Planetary and Space Science 109-110 (2015) 1–20

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

Late Noachian and early Hesperian ridge systems in the south circumpolar Dorsa Argentea Formation, Mars: Evidence for two stages of melting of an extensive late Noachian ice sheet

Ailish M. Kress, James W. Head *

Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI 02912, USA

ARTICLE INFO

Article history:
Received 7 July 2014
Received in revised form
27 October 2014
Accepted 21 November 2014
Available online 5 December 2014

Keywords:
Glaciers
Eskers
Ice sheets
South pole
Mars
Dorsa Argentea Formation

ABSTRACT

The Dorsa Argentea Formation (DAF), extending from 270°–100° E and 70°–90° S, is a huge circumpolar deposit surrounding and underlying the Late Amazonian South Polar Layered Deposits (SPLD) of Mars. Currently mapped as Early-Late Hesperian in age, the Dorsa Argentea Formation has been interpreted as volatile-rich, possibly representing the remnants of an ancient polar ice cap. Uncertain are its age (due to the possibility of poor crater retention in ice-related deposits), its mode of origin, the origin of the distinctive sinuous ridges and cavi that characterize the unit, and its significance in the climate history of Mars. In order to assess the age of activity associated with the DAF, we examined the ridge populations within the Dorsa Argentea Formation, mapping and characterizing seven different ridge systems (composed of nearly 4,000 ridges covering a total area of ~300,000 km^2, with a cumulative length of ridges of ~51,000 km) and performing crater counts on them using the method of buffered crater counting to determine crater retention ages of the ridge populations. We examined the major characteristics of the ridge systems and found that the majority of them were consistent with an origin as eskers, sediment-filled subglacial drainage channels. Ridge morphologies reflect both distributed and channelized esker systems, and evidence is also seen that some ridges form looping moraine-like termini distal to some distributed systems. The ridge populations fall into two age groups: ridge systems between 270° and 0° E date to the Early Hesperian, but to the east, the Promethei Planum and the Chasmata ridge systems date to the Late Noachian. Thus, these ages, and esker and moraine-like morphologies, support the interpretation that the DAF is a remnant ice sheet deposit, and that the esker systems represent evidence of significant melting and drainage of meltwater from portions of this ice sheet, thus indicating at least some regions and/or periods of wet-based glaciation. The Late Noachian and Early Hesperian ages of the ridge systems closely correspond to the ages of valley network/open basin lake systems, representing runoff, drainage and storage of liquid water in non-polar regions of the surface of Mars. Potential causes of such wet-based conditions in the DAF include: 1) top-down melting due to atmospheric warming, 2) enhanced snow and ice accumulation and raising of the melting isotherm to the base of the ice sheet, or 3) basal melting associated with intrusive volcanism (volcano-ice interactions). The early phase of melting is closely correlated in time with valley network formation and thus may be due to global atmospheric warming, while the later phase of melting may be linked to Early Hesperian global volcanism and specific volcano-ice interactions (table mountains) in the DAF. Crater ages indicate that these wet-based conditions ceased by the Late Hesperian, and that further retreat of the DAF to its present configuration occurred largely through sublimation, not melting, thus preserving the extensive ridge systems. MARSIS radar data suggest that significant areas of layered, potentially ice-rich parts of the Dorsa Argentea Formation remain today.

1. Introduction and background

1.1. Definition and nature of the Dorsa Argentea Formation

The Dorsa Argentea Formation is a south-circumpolar deposit on Mars, extending from 270°–100° E and 60°–90° S (Tanaka and Scott, 1987; Head and Pratt, 2001; Tanaka and Kolb, 2001) (Fig. 1). The formation is named for the Dorsa Argentea system of ridges, located between 300°–0° E and 70°–80° S (located in the Hdd member defined by Tanaka and Kolb, 2001) (Fig. 1). The Dorsa Argentea Formation (DAF) comprises a wide range of surface morphologies, textures, landforms, and topography, and many workers have focused on certain subunits or types of landforms within the DAF (e.g., Howard, 1981; Rice and Mollard, 1994; Ruff, 1994; Head and Hallet, 2001a, 2001b; Head and Pratt, 2001;

