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6th international conference on Mars polar science and exploration: Conference summary and five top questions

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ABSTRACT

We provide a historical context of the International Conference on Mars Polar Science and Exploration and summarize the proceedings from the 6th iteration of this meeting. In particular, we identify five key Mars polar science questions based primarily on presentations and discussions at the conference and discuss the overlap between some of those questions. We briefly describe the seven scientific field trips that were offered at the conference, which greatly supplemented conference discussion of Mars polar processes and landforms. We end with suggestions for measurements, modeling, and laboratory and field work that were highlighted during conference discussion as necessary steps to address key knowledge gaps.

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1. Conference summary

1.1. General scientific content

Mars' polar regions are of special interest to atmospheric scientists and geologists alike. The poles have unique and active atmospheric processes coupled to those at lower-latitude regions, as is exemplified by the frontal dust storms that periodically spill over from the polar caps into lower latitudes. Mars' icy deposits at all latitudes are intimately connected to the atmosphere and driven by climatic processes, so the two can only be interpreted in the context of each other. Additionally, just as terrestrial ice caps do on the Earth, Mars' polar caps record past climate conditions over variable timescales in their layers. Thus, the Martian poles and icy deposits are a unique source of important information about Martian history as a whole. The ages of icy deposits on Mars, and thus the climate record that they contain vary greatly. From the seasonal frost that lasts only a fraction of a year to the south polar residual cap (SPRC) that has persisted for maybe a few kyr, and the polar layered deposits (PLD) that were emplaced millions to tens of millions of years ago, we can learn a lot about the current and historical climate on Mars.

For nearly two decades, our understanding of the Martian polar regions has been greatly advanced by the analysis of data acquired by the 1996 Mars Global Surveyor, 2001 Mars Odyssey, 2003 Mars Express, and 2005 Mars Reconnaissance Orbiter spacecraft (MRO), as well as the 2007 Phoenix lander. Data from these missions have yielded valuable observations of topography of the poles, submeter scale images of exposed stratigraphy, radar sounding of internal structure and basal topography, year-round coverage of the thermophysical, radiative and compositional properties of the polar deposits, and in situ investigations of the near-surface composition, including volatiles, and meteorology. Furthermore, comparisons of polar features to terrestrial analogs have proven to be very fruitful

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towards understanding the processes involved in formation of the features.

1.2. History of the polar science conference

The International Conference on Mars Polar Science and Exploration (ICMPSE) has been held regularly since 1998. The locations, dates, and references of proceedings of the conference series are as follows:

- 1st ICMPSE, Camp Allen, Texas, October 18–22, 1998 (Clifford et al., 2000)
- 2nd ICMPSE, Reykjavik, Iceland, August 21–25, 2000 (Clifford et al., 2001)
- 3rd ICMPSE, Lake Louise, Alberta, Canada, October 13–17, 2003 (Clifford et al., 2005)
- 4th ICMPSE, Davos, Switzerland, October 2–6, 2006 (Fishbaugh et al., 2008)
- 5th ICMPSE, Fairbanks, Alaska, September 12–16, 2011 (Clifford et al., 2013)
- 6th ICMPSE, Reykjavik, Iceland, September 5–9, 2016 (this paper)

One hallmark of this conference series is defining a set of key current questions, required observations, and recommended investigations that define the current status and future direction of the field. Typically, about five key questions summarize the most important questions facing the field. The lists of former key questions from each conference can be accessed at the above references, and the list identified at the end of the 5th conference (Clifford et al., 2013), was as follows:

1. What are the physical characteristics of the polar layered deposits (PLD) and how are the different geologic units within, beneath, and surrounding the PLD related?
2. How old are the PLD, and what are their glacial, fluvial, depositional, and erosional histories?
3. What are the mass and energy budgets of the PLD, and what processes control these budgets on seasonal and longer timescales?
4. What chronology, compositional variability, and record of climatic change are expressed in the stratigraphy of the PLD?
5. How have volatiles and dust been exchanged between polar and nonpolar reservoirs, and how has this exchange affected the past and present distribution of surface and subsurface ice?

Significant progress has been made with respect to all of these questions, but as discussed at the 6th conference, important investigations remain to be completed in each. As we discuss in this document, areas of high-priority study have evolved and include a more holistic perspective than an explicit prioritization of the PLD. Additionally, activity driven by seasonal frost and seasonal frost-related processes is an area of investigation that has expanded greatly since the 5th conference.

1.3. The specifics of this conference

The 6th International Conference on Mars Polar Science and Exploration (6th ICMPSE) was held September 5–9, 2016 at the University of Iceland in Reykjavik, Iceland. Reykjavik was chosen as the site of the 6th conference because of the city's relative accessibility to North American and European contributors and due to the proximity of excellent polar geomorphic Mars analogs, including ice caps, active glaciers, flood basalts, and hillside gullies carved by running water. Expert guidance from local scientists at the University of Iceland and the University of Nantes assisted in the organization of multi-day pre-conference and post-conference field trips along with several options for a one-day mid-conference field trip.

The conference was designed to pull together the current state of Mars polar research from many fields, including geologic, atmospheric, and climate sciences. In the presentations, advancements based on current mission data, field studies, laboratory work, and modeling were discussed. Additional foci were on concepts for future measurements and missions needed to answer current questions, and on finding terrestrial analogs that can enhance our interpretation of remote sensing data from Mars. One goal of this meeting was to set options and priorities for such measurements and to serve as an important resource for those scientists wishing to develop instruments, propose missions, or participate as a member of a science team in response to future Announcements of Opportunity. Every session was held as a plenary set of presentations, and after each technical session, ample time was allotted for community discussion. During the conference the authors of this paper recorded outstanding questions and methods that arose during presentations and discussion, and those comprise much of the input to this report.

The 6th ICMPSE attracted more than 100 attendees from eleven countries. A list of the abstracts and sessions can be found on the conference website: http://www.hou.usra.edu/meetings/marspolar2016. Student participants numbered 22, suggesting that Mars polar science is of great interest to incoming planetary scientists. A large percentage of presentations featured recently acquired mission data and recently generated higher-level data products. The new datasets and youthful enthusiasm showed that many new, exciting discoveries are happening.

1.4. Field trips

A total of seven options for field trips were available to participants and guests. There was widespread participation in visiting the outstanding Mars glacial and volcanic analog sites that Iceland has to offer. Expert guides led each trip, revealing the beautiful geology and Martian analogs of Iceland.

Prior to the conference, 21 attendees and guests were led to the north of Iceland to visit numerous volcanic and geomorphic landforms. Highlights included visiting Lake Mývatn and its surrounding rootless cones, hiking over Askja volcano to the caldera lake, seeing the 2014–2015 new Holuhraun lava field, Herðubreið tuya, Jökulsárgljúfur canyons and the Ásbyrgi depression, Dettifoss waterfall, and Húsavík village's whale and exploration museums. Participants slept in shared highland huts and cooked their own food.

Three mid-conference field trips left from Reykjavik on September 7th and returned that evening. An "Interior Iceland" trip explored major aspects of the geology and glaciology of Iceland, including a hike onto Langjökull glacier at Skálpanes with vistas of glacial dynamics and morphology along with subglacial volcanism. Evidence for volcano-tectonic activity was illustrated by shield volcanoes, pillow lavas, extensional faulting, and fractures at Thingvellir National Park. The "West-coast Iceland" field trip demonstrated various Martian analogs, such as periglacial landforms (polygons and patterned ground), debris flows, and gullies. The "Southern-coast Iceland" trip explored Sólheimajökull outlet glacier flowing from the Mýrdalsjökull ice cap and allowed participants to walk on the glacier while observing dirt cones, moulins, and moraines.

