What is the fate of snow trapped in dunes?

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Abstract

Active sand dune fields in cold climate regions commonly incorporate snow and ice from winter precipitation into their internal structure. Sediment transported by dune movement can bury snow, protecting it from solar input and warming. The hydrological importance of this system is not well studied, in particular the ability of such a system to trap and preserve ice that may be later be as stored groundwater. This ice trap may be important for understanding desert ecosystems on Earth, but may also represent an analog mechanism for buildup of ice below the mid-latitude surface of Mars.

Electrical Resistivity Tomography (ERT) imaging was used to investigate the depths of a dune for ice layers in the Red Desert, Wyoming. Data loggers were used to monitor the temperatures and moisture contents of the subsurface surrounding directly observed ice lenses within the dune. The ERT survey revealed that subsurface ice lenses are not incorporated into the dune over long periods. This was consistent with the results of two consecutive seasons of data logger data, which revealed a three-stage life cycle of the ice lens, with eventual complete disappearance of ice in the dune by the end of the warm seasons. Nuclear Magnetic Resonance (NMR) logging revealed an increasing water content of the dune with depth under ice lenses.

This transport and entrapment mechanism for protected snow represents a possible explanation for observations of shallow subsurface ice at mid latitudes on Mars.

Background and Introduction

Sand dunes are likely one of the most widespread geomorphological features in the universe (Breed 1979). Dunes of some kind likely occur on any planetary body with an atmosphere and unconsolidated sediments (Breed 1979). On earth, dunes often trap snow in cold climate deserts (Ahlbrandt and Andrews 1978). Snow drifts to the lee side of the dune and is subsequently buried as sand quickly follows (Steidtman 1973). This trapped snow is better protected from temperature and insolation variation than open snowpack and may contribute significant late-season moisture to these deserts (Steidtman 1973). Limited vegetation is often responsible for arrestment of moving dunes, and the presence of vegetation is dependent on moisture (Chen et al. 2004). Complex food webs may even depend on vegetation that is at least partly reliant on trapped snow's melt.

Sand dunes trapping snow in the subsurface is surprisingly common in cold-climate deserts on Earth. This mechanism is well-understood in many ways. Snow has been recorded trapped within dunes in sites as far afield as the North Sand Hills of Colorado, the Gobi desert, the McMurdo dry valleys, and the Red Desert of Wyoming (Ahlbrandt and Andrew 1978, Chen et al. 2004, Steidtman 1973). Researchers investigated snow within dunes in great detail in the 1970s, with most papers attempting to find paleo-climate indicators that would survive into sedimentary rock records. However, researchers have done very little to try understanding the hydrology of these snow structures after they are buried.

As snow melts into dunes, moisture would be expected to spread homogeneously through the dune (Ritsema and Dekker 1994). In an arid environment, this would lead to an expectation of a positive moisture gradient with depth, where greater moisture is found in the deeper regions of the dune, and the shallow upper part of the dune is drier (Ritsema and Dekker 1994). Ristsema and Dekker report a variety of dune moisture depth profiles, suggesting a relationship between moisture distribution and climate.

While the entrapment of snow and ice in cold-climate dunes is well documented on Earth, we are motived to understand the ultimate fate of the water after the snow melts in part to understand dune hydrology, and in part because of interest in how snow and ice may be trapped in dunes on Mars. In 2009, Byrne et al. used remote sensed imagery to identify water ice at several mid-latitude locations on Mars. This was unexpected to some degree, as water ice had mainly been understood from modeling and observation to exist in polar regions of the red planet that experience more stable cold conditions, rather than the mid-latitudes which experience highly variable temperatures including higher peak day temperatures. These ice deposits were observed at shallow depths in the subsurface, on the order of 5 meters below the surface. Implications of mid-latitude ice are wide-ranging and important, including the search for extraterrestrial life and the ability of future missions to Mars to find water for resupply. Aeolian burial is a mechanism that can exist on the simplest of planetary bodies: it does not require phase change, plate tectonics, or even volcanism; all aeolian processes require are limited atmospheres and unconsolidated sediment (Breed 1979). We observe sand dunes in Earth's most "primitive" (and thereby most Mars-like) deserts, and we know that active dunes exist on Mars. This mechanism for producing ice deposits should not be overlooked, particularly on a planet so simple relative to Earth.

