# Scarp-bounded benches in Gorgonum Chaos, Mars: Formed beneath an ice-covered lake?

Alan D. Howard
Department of Environmental Sciences, University of Virginia, Charlottesville, Virginia, USA

Jeffrey M. Moore
NASA Ames Research Center, Moffett Field, California, USA

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[1] Level, bench-like platforms edged with scarps facing the interior of the Martian Gorgonum Chaos basin may have formed in conjunction with an ancient ice-covered lake. These benches, however, lack the typical features of shorelines associated with wave and current transport and erosion, such as crescentic embayments, spits, barrier islands, and wave-cut cliffs. Rather, the basin-facing platform edges are commonly rounded and cumulate in planform, often evenly encircling buttes protruding above the level of the benches. The benches are postulated to have been formed by outward growth in a quiescent environment, possibly by deformative lateral flow of sediment below the ice-water interface in a perennially frozen lake due to the weight of the ice overburden. *INDEX TERMS:* 1815 Hydrology: Erosion and sedimentation; 1824 Hydrology: Geomorphology (1625); 5415 Planetology: Solid Surface Planets: Erosion and weathering; 6225 Planetology: Solar System Objects: Mars. **Citation:** Howard, A. D., and J. M. Moore (2004), Scarp-bounded benches in Gorgonum Chaos, Mars: Formed beneath an ice-covered lake?, *Geophys. Res. Lett.*, *31*, L01702, doi:10.1029/2003GL018925.

## 1. Introduction and Geologic Setting

[2] High spatial resolution images from the Mars Global Surveyor (MGS) Mars Orbiter Camera (MOC) narrow angle (NA) instrument the Mars Odyssey Thermal Emission Imaging Spectrometer (THEMIS) visual imaging subsystem (VIS) have revealed nearly level, smooth-surfaced benches near the center of the Gorgonum Chaos basin. These benches are bounded by abrupt scarps on the side facing the center of the basin. In this paper we describe these and related features, including their geologic setting, and explore several hypotheses about their origin, concluding that the best explanation is that they formed in association with a late Hesperian or early Amazonian ice-covered lake. Several studies have proposed the former presence of lakes in the cratered highlands of Mars based upon interpretation of features such as interior terraces and flat floors in craters, valleys draining into or from basins, and layered deposits [e.g., *Cabrol and Grin*, 1999; *Moore and Wilhelms*, 2001; *Grant and Parker*, 2002]. These studies have not, however, documented unambiguous lacustrine deposits or landforms. A possible exception is the fluvial fan or delta exposed by eolian deflation at the mouth of a channel system draining into a crater basin [*Malin and Edgett*, 2003].

[3] The Gorgonum Chaos basin is an ancient, highly degraded 220-km diameter depression centered at about 37°S and 173°W (Figure 1). The basin lacks a well-defined rim, and may have been created through erosional integration of at least three impact basins. The center of the concave basin is partially occupied by knobby, generally flat-topped mesas (the "chaos", Figures 1–3) that may once have been a continuous deposit that has been dissected into isolated mesas along linear trends. We use the term chaos, although it is a misnomer because the material forming the mesas has been eroded, rather than transported or collapsed. These deposits were emplaced and eroded into mesas prior to the features discussed here.

## 2. Morphological Features

[4] Three relatively youthful features have been superimposed upon the inner floor of the Gorgonum Basin. These include a complex of nearly level benches (at about −300 m elevation relative to the Mars datum) and associated marginal scarps on the edges facing the basin interior, a nearly level basin floor at about −400 m, and a set of features forming a level ring around the central basin at about −50 m (Figure 1).

### 2.1. Benches and Scarps

[5] The scarp-like outer edges of the benches (facing the basin interior) are extremely convoluted in plan view with enclosed basins and deep, branched reentrants (Figures 2 and 3). These edges are generally smoothly curved, but with a predominance of broadly convex protuberances and reentrants with acute terminations, i.e., a "cumulate" planform (Figures 2a and 3). The benches ring a central interior depression that generally lies 50–200 m below the level of the benches (Figures 2 and 3).

