Geobiology of "Snowball Earth" Deposits of Antelope Island

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Utah Geosites
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M. Milligan, R.F. Biek, P. Inkenbrandt, and P. Nielsen, editors

Cover Image: *View of the outcrops of the lower dolostone of the Kelley Canyon Formation at the geosite. The Great Salt Lake is in the background, toward the west.*

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Utah Geosites showcases some of Utah's spectacular geology, both little-known localities and sites seen by visitors to Utah's many national and state parks and monuments. Theg eosites refle ct the interests of the many volunteers who wrote to share some of their favorite geologic sites. Theli st is eclectic and far from complete, and we hope that additional geosites will be added in the coming years. TheU tah Geological Survey also maintains a list of geosites https://geology.utah.gov/apps/geosights/index.htm.

We thank the many authors for their geosite contributions, Utah Geological Association members who make annual UGA publications possible, and the American Association of Petroleum Geologists—Rocky Mountain Section Foundation for a generous grant for desktop publishing of these geosite papers.

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Presidents Message

I have had the pleasure of working with many different geologists from all around the world. As I have traveled around Utah for work and pleasure, many times I have observed vehicles parked alongside the road with many people climbing around an outcrop or walking up a trail in a canyon. Whether these people are from Utah or from another state or country, they all are quick to mention to me how wonderful our geology is here in Utah.

Utah is at the junction of several different geological provinces. We have the Basin and Range to the west and the Central Utah Hingeline and Thrust Belt down the middle. The Uinta Mountains have outcrops of some of the oldest sedimentary rock in Utah. Utah also has its share of young cinder cones and basaltic lava flows, and ancient laccoliths, stratovolcanoes, and plutonic rocks. The general public comes to Utah to experience our wonderful scenic geology throughout our state and national parks. Driving between our national and state parks is a breathtaking experience.

The "Utah Geosites" has been a great undertaking by many people. I wanted to involve as many people as we could in preparing this guidebook. We have had great response from authors that visit or work here in the state. Several authors have more than one site that they consider unique and want to share with the rest of us. I wanted to make the guidebook usable by geologists wanting to see outcrops and to the informed general public. The articles are well written and the editorial work on this guidebook has been top quality.

I would like to personally thank Mark Milligan, Bob Biek, and Paul Inkenbrandt for their editorial work on this guidebook. This guidebook could not have happened without their support. I would like to thank Jenny Erickson for doing the great desktop publishing and the many authors and reviewers that helped prepare the articles. Your work has been outstanding and will certainly showcase the many great places and geology of Utah. Last, but not least, Thank you to the American Association of Petroleum Geologists, Rocky Mountain Section Foundation for their financial support for this publication.

Guidebook 48 will hopefully be a dynamic document with the potential to add additional "geosites" in the future. I hope more authors will volunteer articles on their favorite sites. I would like to fill the map with locations so that a person or family looking at the map or articles will see a great location to read about and visit. Enjoy Guidebook 48 and enjoy the geology of Utah.

Peter J. Nielsen
2019 UGA President

INTRODUCTION

Antelope Island on Great Salt Lake provides an excellent opportunity to look at one of the world's great geobiological records—the "Snowball Earth." Snowball Earth refers to a unique time in Earth history before the dawn of skeletonized animals where there is substantial evidence to support glaciers at sea level in the equatorial regions. Many researchers have proposed that the only way to achieve this unique condition is to freeze the entire planet, hence the "Snowball Earth" (REFS). We use quotation marks around the name of this global phenomenon because the scope and details of this major climatic phenomenon are still debated. After 30 years of rigorous testing since the idea was proposed (Kirschivink, 1992), this hypothesis is still holding up (Hoffman and others, 2017). Besides being a record of two global glaciations lasting tens of millions of years between 717 and 635 million years ago, there may be a connection between these mega-scale climate changes and the evolution of animal life.