In this study, we seek to understand the hydrological life-cycle of snow lenses periodically buried by aeolian deposition each winter in sand dunes of the Red Desert, WY. Aeolian-protected snow could be the key to understanding snow emplacement on the Red Planet, and also seems to potentially play an important role in desert ecosystems on Earth; the snow represents a longer term, stable water source than most available in the desert. This study is unique in that it brings a non-invasive geophysics angle to try to understand these snow lenses. Our questions are these: How persistent through time are snow layers in dunes? What is the fate of the water in these snow layers? Previous work in this regions suggested that frozen material may be present late into the summer and potentially even permafrost may exist, but we hypothesize that in the current climate that entrapped snow is only an annual, springtime phenomenon. Furthermore, we hypothesize that water partitioning to either the atmosphere (evaporation) or groundwater is driven by timing and volumes of sediment transport. We propose that the deeper snow is buried, the longer it is protected from melting. This study investigates these dune-subsurface snow lenses using near-surface geophysical measurements, direct observation including boreholes, and soil data loggers. Geophysical surveys and logger data reveal a multistage story of delayed melting of snow and subsequent, organized spread of moisture into the subsurface of the dune.

Methods

Over spring 2017 and 2018, we studied snow layers in the Red Lake Wilderness Study area using a combination of direct observation via borehole, data loggers, and geophysics. We used soil bucket augers to bore directly through snow lenses, and were able to observe snow buried in the dunes consistently in the early springs of both years. Snow lens locations were easily identified from the surface by a cracking pattern clearly visible on the scoured lee side of the dune, only observable in the early spring (February-March) visits to the site.

Data loggers were planted both springs using the boreholes dug by auger. Two soil moisture and temperature sensors were planted per borehole, with a sensor of each type both above and below the snow lens in the borehole, approximately 2cm away vertically in either direction from the snow-sand boundary. These Decagon sensors (GS1 and RT-1, respectively) recorded volumetric water content and temperature every 15 minutes for their several months in the site. The GS1 determines volumetric water content by measuring capacitance and using frequency domain (70 MHz). The RT-1 is a simple thermistor. These sensors were intended to detect vertical movement of soil moisture, as well as the thermal seasonal cycle of these snow lenses. The GS1's capacitance to water content conversion was calibrated in the lab using sand samples from the field site in order to yield the best possible water content history. We also calibrated the GS1's sensitivity to temperature effects on moisture readings.

We used 250 Mhz shielded Malå Ground Penetrating Radar (GPR) (GuidelineGeo, Sweden) to investigate the structure of the dune's interior, along a transect parallel to dune movement. The GPR was triggered automatically every 0.5 s and later corrected for topography based on the DGPS elevations. GPR processing was done using ReflexW (Sandmier Software, Germany) and the applied steps included : 1) subtract-mean/dewow to remove low frequency instrument noise, 2) energy decay gain to enhance late-time signals, 3) subtracting average with a 25 trace window to suppress background noise, and 4) a frequency bandpass to suppress trace noise.

We measured unsaturated water content versus depth in the dune using Borehole Nuclear Magnetic Resonance (NMR). NMR sends out an electromagnetic pulse that perturbs hydrogen atoms constituent of water molecules, making them oscillate in a background magnetic field. The NMR measures the time it takes the water to return to its stable status, known as relaxation time. Thus NMR directly reveals volumetric water content and the relaxation time can indicate if the water is bound to grains or free-flowing. Frozen water (snow) does not produce a measurable NMR signal with this instrument setup and is therefore distinguishable from liquid water which can be imaged using this technique. Due to the dynamic nature of the dune, new boreholes had to be dug by hand using a 0.06 m bucket auger every visit to the site. Old boreholes would simply become buried and lost to the dune. These boreholes were typically shallow (<2m), targeting the fresh snow lenses in the subsurface, and NMR was sampled at 0.25m intervals, however one deeper borehole (4.5m) was installed and was sampled every 0.5 m. The logging NMR instrument was a Vista Clara DART NMR, with a frequency of 410-480 kHz, and a minimum echo spacing of 400 microseconds. DART's vertical resolution is ~22.86cm, making our .25m intervals about as fine resolution as we could achieve. The sensitive diameter of the DART is between 0.13 and 0.15 m, so our measurement was free from any disturbance caused by installing the 0.06 m diameter boring.

