North polar cap of Mars: Polar layered deposit characterization and identification of a fundamental climate signal

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

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The record of recent climate change on Mars is encoded in the polar layered deposits within the north polar cap. Individual Mars Orbiter Camera (MOC) images of exposed layer sequences in cliffs and troughs provide the equivalent of high resolution “cores” through many sections in the upper part of the north polar layered terrain. In order to decode this record it is necessary 1) to quantitatively characterize the layers in individual “cores” and 2) to assess possible correlations between “cores” in vertical layered deposit sequences across the cap. 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 (~6 × 10^5 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 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.
1. Introduction

[2] The northern polar cap of Mars is characterized by spiraling troughs cutting through the cap surface (Figures 1a and 1b). Horizontal and subhorizontal layers exposed on the walls of these troughs are thought to contain varying ratios of water ice and dust (Figure 1c). These 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., Soderblom et al., 1973; Cutts, 1973; Blasius et al., 1982; Howard et al., 1982; Thomas et al., 1992]. Layers include dust and water ice but at depth within the cap, CO2 clathrate hydrate ice may be present as well [Mellon, 1996; Kargel and Lunine, 1998].

[3] Layer formation models based on these images called for obliquity cycles to drive climate change to produce the layers [e.g., Squyres, 1979; Toon et al., 1980; Cutts and Lewis, 1982; Howard et al., 1982]. Such approaches are similar to models in which orbital Milankovitch cycles drive ice ages and climate change on the Earth [e.g., Hayes et al., 1976; Imbrie, 1982, 1985; Berger and Loutre, 1994; De Boer and Smith, 1994; Mörner, 1994; Rial, 1999; Elkibbi and Rial, 2001]. Changes in insolation patterns due to quasiperiodic orbital cycles will affect the brightness of an individual layer; the duration and intensity of southern summer influences the occurrence of global dust storms [Kahn et al., 1992] which affects the dust to ice ratio, and in turn the brightness, of the layer deposited at the northern cap. Darkening may also occur through ice ablation and the accumulation of included dust; lightening may occur by deposition of new ice. 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., Squyres, 1979].

[4] 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. [1992] 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.

[5] The advent of much higher-resolution Mars Global Surveyor (MGS) Mars Orbital Camera (MOC) images of the polar layered terrain, combined with the Mars Orbital 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 [Malin and Edgett, 2001]. 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” [Malin and Edgett, 2001; Kolb and Tanaka, 2001; Milkovich and Head, 2001, 2002]. 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 [e.g., Joint Oceanographic Institutions’ Deep Earth Sampling Program, 1965].

[6] 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 and how far can they be traced? Are there any cyclic patterns in the layers and if so, what is their nature and origin? How do such patterns change with depth? 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 polar and volatile history of Mars?

[7] 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.

[8] Similar questions are commonly asked in the study of layered sedimentary sequences on Earth and in the analysis of their relationship to paleoclimatic conditions. Thus we first examine techniques used in the analysis of individual sequences (e.g., sediment cores or rock sections) and their lateral relationships and correlation, and we then apply appropriate techniques to the Mars polar deposits.

2. Earth Sedimentary Sequence Data Analysis Techniques

[9] Terrestrial studies in the field of paleoceanography examine the recent climate history of the Earth using layer
Figure 1. The north polar cap of Mars. (a) Mars Global Surveyor wide-angle image of the north cap (MOC2-231). Box indicates location of Figure 1b. (b) Mars Global Surveyor wide-angle MOC image M00-02101, showing troughs (dark areas) within the northern cap. Line indicates location of Figure 1c. (c) Mars Global Surveyor narrow angle image M00-02100, containing polar layered deposits exposed on trough wall. This image is analogous to an individual stratigraphic section of the polar layered deposit record.
sequences from deep-sea cores. Characteristics such as isotope ratios, foraminifera content, and magnetic susceptibility are used to study changes in factors such as accumulation rate between locations and to search for climate signals [e.g., Shackleton and Opdyke, 1973; Prell et al., 1986; Chappell and Shackleton, 1986; Imbrie, 1982; Lisiecki and Lisiecki, 2002].

On the basis of our review of this literature and discussions with a number of participants, we have adapted two paleoceanographic methods of quantitatively examining layer sequences for application to the polar layered deposits on Mars [Milkovich and Head, 2002, 2003a, 2003b, 2003c, 2004].