Geobiology is a continually evolving field that looks at the intersection of geological context with biological and ecological constraints, using models and assessing validity through a variety of biogeochemical proxies. Put another way, geobiologists recognize that classic studies of biological communities, evolution, ecology, and extinction need to be filtered through geology at scales from plate tectonics to bedrock and substrate. Also, geological processes within a few miles of the surface where sediments convert to rock likely involve microbial interactions. So why should geologists care? Microbe-mineral interactions are now known to be integral to the study of environmental remediation, reservoir characteristics, some economic deposits, as well as the lofty academic pursuits of early Earth evolution and astrobiology. It is with this view that the following discussion of the Snowball Earth deposits on Antelope Island is framed, albeit from a largely geological focus.

LOCATION AND ACCESS

The Snowball Earth geosite is located on Antelope Island State Park (figure 1). It is legal to visit the locations without a permit, although no collecting is allowed. Please take only photos! The following directions start at the Visitor's Center on Antelope Island. From the Visitor's Center, head west then south along Bridger Bay. Turn left (east) at the end of the road, away from Bridger Bay Campground. Follow the signs to the White Rock Group Campground and park at the far, southeastern corner. From here you will walk along the Bone Road Trail, essentially south. After a mile (1.6 km) or so, the trail will slowly climb, eventually connecting with the Junction Trail off the White Rocks Loop Trail. The last section of the trail has a steeper incline (~600 foot [180 m] gain) to the crest. The total trail is 3 miles (5 km) each way from the parking area.

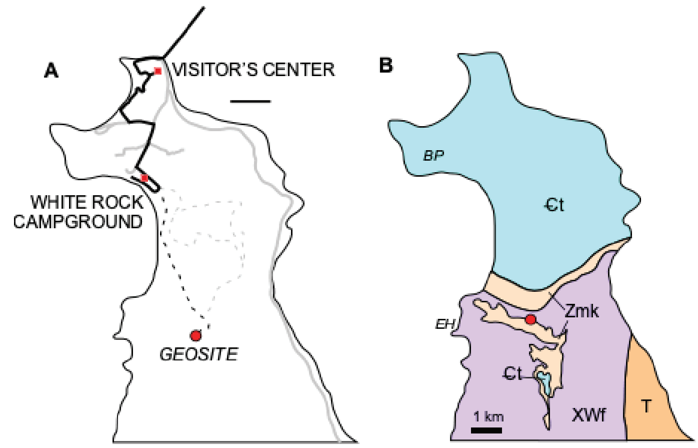

Figure 1. A) Location of geosite on Antelope Island. Upper image shows the major roads (solid) and walking trails (dashed). Black lines illustrate the route in the text; additional routes are in grey. Upper road is the Causeway. B) A simplified geological map of northern Antelope Island. Red dot is the geosite. XWf=Farmington Canyon Complex; Zmk=Mineral Fork and Kelly Canyon Fms.; Ct=Tintic Fm.; T=Tertiary conglomerate. BP=Buffalo Point; EH=Elephant Head. Based on Yonkee and others (2000).

Wearing sturdy shoes and insect repellant are recommended for the walk and there is the potential to take a dip in the lake, so wearing a bathing suit is also recommended. Bathrooms, showers and a snack bar are available at the beach at Bridger Bay. Hats, sunscreen, lip balm, gnat repellent, and several liters of water are highly recommended, especially between May and September.

GPS Locations:
41° 1'29.75"N; 112°14'22.38"W parking area
40°59'13.37"N; 112°13'19.81"W geosite

SNOWBALL EARTH

The recognition of glacial deposits interbedded with marine sediments at low latitudes during several times in Earth's history led to the hypothesis of a "Snowball Earth." Originally coined by Joe Kirschvink (1992) for deposits of Paleoproterozoic age (~2.3 billion years), the term is more commonly associated with the Neoproterozoic record (~1000-540 Ma; Hoffman and others, 1998). Recently, a new geological period, the Cryogenian (717-635 Ma), was established to encompass the duration of the two global glaciations of the Neoproterozoic Era, although the global stratotype, section, and point (GSSP) for the base of the Cryogenian is still being determined (Halverson and others, 2018). In addition to glacial deposits, primarily diamictite (or mud-supported conglomerate), these glacial intervals also include dramatic sea-level changes and enigmatic, massive to banded carbonates with "tubestone" (see a more detailed description below) (figure 2). These carbonate units may also include large crystal fans, that were originally aragonite, which indicate rapid deposition of carbonate and high alkalinity during the deglaciations (Hoffman and others, 2018). Collectively, these carbonate units are called "cap carbonates" because they cap the glacial deposits of each of the two glaciations.