A profile of the dune was made using Electrical Resistivity Tomography (ERT), which essentially maps out a 2-D transect of the dune's resistivity. Snow would be apparent as it has a very high resistivity, and sand's resistivity will vary with water content. That correlation can be described using Archie's law, and a lab experiment to produce such a curve was conducted, hence some ERT figures in this paper showing water content rather than resistivity values. Resistivity was measured using an 8-channel Advanced Geosciences Inc (AGI) SuperSting, with a roll-along (36% overlap) Wenner array measurement. Electrode placement yielded acceptable, low contact resistances with average contact resistance was 1.6 kΩ and a standard deviation of 0.54 kΩ.

Measurements locations were recorded using Global Positioning System (GPS), with borehole and logger locations recorded using a handheld Garmin GPS. GPR and ERT measurement transects were recorded using a Trimble GeoXT Differential GPS, and later post processed using a permanent base station to produce high-accuracy (cm-scale) transects.

Dune movement rate was calculated using historical aerial photography and satellite imagery. The windward surface of the dune was digitized by hand and converted to KML, and displacement was recorded and compared to time between imagery to generate a velocity for these dunes.

Results & Interpretations

Snow was found at the Red Desert field sites readily in early spring in both seasons of field work. Simple boreholes on the downwind side of the dune revealed the top of a snow layer between 10 and 50 cm deep, and approximately 20 cm thick. The ease with which these snow lenses were found year after year across wide areas of the dune (and in fact these lenses were observed in other dunes on the hike to the particular field site, both years) suggests that this is a consistently recurring phenomenon in the Red Desert.

We investigated the depths of the dune in several ways, notably with deep boreholes, ERT (fig. 2), and GPR (fig. 5). Our electrical resistivity tomogram (fig. 2) reveals a non-uniform pattern of resistivity in the interior of the dune. Changes in resistivity are assumed to represent changes in water content in the otherwise materially homogenous dune. Resistivity can be correlated with water content with an Archie’s law equation, derived from lab measurements of sample’s change in resistivity with water content change. We interpret the non-uniform pattern of water infiltration as resulting from melt of discrete, subsequent snow deposits, hence the fingering-out of the plumes from different snow supplies.

Our Ground Penetrating Radar survey was revealing, both by what it illuminated and what it failed to show (fig. 5). At shallow depths, the GPR revealed a typical dune stratigraphy, with sand beds truncated at their tops and overlying other beds. At greater depths, the radar signal is highly attenuated, surprising for a sand dune (typically sand is thought of as a perfect medium for radar survey). We attribute this rapid attenuation with depth to the relatively high water content (and therefore higher conductivity) of these dunes.

Logger data reveal an intimate history of phase change and subsequent dispersal of moisture in the interior of the dune. Initially, snow is protected from significant thermal change and the soil surrounding these layers exhibits a low heat capacity; it is warmed up and cooled down by small amounts repeatedly. As conditions warm, temperature sensors stabilize and then eventually flat line at 0 degrees C for approximately one week until reaching a threshold where they start to climb and moisture values follow quickly. By late March, soil temperatures were all above 0 degrees C (Fig 3). We interpret this as a phase change from solid to liquid water; all of the snow must be raised to 0 degrees in order for the lens to melt to liquid water. After all the snow melts to liquid, a cavity is formed where there once was snow, disturbing coupling of the soil moisture sensors, likely leading to the odd soil moisture readings recorded after April 1, 2018 (Fig 3). Shortly after, we suppose as moisture is further lost from the former snow lens, temperature fluctuations begin to vary rapidly again. This suggests movement of snow-lens melt moisture downward into the dune.

The borehole NMR (fig 4) directly measured intradune water content (theta), which varied with depth in differing patterns depending on season of measurement. In winter, water content was generally higher right at the surface, and decreased with depth up to a point before increasing again through about 2m. In spring (May 2018), water content was lower at the surface, and increased with depth down to .5 m before decreasing again towards 1.5m depth. In summer measurement (June 2017), the water content varied in a similar way as it did in winter; water content was high at the surface and decreased with depth, then increased again through to 1.5m.

