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Cold-climate landforms on Mars and Earth-analogues in Svalbard

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Abstract

Periglacial landforms on Earth reflect cold-climate conditions and are intimately related to processes due to the presence of ground ice and perennially frozen ground, permafrost. The overall objective of this thesis is to investigate the potential of Svalbard as an analogue to Mars cold-climate landforms, and explore past and present processes and surface conditions on Mars by inference from morphological counterparts in Svalbard. Svalbard has unique advantages that make it a very useful study area. Svalbard is easily accessible and offers a periglacial landscape where many different landforms can be encountered in close spatial proximity. These landforms include thermal contraction cracks, slope stripes, rock glaciers, gullies, debris flows, solifluction lobes, protalus ramparts, and pingos, all of which are close morphological analogues to landforms on Mars.

An approach of integrated landscape analysis, inferred from landform assemblages in Svalbard, is aimed to explore modeling landscape evolution on Mars. Key datasets include visual remote sensing data of similar resolution (20–25 cm/pxl) from Svalbard (High Resolution Stereo Camera–Airborne Extended [HRSC-AX]) and Mars (High Resolution Imaging Science Experiment [HiRISE]). Additional data are digital elevation models over both Svalbard and Mars and remote sensing data from Mars, such as Thermal Emission Imaging System (THEMIS) and Context Camera (CTX) images. Field work was done in combination with remote sensing to acquire ground-truth data.

In Svalbard, fluvial and debris-flow processes are evident in the formation of gullies, but the morphological characteristics clearly show that the transport and sedimentation of eroded material are predominated by debris flows. Most investigated gullies on Mars lack clear evidence for debris-flow processes. The Martian gully fan morphology is more consistent with the deposition of small overlapping fans by multiple fluvial flow events. Clear evidence for debris flows on Mars was only found in two new locations, in addition to a few previously published examples. Detailed studies on debris-flow deposits in a young mid-latitude crater on Mars suggest the action of liquid water after Mars' last ice age (0.4–2.1 Ma ago). It may represent the most recent morphological indication of water induced mass wasting on Mars.

An investigation of small-scale lobes on Mars northern high-latitudes and their morphological counterparts in Svalbard (solifluction lobes) further suggests widespread thawing and the presence of transient liquid water in the recent past on Mars. Finally, different qualitative scenarios of landscape evolution on Mars to better understand the action of periglacial processes on Mars in the recent past are proposed.

The results show that field work is a suitable approach in analogue studies and facilitates acquisition of first-hand experience with permafrost environments. Based on the morphological ambiguity of certain landforms, it is concluded that Martian cold-climate landforms should not be investigated in isolation, but as part of a landscape system in a geological and spatial context. Analogous landforms in Svalbard occur in strikingly similar proximity as on Mars, which makes them useful to infer the spatial and chronological evolution of Martian cold-climate surface processes. The analysis of the morphological inventory of analogous landforms and landform systems in Svalbard and on Mars give substantial information to constrain the processes operating on the surface of Mars

Keywords: Mars, Svalbard, Spitsbergen, periglacial, ice, permafrost, Earth-analogues, terrestrial analogues, geomorphology, landforms, solifluction, debris flow, gully, craters, cold-climate

Preface

This thesis is based on the following papers which are referred to in the text by Roman numerals. These papers are reprinted with permission from respective journal.

I. Hauber, E., Reiss, D., Ulrich, M., Preusker, F., Trauthan, F., Zanetti, M., Hiesinger, H., Jaumann, R., Johansson, L., **Johnsson, A**., Olvmo, M., Carlsson, A.E., Johansson, H.A.B., McDaniel, S., 2011. Periglacial landscapes on Svalbard: Terrestrial analogs for cold-climate landforms on Mars. In: Garry, W.B., and Bleacher, J.E. (Eds), Analogs for Planetary Exploration. Geological Society of America Special Paper, Vol. 483, 177–201.

II. Reiss, D., Hauber, E., Hiesinger, H., Jaumann, R., Trauthan, F., Preusker, F., Zanetti, M., Ulrich, M., **Johnsson, A**., Johansson, L., Olvmo, M., Carlsson, A.E., Johansson, H.A.B., McDaniel. S., 2011. Terrestrial gullies and debris-flow tracks on Svalbard as planetary analogs for Mars. In Garry, W.B., and Bleacher, J.E. (Eds), Analogs for Planetary Exploration. Geological Society of America Special Paper, Vol. 483, 165–175.

III. **Johnsson, A.,** Reiss, D., Hauber, E., Zanetti, M., Hiesinger, H., Johansson, L., Olvmo, M., 2012. Periglacial mass-wasting landforms on Mars suggestive of transient liquid water in the recent past: Insights from solifluction lobes on Svalbard. Icarus 218 (1), 489-505. DOI: 10.1016/j.icarus.2011.12.021.

IV. **Johnsson**, **A.,** Reiss, D., Zanetti, M., Hauber, E., Hiesinger, H. Debris flows in a very young mid-latitude crater, Mars: Insights from Earth-analogues in Svalbard (working paper).

V. Hauber, E., Reiss, D., Ulrich, M., Preusker, F., Trauthan, F., Zanetti, M., Hiesinger, H., Jaumann, R., Johansson, L., **Johnsson**, **A.,** van Gasselt, S., Olvmo, M., 2011. Landscape evolution in Martian mid-latitude regions: Insights from analogous periglacial landforms in Svalbard. Geological Society, London, Special Publications 356, 111-131. DOI: 10.1144/SP356.7.

The appended papers are arranged as follows: Paper (I) provide the background and introduce Spitsbergen (Svalbard) as a potential analogous environment for the mid-and-high latitude landscapes on Mars. We present several classical terrestrial periglacial landforms found on Spitsbergen and their use as geomorphological analogues for landforms on Mars. Paper (II) focus on gullies and the depositional mechanisms in gully fan formation on Mars. By comparison to gullies on Svalbard insight is gained on type of displacement mechanism and potential water source. In paper (III), we report on landforms which may indicate extensive freeze-thaw and the presence of transient water in the recent past on Mars. In paper (IV) we report observations on well-defined debris-flow deposits in a young crater on Mars. Paper (V) presents three conceptual models of landscape evolution at mid-latitudes on Mars by inference from landform relationships on Svalbard.

All papers have been produced in collaboration with researchers at the Institut für Planetologie at Westfälische-Wilhelms Universität in Münster, Institut für Planetenforschung, Deutschen Zentrums für Luft- und Raumfahrt (DLR) in Berlin, and Earth and Planetary Sciences, Washington University in St Louis and the McDonnell Center for Space Sciences, USA.

Contribution by the author

As a co-author, I contributed in project planning, field site selection, literature review and field work for paper (I), (II) and (V). I contributed with landform observations on Mars and descriptions of terrestrial analogues for use in paper (I) and (V). I contributed in manuscript preparation and discussions in paper (II). Ideas for paper (III) and (IV) were fully outlined by me. I did most of the literature review, writing, analyses and figure preparation. Reiss provided valuable help on processing images for use in GIS software for paper (III) and (IV). The crater size-frequency distribution measurements in paper (IV) were jointly done by Zanetti, Reiss and me.

Extended abstracts not included in this thesis

Johnsson, A., Johansson, L., Zanetti, M., Reiss, D., Hauber, E., Hiesinger, H., Ulrich, M.R., Olvmo, M., Carlsson, E., Jaumann, R., Trauthan, F., Preusker, F., Johansson, H.A.B., McDaniel, S., 2010. The origin of stripe-like patterns on Martian gully slopes: Using Svalbard Advent Valley as a Mars analogue. 41st Lunar and Planetary Science Conference, the Woodlands, TX (USA), #1665.

Johnsson, A., Olvmo, M., Reiss D., Hiesinger, H., 2009. Latitudinal survey of periglacial landforms and gullies in Eastern Argyre and poleward on Mars. 40th Lunar and Planetary Science Conference, the Woodlands, TX (USA), #2405.

Hauber, E., Preusker, F., Trauthan, F., Reiss, D., Carlsson, A.E., Hiesinger, H., Jaumann, R., Johansson, H.A.B., Johansson, L., **Johnsson**, **A.,** McDaniel, S., Olvmo, M., Zanetti, M., 2009. Morphometry of alluvial fans in a polar desert (Svalbard, Norway): Implications for interpreting Martian fans. 40th Lunar and Planetary Science Conference, the Woodlands, TX (USA), #1648.

Reiss, D., Hiesinger, H., Hauber, E., Zanetti, M., Preusker, F., Trauthan, F., Reimann, G.M., Raack, J., Carlsson, A.E., **Johnsson, A.,** Olvmo, M., Jaumann, R., Johansson, H.A.B., Johansson L., McDaniel, S., 2009. Morphologic and morphometric comparison of gullies on Svalbard and Mars. 40th Lunar and Planetary Science Conference, the Woodlands, TX (USA), #2362.

Carlsson, E., Johansson, H.A.B., **Johnsson***, **A.,** Heldmann, J.L., McKay, C.P., Olvmo, M., Johansson, L., Fredriksson, S., Schmidt, H.T., McDaniel, S., Reiss, D., Hiesinger, H., Hauber, E. Zanetti, M., 2008. Field studies of gullies and pingos on Svalbard – A Martian analog. EPSC Abstracts vol. 3, EPSC2008-A-00480, European Planetary Science Congress, © Author(s) 2008 (*oral presenter).

Johnsson, **A.,** Delbratt, E., Mustard, J.F., Milliken, R.E., Reiss, D., Hiesinger, H., Olvmo, M., 2008. Small-scale polygonal patterns along the southern water-ice margin on Mars. EPSC Abstracts vol. 3, EPSC2008-A-00379, 2008. European Planetary Science Congress, Münster, Germany, © Author(s) 2008.

Carlsson, E., Johansson, H., **Johnsson*, A.,** Heldmann, J.L., McKay, C.P., Olvmo, M., Fredriksson, S., Schmidt, H.T., 2008. An evaluation of models for Martian gully formation using remote sensing and in situ measurements of Svalbard analogues. 39th Lunar and Planetary Science XXXIX, League City, TX (USA), #1852 (*poster presenter).

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II. Terrestrial gullies and debris-flow tracks on Svalbard as planetary analogs for Mars.

III. Periglacial mass-wasting landforms on Mars suggestive of transient liquid water in the recent past: Insights from solifluction lobes on Svalbard.

IV. Debris flows in a young mid-latitude crater, Mars: Insights from Earth-analogues in Svalbard.

V. Landscape evolution in Martian mid-latitude regions: Insights from analogous periglacial landforms in Svalbard.

Part 1

Introduction to thesis

Vi upptäckte mer och mer
och jorden blev större och större.
Upptäckte ändå mer
och jorden blev bara en prick,
en leksaksballong
i oändligheten.

Nils Ferlin
Från mitt ekorrhjul, 1957.

1. Introduction to thesis

1.1. Structure of the thesis

The thesis is divided into four parts. This first part provides a background for the thesis regarding the history and theoretical framework of geomorphology. The aims and objectives are outlined. The section on analogue research is aimed to put the study in general disciplinary context.

The second part introduces Mars and the geological and climatic context of the research. This part is not meant to be exhaustive nor too comprehensive, but rather to briefly review different aspects of Mars geologic history with emphasis on landforms.

The third part provides a more in-depth discussion on the current knowledge on processes and landforms within the ground-ice associated environments on Mars. The case for Svalbard as a potential Earth-analogue environment is discussed. Moreover, the methods used and the major results and conclusions from the appended papers will be summarized.

The fourth part contains the five appended papers, which are referred to by roman numerals.

1.2. Historical overview of geomorphology and planetary analogue research

In geomorphology the research focus as well as the methods applied has changed over time. Great advances have been driven by the introduction of remote sensing and increased computational power. This is especially true for planetary geomorphology, where today's highly sophisticated robotic missions send large volumes of data on a daily basis. The following section will highlight these changes and provide a brief historical overview of terrestrial and planetary geomorphology. Furthermore, some theoretical and practical issues concerning planetary geomorphology will be presented and discussed.

1.2.1. Historical overview

Geomorphology (from Greek: *ge*–earth; *morphe*–form; and *logos*–study or discourse) is the scientific study of landforms to understand past, present and future developments. As such, it involves the description and explanation of landscape forms, processes and genesis on Earth. Modern achievements in planetary exploration has widened this scope and made it possible for geomorphologic inquiry of other planetary surfaces and moons as well (Baker, 2008).

The 18th and 19th century geomorphologic inquiry emerged at a time when both explorers and scientists of the western world were engaged in cataloguing and classifying natural history. Studies had a descriptive approach in which *place* was of primary concern. Consequently, geomorphic inquiry was inherently geographic (Preston et al, 2011). At the time, the dominating idea of landscape *forms* (effect) and landform *drivers* (cause) was by catastrophic events, known as *catastrophism*.

The roots of geomorphology in the English speaking world stem back to the work by James Hutton (1726–1797) in Scotland, who is one of the pioneers of Earth Science (Oldroyd and Grapes, 2008). As a reaction to the perception of catastrophism, the idea of landscape evolution emerged. Hutton gave much thought to extended Earth time and rock-and-soil erosion from the land to the sea, which subsequently became the principles of *uniformitarianism*, specifically, the present is key to the past (Hutton, 1788; 1795). On continental Europe, the German geologist Abraham Gottlob Werner (1749–1817) was one of the first to champion the idea of a geologic time scale by dividing Earth into several rock types, where each rock type formed during a specific period. Even though contemporary earth scientists were beginning to grasp the immensity of geological time, the idea by Hutton that Earth itself had evolved throughout time was a radical departure from accepted knowledge (Preston et al, 2011). Hutton's ideas, though not well received, were saved from obstruction by his friend and biographer John Playfair (1748–1810) who also contributed original ideas of the behavior of river systems (Playfair, 1802). However, as noted by Frodeman (1995), the lack of acknowledgement to geologic time within the philosophy of science can be traced even today,

> *The discovery of "deep" or geologic time equals in importance the much more widely acknowledged Copernican Revolution in our conception of space [...] philosophers have ignored the decisive role played by Hutton and Werner in reshaping our senses of time.*

The lawyer and geologist Charles Lyell (1795–1875) was together with Playfair the major advocates of Hutton's uniformitarianism. Lyell's contributions involved the incorporation of geomorphological and tectonic considerations in order to develop a geologic history of a region (Oldroyd and Grapes, 2008). Lyell's multi-volume *Principles of Geology* (1830–1833) was well-known and the most influential geological work in the middle of the 19th century, and did much to put geology on a modern footing. Developments of geomorphology as an academic discipline at the time were also influenced by Darwin's *Origin of Species*, which proposed that life had evolved through a series of primitive forms, rather than having been created in its present state (Preston et al., 2011). Its application in geomorphology was clear; just as organisms were the results from biological evolution, landforms would have evolved through a series of intermediate steps.

Following the notion of slowly evolving landscapes, the American geomorphologist William Morris Davis (1850–1934) proposed a conceptual model for regional denudation of landscapes: the *cycle of erosion* (Baulig, 1950). Davis' basic concept includes a rapid tectonic uplift, followed by a cessation of the land, which allows the rivers and streams to reduce the surface to a level close to sea-level, the so called *peneplain.* The peneplain was defined as the “mature” end stage of landscape evolution. Davis' theory was inherently qualitative and descriptive in nature and as such difficult to test (Oldroyed and Grapes, 2008). Moreover, the cycle of erosion was predicated upon temperate and humid conditions, whereas extremes of arid and cold conditions constituted interruptions to the "normal" (Weaver, 1965). Davis was the most influential geomorphologist of his time and gained followers such as Lester C. King and Charles A. Cotton, who both were strong proponents to the cycle of erosion, but recognized arid and cold conditions as equally normal and not simply interruptions to Davis' idealized sequence (Weaver, 1965). Davis had nonetheless his contemporary critics. In Germany, Walter Penck (1888–1923) opposed the Davisian cycle of erosion by arguing that denudation and uplift occur simultaneously (Hugget, 2007). Sharp criticism also came from Arthur Strahler (1918–2002) who pointed out the complete lack of process understanding in Davis model (Wooldrige, 1958).