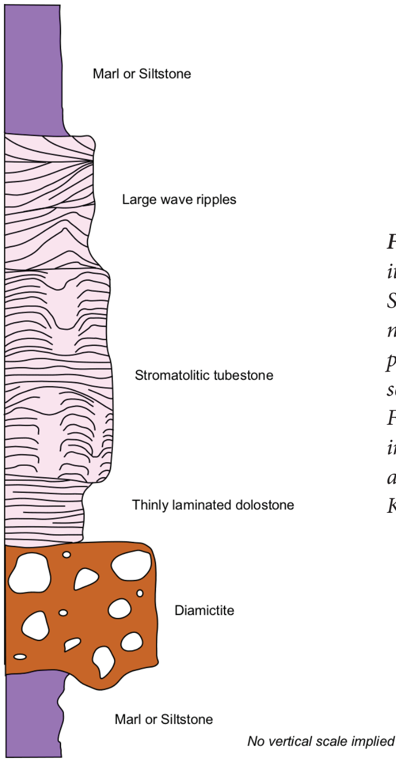

Figure 2. *Highly idealized composite stratigraphic column through a Snowball Earth sequence. In reality, no one location shows all the features perfectly. On Antelope Island, one sees the diamictite of the Mineral Fork Formation and the thinly laminated and stromatolitic tubestone and large wave ripple facies of the Kelley Canyon Formation.*

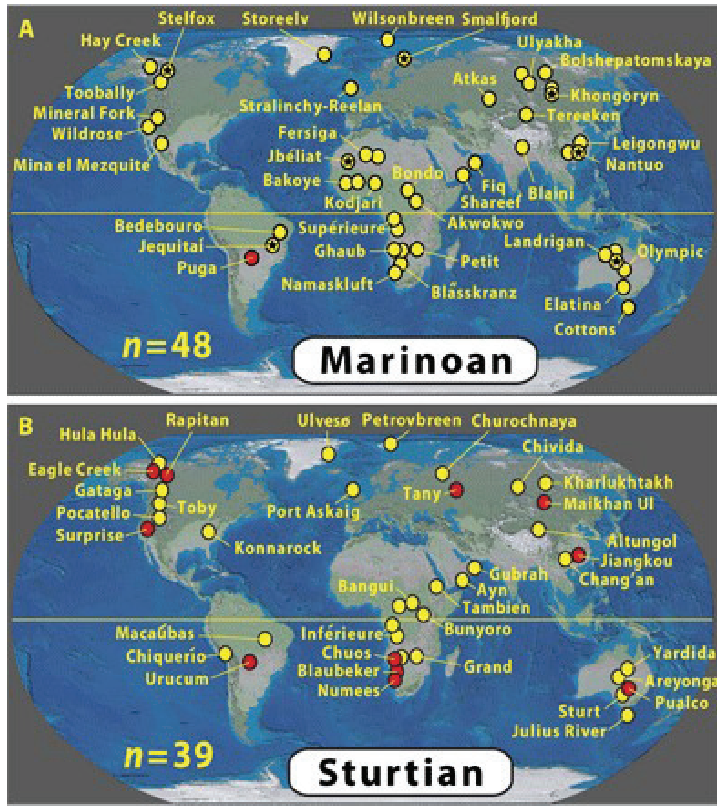

Figure 3. *Global distribution of the three main pulses of Snowball Earth glaciation, plotted on modern distribution of the continents. Note that in the Neoproterozoic, all the landmasses were more or less joined in a supercontinent, Rodinia. Upper (A) is the earlier Marinoan (645-635 Ma) and lower (B) is the later Sturtian (717-659 Ma). Yellow dots indicated glacial or periglacial deposits and red dots show associated iron oxide formation. From Hoffman and others (2017, Figure 4).*

Finally, in the Neoproterozoic, there is a small resurgence of iron formation, suggesting low oxygen or high iron input conditions that is also likely related to the decoupling of the ocean from the atmosphere by ice sheets and the continued input of reduced forms of elements such as iron from sea floor spreading, subaqueous mantle input, and sedimentation (Cox and others, 2013).

