CHAPTER 14

Summary of Results

Papers and manuscripts presented in part III of this thesis are self-contained and present conclusions not only with respect to the topic of the individual paper, but also with respect to a larger context to earlier work and conclusions by other authors on comparable topics. For reference, the reader is referred to individual conclusion sections, i.e., sections on [a] *Seasonal Variations of Polygonal Thermal Contraction Crack Patterns in a South Polar Trough* (section III.8.7, p. 127), [b] *Cold–Climate Modification of Martian Landscapes: A Case Study of a Spatulate Debris Landform in the Hellas Montes Region* (section III.9.5, p. 151), [c] *Current State and Disintegration of Rock-Glacier Landforms in Tempe Terra/Mareotis Fossae* (section III.10.5, p. 167), [d] *Lineated Valley Fill at the Martian Dichotomy Boundary: Nature and Degradation* (section III.11.6, p. 182), [e] *Geomorphic Evidence for former Lobate Debris Aprons at Low Latitudes on Mars* (section III.12.5, p. 193), and [f] *Deposition and Degradation of a Volatile–Rich Layer in Utopia Planitia, and Implications for Climate History on Mars* (section III.13.6, p. 211).

The work presented in this thesis covers geologic as well as geomorphologic aspects of the periglacial environment of Mars. Results are related to knowledge that was gained for comparable terrestrial systems. Conclusions that have been drawn from pieces of work presented herein are associated to common climatic aspects of the youngest epoch of Martian history. Most of the issues that have been raised in the early days of Mariner and Viking already could be supported or have been confirmed by new observations using most recent data from all space-borne imaging instruments in orbit above Mars in combination with topographic data. Some of the results shown herein point towards new aspects on the formation and evolution of geologically recent landforms on Mars (figure 14.1).

It has been confirmed that Mars's climatic environment today is comparable to the terrestrial hyperarid periglacial domain and it has been shown that processes leading to the evolution and formation of characteristic landscapes we now observe on Mars could not have been initiated without incorporation of considerable amounts of volatiles. At locations where such volatiles are abundant, such as the south polar area, processes connected to cold-climatic environments similar to those on Earth do occur even today and produce comparable landforms as shown in the context of seasonal changes of thermal contraction cracking processes (chapter 8). It has also been shown in the same context, that ice–wedge formation, as often proposed by other workers, is not required for producing morphologic features similar to those observed on the Earth. For locations, such as at the south polar cap, where seasonal cycles of deposition and sublimation are predominant, the process of ice-wedge formation can be ruled out but it remains an open issue for Martian mid-latitudes. Recent seasonal changes are observed also at Martian mid–latitude, however, the nature of these particular geomorphic features remains unclear and could be attributed to atmospheric processes also (chapter 11).