2.1. Data Selection and Preparation

To perform the above data analysis methods for Mars, data sets of brightness with depth for the polar layered deposits must be constructed from the available data. First, each MOC narrow angle image is calibrated; then the individual calibrated MOC narrow angle image is combined with the MOLA topography data acquired concurrently with each image. It is important to realize that the appearance of individual layers in a specific image (e.g., Figure 1c) represents an apparent thickness, and is controlled by the slope of the exposed surface (e.g., trough wall). For example, in Figure 2 a vertical view of a layered sequence or section is seen in the MOC image (left) and a particular 550 m long section is outlined in the box by the dark bar. The 550 meters distance is the horizontal distance along the ground and is thus an apparent thickness. A 40° sloping cliff of this same stratigraphic section is also exposed in this image (Figure 2, middle, labeled Ap1) and it is clearly seen that the layers are generally flat-lying and exposed along a very shallow slope (Figure 2, left). The MOLA altimetry data then permit this slope to be measured and a true layer or unit thickness calculated. In this case, MOLA data show that the slope is ~6 degrees and that the actual thickness of the 550 m exposed section is ~60 m, about one tenth of the apparent thickness in the image. It is therefore essential to take topography into account when characterizing individual sections or comparing layer sequences between or among sections.

Each digital picture element (pixel) of an image is characterized by a brightness or gray scale as measured by a digital number, or DN value, that ranges from 0 to 255. Elevations are assigned to each pixel by interpolating between individual topography points from the MOLA profile acquired with the image. Thus each pixel has a DN value and an elevation value that can be used to construct a profile of brightness with depth for each image. All distances within a profile are depths below the cap surface calculated in this way from individual MOLA points and thus are true thicknesses. For example, a MOC narrow angle image (Figure 3a) is shown side by side with DN values (Figure 3b) from that image and the associated MOLA data (Figure 3c). Although the MOLA data are obtained co-aligned with the long axis of the MOC image, the orbital configuration and viewing geometry are rarely normal to the strike of the layers in the individual sections. Thus the profile must first be adjusted to be perpendicular to the strike of the layers. In this way, data sets are constructed (Figure 3d) that are similar to drill cores taken normal to the strike of horizontal beds. In addition, prior to using the Match 1.0 analysis discussed below, each data set is linearly detrended to remove the overall trend from bright at the top of the trough wall to dark at the bottom that is observed in all images (e.g., see Figure 3a). Linearly detrending data sets before matching is a standard technique for this type of analysis [Lisiecki and Lisiecki, 2002]; it allows the details of the data sets to be more clearly observed.

Following these guidelines, the images used in this analysis were selected from four general regions in order to assess potential characteristics and correlations over as wide an area of the cap as possible (Figure 4). Seven images were selected from an area covering $1.6 \times 10^5$ km², or 3.9% of the cap surface, around 280°W (Figure 4, box). This region was chosen because it has a large concentration of high-resolution, clear (unobscured by atmospheric clouds or haze) images in neighboring troughs. Furthermore, several
Figure 3. An example of the construction of the brightness-depth profile. (a) Subframe of MOC image M00-02100. White line indicates location of the MOLA profile. (b) DN profile along location of the MOLA profile. Dark lines connect layers in Figure 3a with equivalent locations in the profile. (c) MOLA topography data associated with the image. (d) Adjusted DN profile corrected for topography.
images included in this analysis have been examined in other polar studies [Malin and Edgett, 2001; Kolb and Tanaka, 2001; Laskar et al., 2002], providing an opportunity to compare results. The three remaining locations for study were chosen from longitudes at approximately 90 degree intervals around the cap from the more intensely sampled 280°W region (Figure 4). At each longitude, two images were selected for analysis. One image from each longitude was at an elevation of approximately −2700 m, corresponding to the upper range of elevation studied in the 280°W region, while the other image was at an elevation of approximately −4000 m, corresponding to the lower range of elevation studied in the 280°W region. This allows us to compare layer sequences, and thus lateral continuity, at these two elevations at four separate locations around the cap. One image was obtained in northern spring (Ls range 0–90°) and twelve images were obtained in northern summer (Ls range 90–180°) in order to minimize any effects from atmospheric hazes, clouds or seasonal surface condensates. Differential defrosting of surfaces in summer images can be due to differences in local steepness or layer composition; only images without obvious frost patches were selected for analysis. Figure 6 shows the locations of all images used in this study.

