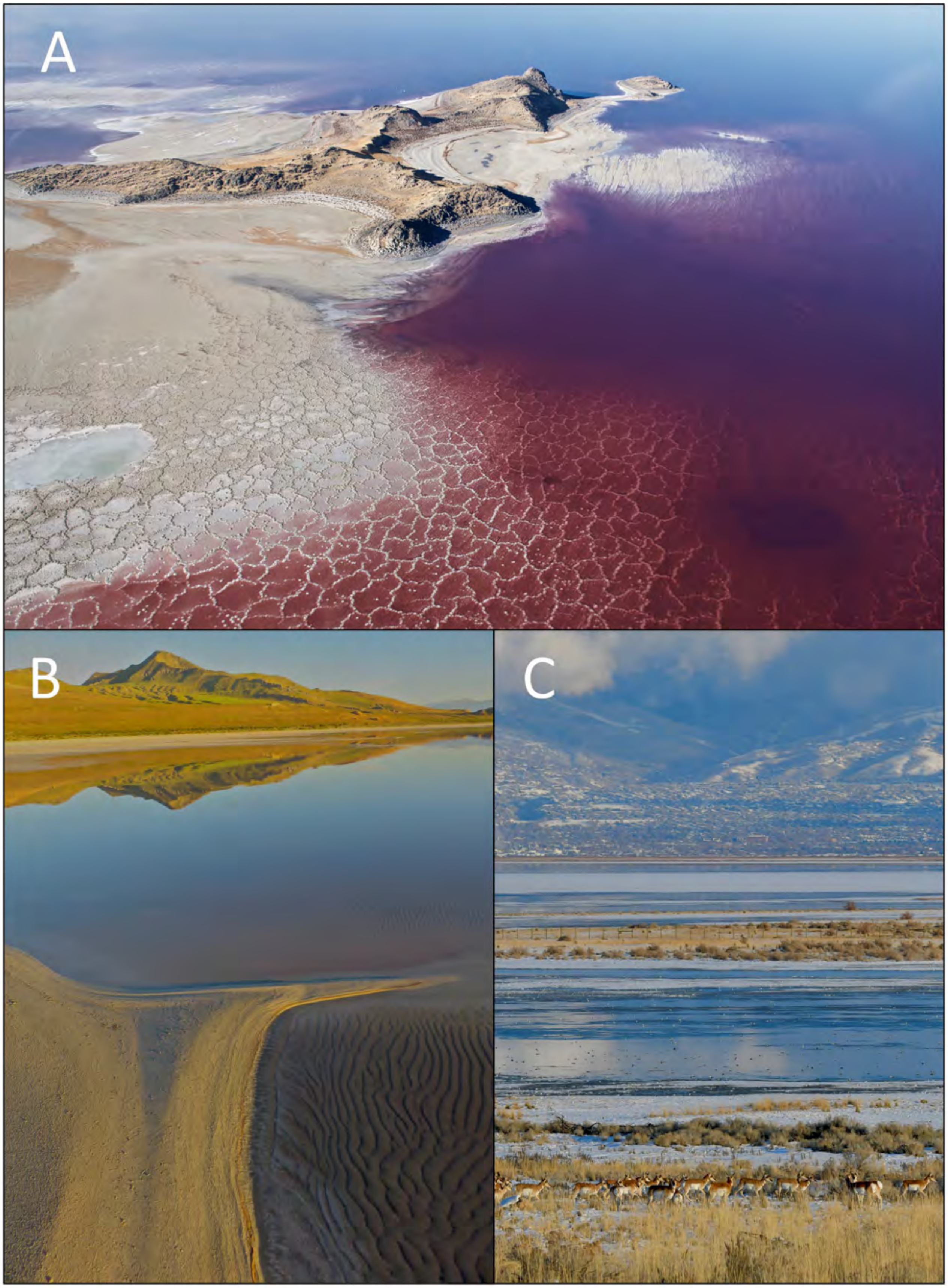

Figure 2. *The GSL-BB system has many geoheritage values including historical, scientific, educational, aesthetic, economic, and societal. A. Polygonal cracks south of Gunnison Island. B. Colorful imagery at Antelope Island. C. GSL lies at the intersection of urban and natural settings (Antelope Island looking east, herd of antelope in the foreground). GSL is a major attraction that draws tourists. GSL enhances the quality of life in the Salt Lake Valley. Images: J. Long.*

