INVERTED FLUVIAL CHANNELS IN TERRA SABAEA, MARS: GEOMORPHIC EVIDENCE FOR PROGLACIAL LAKES AND WIDESPREAD HIGHLANDS GLACIATION IN THE LATE NOACHIAN.

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Introduction: Most Noachian-aged craters on Mars have distinctive morphologic characteristics that suggest they were modified by runoff from rainfall in a predominantly warm and wet early Mars climate [1-4]. However, melting and runoff of frozen water ice (snowmelt) represents a plausible alternative for fluvial erosion in the Noachian [e.g. 2]. Models of the early Mars climate predict widespread glaciation of the southern highlands in the Late Noachian [5-7]. In this case, geomorphic evidence of Late Noachian glaciation should be abundant in the highlands, yet none has been found, perhaps due to its cold-based nature.

In recent work [8], we described a degraded Noachian-aged crater in Terra Sabaea that contained inverted fluvial channel networks and lacustrine deposits. The crater is not breached by fluvial channels and lacks depositional morphologies such as fans or deltas, which sets it apart from previously described open- and closed-basin lakes on Mars that are hydrologically connected to their surroundings [9-10]. Likewise, the crater shows no strong evidence for groundwater sapping [11]. This "closed-source drainage basin" (CSDB) therefore represents a new type of paleolake on Mars. The lack of hydrologic connectivity, along with additional evidence of remnant cold-based glacial morphologies within the crater, led us to hypothesize top-down melting of a cold-based crater wall glacier as the source of runoff and sediment for the fluvial and lacustrine deposits, which produced one or more proglacial lakes within the crater [8]. This interpretation is consistent with model predictions of the early Mars climate [5-7] and is the first potential geomorphic evidence of Noachian cold-based glaciation, sedimentation, and proglacial lake formation found on Mars.

Here, we describe the results of a follow-on survey of the region within 500 km of the first CSDB crater. The purpose of this survey was to determine the occurrence of inverted fluvial channels and associated features elsewhere that may have formed in the same way as those described in the CSDB crater. We identified 42 locations displaying a range of interpreted conditions that can be used to determine the extent to which they underwent fluvial erosion and degradation. Correlations with altitude indicate the potential for widespread fluvial activity and proglacial lake formation that is consistent with cold-based highlands glaciation in the Late Noachian.

Survey results: We searched for examples of features that could be interpreted as inverted fluvial channels regardless of their location. Fig. 1 shows the distribution of the 42 inverted channel networks we identified in the highland region to the northwest of Hellas. Of these, 19 are located within unbreached craters; 17 are within breached craters with at least one inlet but no outlets; and 6 are located in the intercrater plains. The features are not randomly distributed; rather, they form two distinct groupings, one in the southwest of the study area and another in the east, with very few in the north or west. All but one occurs within an elevation range of 0 to +3 km. There are several previously identified closed-basin lakes within the study area [10], but none contained inverted channels.

Inverted channel morphology: The channels within craters generally initiate at slope breaks where the base of the crater wall intersects the floor. The slope break transition is consistent with the interpretations of Davis et al. [13-14], who suggested the transition occurred as streams flowed outward into alluvial basins. The channels likely became indurated and were inverted by later aeolian deflation or volatile sublimation, as evidenced by widespread etched mantle material in the intercrater plains. In larger craters (D>20 km), inverted channel networks are asymmetrically distributed and most often occur downslope of incised or breached portions of crater walls. The channels, typically several km in length, terminate in troughs or moats that are lower than the surrounding crater floors. Smaller craters (D<20 km) tend to have more symmetrical channels in a starburst pattern. Inverted channels outside craters appear to be concentrated in areas of tectonically controlled topography such as at the base of fault scarps or graben. Here the sudden shifts in local slope have led to the deposition of alluvial sediments in much the same way as at the base of crater walls.

Light-toned crater floor unit: A light-toned unit outcrops in a number of crater floors that contain inverted channels and in some low-lying intercrater areas. Stratigraphic relations suggest it is older than the inverted channels. These outcrops belong to a unit that was previously identified by its high thermal inertia [15] and unusual spectral signature of plagioclase feldspar [16-17]. High-resolution visible imagery reveals finely layered polygonal mounds and exposed boulders and talus slopes that suggest active weathering processes. In other locations, the unit forms massive yardang fields with cliff faces 100s of m high and 10s of km long. While the origin of the unit remains unclear, early deposition during the formation of one of the three major impact basins appears promising [15-16]. Recent work suggests the composition of the unit may be consistent with the fallout of large volumes of surface material that would have been vaporized during the formation of a large basin and subsequently condensed and deposited [18].

Discussion: The 42 inverted channel systems represent a wide variety of geologic and hydrologic settings, ranging from completely unbreached, relatively fresh craters to heavily modified craters whose rims are almost completely removed. Despite this variety, clear patterns emerge in the distribution of these features that are indicative of their geologic history and possible origins.

The region has distinctly low valley network density, and the few mapped valley networks in the region are clustered around +2 km elevation [19]. If the fluvial regime were controlled primarily by elevation, and assuming no significant sequestration, lower elevations should have greater overall runoff production due to the accumulation of flow from upslope. Craters would then be more likely to be breached as elevation decreased, which is exactly what we observe. We previously interpreted the unbreached CSDB crater as having a water source derived from top-down melting of a cold-based crater wall glacier, which would not require fluvial breaching in order to produce internal crater runoff. In a regional context, this would imply a glacial margin at or near the altitude occupied by the inverted channels within unbreached craters. The difference between breached and unbreached craters could therefore represent glacial melting occurring within craters (higher elevation) as opposed to significantly upslope of them (lower elevation), which would instead promote runoff and breaching of craters by valley networks.