After the conference, many attendees and guests participated in post-conference field trips. The two-night Southern Iceland trip took participants along the southern coast to visit the South Iceland volcanic zone, which includes the junction between the Eurasian and North American tectonic plates, the infamous Eyjafjallajökull (E-15) volcano, Skógafoss waterfall, the Skeiðarársandur glacial flood (jökulhlaup) outwash plain, Skaftafell National Park, the Jökulsárlón glacier lagoon from the Breiðamerkurjökull outlet glacier, and Höfn village.

On the one-night Western Iceland trip participants visited a settlement center in Borgarnes, Eldborg volcanic crater, birdcliffs at Arnarstapi, Snæfellsjökull volcano (famous for Jules Verne's Journey to the Center of the Earth) and surroundings, the northern part of Snæfellsnes peninsula, and the town of Stykkishólmur with a view to the starting point of Viking age voyages to North America, and a volcano museum.

Finally, on the one-day shield volcano hike, several participants drove to the northern slope of the ~9000 year old Skjaldbreiður shield volcano and hiked to the summit crater at 1060 m. The hike offered views of Langjökull, the second largest ice cap in Iceland, plus Martian analog tuyas and tindar ridges, formed in subglacial eruptions during the last glacial period.

2. Key Mars polar science questions

The following Key Questions were generated by the synthesis team at the 6th ICMPSE based on the results presented by conference attendees. As is common throughout science, all of the biggest currently open questions in Mars polar science relate to areas where we know enough to refine the question we seek to answer, but progress has not yet been sufficient to yield a full understanding. Within this section, we outline our five Key Science Questions. These questions are high-level and provide context for the specific investigations that were expressed at the conference, also included. Within the text, we briefly describe the state of knowledge and highlight important progress that has been made since the 5th ICMPSE. We then describe the context for the listed investigations more fully. Five specific investigations were deemed by the community to be the highest priority going forward. They are underlined in the text.

It is important to stress that the adjective *polar* does not have a single definition. In a geological or atmospheric sense, we use *polar* to refer to high-latitude processes involving the unique thermal environment of the region, and usually involving volatiles in solid form. The scope of the conference and of these questions encompasses not just the polar perennial ice caps, but also seasonal activity related to volatile solid states, the circumpolar plains, and the atmosphere above these locations. In addition, topics also include polar-related ice ages and atmosphere/ice-related processes that have periodically driven significant quantities of ice to equatorial latitudes.

Question 1, Polar atmosphere: What are the dynamical and physical atmospheric processes at various spatial and temporal scales in the polar regions, and how do they contribute to the global cycle of volatiles and dust?

(a) *Quantify the interplay of local, regional, and global circulations in the polar regions, including polar vortex, katabatic winds, transient eddies, among others*
(b) *Characterize the transport of volatiles and dust aerosols into and out of the polar regions*
(c) *Understand and predict the condensation of H_2O and CO_2 ice clouds and their impact on the thermal structure and atmospheric circulation*
(d) *Estimate the amount of CO_2 and H_2O frost deposited and lost at the surface via precipitation, direct deposition, or sublimation*
(e) *Determine dust deposition patterns over the polar caps and the specific mechanisms enabling dust lifting in polar regions*

This question is important to both atmospheric scientists and geologists/ glaciologists, because surface-atmosphere interactions are key to understanding the formation and perseverance of various volatile deposits in the polar regions and mid-latitudes. Moreover, any attempt to extrapolate our knowledge of the current atmospheric activity at the martian poles to the past evolution of those poles (Question 3) should rely on a robust understanding of the current physical and dynamical atmospheric state. Pressure and temperature, winds speed and direction, and volatiles and aerosols content are parameters that describe the atmosphere's current state and its interactions with the surface deposits.

The martian polar ice deposits are characterized by uneven topography and strong local thermal contrasts, which cause local and regional dynamical circulations: notably, baroclinic fronts and transients (Toigo et al., 2002; Tyler and Barnes 2005) and downslope katabatic winds (Spiga, 2011, Smith et al., 2014). The martian polar regions are also strongly affected by the planetary-scale Hadley circulation; for instance in wintertime when the descending branch of this circulation largely modifies the atmospheric thermal structure above the polar caps (Fig. 1, McCleese et al., 2008). Advancing our knowledge of the atmospheric circulation above the martian polar caps is thus a means to assess the current global climate on Mars. The interplay of the polar circulations at all scales is also key to understanding the transport of volatiles and dust aerosols in and out the polar regions and to explain the geomorphic features on the poles, which are modified by the near-surface winds (e.g. chasmae, spiral troughs, dune fields, and eroded reentrants).

At the 6th Conference, the importance of the Martian polar vortex (McCleese et al., 2016, 6th ICMPSE) and its deep connection to the global climate (Guzewich et al., 2016, 6th ICMPSE) were highlighted. Ozone measurements showed that the polar vortex acts as a transport barrier for volatiles (Holmes et al., 2016; Neary et al., 2016, 6th ICMPSE). Martian regional-scale katabatic winds were emphasized as an important component to understand the shape and modification of the polar deposits (*Spiga and Smith*, this issue). The radiative effect of water-ice clouds was acknowledged as a key impact on the thermal structure that needs to be further explored (Neary et al., 2016, 6th ICMPSE; *Spiga and Smith*, this issue), as do the mechanisms for water vapor transport (*Tamppari*, 2016 6th ICMPSE). The formation of CO_2 clouds in the polar regions was shown to modulate the polar circulations (Banfield and Neumann, 2016; Kuroda et al., 2016, 6th ICMPSE), cause potential super-saturation and latent heat release (Kleinböhl et al., 2016; Noguchi et al., 2016, 6th ICMPSE), and lead to snowfall precipitation (Hayne et al., 2016, 6th ICMPSE).

Question 2, Perennial Polar ices: What do the characteristics of Martian polar ice deposits reveal about their formation and evolution?

a. *Determine the energy and mass balance of the polar ice reservoirs, and characterize volatile fluxes (i.e., seasonal deposition and removal, long term accumulation vs. erosion, when and where, at what rates)*
b. *Characterize current/recent perennial ice landforms such as the south polar residual cap and associated features (i.e., distribution, variety, composition, and evolution of the topographical properties) and their relationship with seasonal processes*
c. *Quantify the role and efficiency of dust and sand as agents promoting the preservation of buried volatile reservoirs*
d. *Determine the vertical and horizontal variations of composition and physical properties of the materials forming the polar layered deposits*
e. *Identify and quantify the differences and similarities between the water-ice units of the north and south polar caps*
f. *Identify where ice flow model predictions do not match observations and form hypotheses as to why the two do not match*

The characterization and inventory of the reservoirs of polar ices (Fig. 2) is a work in progress. The Viking mission confirmed the presence of perennial CO_2 ice in the south polar region (Fig. 2c, Kieffer, 1979), with just water ice in the north (Kieffer et al., 1976). Viking also observed a layered structure exposed within the walls