Another influential geomorphologist around the turn of the 19th century was Grove Karl Gilbert (1843–1918), who, by extent, made important contributions to the way extra-terrestrial landscapes is approached (Baker, 2008). Gilbert was, in contrast to Davis and many other geomorphologists at the time, not interested in the historical aspects of landscapes (Baker and Pyne, 1978; Orme, 2002). Instead he was devoted to research based more on physical models and *timeless* properties, contrary to the *time-bound* models which characterized Davis and many of his contemporaries (Bucher, 1941). Timeless properties refer to "laws" of general patterns and behaviors that apply everywhere, whereas time-bound models refer to a specific object and its change with the passage of time (Shumm, 1991). Gilbert (1877) introduced the term *dynamic equilibrium* to refer to any change in a geomorphic system that causes the process or processes to operate in a way that tends to minimize the effect of change; a negative feedback. According to this idea the system adjusts over time so that process rates change in order to minimize changes within the system. Amongst the many contributions to geomorphology made by Gilbert, his study of the lunar craters is worth noting. Two competing hypotheses of either volcanism or an impact origin existed at the time to explain the cratered surface of the Moon. Gilbert (1893) performed classic experiments where he propelled balls of clay and metal into various target materials. By using terrestrial analogues, together with experimental data and telescopic observations of the lunar surface he was able to develop compelling evidence for an impact origin (for an in-depth account of Gilbert see Baker and Pyne, 1978). Gilbert's legacy of analogue research relate well to today's extra-terrestrial geomorphologic enquiry where features cannot be inspected "in the field" (Schumm, 1991).

In the mid 1950's geomorphology shifted from being mostly a historical and descriptive science dealing primarily with the evolution of whole landscapes, to more become process oriented (e.g., Oldroyed and Grape, 2008; Baker, 2008). The change was partly driven by technological advances such as aerial photography, computers and dating techniques (Summerfield, 2005) and partly in reaction to the perceived failure of this earlier thinking (Baker, 2008). At this time, some influential papers served as programmatic statements (Strahler, 1952) and early models for practice (e.g., Bagnold, 1941; Horton, 1945; Strahler, 1950). This shift towards process studies led to a mechanistic and reductionist view on form and process. Tools of trade were inherited from the basic sciences of physics and chemistry and with substantial influence from the engineering literature (Church, 2010). Processes-oriented research in turn had the consequence that temporal and spatial scales of inquiry were diminished. Although, great advances were made between the 60's and 90's in our understanding of small-scale processes and its local effects, disagreement to whether process studies alone could explain large scale evolution of landscapes emerged (Baker, 2008). Process studies are by nature deterministic in that they aim to search for an isolated process (cause) for a resulting landform (effect). Even though valid in the local and short term it is difficult to extrapolate to larger spatial and temporal scales (Shumm, 1991). At the onset of geomorphology, historical geomorphology likewise suffered from the lack of tools to comprehend the myriad of factors influencing the landscape as a whole. With today's technical advances and improved modeling, however, this early approach may be more productive (Summerfield, 2005). Nevertheless, as Berthling (2001, p.5) notes,

> *Process studies has been essential to develop more detailed understanding of the governing parameters and effects of different processes acting upon the landscape through time, thereby improving the possibility of building conceptual models of landscape development with a higher power of explanation.*

In the 1950's system thinking was introduced in geomorphology (Strahler, 1952; Chorley, 1962). As first outlined by L. von Bertalanffy (I950), all things have connections with many other things and the significance of any one depends on its relationships with others (Chishom. 1967). More recently formulated by Church (2010),

> *'System sciences' are ones that seek explanation by integrating the effects of many elements and processes.*

As such, system thinking has the potential to overcome the practical limitations of a reductionist science by viewing the landscape as an idealized series of elements linked by flows of mass and energy (Baker, 2008; Church, 2010). With the increase of computational power that can comprehend the complexities of geomorphological systems, this approach has been producing good results. Modeling of self-organizing patterned ground may serve as an illustrative example (Kessler and Werner, 2003).

Even though planetary geomorphology can be said to date back to Galileo´s first attempt to use a telescope to study the celestial bodies or G.C., Gilbert´s experiments on impact craters, the true birth of modern planetary geomorphology came with the onset of spacecraft exploration of the solar system (Baker, 2008). As such, planetary geomorphology is technology driven and in Baker's (2008) words *adventitious*, meaning that great advances in knowledge come by new missions and instrumentations. Mars is an instructive example on how drastically hypotheses need revisions following the achievement of new missions and instruments that unveiled new aspects of Mars (see Zimbelman, 2001; Baker, 2005). The success of a number of spacecraft and robotic missions to Mars in the late 1970's and in the recent decade has bolstered our understanding of our neighbor planet. Today, a steady stream of satellite data and data from ground roving robotic missions is continuously down-linked for us to analysis. This thesis is based on data from recent and ongoing missions to Mars. These missions are the following: Mars Global Surveyor (1997–2006), Mars Odyssey (2001–ongoing), Mars Express (2003–ongoing) and Mars Reconnaissance Orbiter (2005–ongoing). As for the future direction of arid geomorphology, which relates to adjacent disciplines as well, Tooth (2009) expressed it as follows,

> *[...] geomorphological research on Mars and other planetary bodies represents a new physical and intellectual frontier that offers great potential for further interplay with Earth landscape studies in arid and other climatic regions. While there are concerns about the present health and direction of geomorphology and physical geography, this rich diversity of themes provides evidence for vigorous and focused research in arid geomorphology.*

1.2.2. The use of terrestrial analogous in planetary research

In investigating any planetary surface outside the Earth's you encounter some obvious challenges which are particularly important in planetary science. First, one obvious limitation of investigating the surface of Mars, and other planetary surfaces, is the availability of satellite imagery and complementing data, such as spectroscopy, topography, and radar sounding of subsurface properties etc. During the 1970's Mars surface got a complete coverage by imagery from the Viking orbiters (150–300 m/pixel and selected areas <10 m/pixel). In 2009, the

European Mars Express had returned over 3 terabytes of processed images covering more than 50% of Mars at better than 20 m/pixel, and more than 71% of the surface at better than 40 m/pixel (Gwinner et al., 2009). Even though the coverage of low-resolution imagery is good on Mars, the high-resolution imagery, which is the primary data set in this thesis, covers typically just a few percent of the surface at a resolution between 0.25–12 m/pixel (Malin and Edgett, 2001; McEwen et al., 2007). Thus, an investigation of the distribution of landforms is constrained by the available number of images covering a specific area of interest.

Secondly, validation or ground truth of image interpretations is very limited. That is, planetary geomorphology generally suffers from the inability to field-check hypothesized genetic processes on the actual landform under study (e.g., Zimbelman, 2001). Exceptions are the manned lunar landing sites during the Apollo program and, to an extent, a few local places on Mars that are, or has been, visited by robotic missions.

Thirdly, a particular landform can be the result of different processes. The fact that different initial states can evolve to indistinguishable final states (convergence or equifinality: e.g., Chorley, 1962; Pitty, 1982; Haines-Young and Petch, 1983; Beven, 1996) is especially important for planetary geomorphologists, who lack the possibility to acquire ground truth data by field work.

An approach to overcome the problem of ground truth is by the use of Earth-analogues. The main scope of this thesis is to use this approach to aid us in understanding processes and landform genesis on Mars. The use of Earth-analogues has been long established among scientists who study planetary landscapes (Sharp, 1988). As expressed by Craddock (2011),

> *Terrestrial analogues represent places on the Earth that, in some respect, approximate the geological or environmental conditions thought to occur on another planetary surface either today or sometime in the past. Analog studies are important for providing the ground truth for interpreting data returned by spacecraft.*

The basic premise is that a planetary feature looks similar to a terrestrial feature, whose properties and origin are known. The known causes of the terrestrial analogue might allow us to infer the causes of the planetary feature under study (see Chorley, 1964; Baker, 2008). It has to be stressed, however, that analogues do not prove any causal relationships. Instead, they can help to find lines for further reasoning (e.g., multiple working hypotheses). Some of the most successful analogues in planetary science are those where not only terrestrial field observations are available, but also terrestrial remote sensing data that have a quality and scale comparable to that of planetary data. A similar scale is particularly important, since geomorphic systems are commonly *allometric*, i.e. the components of the systems do not change in constant proportions (Church and Mark, 1980). One consequence of this is that many properties of natural surfaces and landscapes are non-fractal, and the question of how to transfer results from one scale of investigation to another one is one of the most fundamental challenges in geomorphology (e.g., Kennedy, 1977; Summerfield, 2005). This problem is overcome, at least partly, if the scales of observations are similar for the planetary study objects and their terrestrial analogues. It seems mandatory, therefore, that any study using landforms to infer climatic conditions should investigate not a single class of landforms, but a suite of landforms (a landscape) in their geological context. A more comprehensive investigation of the full assemblage of landforms by means of landscape analysis, however, has the potential to reduce the ambiguity in interpreting landforms and to reveal the evolution of the climatic environment in more detail (paper I)

1.3. Aims and objectives

An underlying motivation for this study is to improve the understanding of the role of periglacial processes in shaping the mid-and-high latitude landscapes in recent geologic history on Mars. Like the Polar Regions on Earth, Mars exhibits a wide range of landforms with ground-ice affinity. More firm interpretation of these landforms may gain further insight into the varying processes that have acted upon the landscape through geologic time, past climate conditions and differences in ground-ice content and sediment characteristics.

First, this study seeks to provide new data and interpretations concerning various aspects of periglacial processes on Mars by drawing lines of reasoning from Earth-analogues in Svalbard. Second, it aims to provide conceptual models for landscape evolution by integrated landscape analysis that may be applicable for reconstructions of past climate conditions on Mars. The specific objectives may be summarized as follows:

- Investigate the potential of Svalbard as an analogue environment to Mars cold-climate features (paper I).

- Explore past and present processes and surface conditions on Mars by inference from morphological counterparts in Svalbard (Paper II, III and IV).

- Explore the potential of modeling landscape evolution on Mars by integrated landscape analysis inferred from Earth-analogues in Svalbard (paper V).

Part 2

Introduction to planet Mars

”For the moment it is a world of science, untouchable but inspectable and oddly accessible, if only through the most complex of tools. But unlike the other worlds that scientist create with their imaginations and instruments – the worlds of molecular dynamics and of inflationary cosmology and all the rest of them – this one is on the edge of being a world in the oldest, truest, sense. A world of places and views, a world that would graze your knees if you fell on it, a world with winds and sunsets and the palest of moonlight. Almost a world like ours, except for the emptiness.” – Oliver Morton

2. Introduction to planet Mars

"Science would not advance and cell phones would not work without the study of details, but humanity also will not progress without people backing off and looking at "the big picture" – completing the revolution" - William K. Hartmann

2.1. A brief historical overview – the early days

Mars is one of the four terrestrial planets in our solar system and our second closest planetary neighbor after Venus. The characteristic red hue of Mars comes from evenly spread ferric oxides (rust) across the surface. Because of this, the planet is easily distinguished on starry nights as a reddish dot steadily progressing across the sky. Mars has been known as long as recorded human history (and probably longer) and has been given many names throughout the millennia. The red color has been associated to blood and war, in sharp contrast to fertility and beauty usually associated with the bright Venus. The Babylonians associated Mars with Nergal, their god of war and pestilence, while the Greeks named the planet after their god of war Ares. Later, the Roman conquerors of Greece adopted their association to the planet, but named it Mars after the Roman God of war, a name that still persists today.

In modern history no planet has stirred the human imagination as much as Mars, especially the notion of life elsewhere in the universe. The starting point was in the late 19th century when an Italian astronomer named Giovanni Schiaparelli (1835-1910) began the tedious work of mapping Mars (Fig. 1).

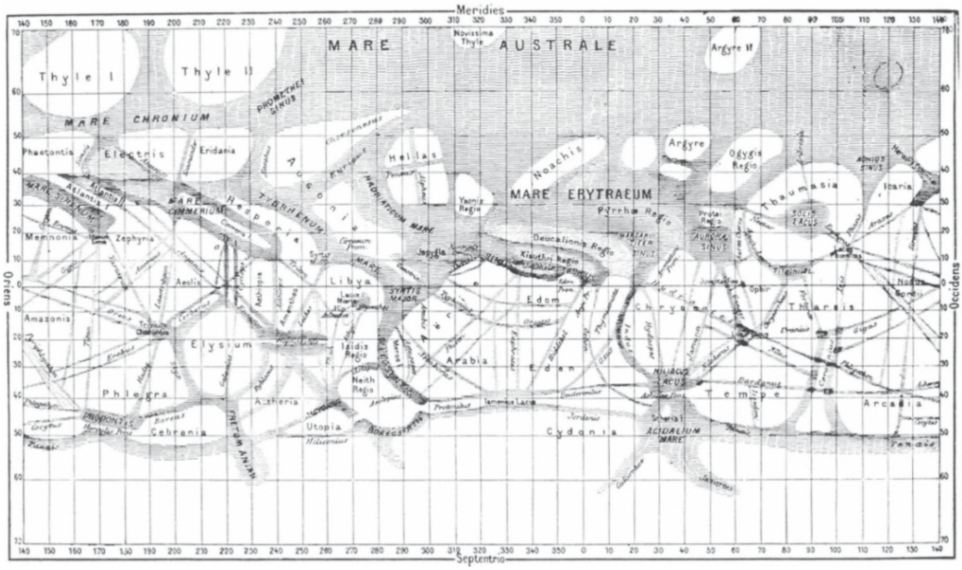


Figure 1. Map of Mars by Giovanni Schiaparelli, based on observations made from 1877 to 1886 (Woodruff and Carney, 2007).

Schiaparelli used a 22-cm diameter refractor to map surface features in unprecedented detail (by those days' standards). Such an exercise involved great patience by the telescope eye-piece, trying to monitor the shimmering image of the planet until atmospheric conditions allowed a sharp image for a second or two. Schiaparelli was inspired by the Mediterranean geology, history, and mythology for his Martian nomenclature. Several categories got Latin names such as *Mare* (sea), *Lacus* (lake), and *Sibus* (bay). Many of these names are still used today. Among several mapped features were the *canali*, an Italian word that indicates either natural *channels* or constructed *canals,* but Schiaparelli did not attach any generic significance to them (Baker, 1993). Naming features on Mars may still be problematic. In terrestrial geomorphology names are inherently genetic since the processes shaping the landforms are often known and well-studied. On Mars on the other hand, naming is still cautiously kept at a descriptive level since processes acting on the surface is poorly constrained due to limited in-situ measurements and the short period of space missions in relation the long time span of landscape development.

