KILOMETER-THICK ICE-SHEETS IN THE NORTHERN MID-LATITUDES IN THE AMAZONIAN: ANALOGS FROM THE EAST ANTARCTIC ICE SHEET AND THE DRY VALLEYS. David R. Marchant[1] and James W. Head[2], [1]Department of Earth Sciences, Boston University, Boston, MA 02215 marchant@bu.edu, [2]Department of Geological Sciences, Brown University, Providence, RI 02912

Introduction: The strong geomorphic similarities between lobate deposits on the northwest flank of the Tharsis Montes [1,2, 12-13] and along the dichotomy boundary between 30° and 50° [3] with terrestrial cold-based glaciers and glacial deposits has led to new hypotheses for geologically recent (Amazonian-age) low and mid-latitude glaciation on Mars [1,4]. A common theme among many of these studies has been to identify individual landscape elements on Mars and match them with terrestrial counterparts from cold polar deserts on Earth [5,6]. Here, we use the documented long-term history of outlet and alpine glaciers along the East Antarctic Ice Sheet in the Dry Valleys of Antarctica as a suitable analog for glaciation along the martian dichotomy boundary. As a guiding principle we note that, just as for terrestrial glacial landsystems, the most recent ice-related deposit/feature along the dichotomy boundary on Mars need not reflect the maximum in ice volume and/or ice configuration.

The Antarctic Dry Valleys (ADV): A terrestrial analog for cold-based glaciation across stepped-bedrock topography. To a first order, the large-scale bedrock geomorphology of the Antarctic Dry Valleys (Transantarctic mountain rift-margin upwarp) approximates the martian dichotomy boundary: the valleys occur within, and dissect, a series of broad, coast-facing escarpments (total relief of up to 3000 m) separated by isolated inselbergs. In the middle Miocene, sometime between 14.8 and 12.5 Ma [7, 8], all but the highest mountains in the Dry Valleys were overrun by a major expansion of East Antarctic ice. During this time, ice spilled across bedrock escarpments and flowed out across low-lying valleys toward the continental shelf. A modern-day counterpart for the maximum-overriding stage is seen inland of the ADV, where glacier ice still overrides stepped bedrock topography (Fig. 1). Ice expansion was triggered when the Antarctic cryosphere transitioned from relatively warm and wet (fostering tundra biota and wet-based alpine glaciation) to today's cold and dry conditions in which sublimation, as opposed to melting, dominates ice recession. A modern-day counterpart for the initial phase of ice-sheet recession during the late Miocene is still observed in areas where small tributary glaciers feed main trunk glaciers (Fig. 2) and where subtle oscillations in ice margins produce multiple drop moraines. Ultimately, during the final stages of glacial overriding, alpine glaciers formed in the lee of emerging nunatacks and at the head of steep alcoves (Figs. 1-2). The alpine glaciers were likely fed from direct precipitation and from wind-blown snow off the surface of diminishing plateau ice caps. As ice recession progressed, ever-larger exposures of bedrock were likely revealed; in areas of steep bedrock scarps, rockfall covered glaciers below, and/or became trapped as englacial debris. This rockfall, along with continued ice sublimation, produced classic debris-covered glaciers (Fig. 3), some of which may still survive to this day along the flanks of the major bedrock escarpments (with subsurface ice being > 8.1 Ma) [14].

Although simplified, the above scenario documents nicely the notion that current debris-covered glaciers in the ADV are remnants of a much larger glacial landsystem. By understanding the sequence of events of the full ADV landsystem, not just the remnant ice-rich deposits, we may better frame pertinent questions regarding the potential advance, retreat and distribution of glacier ice across the martian dichotomy boundary.

Glacial deposits along the dichotomy boundary: Lineated valley fill (LVF) and lobate debris aprons (LDA) in fretted valleys at the dichotomy boundary have been interpreted as glacial in origin [10] formed during periods of higher obliquity [9]. Unknown have been 1) the original thickness of the glacier ice, and 2) the amount of ice-surface lowering, through sublimation, retreat and ice loss, to its presently observed level. We addressed these questions through analysis of an integrated LVF glacial landsystem in the Coloe Fossae region [15] (Fig. 4). We find evidence for a glacial lobe flowing "uphill" that implies that a previous high level of ice was at the distal margin of this lobe. The elevation difference between the upper limit and the current LVF surface is ~920 meters. We interpret this difference to reflect the minimum amount of ice-surface lowering of the valley glacier system during retreat. Consistent with a general lowering of the ice surface are multiple moraines and/or trimlines, and changes in LVF flow patterns, including local flow reversals, as the ice retreated and decreased in thickness. These data suggest that the major Late Amazonian glaciation that produced the LVF in this region involved significantly larger amounts of glacier ice than previously thought, essentially covering the plateau at the dichotomy boundary.