The sediment of the dune was mostly very well sorted quartz grains, equant, well-rounded, and very fine; we would call it a “Quartz Arenite” in rock form. Minimal iron-rich grains were also found in the sand (<1% by volume), actually causing problems at one point with an NMR measurement as the iron material stuck to the NMR probe’s strong magnets, leading to a very high error such that we ended up throwing out that measurement.

Discussion

Where does entrapped water go?

The results of our measurements clearly show that, while snow is regularly stored in these dunes, snow remains a short-lived phenomenon. While burial of the snow in the dune’s subsurface does indeed protect these lenses from solar radiation better than the open snowpack, evidence seems to be against the existence of these snow lenses year-round at this site. Frozen snow-sand-ice matrix would be expected to have resistivity $>10^5$ ohm m (e.g., Kang and Lee, 2015), at least two orders of magnitude greater than our inversion results indicate is present in the due (Figure 2). Both years that we instrumented snow lenses, the snow lenses expired by April and the loggers were reading above 0 values by late March; only a month or so after deposition. Snow lenses are very unlikely to survive long enough to become buried very deep in the dune or last much into summer.

Moisture is found quite deep in the dune and varies spatially and with time. The borehole NMR (Fig 4) is the best tool to measure this water content variation in a vertical profile to any depth (see methods section). Ritsema and Dekker (1994) report VWC profiles in a similar way for their wide spatial variety of dunes; the Red Desert dunes’ profiles are very similar to different locations across the globe depending on what time of year the measurements were made. This might suggest that moisture distribution in a dune changes on a time scale that requires averaging across a year in order to generalize; a measurement at a single point in time may not be enough. The wider, more 2-D distribution of water content through the dune measured by the ERT is similar to the contour plots Ritsema and Dekker (1994) measured with over 250 samples per site; our transect was interestingly most like dunes measured on the beach of Sevilleta and elsewhere in Europe, possibly suggesting that the Red Desert is more wet and vegetated than the dunes Ristema and Dekker measured in White Sands or Juarez. However, we suggest again that timescale is important for moisture distribution in a dune system whether it traps snow or not; both our ERT measurement and the measurements by Ritsema and Dekker are just snapshots of a dynamic system that needs better constraint with more measurements over time. Even when buried by dunes, snow layers seemed to be more effected by sublimation than other processes; Lindsay (1973) found that the snow layers were “overlain by damp and underlain by dry loose sand”, suggesting that little melting took place but upward movement (and perhaps some condensation) took place.

In 1973, researchers found snow lenses in the Red Desert as well (Steidtmann 1973). However, they found a different story: much larger lenses, buried quite deep, and that lasted until at least August (Steidtmann 1973). This led to our hypothesis that snow lenses may last permanently; however, conditions seem to not preserve snow over multiannual timescales during our period of observation. The possibility of climate change effecting dune-snow water storage processes raises questions about the dune ecosystem’s stability: snow melt is one of the most, if not the most important source of moisture for this area (Ahlbrandt and Andrews 1978). Vegetation grows on many of these dunes, predominantly on the crest and lee of the dune. If these snow layers’ slow melting is important to this vegetation, has changing the timeframe of the melt cycle changed this ecosystem? Vegetation is well-known to play an important role in dune stabilization (textbook citation). Is there perhaps some stable state, or a range of states this system fluxes between, balancing vegetation's need for moisture and the dune's ability to trap moisture by burying in snow, understanding that this movement is in part impaired by vegetation?

Chen et. al (2004) investigated the stability of "stationary" sand dunes in Inner Mongolia and identified them as connected to a potential water resource for the region. In this location, groundwater is suggested to control the stability of dunes, but this water was found to originate 500km away from snowmelt in mountainous terrain. This groundwater has stabilized these dunes for over 4500 years; a tremendous amount of time for a dune to reside in the same place (Koster 1988). Similarly, the Nebraska Sand Hills are stabilized in wet periods by vegetation, but in dry periods become mobile and actually create wetlands as they dam streams (Loope and Swinehart, 2000). These suggests to us that if the Red Desert dune field were to be much wetter, the dunes might be stable to the point of immobility. Both with groundwater and vegetation, it seems there is a fine line between dunes being able to trap enough snow to be wet, and the area receiving so much precipitation that the dunes stop moving.