Chan and others, 2003; Chan and Godsey, 2004, 2016). Since Lake Bonneville was the largest pluvial lake in the Western Hemisphere (that is, it was caused by climate change and an increase in effective moisture in the basin and was not fed by glacial meltwater), it is a natural laboratory for study (Figure 3), bolstered by the well-dated shorelines that provide a precise lake hydrograph linked to Pleistocene climate change. Study of the GSL-BB has unparalleled analog value for many other large lake systems. The varied character of the lake is a result of climate change in the basin, causing the lake to range from small and hypersaline to large and nearly fresh. Because the basin is so big and deep relative to the amount of water that enters the system, the lake has remained hydrographically closed for most of its history.

Connecting Lake Bonneville and GSL to lakes farther back into the Pleistocene, subsurface cores like the Burmester core (Eardley and others, 1973; Oviatt and others, 1999), tell the story of only four deep-lake cycles during the past 800,000 years. Lake Bonneville was the most recent of those deep-lake cycles, and the deepest because it had the benefit of input from the upper Bear River and rivers in Cache Valley, which were diverted into the basin after 50,000 yr BP. All together those four deep-lake cycles took up less than 10% of the past 800,000 yr — the rest of the time the lake was shallow, similar to the historic GSL (Oviatt and Shroder, 2016b). Prior to 800,000 yr BP, the lake system stayed at low levels back to about 3 million years ago. Thus, other than the four deep-lake cycles, the history of the GSL-BB system indicates that our modern view of GSL is typical of the past few millions of years — a shallow hypersaline lake in a desert environment.

The combination of geomorphic and the sediment records are valuable analogs for other large lake studies, in part because the record in the GSL-BB system is so intact, with distinctive markers of change over documentable spatial and temporal scales. The landscape expressions are also analogs to understanding geologic processes and applying them to regions of Mars (e.g., Chan and others, 2016).

GSL Ooids

GSL is known as the world's largest lacustrine carbonate depositional system (Baskin and others, 2022). Distinctive carbonate ooids (Figure 4) — coated grains formed where waves agitate the lake bottom sediment — of GSL are long-standing world class examples. These sand-size features form when fine-grained particles, such as brine-shrimp pellets or tiny sand grains, become coated with successive thin, concentric layers of calcium-carbonate crystals (crystals of the mineral aragonite arranged radially outward from the center of the ooid; e.g., Sandberg, 1975; Figure 4A). Recent work of Lincoln and others (2022) suggests that the radial pattern is derived from recrystallization. The GSL ooids contrast with other classic examples, such as Bahamian ooids that have calcium carbonate crystals arranged parallel to the grain coatings rather than radially. Oolitic sand is commonly cemented into beachrock (Figure 4B), which is an indicator of lithification along older shorelines, with cementation aided by microbial activity (Lincoln and others, 2022).

Microbialites

Microbialites are organo-sedimentary mounds formed by the actions of complex microbial mats (Burne and Moore, 1987; Lindsay and others, 2017), and GSL has an extensive distribution in the high-salinity water (Baskin and others, 2022; Carney and Vanden Berg, 2022; Pedone and others, 2023). Photosynthesis by cyanobacteria and sulfate metabolism by other microorganisms create conditions that precipitate calcium carbonate (Burne and Moore 1987). In addition, the extra-polymeric substance (EPS; a term commonly used by people who study microbialites) secreted by the cyanobacteria trap carbonate sediment, which creates a substrate on which new mats grow toward sunlight, hence the mound shape. Some microbialites follow older polygonal crack patterns (Figure 4), possibly because they are texturally different sites that might enhance biomediated growth, but microbialites also occur as individual mound buildups (Figure 5) up to 1.5 m high that cover as much as a quarter of the lake floor (Chidsey and others, 2015; Vanden Berg, 2019; Baskin and others, 2022; Wilcock and others, 2024).

