NORTH POLAR CAP OF MARS: MILANKOVITCH CYCLES AND RECENT CLIMATE HISTORY.

Sarah M. Milkovich and James W. Head, Department of Geological Sciences, Brown University, Providence, Rhode Island 02912 USA

Introduction: The northern polar cap of Mars is characterized by spiraling troughs cutting through the cap surface. Horizontal and subhorizontal layers exposed on the walls of these troughs are thought to contain varying ratios of water ice and dust. These polar layered deposits (PLD), first observed in Mariner 9 images, extend throughout the cap. In Viking images, a thick sequence of PLD is present at each pole and includes exposed sequences of up to 20 regular layers of alternating dark and light material, each layer pair between 10 and 30 meters thick; there are apparent unconformities between some sets of layers. North and south individual polar layers are similar but have some morphologic differences [e.g., 1]. Layers include dust and water ice but at depth within the cap, CO_2 clathrate hydrate ice may be present as well [e.g., 2].

Layer formation models based on these images called for obliquity cycles to drive climate change to produce the layers [e.g.3-6]. Such approaches are similar to models in which orbital Milankovich cycles drive ice ages and climate change on the Earth [e.g., 7-10]. Changes in insolation patterns due to quasi-periodic orbital cycles will affect the brightness of an individual layer; the duration and intensity of southern summer influences the occurrence of global dust storms [11] which affects the dust to ice ratio, and in turn the brightness, of the layer deposited at the northern cap. For example, on Mars a light-dark PLD layer pair might be deposited as the planet moved from low obliquity (favoring ice deposition) to high obliquity (favoring dust deposition) [e.g., 3].

Although extensive analysis and discussion resulted from the Viking data, no consensus was reached on the interpretation of many important aspects of the layered terrain and the individual layers. In a key synthesis paper, *Thomas et al.* [1] summarized what was known about the polar deposits (outlined above) and what was not known. Outstanding issues included the exact composition and ratio of dust to ice of the PLD as a whole, as well as the vertical sequence of individual layers, their correlation, the physical characteristics that cause them, whether they are compositionally distinct from residual frosts, and their relationship with expected climate cycles. The advent of much higher-resolution Mars Global Surveyor (MGS) Mars Orbiting Camera (MOC) images of the polar layered terrain, combined with the Mars Orbiting Laser Altimeter (MOLA) altimetry measurements, has produced a dramatic new data set, equivalent to individual vertical "cores" through the sequence of layers exposed in troughs and cliffs across the polar caps [12]. In these individual "cores", the PLD is shown to contain even more layers than those seen in Viking images, revealing layers with a variety of brightnesses and thicknesses down to the limit of resolution (a few meters) (Figure 1c). Furthermore, comparison of individual images suggested possible correlations of layers between "cores" [12-15]. Thus, the new MOC data set is analogous to an initial oceanographic expedition to a sedimentary basin to undertake a comprehensive collection of deep-sea sediment cores to study the paleoceanography and paleoclimate record on Earth.

The higher-resolution data set raises additional questions concerning the PLD. For individual vertical sections of layers and comparisons between sections, the list of outstanding questions is large and includes the following: What is the scale of individual layers within a single vertical section? Are they laterally continuous within a section? Are they vertically repetitive? Are there any cyclic patterns and if so, what is their nature and origin? Do any such patterns change with depth? What is the temporal meaning of layers and units? Do they correlate with any predicted climate variation, and what does this mean for the polar history of Mars? How far laterally can individual layers and groups of layers be traced? Is there evidence for discontinuities and unconformities? If so, how extensive are they and what do they mean? What is the implication of the dip of the layers for the polar history of Mars? How are regional correlations related to orbital parameters, climate cycles, the origin of troughs, and the general volatile history of Mars?

Characterization of Vertical Sections: As a first step in unraveling the relationship between the polar layered deposits and climate, it is necessary to understand and quantify the characteristics of the layers themselves in individual "cores" or sections. Then it is necessary to establish whether there are any correlations between adjacent sections as well as any regional or cap-wide correlations. Finally, it is important to establish if and how such correlation is consistent with depth in the vertical sections representing changes with geological time. Once the signals encoded in the layers and their lateral and vertical correlations are known, then their relationships to climate change can be assessed. The results reported here are part of an ongoing effort to characterize quantitatively the layers both vertically, by looking for patterns in vertical stratigraphy, and horizontally, by examining variations in layer continuity on local (trough-wide) and regional (cap-wide) scales. The results are then used to assess models of polar history and climate. Similar questions are commonly asked in the study of layered sedimentary sequences on Earth and in the analysis of their relationship to paleoclimate conditions. Thus, we first examined techniques used in the analysis of individual sequences (e.g., sediment cores or rock sections) and their lateral relationships and correlation, and we then applied appropriate techniques to the Mars polar deposits.