We plan to carry out additional work to determine likely melting rates and durations required to form the inverted channels, which could then be used to refine predictions of ice volumes and possible equilibrium line altitudes of Late Noachian glaciation in the southern highlands.

Conclusions: We previously described a single CSDB crater that showed evidence for cold-based crater wall glaciation, sedimentation and proglacial lake formation, but this new work adds a significant body of evidence that such processes were operating at much greater regional scales. Although Late Noachian glaciation has been predicted by climate modeling studies [5-7], our work represents the first potential geomorphic evidence to corroborate these predictions.

Long-standing paradigms of early Mars have posited that the ambient climate must have been temperate enough to support flowing liquid water at the surface for hundreds of millions of years [22-23]. While runoff from rainfall is usually considered the most likely mechanism of fluvial erosion in the Noachian [1-4], the possibility remains that fluvial erosion could have occurred via snowmelt in a subfreezing ambient climate [e.g. 2]. We have provided compelling evidence that fluvial and lacustrine features could have formed in such a climate and that Noachian Mars may have been colder than previously believed.

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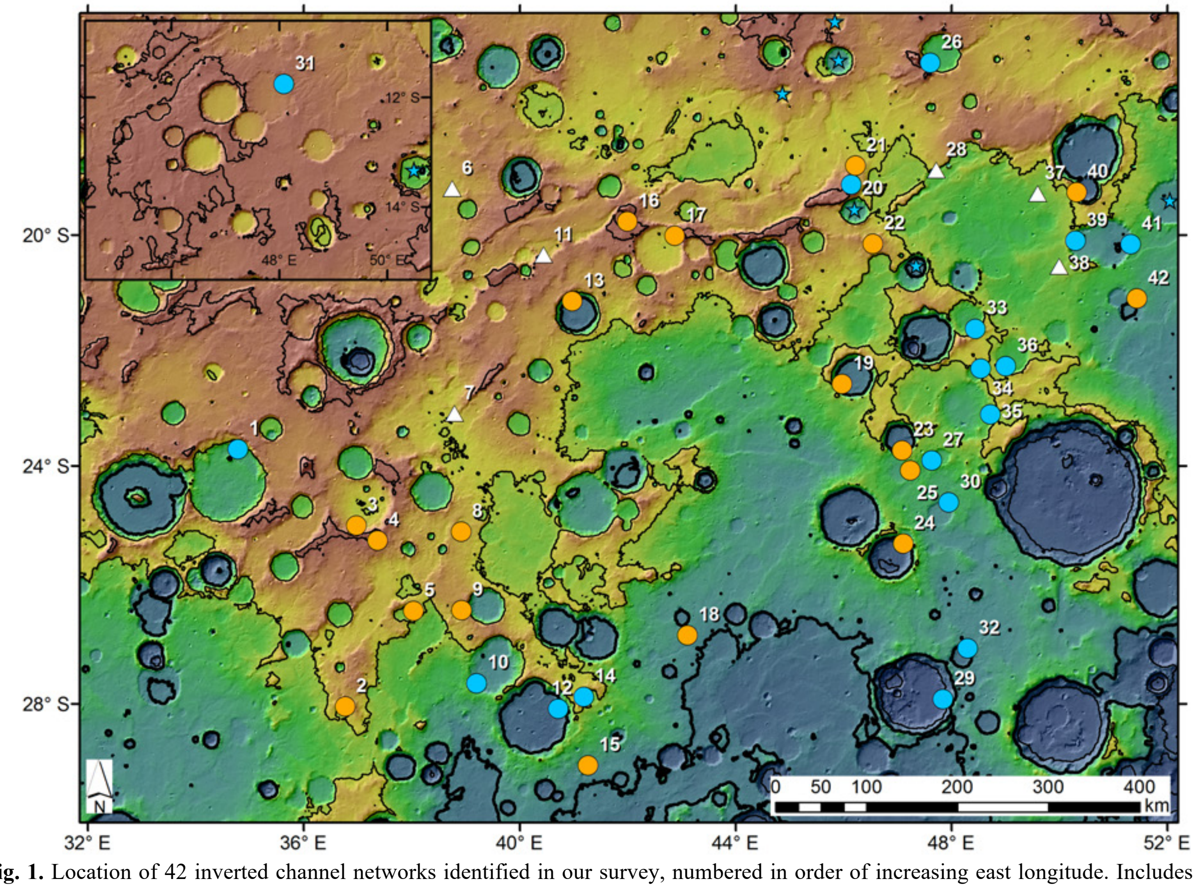

Fig. 1. Location of 42 inverted channel networks identified in our survey, numbered in order of increasing east longitude. Includes unbreached craters (orange circles), craters with one or more inlet breaches (blue circles), intercrater channels (white triangles), and previously mapped closed-basin lakes (blue stars) [10]. Black contour lines marked for each 1 km above the datum; thick black line represents predicted +1 km ELA of Late Noachian highlands glaciation [20-21]; inset shows location of #31 at lower latitude.