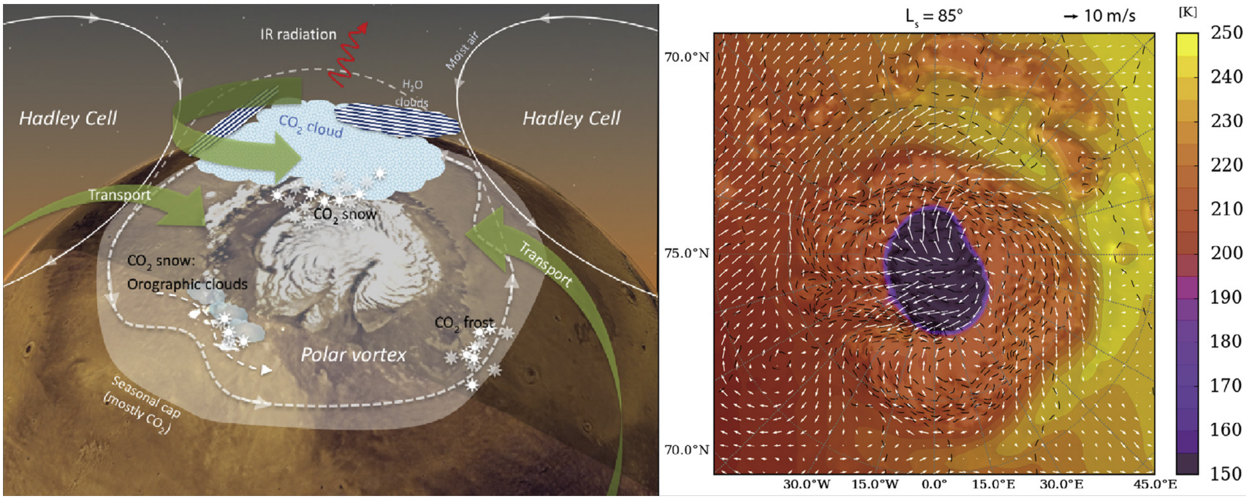

Fig. 1. [Left]. Summary of the major large-scale atmospheric processes in the martian polar regions (McCleese et al 6th ICMPSE, permission granted by D. McCleese). The Hadley cell is the seasonal meridional circulation that connects the polar regions to lower-latitudes, resulting in transport of volatiles. The polar vortex acts somewhat as both as a latitudinal transport barrier and as a circumpolar transport agent in a longitudinal perspective. Extreme temperature conditions in the Martian polar regions lead to the formation of CO_2 and H_2O clouds which, in turn, play a significant role in the radiative budget of the martian polar regions. [Right] Surface temperatures and wind speeds at the north pole during late spring (Spiga and Smith 2016 6th ICMPSE) The transport induced by large-scale circulations is complemented and locally overpowered in the immediate vicinity of the polar caps by mesoscale circulations: downslope katabatic winds modulated by seasonal cap thermal gradients and mesoscale transients.

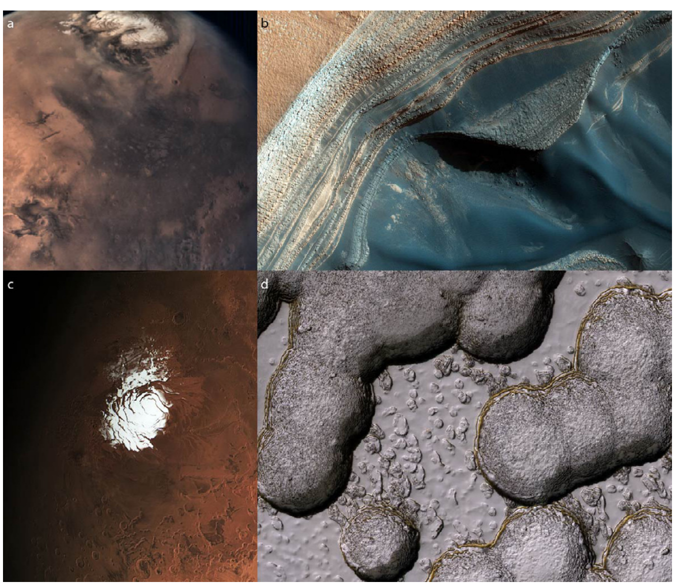

Fig. 2. Perspectives on Mars polar caps. (a) Image of Mars' north pole from the Mars orbiter mission. Large-scale features such as the spiral troughs and Chasma Boreale are visible. Clouds near the polar cap demonstrate the interaction of the polar regions with all of Mars. (b) Sedimentary layers record the history of the north polar cap evolution. HiRISE image ESP_03,6436_2645. (c) South polar residual cap (SPRC, white) and the surrounding SPLD from Mars Express image 3227_1e. The darker colors are due to being covered by a thick dust lag. (d) Sublimation features on the SPRC. HiRISE image ESP_01,4379_0925.

of spiral troughs in both polar layered deposits (PLD), giving them their name (Blasius et al., 1982). Mars Odyssey data were later used to discover and map exposed water ice in the south (Titus et al., 2003; Piqueux et al., 2008). Starting in 2006, MRO observed exposed icy layers down to 1 m thick and applied sounding radar to reveal the internal structure of the PLD (Plaut et al., 2007; Seu et al., 2007; Phillips et al., 2008) and even unveiled large CO_2 units buried near the south pole, with enough mass to double the atmospheric surface pressure if sublimed (Phillips et al., 2011; Bierson et al., 2016). Those units were recently revealed to behave as glaciers (*Smith* et al., 2016b 6th ICMPSE). In addition, analysis of data along with laboratory experiments and mesoscale atmospheric modeling suggested that other optical and mechanical properties of seasonal CO_2 ice (especially albedo) control the distribution and characteristics of volatiles (Kieffer et al., 2000; Colaprete et al., 2005; Langevin et al., 2005; Langevin et al., 2007; Guo et al., 2010). This continued progress contributes to addressing questions regarding the availability and distribution of perennial volatiles and dust on Mars.

These discoveries challenge our understanding of the current mass and energy balance of the polar regions and, by extension, of the global climate (Pilorget et al., 2016, 6th ICMPSE). Current models of cap formation generally struggle to maintain a perennial CO_2 ice cap and exposed water ice in the south under current environmental conditions (Emmet and Murphy, 2016, 6th ICMPSE). Other shortcomings include preventing unrealistically large volatile fluxes to the north as compared to the measured flux (Brown et al., 2016); explaining the observed north/south differences in age and composition; or simply to form and preserve thick stratigraphic stacks of dusty ice in the south (the SPLD, Question 3). Progress with regards to these questions will require an improved understanding of the physical properties of various ices, dust, and their mixtures, as well as a conceptual framework to explain observed stratigraphic relationships that are not fully explained (e.g.. CO_2 ice layers capped by water ice units in the south).

The existence of highly dynamic landforms able to dramatically change in just a few martian years (e.g., "swiss cheese terrain" in the south polar residual cap, SPRC, Fig. 2d) illustrates the need to understand the mass and energy balance of the ice reservoirs at a small spatial and temporal scale. Studying the compositional and physical evolution of these landforms (e.g. Thomas et al., 2000, 2005, 2009, 2013, 2016; Becerra et al., 2015, Buhler et al., 2016 6th ICMPSE; Carpy et al., 2016, 6th ICMPSE; Herny et al., 2016, 6th ICMPSE) can teach us a great deal about the current mass balance of the larger-scale ice deposits. This information can then be used to perfect the input into climatic and landscape evolution models (*Byrne* et al. 2015; 6th ICMPSE, and Question 3) which aim to explain the initial emplacement of these units.

The importance of studying the compositional characteristics of the various units and layers of the icy deposits on Mars cannot be overstated (Question 3). At the moment, we lack in situ measure-

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ments of the polar deposits' composition, grain sizes, or absolute ages, so various remote sensing studies of the physical characteristics of the layers attempt to infer compositional properties (Grima et al., 2009; Fishbaugh et al., 2010a; Limaye et al., 2012; Becerra et al., 2017; Holt, 2016 6th ICMPSC; *Plaut* 6th ICMPSE; *Lalich and Holt* 6th ICMPSE; *Nerozzi* and Holt 6th ICMPSE). Recent results from these studies were the topic of many discussions and presentations during the 6th ICMPSE, and it is accepted that future studies need to continue to search for ways to use remote sensing to derive compositional properties of the layers.

One remaining enigma is the mismatch between models that predict specific stratigraphy associated with ice sheet flow (Fisher, 1993, 2000; Winebrenner et al., 2008) or viscous relaxation (Pathare and Paige, 2005) and radar observations (Karlsson et al., 2011; Smith and Holt, 2015; Smith, 2017). Even at Mars' polar temperatures, all models of ice sheets agree that there should be evidence of flow, so more work is needed on this topic.