For Martian ice-related creep morphologies, such as

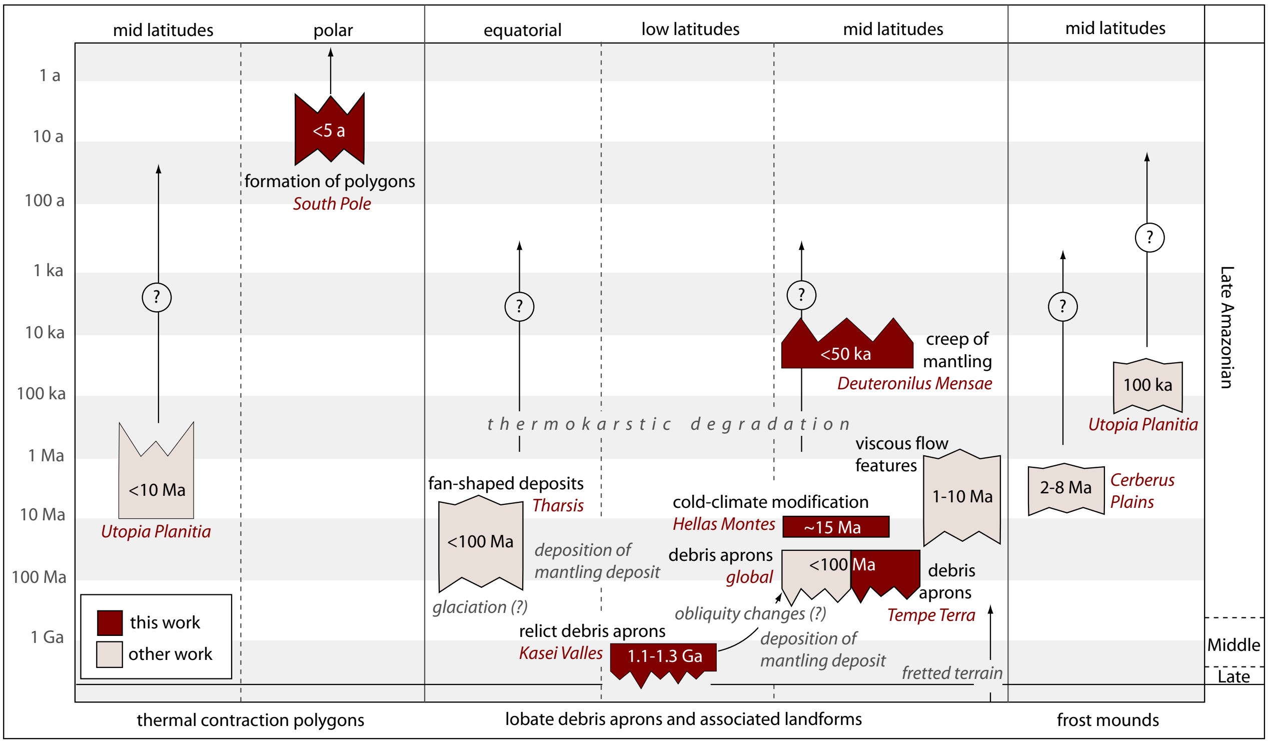

Figure 14.1.: Chronology of processes related to creep of ice and debris, and formation of contraction polygons in mid- and polar latitudes and pingo landforms. Ages for possible frost-mound landforms are from *Burr et al.* (2005) and *Soare et al.* (2005), for details see section 5.2 on Martian candidate landforms.
Ages for mid-latitude contraction polygons are based upon *Mangold* (2005), for details see section 4.2.3.1. Ages for south-polar polygons are based upon direct observations discussed in detail in chapter 8.
Ages for creep-related landforms are based upon estimates and measurements by *Shean et al.* (2004, 2005a) for Tharsis-related fan-shaped deposits. Mid-latitude debris aprons and associated landforms with an age of 50-100 Ma are discussed in, e.g., *Mangold* (2000); *Berman et al.* (2003); *Head et al.* (2005); *Li et al.* (2005). Measurements in Tempe Terra discussed in chapter 10 are in agreement with earlier estimates. For ages of viscous flow features see *Milliken et al.* (2003). Ages for relict debris aprons at Kasei Valles are based upon measurements discussed in chapter 12. The Deuteronilus Mensae lineated valley fill is covered in chapter 11, the cold-climate modification of debris aprons in Hellas Montes are discussed in chapter 9.

lobate debris aprons, lineated valley fill, and concentric crater fill, which are considered analogs for terrestrial rock glacier systems, a variety of new observations have been presented in this work that shed new light on their emplacement history, development, and degradation, while other observations confirm results of earlier work. One basic question is related to the style of emplacement of debris aprons (*Squyres*, 1978). Arguments have been put forward that promote either rock-fall mechanisms (*Squyres*, 1978; *Colaprete and Jakosky*, 1998) or landsliding (*Lucchitta*, 1984; *Mangold and Allemand*, 2001). Based on this work it is suggested that both processes, landsliding and rock fall, have significantly shaped remnant massifs and contributed to debris-apron formation at least in the northern hemispheric Tempe Terra area. There is observational evidence for large landslide scars as well as steep cliffs suggestive of rock fall. Subsequent deposition of a geologically recent mantling deposit has masked out many geomorphic signatures but there is evidence that this mantling deposit also contributes to apron formation in recent times by sliding and slide flow (chapters 10, 12). Global mapping of debris-apron distribution and derivation of geomorphometric key values have shown that debris aprons on Mars are comparable to each other with respect to morphometric ratios and that they compare closely to terrestrial key ratios.

Landslide origin is proposed for a large tongue-shaped debris landform situated at the eastern rim of Hellas Planitia. There is observational as well geomorphometrical evidence that this landform is connected to a sector collapse of an old volcanic construct. The reactivation of this landform under geological recent conditions (around 15 Ma ago) led to formation of a landform similar to a rock glacier (figure 14.1). Such observations of transitional morphologies have been reported from the Earth and it confirms that such processes are similar on Mars also. In connection to this work, a large depression at the eastern rim of Hellas has been identified that was considered to be an impact crater in earlier work but is more probably a degraded volcanic construct. This discovery also sheds new light on the formation of the large eastern-Hellas outflow channels (chapter 9) and requires detailed investigation in the future.

Other open questions are related to the nature and emplacement of lineated-valley fill (*Squyres*, 1978). It has been shown in this work on the basis of image data as well as topographic data that flow is not only perpendicular *or* parallel to valley rims, but that it extends in both directions (chapters 11, 10). Rockfall debris accumulates at the footslope and moves towards the center of the valley, i.e., movement of debris perpendicular to valley walls. It merges with other flows finally moving in rim–parallel direction. This particular observation is based on analysis work conducted in a circular depression and does not necessarily explain all lineated valley fill features. It is also shown in the same context that this lineated fill compares closely to concentric crater fill found at other locations on Mars. It therfore indicates that lineated valley fill, concentric crater fill and lobate debris are not only only related to comparable processes as proposed by *Squyres* (1979) but that they are essentially identical and their appearance is only influenced by surface topography and relief. Age determinations indicating ages below 100 ka have shown that the surface of this infill in the Martian fretted terrain might still be active in recent times (see chapter 11 and figure 14.1).

