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Editorial

Introduction to the fifth Mars Polar Science special issue: Key questions, needed observations, and recommended investigations

1. Introduction

The Fifth International Conference on Mars Polar Science and Exploration – which was held from September 12–16, 2011, at the Pike's Waterfront Lodge in Fairbanks, Alaska – is the latest in a continuing series of meetings that are intended to promote the exchange of knowledge and ideas between planetary and terrestrial scientists interested in Mars polar and climate research (http://www.lpi.usra.edu/meetings/polar2011/polar20113rd.html). The conference was sponsored by the Lunar and Planetary Institute, National Aeronautics and Space Administration, NASA's Mars Program Office, University of Alaska Fairbanks, International Association of Cryospheric Sciences and the Centre for Research in Earth and Space Sciences at York University.

The conference attracted 103 participants from 9 different countries. The conference program consisted of a mix of invited and contributed talks, panel discussions, poster presentations, and a mid-conference field trip. Our local host was Dr. Kenji Yoshikawa, an expert on terrestrial and planetary permafrost and a member of the University of Alaska Fairbanks (UAF) faculty. Fairbanks was chosen as the site of the Conference because of its relative accessibility, the presence of some of the world's leading experts in permafrost, glacial, and polar research at the University of Alaska Fairbanks; and because of its proximity to many examples of cold climate geomorphology such as pingos, ice wedges, and patterned ground. This provided many interesting destinations for the mid-conference field trip, including views of the subsurface at the US Army Corp of Engineers Fox Tunnel.

Over the past 12 years, our understanding of the martian polar regions has been greatly advanced by the analysis of data acquired by the Mars Global Surveyor (1999–2006), Mars Express (2003–present), Mars Odyssey (2001–present), Mars Reconnaissance Orbiter (2006–present), and the Phoenix Lander (2008). These data have yielded the first high-resolution topographic maps of the north and south polar layered deposits, submeter-scale images of the stratigraphy exposed in the polar troughs and reentrants, radar sounding investigations of the internal structure and basal topography of the polar deposits, year-round coverage of the thermophysical, radiative, and compositional properties of the polar atmosphere and surface, and in situ investigations of the near-surface volatile stratigraphy, soil composition, geology, and meteorology of the martian high arctic.

Given the influence of the martian climate on the planet's geologic, hydrologic, and atmospheric evolution, as well as its habitability, understanding Mars' climate history is of crucial importance to the Mars science community. By analogy with terrestrial ice core climate studies, the martian polar deposits may contain the most complete existing record of recent climate change on Mars. But, to decipher this record, we must learn more about the geologic history of the polar regions, including: the ages of the polar deposits, their melting and flow histories, their stratigraphy, and their processes of deposition, erosion and long-term interactions with ice deposits at lower latitudes.

The purpose of the Conference was threefold: (1) to assess the current state of Mars polar and climate research and identify the key questions that must still be addressed; (2) discuss the needed observations, including investigations of terrestrial analogs and analysis of data returned from ongoing and future missions; and (3) to recommend the potential science objectives, measurements, platform options, and instrument suites for future robotic missions to investigate the martian poles. In this way, these meetings are intended to provide guidance for the planning of such missions and to serve as an important resource for those scientists seeking to develop instruments, propose spacecraft, or participate as a member of a science team in response to any future Announcement of Opportunity and to those program personnel seeking to formulate and sustain planetary exploration.

2. Key questions in Mars Polar Science

One of the most important products of each Mars Polar Science Conference is the identification of 'Key Questions, Needed Observations and Recommended Missions'. These are compiled from the presentations and plenary discussions held during the conference and, since 1998, have served as our input into the next revision of the Mars Exploration Program Analysis Group (MEPAG) Science Goals, Objectives and Measurements document. This activity has helped build the scientific justification for the selection and flight of polar-focused missions, as it did for NASA's 2008 Phoenix Lander. The 'Key Questions and Needed Observations' identified at the four previous International Conferences on Mars Polar Science and Exploration were discussed by Clifford et al. (2000a, 2000b, 2001, 2005), and Fishbaugh et al. (2008), while those identified at by the participants of the Fifth Mars Polar Conference are presented in Table 1.