[6] The tops of the benches are exceedingly smooth at the 100 m scale (Figure 3) but exhibit some pitting at the 2–20 m scale (Figure 2B). This pitting appears to post-date formation of the benches and may be related to the pervasive mantle at these latitudes [*Mustard et al.*, 2001]. The benches are very level and can range up to 15 km in width (Figures 3 and 4). The surface defined by the top of the benches is smooth but not absolutely level, systematically varying by about 60 m across the ~60 km width of the basin floor. In the center of the basin, however, the range of bench top elevations is only about 15 m (Figure 4).


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[7] The inner margin of the platforms generally abut against earlier mesas of the Gorgonum chaos and the walls of the Gorgonum Basin with a smooth, abrupt onlap (Figures 2 and 3). Locally, however, the inner edge of the platforms exhibit low ridges paralleling the boundary (Figure 2b). Remnant buttes of chaos in the interior of the basin that rise above the level of the benches are often ringed by narrow benches a few tens of meters wide. Mesas of the Gorgonum chaos that are proximal to the benches commonly exhibit reticulate fissures and cracks suggestive of slump or marginal collapse (Figure 2a).

[8] The scarps edging the benches are generally smooth and range from slightly convex to slightly concave in cross-section (Figure 2). The height of the steep outer scarp

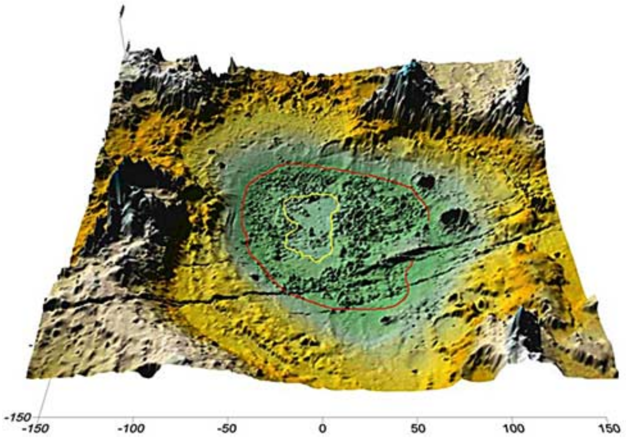


**Figure 1.** The Gorgonum basin. The red line shows a possible shoreline at −50 m, and the yellow line shows the general location of the benchlike platforms at ∼−300 m mapped in Figure 3. Scale in kilometers.

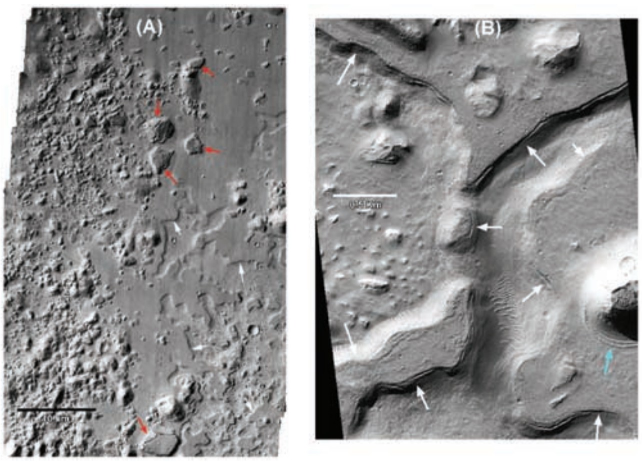


**Figure 2.** Morphological features of benches and scarps. (a) THEMIS VIS V01904003, image resolution ∼17 m/pixel. Remnant buttes of the Gorgonum chaos dominate the left side of the image, and the smooth-surfaced benches form the majority of the central portions of the image, with 20–50 m scarps at their outer edges (white arrows) dropping off into the basin interior (lower right side, which has a smooth to hummocky texture. Red arrows point to chaos buttes with prominent fissures suggesting collapse of the butte edges. (b) MOC M2101910, image resolution ∼4.2 m/pixel. Scarps at the outer bench edges (white arrows) commonly have narrow fissures or benches near the top. Blue arrow shows low parallel ridges found locally at the contact between the inner surface of the benches and the older chaos buttes. The lower basin floor varies from smooth to hummocky texture.