An important motivation for ongoing research is the prospect of correlating radar observations of internal layers and unconformities with optical images of exposures (*Milkovich and Plaut* 2008; Christian et al., 2013) in order to combine the strengths of each data type. Determining the connection between physical characteristics of the layers (e.g., impurities and erosional resistance (Byrne et al., 2016, 6th ICMPSE) or dielectric constant (Lalich and Holt, 2016; 6th ICMPSE) will contribute towards precise modeling of the compositional differences and heterogeneity of these deposits through time (*Becerra* et al., 6th ICMPSE). Finally, a detailed study of layer composition will also contribute to our knowledge of how dust is transported and deposited across the planet (McCleese et al., 2016, 6th ICMPSE; Hvidberg, 2016, 6th ICMPSE).

Question 3, Polar Record of Past climate: How has the Martian climate evolved through geologic history, what are the absolute ages of the observable climate records, and how should we interpret the records of past-states?

a. *Determine and characterize the link between orbitally forced climate parameters and resultant layer properties of the PLD and non-polar deposits, and then invert so as to use the PLD to derive polar and global martian history*
b. *Definitively test the current hypothesis that NPLD formation began at ∼4 Ma*
c. *Estimate the climatic conditions that could have formed the SPLD, given that recent climate is predicted to be unfavorable for accumulation there and that the surface age may be greater than 30 Myr*
d. *Determine if the major SPLD* H_2O *ice units* (AA_1 *and* AA_2*, from* Kolb and Tanaka, 2006*) were deposited in one or multiple periods of favorable climate*
e. *Characterize the processes that led to the buried* CO_2 *ice reservoirs at the south pole, and determine when they took place*
f. *Determine how the SPLD expanse relates to the much larger southern polar deposits in terms of age and climate epochs that are recorded. Specifically, does the Dorsa Argentea Formation (DAF) have origins in an ancient climate and what can DAF presence tell us about that climate?*
g. *Determine the climate forcing that allowed for the development of the south polar residual cap (SPRC), and how it remains in its present-state given that models predict it to be unstable. Estimate its absolute age*

There is abundant evidence to suggest that the internal stratigraphy of the PLD contains a record of past Martian climate. To date, the study of these layers in the north using optical (Milkovich and Head, 2005; *Perron and Huybers*, 2009; *Fishbaugh* and Hvidberg, 2006), topographic (Fishbaugh et al., 2010a, 2010b; *Limaye* et al., 2012; Becerra et al., 2016; 2017) and radar observations (*Putzig* et al., 2009; Smith et al., 2016a.; Holt, 2016 6th ICMPSE) coupled with models of the emplacement of the deposits (Levrard et al., 2007; Greve et al., 2010; Hvidberg et al., 2012), has revealed an important connection between the deposits and the orbital evolution of Mars. However, a detailed understanding of this connection, and how it affects Mars' climatic state and therefore formation of individual layers, is still elusive and will likely remain so until compositional information from in situ sampling is available.

The work above points to various climate environments having been recorded in the PLD over a range of geological periods: the SPRC may only be hundreds of years old (Byrne 2009); the massive CO_2 deposits in the south may be several hundred kyr old (Bierson et al., 2016); the NPLD are estimated to have formed ∼4 Ma (Levrard et al., 2007), and the SPLD must be older than their ∼30–100 Myr inferred surface age (Herkenhoff and Plaut, 2000). In addition, the northern basal unit has been dated at up to 1 Ga (Tanaka et al., 2008), and the Dorsa Argentea formation may represent a relict of an even older period (*Scanlon* et al., 2016 6th ICMPSE). This diverse range of ages thus enables study of many past climates.

Tools developed to better understand the layers of the NPLD (on which most of the work to date has been focused), especially stratigraphic analysis of unconformities (Holt et al., 2010; Smith and Holt 2015; Smith et al., 2016a) and periodicity-analysis of sequences of exposed layers (Milkovich and Head, 2005; *Perron and Huybers*, 2009; *Limaye* et al., 2012; Sori et al., 2014; Becerra et al., 2017), may also be applicable to the older SPLD and basal unit. These may provide much longer baselines for our growing knowledge of Martian climate.

Of particular interest is the age disparity between the NPLD and SPLD. The surface of the NPLD is relatively young at ∼1.5 ka (Landis et al., 2016), and the signals recorded in its stratigraphic record (Putzig et al., 2009; Hvidberg, 2016, 6th ICMPSE) support models of accumulation (Levrard et al., 2007) that place the earliest NPLD ice deposition at ∼4 Ma (Fig. 3). Some units have been delineated for SPLD (Byrne and Ivanonv, 2004; Milkovich and Plaut, 2008; Milkovich et al., 2009), and crater counting estimates put the surface age at ∼30–100 Ma (Herkenhoff and Plaut 2000); however, no estimates of the age of SPLD layers have been established or even seriously attempted. The much older, and much more weathered deposits there make their analysis more complex, so they have been frequently overlooked for their simpler counterpart.

Using the 20 Myr baseline for stable orbital parameters that is mostly accepted by the Mars science community (Laskar et al., 2004), models that do not assume the current SPLD as an initial condition are unable to create them. Even in those models, the SPLD should not have survived the long period from 20 Ma – 4 Ma when the poles were warmer. Earlier times are even more problematic because the long-term average obliquity should have been too high for the SPLD to form or persist. Based on crater statistics, the surface age of the SPLD is 10 to 25 times older than all of the NPLD, and the oldest layers must be even older (Herkenhoff and Plaut, 2000). Therefore, important questions about the age and the composition of the SPLD persist and require much more investigation.

Question 4, Non-polar ice: What is the history and present state of the mid- and low-latitude volatile reservoirs?

a. *Inventory and characterize the non-polar ices/volatile reservoirs at the surface and near-surface (locations, quantities, composition)*
b. *Determine the accessibility of* H_2O *ice deposits as a resource for future human exploration, in particular the conditions and lowest latitudes under which water-ice reservoirs can be found*
c. *Determine the conditions under which the non-polar volatile reservoirs accumulate and persist*

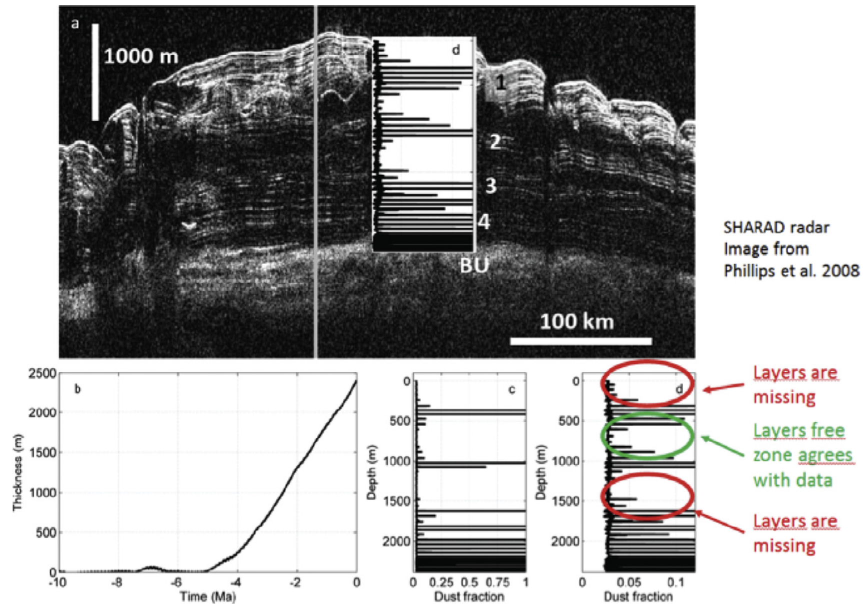

Fig. 3. Model of NPLD growth based on work by Hvidberg et al., (2012). (a) comparison between a SHARAD image and modeled stratigraphic impurities. (b) Modeled thickness of the NPLD from 10 Ma to present (similar to work by Levrard et al., 2007). (c) Simulated dust fraction at a vertical slice. (d) Same as (c) but with finer horizontal scaling to demonstrate how smaller dust fractions can make layers in the NPLD. There is gross agreement between model results and observations (radar - Smith et al., 2016a; and optical - Becerra et al., 2017, Hvidberg, 6th ICMPSE).

