PERVASIVE AQUEOUS PALEOFLOW FEATURES IN THE AEOLIS/ZEPHYRIA PLANA REGION, MARS. D. M. Burr¹, R. M. E. Williams², Alan Howard³, James Zimbelman⁴, Tracy Brennand⁵, Marie-Therese Enga⁶, and Kimberly D. Wendell⁷, ¹Earth and Planetary Science Department, University of Tennessee Knoxville and Carl Sagan Center, SETI Institute (306 EPS Building, 1412 Circle Dr., Knoxville TN 37996, dburr1@utk.edu), ²Planetary Science Institute, ³Department of Environmental Sciences, University of Virginia, ⁴Center for Earth and Planetary Sciences, Smithsonian Institute, ⁵Department of Geography, Simon Fraser University, ⁶Northern Arizona University, ⁷Montana State University.

Introduction: Between the Aeolis and Zephyria Plana, centered on the western two lobes of the Medusae Fossae Formation (MFF), is found the largest population of sinuous ridges (SRs) discovered on Mars to date [1]. The THEMIS visible wavelength images through the July 2007 release show ~150 individual SRs in this region, although future study may reveal additional SRs or show linkages among these ~150 examples. A study of the THEMIS data, augmented by more recent data from the Context Imager (CTX) and High Resolution Imaging Science Experiment (HiRISE) shows morphologies and associations indicative of SR formation by overland paleoflow. In this abstract, we present the evidence for that conclusion, along with an hypothesis for the source of the water for that overland flow and the implications of these features for Martian climate.

Morphologic classification: To facilitate analysis, we have grouped the SRs by both individual morphologies and network patterns.

- Individual morphologies include:
  - Thin: a few tens of meters wide, which width remains constant with distance along the SR. (Fig. 1)
  - Rounded: intermediate in width between thin and flat, with a smooth shape in cross-section.
  - Wispy: the narrowest SRs, with widths of order 10 meters, and the shortest in length. Wispy SRs are near the detection limit in THEMIS images, but can be confirmed in CTX or HiRISE images.
  - Flat: often greater than a kilometer in width, with broad horizontal upper surfaces, sharp lateral edges and steeply dipping sides (Fig. 1).
  - Multilevel: any stacked combination of SR types, almost universally thin on flat (Fig. 1).

- Network patterns include:
  - Isolated: refers to an SR that is not connected or closely adjacent to other SRs within the field of view.
  - Sub-parallel: a network in which individual SRs are roughly parallel or intersect with low (~30°) junction angles; may be connect at one end to a common area (Fig. 1).
  - Branched: a network in which individual SRs intersect at moderate (~30° to ~75°) angles, forming a network typically on the order of tens of kilometers in width (Fig. 1).

Random: a network in which individual SRs intersect at large (>~75°) angles, a wide range of intersection angles, and/or lack obvious directional trend.

Association with fan-shaped forms: About 5% of the SRs are connected to forms that are fan-shaped in plan-view and have radial ridges on their surfaces. We differentiate these fan-shaped forms from more extensive branched networks of SRs, in which the individual SRs are radially oriented. Both fan-shaped forms and branching networks can have radial SRs and comprise a continuum of landforms, but are distinct from each other in terms of size, ridge sinuosity, and the overall apparent topographic form.

Hypothesized origins of SRs: Aeolian, structural/tectonic, and volcanic processes have been inferred to have operated in the Aeolis Plana region [2, 3, 4, 5, 6, 7], but we do not find evidence to support these as the primary processes in SR formation. Instead, the networked appearance and sinuosity of the SRs suggest their formation by a channelized flowing fluid. Through levee buildup, lava channels can become positive-relief features, but would likely have marginal ridges corresponding to the lava levees. Lava channels would also likely have lower sinuosity, without the medial ridges or fan-shaped forms of some of the SRs. Although one flat isolated SR on the Cerberus plains may be a lava channel, we discount volcanism as the primary origin for the large majority of these SRs.

Their individual morphologies, network patterns, and association with fan-shaped forms suggests SR formation by flowing water. Possible terrestrial analogs for the SRs include inverted fluvial channel and glaciolfluvial eskers.