Schiaparelli's work was later translated in several languages, but the English translation was the tipping point for the publics' notion of Mars as an inhabited planet. Popular speculations centered on life and about "who" might be living there, and what they may think of us. *Canali* became *canals* in the English literature and viewed in a historic context, canal building was one of the high-tech activities of the day. When the canal-story crossed the Atlantic it was quickly and enthusiastically absorbed by the eccentric astronomer Percival Lowell (1855-1916). In 1894, Lowell, who was wealthy man, built and financed his own observatory in Flagstaff, Arizona, to be able to survey canals on Mars for himself. Using a 46-cm diameter refractor he began his own investigations of the enigmatic Martian linear features. A year later Lowell had data in hand and he was convinced he had found evidence of Schiaparelli's canals. Taking his findings one step further, they were conclusive evidence of an advanced civilization. The canals, he believed, were attempts to irrigate the lower latitudes with meltwater from the polar caps on a dying planet. These ideas may sound outrageous today, but at the time, belief in the existence of life in the universe (even intelligent) was common and almost established as a fact. As a historic anecdote, the French widow Clara Gogoet Guzman, who was contemporary with Lowell, established FFr 100.000 to the person or nation that first succeeded in establishing dialogue with another planet or star, although it is said she "excluded Mars because it would be too easy to establish contact" (Caidin and Barbree, 1976). Far from all contemporary astronomers agreed with Lowell's findings, but he was a skilled persuasive writer and speaker, and his ideas lived in the minds of the public for the rest of his life. As noted by Carl Sagan (1973) there was never any doubt that the canals of Mars were the products of intelligence. The question was on which side of the telescope the intelligence was located (Baker, 1993)

Today, we know that there are no canals on Mars, but Lowell's legacy lives through mainstream media. In fact just a few linear features observed by Schiaparelli and Lowell exist at all, namely Valles Marineris and the linear arrangement of the Tharsis volcanoes. Sagan and Fox (1975) declared, "The vast majority of the canals appear to be largely self-generated by the visual observers of the canal school, and stands as monuments to the imprecision of the human eye-brain-hand system under difficult observing conditions" (Woodruff and Carney, 2007).

The notion that Mars harbor life was long-lived in the minds of the public and scientists. Ironically, the real setback came with the first successful flyby mission to Mars by Mariner 4 in the 60's. Images showed a cratered, desolated planet, not much different than our Moon. The notion has changed once again to the positive due to research on the persistence of terrestrial organisms (extremophiles), new insights on the similarities between Earth and Mars at the early stages of planetary evolution, and the compelling evidence for water on Mars surface in the distant past.

2.2. Past and ongoing missions to Mars

Since the beginning of 1960's there has been numerous attempts to explore Mars by spacecraft. This is partly motivated by Mars close proximity to Earth, but more so for the quest to answer the question whether Mars once harbored life. It has been by no means an easy task and approximately two thirds of all missions have failed for known and unknown reasons. Table 1 summarizes all the missions to date and briefly note their outcomes.

Table 1. Summary of missions to Mars. Successful missions are shown as bold.

Mission	Start	Mission type	Outcome
Marsnick 1 (USSR)	1960	Fly by	Failed to reach Earth orbit
Marsnick 2 (USSR)	1960	Fly by	Failed to reach Earth orbit
Sputnik 29 (USSR)	1962	Fly by	Achieved Earth orbit only
Mars 1 (USSR)	1962	Fly by	Communication failure
Sputnik 31 (USSR)	1962	Fly by	Achieved Earth orbit only
Mariner 3 (USA)	1964	Fly by	Communication failure
Mariner 4 (USA)	1964	Fly by	22 recordings of surface
Zond 2 (USSR)	1964	Fly by	Communication failure while passing Mars
Mariner 6 (USA)	**1969**	**Fly by**	**75 images of Mars' surface**
Mariner 7 (USA)	1969	Fly by	126 images of Mars' surface
Mars 1969A (USSR)	1969	Lander	Launch failure
Mars 1969B (USSR)	1969	Lander	Launch failure
Mariner 8 (USA)	1971	Orbiter	Launch failure
Kosmos 419 (USSR)	1971	Orbiter/Lander	Achieved Earth orbit only
Mars 2 (USSR)	1971	Orbiter/Lander	Lander failed; Orbiter sent television
Mars 3 (USSR)	1971	Orbiter/Lander	Some data; lost communication after 4 min
Mariner 9 (USA)	**1971**	**Orbiter**	**6876 images of Mars' surface**
Mars 4 (USSR)	1973	Orbiter	Failed to reach Mars orbit
Mars 5 (USSR)	1973	Orbiter	Some data; lasted a few days
Mars 6 (USSR)	1973	Lander	Little data return
Mars 7 (USSR)	1973	Lander	Little data return
Viking 1 (USA)	**1975**	**Orbiter/Lander**	**Both successful; landed in Chryse Planitia**
Viking 2 (USA)	**1975**	**Orbiter/Lander**	**Both successful; landed in Utopia**
Phobos 1 (USSR)	1988	Orbiter	Communication failure *en route*
Phobos 2 (USSR)	1988	Orbiter	A few thermal images, lost communication
Mars Observer (USA)	1992	Orbiter	Communication failure just before arrival
Mars Global Surveyor (USA)	**1996**	**Orbiter**	**Very successful; more than 200 000 images**
Mars 96 (Russia)	1996	Orbiter/Lander	Failure to start
Mars Pathfinder (USA)	**1996**	**Lander/Rover**	**Successful mission; landed in Ares Vallis**
Nozomi (Japan)	1998	Orbiter	Failure to reach Mars' orbit
Mars Climate Orbiter (USA)	1998	Orbiter	Communication failure on arrival
Mars Polar Lander/ Deep Space 2 (USA)	1999	Lander/Penetrators	Lander failure
Mars Odyssey (USA)	**2001**	**Orbiter**	**Successful mission; still operating**
Mars Express (Europe)	**2003**	**Orbiter/Lander**	**Stereo imagery and spectroscopy, lander lost upon landing**
MER Spirit (USA)	**2003**	**Rover**	**Highly successful; lost communication in 2009**
MER Opportunity (USA)	**2003**	**Rover**	**Highly successful; still operating**
Mars Recon. Orbiter (USA)	**2005**	**Orbiter**	**Highly successful; high resolution imagery and spectroscopy. Still operating.**
Mars Phoenix Lander (USA)	**2007**	**Lander**	**Highly successful; confirmation of ground ice at high latitudes.**
Phobos Grunt (Russia)	2011	Sample return	Failed to leave Earth orbit
Mars Science Laboratory (USA)	**2011**	**Rover**	**Mission ongoing; habitability and early Mars conditions. Target; Gale crater.**

2.3. Physical characteristics and orbital parameters

Mars is the outermost of the terrestrial planets and one and a half time more distant from the sun than Earth. Mars is roughly half as big as the Earth in size and the total land area approximates Earth's total continental land surface. Mars has two small moons, Phobos and Deimos, which are generally believed to be two asteroids that have been caught by Mars gravitational pull (Boyce, 2002). Due to Mars lower density, the gravity is only 3.72 m/s^2 compared to Earth's 9.81 m/s^2. Like Earth, Mars is also subjected to quasi-periodic changes in the orbital and axial characteristics. Earth's cycles, called Milancovic cycles, are known to cause climate changes such as ice ages. On Mars, these orbital and axial variations are even greater and consequently the climate has varied significantly over time (Laskar, 2002; Laskar et al, 2004). Three well-understood orbital and rotational periodicities affect insolation at Mars' poles (Laskar et al., 2002): (1) an obliquity variation (120,000 years), (2) a climatic precession (51,000 years), and (3) an eccentricity variation (95,000 to 99,000 years); the first has the largest influence on Martian climate (Mellon and Jakosky, 1995). The cause for these orbital variations is Mars' lack of a stabilizing Moon (Laskar et al., 1993), since Phobos and Deimos are too small to have any influence, and the gravitational perturbations caused by Jupiter and the Sun. Currently the obliquity of Mars is 25.11° which is just slightly more than Earth's 23.44°. This means that Mars experience seasons like Earth. However, the obliquity of Mars changes much more over the course of geologic time and is considered to be the major climate forcing with significant geomorphologic effects at mid-to-high latitudes (Head et al, 2003a; Forget et al., 2006; Levrard et al, 2007; Morgenstern et al, 2007; Madeleine et al, 2009). Table 2 summarizes the orbital parameters of Mars and their comparison to Earth's. A more thorough discussion on implication for climate will follow in section 6.

A Martian year is almost twice as long as Earth's (~687 Earth days) and the Martian day (sol) is only 37m and 22s longer. The differing periods bring Mars and Earth into alignment relative to the Sun on a 780-day cycle. Due to the eccentric Martian orbit, however, the annual energy input is unevenly distributed between the hemispheres (Fig. 2). The distance to the sun varies as much as 1.64 AU to 1.36 AU over a Martian year. Mars is closest to the sun when the southern hemisphere experience summer and consequently the southern summers are a lot warmer than the northern summer. The eccentricity of orbit also has consequences for the length of each season. In the north the winter is the shortest season (~4 months) while spring is the longest (~7 months) (Table 3).

Table 2. Planetary constants for Mars and Earth and the ratio between them. A major difference is the eccentricity of orbit which is more than 5 times as large for Mars.

Parameter	Mars	Earth	Ratio (Mars/Earth)
Mean distance from the Sun (AU)[a]	1.52	1	-
Solar irradiance (w/m^2)[a]	589.2	1367.6	0.431
Sidereal orbit period (days)[a]	686.980	356.256	1.881
Sidereal rotation period[a]	24.6229	23.9345	1.029
Orbit eccentricity[a]	0.0935	0.0167	5.599
Axial obliquity[a]	25.19°	23.44°	1.075
Orbit inclination[a]	1.85°	0.00°	-
Gravity (surface) ($m\ s^{-2}$)[b]	3.72	9.81	0.379
Planetary radius (equatorial) (km)[b]	3394	6378	0.532
Bulk density (g/cm^3)[c]	3.924	5.515	0.711

[a]From Williams (2010).
[b]From Zurek et al. (1992).
[c]From Faure and Mensing (2007)

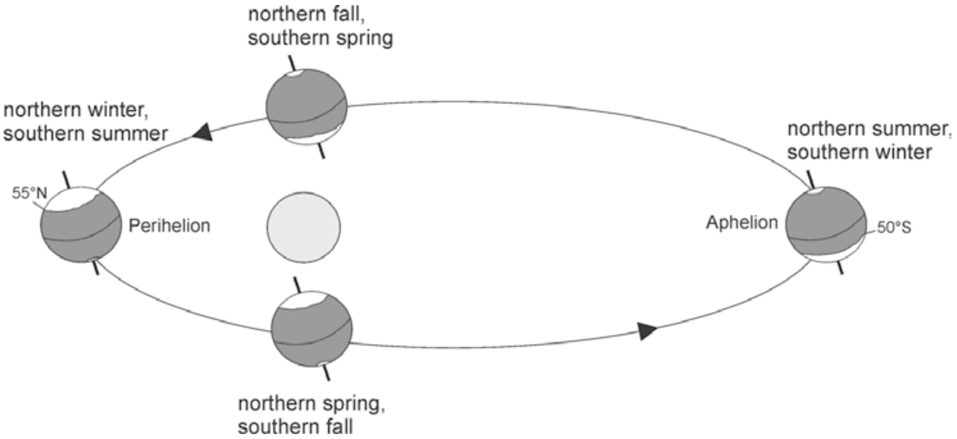


Figure 2. Illustration of the eccentric orbit of Mars. When Mars is in perihelion the southern hemisphere experience summer. The opposite occur in aphelion.

Table 3. The length of Martian seasons in Earth days. Due to the large eccentricity of Mars the northern spring is currently the longest season.

Martian seasons		
Northern spring	$L_s = 0–90°$	199 Earth days
Northern summer	$L_s = 90–180°$	183 Earth days
Northern fall	$L_s = 180–270°$	147 Earth days
Northern winter	$L_s = 270–360°$	158 Earth days

From Carr (2006).

2.4. Present climate and atmosphere

The atmosphere is composed of CO_2 (95.3%), N (2.7%), and Ar (1.6%) (Table 4). Mars' present-day climate system is complex, highly variable and not fully understood. The climate can be characterized as a cold, hyper-arid desert. This is because Mars only possess a thin atmosphere, with very limited water content, and consequently low latent heat release (Leovy, 2001). The thin atmosphere also leads to a very low surface pressure with a mean of ~6 mbar, but a range from 1 mbar to 14 mbar depending on location and season (compared to 1013 mbar on average at sea level on Earth). Seasonal variation corresponds to as much as 20% owing to CO_2-condensation at the poles during winter (e.g., Zurek et al., 1992). Despite the fact that CO_2 is the major component, the greenhouse effect is only ~5°C due to the thin atmosphere (Barlow, 2008). The corresponding low atmospheric heat balance makes the diurnal and seasonal temperature variations much larger than those in terrestrial deserts. Maximum diurnal near-surface atmospheric temperature range is about 30°C on Earth and about 60°C on Mars. Seasonal daily averages of surface air temperatures range up to 90°C in Martian polar regions (Zurek et al., 1992), but only up to about 50°C in the extreme terrestrial climate of northeastern Siberia (Leovy, 2001). Global average surface temperature is -53°C. Due to similarities in inclination of the spin axis and rotation the general circulation is controlled by similar processes: on both Earth and Mars, the Hadley circulation (the process that generates trade winds) is important at low latitudes, whereas "baroclinic" planetary waves (a succession of low and high-pressure zones) dominate the weather system at mid-latitudes (Boyce. 2002).

Table 4. The atmospheric constituents on Mars.

Gas	Abundance
CO_2	95.32%
N_2	2.7
^{40}Ar	1.6
O_2	0.13
CO	0.07
H_2O	0.03[a]
$^{36+38}Ar$	5.3 ppm
Ne	2.5 ppm
Kr	0.3 ppm
Xe	0.08 ppm
O^3	0.04–0.2 ppm[a]

[a]Variable with season and location.

From Owen (1992)

The presently low average temperature and low average atmospheric pressure prohibit conditions for liquid water almost everywhere on Mars. Water at the surface would freeze and quickly sublime into the atmosphere. There are, however, a few places where water potentially could exist at the surface for short periods of time, i.e., on the floor of the Hellas impact basin. Figure 3 show a thermodynamic phase diagram for pure water and the temperature and atmospheric pressure ranges on Mars.

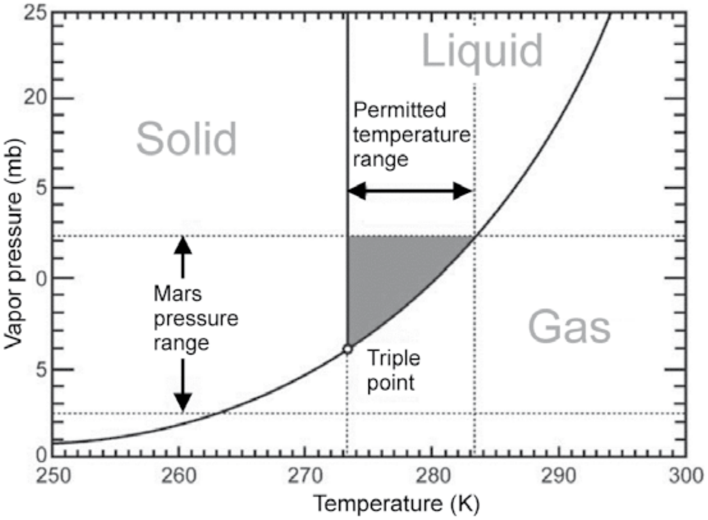


Figure 3. A phase diagram for pure water as a function of temperature and pressure. If the air pressure (any gas) is below the water saturation pressure (right line), liquid water is extremely unstable (boiling). If the air pressure is above the saturation water pressure, but the partial pressure of water is below it (as often on Mars where the pressure is mostly due to CO_2), liquid water can exist, but it evaporates more or less quickly depending on the conditions just above the gas–liquid interface (the farther from the evaporation line, the more stable) (modfied from Haberle et al. 2001).

2.5. Surface geology

In the following sections the geologic time scales of Mars and some of the more prominent geologic features will be presented. The geologic periods and the events that characterize them will be briefly described.