2.2. Fourier Analysis

[13] The first method is Fourier analysis, which takes a signal and breaks it down into sine and cosine components. The components are then examined for dominant wavelengths, which indicate the existence of patterns in the signal. The length scale of the most significant pattern is the dominant wavelength. Using this method, the potentially changing depositional environment recorded by layer sequences can be characterized. In terrestrial analyses where layers can be age dated, Fourier analysis can also reveal the timescales on which the patterns within the layers occur; thus Fourier analysis can be used to look for periodic climate signals [e.g., Longo et al., 1994]. Fast Fourier Transforms (FFTs) are the numerical method of performing Fourier analysis used in this study and Figure 5 is an example of a result from the FFT analysis. The top graph in Figure 5 plots the signal to be analyzed. This includes the pattern of layers in the vertical stratigraphic sequence (recorded by variations in brightness values, DN) as a function of vertical distance down the sequence of layers from the top of the core or section, to the bottom (youngest to oldest). The bottom graph in Figure 5 shows the power spectrum as a function of spatial wavelength, and illustrates the wavelength patterns found in the signal. The highest peak is the dominant wavelength; in this example the dominant wavelength is ~30 m.

2.3. Matching Program

[14] The second method is used to analyze correlations between data sets by matching the shapes of the data sets. In this method, for example, a distinctive peak or wiggle in the plot of one data set is correlated to a similarly distinctive peak or wiggle in the other. This technique is used in terrestrial studies not only to correlate two or more layer sequences but also to study changes in accumulation rates between locations [e.g., Prell et al., 1986; Herbert, 1994]. Traditionally done by hand, this technique is now beginning to be computerized, a development that we adopted by using the Match 1.0 program of Lisiecki and Lisiecki [2002] to perform the matching analysis.

[15] The Match 1.0 program utilizes dynamic programming, a class of algorithms used in optimization programs where one problem is divided into multiple subproblems. All possible solutions for the subproblems are considered, producing an optimal solution for the overall problem. In this technique, each data set is divided into many small intervals; data within each interval of one data set is compared with those in each interval of the other data set. The sequential order of the intervals is preserved. In stratigraphic analysis, the data sets consist of information (for example, δ18O) with depth; the values of depth are adjusted so that the interval from one data set is compressed or stretched to increase the amount of fit with the other data set. The amount of compression or stretch is interpreted as a measure of the change in net accumulation rate (NAR) between each data set. User-adjusted penalties are assigned for changes in NAR within intervals and for nonmatched intervals. Such penalties prevent physically unrealistic results, such as multiple peaks from one data set being compressed to match a single peak in the other data set. For more information on the assignment of penalties and the details of the Match 1.0 program, refer to Lisiecki and Lisiecki [2002]. For each alignment of intervals, a score is calculated that includes the assigned penalties as well as the sum of the squared differences of all data points within the matched interval. The best alignment is the one that minimizes the cumulative score calculated from the matched intervals. In this way, the algorithm selects the best overall solution rather than forcing a local solution through extreme measures such as rapidly changing accumulation rates. The
quality of the match is indicated by the coefficient of determination, $r^2$, which indicates the percentage of the variation within each data set that is related to the variations in the other data set.

[16] An example of this approach from our analysis is shown in Figure 6. Here the top graph shows two data sets prior to being matched. Each data set represents a vertical profile of brightness with depth of the upper part of the layered terrain on Mars. The middle graph plots the two data sets once they have been matched to each other. The starting depth of the matched data is lower from the prematched data due to a failure of the program to find a good match in the upper section of the data. A visual check of the images indicates that many small-scale layers are obscured in the upper part of one image, possibly by surficial frost deposits. The bottom graph in Figure 6 shows the change in relative net accumulation rate (NAR) between the two data sets assuming that the two cores or sections have been properly matched (Figure 6, middle). This matching technique and FFT analysis provide a potentially very important approach to analyzing the nature of individual columns, the assessment of vertical patterns in individual columns, correlations between columns, and the detection of local to regional patterns of net accumulation rates in the polar deposits.

