MARS CRATER MODIFICATION IN THE LATE NOACHIAN: EVIDENCE FOR COLD-BASED CRATER WALL GLACIATION AND ENDORHEIC BASIN FORMATION.

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Introduction: Mars is currently characterized by a hypothermal, hyperarid climate (mean annual temperature, MAT ~213 K) that is thought to have persisted throughout the Amazonian, the most recent period of Mars history (~3.4 Ga to present) [1]. The distribution of water ice on Mars has changed over time due to periodic variations in spin axis obliquity [2]. During periods of relatively higher obliquity than present, water ice is mobilized from the poles and deposited as snow and ice in the mid-latitudes, producing cold-based glacial landforms [3]. Amazonian cold-based glaciation in crater interiors has left a variety of distinctive morphologic features that permit the recognition of both the glacial phase and the transition to post-glacial conditions [4-7].

Geologic evidence suggests that the ambient climate in the Noachian (~4.0–3.7 Ga) was significantly different than that of the Amazonian. Abundant fluvial and lacustrine features have been interpreted to indicate the presence of a warm and wet climate characterized by MAT >273 K with rainfall and runoff occurring intermittently over tens of millions of years [8-9]. However, global climate models predict Noachian MAT ~225 K, well below that required to sustain rainfall and runoff [10-11]. These models also predict an adiabatic cooling effect such that surface water will be deposited preferentially as snow and ice in the southern highlands and south polar cap. Supporting geomorphic evidence for this hypothesis has been elusive due to the fact that glaciation in such an environment is predicted to be cold-based [12]. Thus, the distinctive characteristics typical of wet-based glacial conditions, such as drumlins, eskers, and widespread distal retreat and meltwater features, are not predicted to occur [3].

We report here on the geology of a 54-km diameter Noachian-aged crater in the southern highlands that displays evidence for ancient glaciated walls and drop moraines similar to cold-based features seen in glaciated craters in the Amazonian. In addition, we document a broad system of proglacial sediments, inverted fluvial channels, and lacustrine deposits whose drainage basin is contained completely within the crater (an endorheic basin). These observations provide evidence of top-down melting of cold-based crater wall glaciers in the highlands of Noachian Mars.

Geology of Crater B: The crater we analyzed is located in Noachian-aged highlands terrain ~800 km northwest of the Hellas basin rim in Terra Sabaea. In a regional study of Terra Sabaea crater floors, Irwin et al. [13] noted that the interior of this crater, which they designated "B," contained an etched floor unit with darker sinuous ridges that may have been inverted fluvial channels. On the basis of this previous work, we mapped the interior of crater B in detail using CTX and HiRISE visible images (Fig. 1A-B). These data reveal an ensemble of additional features not previously described in Noachian-aged craters. We derive a lower limit crater age date for this ensemble of ~3.5 Ga, or Late Noachian–Early Hesperian (LN–EH).

A series of arcuate, *upslope-facing scarps* (Fig. 1C) with convex downward planforms occurs near the base of the wall. We interpret the upslope-facing scarps to represent remnant drop moraines from glaciers that once occupied the crater wall alcoves on the basis of their distinct similarity in morphology and location to convex-downward, upslope-facing scarps seen in Amazonian-aged glaciated craters [4-5] and in cold-based glacial environments in Antarctica [14].

A distinctive 1-3 km-wide *sediment band* (Fig. 1C) occurs along the base of the crater wall, often superposing the upslope-facing scarps. We interpret this sediment band to be formed by proglacial sedimentation on the basis of its similar proglacial position and grain size to proglacial sand deposits observed along cold-based glacial fronts in Antarctica [15-17].

Inverted tributary ridges (Fig. 1D) typically ~200 m wide and ~20 m high are distributed circumferentially throughout the crater floor and follow the same general morphologic trend from the crater wall, extending radially along the gently sloping floor, where they terminate at the margin of a distinctive *interior deposit* (Fig. 1E). We interpret these ridges as a system of exhumed fluvial channels on the basis of 1) their similarity to inverted fluvial channels documented elsewhere on Mars [18-20] and dating from the same LN–EH time period; and 2) their similarity to glaciofluvial valleys and inverted channels observed in recently glaciated Amazonian craters [6-7]. We interpret the interior deposit as the location of a former lake and depocenter for sediment transported by the fluvial channel system on the basis of its location in the lowest part of the crater floor and the interpreted paleoflow direction of the inverted fluvial channels.

Discussion and Conclusions: This ensemble of closely interrelated wall features, floor ridge systems and interior plains suggests a common process operating in the LN–EH to produce an endorheic basin fed by an internal fluvial drainage system. We conclude that crater B underwent the following geologic history: 1) crater wall glaciation in the Late Noachian and cold-based glacial flow toward the crater floor to produce convex-downward, upslope-facing drop moraine scarps; and 2) a transition to post-glacial conditions characterized by sufficiently high atmospheric temperatures to cause top-down melting of the cold-based glaciers and drainage of meltwater into the crater interior to form an endorheic (internally drained) crater basin lake.