Inverted fluvial channels: River channels may become inverted into positive relief features through infill of the channel floor and subsequent regional erosion that removes the surrounding terrain. The infill may occur through infill of the channel by lava, deposition by the river of a coarse-grained lag, or geochemical cementation of sediments. The subsequent erosion is commonly accomplished by aeolian and/or fluvial processes, occasioned by a change in base level or changing climate/environmental conditions. The result of this removal of the surrounding terrain is the channel floor left in positive relief [cf. 8].
Eskers: Glaciofluvial ridges may form from sedimentation in ice-walled meltwater channels associated with glaciers [9]. Such meltwater channel fills may occur in supraglacial channels, in englacial or subglacial conduits, or within ice-walled canyons near the glacier margin, provided there is adequate sediment supply. Melting of the supporting ice associated with warming climate leaves sinuous sedimentary ridges, or eskers (Fig. 4) [see 10 for a review of esker formation mechanisms]. Because subglacial flow is controlled by the equipotential surface, esker occur both on negative slopes (where water flow was downhill) and on positive slopes (where water flow was up-gradient). Terrestrial eskers are found in association with other glacial landforms such as drumlins and moraines.

Origins of selected SR types:
1. Flat and Multilevel (Thin on Flat) SRs in Branched or Sub-Parallel Networks: Most flat SRs are located along the eroded interior edges of the MFF lobes or along the erosional scarp adjacent to the Aeolis Planum highlands. These SRs have flat upper surfaces with steep side slopes that transition abruptly to the surrounding terrain. This sharp-edged appearance and the geologic context indicate that these SRs are composed of material that is more resistant to erosion than the surrounding terrain. Some flat SRs transition from continuous features into curved lines of disjointed, adjacent knobs (Fig. 1) which we infer to be the result of advanced erosion. The discrete, high-relief shape of the knobs, some of which maintain their flat-topped morphology, also implies erosion of a cohesive, indurated, or resistant substrate.

Fluvial channel inversion requires some form of erosional resistance relative to the channel surroundings. Therefore, the inference that these flat SRs are more resistant to erosion than the surrounding terrain supports their formation as inverted fluvial features. The flat-topped morphology, which is the most common morphology observed for inverted fluvial channels in Utah [11], is consistent with their formation as inverted channels. Most flat SRs have a branched or sub-parallel network pattern. These network patterns commonly characterize fluvial networks (e.g., 12), supporting the interpretation of flat SRs in branched or sub-parallel networks as inverted fluvial features.

The lowest levels of multilevel SRs always have flat morphology. Like flat SRs, multilevel SRs are commonly associated with scarps, and most multilevel SRs also have branched or sub-parallel networks. Because of their morphological, contextual, and network similarity to flat SRs, we hypothesize that steep-sided, multilevel SRs are also a result of exposure of indurated materials by backwearing and/or downwearing of the surrounding volume of material. The superposition and co-linearity of the upper and lower ridges, even where they branch and loop, indicate that the superposed ridges making up multilevel SRs are genetically related.

The observed plan-view morphology bears a qualitative resemblance to the floodplains simulated by meander models [e.g., 13, 14, 15]. In addition, flat and multilevel SRs show narrow, semi-concentric or sub-parallel, curved ridges on their upper surfaces, similar in morphology to scrolled floodplains. Thus, the lower, flat SRs may reasonably represent a sedimentary unit that was deposited across a floodplain by a meandering channel and is now resistant to erosion, due either to cementation or to clast armorining. The upper, thin SRs would have formed through inversion of narrow fluvial channels set in a less resistant sedimentary substrate on top of the lower, flat SRs that formed through inversion of floodplains.

2. Rounded (and Sharp-crested Thin) Isolated SRs: In contrast to flat SRs, rounded SRs have a smooth topographic cross-section with side slopes that grade gently into the surrounding terrain (Figure 3). This appearance suggests that rounded SRs formed by loose sedimentation rather than by induration and subsequent differential erosion, a suggestion supported by a lack of aeolian erosive morphology. These indications of formation by loose sedimentation are most consistent with formation as eskers. The most diagnostic characteristic distinguishing eskers from inverted fluvial channels is irregular change or increase in elevation in the down flow direction. MOLA topography shows that the SRs cross elevation increases of up to ~100 m (Figure 4). These topographic highs are local maxima, so that elevation increases regardless of the direction of flow along the SRs. Eskers may commonly cross topographic divides, whereas rivers cannot flow upslope. Thus, the profile of the SRs over these local topographic divides, whereas rivers cannot flow upslope. However, still other characteristics are inconsistent with an esker origin. The pronounced sinuosity of some rounded SRs is atypical of eskers, which do not commonly form high sinuosity meander loops. Also, definitive glacial landforms around these rounded SRs are largely lacking, although limited possibilities exist, including a thin SR with a medial ridge that is morphologically similar to sharp-crested eskers in Canada.

In summary, our preferred hypothesis for the origin of rounded SRs is as subglacial conduit fills or eskers, based on the topographic data. In this context, some
thin SRs may be glacial moraines, with which they show a morphologically similarity. However, given some inconsistencies of the data with a glaciolfluvial interpretation, our alternative hypothesis for the rounded SRs is as inverted fluvial channels.