Located on the western flanks of Phlegra Montes is a ~32 km diameter impact crater with a smaller, ~8 km diameter crater on its northeast rim (Fig. 5) [16]. Although containing a sharp rim crest, the larger crater has undergone significant modification; its floor is filled with concentric ridged terrain arrayed around the interior, a texture typical of "concentric crater fill". We interpret the lobe in the small crater to have been formed from debris-covered ice that accumulated in the main crater interior and then flowed downslope northward into the smaller crater on the rim, filling it sufficiently to cause two small lobes to breach its northern rim. Topography data provide information on the initial configuration required for this scenario and suggest that a total thickness of ice of ~1000 m is required to fill the large crater, flow into, and breach the northern rim of the small crater. This thickness is comparable to that interpreted to have been present in Coloe Fossae. These data add to evidence that the formation of Amazonian mid-latitude LDA/LVF deposits involved ice sheets with thicknesses measured in hundreds of meters to several kilometers.

Conclusions: Analysis of the distribution of glaciers and glacial deposits that formed during the build up, maturation (glacial overriding of km-high bedrock escarpments), and ultimate sublimation of Miocene-age cold-based glaciers in the Antarctic Dry Valleys (ADV) provides important insight into the interpretation of candidate glacial deposits along the martian dichotomy boundary [4,5]. These analogs strongly suggest that the dichotomy boundary was largely covered by a plateau icefield during parts of the Amazonian. Subsequently, recession caused bedrock to be exposed and debris-covered glaciers to form; the current LVF/LDA configuration represents the terminal stages of this phase.

References: [1] J. Head and D. Marchant, *Geology*, 31, 641, 2003; [2] D. Shean et al., *JGR*, doi:10.1029/2004 JE002360, 2005; [3] J. Head et al., *EPSL*, 24, 663, 2006; J. Head et al., *GRL*, 33 L08S03, 2006; [4] J. Head and D. Marchant, LPSC 37, 1127, 2006; [5] D. Marchant and J. Head, *LPSC 34*, 1361, 2003; [6] D. Marchant and J. Head, *LPSC 35*, 1405, 2004; [7] G. Denton et al., *Geografiska Annaler* 75, 155-204, 1993; [8] D. Marchant et al., Geografiska Annaler 75, 269-302, 1993; [9] J. Laskar et al., Icarus, 170, 343, 2004; [10] J. Fastook et al, *LPSC 36*, 1212, 2005; [11] D. Shean et al., *LPSC 36*, 1339, 2005; [12] D. Shean et al., *LPSC 37*, 2006; [13] D. Shean et al., *LPSC 36*, 2190, 2005; [14] D. Marchant et al., *GSA Bull*. 114, 718-730, 2002; [15] J. Dickson et al., *Geology*, in revision, 2008. [16] J Head et al., B-V Micro 46, #24, 2007.

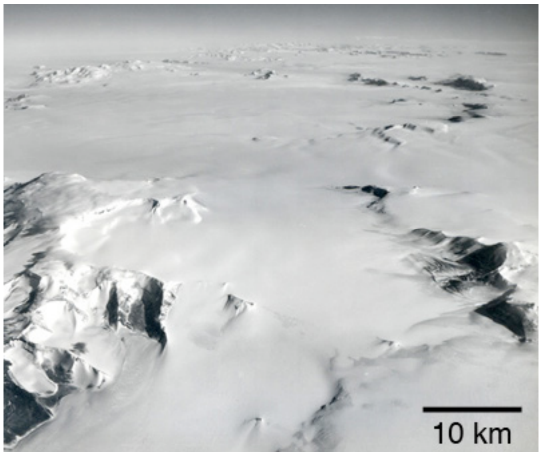

Fig. 1. Modern-day overriding of mountains inland of the ADV. Emerging nunataks show lee-side debris-covered glaciers. Inland ice shown passing over a broad plateau.