While each piece of evidence is suggestive, it is the sum total that points to the occurrence of extreme glaciations. What makes this particular interval a global "Snowball Earth" is the presence of glacial deposits and related cap carbonates in paleoequatorial regions as well as higher latitudes (figure 3). Furthermore, climate models show that once polar ice sheets grow to about 30 degrees north and south latitudes, there will be a runaway ice-albedo effect (ice reflecting the sun's heat) in which ice covers the planet by growing into equatorial regions (Budyko, 1969). There is also mounting evidence that conditions led to sluggish ocean currents that would have significantly impacted global nutrient fluxes. Altogether, the evidence points to a dramatic time of globally extensive glaciations, hence the "Snowball Earth" (e.g., Hoffman and others, 2017).

So how does this work? The geological and climatic forcing mechanisms that led into a global glaciation and also terminated these glaciations are still debated. In part, this is due to the paucity of Neoproterozoic geologic deposits and challenges in finding dateable material (such as volcanic ash), although many new age models for many Cryogenian strata are being generated; all point to two global glaciations, the Sturtian glaciation (717-635 Ma) and the Marinoan glaciation (>640-635 Ma) (e.g., Calver and others, 2013; MacDonald and others, 2010; Prave 2016). Also, geologic data influence climate models and there are multiple competing models that are equally valid (e.g., Bechstaedt and others, 2018). It is generally accepted that the conditions were unique, both with regards to continent location and ocean currents. Also, there were a series of positive feedback loops that, once initiated, led to rapid cooling of the continents.

The major feedback loop had to do with Earth's albedo. The 'albedo' is a measure of the reflectivity of solar radiation. White ice is reflective, so as permanent ice builds on the continents and oceans, more solar radiation is reflected, leading to cooling and the growth of more ice. Additionally, by gathering the continents in the lower latitudes (as evidenced by the paleomagnetic record (e.g., Sohl and others, 1999), there is also an increase in overall albedo because continental rocks reflect more energy than ocean waters and solar radiation is focused on the tropics (Hoffman and Schrag, 2002. The Cryogenian was the time when Rodinia, a major supercontinent, was in the process of breaking apart. Although the orientation is still being debated, the location and orientation of Rodinia continental pieces affected ocean circulation and nearly all models show the individual continental plates amassing in middle to low latitudes (Li and others, 2013). Once ice develops, sea level is lowered, exposing more continental shelves, thus further increasing albedo (Kirshvink, 1992). One of the big challenges is covering the oceans with ice. Ocean water has a high heat capacity, making it possible to insulate against ice growth, no matter how strong the overall global albedo. In many models, regions of the tropical ocean remain ice free (e.g., Baum and Crowley, 2001; Abbott and others, 2011). Either way, the evidence thus far is overwhelming that vast regions of the planet had permanent ice cover, all the way down to the tropics. Finally, all this ice would lead to an overall drying of the atmosphere, eventually leading to the shutdown of the hydrological cycle during the Cyrogenian (Hoffman and others, 1998).

Of course, the big problem is, how does the Earth recover from a Snowball Earth? The positive feedback loops to transition the planet into a "Snowball Earth" state means there is a tipping point at which the Earth could remain permanently frozen. The most accepted models for getting out of a frozen world rely on the buildup of volcanic CO_2 in the atmosphere triggering a rapid meltdown through greenhouse heating (Kirschvink, 1992; Caldeira and Kasting, 1992; Hoffman and Schrag, 2002). Normally, the CO_2 gas would be consumed by continental weathering and entrenchment in the oceans, but in a frozen world, these sinks would be blocked. But, as the CO_2—as well as methane and other greenhouse gases—built up in the atmosphere, they would block the reflected solar radiation and Earth's own heat emissions from escaping to space, thus leading to global warming.