Dunes in the context of paleoclimate

The 1970s and 80s saw a flurry of papers about snow in dunes, or "niveo-aeolian" interaction, with the intent of observing the features left after ice melts out to be used as paleoclimate indicators. Ahlbrandt and Andrews, 1978 describes "distinctive features" left behind by ice lenses melting in the North Sand Hills near Walden, CO. A similar study in North West Alaska is described by Koster and Dijkmans in their 1988 paper, again regarding these features as paleoclimate indicators. The broad spatial distribution of cold-climate dune systems suggests that this hydrological system is likely quite important for local ecosystems, and may be highly important as one of the simplest mechanisms for storing water. In more dry, and thus more primitive environments this may be the only source of freshwater or water at all: J.F. Lindsay observed interbedded snow layers in dunes in the lower Victoria Valley of Antarctica in 1973. Environments with limited precipitation, high sublimation rates and very cold climate regimes may not be able to store moisture well without such burial taking place.

Context for interpreting ice cored dunes on Mars

In 2009, Byrne et. al used remote sensing to watch as a meteorite impact exposed subsurface water ice on Mars. Especially interesting was that these deposits were found at mid-latitudes (surface ice on Mars is understood to migrate from pole to pole with the season), and that they were fairly shallow; up to 1 meter below the surface. Given the right conditions, we suggest that burial by dune movement might be a convincing method for trapping and preserving this ice on the Red Planet.

Conclusions:

Dunes provide a rapid mechanism for burying snow accumulation and protect that snow from solar input more than snow on the open surface is protected. We hypothesized that such entrapped snow is, in the current climate, an annual, springtime occurrence. We also hypothesized that water partitioning to either atmosphere or groundwater is driven by timing and volume of sediment transport. Essentially, we suggested that the deeper snow is buried, the longer it is protected from phase change.

We can, through multiple observations, conclude that entrapped snow is a shallow, annual, short-lived phenomenon rather than a long-term deep buildup of permanent snow or ice. Our observations of the snow layers that do form all show full melting of the snow by late spring.

Also, our resistivity measurements of the dune found no extreme outliers in the resistivity range that would suggest snow was buried at depth. Lastly, our direct boreholes, dug several meters deep on both the windward and lee side of the dune, found no snow greater than half a meter down at any point in time.

While our study did not directly quantify water partitioning in this system, our observations allowed us to learn a significant amount about how phase change and subsequent water partitioning works in this system. Our observations show that snow is initially protected from significant thermal variation by its burial; subsequently, while the snow melts, the sand above the snow is far more wet than the sand below, suggesting that significant atmospheric loss occurs (sublimation or evaporation). After some time, the two moisture sensors show the same value, suggesting an equal amount of moisture movement both out of and into the dune occurs. More sediment transport onto the dune should shift this system towards more moisture moving downward into the dune; less sediment should shift the snow layer towards sublimation and evaporation.

Dunes are often simply left to the desert; perhaps they are too often overlooked as a well-understood system. While the movement of dunes and the sorting they produce is well documented, the hydrology of such niches seems to be left out to dry. In order to understand such a dynamic system, permanent boreholes, sampling, or destructive excavation seem to be non-ideal methods. Water changes far too quickly in any soil to only sample once. Using geophysical methods to measure temporal variation in moisture content and spatial distribution of that water allows us to take a “time-lapse film” of liquid water movement in the subsurface, as well as allowing us to capture phase change.