**Stratigraphic and topographic context:** On the map of [17] the large majority (97%) of the SRs in this study are found in units dated to the Amazonian epoch. These stratigraphic data indicate that the large majority of visible SRs were formed during the emplacement of the lower and middle members of the Medusae Fossae Formation, which are dated as having been laid down during the early to middle Amazonian epoch (~3.0 Ga [18]), although it may have extended back into the early Hesperian [19]. However, the relatively young age of these units may reflect erosion and not emplacement. A very small percentage of SRs on the Aeolis Mensae southern highlands are located on units dated to the Noachian (~3.5 Ga [18]). However, these SRs could have formed after the Noachian, for example, in a younger, thin mantling unit that has since eroded. Thus, in spite of a few SRs situated on Noachian-aged units, all SR formation may have been confined to that later period during which the lower and middle units of the western MFF were emplaced.

**Global context:** The ~150 SRs in the Aeolis/Zephyria Planum are found in an area of ~200,000 km². For comparison, approximately the same number of similar landforms has been recorded outside of the Aeolis and Zephyria Planum region in a preliminary global database of SRs on Mars [1= Williams 2007 or more recent ref?]. Thus, the SRs within this study region represent the greatest regional population and cover the largest contiguous area of SRs yet identified on Mars. Like troughs and valley networks elsewhere on Mars, they also record the transport pathways linking sediment source areas and depositional sinks.

Despite considerable mapping [20, 21], no SRs have been found in the eastern MFF region (east of ~180°E). The eastern portions of MFF have been interpreted as the youngest deposits and the western portions as the oldest [4, 17, 22]. In addition, fluvial channels buried by eastern MFF materials and interpreted to predate MFF deposition [20] may instead be confined to the very lowest stratigraphic units of the MFF deposits. Taken together, these interpretations suggest that the relative timing of the events that formed the SR features was confined to only the earliest portions of MFF emplacement. Both geologic mapping with MOLA topography [21] and MARSIS radar sounding data [23] suggest that the eastern MFF deposits could be up to 2.5 km thick near the Gordii Dorsum escarpment (near 5°N, 215°E). This thickness is in marked contrast to the western MFF, where the deposits are all relatively thin (several tens to hundreds of meters in thickness) [20, 23, 24, 25]. Either the thicker deposits in the eastern MFF have not been eroded to sufficient depth to expose the early time interval represented by the SRs in the western MFF, or SRs were no longer being formed when the later (upper) members of the eastern MFF were deposited.

**Implications for origin: regional orographic precipitation:** If our hypothesis for the features’ origins is correct, then conditions at Mars’ equator were sufficiently temperate and humid during the time that the lower and middle MFF units were being emplaced to produce overland flow. Based on their distributed network morphology, the source of the flow that formed the SRs is inferred to be atmospheric. MARSIS data show that during early MFF emplacement, the location of this extensive SR population may have been a site of a topographic rise of ~2500 m from the (paleo-) Cerberus plains up to the Aeolis Planum highland [23]. This sharp and significant topographic rise would have caused orographic lifting of southward moving air masses. Orographic lifting results when an air mass is forced to move up a topographic obstacle; as the air mass increases in altitude, it cools, producing clouds and precipitation. Given the wide areal distribution of the SRs and the distinct increase in elevation from the (paleo-) Cerberus plains to Aeolis Plana, we hypothesize that the SRs were fed by runoff from orographic precipitation.

**Discharge calculations:** We have estimated discharge rates for the best-preserved SRs [26]. For interpreted inverted channels (including both individual thin SRs and superposed thin SRs in multilayer morphologies), we measured SR length, width, sinuosity, and meander wavelength. For interpreted inverted floodplains (including both individual flat SRs and subjacent flat SRs multilayer morphologies), we measured SR meander belt width. These measurements were then used in various terrestrial empirical equations scaled for Martian gravity to estimate discharges. The average discharge of the 18 SRs for which likely valid measurements could be obtained is 27 m³/s.

**Conclusions:** A large population of SRs in the Aeolis/Zephyria Planum indicate that channelized surface flow occurred in the late Hesperian to middle Amazonian epochs at Mars’ equator. We hypothesize that this flow was fed by orographic precipitation associated with a paleo-scarp between the Cerberus plains and the southern highlands. A fuller description of this work may be found in [27]. On-going mapping of this region and of these SRs will help to refine both the dates and discharges for these runoff features.

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Fig. 1: Mosaic of THEMIS images showing example SRs: ‘BRNCHD’ = branched network pattern, ‘SBPRL’ = sub-parallel network pattern, ‘MTL’ = multilevel individual morphology. White arrows point to a flat SR transitioning to a series of collinear knobs.