The next phase varies between models, but it is clear that warming would ensue. As the ice eventually thins and melts off the continents, there would be intensive continental weathering by carbonic acid, leading to a rapid buildup of carbonates in shallow water (hence 'cap carbonates'). The $\delta^{13}C$ values (ratio of heavy carbon to the biologically favored light carbon) through this interval is well below typical ocean values of the past 550 million years. The light values are interpreted as a result of influx of mantle CO_2, hence volcanic input (Veizer and others, 1999), and a great reduction in biological fractionation of carbon isotopes (Hoffman and others, 1998).

An alternate model, called the "Slushball Hypothesis" allows for a dominantly ice-covered Earth but with enough open water, particularly in the low latitudes, for a full hydrologic cycle (e.g., Pollard and Kasting, 2005) and a refugia for biota (Kirschivink, 1992). This could explain some of the sedimentary features that are difficult to reconcile with a fully frozen Earth and also takes other climate models into account which do not fully freeze-over the oceans. A new model relies more heavily on the break-up (rifting) of Rodinia into its lithospheric progeny (Li and others, 2013) and the impact of rifted margins on glacial stratigraphy, cap carbonate facies distribution and the enigmatic iron formations. Specifically, rifting of Rodinia would lead to rift margins that could trap oxygen-poor water, leading to basin-specific iron-formations (Baldwin and others, 2012). The tectonic reorganization could also shift ocean currents, thus driving more localized ice conditions.

GEOLOGICAL SETTING

Antelope Island is a classic Basin-and-Range uplift and, though it is small relative to the other ranges, it is the largest island (42 square miles [110 km^2]) in the Great Salt Lake and exposes a wealth of geologic information (King and Willis, 2000) (figure 1B). The oldest outcropping units are early Paleoproterozoic metamorphic units of the Farmington Canyon Complex. Sharply overlying the metamorphic basement are the conglomerate and finer-grained units of the Mineral Fork Formation (glacial deposits). These strata are overlain by dolostone of the basal Kelley Canyon Formation (cap carbonate). The remainder of the Kelley Canyon is composed of shale and siltstone and minor carbonate. The Cambrian Tintic Quartzite unconformably overlies the Kelley Canyon and dominates the northern part of the island, where one enters via the causeway (Antelope Island Road) (figure 1B).

Like most of the eastern Basin-and-Range, Cretaceous-age Sevier thrusting dictates the structural geology, resulting in a series of thrust slices (Yonkee and Weil, 2015). The Sevier orogeny caused brittle-to-ductile deformation with outstanding exposures of shearing on Antelope Island. In fact, it is important to note that the Neoproterozoic succession on Antelope Island is significantly thinner than nearby age-equivalent units to the west and north because it is on a different thrust sheet (Levy and Christie-Blick, 1989; Yonkee and others, 2000, 2014). This geosite focuses on an excellent outcrop of the upper stratigraphy of one of these thrusts that brings the Neoproterozoic Mineral Fork and Kelly Canyon formations over the Cambrian Tintic Quartzite (figure 4).

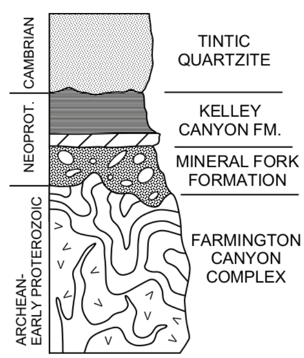

***Figure 4.** Simplified bedrock stratigraphy of geosite on Antelope Island. No vertical scale is implied. Units of focus are the Mineral Fork Formation and lower dolostone member of the Kelley Canyon Formation. Based on Yonkee and others (2000; 2014).*

Neoproterozoic Succession on Antelope Island

The most accessible exposures of the Neoproterozoic strata lie at the top of the ridge running east from Elephant Head. At this location, the Mineral Fork Formation comprises mostly diamictite (conglomerate with a fine-grained matrix) up to 200 feet (60 m) thick though structural thinning and thickening throughout limits the integrity of this value (Yonkee and others, 2000) (figure 4). Some of the thickness variation is due to irregularities on the nonconformity surface atop the basement. Clast sizes within the diamictite vary from granules to boulders, and clast lithology is limited to metamorphic material derived from the underlying

Figure 5. Outcrop of strained diamictite from Antelope Island. Note the variety of clasts. 2014 Wasatch-Uinta Field Camp students for scale.