2.5.1. Geologic timescale

In the absence of a Martian rock sample of known source region the more broad division of geologic periods is mainly based on stratigraphic relationships and the occurrence of certain geologic processes (Tanaka et al., 1992). However, by applying crater size-frequency measurements refinements of the relative ages of different geologic units has been made (Fig. 4, middle bar) (Hartmann and Neukum, 2001; Hartmann, 2005). With the onset of spectral investigations of surface minerals an additional window to Mars past history has been opened. The discovery of secondary minerals such as phyllosilicates (clays) and sulfates made Bibring et al., 2006 propose an additional scale based on a mineralogical evolution sequence (Fig. 4, lower bar). In table 5 major events that characterize each geologic period is presented and figure 5 shows the geographical distribution of different surface ages. To put this thesis in perspective, all the appended papers deal with conditions during the very Late Amazonian, i.e., less than in a few million years' time.

2.5.1.1. Pre-Noachian

Due to the lack of plate tectonics and extremely low erosion rates on Mars very old events has been preserved in the landscape. Despite this, geologic events during the pre-Noachian are mostly unknown. The pre-Noachian extents from the time of formation of the planet 4.5 Gyr ago to the time of formation of the Hellas impact basin, which is estimated to have taken place between 4.1 Gyr ago to 3.8 Gyr ago (Carr and Head, 2010). This is the time of the Early Heavy Bombardment when debris, left over from the Solar System formation, impacted the young solidifying planets. Thus no cratering record remains from this period. A short period called the Late Heavy Bombardment followed of which we see the marks on the surfaces on the Moon, Mars and Mercury (Melosh, 2011). A meteorite found at Allan Hills in Antarctica in 1984 and later determined to come from Mars gives us some clues about the planet's early history. The meteorite, called ALH84001, indicate that Mars accreted and differentiated remarkably fast, within a few tens of millions of years of Solar System formation (e.g., Lee and Halliday, 1997; Borg et al., 2003). Some of the very early events probably include the formation of the global crustal *dichotomy* (Carr, 2006), which is a change in elevation between the northern and southern hemispheres. The crust is thinner beneath the northern plains than that beneath the southern highlands. Although volcanism is believed to have been intense due to the increased thermal heat flux, most traces have been erased by succeeding lava flows and impacts. The volcanic province Tharsis probably started forming at this time. Volcanism would have been accompanied by outgassing of volatiles such as water and sulfur. The amount of volatiles acquired during these early events is, however, poorly constrained. The initial inventory of volatiles are difficult to know due to uncertainties in the initial mix of materials accreted to form the planet (e.g., Lunine et al, 2004), atmospheric loss due to impact erosion (Melosh and Vickery, 1989), the efficiency of outgassing of water and its retention during accretion (Matsui and Abe, 1987), losses due to solar wind interaction (e.g., Jakosky and Jones, 1997), uncertainties on the intensity of volcanism that followed the accretion period (e.g, Phillips et al., 2001) and how much volatile rich material was added to the planet after global fractionation (Chyba, 1990). Intriguingly though, measurements by the Mars Global Surveyor mission found large magnetic anomalies, mostly in the southern highlands (Acuña et al., 1999; Connerney et al., 1999). These anomalies may imply that Mars could have generated a magnetic field at some time in the very distant past.

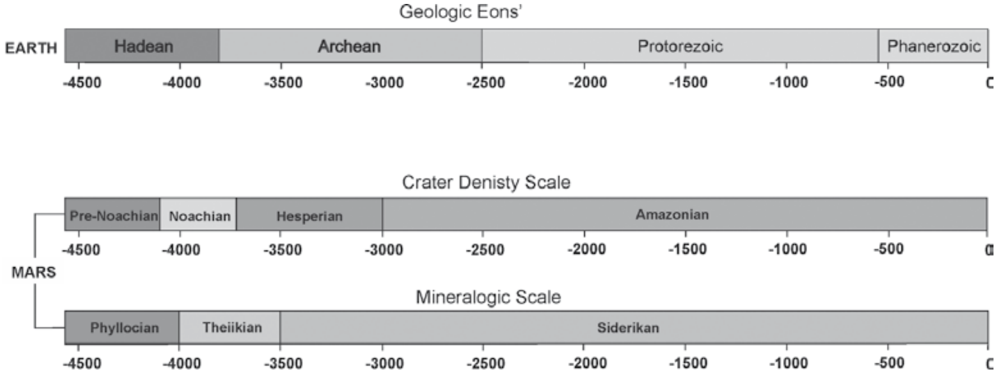


Figure 4. Simplified geologic time scales of Earth and Mars. Mars' geologic periods are approximate and are based on stratigraphic relationships and crater density analysis (middle bar) (Hartmann, 2005) and geochemical analysis (lower bar) (Bibring et al., 2006). The Noachian represent the episode of Late Heavy Bombardment on Mars and the time when liquid water is believed to have been stable (clay formation). At the start of Hesperian the bombardment had declined but volcanic activity was still abundant, water levels and atmosphere pressure decreased and water became more acidic (sulphates formed).

Table 5. Geologic time periods and their corresponding major geologic events on Mars. Selected references for each event is provided.

Time period	Key events	Selected references
Amazonian ***c.* 3.0 Ga–present**	Gully formation	*Malin and Edgett, 2000; Reiss et al., 2011*
	Thawing	*Gallagher et al., 2011; Johnsson et al., 2012*
	Small-scale polygons	*Mangold, 2005; Levy et al., 2009*
	Fractured mounds	*Burr et al., 2009; Dundas and McEwen, 2010*
	Glaciations	*Head and Marchant, 2003; Madeleine et al., 2009*
	Latitude dependent mantle	*Mustard et al., 2001; Morgenstern et al., 2007*
	Polar layered terrain	*Jakosky et al., 1995; Milkovich et al., 2008*
Hesperian ***c.* 3.7–2.9 Ga**	Outflow channels	*Baker, 1982; Baker, 2001*
	Episodic seas	*Parker et al., 1989; Fairén et al., 2003*
	Volcanism	*Greeley and Spudis, 1981; Head et al., 2002*
	Canyons	*Lucchitta et al., 1992; Carr, 2006*
	Sulfate formation	*Chevrier and Mathe, 2007; Milliken et al., 2009*
	Dorsa Argentea Formation	*Tanaka and Scott, 1987; Head and Pratt, 2001*
Noachian ***c.* 4.1–3.7 Ga**	Impact craters	*Barlow, 1988; Barlow, 2010*
	Valley networks	*Baker et al., 2001; Carr, 2006*
	Tharsis Bulge	*Carr, 2006; Bleacher and Dohm, 2009*
	Hydrous weathering	*Mustard et al., 2008; Gaudin et al., 2011*
	High erosion rates	*Craddok and Howard, 2002; Golombek et al., 2006*
Pre-Noachian **4.5–*c* .4.1 Ga**	Global dichotomy	*Nimmo and Tanaka, 2005; Andrews-Hanna et al., 2007*

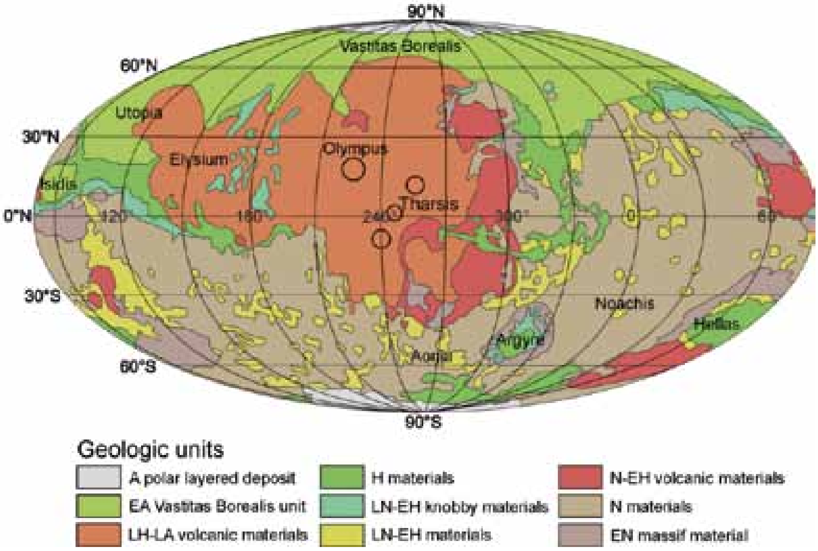


Figure 5. Generalized global geologic map. Legend: Early and Late (E and L), Noachian, Hesperian, and Amazonian (N, H, and A). Tharsis and major volcano's for reference. Note the predominance of older Noachian terrains on the cratered southern highlands. Amazonian terrains occur on the northern lowlands and the volcanic regions. Youngest units correspond to the polar layered deposits (modified from Nimmo and Tanaka, 2005).

2.5.1.2. Noachian

The Noachian represents a very chaotic time in Mars evolution, dominated by high rates of impacts. Impacts distributed ejecta globally and created a highly brecciated regolith with high porosity to kilometer depths. This so called Late Heavy Bombardment is estimated to have ceased around 3.8 Gyr ago and which marks the end of the Nochian period. Impact rates then remained low for the rest of the planets history (Barlow, 2008). During the Noachian volatile-rich magma transported water, carbon dioxide and other volatiles to the planet's surface which helped to form the early atmosphere. Several lines of evidence such as surface morphology and the discovery of phyllosilicates (clays) (Bibring et al., 2006), suggest that Mars' early atmosphere was dense (few bars) and wet (Soderblom and Bell, 2008). The composition of this early atmosphere is, however, not fully constrained (Carr and Head, 2010). An atmosphere primarily composed of CO_2 and H_2O is not likely to raise the temperature enough for water to be stable at the surface allowing for precipitation to occur precipitation to occur, considering the cooling effect of CO_2-clouds and the expected lower energy input by the Sun at this time (Kasting, 1991). The presence of other greenhouse gases such as SO_2 and CH_4 and/or the additional release of gases from large scale impacts (Segura et al., 2002) and volcanism may be other possible explanations (Carr and Head, 2010). Recent developments, however, has challenged the traditional view of a "warm and wet" early Mars (Head, 2012). Though not firmly proven, one solution may instead be the occurrence of punctuated volcanism in which the climate temporally became enough warm for water to be stable at the surface (Halevy and Head, 2012). In this scenario Mars may have been dominated by cold and dry conditions for most of its geologic history, but with transient warm periods during the Noachian. Volcanism during this period was likely concentrated to the Tharsis plateau (Phillips et al, 2001). Despite that Mars probably has been volcanically active for 98% of its geologic time; most of Tharsis was accumulated already during the late Noachian (Carr, 2006).

Other distinguished features of the Noachian, as compared with later times are relatively high erosion rates and valley formation. The rapid decline in erosion is clearly evident when comparing Noachian impact craters to later ones. Noachian craters have highly eroded rims and partly filled interiors, which are in sharp contrast to Hesperian craters which generally have all their primary impact features preserved. Estimates of the erosion rates suggest at least 2–5 order of magnitude higher rates during Noachian than later times (Carr, 2006). However, even at peak erosion this would be equivalent to low average rates on Earth (Golombek et al, 2006).

Some of the most intriguing features of the Noachian period are the valley networks. Similar to the rapid decline in erosion rates, the valley dissection seem to have ceased at the end as well. The valleys form characteristic dendritic networks which converge at local low. This suggests that lakes were common. Valley networks are common throughout the Noachian terrains and are often accompanied by other fluvial features such as central channels, alluvial fans and deltas (Carr, 2006). Due to the apparent low drainage densities, amphitheater heads and tributaries, and rectangular cross sections, some early researchers suggested that groundwater sapping was the major agent of formation (e.g., Pieri, 1980; Baker et al, 1990). With the advent of high resolution imagery and altimetry, however, it was found that the networks were more intricate than previously envisioned. The formation of the valleys seems to require surface runoff either by rainfall and/or by melting snow (e.g., Haberle, 1998). Even though there is a general agreement that the eroding agent is liquid water the duration and the climate conditions is still unclear (e.g., Carr, 2006; Carr and Head, 2010). Nevertheless, the Martian atmosphere began to dissipate to its current thin state toward the end of the Noachian period. Three factors likely contributed to the loss of the Martian atmosphere, (1) gradual seepage of lower-density atmospheric gases into space via Jean's escape (thermally driven escape of light molecules) from the Martian exosphere (Krasnopolsky and Feldman, 2001), (2) atmospheric erosion by charged particles in the solar wind (Dehant et al., 2007), and (3) impact erosion from large impacts such as those forming Hellas and Argyre (Melosh and Vickery, 1989).

2.5.1.3. Hesperian

At the transition from the Noachian into the Hesperian period ~3.8 Ga ago, impact rates declined significantly. Hesperian impact craters are generally well preserved, which suggest that erosion rates also declined sharply by the late Noachian and remained low for the rest of the geologic history. The rapid decline in erosion rates and the cessation of valley network formation by the time of the Hesperian suggest that climate changed drastically. Volcanism, on the other hand, continued through the Hesperian and exceeded impact cratering as the primary geologic process. Hesperian volcanism is most evident in the form as ridged plains and low shield-like central edifices (Greeley and Spudis, 1981). As a consequence of the crustal stresses from the formation of the Tharsis bulge, major tectonic events took place during the Hesperian. The most prominent features are the immense Valles Marineris canyon systems, which extend for more than 4000 km on the east side of the Tharsis plateau. Other characteristics of the period are the formation of large outflow channels and the cessation of clay formation. Most of the sulfate-rich deposits found are linked to Hesperian terrains. This suggests that liquid water was becoming more localized in extent and turning more acidic due to interaction with the sulfur dioxide, forming local acidic aqueous environments (Andrew-Hanna et al., 2007). Investigations by the Opportunity Rover provide in situ evidence that Meridiani Planum was once covered by an acidic sea (Squyres et al., 2004). Possible alternative explanations for sulfate deposits without the involvement of water includes primary weathering due to acid fogs forming sulfate-rich weathering rinds that eroded and were redeposit by wind (for more details see Carr and Head, 2008).

Outflow channels are some of the most prominent erosion features on the surface of Mars (Tanaka et al., 2005). Even though there exist ambiguous evidence for a fluvial origin for some of these features others may have formed by other means, e.g. lava flows (Leverington, 2004). The outflow channels start abruptly which suggest that they have formed by rapid release of large volumes of subsurface water. The exact mechanism for the release is still under debate, but one hypothesis states that ground water has become pressurized by an aggrading cryosphere. Fracturing of the cryosphere may have allowed the water to reach the surface by artesian pressure (Carr, 2006). This notion is supported by morphological evidence by that fact that some channels emanate from systems of grabens and rubble filled depressions (Carr, 1974; Wilson and Head, 2004; Gathan et al., 2005). Others may be the result of lake drainage (e.g., Harrison and Chapman, 2008) or release of meltwater from ice sheets (e.g., Hovius et al., 2008). Whether the amount of water was enough to form an ocean at the northern lowlands is still under debate. The lack of outflow channels during the Noachian may have been the result of a higher geothermal heat flux and a thinner cryosphere.

2.5.1.4. Amazonian

The latest and also the most extensive geologic time period is the Amazonian (~3Ga to present). It extends for approximately 60% or two thirds of Mars history. In contrast to earlier periods the Amazonian lacks major fluvial episodes, even though they are not completely absent. There are some evidence for early and middle Amazonian valley incision by fluvial activity (e.g., Warner et al., 2009), but these are extremely sparse compared to the dense valley networks of the Noachian and the immense outflow channels of the Hesperian. Amazonian outflow channels start at fault-created fissures and have crater ages that range from 2 to 140 Myr (Berman and Hartmann, 2002). If formed by water, they imply that water may still be present a depth and that surface release may occur even today due to dike emplacement or by faulting (Head et al, 2003b). Nevertheless, the iron minerals formed during this time were anhydrous ferric oxides, displaying little evidence of interaction with liquid water (Bibring et al., 2006).