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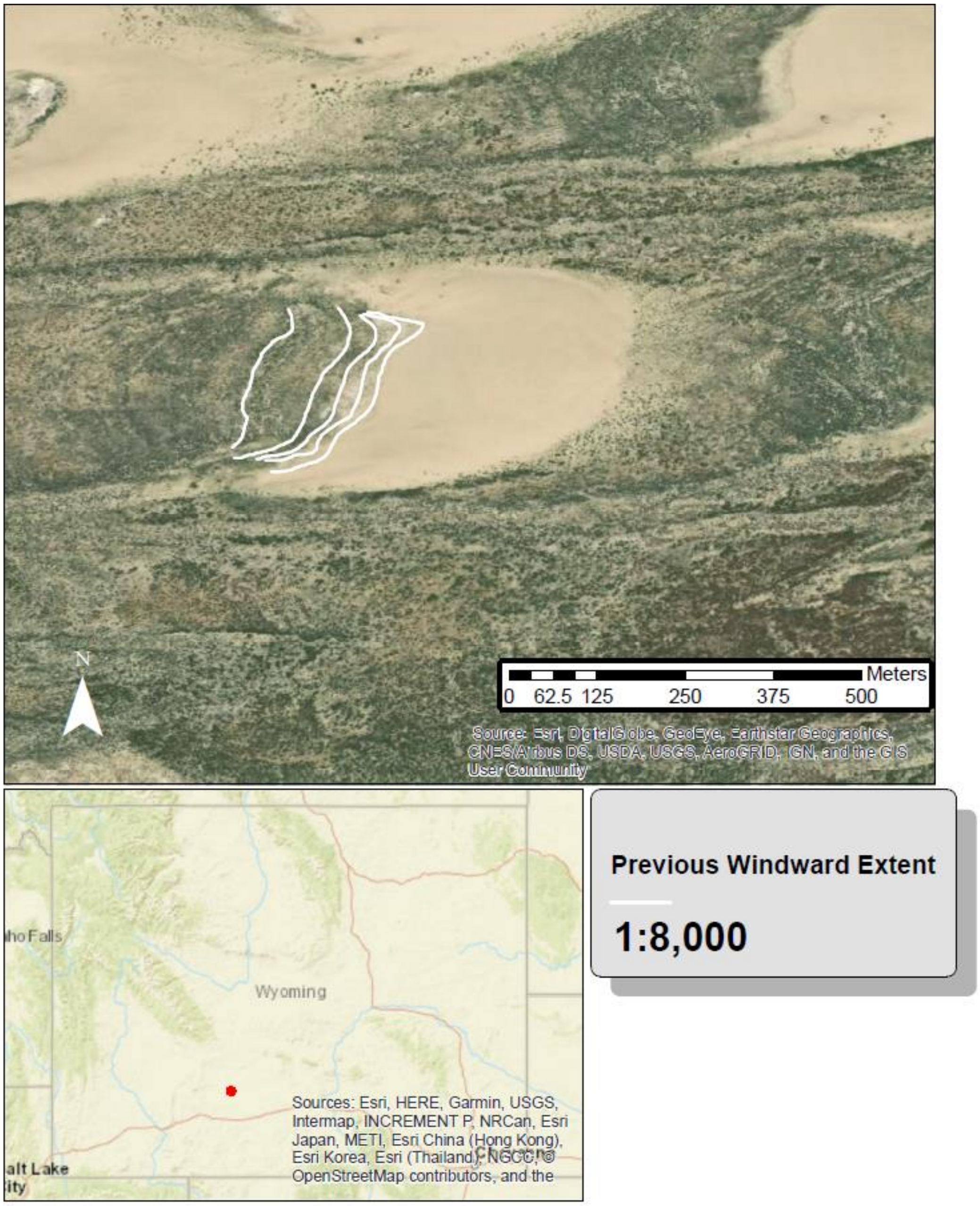
Figures:



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

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Figure 1: Top: Study site dune, with previous windward extents marked by white lines. Bottom: Location of the Red Lake Wilderness Study Area and field site.