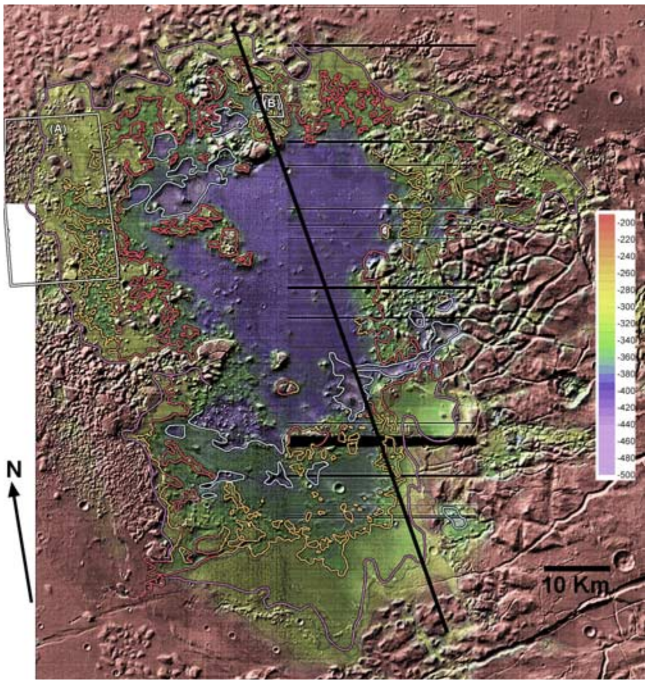


**Figure 3.** Map of bench platforms. Image base is THEMIS 100 m/pixel IR. The scarp at the outer edge of the platforms is mapped as follows: (ORANGE) based on MOC NA images (∼2–5 m/pixel) and THEMIS VIS images (∼17 m/pixel); (RED) based on THEMIS IR images (∼100 m/pixel). The approximate inner edge of the bench deposits (ignoring included knobs) mapped in VIOLET. Scarps below the level of the main benches are shown in CYAN. Units were not mapped in regions of dense chaos mesas, particularly at the left and right sides of the basin. The base image is elevation-cued, varying from purple at −450 m to red above −200 m. Boxes show locations of Figures 2a and 2b. Black diagonal line shows location of Figure 4.

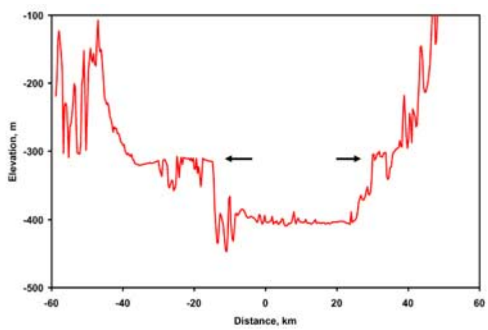


**Figure 4.** Representative MOLA profile crossing the bench platforms. North to right. Vertical exaggeration about 200×. Arrows are at platform level. MOLA orbit number 17909.

between the benches and the basin floor is typically 20–50 m. (Figure 4). The scarps often exhibit narrow benches or shallow fissures at the top edge (Figure 2b). Some of the south-facing scarp edges have been subsequently modified, roughening the surfaces and producing basal ramparts as also occurs elsewhere in the martian highlands [*Mustard et al.*, 2001; *Malin and Edgett*, 2001]. Similar modification occurs on the chaos mesas, sometimes with recent gully development [*Malin and Edgett*, 2000]. The outer scarp edges appear to be devoid of blocks or mass-wasting landforms resolvable at MOC NA scale (>2–5 m). This contrasts with the sideslopes of the chaos mesas, which commonly have produced numerous resolvable blocks produced during backwasting.

### 2.2. The Inner Basin Floor

[9] Most of the inner basin floor is a flat plain at an elevation of about −400 m. However, a few irregularly-shaped depressions several km in diameter extend below this level, primarily around the edges of the basin (Figure 3). Elevations in the depressions locally extend below −450 m. In some locations, particularly at the south and northeast edges of the inner basin floor, platform benches also occur below the main bench level, typically at elevations of about −350 m. At least locally the higher bench seems to be superimposed upon the top of the lower benches. Scarps at the edge of lower benches at ∼−350 and −400 m are mapped in cyan in Figure 3. The inner basin floor is generally smooth to hummocky at the 100 m scale. A number of knobs on the basin floor may be degraded remnants of the km-scale Gorgonum chaos. Locally there occur low amplitude lineations and reticulate banding of uncertain origin and age, as well as fields of low knobs of ∼25 m scale.