Microbialite growth is sensitive to water chemistry and depth (light), wave energy, substrate, and other environmental factors (Kanik and others, 2020). Cyanobacteria-based mats represent the earliest fossilized life form on Earth; layered and mounded accumulations of microbialites are well-preserved in carbonate rocks in the geologic record. The longevity and adaptability of microbialites accounts for their distribution on our planet in modern extreme environments, such as GSL. The study of GSL microbialites has implications for the search for biosignatures on Mars (Noffke, 2015; Chan and others, 2019; Gill and others, 2023).

Mineralogy and Mirabilite

Evaporite minerals such as halite (NaCl) have a long history of being extracted from GSL waters

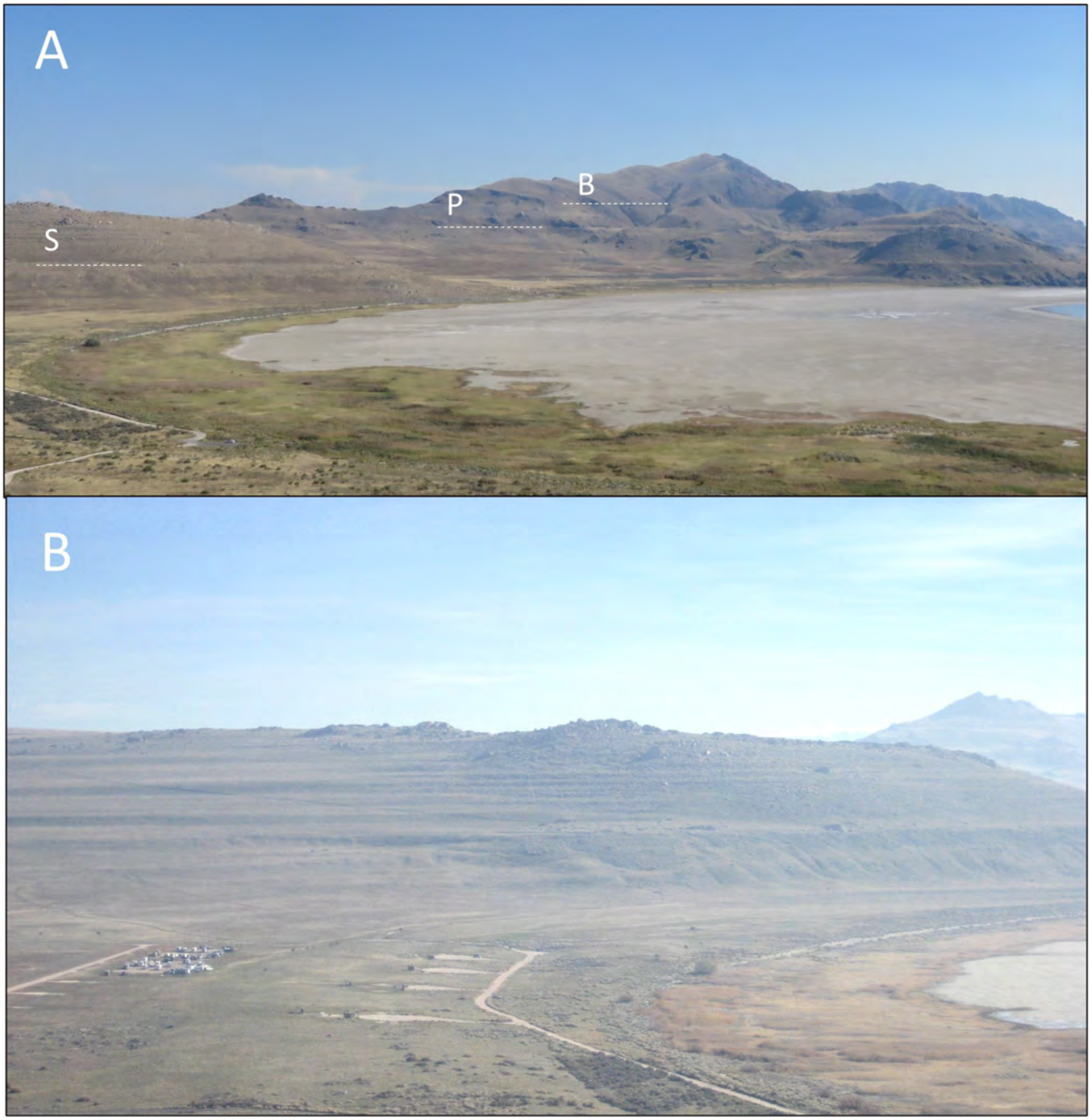

Figure 3. *Shorelines of Lake Bonneville in Antelope Island State Park preserved at White Rock Bay and superimposed on the mountain bedrock. The landforms are a valuable record of geologic history and climate change. A. Prominent shorelines (photo taken in 2014): S = Stansbury shoreline, B = Bonneville shoreline, P = Provo shoreline. B. Many shorelines formed during the rising and falling phases of Lake Bonneville, here showing well-preserved examples between the Stansbury and Provo shorelines on this hillside; GSL at far right (barely in sight; photo taken in 2012). Images: M. Chan.*

(Gwynn, 2002b). Additionally, unusual cold-water, saline-lake minerals, such as mirabilite (hydrated sodium sulfate, Na_2SO_4•$10H_2O$, also known as Glauber's salt), occur in spring mounds that are visible during winter months (Figure 6). Groundwater seems to be partially dissolving a subsurface mirabilite layer, and then the mirabilite minerals are reprecipitated at the surface where spring water emerges. Once the sodium-sulfate-rich spring water hits the cold winter air, mirabilite crystals form and build up a collection of small, mounded terraces, with beautiful crystals (Figure 6) that are stable only in sub-freezing dry environments. Some of the mirabilite-rich springs have colorful pools that are being studied for the associated microbial life (e.g., Jagniecki and others, 2021; Gill and others, 2023). These unusual mineralogies have implications for astrobiology and understanding life in extreme environments.