Even though the Amazonian represent such a long time span, basic planetary processes such as impact cratering, volcanism and tectonism are modest compared to earlier periods. The extremely low weathering and erosion rates that typified the late Hesperian continues throughout the Amazonian (Golombek et al, 2006). Volcanic activity was largely confined to the still growing Tharsis region and Elysium. Crater chronology suggests, however, that eruption rates fell by a factor of ten compared to Noachian and Hesperian (Hartmann and Neukum, 2001).

Processes having the most prominent effects in landscape modification during the Amazonian are wind and ice (Carr and Head, 2008). The most frequent processes on Mars today are dust storms and local occurrences of dust devils. Storms are efficient in redistributing the dust around Mars and topographic niches like craters acts as dust traps (Carr, 2006). Dust devils are frequent atmospheric phenomena, which can cause local and limited erosion of the top most sediment layer forming so called dust devil tracks (e.g., Reiss et al., 2012).

Compared to previous geologic periods the action of ice is clearly evident in the Amazonian landscape in the form of glacial and ground-ice associated landforms (Kargel, 2004). One of the more surprising discoveries of the Amazonian landscape is the presence of a mantling unit at mid-and-high latitudes on both hemispheres on Mars. The mantling unit is a surficial, several meters thick and mutes the topography (Kreslavsky and Head, 2000). The characteristics of the mantle unit will be dealt with in more detail in section 6.1. A second major discovery was the gully landforms on interior crater walls, mesas and central peaks within craters (e.g., Malin and Edgett, 2000). Their distribution and morphology suggest erosion by liquid water in the recent past on Mars and they are dealt with in more detail in paper II.

2.5.2. The global dichotomy

One of the most noticeable geologic features on Mars is the so-called global dichotomy (Fig. 6). This hemispheric dichotomy is evident in three ways. Firstly, there is a bimodal distribution of elevations, with a difference of 5.5 km between the two hemispheres (Aharonson et al., 2001). The boundary is transitional in most places, but on average the southern hemisphere is 5.5 km higher than the northern plains. As a consequence, the planets center of figure and the center of mass is offset by almost 3 km along the polar axis (Smith et al, 1999). Secondly, the northern hemisphere is more sparsely cratered than the southern hemisphere, which is heavily scarred by impacts. This surface expression, however, are superficial since a heavily cratered surface are located at a shallow depth beneath the surface of the northern plains as revealed by the MOLA instrument (Frey et al., 2002). Thirdly, the dichotomy is expressed as a difference of crustal thickness. Using global topography and global gravity field data Neumann et al. (2004) were able to derive crustal thickness with peak values of 32 km for the northern plains and 58 km for the southern highlands. The thinnest crust is found in the impact basins Hellas and Isidis which today have infill of several kilometers (Carr, 2008).

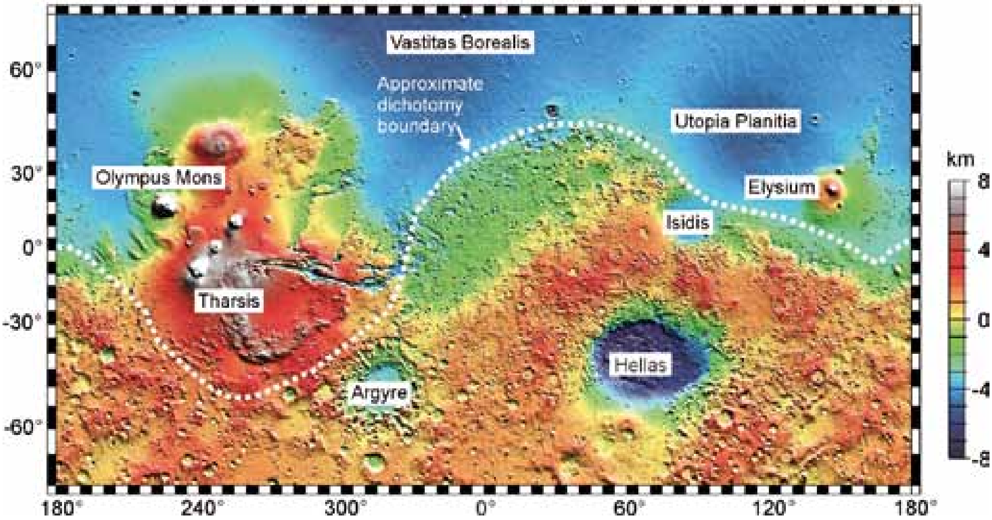


Figure 6. Mars Orbiter Laser Altimeter (MOLA) map in Mercator projection to 70° latitude. White outline shows the approximate extent of the dichotomy which is the boundary between the northern plains and southern high lands. Image credit: NASA/JPL/GSFC.

The dichotomy has been under scientific scrutiny for decades and a number of hypotheses have been proposed to explain its origin such as a single large impact (Wilhelms and Squyres, 1984), overlapping multiple large impact craters (Frey and Schultz, 1988), spreading of oceanic crust (Sleep, 1994), and mantle overturn (Solomon et al., 2005; Nimmo and Tanaka, 2005). A recent study by Andrews-Hanna et al (2008), however, provides supporting evidence for a single impact origin. By tracing the dichotomy boundary beneath the Tharsis province they found that the dichotomy forms an ellipse measuring approximately 10,600 by 8,500 km. The elliptic form is best explained by an impact origin. This would represent the largest known impact in the solar system (Andrews-Hanna et al., 2008).

2.5.3. Volcanism and tectonics

Albeit being the second smallest planet in the solar system Mars hosts the most impressive volcanoes in the solar system. Mars has been geologically active for most of its history (e.g., Werner, 2009; Robbins et al., 2011). Signs of past volcanism at the surface of Mars is extensive, but not uniformly distributed and includes a diversity of volcanic landforms such as pyroclastic cones (Fig. 7A), stratovolcano-like summits (Fig. 7B), as well as vast volcanic plains. Olympus Mons, for example, reaches staggering 21 km above the reference level (defined as Mars' mean radius of 3,389.51 km) and measures 550 km across (Fig. 7C). Olympus Mons is classed as a shield volcano of the same type, as for example, the Hawaiian volcano Mauna Kea. The descriptive name derives from the dome shaped form, which results from eruptions by basaltic low-viscosity lava that flow laterally long distances before solidifying. The Tharsis Plateau, which dominates the western hemisphere of Mars, probably started forming in the early Noachian. By the end of the Noachian it had been largely built (Carr, 2006). Tharsis forms an enormous bulge on the surface of Mars that rises several kilometers above the surrounding terrain with three large volcanoes close to the summit. The total volume of rock accumulation at Tharsis is equivalent of a 2 km thick global layer (Carr and Head, 2010). On the opposite side of the planet is the Elysium province which also consists of a number of volcanoes. A third prominent volcanic center can be found around the Hellas impact basin (Carr, 2006). Some of the youngest volcanic activity can be found in the Cerberus plains region were eruptions originate from fissure volcanism in the Cerberus Fossae system. A recent report by Berman and Hartmann (2002) suggests these lava flows to be less than 20 Ma based on crater count analysis. Common types of volcanism on Mars seem to be effusive volcanism and explosive eruptions by basic to ultrabasic extrusions, which is possible under Martian gravity and atmospheric pressure conditions (Head and Wilson, 1998). However, a recent report by Brozˇ and Hauber (2012) suggests that explosive volcanism has also occurred in local places by the identification of conical features interpreted as pyroclastic cones in the Tharsis region. Moreover, an investigation of the volcano Apollinaris (Fig. 7D) using an ash dispersal model and morphologic evidence suggests that pyroclastic eruptions have dominated for most of the volcano’s lifetime (Kerber et al. (2011). For a more comprehensive overview on current knowledge on volcanism on Mars the reader is referred to Werner (2009) and Robbins (2012).

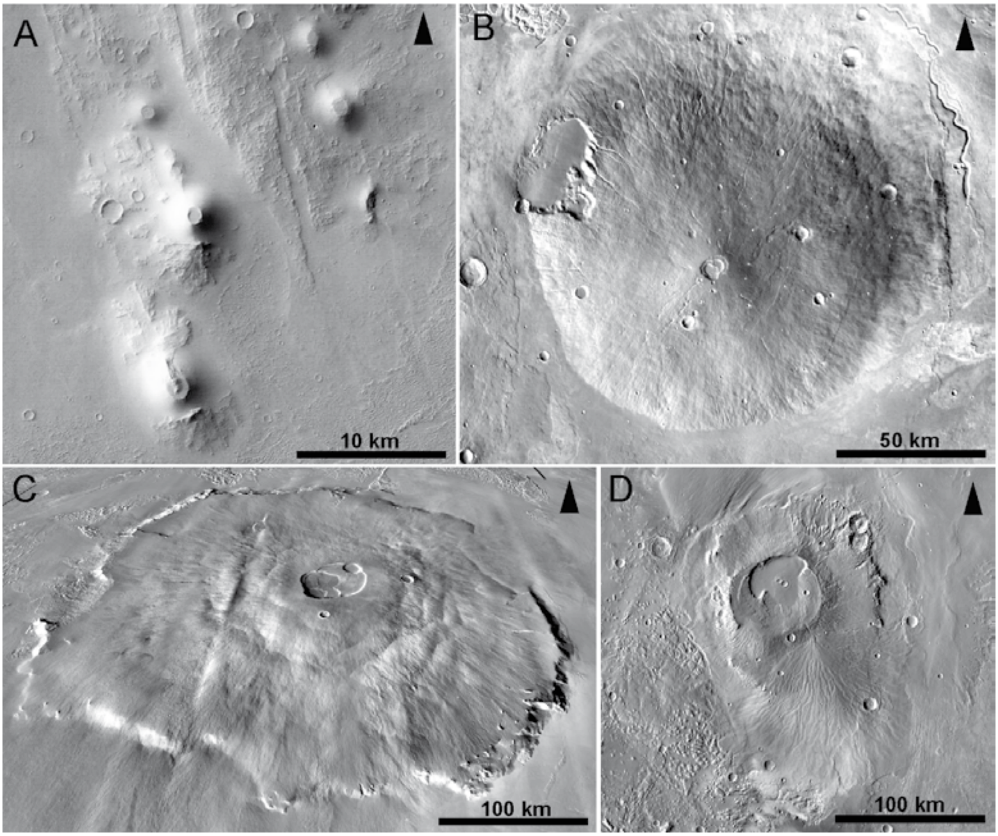


Figure 7. Variety of volcanoes on Mars. (A) Cones recently interpreted to be pyroclastic cones formed by explosive volcanism (Brozˇ and Hauber, 2012) HRSC image h1023_0000_ND3. Image credit: ESA/DLR/FU Berlin (G., Neukum). (B) Hecatus Tholus, one of the Elysium volcanoes, as seen in a mosaic of daytime THEMIS IR. Flanks show evidence of fluvial erosion probably from melting snow at the summit (Fasett and Head, 2006). Image credit: NASA/JPL/UoA. (C) Oblique view of Olympus Mons, the immense shield volcano NW of Tharsis. Note the sequence of caldera collapses on the summit. THEMIS daytime IR. Image credit: NASA/JPL/UoA. (D) At the south border of the Elysium Province lays Apollinaris Patera, an ancient volcano with unusual flow features which may be pyroclastic flows (Kerber et al, 2011). THEMIS daytime IR. Image source for all images: Google Earth. Image credit: NASA/JPL/UoA.

In terms of endogenic processes Mars has also been subjected to tectonics. This is for most cases a consequence of the long going volcanic activity and the stresses it has caused in the Martian crust. An illustrative example is the buildup of the Tharsis bulge which dominates the western hemisphere. The load that Tharsis represents has deformed the lithosphere (Phillips et al., 2001) and caused modification by tectonics at a regional scale (Fig. 8). These features are extensional features such as tension cracks (Fig. 9A), simple and complex graben (Fig. 9B), rifts, troughs and polygonal troughs. Contraction features are seen as wrinkle ridges, lobate scarps and fold belts (e.g., Head, 2007).

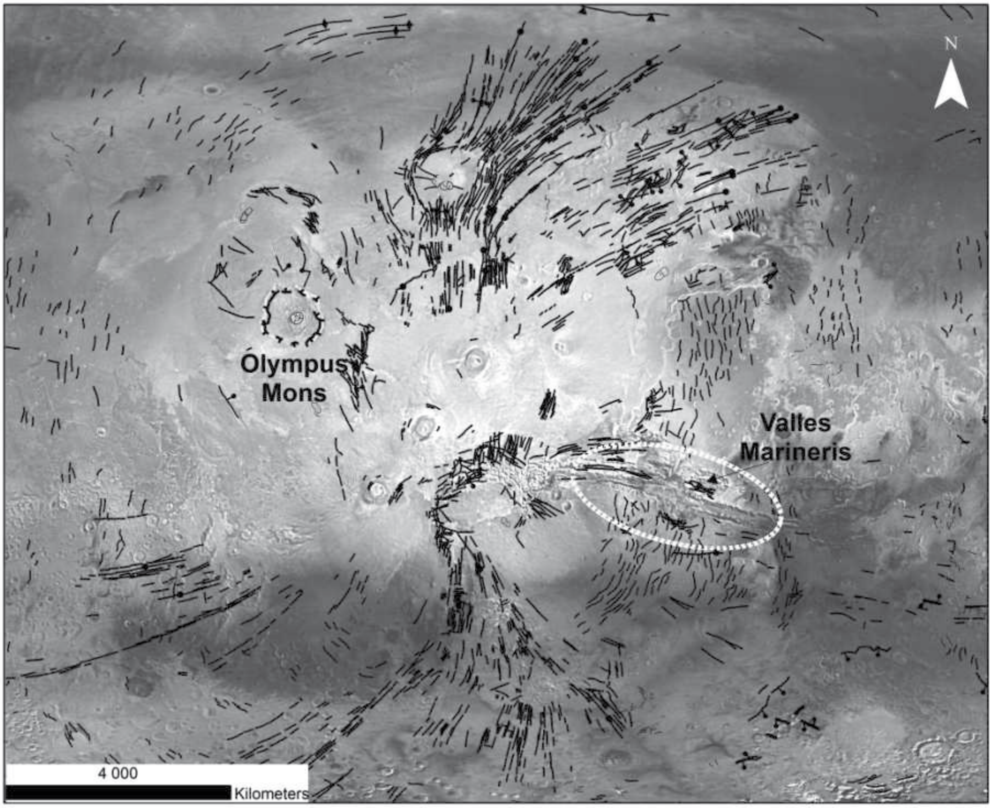


Figure 8. Equidistant cylindrical projection of the Tharsis bulge. The buildup of Tharsis caused considerable stress on the lithosphere with resulting faults radiating from the center. Olympus Mons lay NW of the Tharsis bulge. The east side is dominated by the Valles Marineris which is a large rift system.