### 2.3. A Basin Ring Feature

[10] A set of linear features can be traced around three sides of the Gorgonum basin at an elevation of about −50 m. This ring is exterior to the benches, scarps and basin floor described earlier. It is delineated by one or more of the following features: (1) a low scarp facing towards the basin interior; (2) a band about 200–500 m wide with a fine-textured bumpy or reticulate surface; (3) a sharp transition from lower to higher thermal inertia within the ring in THEMIS IR (infrared) images; or (4) a sharp transition from smooth basin floor exterior of the ring to a hummocky texture within. Sparse, shallow channels occur on the smooth floor of the Gorgonum basin above the −50 m ring, but not inside of it. The basin ring features are not distinguishable within zones of chaos or grabens of the Sirenum Fossae due to the steep, complex topography.

## 3. Hypotheses for the Origin of the Benches and Scarps

[11] Eight hypotheses have been evaluated for the formation of the Gorgonum benches.

### 3.1. The Benches Form by Subaerial Backwasting of a Near-Horizontal Resistant Bed

[12] Erosion of resistant sedimentary or volcanic cap-forming strata overlying weaker materials is the origin of most scarps on, for example, Earth's Colorado Plateau. Such scarps typically retreat by a combination of mass-wasting, fluvial, and sapping processes. High-resolution MOC images fail, however, to show mass wasting features such as slumps or talus accumulations on the scarp edges or a pronounced cliff face at the top of the scarps. Similarly, fluvial channels and alluvial fans are absent from the scarp faces. In addition, scarps formed by back-wasting generally display a planform characterized by sharp projections and shallow, broadly curved reentrants, opposite to the observed pattern of sharp reentrants and broadly curve projections which typically form by outward growth [*Howard*, 1994, 1995]. Furthermore, the enclosed depressions cannot be explained by erosional backwasting. These observations suggest that erosional backwasting of a caprock is not an adequate explanation for the Gorgonum benches.

### 3.2. The Interior Depressions Have Formed by Eolian Deflation

[13] Eolian deflation has been suggested as an explanation for pitted terrain near the south pole [*Sharp*, 1973], and for erosion of thick sequences of sedimentary deposits in impact basins [*Malin and Edgett*, 2000]. Deflation basins also occur in terrestrial deserts [e.g., *Breed et al.*, 1989], sometimes resulting from decline of groundwater levels in friable sediments. Yardangs or other obvious eolian erosional features, however, have not been identified within the basin, and other processes must be invoked to explain the origin of the planar bench deposit.

### 3.3. The Benches Form by Selective Subsidence of the Basin Floor

[14] Such subsidence would presumably occur by solution of a soluble bed or sublimation or melting of a layer of subsurface ice. The thickness of the putative layer would have averaged about 100 m. The soluble deposit or ice would presumably have accumulated within a former lake or playa. Decay of ground ice in terrestrial periglacial terrain to form alases or thaw lakes could be an analog, as might development of solutional basins on the High Plains of the U.S. Great Plains [*Paine*, 1994]. This mechanism could account for enclosed depressions. This hypothesis, however, faces several difficulties. The basin floors are smooth rather than exhibiting irregular topography due to differential collapse. The smooth edges of the scarps and lack of evidence of rotational failures argue against basin extension by subsidence. As with the subaerial backwasting hypothesis, this mechanism has difficulty explaining the smooth, broadly convex scarp planforms.

### 3.4. Formation as Clastic Sedimentary Shorelines in an Open-Water Lake

[15] By this scenario the bench platforms would form by fluvial delivery of sediment, whereas the scarps would be coastal beaches formed by waves and currents. This is an unlikely scenario, for several reasons. The benches show no surface features suggestive of fluvial transport. Sources of sediment for isolated benches and long, convoluted peninsulas are difficult to explain. There is no evidence of classic coastal features such as spits,

overwash deposits, coastal dunes, barrier islands or offshore bars.

### 3.5. Formation as Chemical Sedimentary Deposits in an Open-Water Lake

[16] This scenario would involve outward growth of reef-like structures due to either inorganic or organic deposition. The cumulate planimetric form of the benches is consistent with this scenario. However, open-water deposition would presumably also involve coastal processes, for which there is no evidence. No spectral signature of chemical deposits has been recognized to be associated with this area. Reef deposits might be expected to have a high thermal inertia, but no strong signature has been identified.