In addition to the five Mars Polar Science Conferences, there have also been three related workshops focusing more specifically on the Mars polar energy balance and CO_2 cycle. Summaries of these meetings, with their own set of recommendations, were reported by Prettyman and Titus (2004), Titus and Colaprete (2005) and Titus and Michaels (2009).

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Table 1
Key questions in Mars Polar Science.[a]

1. What are the physical characteristics of the polar layered deposits and how are the different geologic units within, beneath, and surrounding the PLD related?
   A. What are the physical, thermophysical and rheological properties of the PLD? And how do they vary, both geographically and stratigraphically?
   B. What geophysical insights do the PLD provide regarding the past and present thickness, rheology, and heat flow of the polar lithosphere?
   C. What is the nature of the topography and geology beneath the PLD, and how have they influenced the PLDs' form and history?
   D. What is the nature of the north-polar basal unit? And how does it differ from the overlying PLD?

2. What are the depositional, erosional, and deformational histories of the PLD?
   A. How did the polar troughs and major reentrants form? And how do they evolve with time?
   B. Has the flow of the polar layered deposits affected their local or overall shape? If not, how can the apparent lack of flow be reconciled with lab-derived rheologic data?

3. What are the mass and energy budgets of the PLD, and what processes control these budgets on diurnal, seasonal and longer timescales?
   A. How does the current radiation budget vary with time of day and season, and how is it affected by the presence of ice and dust in the atmosphere?
   B. What is the current mass balance (mechanisms, rates, temporal and spatial variability) of CO_2, H_2O and dust?
   C. What are the causes of the north/south asymmetry in the evolution and physical characteristics of the polar deposits?
   D. What are the causes of the observed interannual variations in dust storm activity and general circulation of the atmosphere?
   E. By what processes, and to what extent, has in situ modification (e.g., grain metamorphism, regelation, geochemical alteration, ice segregation, etc.) affected the physical and chemical evolution of the PLD and circumpolar terrains?
   F. What is the cause of, and how repeatable are, recurrent dust and atmospheric ice events, and what is their effect on the mass balance of the poles?

4. What chronology, compositional variability, and record of climatic change is expressed in the stratigraphy of the PLD?
   A. How old are the polar layered deposits? How can the internal layers be dated (relatively and absolutely), and what portion of Mars' history do these layers represent?
   B. How does the composition of the residual caps and PLD (including H_2O, CO_2, dust, gas hydrates, trace gasses, stable isotopes, and salts) correlate with geographic location and layer stratigraphy? What does this variability say about the climatic evolution of the PLD?
   C. What implications does the presence of massive reservoirs of CO_2 have for the past and future evolution of the PLD and climate? And how did such reservoirs form?
   D. How is the stratigraphy of the PLD related to cyclic variations in insolation and in the global cycles of H_2O, CO_2, and dust?
   E. How is the stratigraphy of the PLD related to episodic events such as impacts, volcanic eruptions, global dust storms, and melting?
   F. What is the internal structure, range in thickness, continuity, and extent of layers throughout both of the PLD? Do any stratigraphic features or unconformities in the north and south correspond to the same event?

5. Are there places within or associated with the PLD, where liquid water is or was present? And could these places have provided habitats for, or preserved evidence of, past or present life?
   A. Is there evidence of past or present melting and, if so, when and where did/does it occur?
   B. Are there any polar environments on Mars (e.g., endolithic, stromatolitic, ice-rich permafrost or transient brines), capable of sustaining life?
   C. Are there molecular biomarkers or microfossils preserved in the PLD?

6. How have volatiles and dust been exchanged between polar and non-polar reservoirs? And how has this exchange affected the past and present distribution of surface and subsurface ice?
   A. What is the current distribution of exchangeable reservoirs of volatiles and dust? What characteristics influence their stability?
   B. How are volatiles and dust transported to and from the polar regions, and over what time scales? What is their present exchange rate?
   C. How has the distribution of ice varied in response to astronomically-induced changes in insolation and climate, and over what timescales?
   D. Are low-latitude viscous flow features, mid-to-high-latitude gullies and mantling deposits, and shallow ice-rich regolith at high-latitudes indicative of changes in climate and volatile exchange?