* Corresponding author.

http://dx.doi.org/10.1016/j.pss.2014.11.025
0032-0633/

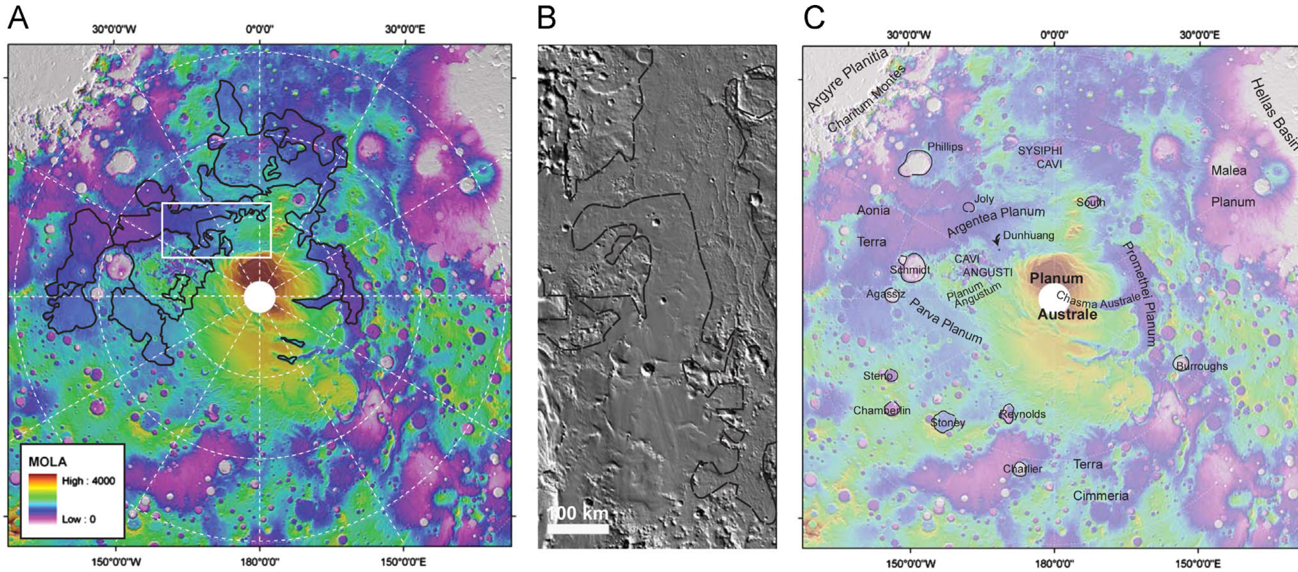

Fig. 1. (a) Context map. MOLA color over MOLA shaded relief in a polar stereographic projection from 60°–90° S. Members of Dorsa Argentea Formation are outlined in black (after Tanaka and Kolb, 2001). Color data are stretched from 0 m (datum) to 4000 m, white to red. b) Enlargement showing the Dorsa Argentea ridge system, rotated 90 degrees clockwise. Dashed outline corresponds to the Hdd boundary of Tanaka and Kolb (2001). c) Context map with nomenclature of features and regions.

Milkovich et al., 2002; Ghatan and Head, 2002; Ghatan et al., 2003; Ghatan and Head, 2004). In their 1:15,000,000 scale geologic map of the polar regions of Mars produced from Viking images, Tanaka and Scott (1987) identified two subunits to the DAF, Hdu (the upper member) and Hdl (the lower member). A third related unit, Hesperian-Noachian undivided material (HNu), was also identified, consisting of rough blocky terrain closely associated with the DAF.