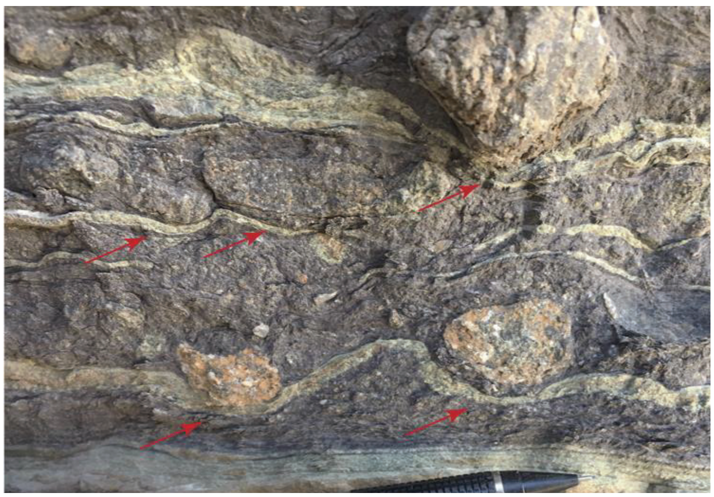

Figure 6. Dropstones in the Mineral Fork Formation on Antelope Island. The criteria for recognizing dropstones is that the laminations under the clasts are 'pierced', indicating a definitive glacial origin for the deposit (see red arrows). The clasts drop from melting icebergs and fall onto the seafloor, piercing and deforming the mudstone layers.

Figure 7. View of the outcrops of the lower dolostone of the Kelley Canyon Formation at the geosite. The Great Salt Lake is in the background, toward the west.

basement (figure 5). The lack of sorting, great variety of clast sizes, and fine-grained matrix suggest a glacial or mass-flow origin. The occurrence of dropstones east of Elephant Head indicates a definitive glacial origin (figure 6). Dropstones are outsized clasts that drop from melting icebergs or sea ice and disrupt the underlying laminations. At a minimum, one can see at this outcrop the great diversity in size and composition of the clasts. This certainly points to a dynamic process!

Overlying the Mineral Fork Formation is the basal dolostone of the Kelley Canyon Formation. To find the best outcrops, walk west from the diamictite wall to the low outcrops in the saddle (figure 7). It is worth your time to poke around as there are a variety of fabrics preserved in the dolostone. While most of the pink to white dolostone is massive to thinly laminated (figure 8), some blocks contain beds of the exotic "tubestone" (Cloud and others, 1974) (figure 9).

Both fabrics are indicative of "cap carbonates" associated with Neoproterozoic glaciations globally. The current model is that once CO_2 reached a tipping point in the atmosphere, there was rapid global warming which then led to melting of the ice sheets. The CO_2, in the form of carbonic acid, was free to chemically weather the continents, leading to a massive flux of dissolved material into the oceans. Furthermore, the CO_2 also built up in the oceans itself, leading to a rapid deposition of calcium carbonate minerals, hence the thick beds of in situ tubestone, and at other localities, in situ aragonite fans (Hoffman and Schrag, 2002). (The dolomite mineral was probably not original but replaced the original aragonite after burial.)

The tubestone is more enigmatic, though also found globally in cap carbonate sequences. Here on Antelope Island, the facies consists of parallel tubes, a few centimeters wide, separated by regions that are finely laminated (Hayes and Dehler, 2011) (figure 9). Both fabrics are now dolomite. For many years, it was believed the tubes represented gas escape structures, where ascending gas bubbles disrupted the laminated sediments (Cloud and others, 1974). More recently, Kennedy and others (2001) specified that the gas was methane and the release of such a volume of greenhouse gas would have further intensified the exit from a Snowball Earth. Other ideas have also been suggested, such as early vertical animal burrows, but the evidence does not support these ideas.