[a] As identified by the participants of the 5th International Conference on Mars Polar Science and Exploration (September, 2011).

3. Recommended missions

Advances in understanding Mars polar evolution and processes requires long-baseline observations of interannual, seasonal and diurnal change, while advances in understanding the record of past climate change requires accurate, detailed examination of the physical record itself. Unfortunately, our ability to conduct these needed observations is heavily constrained by the limited number and lifetimes of our orbital and in situ assets, as well as the technical and budgetary constraints on the number and complexity of the scientific investigations included in their payload. Even so, recent and anticipated missions, such as Mars Express (MEX), Mars Odyssey (ODY), Mars Reconnaissance Orbiter (MRO), Mars Atmosphere and Volatiles EvolutioN (MAVEN), and the ExoMars Trace Gas Orbiter (TGO) either have provided or promise to provide significant insights into the processes and conditions affecting the poles, and the Mars Polar Science community urges that these missions be continued as long as possible.

However, to make meaningful progress in addressing the Key Science Questions identified in Table 1, it will require the flight of new, dedicated polar missions and a willingness to accept greater technical risk to take advantage of promising investigative opportunities that maximize scientific return.

The three highest priority Mars polar missions, identified by the participants of the Fifth Mars Polar Conference, are similar to those advocated by the participants of the First Mars Polar Conference (Clifford et al., 2000a,b): (i) a rover traverse down a polar trough wall, sampling the exposed stratigraphy of the Polar Layered Deposits (PLD), (ii) an ability to drill into the interior polar cap to reveal the polar stratigraphy to a depth of ~10–150 m, and (iii) one or more polar meteorological stations as part of a long-duration global network. These are discussed in more detail in the following sections.

3.1. Rover traverse down a polar trough wall

A rover traverse down the exposed stratigraphy of a polar scarp or trough wall provides an opportunity to directly sample the geologic and climatic history preserved in the polar ice at a fraction of the cost of a more traditional ice coring drill, including the capability of multiple traverses to assess lateral variations. This strategy was first proposed by Fisher (1993) based on the original terrestrial implementation by Reeh et al. (1991) who, by conducting a 700-m cross-strata traverse at the margin of the Greenland ice sheet, were able to sample a continuous record of over 10^5 years of Earth's climate history. By equipping a Mars polar rover with a shallow (~1–3 m) ice-coring drill, and by drilling at small enough intervals during the descent down a trough wall to ensure overlap between successive vertical cores, it should be possible to sample and analyze a similar continuous record of martian polar stratigraphy extending to a depth of as much as 1 km or more. This strategy provides a way of conducting in situ measurements of stratigraphic variations in the relative abundance of ice and dust; the thickness and scale of individual layers; the compositional, thermophysical, and textural properties of the polar ice – including the potential presence of volcanic ash, salts, atmospheric isotopes, micrometeorites, and possible biomarkers of indigenous life – in a single, comparatively low-cost mission. An important enhancement to such a mission would be the inclusion of an in situ dating technique, such as thermal luminescence (Lepper and McKeever, 2000), to aid in the interpretation of the stratigraphic record.

For conducting stratigraphic investigations of the polar layered deposits, a rover traverse down a polar trough wall has a number of logistical, operational and scientific advantages over a traditional mechanical drill. However, it also faces some significant and unique challenges, perhaps the most important being: (1) barriers to mobility caused by the topographic relief associated with the outcrops of the polar strata and (2) the post-depositional alteration of the strata caused by their exposure to the atmosphere and to large annual and climatic variations in surface temperature and dust/volatile deposition and ablation.

3.2. Mars polar drill

The complications associated with a rover traverse down a polar trough wall can be eliminated by conducting drilling investigations on some level interior expanse of the polar layered deposits, using a fixed lander. But placing a traditional mechanical drill on a spacecraft, capable of sampling the PLD to depths of ~10–100 m, has its own set of significant challenges, including: mass, power, and the complexity of the drilling system – as well as that of the supporting systems required for core removal, handling and analysis.

