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Putative eskers and new insights into glacio-fluvial depositional settings in southern Argyre Planitia, Mars

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ABSTRACT

We present new insights into possible formation mechanisms and implications for previously identified landforms of putative glacio-fluvial origin along the southern rim of the Argyre basin on Mars. We compiled a detailed geomorphologic map of the study area and conducted morphometric and stratigraphic analyses of specific features, e.g., esker-like sinuous ridges on layered terrain. Based on their morphology and orientations, we subdivided the sinuous ridges on the southern Argyre basin floor into two populations, which could reflect changing conditions of glacial retreat. With the transition and oblique path methods we quantified the ice thickness of the glacier under which the first, lesser degraded, population of ridges probably formed. Our results imply an ice sheet thickness of $\sim$2 km and at least $\sim$100,000–150,000 km³ of ice on the southern floor of the Argyre basin during the time those ridges were deposited ($>30\times$ the volume of Vatnajökull, Iceland). The second population of ridges is more degraded and shows layers occasionally extending into the surrounding layered terrain. Comparisons with the morphology surrounding the Piedmont-style Malaspina Glacier in Alaska show similarities, suggesting population II formed during a glacial retreat involving back- and downwasting of stagnant ice lying beneath fresh outwash sediments, creating degraded and layered lag deposits around the emerging eskers. If outwash sediments were fed by the same drainage source as the eskers, sections of layers can extend from a given ridge into the surrounding deposits. The differences between the two ridge populations are probably a result of the subglacial drainage direction changing from northward to north-eastward around 3.6 Ga ago. This was likely coupled with the deposition of less or no outwash sediments resulting in a decrease of lag deposits. A subsequent phase of stagnant glacial retreat left no terminal moraines and largely preserved the population I ridges, thus implying sufficient glacial thinning in order for the ice flow to stop. This, in turn, may have been caused either by sublimation in a cold but increasingly dry climate, or by melting and increased glacier surface runoff due to rising temperatures.

1. Introduction

With a diameter in excess of 1500 km and an average depth of $\sim$3000 m below the datum, the Argyre basin is one of the largest impact basins on Mars (e.g., Wood and Head, 1976; Tanaka et al., 1992). Its southern rim consists of up to $\sim$8 km high plateau mountains and appears to have been heavily modified since its formation (e.g., Hodges, 1980; Kargel and Strom, 1990). Among the most prominent features found along the Argyre rim are semi-circular mountain ridges, U-shaped valleys and streamlined hills, which have been interpreted as cirques, ancient glacier-beds and drumlins, respectively (e.g., Kargel and Strom, 1992; Hiesinger and Head, 2002; Banks et al., 2008; Raack et al., 2012). Furthermore, layered material exposed on the Argyre basin floor has been interpreted as sediment infill by three large channels originating near the Martian south pole and terminating in Argyre Planitia (e.g., Head and Pratt, 2001; Ghatan and Head, 2004; Dickson and Head, 2006).

In addition to these observations, the nature of sinuous ridges on the southern basin floor, up to $\sim$300 km in length, $\sim$160 m in height and mostly several hundreds of meters wide, has been particularly debated (e.g., Kargel and Strom, 1992; Jöns, 1987; Hiesinger and Head, 2002; Banks et al., 2009). Possible interpretations include rapidly solidified mud waves (Jöns, 1987), linear sand dunes (Ruff, 1992), tectonic wrinkle ridges (e.g., Scott and Tanaka, 1986), lava flow features (Theilig, 1986; Ruff and Greeley, 1990), exhumed igneous dikes (Carr and Evans, 1980; Head et al., 2006), lacustrine spits and barrier bars (e.g., Parker, 1994), glacial moraines/crevasse fill ridges (e.g., Kargel, 1993; Benn and Evans, 1998), inverted fluvial channels (e.g., Kargel, 1993) and eskers

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(e.g., Kargel and Strom, 1992; Hiesinger and Head, 2002; Banks et al., 2009). Hiesinger and Head (2002), Banks et al. (2009), and Coleman (2011) argued that the observed characteristics (Table 1) of the largest ridges, e.g., their mostly visible horizontal bedding and occasional ascension of topographic gradients, are most consistent with an interpretation as eskers, i.e., deposits of meltwater-flows within sub- or intraglacial tunnels.