[17] In order to check the validity of the match results, the brightness-depth profiles from several images were inverted (in effect, reversing the sequence of layers) and then compared to noninverted or normal profiles. First, the profile from M00-02100 was reversed and matched with the noninverted M00-02100 profile. When run through the Match 1.0 program using the same level of penalties assigned for nonmatching intervals and changing NAR, as used in the rest of this analysis, only an extremely poor match with $r^2 = 0.18$ could be achieved. Secondly, profile M00-02100 was reversed and matched with M00-01714. No match was found between the two profiles. When the stringency of the matching requirements was relaxed, a poor match could be found with $r^2 = 0.40$ (shown in Figure 7a). These two examples are in contrast to every other section comparison made with the normal (non-inverted) profiles, where good matches were immediately found each time.

[18] An additional independent check of the match results was conducted on three images from within a single trough: M00-01754, M00-02100, and M03-04652 (Figure 7b). A layer with a distinctive erosional pattern called the “marker bed” is observed running throughout this trough [Malin and Edgett, 2001; Kolb and Tanaka, 2001] and can be clearly identified in these three images. This marker bed serves as an analog to volcanic ash layers (“bentonites”) sometimes seen in terrestrial sedimentary sequences and deposited essentially instantaneously over great distances to form a very close approximation to a stratigraphic “time line.” After the independent matching analysis was complete, the marker bed was identified in each postmatch image profile.
(Figure 7b). This distinctive layer occurs along a line of constant elevation and parallel to correlated peaks in the three profiles, indicating that the Match 1.0 program was very successful in correlating layers within this trough.

3. Application of Terrestrial Techniques to Martian North Polar Deposits

[19] We analyzed each of the thirteen images (Figure 4) in the manner described above (Figures 1–7). The image numbers, specific locations and other related data are listed in Table 1. Initially, the complete vertical sequences of the images were analyzed, but it soon became apparent that the overall darkening toward the bottom of the image in the brightness-depth profiles resulted in a lower signal-to-noise ratio in the data toward the base. In order to utilize the highest signal-to-noise data, we confined our FFT analysis to the top 200 m of each image. The FFT results for all 13 images are shown and summarized in Figures 8a and 8b. On the basis of this analysis, dominant wavelengths were observed in each of the sections (Figure 8b). Dominant wavelengths were similar, ranging from 23 m to 35 m, with the mean dominant wavelength ~29 m and the median dominant wavelength 29 m. We therefore conclude that the widely spaced sections analyzed (Figure 4) have a mean dominant wavelength, or thickness, of about 30 m.

[20] Secondary wavelengths, considered to be peaks in the FFT results that are not as strong as the dominant wavelengths, but still stronger than the rest of the resulting signals, are found in about half of the images analyzed. These wavelengths range from 17 to 37 m. The secondary wavelengths may be a result of climate influences, but due to their wide range and the fact that they are not found in all images, we conclude that they are not the primary signal of climate influence on layer formation and we are characterizing them further in a related study.

[21] We next investigated how well individual sections correlated with one another. Five of the images in the 280° W region were matched to a seventh image, M00-02100. This latter image was selected as the reference image to which all other images would be compared because previous analyses have examined it in detail [e.g., Laskar et al.,]
Figure 7. Testing the matching program. (a) First, profile M00-02100 was reversed and matched with itself, and only an extremely poor match with $r^2 = 0.18$ could be achieved. Second, profile M00-02100 was reversed and matched with M00-01714. No match was found. When the stringency of the matching requirements was relaxed, a poor match could be found with $r^2 = 0.40$ (shown here). (b) Correlation of profiles of brightness with depth from three images taken within a single trough after matching with the center image, M00-02100. The location of the “marker bed” identified by Malin and Edgett [2001] is indicated, and its position provides an independent check on the quality of the matching analysis. The matching process adjusted the spacing of data with depth in each profile; the amplitude of the variations of brightness remains unchanged. The dominant wavelength for the upper 200 m of each profile ranged from 26 m to 33 m with an average of ~30 m.
Table 1. Image Information

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2002]. The results of the matching analysis are summarized in Figure 9. Four of the five sections display a good match with the target image, M00-02100, with 0.6 \( \leq r^2 \leq 0.8 \) (Figure 9b). Relative net accumulation rates between images were always less than a factor of 2.5. This means, for example, that a layer 5 m thick in M00-02100 might be up to a maximum of 12.5 m thick in M00-03037, approximately 200 km away, but was commonly much less. The fifth image displays a poorer match \( (r^2 = 0.44) \). This image is of lower resolution than the other images (13 m/pixel compared to 2–4 m/pixel); thus the details in the layer sequence are missing, which may be a factor that prevents a higher quality match with the high resolution images.