A viable alternative to a mechanical drill is an instrumented thermal probe (also called a cryobot) that lands on the surface of the PLD and then, through the use of resistive heating, melts its way through the ice, unwinding a thin cable behind it that is used for power and data transmission between the cryobot and the support equipment left on the surface (e.g., Philberth, 1962; Hansen and Kersten, 1984; Zimmerman et al., 2001; Hecht et al., 2009). The meltwater generated by the probe can be allowed to either refreeze behind it (making the probe's journey through the ice a one-way trip) or be pumped to the surface through a small tube, leaving the borehole unobstructed. The cryobot approach requires less power, is simpler in design, and is more compact than a traditional mechanical drill. It can carry a sideways-looking camera to capture images of strata during its descent, with an ability to resolve features as small as 10^{-3}–10^{-5} m. Meltwater delivered to in situ instruments at the surface can be investigated for chemistry, isotopic variations, dust content, as well as other climate markers. It could also include a Distributed Temperature Sensing (DTS) system, consisting of a lidar operating through a fiber optic cable (Hurtig et al., 1994; Selker et al., 2006; Tyler et al., 2009). Because local temperatures alter the light transmission characteristics of the cable, the average speed and dispersion of light, due to Raman scattering, can be monitored to provide temperature information along the cable with a spatial resolution of ~1 m. By comparing the ratio of the amplitudes of the back-scattered temperature-dependent (and higher frequency) anti-Stokes component with the temperature-independent (and lower frequency) Stokes component, the average temperature over any given length of the cable can be determined to an accuracy of ±1 °C, with a resolution of 0.01 °C (Selker et al., 2006; Tyler et al., 2009). Thus, temperatures gradients within the polar ice, associated with climatic fluctuations and geothermal heating, can be determined with great precision.

One example of a small Mars-compatible thermal drill, developed by JPL (Hecht et al., 2009; Bentley et al., 2009), successfully bored through 50 m of Greenland ice in approximately 2 days, returning meltwater for analysis and performing downhole imaging. Studies of potential Scout-class missions using such a cryobot indicate that a 50-m descent is possible using a solar-powered Phoenix-like platform for a summer mission. With an Advanced Stirling Radioisotope Generator (ASRG) the potential depth of investigation is increased to 150-m, transecting numerous strata (Hecht et al., 2009). This long-lived surface station could also serve as an element of a meteorological and geophysical network, including a panoramic imager and meteorology station that measures pressure, temperature, humidity, and wind that can be used to characterize the surface heat and water balance, and monitor both weather patterns and seismic activity.

3.3. Global, long-duration multi-station meteorological network

To understand the nature of past climates and correctly interpret the climate record preserved in the polar layered deposits, we must first understand the nature of the present climate. The key to this is understanding the general circulation of the martian atmosphere, which governs the planet's climate system through its control of the coupled seasonal cycles of carbon dioxide, water, and dust and understanding its local interactions with ice-rich surfaces. However, such knowledge can only be obtained by a significant increase in the resolution, frequency, and duration of local and global atmospheric monitoring. Although not exclusively a polar mission, the deployment of a global, long-duration multi-station meteorological network – including one or more polar stations – is a necessary and critical step in acquiring this knowledge.

The simplest implementation of such a network would utilize stations capable of recording high-resolution temporal measurements of atmospheric pressure and optical depth at 16 globally distributed sites over several Mars years (Haberle and Catling, 1996; Harri et al., 2007). Stations with this limited payload can be designed small and light enough that they can be flown on a single medium-sized launch vehicle or deployed incrementally over several mission opportunities. Possible meteorological enhancements to the station payload include measurements of local temperature, insolation, relative humidity, wind speed and direction, accumulation and ablation. The addition of a standard geophysical package, including a seismometer, dielectric spectrometer or multifrequency GPR, and subsurface heat flow probe, would provide other critical knowledge about the large-scale seismic, electromagnetic, and geothermal properties of the PLD – but with a corresponding increase in station complexity, mass, power requirement and cost.

To remain operational through the polar winter, over a total duration of several martian years, such stations may require the use of advanced power sources, such as fuels cells, high capacity batteries, Radioisotope Thermoelectric Generators (RTG) and Stirling Radioisotope Generators.