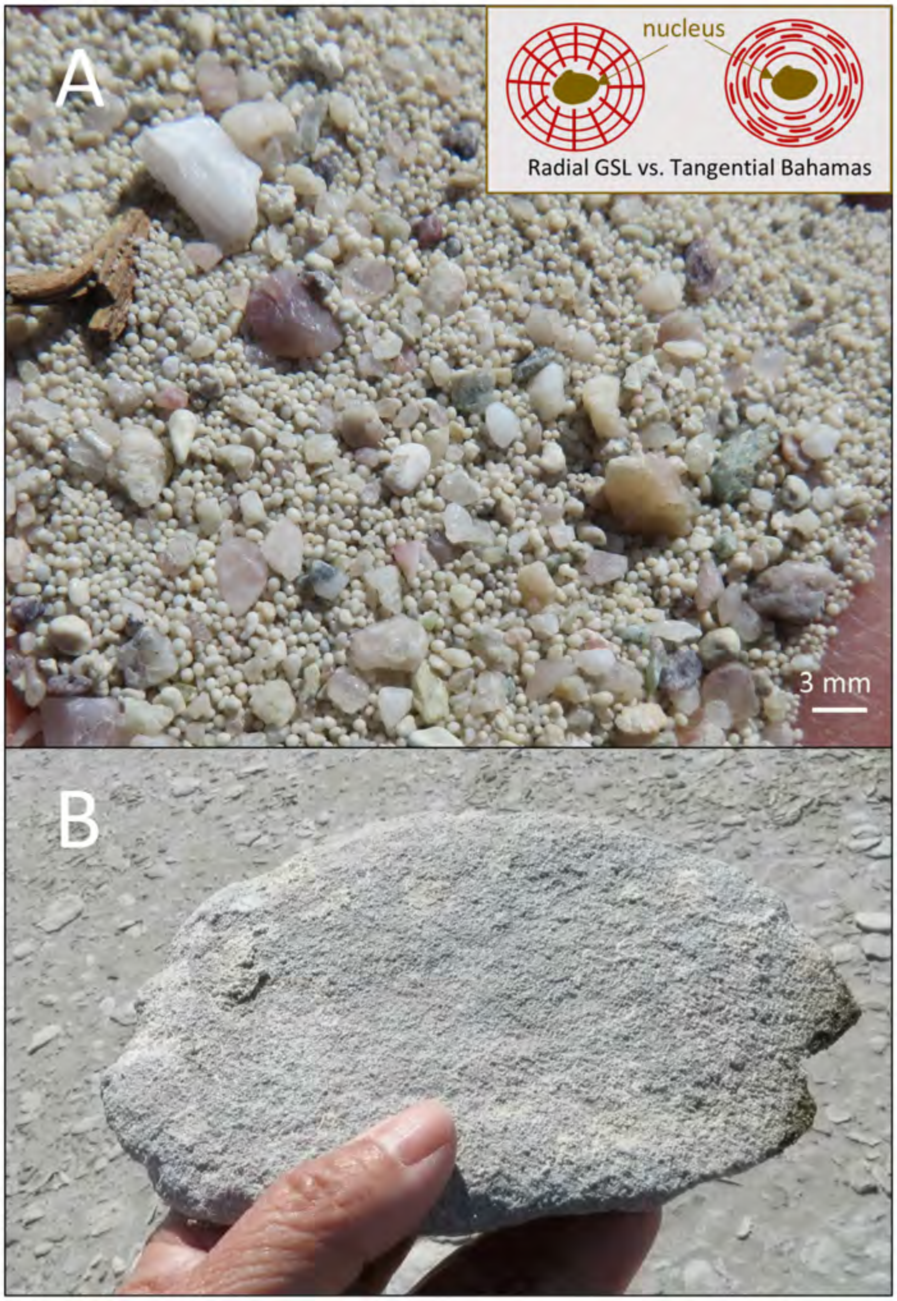

Figure 4. *Distinctive GSL features from the north side of Antelope Island that have scientific value. A. Loose spheroidal oolitic sand (mostly ~ 0.2 to 0.5 mm diameter) with scattered weathered siliciclastic granules derived from nearby bedrock exposures; diagrammatic inset shows GSL radial structure of GSL ooids vs. the common marine tangential structure exemplified in Bahama ooids. B. Cemented beachrock composed of oolitic sand. Images from Bridger Bay, Antelope Island, M. Chan.*

Ecosystem Significance

GSL is a delicately balanced ecosystem (Figure 7). The extreme conditions of GSL gives rise to a rich biodiversity and a special set of lifeforms, including brine shrimp and brine flies and the microorganisms that feed them, which have implications for understanding life adaptations in extreme environments (Baxter and Butler, 2020). The GSL provides important food and shelter to over 10 million migrating birds (Sorenson and others, 2020; GSLEP, 2022), in addition to generating billions of dollars in revenue from tourism and the brine-shrimp industry (Bioeconomics, 2012).

