

REGIONAL POLAR GLACIATION IN THE HESPERIAN PERIOD OF THE HISTORY OF MARS: THE SOUTH CIRCUMPOLAR DORSA ARGENTEA FORMATION AS AN ANCIENT ICE SHEET REMNANT. J. W. Head¹ and D. R. Marchant², ¹Dept. Geol. Sci., Brown Univ., Providence, RI 02912 USA (james_head@brown.edu), ²Dept. Earth Sci., Boston Univ., Boston, MA 02215 USA.

Introduction and Background: Polar regions represent cold traps for planetary volatiles and analysis of these areas permits an assessment of the amounts and types of volatiles, their stability and mobility, and the geological record of climate change. Present polar deposits on Mars consist of a thin residual ice unit (Api) overlying a thick sequence of layered deposits (Apl), and are of Late Amazonian age [1,2]. The individual layers in the current deposits are thought to be related to variations in orbital parameters [3], which cause changes in insolation and climate, and corresponding variations in dust and volatile stability, mobility, transport and deposition [e.g., 4,5]. Recent analysis of the history of orbital parameters has shown that the current martian climate is likely to be anomalous, and that Mars may have spent much of its history at considerably higher obliquity than its present value [3]. Indeed, glacial deposits at mid-latitudes [6,7] and huge tropical mountain glaciers [8-10] dating from earlier in the Amazonian are testimony to the mobility of polar ice and its transport and deposition equatorward during periods of higher mean obliquity [11].

More uncertain, however, is the nature of the climate of Mars prior to the Amazonian period. Do the polar deposits wax and wane during these climate changes or do they completely disappear? What evidence is there for the earlier climate history of Mars? It has been hypothesized on the basis of the nature and distribution of valley networks that Noachian Mars may have been "warm and wet" [12], that a global cryosphere developed subsequently [13] and that the global cryosphere was breached in numerous places and huge quantities of subsurface water were released into the northern lowlands during the Late Hesperian [14]. What was the nature of polar deposits during this earlier period? What was the volatile inventory and where was surface and near-surface water sequestered? Was the groundwater system leading to the outflow channels fed from basal melting of south polar ice deposits [13]? Did the outflow channel deposits lead to temporary but fundamental changes in climate [15]? Did the bodies of water formed by the outflow channels immediately migrate to the poles to produce polar ice sheets [16]? To address these and related questions we have been studying the south circumpolar Dorsa Argentea Formation, a unit mapped as Hesperian in age and displaying evidence of features related to glaciation. Here we summarize the nature of the DAF and implications for Hesperian polar environments and history.

The Dorsa Argentea Formation: The set of Hesperian-aged south circumpolar deposits represented by the Dorsa Argentea Formation (DAF) [e.g., 1,17,18] has been interpreted to be a volatile-rich polar deposit representing more than twice the area of the present Amazonian-aged layered terrain and residual polar ice,

which it currently underlies. This huge polar ice-related deposit makes up about 2% of the surface of Mars and has undergone significant evolution since its emplacement. The deposit characteristics (e.g., smooth, pitted and etched deposits, pedestal craters, sinuous ridges interpreted as eskers, fluvial channels around the margins, marginal ponds and lakes, etc.) indicate that the DAF contained significant quantities of water ice, and that it represented a circumpolar ice sheet that subsequently underwent meltback and liquid water sub-ice sheet drainage, ponding in adjacent valleys, and ultimately draining, through surface subaerial channels, down into the Argyre basin more than 1000 km away. Among the most critical questions is the cause of the melting, the fate of the meltwater, and whether surface water reentered the groundwater system to recharge the global hydrologic system [e.g., 13]. Sources of melting include: 1) top-down heating: from general atmospheric evolution and global climate change, or from orbital-parameter-induced polar insolation changes, 2) bottom-up heating: from a general increase in geothermal flux, from specific intrusions or extrusions leading to magma-ice-contact melting, or: from increased ice thickness and load-induced basal melting.

Particularly striking examples of magma-ice-contact melting are candidate subglacial volcanoes within the DAF [19]. Seventeen anomalous mountains (originally mapped by [1], and now called Sisyphi Montes) form an unusual cluster in the central part of the DAF. The mountains occur over a large area, have separation distances of ~175 km, are typically 30-40 km in diameter, and ~ 1000-1500 m high, with their bases near ~1200 m elevation. Many members of this population are located on or adjacent to a 660 km long line extending toward the south pole. On the basis of their morphology, distinctiveness, alignment and isolation relative to other landforms, these features have been interpreted to be predominantly of volcanic origin [19]. A significant number of these features show unusual shapes, including flat tops and flat tops with a summit cone. Several of the mountains display sinuous channels around their margins and bases. These and other characteristics are interpreted to mean [19] that many of the mountains represented volcanoes that had erupted subglacially beneath the DAF (tuyas), and that the meltwater products could be traced from these regions to the margins of the deposit where they drained along eskers and channels into adjacent lakes or distant basins. The topography of the mountains suggested that the ice sheet averaged at least 1.4 km thick at the time of the eruptions.

