N92-10774

GLACIAL GEOLOGY OF THE HELLAS REGION ON MARS;

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Introduction. We recently presented a glacial geologic interpretation for Argyre [1], which we now extend to Hellas. This glacial event is believed to constitute an important link in a global cryohydric epoch of Middle Amazonian age [2, 3]. At glacial maximum, ice apparently extended far beyond the regions of Argyre and Hellas, and formed what we term the Austral Ice Sheet, an agglomeration of several ice domes and lobes including the Hellas Lobe.

Regional landform associations. The Hellas Lobe originated on the summit and slopes of the giant shield volcano Amphitrites Patera, and dominated northward inflow into the Hellas impact basin (Figs. 1 and 2). The Hellas-facing side of Amphitrites Patera is dominated by a ridge-and-trough structure, indicating pervasive scouring perhaps similar to that of glaciated lineated terrains in Canada [4]; thus, we term this region the lineated terrain. The erosive agent appears to have been an aerially extensive, high-standing medium such as ice. It efficiently erased most craters smaller than 2 km, apparently at essentially a discrete point in geologic time [5]. The erosive agent flowed around several of the largest craters, preserving their rims while severely degrading or completely removing their ejecta blankets, and producing deep upslope and lateral fluting. Orientations of lineations are strongly correlated with large-scale topography, thus confirming an essentially down-slope movement of the erosional medium. Subsidiary fluvial erosion, probably by glacial meltwater, also occurred.

The lineated terrain passes northward into a complex region on the floor of Hellas including an area of streamlined ridges and equant hills interpreted as a drumlinoid terrain; the orientations of drumlinoid features are consistent with northward flow of ice from the lineated terrain. Long, sinuous ridges, believed to be eskers [6], are also present but uncommon. Drumlinoid terrain grades northward into a region interpreted as hummocky ground moraine formed by glacial till deposition and massive ice disintegration. Hummocky deposits form thick blankets of material terminating northward along transverse cuspate ridges and escarpments, consistent with our interpretation that these are moraines of southward derivation. The cuspate ridges spaced across the floor of Hellas mark terminal and recessional margins of the former Hellas Lobe. At glacial maximum ice apparently flowed to and terminated near the deepest part of the basin. Other ridges in the northern part of Hellas resemble lunar-type wrinkle ridges and have not been mapped.

Smooth channel-fed plains, interpreted as proglacial lake deposits, are widespread on the floor of Hellas, especially in the east-northeastern sector. Large channels entering the area from highlands to the east become subdued and strongly anastomosing, apparently indicating transition to a depositional regime as the channels entered the lake area. Escarpments in the glaciolacustrine plains area may have been wave-cut, and thus possibly indicate former lake levels. Moraine-like ridges in the vicinity of the glaciolacustrine plains area are often flat-topped, also consistent with erosional planation by wave activity.

Volume of the Hellas Lobe. The Hellas Lobe extended nearly 1500 km from Amphitrites Patera to its northern terminus and covered an area of approximately 1.5×10^6 km^2. We constructed a simple model of the ice profile based on Bingham rheology and a combined parabolic and inclined plane solution incorporating isostatic adjustments. The model thickness of ice on the slopes of Amphitrites Patera ranges from 450 to 900 m, consistent with the heights of ridges and the flowage of ice around large craters. On the basin floor the parabolic solution indicates ice thicknesses ranging to nearly 4000 meters. The integrated volume of the Hellas Lobe model is 4.7×10^6 km^3. If the Hellas Lobe was typical of the entire Austral Ice Sheet, and if this ice sheet covered around 12% of the planet's surface (2/3 of the area lying between the South Pole and 40° S. Lat.), then the total ice volume would be 5.5×10^7 km^3, equivalent to a global layer of water 340 meters thick. This estimate is of the same order as the water budget of Mars calculated on independent grounds [e.g., 7, and other references in 2].