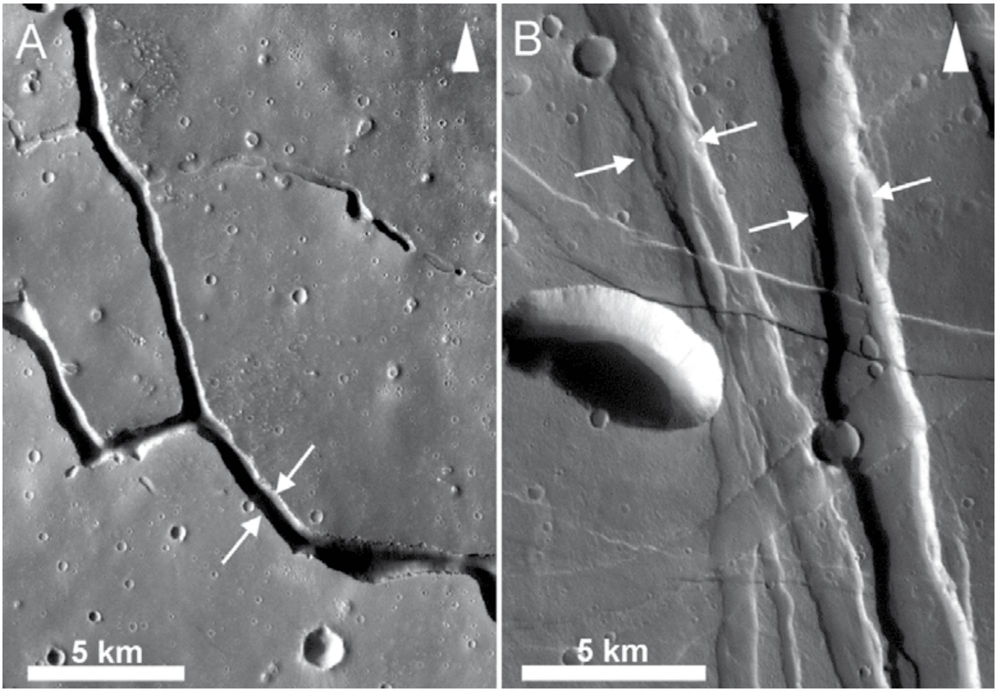


Figure 9. Example images of tectonic features (white arrows): (A) Fractures (21.11°N/123.31°E; THEMIS: V05301014), and (B) Simple graben which are the most common extensional features on Mars (15.72°N/237.83°E; THEMIS: V40351003) on Mars. Image credit: NASA/JPL/Arizona State University.

2.5.4. Impact craters

The term *crater*, Latin for cup, was first introduced by Galileo in 1610 to describe the near circular depression observed on the lunar surface. Craters may come in a range of morphologies which is based on the type of impact (dense or porous), size, velocity, target properties and the angle of impact. Basic crater morphology is, however, a bowl-shaped depression width a depth/diameter ratio close to 0.2 (Carr, 2006). Horizontally layered bedrock crops out beneath the crater rim, and further down talus usually converge or terminate against a flat floor. The material which is excavated and radially dispersed by the impact is called the ejecta. Based on terrestrial experience, the first notion was that they represented volcanic summit depressions. However, early studies on: (1) analogue reasoning (Gilbert, 1893), (2) hypervelocity impacts by Ives (1919) and Gault et al. (1968), (3) insights on the physics of nuclear and chemical explosions (e.g., Roddy et al, 1977), (4) and identification of shock metamorphic features in rocks surrounding Meteor Crater (aka, Barringer Crater) and Ries Crater (Shoemaker and Chao, 1962; Shoemaker, 1963) lead to the acceptance that craters could be the result from collisions of large chunks of space debris. This is one of the first instructive examples of the problem of equifinality, that is, different sets of processes resulting in similar looking landforms (Gilbert, 1886). Equifinality is a particular challenge in planetary science since, with few exceptions, only remote sensing data is available (e.g., Zimbelman, 2001).

Impact craters are by far the most common geologic feature on Mars, which this is true also for the other terrestrial planets and the Moon. On Earth, however, most traces of impacts have been obliterated by erosion and plate tectonics. On Mars, many landforms have been preserved since plate tectonics is lacking and due to extremely low erosion rates. Impact craters are important for two main reasons; they provide insights into (1) the geologic evolution and, (2) the near-surface structure of Mars. More than 42,000 impact craters ≥5 km in diameter have been cataloged across Mars (Barlow, 1988), and the number of smaller craters is even greater. On Mars, craters display a range of morphologies which are both related to the size of the impact, velocity and the target material properties. The gross primary impact morphologies are size-dependent and typically classed as simple craters or complex craters. Simple craters are bowl-shaped and typically <7 km diameter on Mars, whereas complex craters are larger and have a central peak. An additional type of craters is called multi-ring craters but these are not very common and relates to the huge basin forming impacts, for example Hellas and Argyre. These three types of craters occur also on other planetary surfaces like the Moon. In the following sections two types of Martian craters are presented that are relevant for paper IV.

2.5.4.1. Rampart craters

Martian impact craters, however, display a variety of ejecta and interior features which differ from those seen on dry and atmosphere-free bodies like the Moon (Barlow et al. 2000). These features were first clearly revealed in Viking Orbiter images and included layered (or "fluidized") ejecta patterns and a high number of craters with central pits (Fig. 10) (Barlow, 2006). Craters with the fluidized ejecta are called rampart craters, which are classified according to the number of ejecta layers as single-layer, double-layer and multiple layers. Two models have been proposed to explain the "fluidization": (1) impact into a volatile-rich material (e.g., Carr et al., 1977; Wohletz and Sheridan, 1983; Stewart and Ahrens, 2003, Senft and Stewart, 2008), (2) the ejecta curtain interacting with the thin Martian atmosphere (e.g., Schultz and Gault, 1979; Schultz, 1992; Barnouin-Jha and Schultz, 1998). In the former case, melt water and/or water vapor interacts with the ejecta curtain produced by ballistically ejected debris, resulting in emplacement of the ejecta as a ground-hugging debris flow. In the latter case fine-grained material from the ejecta curtain is entrained into the vortex ring, which is an effect when the atmosphere deflects around a protruding ejecta curtain. Material is then transported away from the crater and deposited into layered ejecta patterns. Laboratory experiments and numerical modeling have been conducted to demonstrate that both mechanisms can produce many of the observed layered ejecta morphologies (e.g., Barnouin-Jha and Schultz, 1998; Barnouin-Jha et al., 1999a, 1999b). Barlow (2006), however, points out that single layer ejecta craters are found only at latitudes where near-surface ground-ice is been expected. This notion is supported by the fact that at higher latitudes smaller crater diameters are needed to display the rampart morphology, that is, less excavation is required to reach volatile-rich layers. This so-called "on-set diameter" is consistent with predictions of subsurface ice on both hemispheres (Barlow, 2010).

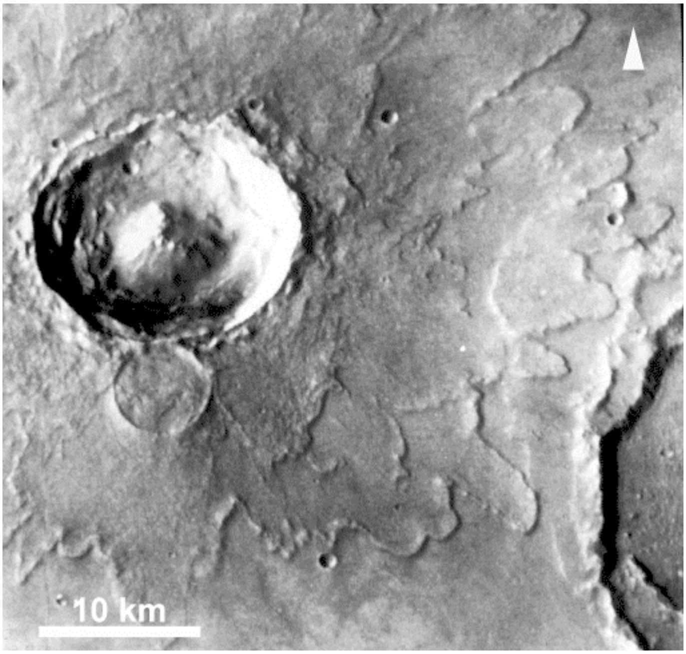


Figure 10. An example of a complex rampart crater named Yuty (22°N/326°E). One of the morphological attributes for a complex crater is the central peak. The ejecta deposits around consist of many overlapping lobes. Craters with this type of ejecta deposit are known as multiple-layered-rampart craters. This type of ejecta morphology is characteristic of many craters at equatorial and mid-latitudes on Mars. Viking Orbiter image 3A07. Image credit: NASA.

2.5.4.2. Rayed craters

Rayed craters are distinguished by the presence of radial lineaments around the crater, which are readily identified by a contrast in albedo with respect to the overlain surface materials. On Mars, such differences may be obscured from view by multiple processes known to be active on the Martian surface, including: glacial modification, dust deposition, aeolian reworking, and volcanic flows (Schon and Head, 2012). Thus, as relatively ephemeral features, crater rays are very useful chronologic markers, which are believed to represent the youngest impacts. Generally, the distinctiveness of crater rays arises from both compositional and maturity differences (e.g., Hawke et al., 2004). Even though they may be difficult to distinguish by visual inspection alone, in nighttime THEMIS infrared data they are clearly defined (Fig. 11A) (Tornabene et al., 2006). In particularly fresh craters they may be distinguishable also in daytime THEMIS infrared (Fig. 11B). Although very common on the lunar surface the first unambiguous evidence for rayed craters on Mars came with the discovery of Zunil crater (McEwen et al, 2005).

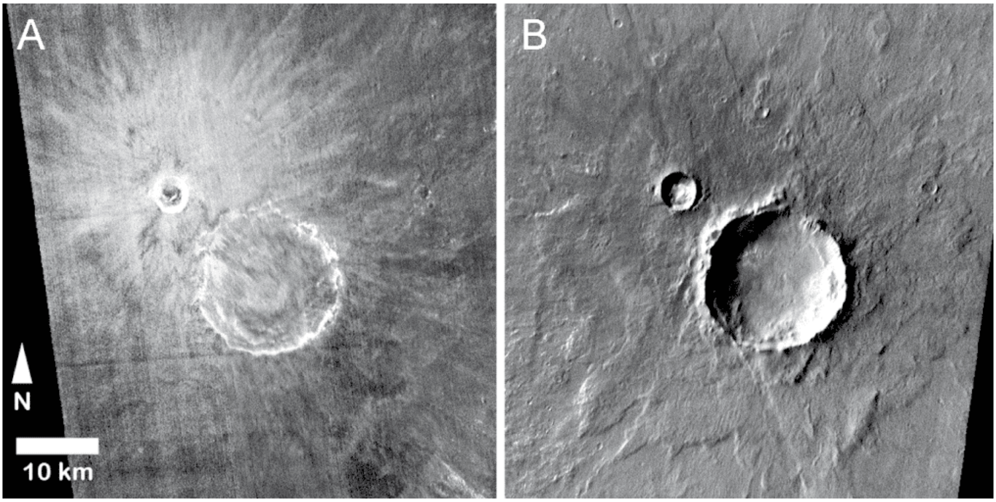


Figure 11. An example of a rayed crater on Mars (paper IV) which is superposed on the ejecta of a single-layer-ejecta rampart crater. (A) Nighttime THEMIS-IR highlights the rayed crater ejecta. (B) Daytime THEMIS-IR likewise shows a rayed signature but as darker rays in contrast to surrounding terrain. Image credit: NASA/JPL/Arizona State University.

3. The Martian landscape

From a geomorphologic viewpoint the Martian landscape is one of the most fascinating planetary surfaces in the solar system. Due to the low erosion rates during and due to the lack of plate tectonics, Mars has preserved landforms from past geologic events. In this sense Mars is an invaluable geologic archive to processes and events that have shaped the planet since the formation of the Martian crust. The Martian landscape bear witness of the presence of past rivers and lakes, a dramatic early shift in climate, migrating dune fields, cataclysmic meteoric impacts and flooding, and global changing volcanic activity. More recently there are lines of evidence for regional glaciations, vast expanses of patterned ground indicating processes in ice-rich substrates, surface erosion by dust-devils and very recent episodic melting of snow or ice to form erosion landforms on slopes, so called gullies. In the following sections a number of landforms will be presented that reveal these stories from the past and present. Due to the rich variety of environments and landforms only a selected few will be discussed. For more in-depth discussions on Martian surface features I would like to refer to Carr (2006) and Balme et al. (2011).

3.1. Fluvial landforms

Liquid water cannot exist on the Martian surface under the low temperature and low atmospheric pressure conditions today. One of the most striking observations made by the Mariner 9 spacecraft was the discovery of what looked like dried-up riverbeds, the so called valley networks, and immense channels that seemed to have formed by catastrophic flooding, called outflow channels. Valley networks resemble terrestrial river systems in their dendritic form and suggest a mechanism of either sapping of groundwater or erosion by surface runoff due to precipitation. The majority of valley networks are found in the very ancient Noachian terrains. Outflow channels are very large, scoured channels. These are younger and Hesperian in age and emanated from collapsed depressions of jumbled rocks, called chaotic terrain. These observations came at a time when Mars was considered a dry and Moon-like planet so their discovery had a profound impact on our perception about Mars. More recent discoveries by the late Global Surveyor spacecraft is the gully-shaped forms that are found on much younger, Amazonian aged surfaces at the mid-to-high latitudes. These slope features are linked to very recent changes in climate, and suggest that water occasionally may still flow on Mars. In this section these three major landforms will be presented.

3.1.1. Valley networks

Valley networks are branching valleys, typically a few kilometers wide, and up to hundreds of kilometers long and the majority are found in the cratered uplands (Fig. 12A). While the early low-resolution observations suggested that valley networks were local features and immature systems, later high resolution imagery (Fig. 12B) has unveiled them as more intricate and extensive (Carr, 2006). Their formation has been a matter of controversy and several hypotheses have been proposed. Early ideas of glaciations, mass wasting, faulting and erosion by CO_2, wind and lava have now been replaced by a general consensus on water erosion. But whether it is surface runoff following rainfall (Carr and Malin, 2000; Craddock and Howard, 2002), or groundwater sapping from beneath a breached cryolithosphere (global permafrost shell) (Squyres and Kasting, 1994; Gaidos and Marion, 2003) is still debated. The majority of valley networks are distributed along the dichotomy boundary, where also playa-like deposits have been observed (e.g., Grotzinger et al., 2005; McLennan et al., 2005). These deposits were investigated in-situ at the Mars Exploration Rover Opportunity's site in Meridiani Planum. The playa environment and the distribution of valley networks made some researchers suggest that they formed due to an early hydrological cycle on Mars (Andrews-Hanna et al., 2010).

Discoveries of ancient deltas provided further support of a sustained hydrological cycle on Mars (Malin and Edgett, 2003). The delta found in the crater Eberswalde, is a fan-like landform consisting of a suite of sinuous ridges (Fig. 13A) and a complex of layered sedimentary rock (Fig. 13B). The sinuous ridges display features typical of terrestrial rivers such as meandering bends (Fig. 13C). The inverted form of the delta has been interpreted to result from deposition and cementation of fluvial sediments and later differential erosion of the weaker surrounding material (Malin and Edgett, 2003). Though the geomorphic evidence is compelling, the fluvial nature for the valley networks and associated landforms is still problematic. This is based on climate modeling which finds it very difficult to warm Mars enough so that liquid water may exist at the surface (Haberle, 1998). Some additional issues associated with the notion of a warm and wet early Mars is (1) the difficulties to warm early Mars when the solar energy was less that it is today (Kasting, 1991); (2) the difficulty of sustaining a thick CO_2–H_2O atmosphere against losses of weathering (i.e., weathering to convert CO_2 to carbonates and sequester it in the ground); (3) the vulnerability of Mars' early atmosphere to impact erosion by large impacts; (4) the low amount of weathering products that would have been expected from warm Mars (Bandfield et al., 2000); and (5) the abundant detection of easily weathered minerals such as olivine (Hoefen et al., 2003).

