EVIDENCE FOR GROUNDWATER SAPPING ON MARS FROM JUNCTION ANGLES OF NIRGAL VALLIS TRIBUTARIES.

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Introduction: Nirgal Vallis is a ~500-km-long, ~5-km-wide branching valley network that erodes terrain mapped as Noachian plains [1] and drains into Uzboi Vallis to its southeast [2]. Nirgal Vallis has morphological characteristics (such as amphitheater-headed tributaries) that are similar to valleys on Earth potentially formed by groundwater seepage, for example, on the Colorado Plateau, in Florida, and in Hawaii [3-6]. For this reason, Nirgal Vallis is one of the most likely candidates to have been formed by large-scale groundwater sapping on Mars [7, 8].

In recent years, the hypothesis that seepage erosion is an important process for forming large canyons such as Nirgal Vallis has been challenged on the grounds that groundwater erosion on Earth is generally observed primarily in loose sediments or easily erodible rock [9]. In addition, some of the proposed terrestrial examples of groundwater sapping have been shown to be the result of large, runoff-driven floods [10] or waterfall-driven erosion [11] rather than groundwater processes. Here we re-examine planform characteristics of Nirgal Vallis to help test the hypothesis that its formation is consistent with groundwater sapping.

Methods: One way to compare Nirgal Vallis to known Earth analogs is to look at the junction or bifurcation angles that tributaries make with the trunk valley. A recent comprehensive study of groundwater sapping systems on Earth using mathematical models, field observations, and laboratory experiments [12] suggests that headwater growth follows a simple geometric model, and produces tributary drainage networks of a specific geometry. Springs grow toward a groundwater source, and when the spring reaches a critical point, bifurcation occurs at an angle of $\alpha = 2\pi/5 = 72^\circ$ [12].

For this reason, we measured the angles between Nirgal Vallis tributaries using data from the Mars Reconnaisance Orbiter Context Camera (CTX) [13] superimposed on a THEMIS IR basemap [14]. There is nearly complete coverage of CTX data at ~6 m/px over the valley. Although aeolian infilling, mass wasting, and impact cratering locally obscure the detailed configuration of some portions of the valley, as noted by [9], most tributaries remain measurable and junction angles are likely to be unchanged by modification processes. From this data, a total of 109 tributary junctions of Nirgal Vallis were mapped (Fig. 1).

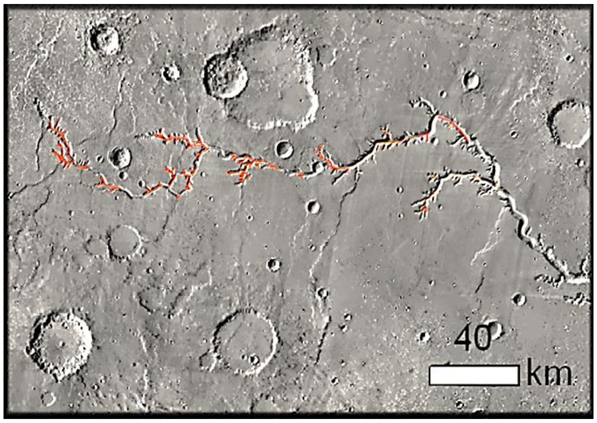

Figure 1. The western portion of Nirgal Vallis. Measured tributaries are highlighted in red.

Observations and Results: The observed average bifurcation angle for Nirgal Vallis tributaries is 71.1º with a standard deviation of 21.5º. The distribution of the observed angles is shown in Figure 2. Consistent with suggestions of earlier studies [4,7], these values are higher than is typical for runoff-dominated drainage networks.

An interesting factor affecting this distribution is that some tributaries appear to have been strongly influenced by wrinkle ridges that intersect Nirgal Vallis, as has been noted in brief before [8]. Tributaries near these wrinkle ridges tend to trend parallel with the ridges, which can lead them to form junctions at high angles to the main valley (Figure 3), including at angles >90°. Of the junctions we measured, ~10% ap-

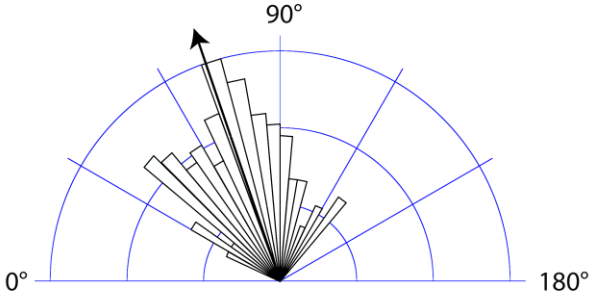

Figure 2. Rose diagram showing measured junction angles of Nirgal Vallis tributaries. Angles greater than 90° occur when the tributary is sourced downstream of its junction (e.g., Fig. 3).