Depth of erosion. The vertical scale of troughs and ridges in the lineated terrain suggests erosion to a depth of order 500 m in the most strongly affected localities. We base an independent estimate on crater statistics. In a separate abstract [5] we show that the lineated terrain exhibits a great deficiency of craters in the 1-2-km size class, and a smaller deficiency between 2-4 km, a feature attributed to glacial erosion. The average ratio d:D (depth : Diameter) for fresh, simple craters on Mars is 1:6, indicating d = 170 and 670 m for fresh craters having D = 1 and 4 km, respectively. A crater would probably be obscured if erosion occurred to a depth of 0.6d. Thus, the cratering record indicates that the lineated terrain has suffered widespread erosion to a depth of 100 m and locally to 400 m (based on removal of most 1-km and some 4-km preglacial craters). We take 200 m as a rough average erosional depth.

Chronology of glaciation. Statistics for fresh craters indicate a Middle Amazonian age of glaciation in Hellas. The Middle Amazonian also saw extensive cryohydric activity elsewhere on Mars. The Argyre region apparently also was glaciated during the Middle Amazonian, and lobate debris aprons (rock glaciers?) were widely deposited in the Northern Hemisphere [3], collectively indicating a global humid epoch of glacial-periglacial conditions within this period. Earlier indications that fluvial erosion on Alba Patera may have been synchronous with glaciation now seem more doubtful since this fluvial event may have occurred in the later part of the Early Amazonian or earliest Middle Amazonian, before the glacial event [8]. The absolute chronology is more problematic. However, in an accompanying abstract we estimate that Middle Amazonian glaciation in Hellas probably occurred not earlier than 2300 million years ago and not later than 250 million years ago. We cannot exclude the possibility that older episodes of glaciation may also have occurred in this area.

We estimate the duration of glacial erosion in the lineated terrain by considering the average rate of glacial erosion on Earth. Laurentide glaciation eroded an average of about 150 meters of rock from affected areas over the past 3 million years [9]. Approximately half of this period represents glacial epochs and half is interglacial. Thus, the average rate of Laurentide glacial erosion calculated for the glacial epochs is about 0.010 cm y^{-1}. At this rate 200 m of erosion in the lineated terrain would require 2 x 10^6 years of glaciation. Of course martian glacial erosion rates may not have been similar to terrestrial rates. Amphitrites Patera, being a shield volcano, would likely be composed of highly fractured volcanic rock, thus enhancing the efficiency of plucking and favoring high erosional rates and short durations; warm-based glaciers, as we believe the Hellas Lobe was, would also favor high erosional rates. On the other hand, the lower surface gravity on Mars would decrease shear stresses and erosional rates relative to the Earth (this factor, however, is partially offset by a thickening of the martian ice sheet relative to terrestrial ice sheets also due to the g factor). Thus, two million years is an order-of-magnitude estimate of the duration of Middle Amazonian glaciation in the Hellas region.

Alternative mechanisms. We acknowledge that morphologies discussed here can be explained nonglacially. For example, winds may have scoured the lineated terrain. Dust storm activity apparently cycles a meter or so of dust between hemispheres on the relatively short precessional timescale, resulting in dramatic atmospheric effects but very little actual erosion of rock, as testified by the preservation of many blocks at the Viking landing sites on terrains which must be on the order of a billion years old [10]. It seems unlikely that hundreds of meters of erosion of apparently basaltic lava in the lineated terrain could have occurred. Anyway, aeolian processes would not likely produce downslope orientations of lineations in the lineated terrain; the magnitude of the negative thermal anomaly associated with Hellas is less than half that of the positive Tharsis anomaly where no orographically-associated aeolian erosion is observed; at Hellas the maximum vertical component of mechanically- and thermally-forced orographic winds is on the order of only a few cm sec^{-1} [11]. Furthermore, other processes would be required to explain young fluvial systems on the lineated terrain and other glacial-appearing morphologies in the Hellas region. The regional associations and ordered sequences of landforms, their relationships to large-scale topography, and the age of this event relative to other proposed glacial/periglacial events on Mars, are all well explained by glaciation. Alternative hypotheses will have to compete with the economy of the glacial hypothesis in explaining these important aspects as well as the morphologies of individual landforms.