The endorheic crater B basin, with completely internal drainage, lies in contrast to the similarly-aged open-basin lakes (inlet channel, filling and breaching of rim through an outlet channel) and closed-basin lakes (inlet channel, but no breaching) on Mars, which are generally found at lower elevations [21-22]. The lack of either intercrater fluvial dissection or significant exterior drainage into crater B argues against an origin for the fluvial and lacustrine features as the depositional remnants of fluvial valley networks derived from areally distributed rainfall and runoff. We hypothesize that a brief period of atmospheric warming caused top-down melting of cold-based crater wall glaciers during the transition from Late Noachian climate conditions to conditions typical of the later Hesperian and Amazonian, which would then disfavor altitude-dependent glaciation. Recognition and documentation of this ensemble of features and their close interrelationships provides specific criteria to search for other examples of past glaciation in the southern highlands in order to further test hypotheses of Mars climate evolution.

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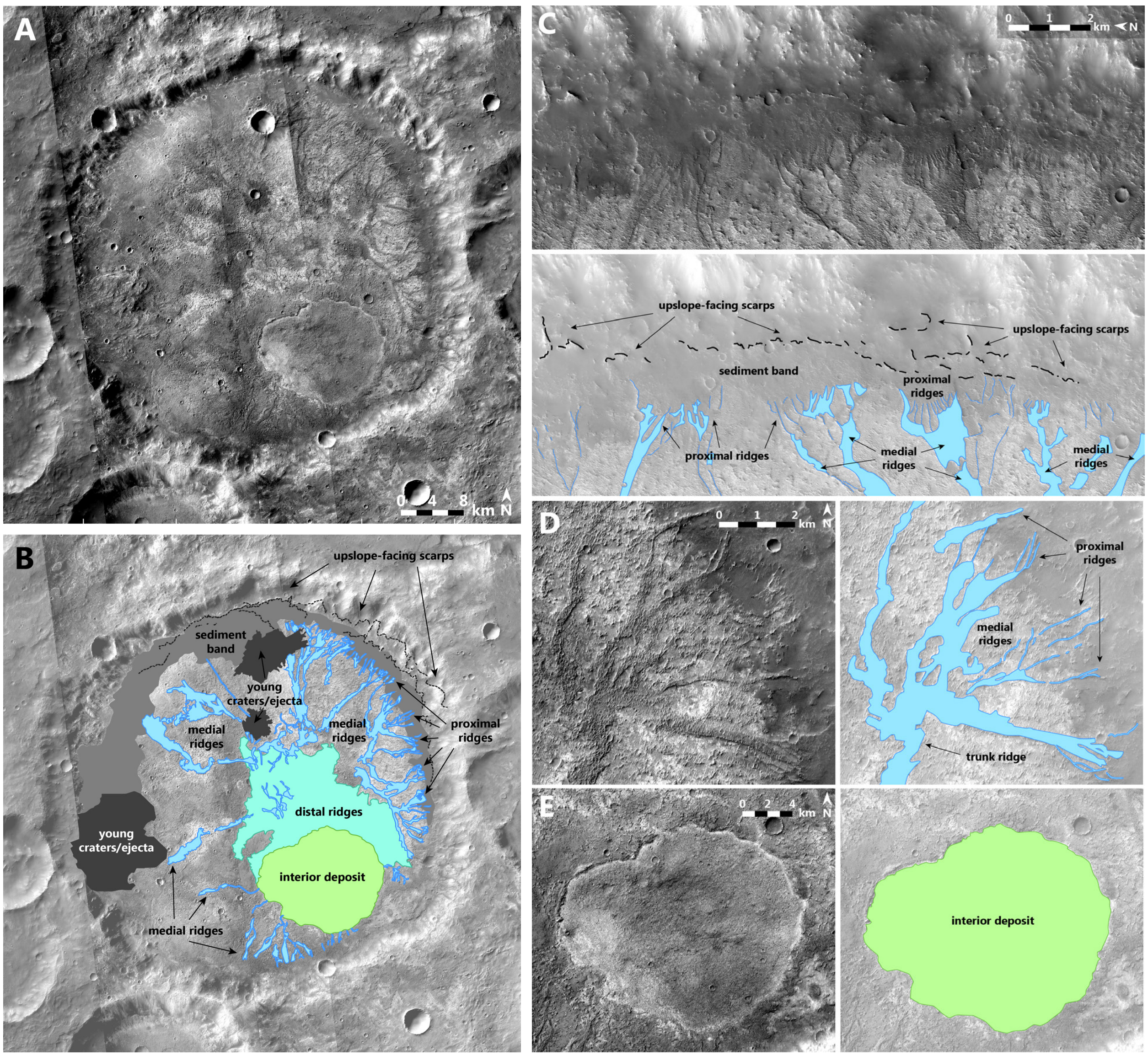

Fig. 1. (A) CTX visible image mosaic of 54-km diameter Noachian-aged crater B (20.3°S, 42.6°E). (B) Sketch map overlay showing the major geologic features within crater B. *Inverted tributary ridges* (blue) begin near the crater wall base in association with *upslope-facing scarps* (dotted lines) and *sediment band* (gray), and extend radially toward the *interior deposit* (green). (C) Detail of relationship between upslope-facing scarps, sediment band, and proximal and medial ridges. (D) Detail of inverted ridges. (E) Detail of interior deposit.