Elsewhere in the Dorsa Argentea Formation, the topography is disrupted by a series of large irregular depressions (Cavi Angusti) whose origin has been attributed to eolian deflation and subglacial melting [e.g., 20,

and references therein]. Analysis of the largest of these depressions (~ 50 x 100 km in diameter and up to about 1500 m deep) shows terraced interiors, centrally located equidimensional and elongated structures interpreted to be edifices, and associated lava flow-like structures. An equidimensional mountain ~12 km in diameter and ~770 m high is centrally located within the basin, has anomalously steep sides and a flat top, and is perched on a low platform with lobate edges, extending about 2.5 km away from the edifice base in all directions. A lobate flow-like feature, 30 km long and 14 km wide, with clear terminal scarps, extends away from the base of the mountain toward the north, parallel with the elongate trend of the basin. The elongated structure is a ridge located to the northwest of the central mountain, is elongated in the direction of the long axis of the basin, has a similar height, and also rests on a platform. Together, these edifices and lobate structures are interpreted to be volcanic edifices and associated lava flows. Their central location in the depression in the Dorsa Argentea Formation strongly suggests that these features represent subglacial eruptions, and that their formation is directly related to the presence of the large depression, which is interpreted to be due to volcano/ice interactions and melting [e.g., 20]. Indeed, volume estimates and heat transfer calculations [20] are consistent with such a mechanism involving a combination of intrusion and subglacial extrusion similar to that observed in Icelandic subglacial eruptions and meltwater generation.

Regional topography and ice-sheet geometry strongly suggest that any meltwater generated would drain to the north into the adjacent low areas. Evidence that this occurred includes an outlet and broad sinuous channel at the northern end of the largest depression, an unusual set of features interpreted to be a lake margin environment [e.g., 21] at the edge of the DAF less than ~150 km to the north of the basin, and a 300 x 800 km depression interpreted to be the site of a lake, which itself drains to the north into the Argyre basin [18]. Seven additional basins in Cavi Angusti contain mountains and ridges, usually centrally located, which are also interpreted to be the remnants of subglacial eruptions, formation of englacial lakes, and subsequent meltwater drainage to the north [20]. In summary, new spacecraft data support the interpretation that a significant part of the geomorphology of the Cavi Angusti region of the DAF is plausibly interpreted to be due to volcano/ice interactions [20], an interpretation originally proposed by Howard [22] using low-resolution image data.

Furthermore, the eastern part of the volatile-rich DAF shows evidence of meltback, drainage and ponding of meltwater [23] adjacent to the region of interpreted subglacial volcanoes [e.g., 19]. Channels leading from the margins of the DAF enter nearby craters, and channels connecting the craters provide evidence for extensive crater flooding, ponding and filling, overtopping, downcutting, and further drainage through a series of craters into the Prometheus Basin, over a distance of ~600 km and involving a total vertical drop of ~800 m.

Topographic evidence indicates that water filled some craters to depths of at least 200 m, and possibly up to 600 m, with minimum volumes of 10^{12} m³. Along the central and western margins of the DAF, five sinuous valleys begin near the DAF edge and are carved into surrounding Noachian cratered terrain, extending for distances of up to 1600 km before emptying into the Argyre Basin, ~1-3 km below their starting elevations [18,24]. The extension of these valleys into the DAF can be traced for hundreds of km due to the presence of aligned linear pits and basins and some preserved esker-like features on their floors [24]. The directions lead to the regions of Sisyphi Montes, the collection of isolated and aligned mountain features interpreted to be subglacial volcanoes [19].

Summary and Conclusions: The margins of the huge circum-south polar Dorsa Argentea Formation, interpreted to be an Hesperian-aged polar ice sheet, show evidence of extensive eskers [e.g., 18], marginal lakes [e.g., 21,23], and drainage channels extending from the DAF margins for hundreds of km into surrounding depressions such as the Argyre basin [24]; these features provide evidence that recharge of the global aquifer is very likely to have taken place during this time. Although polythermal glaciation, due to the accumulation of polar ice deposits to thicknesses in excess of 3-4 kilometers (thus raising the melting geotherm into the base of the thickest part of the ice, permitting basal melting [13]) or higher global geothermal gradients in earlier martian history, cannot be ruled out, there is compelling evidence that a significant part of the meltwater is related to subglacial volcano-ice interactions. We believe that a significant portion of the volatiles may remain in the deposit, and thus that they were removed from the active hydrologic system. Therefore, the Dorsa Argentea Formation appears to represent an accessible polar climate record dating from early Mars history.

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