

16. Fluvial, Glacial and Volcanic Interaction

In this chapter, we briefly discuss landforms that are related to fluvial, glacial and possible periglacial processes. The latter are found at the dichotomy boundary, as lobate debris aprons as well as concentric crater and lineated valley fill. These landforms are considered to be composed of substantial amounts of ice and debris (e.g. Squyres, 1979), although this remains unproven. They occur at the highland–lowland boundary of Mars as well as in the vicinity of the large impact basins of the southern hemisphere. Flow– and creep–related landforms, which were observed in the eastern Hellas Planitia area, have already been stratigraphically integrated into a broader context (e.g. Head *et al.*, 2005; van Gasselt *et al.*, 2005).

All age determinations indicate that these landforms in addition to the polar caps (Fishbaugh and Head, 2001) were formed in the latest period of the Late Amazonian epoch (roughly tens to hundreds of million of years ago). These landforms were formed by possible ice–related processes in very recent geological times. Old morphologies, suggesting the involvement of ice in their formation, are not found. Nevertheless, polar–cap surrounding deposits, e.g. at the South Pole, can be substantially older (Head and Pratt, 2001), while the ice just remains as a global cryosphere at a certain depth (Kuz'min, 1983). Speculations of relict polar caps in the Medusae Fossae and Terra Arabia region were initially discussed by Schultz and Lutz (1988), who interpreted the layered and easily deflated (yardangs) deposits in the Medusae Fossae region. Antipodal (Terra Arabia) layering further supported this idea. Neutron spectrometry results have strengthened this interpretation (see Chapters 14.4 and 14.2).

As mentioned earlier, other remnants of glacial or periglacial processes are found, for example, at the western foot of Olympus Mons as

well as on the three large volcanoes that make up the Tharsis Montes. Phreatomagmatic processes at the flanks of Elysium Mons and Hadriaca Patera are examples of volcanic–ice interaction, but appear to have occurred much earlier in Martian history. At the eastern flank of Olympus Mons (as well as at many flanks of other Martian volcanoes), fluvial landforms that suggest melting of permafrost or ice–rich surface layers are observed. Landforms related to Athabasca, Mangala and Kasei Valles indicate a close interaction of volcanic and fluvial processes (see earlier Chapters 12, 14.5, and 15). Ages found for related morphologies cover the entire geologic history of Mars (at the latest starting around 3.6 Ga ago, e.g. in Kasei and Mangala Valles, but also appearing as recently as the last 100 Ma, e.g. in Athabasca Valles).

A complex interplay of various processes, such as volcanism, precipitation and accumulation of ice as well as sedimentation and accumulation of atmospheric dust, resulted in the formation of geologic bodies of significant volumes (Neukum *et al.*, 2004; Basilevsky *et al.*, 2005). This interplay occurs in a specific environment of Mars, where voluminous volcanic eruptions alternate with long periods of volcanic dormancy (Neukum *et al.*, 2004; Hartmann and Neukum, 2001; Wilson *et al.*, 2001). This interplay occurred against the background of variations in the obliquity of the rotation axis (Laskar *et al.*, 2004), which would significantly change latitudinal relations of the planet's climate with time and even atmospheric pressure (Kreslavsky and Head, 2005).

The existence of water–ice at the polar caps (Bibring *et al.*, 2004) has been proven spectrally, while it has been proposed for the cryosphere (Kuz'min, 1983; Carr, 1996) and locally on the surface (Lucchitta, 1981) from indirect evidence. Neutron anomalies, (Feldman *et al.*, 2002; Mitrofanov *et al.*, 2002), partly con-

centrated at the Medusae Fossae Formation and in Arabia Terra, have been discussed, in addition to other explanations such as relics of ancient polar deposits at times of different Martian spin-axis obliquity. Considering strong variations of the axis tilt, the deposition of ice in mid-latitudes or even in equatorial regions is possible (Mellon and Jakosky, 1995).

At the western flanks of Olympus Mons and Tharsis Montes, Viking imagery revealed surficial deposits (mapped by Scott and Tanaka (1986)) that were described as fan-like corrugated sheets (as wide as 600 km) and appear to override topographic obstacles without deflecting the internal structure). Besides a possible volcanic origin, Lucchitta (1981) suggested that they were recessional moraines of former ice-ages. Based on high-resolution imagery of Mars Global Surveyor (Head *et al.*, 2003) and HRSC imagery (Neukum *et al.*, 2004; Head *et al.*, 2005), a glacial origin is supported.