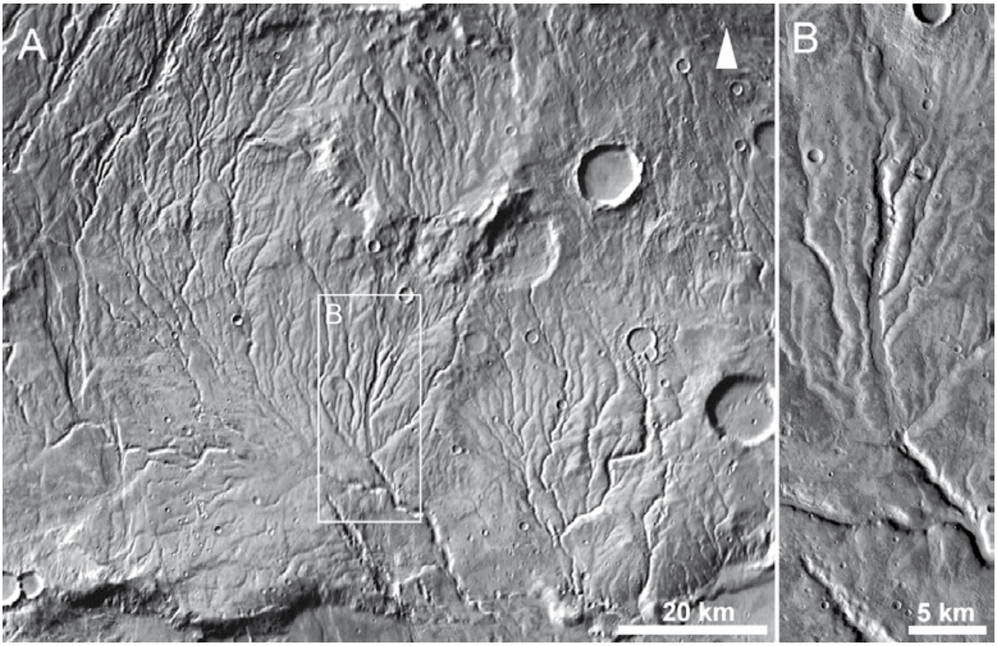


Figure 12. The famous Warrego Valles drainage basin on Mars which probably formed during the Noachian. (A) Image mosaic of THEMIS daytime IR showing the extent of the dendritic drainage area. Image source: Google Earth. Credit: NASA/JPL/UoA. (B) Close up of channels within the system (42.31°S/267.51°E; THEMIS daytime IR; V6907004). 1st and 2nd order channels are clearly distinguished. Image is 17 km across. Image credit: NASA/JPL/UoA.

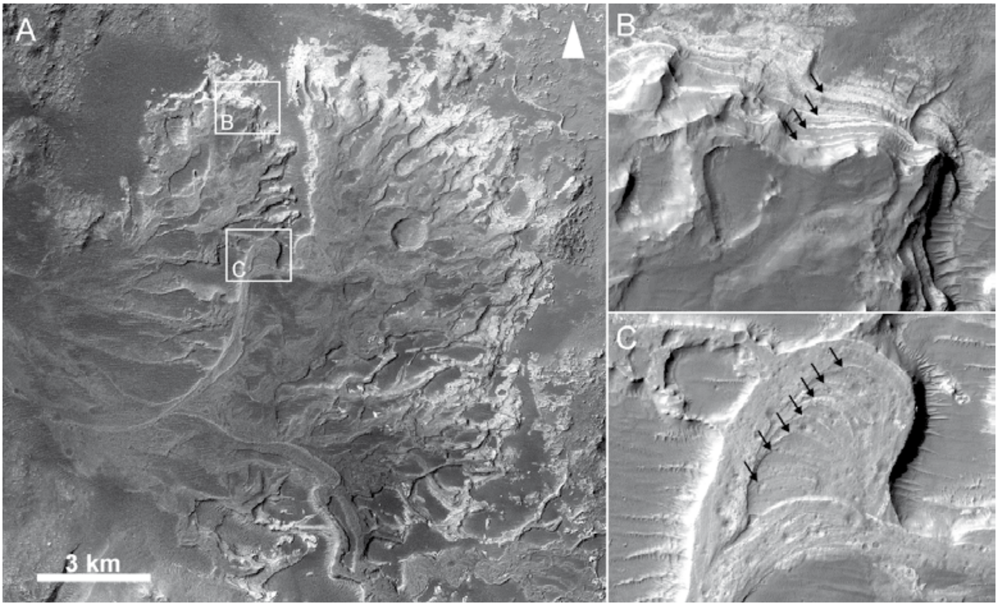


Figure 13. Morphologic evidence for continuous flow within the Eberswalde crater (24.0°S/326.4°E). (A) Context MOC image (MOC2-1225) of an inverted delta. (B) Close up HiRISE (PSP_001534_1560) image show the layered structure of the deposits (black arrows). (C) Close up of the preserved point bar. Note signs of succeeding growth of the bar (black arrows). The Eberswalde delta is one of the most compelling evidences of extended fluvial erosion and deposition during the Noachian. Image credit: NASA/JPL/UoA.

3.1.2. Outflow channels

Some of the more prominent features on Mars are the so called outflow channels. They vary greatly in size from less than 1 km across to, over 400 km across, which is the case for Kasei Valles, the largest outflow channel on Mars (Fig. 14). At their largest scale, typical features are broadly anastomosing channels (Fig. 15A) separated by residual uplands, or "tear-drop islands"(Fig. 15B), of pre-flood-modified terrain and hanging valleys (Fig. 15C). The channels have low sinuosity and high width–depth ratios (Carr, 2006). The outflow channels probably dates back to events during the Noachian/Hesperian boundary (e.g., Dohm et al., 2000) and during the early Amazonian (Ivanov and Head, 2001), while some may be as young as less than 10 Ma (Hartmann and Berman, 2000). They occur in a wide variety of geological settings and typically emanate from local depressions of jumbled rocks, named chaos terrain (Carr, 2006). Some, however, are located near grabens and are likely associated with fissure volcanism (e.g., Head et al., 2003b). The origin of outflow channels is still enigmatic, but water is thought to be the eroding agent in a majority of cases. This water has been released from beneath a breached cryosphere (Baker, 2001). The mechanism of release likely varies from volcanism, impacts and tectonics (Carr, 2006). The outflow channels, however, imply immense amounts of water and the question to what extent it influenced the climate is still not clear (Carr, 2006). On Earth, out flow channels mostly refer to outflow from a lake (normally ice-dammed). The Channeled Scablands in the USA may act as a close analogue for the Martian outflow channels (Baker, 2009).

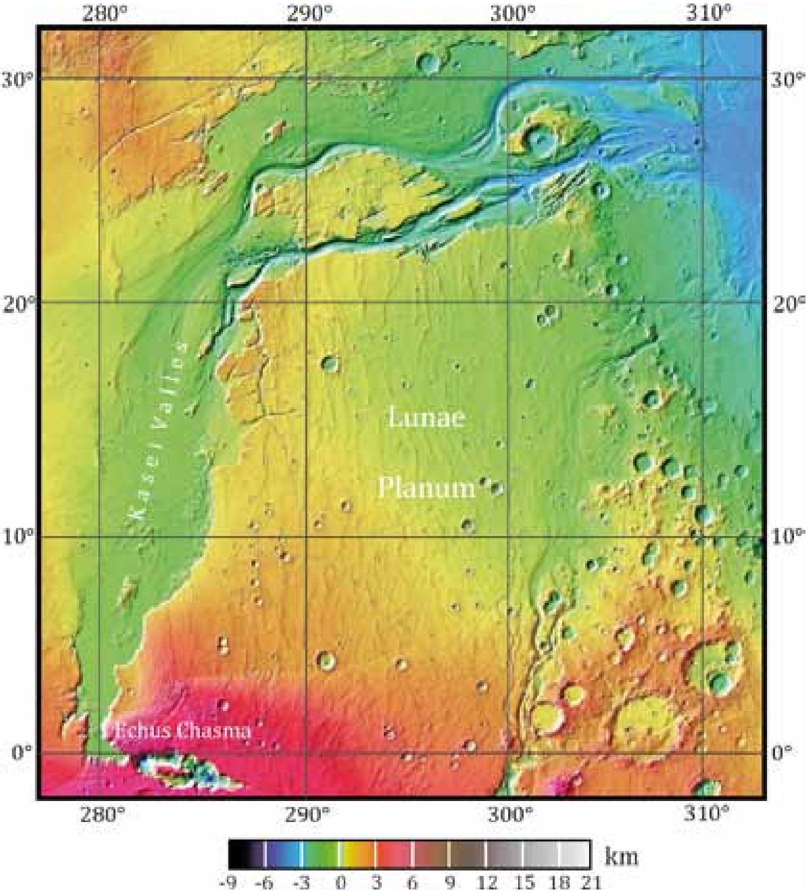


Figure 14. Topographic map of Kasei Valles, the largest outflow channel on Mars. The source region Echus Chasma (lower left) suggest that water reached the surface from a deep aquifer. Kasei Valles is located in the northern hemisphere (modified from FU Berlin/MOLA).

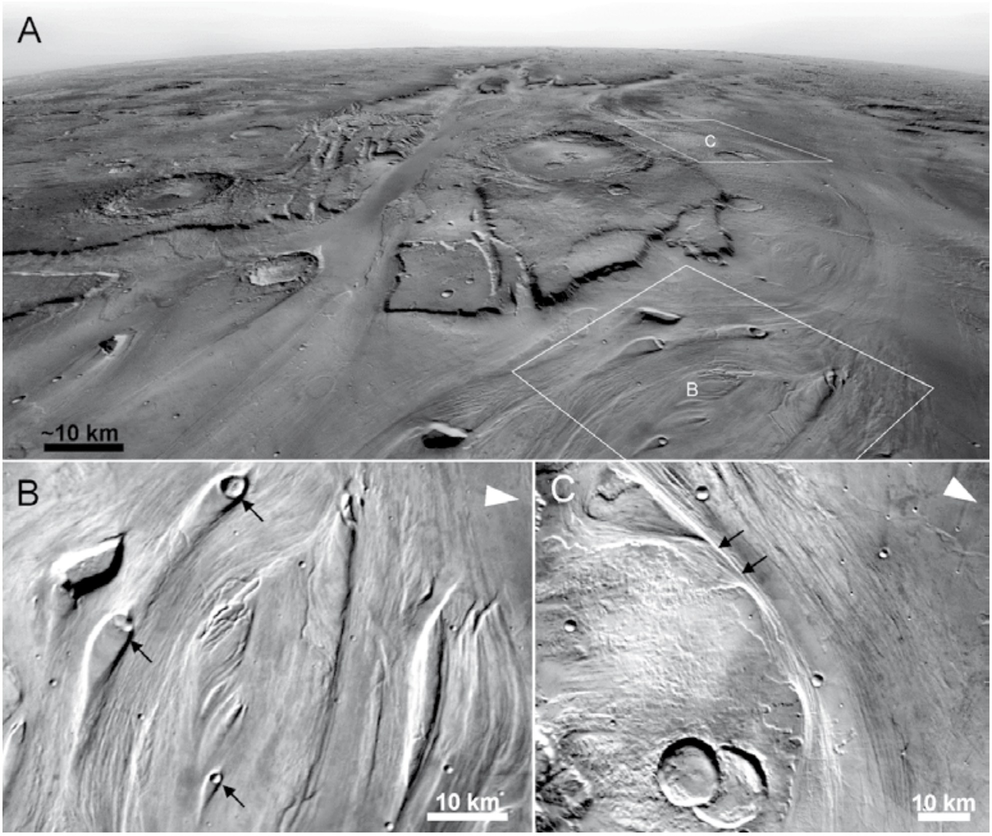
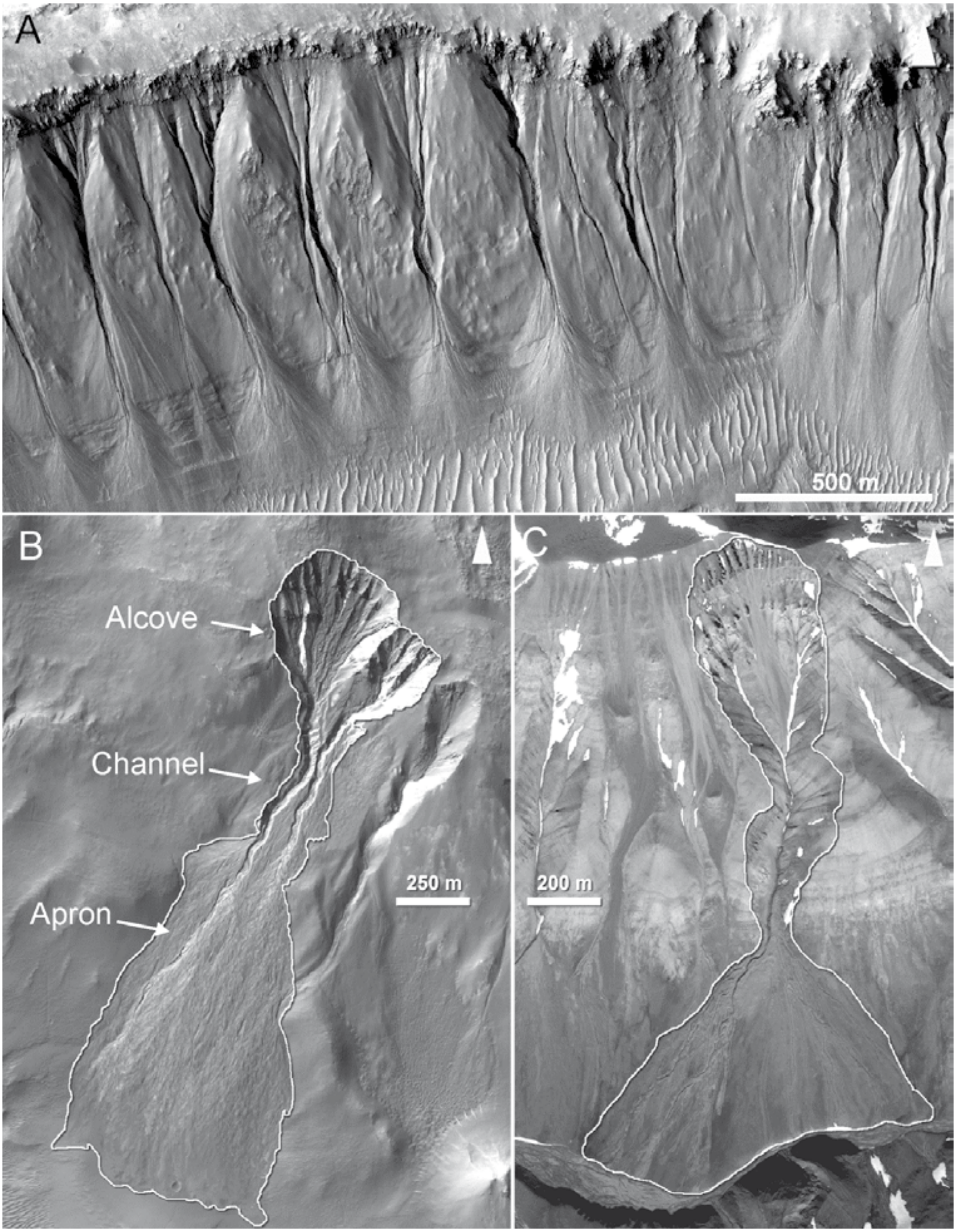


Figure 15. The Kasei Valles erosion bed forms where the channels reaches the northern low lands. (A) Computer rendered oblique view of the anastomosing channels. Area represents the upper right quadrangle (20°-30°N/300°-310°E) in figure 15. (B) Characteristic tear-drop shaped islands within the channel (black arrows). Craters have acted as obstacles for the flowing water and sediments has been preserved leeward of the craters. (C) Scoured channel floor and a "hanging" valley (black arrows). Image credit: NASA/JPL/Arizona State University, R. Luk.