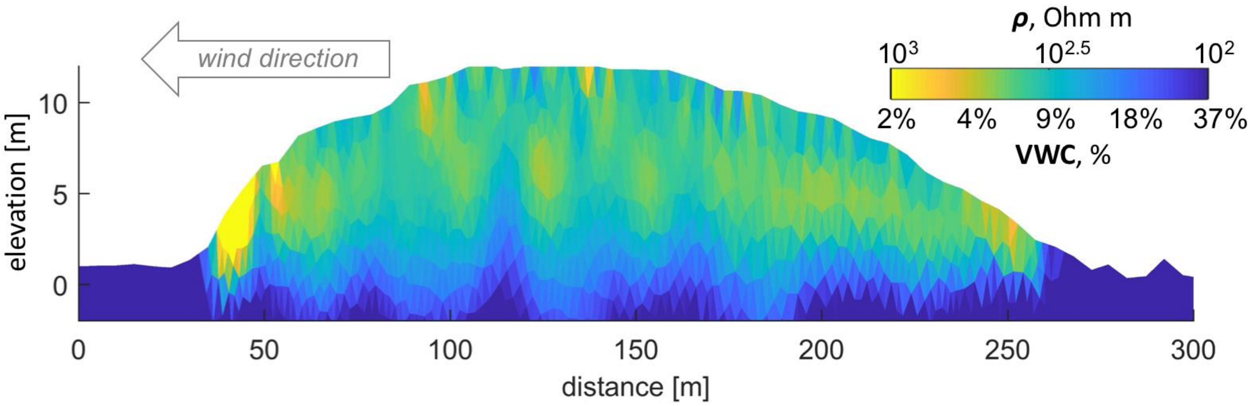
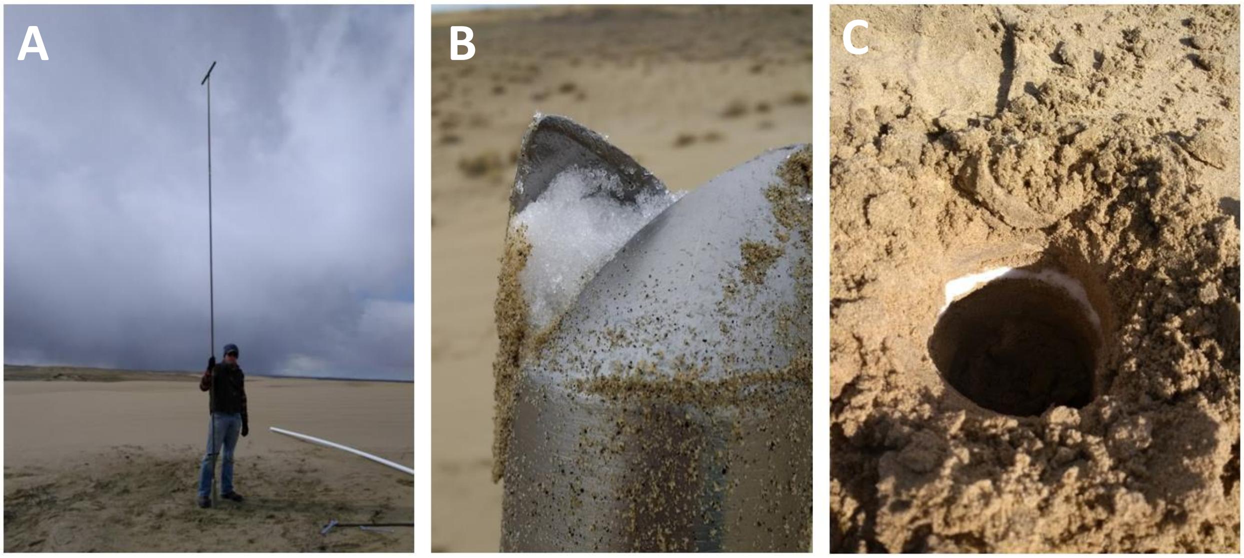


Figure 2: Dune Resistivity Profile. Light, hotter colors indicate high resistivity and low volumetric water content. Dark, cooler colors indicate low resistivity and higher volumetric water content.



Photos Left to right: A: Hand-turned Bucket Auger fully deployed, well casing to right of technician. **B**: Snow in Auger from buried layer. **C**: Snow layer in the shallow subsurface of the dune.