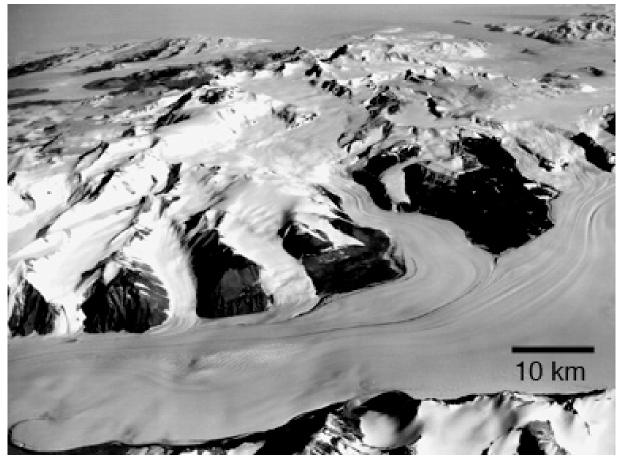

Fig. 2. Transitional stage from glacial overriding to ice-free ADV. Tributary glaciers merge with established trunk-glacier systems. Flow lines show ice deformation in association with compression from interaction and flow of merging glaciers.

Fig. 3. Formation of debris-covered glaciers. Small alpine glaciers emanating from alcoves are covered with debris via rockfall. This is the last phase of deposition associated with initial ice-sheet overriding of mountain topography.

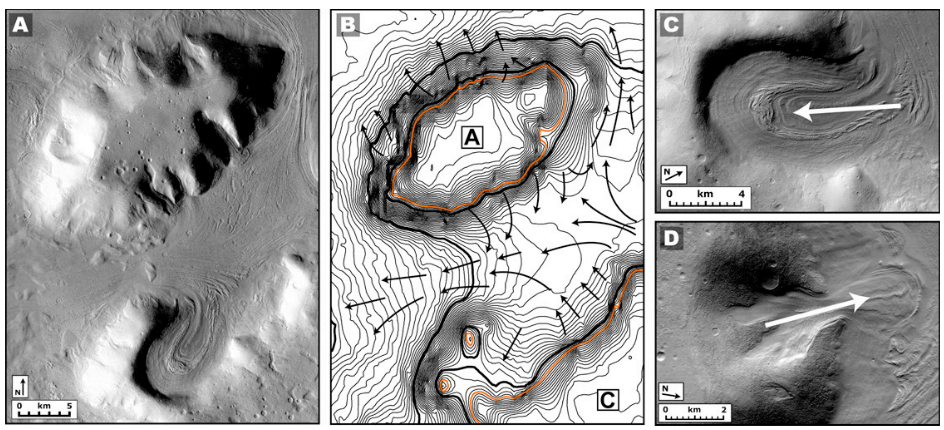

Fig. 4. Coloe Fossae glacial highstand. a) MRO CTX image PO1_001570_2213. b) 100 m contour map. c) Loop-shaped lobe entering into the box canyon, with ice sourced from the main trunk valley. d) Tributary debris-covered valley glacier emerging from the northern slope of massif A and joining a main trunk valley.

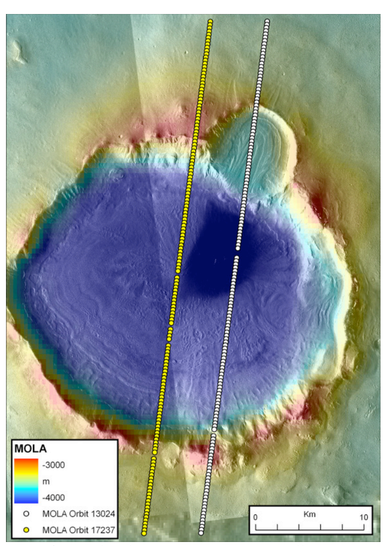

Fig. 5a. MOLA topography over CTX image mosaic at 43°N, 158°E.

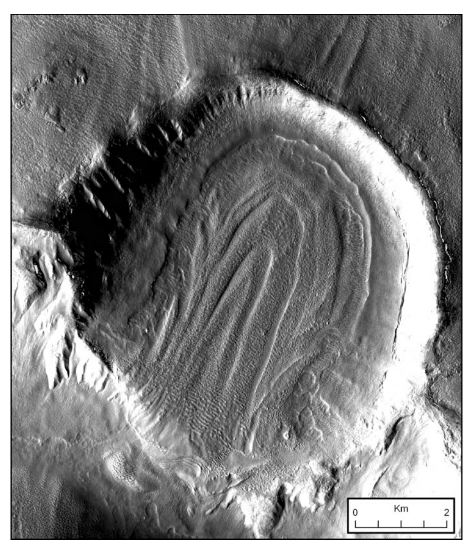

Fig. 5b. Crater fill entered this crater and filled it. Subframe of CTX image P01_001553_2232