d. *Determine how chemical differences (*i.e. *presence of salts) influence the movement of volatiles and their impact on habitability*
e. *Investigate if liquid water exists or has existed in locations associated with mid- and lower-latitude ice deposits. Could these have provided habitats for, or preserved evidence of, past or present life?*

Question 4 focuses on characterizing non-polar volatile reservoirs, especially in the context of understanding their link to polar ice through climatic changes. In addition to its purely scientific value, this topic is also important because of the potential for these reservoirs to serve as resources for future human exploration and/or to harbor habitable conditions. The ice at mid- and lower-latitudes is deposited during periods of high obliquity (Fig. 4h) and sublimated away during low obliquity (Head et al., 2003; Mellon and Jakosky, 1995; Madeleine et al., 2009), responding relatively quickly to equilibrium conditions at those latitudes through atmospheric exchange. Mars Odyssey Gamma Ray and Neutron Spectrometer results (Boynton et al., 2002; Feldman et al., 2002; Mitrofanov et al., 2002) found the water-equivalent hydrogen contents in the upper meter of the surface that are consistent with models of ice stability (Mellon et al., 2004; Schorghofer 2007), corroborating the interpretation that the present ice distribution is in equilibrium with the current climate. However, recent impacts expose and excavate pure water ice (Figs. 4d & e) at latitudes extending further equator-ward than these models predict. This ice has been observed to rapidly sublime, evidence that ice at these latitudes is unstable at the surface in the current climate (Byrne et al., 2009; Dundas et al., 2014).

There are many deposits of nearly-pure water ice across the mid-latitudes, such as lobate debris aprons (Holt et al., 2008; Plaut et al., 2009), thermokarstic morphologies (Viola et al., 2015; Dundas et al., 2015a), and extensive deposits 10–100 m thick (Bramson et al., 2015; Stuurman et al., 2016a) (Fig. 4). The Phoenix lander (at 69° N) found both pore-filling and excess ice within the upper centimeters of the surface (Mellon et al., 2009; Smith et al., 2009). These morphological features, along with lineated valley fill and concentric crater fill, have been interpreted as parts of an integrated glacial system characteristic of the Amazonian climate (Levy et al., 2010) and contain large amounts of water ice (Karlsson et al., 2015). Meanwhile, at even lower latitudes, global circulation models suggest that ice is deposited on the flanks of volcanoes as tropical mountain glaciers in high obliquity excursions (Forget et al., 2006) or on the Tharsis plateau (Madeleine et al., 2009), and remnants of these deposits may persist today under a thick protective cover of debris (Fastook et al., 2008; Scanlon et al., 2015).

The emplacement mechanisms and ages of all these volatile reservoirs are still relatively unknown. Crater counting studies point towards at least some of these features being 10 s to 100 s of Myr old (Levy et al., 2010; Viola et al., 2015), making them older than the recent high-obliquity excursions that are thought to redistribute polar ice to the mid-latitudes. Studies of the thickness and physical properties of the debris cover needed to protect and preserve the various non-polar ice reservoirs are ongoing through observational (*Baker and Carter,* 2016 6th ICMPSE; Petersen et al., 2016a 6th ICMPSE), modeling (Bramson et al., 2016, 6th ICMPSE) and terrestrial analog (Petersen et al., 2016b, LPSC 2016) efforts, but further modeling and observations are necessary to fully understand the stability of the ice in these regions. Progress is also being made to quantify the amount of ice currently present or recently lost in the mid-latitudes (Stuurman et al., 2016b, 6th ICMPSE; Bramson et al., 2016 6th ICMPSE; Schmidt et al., 2016, 6th ICMPSE; Bhardwaj and Martín-Torres, 2016 6th ICMPSE). However, these inventories are predominantly in the north, and measurements of their depth below the regolith surface are necessary if we wish to fully understand the link between these reservoirs, polar ice, and the climate.

Question 5, Present day surface activity: What are the roles of volatiles and dust in surface processes actively shaping the present polar regions of Mars?

a. *Determine the processes by which seasonal* CO_2 *(alone, or in conjunction with other surface materials) acts as an agent of geomorphic change, forming and changing landforms that include but are not limited to gullies/alcove-aprons, dunes, and araneiform terrain, both on long and short-timescales*

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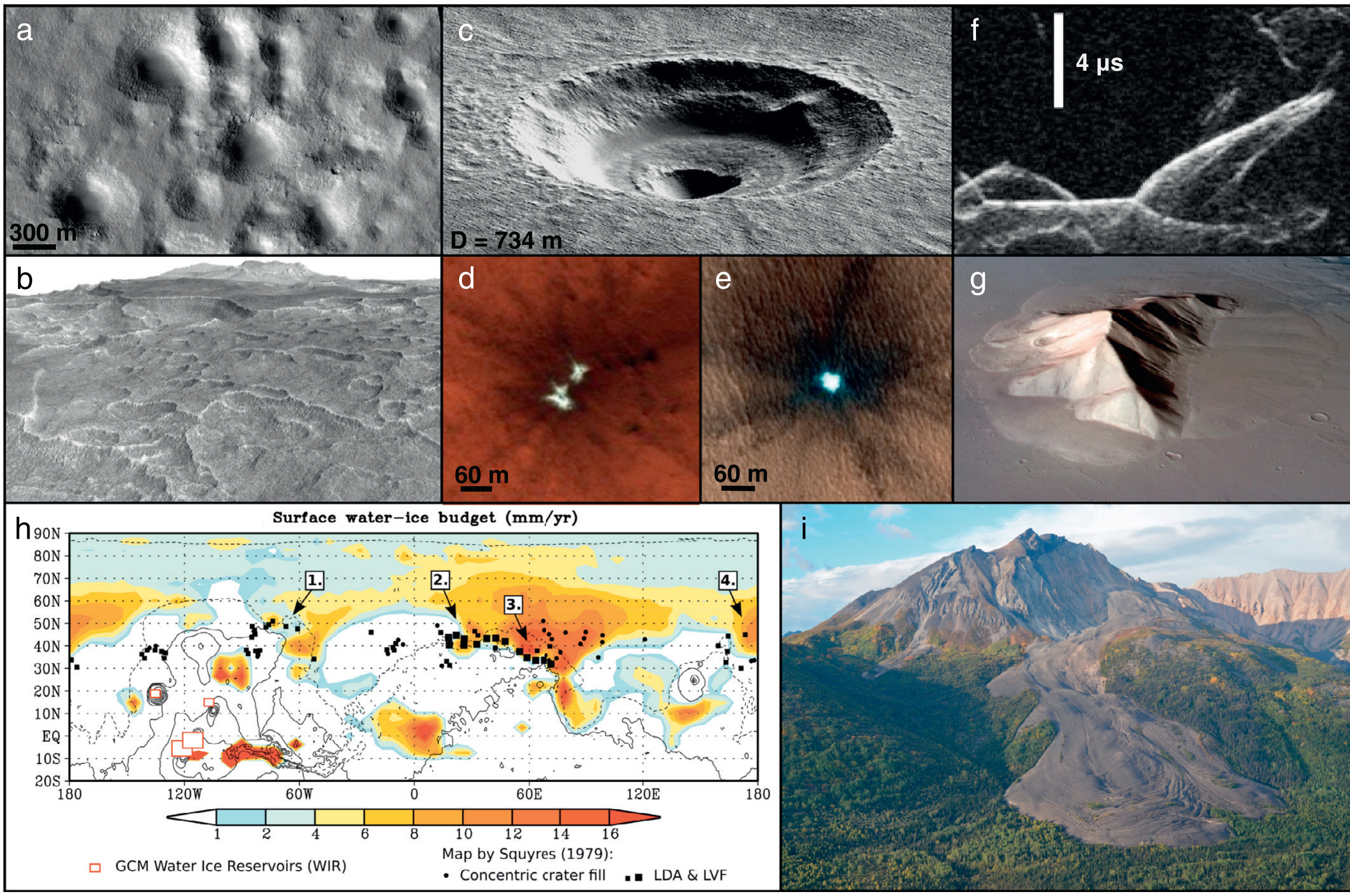