Life on Earth needs water, yet water in the GSL watershed has been extracted and diverted for many purposes, such as for growing alfalfa and building housing subdivisions and supporting infrastructure. This has significantly impacted the inflow and replenishment of the lake, which has been drying and could

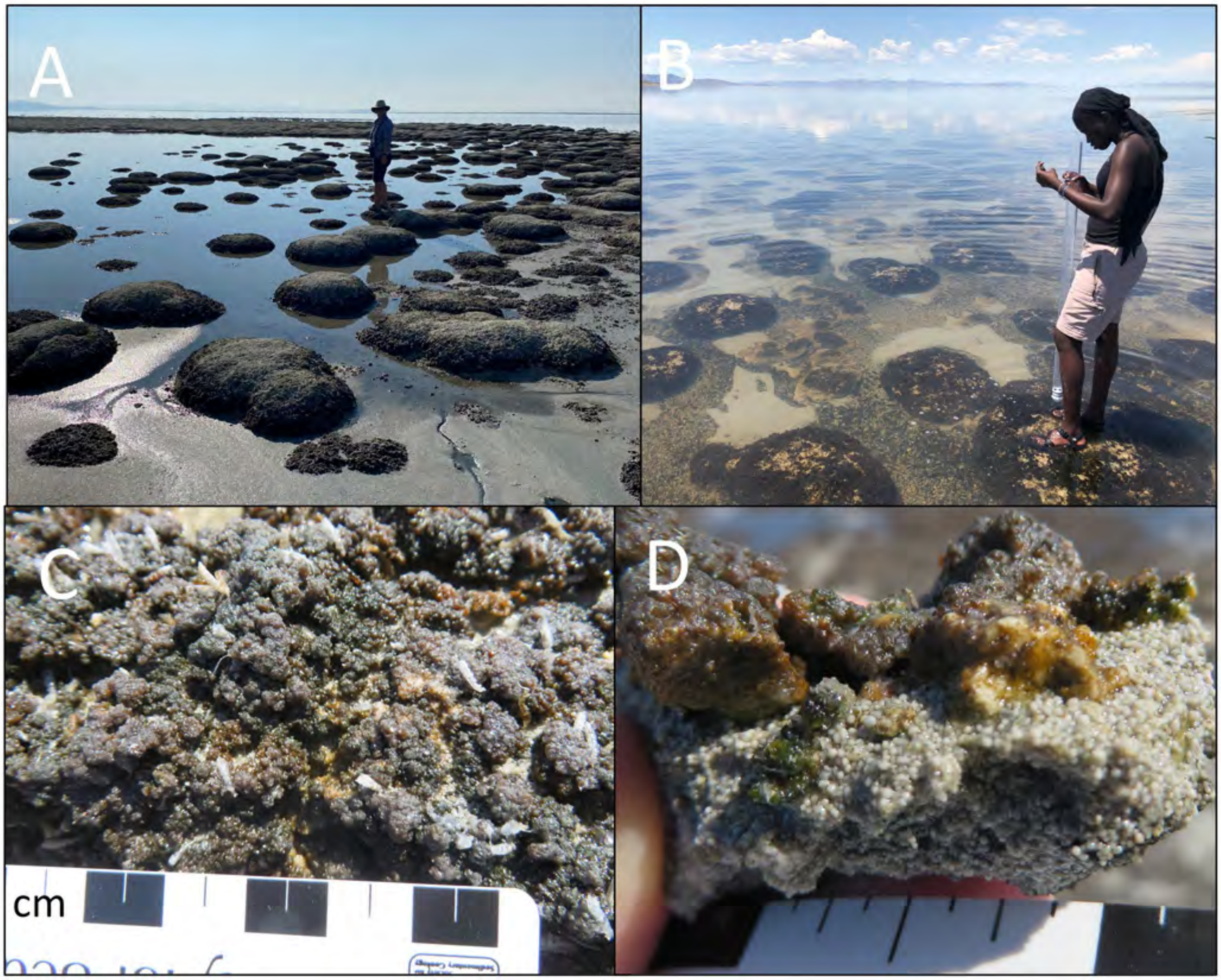

Figure 5. *Microbial mounds of GSL at Bridger Bay, Antelope Island State Park have important implications for understanding early life, with applications to astrobiology. A. and B. buildups; C. and D. cyanobacteria growth holding together oolitic sand grains, with some elongate brine-fly pupae cases. Images A, B: B. Baxter. Images C, D: M. Chan.*

potentially leave a basin of toxic dust that could impact regional communities (Flavelle, 2022). Declining GSL water levels threaten economic activity, public health in adjacent communities and ecosystems of GSL (Larsen, 2022; Great Salt Lake Strike Team report, 2023). It is clear that strategies to improve water management and increase deliveries to the lake are critical. GSL is an extreme ecosystem of biodiversity and geodiversity that is too important to lose.