### 3.6. Formation as Chemical Sedimentary Deposits Within an Ice-Covered Lake

[17] Although this eliminates the problem of the lack of coastal erosional features, all the other problems of 3.5, above, remain, plus the source and deposition mechanism of solutes would need to be resolved.

### 3.7. Formation as Clastic Sedimentary Deposits at the Base of a Perennially Ice-Covered Lake

[18] In this scenario the sediment would primarily be deposited at the edges of the benches, which would grow inward towards the basin center. This explanation would be consistent with the generally cumulate planform of the scarps. It is also consistent with the lack of open-lake coastal landforms. However, a mechanism for sediment delivery to, and preferential sediment deposition at, the inner scarp edges would have to be identified. No morphologic features of the benches suggest lateral transport across the tops of the benches, nor do they suggest a means to deliver sediment to the ends of long, peninsular benches. This scenario also has difficulty explaining free-standing benches in the center of the lake. Although sediment can be deposited through an ice cover [*Squyres et al.*, 1991], it generally occurs through cracks and fissures, resulting in small mounds rather than large benches.

### 3.8. Deformation of Soft, Pre-existing Sedimentary Deposits Due to the Weight of Overlying Ice in a Perennially Frozen Lake

[19] This is our preferred explanation. The pre-existing sediments would presumably have originated by lacustrine, fluvial, or airfall deposition. A number of features can potentially be explained by this scenario. The cumulate planform is would be a natural consequence of viscous flow of sediments due to compression from above. This scenario was experimentally investigated by compressing "deposits" of mustard beneath a Plexiglass (R) cover. The blobs of mustard expanded and co-joined, resulting in generally cumulate planforms, enclosed depressions, and isolated benches. The cracks and small benches at the top of the scarps at the edge of the Gorgonum benches (Figure 2b) might have been formed by the tensional stresses that would occur at the top of a scarp being extruded. The isolated benches in the center of the basin might be deformed buttes of the pre-existing Gorgonum chaos. New sediment does not necessarily need to be added to the basin during formation of the benches. If the −50 m basin ring marks the upper surface of the ice-covered lake, this would imply an ice cover up to 250 m thick. The shallow fluvial incision on the Gorgonum basin floor above the −50 m level might indicate runoff as a source of water for the lake. The cracked and fissured mesas of the Gorgonum chaos near the edge of the bench deposit (Figure 2a) could have been caused by the weight of the overlying ice (or alternatively, by dissolution or melting of layers within the mesas).

## 4. Discussion

[20] Here we address conclusions and uncertainties related to the preferred hypothesis of origin of the benches as sediment deformed beneath a thick ice cover. The pristine nature of the benches indicates that if an ice cover were present, it had to sublimate away and had to be nearly pure $H_2O$. In addition, the ice cover would have had to be monolithic due to the smooth surface of the benches.

[21] Large platforms of sediment deformed beneath static ice have apparently not been described in the terrestrial literature. Overconsolidation and deformation of sediments beneath the edges of terrestrial glaciers is common [e.g., *Benn and Evans*, 1998; *Van der Wateren*, 2002], but the morphology of such tills and associated landforms is dominated by horizontal glacial flow. If compression by ice formed the Gorgonum benches, the ice was essentially unmoving, presumably locked by the edges of the basin and the chaos buttes extending into or through the ice. Although they are described primarily as local deposits occurring at the edges of glaciers, "squeeze" moraines are postulated to result from flow of sediments due to the pressure of overlying ice [*Benn and Evans*, 1998; *Kirkbride*, 2002].

[22] A variety of issues remain to be resolved with regard to the favored hypothesis, including the hydrological budget of the ice-covered lake, the nature of the ice thickness changes that caused vertical forces on unfrozen sediment below the ice cover, the requisite sediment, ice, and unfrozen water (brine?) properties, and why the ice base stabilized at ∼−300 m.

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A. D. Howard, Department of Environmental Sciences, University of Virginia, P.O. Box 400123, Charlottesville, VA 22904-4123, USA. (ah6p@virginia.edu)
J. M. Moore, NASA Ames Research Center, MS 245-3, Moffett Field, CA 94035-1000, USA. (jeff.moore@nasa.gov)