PLANETARY SCIENCE

Are there active glaciers on Mars?

Arising from: J. W. Head *et al. Nature* **434,** 346–351 (2005)

Head *et al.*[1] interpret spectacular images from the Mars Express high-resolution stereo camera as evidence of geologically recent rock glaciers in Tharsis and of a piedmont ('hourglass') glacier at the base of a 3-km-high massif east of Hellas. They attribute growth of the low-latitude glaciers to snowfall during periods of increased spin-axis obliquity. The age of the hourglass glacier, considered to be inactive and slowly shrinking beneath a debris cover in the absence of modern snowfall, is estimated to be more than 40 Myr. Although we agree that the maximum glacier extent was climatically controlled, we find evidence in the images to support local augmentation of accumulation from snowfall through a mechanism that does not require climate change on Mars.

Head *et al.*[1] identify an accumulation area for the hourglass glacier in an 'alcove' above its upper crater (Fig. 1a). However, the arcuately banded ice that originated from the canyon draining most of the alcove is topographically lower than, and appears to be pinched out by, flow from either side (http://esamultimedia.esa.int/images/marsexpress/180-170305-0451-6-an-01-Hourglass.jpe). Hence, the greatest ice flux must have come from small areas at the foot of the adjacent slopes and not from the larger area drained by the canyon, as would be expected for a snowfall-fed glacier. This suggests that the most recent source of ice was not associated with snowfall in the accumulation area, even though earlier it may have been.

What is the source of the most recent ice? Insight may come from another apparently ice-filled double crater (Fig. 1b) that lies on the flat plain only 35 km away and at the same elevation as the distal crater, according to Mars Orbiter Laser Altimeter data (http://ltpwww.gsfc.nasa.gov/tharsis/mola.html). Despite the absence of potential accumulation areas, similarly banded and presumably debris-covered icy flows still fill the craters and point to a source within each crater. The observation that these glaciers lack distinct accumulation areas, together with the absence of glaciers in many comparable locations elsewhere on the surrounding plain, argues against a solely climatic origin.

These observations are consistent with the glaciers having been formed by groundwater erupting from exposed aquifers, or from fractures in an icy regolith, and then freezing near the surface (*aufeis*). This idea was proposed by Garlick[2] for a palaeoglacier that originated from a fissure on Arsia Mons.

Where could such large amounts of groundwater come from? Possibilities on Mars include melting permafrost and dewatering of hydrous compounds[3–7] by heating due to increased geothermal gradients, magma intrusions or impacts. The long-term stability of shallow groundwater and ice at the latitude of the hourglass craters is debatable. But geologically recent gullies heading part way up slopes have been interpreted as evidence for shallow deposits (at depths of less than 0.5 km) of groundwater or ice at similar latitudes, including locations nearby[8]. Moreover, *aufeis* feeding of glaciers is not directly related to climate fluctuations, raising the possibility that some of the glaciers identified by Head *et al.*[1] remain active.

We find support for the *aufeis* hypothesis in a Mars Orbital Camera high-resolution image of the hourglass glacier (Fig. 1c), which shows a band of light-coloured, crevassed ice that is within about 250 m of the uphill edge of the glacier. It seems to be flowing from the slope at the southern edge of the crater to the west of the canyon. Downslope, the crevassed ice becomes progressively covered by dark debris. The Mars Orbital Camera image cited by Head *et al.*[1] shows only the distal, lightly cratered, inactive part of the glacier. Because ice on Mars sublimes rapidly until it is covered, the exposed and crevassed ice in the proximal glacier must be active. The presence of relatively bare, subliming ice and the absence of an accumulation area raise the possibility that water, or ice, is erupting on the martian surface today.

We conclude that martian glaciers could be fed from above or below. This could be by snowfall during climatically favourable times, as argued by Head *et al.*[1], or by extrusion of groundwater, as we argue here. These two mechanisms are not mutually exclusive and their relative contributions may differ spatially and vary temporally: during climates that support snowfall, both may operate; at other times, diminished glaciers may still be supported by *aufeis*. We consider the relative contribution of snowfall and extrusion mechanisms to the growth and extent of glaciers as an outstanding question in martian glaciology.