Societal Value

There is no doubt that the GSL and the Bonneville Basin comprise an aesthetical geoheritage landscape that is visually appealing and that inspires a sense of awe and wonder (Figure 8). The landscape of GSL, enhanced by open space and the natural setting of flora and fauna, has cultural and historical roots, and impacts economic development and tourism as well as quality of life. Shrinking water levels of GSL have put this ecosystem into a state of crisis. Diminishment of the GSL will threaten wildlife and further degrade Utah's air quality.

Society needs geoheritage sites like GSL because these sites are critical to advancing knowledge about water, climate and environmental changes, evolution of life, minerals and resources, and other aspects of the nature and history of Earth (Geological Society of America, 2022). Numerous studies show that nature and the outdoors provide positive impacts on mental health and cognition (e.g., Bratman and others, 2019; Weir, 2020). GSL is an outdoor classroom that enhances public understanding and engagement with science (Figure 8), while providing recreational areas that improve quality of life, as well as economic support to local and regional communities as tourist destinations and as vital mineral and water resources.

CONCLUSIONS

Drying of Pleistocene Lake Bonneville, which ended about 13,000 years ago, left both ancient shore-

Figure 6. *Mirabilite mounds and terrace structures (A, B), with large, cm+ scale crystals growing in cold colorful pools (C, D - colored green by cyanobacteria) at White Rock Bay, Antelope Island State Park. These mineralogies have important implications for life in extreme environments. Winter images (2020): A-C: M. Chan. Image D: D. Eby.*

lines and the modern GSL, the largest saline lake in the Western Hemisphere. This GSL-BB system, as a whole, is a unique and valuable geoheritage archive of climate change and an extreme ecosystem that is often underappreciated and is now under threat of being lost. The GSL-BB hosts world class examples of landforms related to climate history, ooids, microbialite mounds, and evaporite minerals (e.g., halite and mirabilite). The microbialite and mirabilite features have implications for astrobiology and understanding life in extreme environments. Specifically, geoheritage sites like GSL are critical to the geoscience profession, to conserve sites of geoscience importance related to Earth processes, Earth history, and history of geologic thought. These sites are the training ground for the next generation of environmental scientists who will grapple with global societal issues and the complexities and balance of nature. The biodiversity and geodiversity of GSL and the Bonneville Basin make this a remarkable geoheritage jewel of Utah's west desert.