In a critical paper on the subject, Corsetti and Grotzinger (2005) noted some key features overlooked by previous researchers. First, the tubes were not necessarily round in cross-section. In fact, most were of complex, multi-lobed forms. Also, while they looked to be filled with solid mud (micrite) compared to the laminated facies, in truth it is quite common to find laminae extending across the tubes. If you look around carefully at the outcrop on Antelope Island, you will find examples of these tube-crossing laminae.

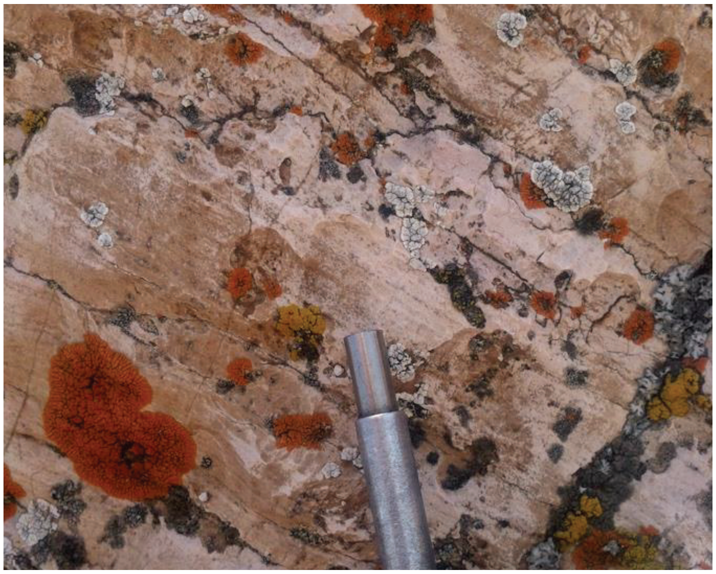

Figure 8. Finely laminated lithofacies of the basal Kelley Canyon Formation, Antelope Island. This is the dominant fabric in most basal cap carbonates worldwide, though it is not by itself diagnostic of the "Snowball Earth." Magnet is 5 mm across.

Figure 9. "Tubestone" of the Kelley Canyon Formation from Antelope Island. Upper photo is a field view of upper surface showing 'tube' tops, which are sediment infilling between columnar stromatolites. Lower photo is a polished vertical cut. Note the stromatolitic laminations of the columns, separated by sediment and cement-filled 'tubes.' Lower image from Hayes (2013).

This new evidence pointed to the 'tubes' not being erosional but rather constructional features. The most likely hypothesis is that the laminated facies represents stromatolites and the 'tubes' are the spaces between the stromatolites, often filled with dolomicrite, but also sparry dolomite and iron oxides. Stromatolites are a type of fossil that records the growth of microbial mats. As the mats grow and decay and repeat, they may deposit layers of cement or grains, and are thus preserved in the rock record as a sequence of thin, millimeter-scale layers. One layer grows on another, ultimately building up a vertical or domal structure. In the Antelope Island example, the stromatolites are mostly vertical, resembling folded curtains. Occasionally, the microbial mats expanded across the mud flat to the next stromatolite; this is the preservation of laminae across the tubes.

SUMMARY

Outcrops of the Neoproterozoic Mineral Fork Formation and basal Kelley Canyon Formation exposed on the ridge above Elephant Head on Antelope Island State Park provide an accessible and excellent window into the 'Snowball Earth' episode. That unique time of global glaciation led to glaciers at sea level near the equator while the end-glaciation is recorded by thick dolostones preserving bizarre 'tubestone' stromatolites. While there are many other features diagnostic of 'Snowball Earth' such as iron formation and other dolostone fabrics, Antelope Island preserves the two main facies: diamictite as evidence of glacial deposition and 'tubestone' cap carbonate. Furthermore, the views of Sevier-aged deformation and expansive views of the island and lake make this an excellent geosite for a short day trip from Salt Lake City.

ACKNOWLEDGEMENTS

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