[22] The seventh image, M00-01714, in the 280° W region (Figure 9) only partially matched the target image (Figure 10). However, the upper section of M00-01714 matched the lower section of the target image with \( r^2 = 0.46 \) (Figure 10a). We thus explore the possibility that this image exposes a lower section of the stratigraphic sequence than that exposed in the target image. In testing this hypothesis we found that the two images expose the same overlapping layer sequence for about 200 m (Figure 10b). This result is confirmed by a second matching analysis with another image in this region, M00-03037. This latter image displayed a similar overlap with the layers in the upper section of image M00-01714 with \( r^2 = 0.65 \). One possible reason for the remarkably deep exposure of the layers in image M00-01714 is that this area is near the junction of four troughs (Figure 10c) and thus may have experienced a somewhat anomalous erosional history compared to neighboring regions.

[23] To assess further the presence or absence of any lateral correlations in other parts of the cap away from the initial test areas, other images from ~90°W around the remaining parts of the cap (Figure 4) were then matched with both the target image from 280°W (M00-02100) and the image exposing layers lower in the stratigraphic sequence (M00-01714). Of the six images examined from the rest of the cap, five display a good match with the target image, with \( 0.5 \leq r^2 \leq 0.7 \) (Figure 11a; dark gray bars). This supports the interpretation that the individual sections record portions of the same stratigraphic record over a large part of the north polar cap. Furthermore, the matching program also reveals that there is a significant overlap in the same five images with the lower image (M00-01714), with \( 0.5 \leq r^2 \leq 0.8 \) (Figure 11a, light gray bars). This suggests that the lower part of the sequence is also being sampled in these five sections that are widely dispersed over the north polar cap.

[24] The matching program also provides data on relative NAR (Figure 11b). Our analysis shows that relative NAR between images is predominantly less than a factor of ~2.5, although one image has a brief spike up to a factor of 4. This means that even over distances of many hundreds of km, the thicknesses of individual layers only vary by up to about a factor of ~2.5. This tells us that although the layers are continuous across the entire cap, they do not have uniform thicknesses. Variations in thickness may be due to nonuniform deposition or postdepositional modification such as erosion, sublimation, or polar cap processes such as flow. The relative net accumulation rate drops to zero in regions within several matched images; this implies the existence of gaps in the stratigraphic record or small unconformities throughout the PLD. However, no large or systematic breaks in the stratigraphic sequence are detected from trough to trough. This suggests that the unconformities noted by previous researchers [e.g., Howard et al., 1982] are very modest, occur on a local scale where polar topography is very complicated, or developed uniformly on different scars and thus do not disrupt the matching process. The question of the locations and scales of the unconformities is a significant one for polar history and is currently being investigated.

[25] No significant trends in accumulation rate with distance from the pole have been found in the analysis to date, which implies that any effects of internal cap flow causing the layers to thin toward the edges of the cap are not seen. Thus such an effect may not occur on this scale or in the upper several hundred meters of the cap. Further analysis of these results is underway.

[26] The sixth image displayed a poor match \( (r^2 < 0.4) \) to both the M00-02100 and M00-01714 images as well as very anomalous relative accumulation rates of up to a factor of 8. This image (Figure 4) is located on the inner wall of Chasma Boreale; this wall is many times steeper than the trough walls that expose the layers examined elsewhere. The steepness of the wall effectively reduces the resolution of the image of the layers in the wall - the details of the layer sequence are lost and thus the matching analysis results are poor.

[27] The matching analysis also provides information on which individual layers are recorded in each image and how each of the images vertically overlaps. This is equivalent to comparing specific individual beds in each of the different stratigraphic sections and then comparing the individual stratigraphic sections to show how they are correlated and where they overlap. From this information it is possible to construct a composite stratigraphic sequence from several stratigraphic sections.