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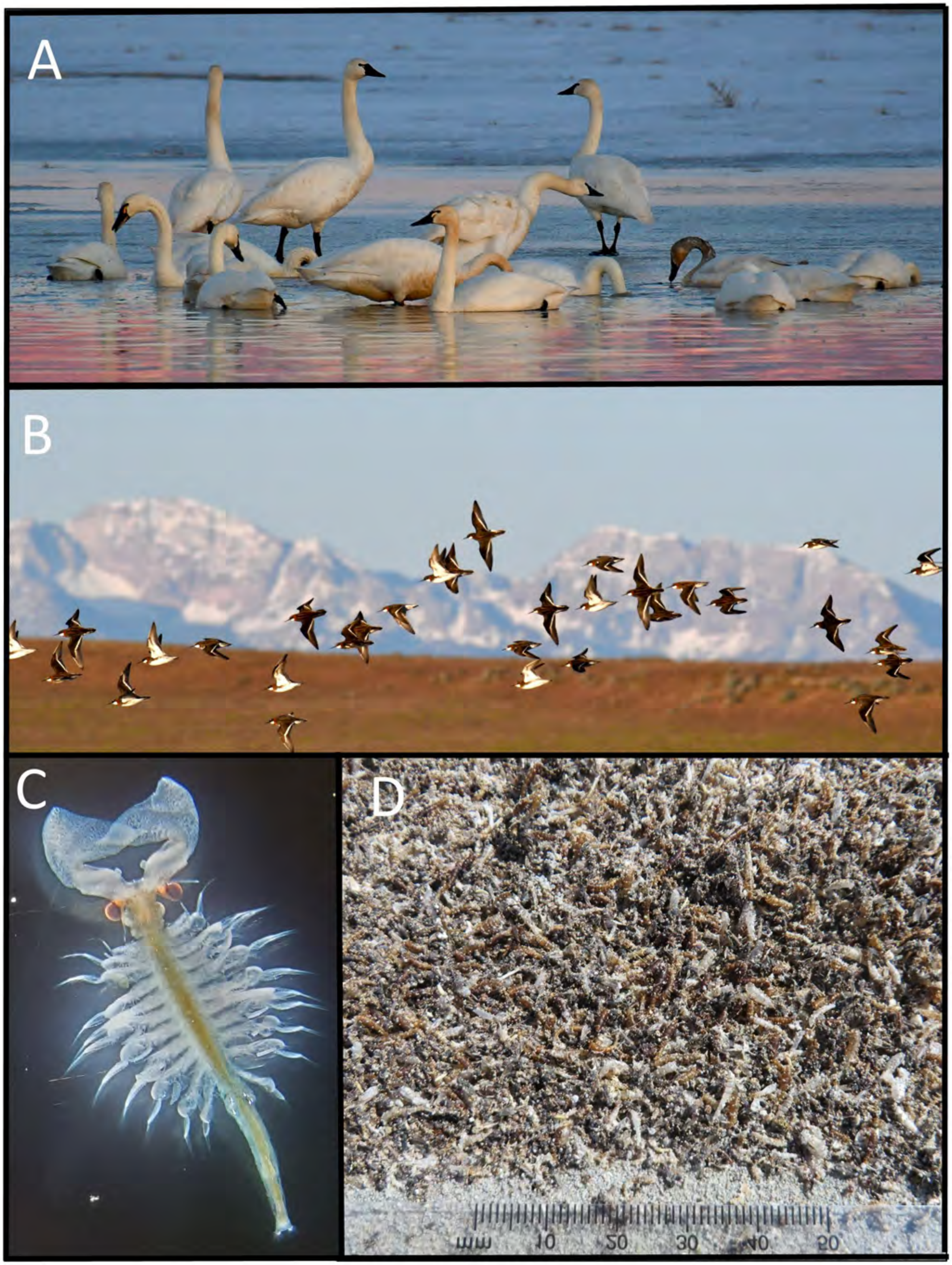

Figure 7. *GSL is a delicately balanced ecosystem. Waterfowl at Farmington Bay Wildlife Refuge on the eastern edge of GSL include migratory populations of Tundra Swans (A) and Phalaropes (B). C: a male GSL brine shrimp with impressive claspers; brine shrimp produce eggs/cysts that are harvested from the lake and sold in aquaculture shops (e.g., fish food), and they provide food for migratory birds. D: Brine-fly detritus, including pupae cases along the beach of Bridger Bay, Antelope Island State Park. Images A, B: J. Long. C: Bridget Dopp. D: M. Chan.*

Figure 8. *GSL is an outdoor laboratory for science, enjoyment of nature, and societal quality of life. Tourists and residents alike find refreshment and a sense of wonder and learning at GSL, Bridger Bay, and Antelope Island State Park. The Stansbury shoreline is visible on the slopes of Buffalo Point in the background in A. Many people enjoy GSL (B, C) year-round. Image A: M. Chan. B, C: J. Long.*

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