Conclusions. 1) Hellas was apparently heavily glaciated. 2) Glaciation was young by martian standards (Middle Amazonian), and ancient by terrestrial standards. 3) Glaciation occurred during the same period that other areas on Mars were experiencing glaciation and periglacial activity. 4) Glaciation occurred as a geologically brief epoch of intense geomorphic activity in an era characterized by long periods of relative inactivity.

References. 1. Kargel, J.S. and Strom, 1990, Lun. Planet. Sci. XXI, 597-598. 2. Baker et al., 1990, Nature. 3. Strom et al., 1991, Lun. Planet. Sci. XXII (ABSTRACT), this volume. 4. Smith, H.T.U., 1948, Amer. J. Sci. 246, 503-514. 5. Johnson et al., 1991, Lun. Planet. Sci. XXII (ABSTRACT), this volume. 6. Kargel et al., 1991, Lun. Planet. Sci. XXII (ABSTRACT), this volume. 7. Carr, M.H., 1987, Nature 326, 30-34. 8. Gulick, V.C, and V.R. Baker, 1990, (ABSTRACT) Lun. Planet. Sci. XXI, 443-4, and private comm. 9. Bell, M. and E.P. Laine, 1985, Quat. Res. 23, 154-174. 10. Arvidson, R., E. Guinness, and S. Lee, 1979, Nature 278, 533- 535. 11. Webster, P.J., 1977, Icarus 30, 626-649.

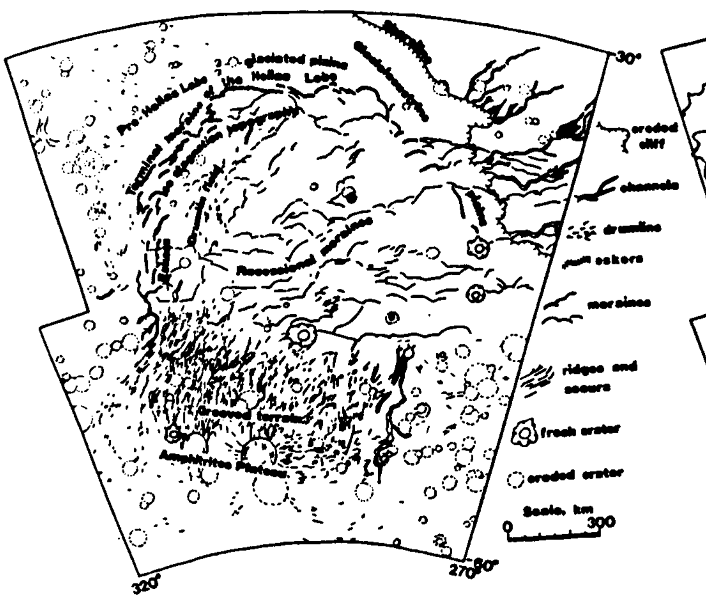

Figure 1. Distribution of selected glacial features in Hellas.

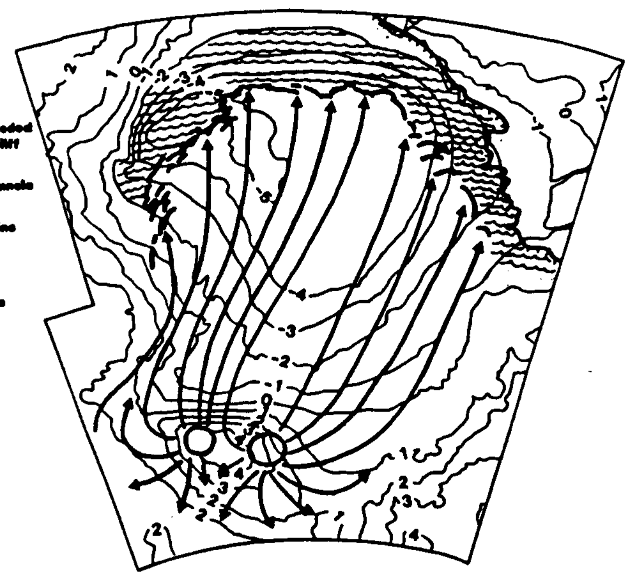

Figure 2. Schematic ice flow lines and former distribution of glacial ice and a proglacial lake in Hellas.