Fig. 4. Various lines of evidence for non-polar ice. (a) sublimation expanded craters, HiRISE image ESP_02,8411_2330; (b) perspective view of scalloped depressions in Utopia Planitia, HiRISE DTM DTEEC_0,0,1938_2265_0,0,2439_2265_U01; (c) 3D view of terraced crater in Arcadia Planitia, perspective from HiRISE DTM DTEEC_01,8522_2270_01,9010_2270_A0 made by Ali Bramson; (d and e) ice exposing impacts, HiRISE images ESP_02,5840_2240 and ESP_03,2340_1060; (f) SHARAD observation 4087,301 of lobate debris apron (LDA) in Deuteronilus Mensae; ice > 500 m thick (g) 3D view of LDA in Promethei Terra, perspective made by Ernst Hauber; (h) global climate model simulation suggesting ice transport to non-polar regions during obliquities greater than 30°, figure modified with permission from Madeleine et al., 2009; (i) Sourdough Rock Glacier in Alaska, a potential analog to Martian LDAs; image courtesy of Eric Petersen and Jack Holt.

b. *Quantify the amount of* CO_2 *needed for the observed geomorphic processes to occur. Characterize what form (snow or direct deposition), when, and where that* CO_2 *is deposited/accumulated seasonally*
c. *Determine the present rate of activity and the time needed to produce the existing surface features. Detect changes in environmental conditions as recorded within these landforms*
d. *Observe the distribution of seasonal and diurnal* H_2O *and* CO_2 *frost deposited each year, from within the seasonal cap down to the lowest latitudinal-extent*
e. *Characterize inter-annual variability in polar surface processes and determine their relationship to volatile cycles, dust cycles, and weather*
f. *Determine the present-day role and extent of seasonal polar deposits of* H_2O *ice and liquid within surface changes*

Question 5 deals with the surface activity presently observed within the Martian polar and mid-latitude regions that results in the formation of geomorphic features within regolith, bedrock materials, and dune fields. Question 5 acknowledges the correlated timing and location with seasonal frost (which is primarily composed of CO_2 and may contain relatively large amounts of snowfall or sintered ice). Relevant surface features – such as gullies (Dundas et al., 2012; 2015b; 6th ICMPSE; Hansen et al., 2011; 2015; Harrison et al., 2015), linear gullies (Diniega et al., 2013; Pasquon et al., 2016a; McKeown et al., 2016 6th ICMPSE), outgassing fans (Thomas et al., 2010), and araneiform terrain/spiders (Piqueux and Christensen, 2008; Hansen et al., 2010; Portyankina et al., 2017), had been observed and discussed prior to the 5th ICMPSE (e.g., Balme et al., 2006; Heldmann and Mellon, 2004; Piqueux et al., 2003). However, definitive activity had not yet been identified, and, the 5th ICMPSE report did not include investigations of this type of surface activity within its list of key questions.

Thanks to a sufficient temporal baseline and repeated coverage with high-resolution images direct detection of surface changes correlated with spectral detections of seasonal frost are increasingly common (Brown et al., 2010, 2012). As of the 6th ICMPSE, many types of present-day activity have been identified, and associated landforms have been mapped and measured, but the processes behind these changes remain subjects of debate. For example, present-day gully formation activity within the southern mid-latitudes (Dundas et al., 2012; 2015b) and northern polar dunes (Hansen et al., 2011; 2015) coincide with the presence of seasonal frost. Processes that mobilize large amounts of sand or rocky regolith have not yet been identified, so investigations, beyond the presence of frost, into the environmental conditions required for this activity to occur are underway (e.g., Diniega et al., in press, 6th ICMPSE, McKeown et al., 2016 6th ICMPSE; Mount and Christensen, 2016 6th ICMPSE; Pasquon et al., 2016b, 6th ICMPSE).

In addition, some features within the SPRC are of geomorphic interest. For example, SPRC halos that form near the so-called "swiss-cheese" sublimation pits of the SPRC are variable from year

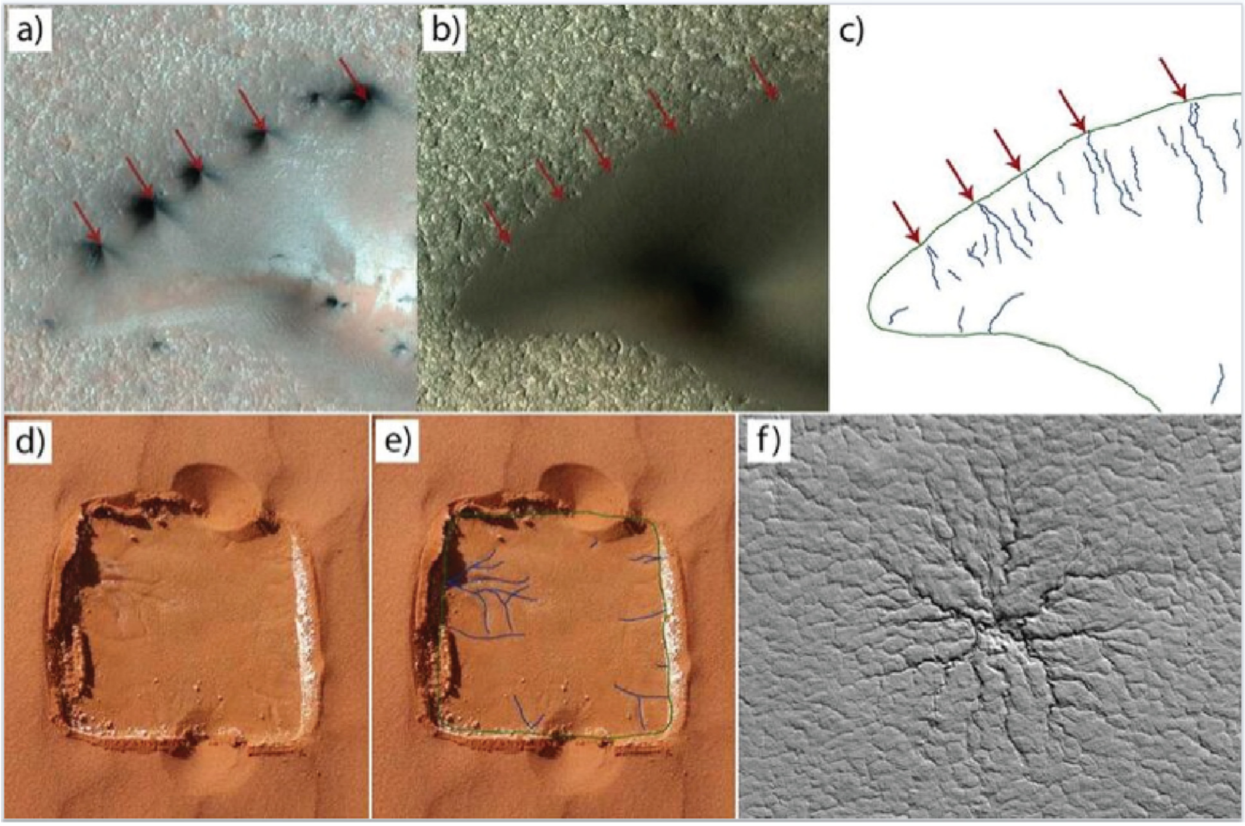

Fig. 5. Geomorphologic features hypothesized or observed to form in the presence of seasonal frost sublimation. (a) and (b): Early spring to summer comparison of an active North polar dune, HiRISE images ESP_01,6111_2600 and ESP_01,8445_2600; (c) outlines of the dune and furrows from (b). Furrows on dunes are geomorphic markers of CO_2 gas flow interacting with substrate materials under seasonal frost deposits. (d) and (e): Field experiments in Utah: a pit and small channels formed when a CO_2 block was partially buried within sand and allowed to sublimate. (Photograph provided by C.J. Hansen.) (f): Araneiform (spider) likely caused by CO_2 gas flow beneath a CO_2 frost deposit, HiRISE image PSP_0,0,5579_0935.