We have studied hydrothermal, fluvial, and glacial activity periods, which were visible in HRSC and MOC imagery. Evidence of very recent and episodic formation of landforms related to these processes is based on our crater counts. Here, we summarize the distribution and time frame of glacial or ice-related morphologic features found in HRSC imagery. Additionally, high-resolution MOC images were used to constrain the crater size-frequency measurements performed on HRSC images. A detailed description of the geologic evidence and ages can be found in Neukum *et al.* (2004); Head *et al.* (2005); Murray *et al.* (2005); Hauber *et al.* (2005), which are attached in Appendix C. In these papers, the arguments for interpreting most of the aforementioned units as glacial, fluvial, or hydrothermal in origin are discussed and not repeated here. Detailed morphological studies and crater counts at the base of Olympus Mons (Neukum *et al.*, 2004) and Hecates Tholus (Hauber *et al.*, 2005), south of Elysium (Murray *et al.*, 2005) and at the southeastern rim of Hellas (Head *et al.*, 2005) have been performed. Fig. 16.1 summarizes the crater frequencies measured at these landforms. Some

have been interpreted as landforms that suggest ice on the surface (or under a dust cover) may even be present today. All landforms formed during the last 500 Ma.

A brief summary of the major findings is given below:

Based on crater counts, the different lobate deposits at the Olympus Mons western foot formed in several phases, about 280 Ma ago, 130 Ma ago, acting between 60 and 20 Ma ago, and ending possibly 4 Ma ago. Roughly similar ages (about 450 Ma, 200 Ma, 100 Ma and between 80 and 20 Ma) are obtained volcanic deposition at the Olympus Mons flanks, indicating a possible correlation between these processes (see Chapter 15 and Neukum *et al.*, 2004, for a detailed interpretation).

At the eastern flank of Olympus Mons, glacial landforms have not been observed, but fluvial features are seen at its bases and surrounding plains units. Crater size-frequency distributions at the western and eastern plateau edges reflect similar periods of volcanic eruption. A correlation between these episodes at the lower flanks, upper summit plateau and the caldera is expected and suggested by our measured crater size-frequency distributions (see Chapter 15). Eastwards, eruption episodes which happened about 500 Ma, 200 Ma and 100 Ma ago are recognized. The surrounding plains and lava aprons indicate more recent episodes of volcanic activity (summarized in Chapter 15). The ages of possible fluvial landforms indicate that these processes might have been triggered by the volcanic activity.

Other than the very young glacial deposits found in equatorial regions (e.g. Olympus Mons western scarp (Neukum *et al.*, 2004; Basilevsky *et al.*, 2005; Head *et al.*, 2005) and the approximately 5 Ma old "pack-ice" sea south of Elysium Mons (Murray *et al.*, 2005, for details also see Chapter 12), glacial or ice-related landforms of very young age have been recognized north of Elysium Mons at the northwestern margin of Hecates Tholus (Hauber *et al.*, 2005). An amphitheater-like structure, whose morphology strongly suggests it was the result