[28] Using this approach, a composite stratigraphic column was constructed from the three images with the highest signal-to-noise ratio and the least apparent modification by frost and atmospheric effects. This composite stratigraphic column can then be used to examine the vertical characteristics of the layers with a single Fourier analysis of the entire stratigraphic column, thus reaching deeper into the stratigraphic sequence than possible with each of the indi-
individual profiles (Figure 12). Employing this method on the composite stratigraphic column reveals the following four zones: 1) Zone 1: The top interval of the section, approximately 300 m thick, contains a dominant wavelength of about 30 m which falls within the observed range (24 to 35 m) of dominant wavelengths found in the individual images. 2) Zone 2: Below the upper part of the section is an interval ~100 ± 30 m thick in which no signal was detected. To test if this lack of a signal was due to the increasingly poor contrast with depth due to the general darkening trend, we increased the contrast in a range of steps and performed the analysis again on each step. Even when the contrast of the brightness profile was increased, no signal was found, and we were thus still unable to detect a dominant wavelength in this interval. We call this the “no periodic signal” region. 3) Zone 3: Stratigraphically underlying the “no periodic signal” region we found a section approximately 200 m thick that was characterized by a dominant wave-
length of \( \sim 35 \) m. 4) Zone 4: Below this section, the 200 m thick remainder of the column has multiple wavelengths and no single dominant wavelength. Instead of a single dominant \( \sim 30 \) m wavelength, there are strong signals at 17, 24, and 27 m. In summary, the composite stratigraphic section is about 800 m thick (about one-quarter of the thickest part of the north polar cap) and consists of four subdivisions, including an upper Zone 1 and an intermediate Zone 3 with dominant wavelengths of about 30 m, separated by an approximately 100 m thick layer (Zone 2) containing no detectable signal. Below these three zones lies a fourth zone with multiple significant wavelengths but no dominant wavelength.

4. Discussion and Conclusions
4.1. Areal Extent of Correlated Layers and Implications for Formation Models
[29] We interpret the layers recorded in twelve of the thirteen images analyzed to be part of a single laterally
extensive deposit extending throughout at least three-fourths of the polar cap (Figure 4).

[30] The origin of the residual ice layer (unit Api of Tanaka and Scott [1987]) and its relationship to the underlying layered terrain (unit Apl of Tanaka and Scott [1987]) have been uncertain and Thomas et al. [1992, p. 775] state that “it is not known if they may grade into the underlying layered deposits.” The correspondence of the residual ice layer (Api) distribution to the location of the stratigraphic sections sampled in this analysis, coupled with the correlation of the underlying layers over the same area (Figure 4), suggests that the residual ice layer (Api) is likely to be the presently forming top of the uppermost layer in the stratigraphic sequence.

4.2. Tests of Layer Formation Models

[31] Layer formation models can be classified as falling between two end-members: 1) Layers are deposited uniformly across the cap irrespective of underlying topography, and 2) Layers are deposited only in association with a single trough (in effect, each trough contains an independent system of layers) [e.g., Howard et al., 1982]. In between these two extremes are models where layer deposition is nonuniform due to the influence of trough geometry and insolation intensity on water ice stability. The role and effect of internal flow of the ice cap is much debated, but may influence the existence of the troughs and the layers exposed on the trough walls [e.g., Hvidberg, 2003; Fisher, 1993, 2000]. The correlation and continuity of layers across the polar cap documented here strongly suggests that the formation of layers is not confined to within a single trough as previously envisioned in some models for layer formation (e.g., model A described by Howard et al. [1982]). Our data suggest that deposition of layers must occur across almost the entire cap, consistent with those models closer to end-member model 1, such as the model of Squyres [1979] and models B through H described by Howard et al. [1982].

Figure 9. Results of matching analysis of six images with target image (M00-02100) in the 280°W region. (a) Zones of coefficient of determination ($r^2$) percentages for match overlap upon map of image location; $r^2$ ranges from 0 to 1, with 1 corresponding to an exact match of all data points. (b) Coefficient of determination values for each match with M00-02100.
model described above. A similar result for the internal structure of the southern polar layered deposits was found by Byrne and Ivanov [2004], whose stratigraphic analysis of bench-forming layers in the southern cap reveal that layer exposures are consistent with a simple dome-shaped topography. Further investigation of the internal structure of the layers within the northern cap is being carried out through an examination of layer stratigraphy in regions where the three dimensional structure of the layers is displayed, such as eroded trough bottoms or locations where multiple troughs come together.

4.3. Identification of a Fundamental Climate Signal

[31] The upper part of all images have a dominant wavelength of approximately 30 m; since this wavelength is observed in every image thus far analyzed, we interpret it to be a signal produced by quasiperiodic climate change. Figure 14 shows an image with a 30 m vertical depth scale bar to illustrate 30 m sequences of layers within the image itself.