Alan R. Gillespie, David R. Montgomery, Amit Mushkin
Quaternary Research Center and Department of Earth and Space Sciences, University of Washington, Seattle, Washington 98195-1310, USA
e-mail: alan@rad.ess.washington.edu

1. Head, J. W. *et al. Nature* **434,** 346–351 (2005).
2. Garlick, G. D. *Geol. Soc. Am. Cordilleran Section* abstr. 20, 162 (1988).
3. Sharp, R. P. *J. Geophys. Res.* **78,** 4073–4083 (1973).

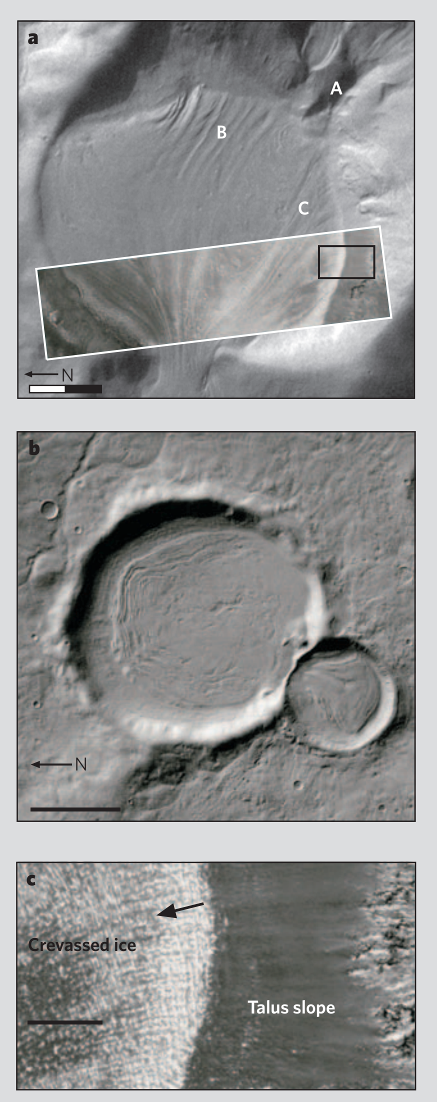

Figure 1 | Images interpreted to show *aufeis* on Mars (257.3 °W, − 39.5 °S). a, High-resolution stereo camera (HRSC) image (about 20 m per pixel) of the upper basin of the 'hourglass' glacier and the mouth of the canyon (location A) draining the largest part of the proposed accumulation area (not shown); inferred *aufeis* source areas are near locations marked B and C. Images are taken from Mars Express orbit 451. The overlay (white outline) is part of higher-resolution (4.2 m) Mars Orbital Camera (MOC) image, M1102128. Black box, area enlarged in **c. b,** A second 'hourglass' glacier from the same HRSC image, about 35 km north of the area shown in **a. c,** Enlargement of the area in a black box in the MOC overlay in **a.** The reticulate pattern is interpreted as a crevasse field below the talus slope. Arrow showing flow direction spans the light-coloured, relatively bare ice that becomes increasingly covered farther north. Scale bars: **a,** 2 km; **b,** 5 km; **c,** 300 m.

4. Luchitta, B. K. *Icarus* **45,** 264–303 (1981).
5. Komatsu, G. *et al. Lunar Planet. Sci. XXXI* abstr. 1434 (CD-ROM) (Lunar and Planetary House, Houston, 2000).
6. Kargel, J. *Mars — A Warmer, Wetter Planet* (Springer–Praxis, Chichester, UK, 2004).
7. Montgomery, D. R. & Gillespie, A. *Geology* **33,** 625–628 (2005).
8. Malin, M. C. & Edgett, K. S. *J. Geophys. Res.* **106,** 23429–23570 (2001).

doi:10.1038/nature04357

PLANETARY SCIENCE

Head et al. *reply*

Replying to: A. R. Gillespie, D. R. Montgomery & A. Mushkin *Nature* 438, doi:10.1038/nature04357 (2005)

Gillespie *et al.*[1] concur with our interpretation that certain lobate equatorial and mid-latitude features on Mars are due to debris-covered glaciers formed largely during past periods of increased spin-axis obliquity, when climate regimes favoured snow and ice accumulation and glacial flow[2]. They suggest that the 'hourglass' deposit, dated at more than 40 Myr old[2], could be active today owing to an additional mechanism that supports "local augmentation of accumulation from snowfall" without climate change on Mars. This mechanism requires the present, or very recent, release of groundwater to the surface to form *aufeis* (groundwater-fed 'glaciers') where the groundwater is generated by dewatering of hydrous compounds or melting by magmatic or impact-generated heat. We assess whether this suggestion applies to the deposits in question — it was previously proposed for much older deposits in other areas of Mars[3,4]. We make particular reference to the key relationships in the accumulation zones.

