RE-EXPLORING THE FORMATION OF MARTIAN SINUOUS RIDGES. S. M. Metzger, Dept. of Geology, MS-172, University of Nevada, Reno, 89557, metzger@scs.unr.edu

Introduction: Recent MOLA and MOC data from the Mars Global Surveyor mission have reinvigorated interest in Martian Sinuous Ridges (MSR). Such interest stems from formation interpretations that invoke contributions from large-scale ice caps, oceans, and/or surface drainage networks. If substantial volumes of water are indeed responsible for the construction of these ridges, then the ridges provide important records of very different climate in Mars' past. This report will review MSR research over the past decade, summarize proposed MSR formation mechanisms, relate such proposals to testable mechanisms active in terrestrial settings, and hopefully provide context and grounding to the current discussion.

MSR have been the subject of scrutiny since their observation in Viking orbiter images (Howard, 1981). These features consist of a long, narrow elevation following a sublinear-to-highly-arcuate trend, sometimes with adjacent ridges or in an arborescent, bifurcating pattern. Positive relief is usually low, rising a few tens of meters or less above the local surface. Ridge crest and width morphology shows little deviation along their considerable lengths. The ridges can extend many tens of kilometers (several are over 200 km long) with essentially no gaps. MSR are found running along the center of troughs, spreading across the floors of large basins (i.e. Argyre) and emerging from under mantling deposits (i.e. Dorsa Argentea).

Kargel and Strom (1990, 1991) sparked considerable debate when they proposed that MSR were eskers formed during the meltout of regional scale glaciers. Such an explanation implies a climate capable of sustained snowfall and the eventual release of substantial quantities of meltwater. Metzger (1991, 1992) undertook field study of terrestrial eskers in New York State to appraise various esker formation mechanisms and relate those findings as analogs to the MSR (Metzger, 1994).

Terrestrial Analog Field Study: Metzger (1994) identified over 100 eskers atop various bedrock and terrain types, and field mapped nearly 50 of them. Cross sections were measured at numerous locations along each esker and, where available, internal bedding was examined. Esker morphology is found to vary widely; crests rise and fall (averaging 18 m with side slopes around 20°), widths fluctuate considerably (averaging 115 m), and any ridge longer than 5 km (study average is 8.2 km) is actually a string of segments whose gaps comprise at least 33% of the total system length. Average ridge sinuosity of 1.2 and bifurcation branches every 5 km are similar to many alluvial channel rivers.

Internal exposures indicate that terrestrial eskers with well-defined surface appearance have retained their original bedding structures without significant post-depositional disruption or slumping. Their clasts are generally sand-sized or larger, composed of a diverse assortment of lithologies but none whose weak composition or induration made them friable.

Bedding structures, ridge morphology, and clast distributions within the NYS eskers are consistent with formation mechanisms articulated by Rothlisberger (1972) and Shreve (1972, 1985) wherein subglacial hydraulics generate coalescent drainage networks along the base of glaciers in a manner that follows the local topographic lows. Such networks do not linger within the "mid-level" englacial environment. Furthermore, given that every well defined ridge was relatively free of bedding disruption, it is reasonable to conclude that drainage channel deposits formed on top of the glacier or within it will not produce distinct ridges when the ice mass wastes away beneath them. Lastly, ice-walled drainage systems are prone to the same dynamic fluctuations as are subaerial rivers. Thus, depositional sections along the channel will be interspersed with scour sections, sections of channel migration complete with cutbanks and point bars, and are prone to resuspension of deposits as channel conditions evolve. Literature on terrestrial eskers reinforces the NYS findings that esker morphology is highly variable.

Proposed MSR Formation Mechanisms: MSR have been located in widely dispersed areas of Mars (including Argyre Basin, Dorsa Argentea, and Utopia Planitia). Given their varied settings and the challenge of explaining the water required for the development of eskers, alternative formation mechanisms have been put forth. Because this review is focused on geomorphic processes linked to the Martian climate, little attention will be directed toward tectonic or igneous-based formation; but there is little support for such mechanisms in any case.