Results: We use two techniques commonly employed in paleoceanography for the study of deep-sea sediment cores on Earth to establish the characteristics of layers in individual cores (Fourier analysis) and to determine the correlation between cores (curve-shape matching algorithms). Application to "cores" (vertical sections) of the north polar layered terrain on Mars reveals several fundamental properties of north polar cap stratigraphy: 1) Fourier analysis of the layer vertical sequences reveals a characteristic and repetitive wavelength of ~30 m thickness throughout the upper part (Zone 1) of all sequences analyzed. 2) Application of curve-shape matching algorithms demonstrates that layers correlate across at least three-quarters of the cap (~$6x10^5$ km^2) in the 13 images analyzed to date. 3) Assessment of geometric relationships shows that layers are not horizontal, but rather have an apparent dip of approximately 0.5 degrees. We interpret these results (Fig. 1) as follows: 1) The fundamental ~30 m signal is interpreted as a climate signal that may correspond to a 51 kyr insolation cycle. 2) The lateral correlation and broad distribution of these layer sequences strongly imply that layer accumulation processes are widespread across the cap, rather than confined within a single trough or region. 3) Local to regional variability in individual layer thicknesses (and thus accumulation and sublimation rates) is typically less than a factor of 2.5, providing the ability to study regional trends, but often making it difficult to correlate visually the vertical sequences in individual cores. Finally, initial examination of layers located deeper in the stratigraphic sequence within the north polar cap than the ~300 m thick Zone 1 provides evidence for a unit less than 100 m thick (Zone 2) in which the fundamental ~30 m sequence is not detected. We interpret this as a deposit having formed during a recent high-obliquity phase of Mars, during which time polar volatiles underwent mobilization and were transport equatorward, leaving a polar lag of dust-rich material. The most recent "ice age" (~0.5-2 Ma) offers a plausible candidate for this period of ice cap removal and lag deposit formation. An underlying Zone 3 (~200 m) contains a dominant 35 m signal, and a lowermost Zone 4 (~200 m) contains multiple signals but no dominant one. Together these four zones represent ~800 m of vertical stratigraphic section, about one-fourth of the total thickness of the cap. These findings support earlier interpretations that orbital parameter variations could cause significant erosion and possibly complete removal of the polar caps. The interpreted crater retention ages of the layered terrain are consistent with the correlations and vertical sequences described here, suggesting that the polar caps wax and wane throughout geological history, depending on the evolution of orbital parameters. Definition of the ~30 m unit signal holds promise for determining 1) the detailed origin of individual layer types, 2) the nature of deposition and sublimation processes and their relation to insolation geometry across the polar cap, and 3) correlation with and comparison to the south polar layered terrain record.

References: [[illegible] ess, 1992; [2] M. Mellon [illegible] Squyres, *Icarus*, 40, 24 [illegible] , 44, 552, 1980; [5] J. C [illegible] 1982; [6] A. Howard et [illegible] ays et al., *Science*, 194, [illegible] , 50, 408, 1982; [9] J. In [illegible] A. Berger and M. Loutre [illegible] ahn et al., *Mars*, UA Pre [illegible] gett, *JGR*, 106, 23429, 2 [illegible] a, *Icarus*, 154, 22, 2001 [illegible] *LPSC 32*, 1973, 2001, [1 [illegible] *ro 36*, 69, 2002.

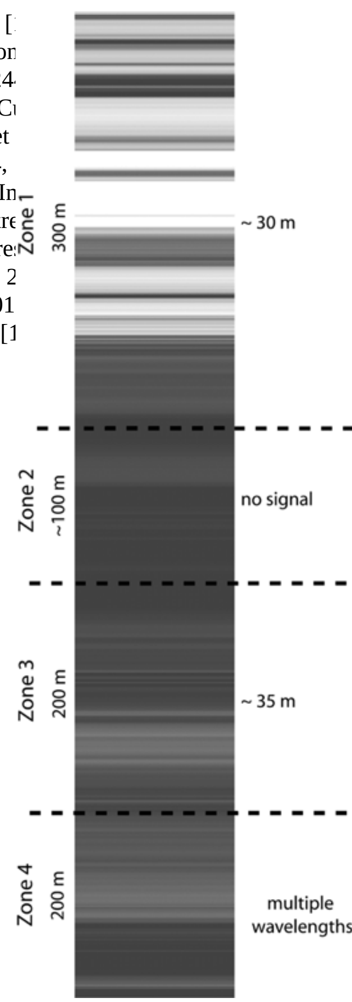

Figure 1. Composite stratigraphic column for the north polar cap showing the four zones recognized.