In order to also explain the formation of continuous layers extending from some ridges into the surrounding landscape as it is revealed in meter-per-pixel scale imagery (Banks et al., 2009) the following models have been suggested:

1) Periglacial lacustrine processes in which sedimentary deposition occurred in interfingering and oscillating, i.e., repeatedly advancing and retreating, masses of ice, lake water, and glacial stream water were responsible for layers transitioning from eskers into the surroundings (Parker, 1989, 1994; Kargel and Strom, 1992; Parker et al., 2000, 2003; Kargel, 2004). Such sequential and periodic scenarios have also been proposed as being suited to explain the formation of the vast layered deposits surrounding the ridges as lake sediments, as well as the lack of debris fans at the termini of any proposed eskers (Metzger, 1991; Kargel and Strom, 1992; Banks et al., 2009).
2) The layered terrain might have been emplaced before the ridges as lacustrine deposits by an ice-covered lake. In the shallower regions of the southern basin, the ice was grounded and meltwater formed subglacial channels in which esker-like ridges were deposited. Sublimation and migration of water into the substrate finally exposed the eskers (Hiesinger and Head, 2002). Such a scenario would also be consistent with climate models showing that temperatures in Argyre Planitia likely were below freezing for most of the geologic history of Mars (e.g., Haberle et al., 2000; Kreslavsky and Head, 2001; Fairén, 2010).
3) The layered surroundings of the ridges may have been sedimented by meltwater from the esker-forming sub-ice tunnels penetrating adjacent cavities beneath an ancient glacier, thereby allowing for contiguous layers transitioning out of the ridges (Banks et al., 2009).

As we will demonstrate in this work, none of these models conclusively explains three crucial observations in southern Argyre Planitia (Table 2): (a) the great relative variation in preservation among the sinuous ridges along with (b) the transitions of layers occurring between two ridges and their surroundings within an area of ~30,000 km² and (c) the vast extent of the layered terrain (at least ~57,000 km²) in general.

Consequently, we propose an alternative formation model based on terrestrial analogy. Furthermore, we present a detailed geomorphological map of the area encompassing the sinuous ridges along the southern rim of Argyre Planitia based on state-of-the-art datasets. We also perform a computational reconstruction of the glacial load implied by the morphometry and morphology of the ridges with methods outlined by Shreve (1985b) for terrestrial Pleistocene eskers. Thereby, we give a minimum estimate of the ice volume

Table 1
Summary of different formation hypotheses of layered sinuous ridges in southern Argyre Planitia modified after Banks et al. (2009). Numbers in brackets indicate the following references, which propose a respective model or upon which a general model proposition is based: [1] Jöns (1987); [2] Ruff (1992); [3] e.g. Scott and Tanaka (1986); [4] Theilig (1986), Ruff and Greeley (1990); [5] e.g. Head et al. (2006); [6] e.g. Parker (1994); [7] Kargel (1993), Benn and Evans (1998); [8] e.g. Kargel (1993); [9] e.g. Kargel and Strom (1992), Hiesinger and Head (2002), Banks et al. (2009). Listed horizontally are observed characteristics of the ridges. "+" and "–" indicate an observation to be consistent or inconsistent with the proposed model."0" marks observations which are possible but uncommon.

Model	Evasion of topographic obstacles	Symmetric cross-section and large size	Horizontal bedding of fine layers	Braiding and sinuosity	Partial location within trough	Ascension of topographic gradient	Ridge height/bed slope dependence
Instantaneously solidified mud waves [1]	+	**0**	–	–	**0**	–	–
Linear dunes [2]	**0**	–	+	–	–	+	**0**
Tectonic wrinkle ridges [3]	–	–	**0**	–	–	+	–
Lava flow features [4]	+	–	**0**	+	**0**	**0**	+
Igneous dikes [5]	**0**	**0**	–	**0**	**0**	+	**0**
Lacustrine spits and barrier bars [6]	+	–	+	+	**0**	–	–
Glacial moraines/ crevasse fill ridges [7]	–	**0**	–	**0**	**0**	+	**0**
Inverted fluvial channels [8]	+	+	+	+	+	–	+
Eskers [9]	+	+	+	+	+	+	+

Table 2
Summary of previously proposed depositional models for layers extending from the sinuous ridges into the surrounding layered terrain in southern Argyre Planitia. Numbers in brackets indicate the following references, which propose a respective model or upon which a general model proposition is based: [1] Banks et al. (2009); [2] e.g., Parker et al. (1986), Kargel and Strom (1992), Hiesinger and Head (2002); [3] Banks et al. (2009). "+" And "–" indicate that a model can or cannot conclusively explain an observation."**0**" signifies that the correlation is only viable under certain circumstances.

Depositional model	(a) Good preservation of eskers	(b) Transition of layers into surrounding	(c) Vast extent of layered terrain
1) Oscillating periglacial regime [1]	–	+	+
2) Sequential lacustrine-glacial deposition [2]	+	–	+
3) Interconnected subglacial tunnels and cavities [3]	**0**	+	–
This work: proglacial environment involving down- and backwasting	+	+	+