4.4. Net Accumulation Rates

[34] Within the individual 30 m thick sequences of layers there is variability in the thicknesses of individual layers. By examining the relative changes in net accumulation rate between images from the matching analysis, it can be seen that layer thicknesses vary up to a factor of ~2.5 both vertically within an image and laterally between images. This implies the existence of local scale climate effects not considered in current layer formation theories. For example, the distance from the pole could affect deposition rates, although no trends with distance from the pole have been observed to date in the relative NAR between images from neighboring troughs. Changing relative NAR between neighboring troughs may be due to the different geometry and orientation of the individual troughs. The trough geometry and orientation could affect insolation intensity [Hecht, 2002] or katabatic wind flow, which in turn would affect erosion of material through sublimation and erosion [e.g., Howard, 2000]. These effects may also cause variations in NAR between locations within a single spiraling trough.

4.5. Regional Stratigraphic Characteristics of Recent Polar Deposits

[35] Analysis of the composite stratigraphic column reveals a 300 m thick upper unit with a dominant wave-
Figure 11b. Data for all matching results to date. “MB” on matches with image M00-02100 indicates the location of the “marker bed” identified by Malin and Edgett [2001].
Figure 11b. (continued)
Figure 11b. (continued)
length of ~30 m (Zone 1) overlying a ~100 m thick unit with no signal (Zone 2). Below these two units lies Zone 3, containing a dominant wavelength of ~35 m, and Zone 4, characterized by multiple wavelengths, but no single dominant signal. We interpret these dominant wavelengths as climate signals. In order to assess how these proposed climate signals might relate to geological time and recent climate history, we compare the characteristics of the signals and the stratigraphic units with recent climate studies.

4.6. General Darkening Trend With Depth

[36] An additional trend described above is the general darkening of the polar layered deposits as a function of depth within the polar layered terrain record examined to date. One plausible interpretation for this brightness trend is the corresponding generally increasing trend in mean obliquity as a function of time (Figure 15 and Laskar et al. [2004]). In this case, the combination of increased dust storm activity and decreased ice deposition and retention during periods of mean high obliquity [e.g., Jakosky et al., 1995; Richardson and Wilson, 2002; Haberle et al., 2003; Mischna et al., 2003] could produce a higher dust-to-ice ratio and a general darkening of the resulting deposits. Another interpretation is that variations in the rate of summer defrosting cause the general darkening trend. The base of the troughs may defrost more efficiently than the tops due to microclimate or microtopographic effects including colder temperatures at the top of the trough from the proximity of the perennial ice or greater reflected components of radiation near the trough bases.

4.7. Correlation of Signals With the Predicted Climate Record

[37] Laskar et al. [2002] compared the brightness with depth profile of one MOC image (M00-02100, the same image used in the matching analysis) with calculated insolation cycles. The insolation cycle in the last 0.5 Myr is driven by climatic precession and has a period of 51 kyr [Laskar et al., 2002]. Laskar et al. [2002] found that the upper 250 m of the single image profile corresponds to an accumulation rate of 0.05 cm/yr. The assumption that the 30 m layer sequence (observed in 13 images in this study) is accumulated in a single insolation cycle leads to a net accumulation rate of approximately the same value, 0.06 cm/yr. Precession-dominated layer packet formation is also consistent with the work of Hochl [2003], who addressed the relative contribution of different orbital elements to the climate forces interpreted to be responsible for the formation of water-related features such as gullies on crater walls.

[38] Previous estimates for accumulation rates of the polar caps include a wide range of rates. Herkenhoff and Plaut [2000] have estimated the surface age as less than 120 kyr on the basis of the absence of impact craters larger than 300 m in diameter, corresponding to a resurfacing rate of 0.12–0.47 cm/yr. Earlier estimates assumed that each 30 m layer pair observed in Viking imagery was formed in an obliquity cycle, suggesting rates of $10^{-3}$ cm/yr [Hofstadter and Murray, 1990]. For comparison, terrestrial accumulation rates for polar and glacial environments range from a few cm/yr in the last 100,000 years in East