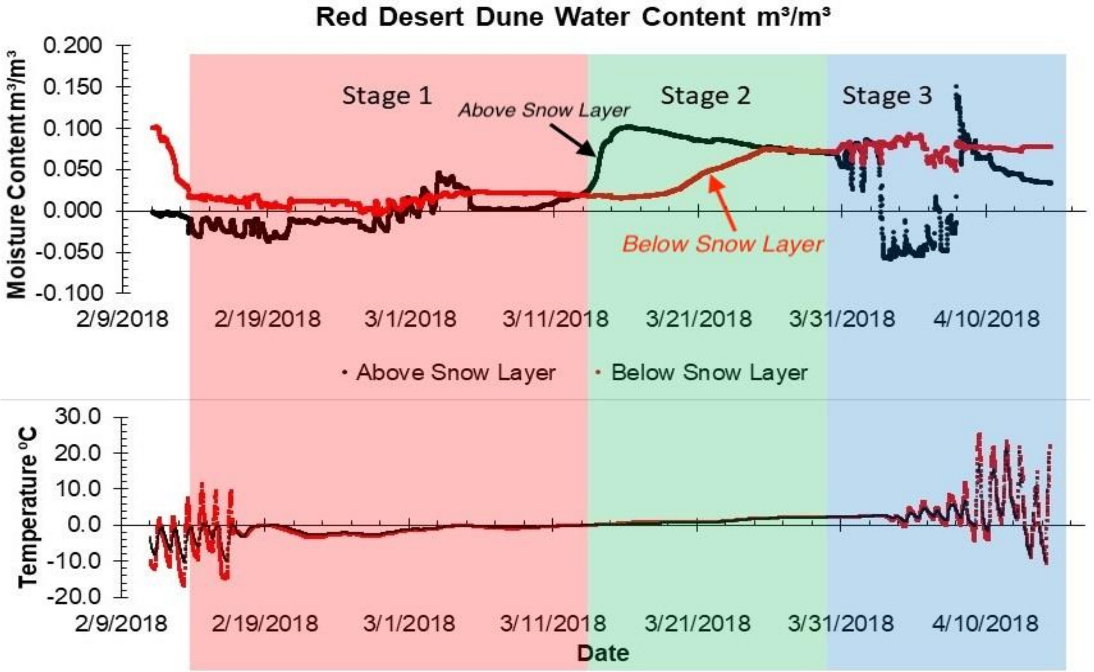


Figure 3: Soil moisture and temperature loggers over the lifetime of a snow lens, 2018.

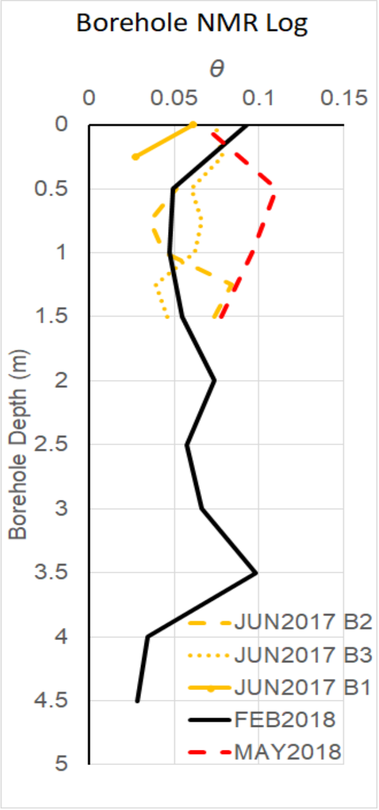


Figure 4: Borehole NMR collected from June 2017 to May 2018.

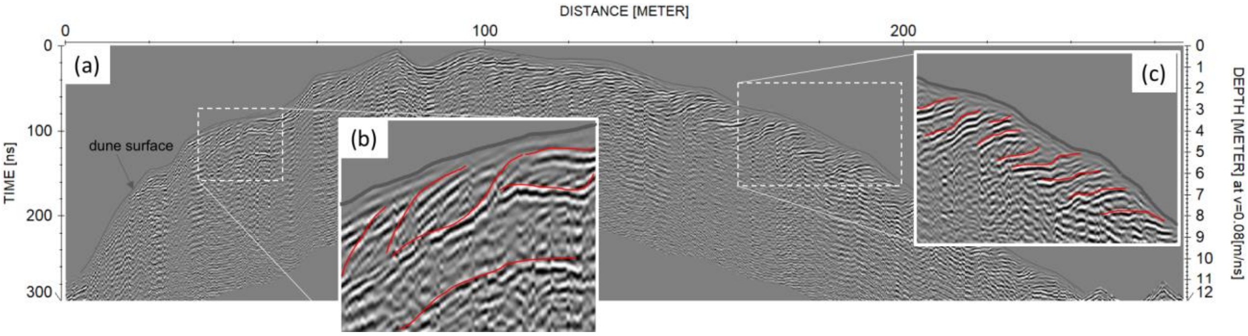


Figure 5: a) Ground penetrating radar image of the dune. Insets show (b) the leeward side of the dune and (c) the windward side of the dune.