4. Other needed observations/investigations

The Conference participants also identified a number of other high-priority observations/investigations as having an especially high scientific importance:

4.1. Observations from Earth and by continuing Mars missions

- Systematic daily and global atmospheric observations: MRO MARCI & MCS; MEX PFS; ODY THEMIS.
- Seasonal survey and targeting of polar surfaces: MRO CRISM IR, CTX & HiRISE imaging (especially stereo pairs for digital elevation maps), MEX OMEGA & HRSC color stereo.
- Subsurface profiling of polar caps and non-polar ice deposits: MRO SHARAD and MEX MARSIS PLD data.

4.2. Observations by future Mars missions

- Improved seasonal, and especially diurnal (including night time), remote sensing coverage of both poles (currently, most data are acquired at mid-afternoon).
- Multiple profile measurement of atmospheric CO_2 condensation during the polar night (using a LIDAR array).
- Electromagnetic investigations of the PLD, conducted from orbit (by an imaging SAR) or in situ (by a mast-mounted microwave imager or a rover-mounted GPR), offer the opportunity to conduct high-resolution investigations of the internal stratigraphy, structure and composition of the cap, as well as the ability to detect diurnal and seasonal variations in the occurrence of brines and thin films of super-cooled water.
- Measurements of current atmospheric escape processes by MAVEN, to be launched in November 2013.
- Measurements of atmospheric fields and trace gases from the ExoMars Trace Gas Orbiter, slated for launch in 2016.
- Continued Earth-based telescopic and spectroscopic observations of Mars.

5. Mars Polar Science special issue

To help capture the output of the Fifth International Conference on Mars Polar Science and Exploration, the conveners made arrangements with Icarus for the publication of this special issue. The papers contained in this special issue address a broad range of topics related to the nature and evolution of the martian polar deposits, including their: thermal, radiative and rheologic properties; composition, stratigraphy, and age; seasonal, interannual, and climatic behavior; interaction with the atmosphere. Also discussed are the potential insights provided by the study of terrestrial analogs. These papers complement the 74 papers published in the previous four Mars Polar Science special issues (Icarus v. 144, April 2000; Icarus v. 154, November 2001; Icarus v. 174, April 2005; and Icarus v. 196, April 2008), which represent the largest and most-cited collections of work on Mars Polar Science published to date.

Given the success of the Fifth Mars Polar Conference, plans are now underway for a sixth conference that is tentatively planned for Iceland in 2015. Given the success of the previous five conferences, and the ongoing analyses of data from the continuing missions and that anticipated from MAVEN, the Sixth Mars Polar Science Conference should be a great meeting. We hope to see you there.

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Stephen M. Clifford
Lunar and Planetary Institute,
3600 Bay Area Blvd., Houston, TX 77058, United States
E-mail address: clifford@lpi.usra.edu

Kenji Yoshikawa
Water and Environmental Research Center,
University of Alaska Fairbanks, PO Box 755860,
Fairbanks, AK 99775, United States

Shane Byrne
Lunar and Planetary Lab,
1629 East University Blvd., Tucson,
AZ 85721, United States

William Durham
Dept. of Earth, Atmospheric, and Planetary Sciences,
Massachusetts Institute of Technology,
77 Massachusetts Ave., Cambridge,
MA 02139, United States

David Fisher
University of Ottawa, Dept. of Geology,
Marion Hall, Ottawa, Ontario, Canada

Francois Forget
Laboratoire de Meteorologie Dynamique,
Institut Pierre-Simon Laplace, Paris, France

Michael Hecht
MIT Haystack Observatory, Off Rte. 40, Westford,
MA 01886, United States

Peter Smith
Lunar and Planetary Lab, 1629 East University Blvd., Tucson,
AZ 85721, United States

Leslie Tamppari
Planetary and Earth Sciences Section, Jet Propulsion Laboratory,
M/S 264-535, 4800 Oak Grove Dr., Pasadena, CA 91109, United States

Timothy Titus
U.S. Geological Survey, 2255 N. Gemini Dr., Flagstaff,
AZ 86001, United States

Richard Zurek
NASA Mars Program Office, MS 321-690, Jet Propulsion Laboratory,
4800 Oak Grove Dr., Pasadena, CA 91109, United States

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