to year (Becerra et al., 2015). While changes have been monitored and features mapped (Thomas et al., 2016; Buhler et al., 2016, 6th ICMPSE), questions regarding the processes that cause this variability persist. Recent heuristic models of the evolution of swiss-cheese terrain (discussed under Question 2) show that they may be late-stage evolution of quasi-circular pits (Buhler et al., 2016, *6th* ICMPSE), but a full model of the morphologic evolution, timescales, and environmental conditions of these features needs to be resolved.

To interpret the environmental record preserved by the variety of polar landforms, the processes behind their formation and modification should be characterized. Such processes act at the boundary between the atmosphere and surface, and may not have a terrestrial analog due to the presence of subliming CO_2 ice (i.e. as proposed for linear gullies (Diniega et al., 2013), araneiforms (Kieffer et al., 2006), and dune furrows (Hansen et al. 2011) (Fig. 5). Araneiforms are radially converging systems of branching troughs often exhibiting fractal properties. To optimally interpret these features as records of polar processes and conditions, it will be important to estimate the amount of CO_2 needed and the physical state required during deposition for the geomorphic processes to occur. This should lead to testable predictions of how, when, and where volatiles must accumulate seasonally that can be tested with observations of the growth and extent of the seasonal cap. Additionally, information on how dust, sand, or water (in solid or liquid form) may enhance or control the geomorphic processes is needed.

As repeat observations are acquired, inter-annual variations in activity become apparent, but the controls on that variation between years are unresolved. For example, are inter-annual weather variations (Hayne et al., 2016, 6th ICMPSE) responsible for the differences seen in alcove-apron formation rates and sizes within the north polar erg (Diniega et al., in press, 6th ICMPSE)? If so, this knowledge should aid in identification of the underlying geomorphic process forming the alcove-aprons and may yield information about other polar processes occurring under similar conditions. Addressing Question 5 will extend our understanding of the most active surface processes on Mars.

2.1. Mars community priorities

Recently, based on the top five questions and 29 objectives within, the Mars polar science community conducted a survey of what objectives are the highest priority. The community found that objectives 3a, 2a, 4a, 2d, and 3e should be the highest priorities going forward. The first four priorities closely resembled the priorities of previous ICMPSE summaries; however, the inclusion of Objective 3e, regarding the "*buried* CO_2 *ice reservoirs at the south pole*" was entirely new. This illustrates the rapidity of how discoveries bring new questions to the fore.

3. The interconnected nature of Mars polar science

Mars polar science is inherently interdisciplinary, and there are many lines of research described above that could feed into multiple Key Questions. The interconnected nature of Mars polar science makes it difficult to define investigations within a simple scheme as we have done above. Not recognizing this can obfuscate the importance of each investigation, so in this section we highlight sev-

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eral lines of research that are important for multiple Key Questions.

The atmosphere plays a critical role in many polar processes. Because of sublimation and deposition at the surface, the *transport of volatiles and dust aerosols into and out of the polar regions* (Question 1b) is intimately related to the *energy and mass balance of the polar ice reservoirs* (Question 2a). This energy and mass balance is in turn connected to *cloud condensation* (Question 1c) and to the *inter-annual variability in polar surface processes and their relationship to volatile cycles, dust cycles, and weather* (Question 5e). The interplay between the poles and the atmosphere affects the entire planet, especially the surface pressure. For this reason, *estimating the amount of* CO_2 *and* H_2O *frost deposited and lost at the surface* (Questions 1d and 5d) over both large and local-scales is required to test models of *the processes by which seasonal* CO_2 *acts as an agent of geomorphologic change and the timing of and quantity of* CO_2 *involved in this activity* (Questions 5a and 5b). Furthermore, identifying *dust deposition patterns over the polar caps* (Question 1e) will help *quantify the role and efficiency of dust and sand as an agent promoting the preservation of buried volatile reservoirs* (Question 2c), which can also play a role in the *formation of non-polar ice deposits* (Question 4a). Many of these investigations also depend heavily on models of *atmospheric circulation* (Question 1a).

A better determination of *the vertical and horizontal variations of composition and physical properties of the materials forming the PLD* (Question 2d) is necessary to *link orbital forcing and the resultant climate parameters to layer properties* (Question 3a). To do that, keeping in mind that the present is the key to the past, we must *determine the present-day role and extent of seasonal polar deposits of* H_2O *ice* (Question 5f). Additionally, in order to characterize the *current/recent perennial ice landforms* (Question 2b) it is necessary to first *estimate how, when, and where* CO_2 *is deposited/accumulated seasonally* (Question 5b) and to *determine the present rate of activity and the time needed to produce the observed surface features* (Question 5c).

Determining how the polar regions evolve requires the consideration of environmental conditions and active processes over a range of scales. Some processes and conditions operate on a global scale, some within a hemisphere, and some at only a local scale (Question 1a). For example, to interpret the formation of the terrain types found only within the south polar region, it may be necessary to understand the source of hemispheric differences (Question 2e), including an explanation for the difference in *apparent ages of the two caps* (Question 3b and 3c). This question requires the determination of the reasons behind the *different compositions* of each cap (Questions 3d, 3e, 1b, 1d, and 1e), and the *current stability of the observed perennial caps in the south* (Question 3c). Because the poles are not an isolated system, an *inventory of non-polar volatiles* (Question 4a) and an understanding of the *timescales and conditions of which they evolve* (Question 4c) will also lead to a better characterization of *polar evolution* (Questions 3b and 3c) and the processes that affect *atmospheric transport of volatiles and dust aerosols into and out of the polar regions* (Question 1b).

The climate record and current seasonal activity are related to the accumulation and preservation of non-polar ice. In order to *determine under which conditions the non-polar volatile reservoirs accumulate* (Question 4c) it is necessary to *estimate the amount of* CO_2 *and water frost deposited or lost at surface* (Question 1d) and to *determine how to link orbital forcing and resultant climate parameters to layer properties at non-polar deposits* (Question 3a).

Acting alone, members of the science community can make progress toward answering individual questions, but collaboration between scientists of different fields is necessary to connect information about processes, physical conditions, and observables, and to ensure consistency within the models and assumptions used. These collaborations support Mars polar science as a whole.

4. Measurements, modeling, and field work

Many topics have seen measurable progress since the 5th ICMPSE. However, several investigations and measurement datasets were emphasized during the meeting as important to continue advancing. Here we focus on the measurements that were most frequently noted during the 6th ICMPSE as necessary for further progress in Mars polar science.

4.1. Flight observations

The measurements most often mentioned as needed by the community included temperature, pressure, and wind speed profiles near the polar caps between the surface and 10 km altitude. Because the seasonal variation of the poles is such an important driver of polar weather, global atmospheric circulation, and historical climate, these measurements should be acquired for as long a duration as possible. This will help to quantify the significance of insolation on the diurnal cycle, providing the necessary information to understand atmospheric convection, larger atmospheric circulation, and the ground-atmosphere interactions, including mass transport and the development of the CO_2 seasonal frost. Continued measurements of cloud abundances and aerosol fraction are needed to fully understand their cycles over a range of time scales.