Figure 12. Composite stratigraphic column for the north polar cap showing the four zones recognized. The dominant wavelength as calculated by FFT analysis for each segment of the column is listed on the right side of the column. The stratigraphic thickness of each zone is shown on the left side.
Antarctica [Siegert, 2003] to 40 cm/yr in the last few hundred years in Svalbard [Pohjola et al., 2002]. Climate models [e.g., Jakosky et al., 1995; Richardson and Wilson, 2002; Haberle et al., 2003; Mischna et al., 2003] using calculated orbital variations [e.g., Touma and Wisdom, 1993; Laskar and Robutel, 1993; Laskar et al., 2004] have examined how the regions of water ice stability change with Martian orbital parameters. Head et al. [2003] have recently combined these studies with geological observations and interpreted the recent climate history of Mars. During periods of mean high obliquity, there is net removal of volatile material from the polar cap and net deposition at the lower latitudes. This period, an “ice age,” results in a lag deposit of dust building up on the polar cap. During times of mean low obliquity, volatile material is again deposited on the cap while the rest of the planet experiences an “interglacial” period. Figure 15, adapted from Head et al. [2003], shows the obliquity during the most recent ice age and interglacial episodes. If a 30 m layer sequence is indeed accumulated in 51 kyr, then the upper 300 m section of the PLD (Zone 1) was accumulated in the last 0.5 Myr. This time period corresponds to the period of time since the end of the last ice age. We therefore tentatively interpret the “no periodic signal” layer (Zone 2) located beneath the upper 300 m (Figure 12) as the lag deposit built up in the last ice age. A closer examination of the “no periodic signal” Zone 2 with extremely enhanced image contrast reveals layers of varying brightness within this region of the stratigraphic column (Figure 16). The length of the profile within this zone is too short to explore in further detail with FFT analysis; it is unclear whether the “no periodic signal” zone consists of a single thick region with no climate signal or multiple thin layers with no climate signal separated by other brighter, presumably more ice-rich layers. If the latter, then the darkest layers observed in Figure 16 may be multiple lag deposits a few meters to tens of meters thick. Since this is the limit of resolution of the data, it is possible that thinner lag deposits are present. A region of multiple thin, dark lag deposits separated by more ice-rich layers is consistent with a depositional environment that oscillates between acting as a volatile source and a volatile sink, the situation experienced by the polar cap during the last ice age before ~0.5 Myr ago. There are no features observed in the

Figure 14. Subframe of M00-01754. Diagonal line extends 30 m in the vertical direction representing the stratigraphic thickness (that is, a 30 m change in elevation for the flat-lying sequence). The scale bar extends 200 m in the horizontal direction (200 m on the surface in the image).

Figure 15. Recent Martian climate and insolation. (a) Obliquity values for the last 3 Myr. Periods of time when obliquity regularly reaches values over 30° are suggested to be ice ages, characterized by net removal of volatiles from the polar cap. The low amplitude curve is Earth’s obliquity variation during the same time period. (b) Insolation values for the north and south polar caps in the last 1 Myr. Figure after Head et al [2003].
The pole experienced conditions that favored the removal of ice. Layers or by unconformities due to the extended time the hiatus might be recorded as additional “no periodic signal” to be at 5 Myr ago [E01005]. There may be another depositional hiatus due to an “ice age” predicted from the previous ice age. We predict that below this section may contain a lag deposit formed during a glacial period. Therefore we tentatively conclude that the layer sequences observed in the uppermost section of PLD may not correspond to obliquity variations.

4.8. Summary

[41] In this analysis we have demonstrated the utility of techniques used in the study of terrestrial paleoclimate records in characterizing polar layer sequences in order to understand the recent climate history of the north polar cap of Mars. In doing so, we have found that the layers within the upper 300 m of the PLD (Zone 1) are continuous throughout a majority of the cap, and that there is an ~30 m signal within these layers interpreted to be of climatic origin. We also found evidence for a “no periodic signal” zone in the vertical section (Zone 2), interpreted as a possible lag deposit. The units (Zones 3 and 4) immediately underlying this are characterized by distinctive signals that are different than those in Zone 1. This upper ~800 m thick section stratigraphic column (Zones 1–4) represents one-quarter of the maximum thickness of the north polar cap. The configuration of these deposits suggests that the layers are deposited parallel to the current cap topography. We are currently investigating how this upper section of the polar layered deposits relates to the south polar, considering the disparity in apparent surface ages between the two caps [Herkenhoff and Plaut, 2000], as well as the record in the lower part of the north polar PLD and the polar basin unit identified by Malin and Edgett [2001] and extensively discussed by Byrne and Murray [2002] and Fishbaugh and Head [2004]. Studies underway are also assessing the internal structure of the cap in greater detail to test for unconformities and layer deformation. Important issues in Martian polar history raised by this analysis include the temporal and spatial relationship between layer formation and trough and chasma development and evolution within the cap as well as the presence (or lack thereof) of old north polar deposits.

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