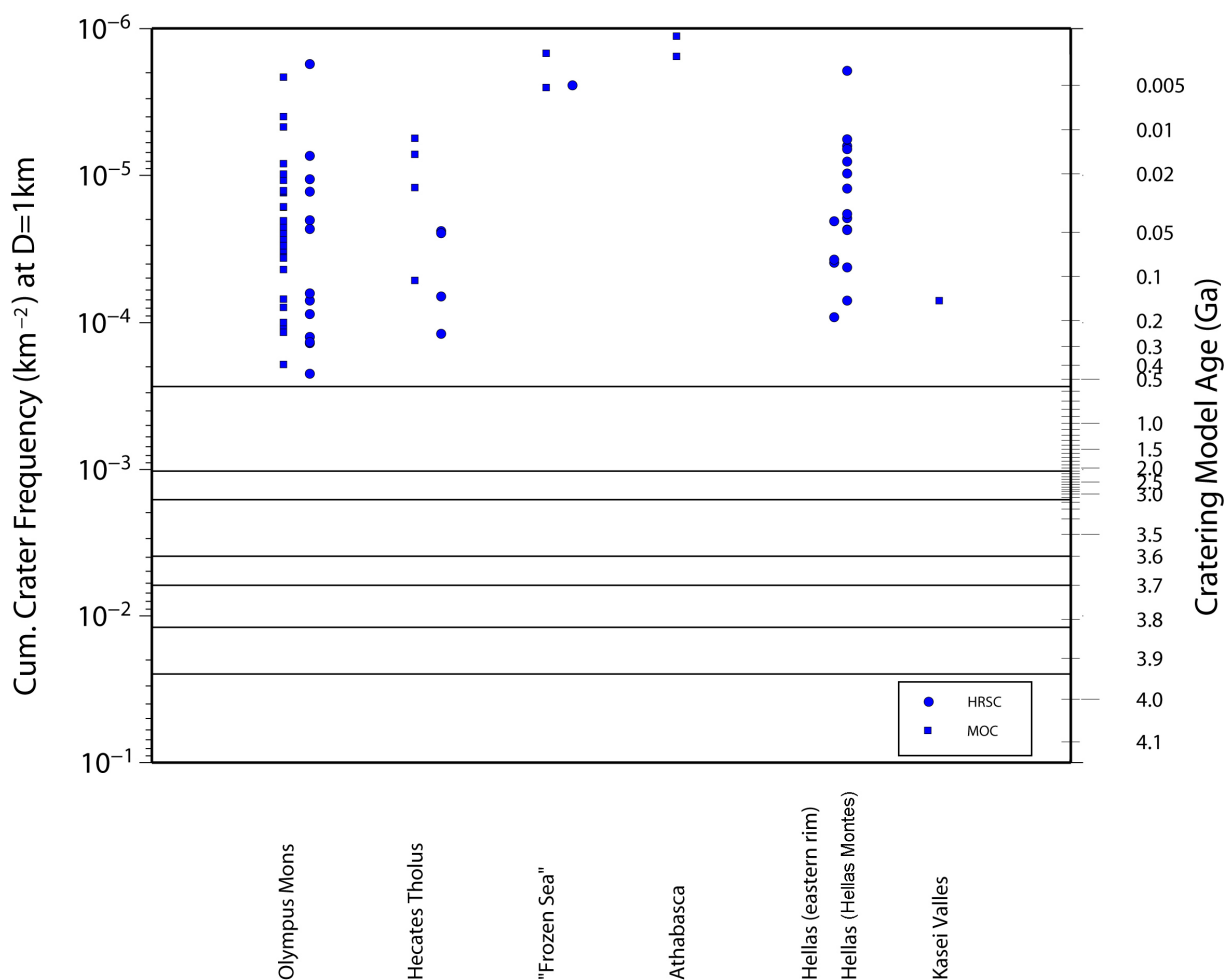


Figure 16.1.: Summary of crater frequencies N_{cum} (1 km) (left scale) and model ages derived by applying the cratering chronology model of Hartmann and Neukum (2001) (right scale) for recent fluvial and glacial activity in close vicinity of Olympus Mons, Hecates Tholus, in Elysium Planitia, and in the Hellas eastern rim region (Neukum *et al.*, 2004; Hauber *et al.*, 2005; Head *et al.*, 2005; Murray *et al.*, 2005; Werner *et al.*, 2003a; van Gasselt *et al.*, 2005). Horizontal lines show the epoch boundaries, see Chapter 5, Fig. 5.1.

of an explosive flank eruption about 350 Ma ago, is probably filled by glacial deposits of very recent ages (between 5 and 24 Ma, Hauber *et al.*, 2005).

The finding of low-latitude glacial landforms or relic-glacial landforms formed in very recent times (tens to hundreds of millions of years), contradicts the present climate situation (cf. e.g. Richardson and Wilson, 2002; Mischna *et al.*, 2003; Haberle *et al.*, 2003). Nevertheless, general climate circulation models (Mellon and Jakosky, 1995), allow for the redistribution

of water-ice that was restricted to polar regions to be deposited towards the equator if the Martian spin-axis obliquity changed. Past obliquity changes (Laskar *et al.*, 2004) permit recent "ice ages" in low latitudes, as recorded in the morphology, for example, debris aprons (dichotomy boundary), rock and piedmont glaciers (Olympus Mons, Hecates Tholus and Hellas rim), and suggested by the derived surface ages.

Van Gasselt *et al.* (2005) proved through morphological arguments that mass wasting processes, possibly driven by the presence of

ice, occurred episodically. This is supported by crater frequency measurements. Similar episodicity is found at Hecates Tholus and Olympus Mons. In the latter case, the release of water might have been triggered by volcanic activity, and which is indicated by correlating ages found for both processes. A triggering of water release as a result of volcanic activity is observed in the cases of Athabasca and Kasei Valles in most recent times. There, volcanic activity can be linked directly to possible (sub-)surface ice melting. In other places, such a relation is suggested by morphology and surface ages found, e.g. at Olympus Mons during the last 500 Ma.

The general occurrence of fluvial and (peri-) glacial landforms, formed over the latest 500 Ma of the Martian history, might be related to volcanic activity which might induce short-lived atmospheric changes, which support the subsequent deposition of ice and the formation of ice-containing landforms.

These activity phases might also be related to changes in obliquity and/or solar flux, but both relations remains speculative. The results of this thesis strongly support the idea that recent climate changes have occurred and can be explained by an obliquity change of the spin axis or the solar cycle, as seen on Earth. On Earth, ice ages are recorded morphologically in very recent geologic history. For Mars, such a short time scale cannot be resolved on the basis of crater counts. Thus, changes in obliquity or recent climate changes remain speculative.