Rice and Mollard (1994) suggested that "inverted topography" could form if a river channel deposited gravel lag, even briefly, over finer material in a region. Subsequent protracted aeolian deflation could strip away that finer material, except where the gravel protected it. They also suggested that soil slump into existing channels may explain the MSR found in troughs. Thermokarst mechanisms, especially in river channels, have been proposed by Costard (1995). Metzger (1993) described an ice levee-creating debris flow process but MSR appear to lack the expected levee breach splay deposits along their flanks.

Ruff (1994) identified anastomosing aeolian dunes in Arizona and Australia that share a strong resemblance with the Dorsa Argentea MSR. Such features are uncommon amongst otherwise-linear terrestrial dune fields and may therefore be difficult to apply to the larger-scale MSR.

Parker (1987) has long lead the charge that lacustrine features are present in various basins and across the northern lowlands. Given that relatively short-lived bodies of glacial meltwater derived from Quaternary deglaciation have produced pronounced terrestrial shore features, it is reasonable to presume that lakes or oceans on Mars will readily generate berms and spits within their basins. At issue is whether MSR are linked to appropriate shore and shallow depth assemblages.

Grant and Schultz (1990) considered that the Thumbprint terrain in Utopia and Isidis might be recessional moraines formed at a glacier's terminus. Lockwood and Kargel (1994) considered it to be Rogen moraines (large parallel rows of ice-pushed till within the ice marginal zone). Metzger (1995) suggested that dust-rich Martian ice packs may slough off sheets of residual dust blankets (which may accumulate as the ice volatiles sublime), leaving subparallel row deposits.

Because of the apparent interlinking and anastomosing pattern of the ridge system in Dorsa Argentea, plus its seeming emergence from an overlying mantle of relatively fine material, a groundwater-based process is currently suggested. If a unit of low permeability developed a fracture pattern following emplacement, or if a porous set of dunes were covered by impermeable dust, then a network of pathways could allow groundwater "piping" through the buried unit. Dissolved minerals might then react with the unit in contact with the groundwater flow to further cement it. Subsequent removal of the overburden would reveal the piping routes as preferentially erosion resistant positive relief.

Recent Developments: The precise global mapping of topography by the MOLA instrument indicates that the northern lowlands are comprised of very flat surfaces. This degree of uniform flatness is usually produced on Earth by lacustrine or marine sedimentation in the middle of a basin. Malin and Edgett (2000) have pointed out that regional lava pooling may provide similar results.

Another MOLA outcome is that the MSR are shown to be somewhat less "perfectly consistent" then they appear in Viking images. Still, they are substantially more consistent than any terrestrial esker morphologies even though those on Earth have been subjected to only a few thousand years of post-formation erosion (versus potentially billions of years for MSR).

MOC images have provided fuel to several contrasting formation proposals. Whereas Malin and Edgett see lava evidence but no shorelines, Parker and Grant (2000), in concert with MOLA data, and DeHon (2000) have presented a complex drainage pathway and history suggesting large flow volumes through the Argyre Basin, as elsewhere, and down into the northern hemisphere.

Head et al. (2000) has worked to demonstrate a soup-to-nuts hydrologic system from an ancient placement of the south polar cap, through the development of esker outflow deposits (now seen as the Dorsa ridge complex), to fan deposits and/or ponding further toward the equator, possibly linking into the Parker and Grant proposed system. Jons (1992) proposed a mud lake adjacent to the south pole.

Conclusions: Many of the mechanisms proposed for MSR formation involve substantial quantities of water. Those requiring large amounts to persist on the Martian surface are more at odds with the thin atmosphere interpreted to have existed for most of the planet's history. In all the proposed mechanisms there are a suite of predicted features that can be tested with existing MOC images and MOLA-derived topography. The current topography will need to be corrected for tectonic influences, especially if large quantities of water or lava have rested on the surface. Isostatic rebound calculations have proven to be an arduous exercise, however, even in readily accessible terrestrial settings.

Regardless of which formation mechanism has produced the sinuous ridges on Mars, each process that best explains each specific MSR is the likely result of land-atmosphere interactions. Therefore, each MSR is a vital record of past climate dynamics. We must not paint them with too broad a brush or we will lose their potential contribution to Mars' history.

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