Although the main distribution of lobate debris aprons and associated landforms is connected to two latitudinal belts at Martian mid-latitudes, it has been shown on the basis of image data and geomorphometry that traces of debris aprons are found farther towards the south at least at two locations on Mars. The age of these traces could be determined as at least 1 Ga. These traces indicate the former presence of lobate debris aprons supporting the idea of changing environmental conditions that have caused their disappearance (chapter 12). These changes confirm modelling results related to variations of the planet's spin-axis (e.g., *Laskar et al.*, 2004). In the future, age estimates could help to stabilize modelling attempts that are limited due to to large uncertainties prior to 10-20 Ma ago (chapter 12, figure 14.1).

Degradation of such valley-fill landforms are similar to what is observed today at northern and southern hemispheric debris aprons. Indicators for thermokarstic degradation and disintegration have been reported from various places on Mars and have been confirmed by this work in the areas of eastern Hellas Planitia, Tempe Terra, and Deuteronilus Mensae (chapters 12, 11, 9). It has been shown that degradation is particularily related to a thin mantling deposit which has been identified at all locations studied in this work. There are additionally indicators that show that landscape degradation is not only associated to surface mantling but also to the subsurface and it is considered most probable that certain areas at the Martian fretted terrain are shaped by degradation of Martian permafrost through the release of considerable amounts of debris and ice. In conclusion, landscape formation at areas studied in the Martian fretted terrain are shaped by two main processes, an older permafrost degradation process and a younger process related to the disintegration of a young mantling deposit. Appearance, development and disintegration are probably controlled by obliquity variations of the planet's spin axis. With respect to the composition of the debris-ice mixtures, it is indicated that the amount of ice is probably higher when compared to terrestrial rock glaciers and debris is more fine-grained.

From the more technical point of view, data analyses conducted in this work present the first regional maps of occurrences of thermal contraction polygons at the Martian circum-south polar cap, including not only the residual ice cap and the layered deposits but also adjacent highland terrain that are both under the influence of seasonal carbon-dioxide ice depostion cycles. Image data analyses have been conducted that present observations under variable seasonal conditions and yield new results on a geologically active Mars (chapters 8, 4). Also, an updated view of the occurrences of thermal contraction patterns in the north–eastern quadrangle of Mars on the basis of most recent image data show a more detailed view of the exact distribution of thermal contraction polygons and indicate occurrences of such features at lower mid–latitudes (chapter 4).

Furthermore, occurrences of lobate debris aprons have been re–mapped on a global scale using recent image data and present, in combination with data obtained in earlier work (*Squyres*, 1979) a more detailed view of the distribution of these landforms (chapter 12). Apart from this, the global inventory of lobate debris aprons has been analyzed geomorphometrically in order to obtain new insights into the general characteristics of such features and information on latitudinal or other geographical dependences (chapter 10). For the landscapes investigated in this thesis, no indicators for "true"–glacial processes could be found. Apart from an atmospheric contribution of ice, i.e., a mantling deposit, no morphologic traces comparable to a glacial system have been identified, mainly because the absence of the required geomorphologic context, e.g., glacial sequence, traces of glaciofluvial activity, typical subglacial landforms, did not allow to draw these conclusions. However, the presence of such landforms can not be ruled out and there is an abundance of indicators that show that transitional landforms characteristic of both, the glacial as well as the periglacial environment, seem to exist. Currently, it is not possible to separate both landforms using established terrestrial definitions. Environmental conditions on Mars and processes, such as the deposition of ice–rich mantling, lead most probably to a set of landforms that is different from that of the Earth.

Some experiments need to be conducted regarding the behaviour of carbon dioxide ice under a thick overburden load that might lead to pressures beyond the triple point of carbon dioxide and the short–term stability of its liquid phase. Subsequent diffusion processes might probably modify the rheology of such debris–transport systems. As long as the influence of this main atmospheric constituent is not understood completely, the behaviour of ice–related creep under Martian environmental conditions will also remain uncertain and terrestrial data will not be transferable – or scalable – to the environment of Mars.

Some questions will be probably answered as soon as the High–Resolution Imaging Science Experiment aboard Mars Reconnaissance Orbiter covers more areas and images key regions at highest resolution of up to 30 cm/px. Also, the Shallow Subsurface Radar Experiment with a horizontal resolution between 0.3 km and 3 km and a vertical resolution of 15 m aboard MRO will help to identify possible large and even small-scale reservoirs of water and ice.

Detailed image data as well as multi-temporal data coverage and knowledge about the vertical distribution of ice in the subsurface in combination with high–resolution topography data will allow more–dimensional image interpretation and bring up new results regarding the development of the Martian cold–climatic environment. □