Atmospheric measurements are required for the refinement and validation of atmospheric models, which greatly extend our understanding of the full transport over and around the poles and climate variability and better support landed missions. Besides the polar community, these measurements were also recognized as high-priority within the NASA-chartered Mars Exploration Program Analysis Group (MEPAG) Next Orbiter Science Analysis Group (MEPAG NEX-SAG, 2015).

The second major knowledge gap discussed at the conference is the quantity, distribution, and properties of ice within 10 m of the surface. This includes the regolith-pure ice boundary equator-ward of ∼80°, the thickness of that ice, and the uppermost layers of the PLD. Evidence suggests that massive ice deposits are widespread in the northern and southern hemispheres, but additional, thinner deposits, as well as the regolith-ice boundary of already-known ice, are too shallow to detect with current instrumentation. Thus, the Phoenix landing site is the only location on Mars where we have measured the quantity and distribution of shallow ice less than 10 cm from the surface. High-resolution measurements of this type would directly answer investigations in Question 4 and potentially Question 5. They would also provide critical constraints to answer all sub questions to Question 2. Most critical to NASA's long term goal of developing resources on the surface for human exploration is question 4b: *Determine the lowest latitude and conditions under which water-ice reservoirs can be found.* These measurements were also recognized within the NEX-SAG report (MEPAG NEX-SAG, 2015) as high-priority for both science and resource objectives.

The primary measurement request from the 5th ICMPSE was compositional sampling of the vertical stratigraphy of the PLD. At the 6th Conference, we again agree that this would provide invaluable knowledge for advancing questions about the nature of the PLD (Question 2) and the climate history recorded within (Question 3) as well as provide measurement towards constraining the transport of dust towards the poles (Question 1).

Of primary importance for new measurements would be in situ sampling of individual layers in stratigraphic context to determine ice/dust mixing ratios and physical separation. With such measurements we could make significant strides to understanding the fundamental components of the polar ice deposits. (We recognize the difficulty of acquiring such measurements, so this is a long-term goal but of high priority.) Additionally, higher resolution vertical sampling from orbital assets should reveal finer details about the vertical distribution of materials in the PLD.

Orbital and in situ measurements of the development and retreat of the seasonal CO_2 cap, including microscopic imaging of ice crystal evolution as a function of time and monitoring of diurnal frost should help better constrain the physical and optical properties of the polar materials, hence improving mass/energy balance models, and ultimately weather and global climate predictions

The study of seasonal and inter-annual variability requires regular and overlapping observation of features over multiple Martian years. It is only recently that observational data has been sufficient for these types of studies – and this has yielded results in e.g., recent advances in identification of present-day small-scale surface activity (see Question 5). Thus, while some new data was also requested at the 6th ICMPSE, it was recognized that it is very important to maintain the existing data acquisition, to further extend the temporal baseline.

4.2. Laboratory experiments

Laboratory measurements have made major contributions to polar science. Concerning volatiles, measurements of the optical properties of ices, in pure or clathrate form will inform our remote sensing based investigations of ice and crystal evolution. Experiments designed to consider the effects of soil and salt constituents in icy deposits will help the community estimate sublimation rates or efficacy of protecting the volatiles in a meta-stable environment.

Present day surface activity, especially in landform evolution, is not fully understood, and terrestrial analogs are often unavailable. Designing experiments that move grains in Martian environmental chambers with the proper conditions is of the utmost importance. Besides the obvious experiments in wind tunnels that consider the mobilization of particulates and sublimation of volatiles, experiments designed to monitor the interactions between CO_2, H_2O, dust, or mixtures of the three can provide information necessary to reveal the processes behind some of the processes on Mars that have no terrestrial analog.

Finally, knowledge of the rheology of Martian materials, such as icy dust or dusty ice is still mostly unknown under Martian environments. Experiments may be able to explain how layered deposits at the poles and mid-latitudes can resist viscous flow as glaciers, even over millions of years, when models have been unsuccessful to date.

4.3. Terrestrial analog studies

Terrestrial analogs are often the best sources of information for explaining landform evolution because of the accessibility to real-world examples and the possibility to observe activity at full scale. Features such as gullies, patterned ground, dunes and ripples, and thermal cracks can be observed to change on Earth due to many processes. Unstable mid-latitude glaciers and buried ice deposits are preserved under debris covers on Earth (Fig. 6). Better constraining the stability of ice-rich features on our own planet could shed light on the preservation mechanisms acting on Mars in the current day and in the past. Combining the knowledge of terrestrial geomorphology with open Martian questions may be the quickest and most economical method to answering those questions.

4.4. Model development and prediction

Modeling of atmospheric and surface processes has provided some of the biggest breakthroughs in understanding Martian polar processes. Advances range from better characterization of long-term climate variations and PLD formation to global atmospheric circulation to dust devils. In particular, global circulation models and mesoscale atmospheric simulations have advanced significantly in the last decade, informing how the current atmosphere shapes polar frost deposits and how orbital variability has driven ice sublimation and accumulation over millions of years. More targeted and high-resolution modeling that incorporates atmospheric observations can augment those studies.

Fig. 6. Buried ice in Nautagil canyon on the flank of Askja in northern Iceland, where the air temperature frequently gets above freezing. This ice is shaded much of the day by a steep canyon and overlain by ~0.5 m of modern till. The lag deposit is thicker than the thermal skin depth, protecting the ice from year to year. This site was visited on one of the conference field trips and could be a terrestrial analog to Martian lobate debris aprons or other mid-latitude ice deposits that are preserved as long as they remain buried. Credit: Paul Hayne.

Additionally, landscape evolution modeling that includes interactions between CO_2 frost and granular materials is just starting to gain traction. These studies will look at possible frost-related geomorphological processes forming small-scale surface landforms or at how pressure builds beneath a translucent ice slab and where/how that pressure is released, possibly leaving a geomorphic record.

We recommend that modeling polar activity be supported at all levels as it provides crucial tests and links between limited flight observations, narrowly focused laboratory experiments, and potential terrestrial analogs. The combination of all of these techniques is needed for major advances in our understanding of the Martian polar environment.

5. Summary and conclusion

The Mars polar science community has made excellent progress in the eighteen years since the 1st ICMPSE was held. Significant progress includes the determination of bulk material properties of the NPLD and SPLD, measuring the distribution of permanent water and CO_2 ices at the poles, and an improved characterization of mid-latitude ice. Further milestones include model-based interpretations that the PLD are not permanent features and that at least the NPLD most likely formed within the last 4 Myr. Our understanding of how global circulation affects the polar deposits, and how the poles affect global circulation has also grown significantly.

Our progress has also shed light on new, often more specific, science questions. For example, the community began the initial inventory of ice by asking questions such as “what material comprises the ice; where is it; and how much is there?” As many of those initial surveys and reconnaissance near completion, the community is now asking more nuanced questions such as “when was the ice emplaced at its current location," and "what can presence and distribution of the ice tell us about Mars' history?"

Because of the interconnected nature of Mars polar science and the many advantages of collaborative progress, it is important for the Mars polar science community to gather regularly to share and discuss results and to prioritize remaining science questions. At the 6th Conference the community voted and agreed that four years is the appropriate cadence for these meetings. That duration allows for the consideration of new priorities and for the development of new studies with impactful science. It also assures that doctoral students working on polar topics will have an opportunity to meet with their predecessors. With that in mind, we anticipate that the 7th ICMPSE will be held in Patagonia, Argentina in early 2020.

This document outlines many of the most important scientific discoveries in the history of Mars Polar Science, and it underscores the numerous, interesting questions that remain open. We believe that answering these questions will help move forward Mars science and provide critical knowledge required for future exploration, both robotic and human.

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