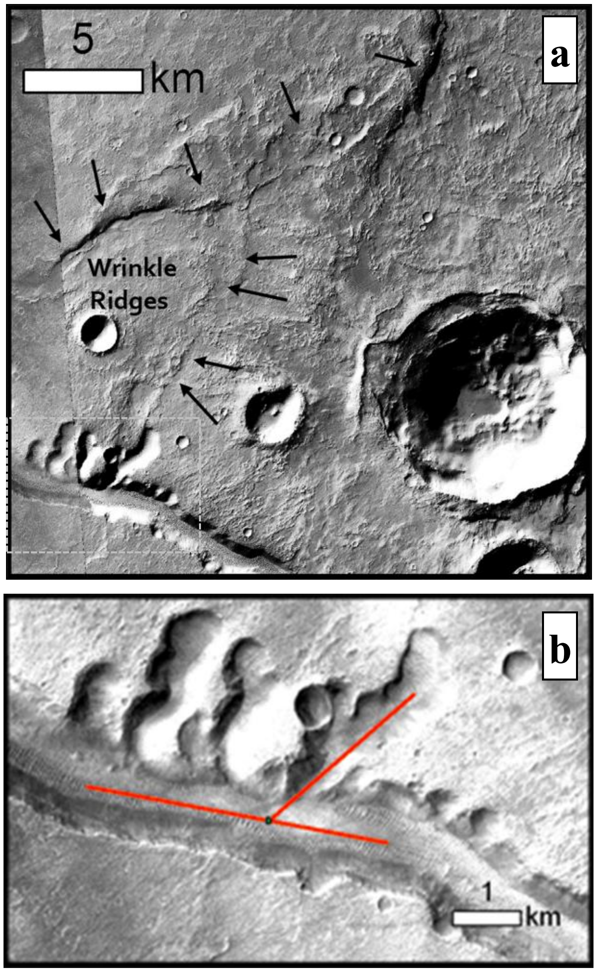

Figure 3. (a) Broad context and (b) local view showing the structural influence/control of a Nirgal tributary by an extension from a nearby wrinkle ridge. A number of the junctions (particularly with angles >90°) appear to have been are affected by tectonic control on valley formation.

pear to be structurally influenced by wrinkle ridges or other faults, although in some cases this interpretation is ambiguous.

Discussion: The fact that the observed mean bifurcation angle for Nirgal Vallis tributaries agrees with theoretically determined expectations [12] provides new independent evidence that Nirgal Vallis may have formed via groundwater sapping. In addition, the alignment of tributary valleys with wrinkle ridges that intersect Nirgal Vallis suggests structural controls influenced valley formation (e.g., Fig. 3), which is also consistent with a sapping origin. Evidence suggests that tectonic controls may be important to the sapping process at some locations on Earth as well [3]. The variability we observe in junction angles is thus likely partially driven by structural factors modifying hydrological behavior.

A number of open questions remain. A source and supply of groundwater to erode Nirgal Vallis's substantial volume remains unclear. Additional work is also necessary to understand the physical properties of the eroded material. It remains uncertain whether incision of the valley required substantial bedrock erosion, since the subsurface of Noachian terrains on Mars may have been substantially brecciated. Chemical and physical weathering may also have led to initially high porosity and hydraulic conductivity that could both enhance the potential delivery of water to the valley and speed erosion. Alternatively, if erosion of bedrock is required, it may pose a significant challenge to accomplish in the context of a groundwater erosion scenario [10].

Finally, as has been noted repeatedly since the discovery of valley networks on Mars [e.g., 15], Nirgal Vallis is morphologically unusual, and likely has a distinct formation process from valley networks elsewhere on Mars [8, 16]. More fully understanding the origin of Nirgal Vallis is important. If, as we support here, Nirgal Vallis formed via groundwater sapping, it requires an integrated hydrological system of substantial extent. This implies temperatures were warm enough at one time to allow abundant liquid water to exist in the upper portion of the crust, and possibly at the surface if recharge of this system occurred.

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