Glacial accumulation zones are areas characterized by a yearly net addition of ice, and are separate from ablation zones, which undergo a yearly net loss of ice. In active valley glaciers and in the source regions for broader piedmont glaciers, the accumulation zones are commonly centred on steep-sided alcoves that provide broad traps for wind-blown snow and lie in shadow, producing colder temperatures. The accumulation zone for the hourglass deposit on Mars was thought to be the entire alcove region east and southeast of the hourglass deposit[2] (Fig. 2a, b, d of ref. 2). Snow and ice accumulating in this entire alcove region probably formed distinct glaciers that moved downslope and converged to form multiple lobes, the remnants of which are seen in the upper part of the hourglass.

Changes in ice velocity, as might occur with changes in ice thickness related to deepening of bedrock topography, compressed and folded the ice, eventually merging all lobes together, then to flow through the neck of the hourglass. When climatic conditions changed, the distribution of snowfall and snow accumulation probably also changed, resulting in the cessation of ice accumulation and flow; the ice and snow deposits disappeared, and dry mass-wasting dominated, producing the talus piles superposed on top of the glacial deposits at the base of the slope (Fig. 2a–d of ref. 2, and Fig. 1a, c of ref. 1).

We therefore interpret the configuration and morphology of the lobes, as well as the abrupt contact between the base of the slope and the glacial deposits, to be a natural consequence of both the shape of the initial accumulation zone and its postglacial evolution. The candidate *aufeis* in the high-resolution image (Fig. 1c of ref. 1) appears morphologically similar to the floor deposits across the entire frame; we interpret its relative brightness to be due to a dust cover that was formed on the margin of the encroaching talus slope.

Nearby craters with similar scales, hourglass-like shapes, and lobate flow-like deposits (Fig. 1b of ref. 1) can also form from local crater-wall accumulation zones. In these cases, the crater interior walls are optimum locations for snow and ice accumulation, resulting in glacier-like, lobate flow down the walls and out onto the crater floor, a phenomenon that has been well documented in mid-latitude crater interiors[5,6]. Alcoves along crater walls create an environment favourable to the collection of snow and ice, and may provide steep cliffs that act as sources for debris that, together with ice sublimation, create debris-covered glaciers, much like those that occur in the Mars-like Antarctic Dry Valleys (Fig. 3a, b of ref. 2).

On the basis of these considerations, groundwater-fed 'glaciers' do not seem to be required in these locations. We agree that this mechanism should be investigated, particularly for deposits formed earlier in the history of Mars, when thermal gradients were such that groundwater may have been much closer to the surface.

J. W. Head*, G. Neukum, R. Jaumann, H. Hiesinger, E. Hauber, M. Carr, P. Masson, B. Foing, H. Hoffmann, M. Kreslavsky, S. Werner, S. Milkovich, S. van Gasselt, The HRSC Co-Investigator Team
*Department of Geological Sciences, Brown University, Providence, Rhode Island 02912, USA
e-mail: james_head_III@brown.edu

1. Gillespie, A. R., Montgomery, D. R. & Mushkin, A. *Nature* **438,** doi:10.1038/nature04357 (2005).
2. Head, J. W. *et al. Nature* **434,** 346–351 (2005).
3. Carr, M. *J. Geophys. Res.* **100,** 7479–7507 (1995).
4. Lucchitta, B. K. *J. Geophys. Res.* **89,** suppl.B 409–418 (1984).
5. Howard, A. *Lunar Planet. Sci. XXXIV* abstr. 1065 (2003).
6. Marchant, D. R. & Head, J. W. *6th Int. Mars Conf.* abstr. 3991 (2003).

doi:10.1038/nature04358