Head and Pratt (2001) analyzed these units with Mars Orbiter Laser Altimeter (MOLA) data. They found the relationships of the units to be stratigraphically ambiguous in some locations, with both the unit margins and interpreted sequence often appearing inconsistent with topographic relationships. Head and Pratt (2001) therefore combined all three units together in their investigation of south paleopolar deposits. Mars Global Surveyor (MGS)–based mapping by Tanaka and Kolb (2001) supports the finding of Head and Pratt (2001) that the Viking-based subdivision of the area is inconsistent with the MOLA data. Tanaka and Kolb (2001) redefined the outer boundary of the DAF and subdivided the formation into eight members primarily on the basis of 1) geographic location, 2) unit margins determined from topography, and 3) morphology (Fig. 1). The relative stratigraphy of the major units, as deduced by Tanaka and Kolb (2001), is from oldest to youngest: the Rugged member (Hdr), the Argentea member (Had), the Dorsa member (Hdd), the Promethei member (Hdp), the Sisyphi member (Hds), and the Cavi member (ANdc). Head and Pratt (2001) assessed these units with MOLA data and showed that Hda and Hdd are generally the thinnest members, Hds is the next thinnest, and ANdc is the thickest. Hdr is not a plains or plateau-type member, making its relative thickness difficult to ascertain.

1.2. Hypotheses of origin for the Dorsa Argentea Formation

Three different origins have been proposed to explain the nature and origin of the DAF and associated features. Early work by Tanaka and Scott (1987) suggested that the deposit formed predominantly from lava flows, a scenario primarily supported by the lobate fronts of some of the unit margins, considered to be consistent with a lava flow origin. They identified a shield-like structure as a possible source vent within the boundaries of the DAF, 50 km south of Cavi Sisyphi, in member Hdr as mapped by Tanaka and Kolb (2001). Tanaka and Kolb (2001) proposed a new origin on the basis of their mapping with MGS data, which is a variant of the volcanic model of Tanaka and Scott (1987). They retained a flow-related origin in their new model, but instead of lava, they proposed a mechanism involving the expulsion of fluidized, volatile-rich subsurface regolith material, released to the surface through “instabilities” and “triggering mechanisms.” Their model is largely based on the hypothesized accumulation of extensive subsurface aquifers of H_2O and/or CO_2 in the south polar region during the Noachian. According to Tanaka and Kolb (2001), during the Hesperian, triggering mechanisms such as impact-induced marsquakes or intrusive magmatism cracked these aquifers and released widespread, volatile-laden regolith debris flows onto the surface to form the DAF deposits and associated features. Again, the lobate fronts of the deposit are interpreted as evidence supporting a flow-related origin. The sinuous ridges are interpreted as inverted stream topography resulting from infilling of preexisting channels, followed by later exhumation. Pedestal craters are cited as evidence for vertical thinning of the deposits. A clear origin for the cavi is lacking in this model, although Tanaka and Kolb (2001) suggest that the cavi may have served as source vents for the expelled subsurface volatiles (see discussion in Ghatan and Head, 2004). Head and Pratt (2001) proposed a third and separate scenario for the origin of the DAF. In their model the DAF represent the remnants from melting and retreat of a previously widespread circumpolar dust-rich ice sheet. In this model, Head and Pratt (2001) interpreted the features associated with the DAF as follows: 1) sinuous ridges within the margins of the DAF are interpreted to be the martian equivalent of terrestrial esker systems (as originally proposed by Howard, 1981), 2) sinuous valleys that lead away from the margins of both the 0° W and 70° W lobes of the DAF and terminate in the Argyre basin are interpreted as evidence for lateral transport of significant volumes of meltwater away from a melting ice sheet, 3) a smooth floored, low-lying, topographically enclosed basin (Argentea Planum, referred to as Schmidt Valley by Head and Pratt, 2001) located at the margins of the DAF is interpreted as evidence for ponding of meltwater along the edges of the deposit (Dickson and Head, 2006), 4) pits and cavi located within the DAF are interpreted as evidence for volatile loss and vertical degradation of the deposit, and 5) pedestal craters within the margins of the DAF