3.1.3. Gullies

Before the arrival of the Mars Global Surveyor (MGS) spacecraft in 1997 only the valley networks and outflow channels were the known geomorphic indicators of possible flowing water in Mars geologic past. While valley networks is suspected to form under very different climate conditions than today and the outflow channels are connected to isolated dramatic events, the discovery of gullies was a great surprise for the planetary science community. By the advent of the narrow-angle Mars Orbiter Camera (MOC) onboard MGS, scientist could now resolve objects at the surface that were just a few meters across. Discovered were small, seemingly young erosional features incised into steep slopes (Fig. 16A). Gullies consist of an upper theatre-shaped alcove that tapers downward to converge on one or more channels that extends further downslope, commonly terminating in triangular debris apron, or fan (Fig. 16B) (Malin and Edgett, 2000). In plan form they show a striking resemblance to gully landforms in Svalbard (Fig. 16C). Gullies are discussed in more detail in paper II, and more briefly in paper IV and V.



Figur 16. Gullies on Mars and Earth. (A) HiRISE image ESP_011727_1490 (30.9°S/316.1°E) of interior crater gullies on the southern hemisphere on Mars. Gullies are believed to be young landforms and in this particular image the aprons are superpose the aeolian ripples. (B) They have a typical morphology consisting of an alcove, channel and debris fan (HiRISE image PSP_006888_1410 at 38.5°S/319.8°E). (C) Gully in Hanaskogdalen on Spitsbergen which is of similar morphology and dimensions (HRSC-AX image). Image credit: NASA/JPL/UoA and DLR.

The fluvial character of the gullies were puzzling, since the Amazonian period of Mars has generally been characterized as having climatic conditions similar to those observed today, such as a low-temperature, low-pressure, hyper-arid environment dominated by eolian activity (Carr, 1996; Golombek et al., 2006; Marchant and Head, 2007). While this impression is likely accurate for globally averaged conditions over time, the discovery of extremely young gullies at mid-to-high-latitudes may suggest that conditions have been adequate for transient surficial flow of liquid water, at certain locations at certain times, within the last several million years (Malin and Edgett, 2000). While numerous "dry" hypotheses has been proposed to explain their formation such as dry mass movements (Treiman, 2003), and CO_2 driven processes (Musselwhite et al., 2001), the general view today is that liquid water is the primary agent of erosion for the majority of gullies. This notion is supported by the latitudinal distribution (e.g., Milliken et al., 2003; Dickson et al., 2007; Kneissl et al., 2010), Earth analogue studies (e.g., Head et al., 2007; Reiss et al., 2011), detailed geologic studies (e.g., Schon et al., 2009a; Reiss et al., 2010), and climate modeling which all suggest that scenarios of melting ground ice and/or melting snow packs are more likely sources of water(e.g., Costard et al., 2002; Head et al., 2008). For a more detailed description and discussion on gullies please see paper II (Reiss et al., 2011) and associated landforms in paper IV.

3.2. Aeolian landforms

At present-day Mars the actions of global dust storms can veil the surface from our satellite cameras and on the surface marching schools of dust-devils leave their swirling markings as they move along (Fig. 17A). Despite the very thin atmosphere winds has had an active role throughout Mars geologic history. This becomes clearly evident from the wide variety of aeolian features that are seen on the surface such as yardangs (Fig. 17B), vast dune fields (Fig. 17C), channel entrenched ripples, wind streaks (dust deposited lee-ward of obstacles), and wind-abraded rocks.

Our understanding of planetary aeolian processes is based largely on Earth analogs coupled with theoretical modeling and wind tunnel experiments (Craddock, 2011 and references therein). On Earth the fragmental debris available for wind transport is mainly quartz sand that has been derived from mechanical and chemical weathering of granitic rocks (Carr, 2006). Sand spend a relatively short time at the surface before being transported to the oceans where it gets buried and by time lithified and incorporated into the sedimentary rock record. The situation on Mars is quite different. Since Mars has lacked bodies of water at the surface for most of its geologic history no such sands sinks are available. Granitic rocks, if present at all, would constitute a very minor source for quartz sand (Melosh, 2011). Thus, most of the loose sediments we observe today were probably produced during the Noachian when erosion rates were much higher than today. Dust (very fine-grained material) and sand on Mars are therefore very ancient.

Dunes are common landmarks on Mars, and especially abundant in the high latitudes forming *ergs* (dune seas) surrounding the polar caps. Dunes are also common within impact craters which act as dust traps. Even though dunes on Mars show striking similarities to terrestrial dunes, much of their formation and evolution is not fully understood (Melosh, 2011). Early temporal investigations using MOC imagery did not indicate any movements of dunes (Zimbelman, 2000; Malin and Edgett, 2001), and part of the problem was believed to be the thin, low density, atmosphere (e.g., Almeida et al., 2008). Consequently, the dunes were believed to be relict forms inherited from earlier climate regimes, with only minor changes over time (e.g., Bourke et al., 2008). It was found, not until very recently, by analyses of multi-temporal high resolution data sets that this notion may be wrong. It was found that most dunes and ripples move at a rate of a few meters per year under current atmospheric conditions. However, coarse-grained dunes may need conditions of a past Martian climate in order to move (Bridges et al., 2012).

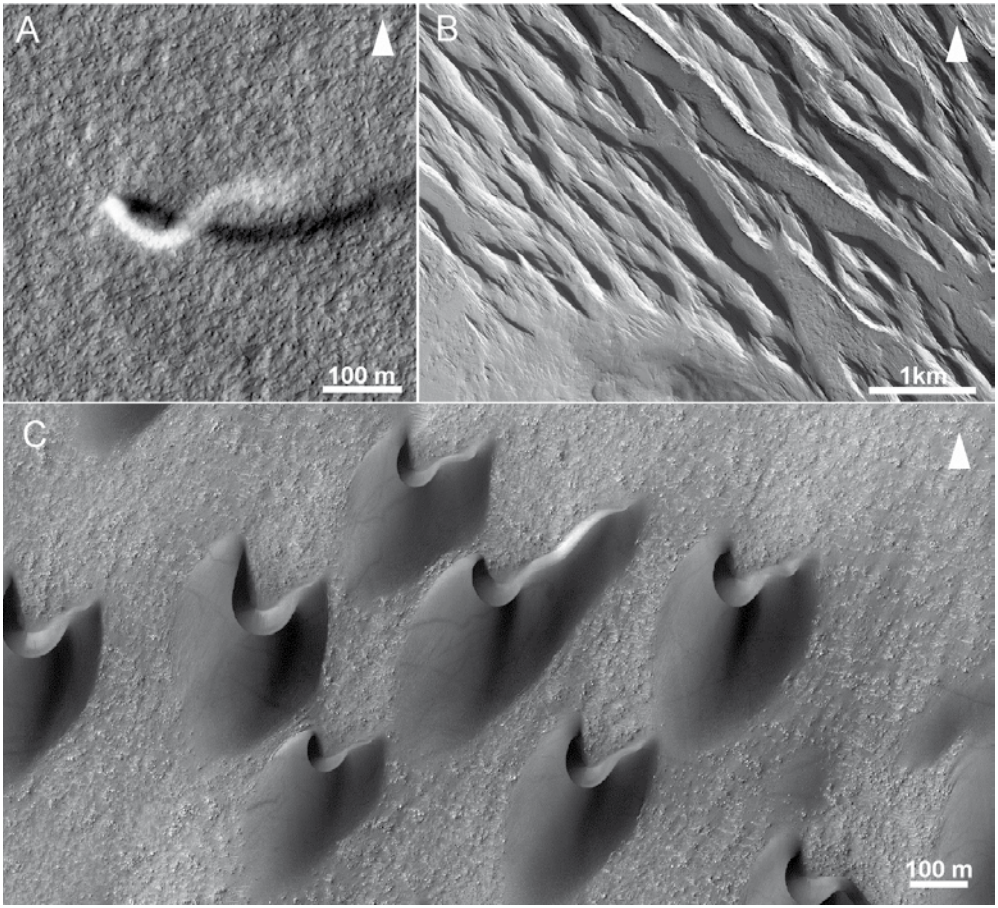


Figure 17. Examples of aeolian features on Mars. (A) Active processes such as dust devils are very common. In this HiRISE ESP_026051_2160 subset a swirling dust devil has been imaged which is approximately 30 m in diameter (35.82°N/207.5°E). The dark streak is the dust devil's shadow. (B) Yardang's are common in the equatorial regions and show ancient wind regimes. (HiRISE ESP_021568_1925, 12.25°N/199.8°E) (C) The most abundant wind sculpted features on Mars are the dunes. HiRISE image ESP_019559_1390 of typical barchanoid dunes of low albedo sediments (40.86 °S/335.0°E). Wind direction from NE to SW. Image credit: NASA/JPL/UoA.

3.3. Glacial landforms

Already in the 1980's came the suspicion that Mars may contain large amounts of ground ice and/or debris covered ice at high latitudes. This notion came from the apparent smoothing of the terrain at these latitudes, such as low-gradient slopes and muted topography. These effects were interpreted as results from viscous creep of ground-ice (Squyres and Carr, 1986). Today, there is a wide range of landforms that are interpreted to be the result from present and past actions of glaciers such as moraine-like features (e.g., Arfstrom and Hartmann, 2005), lineated valley fill (e.g., Levy et al., 2007) , concentric crater fill (Levy et al, 2010), lobate debris aprons (e.g., Hauber et al., 2008). These observations are also supported by modeling (e.g., Forget et al., 2006; Madeleine et al., 2009). Milliken et al. (2003) identified tongue-shaped features in the mid-latitudes that they interpret as slow creep of ice-rich sediments (Fig. 18A), not unlike rock glaciers on Earth (Martin and Whalley, 1987). Other features resembling cirque glaciers (Fig. 18B) and protalus ramparts (Fig. 18C, and discussed in paper I and V) are seen in the mid-latitudes.

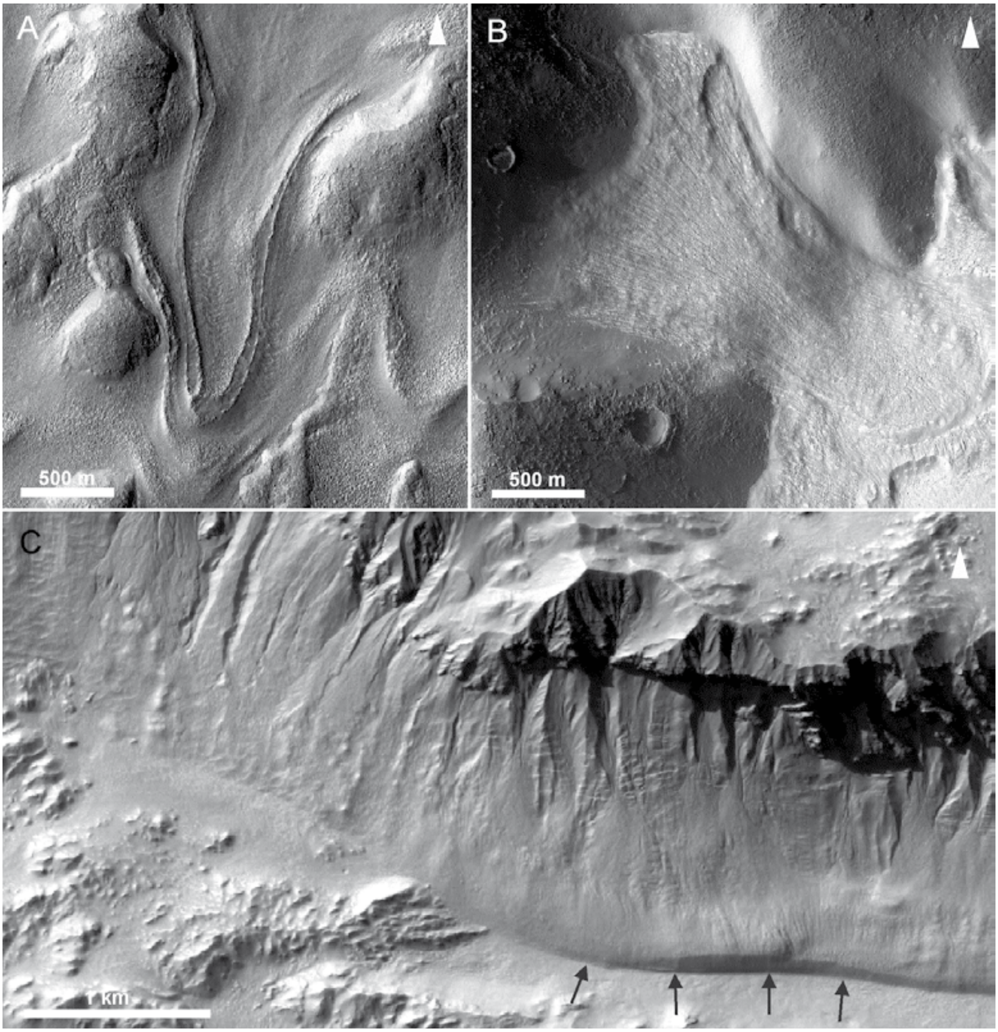


Figure 18. Types of possible glacial landforms on Mars. (A) HiRISE image of a tongue-shaped feature which has been interpreted to be debris covered glacier similar to Earth's rock glaciers (Milliken et al., 2003; Souness et al., 2012). (B) Possible cirque glacier. (C) Protalus rampart-like landforms in Hale crater (Hauber et al., 2011a) (black arrows marks the flow front). These may suggest frequent snow avalanches and subsequent dust deposition during episodes of higher obliquity. Image credit: NASA/JPL/UoA.

Part 3

Cold-climate landforms on Mars and Earth-analogues in Svalbard

4. Permafrost and ground ice on Earth

Permafrost is defined as any ground that remains at or below 0°C (~273 K) for at least two or more consecutive years, regardless of the presence of ice. Since the presence of mineral salts or higher pressure can depress the freezing point of water below 0°C, permafrost is not necessarily frozen (e.g., French, 2007). On Earth, approximately 20% of the land surface is underlain by permafrost, and its presence is typically seen as a range of landforms such as polygonal-fractured ground (wedge polygons), creep of rock-and-ice substrates (rock-glaciers), ice-cored mounds (pingos), sorting a clasts (sorted stone circles, nets, labyrinths and stripes), and slow mass wasting due to thaw or frost action (solifluction lobes). Collectively, these structures are called "periglacial" (Everdingen, 2005) and their morphological counterparts are observed on Mars. A review of these processes and their use in our analogue research is provided in paper (I). Sorted ground and solifluction occurs within the active-layer, which is defined as the layer of ground that is subject to annual and/or diurnal thawing and freezing in areas underlain by permafrost (Everdingen, 2005). Solifluction landforms in Svalbard and their counterparts on Mars are specifically dealt with in paper (III). One of the most important features in periglacial landscape dynamics is the occurrence of ground ice. Four main types of ground ice can be distinguished; segregated ice, wedge ice, intrusive ice, and pore or interstitial ice (Yershov, 2004; French, 2007). Segregated ice is the general term for ice accumulation in fine-grained soils with high ground-ice contents; it is formed by pressurized migration of water to the freezing front through the adjacent soil pores. It can be distinguished from pore or interstitial ice by its ice content and its structures. Pore ice merely cements the soil (French, 2007). Large bodies of ground ice mainly occur in the upper part of frozen ground. Pingos contain either intrusive ice cores that result from intrusion water under artesian pressure, or segregation ice by pore-water extrusion and freezing by aggrading permafrost in wet sediments (e.g., Williams and Smith, 1989). Ice-wedge bodies are developed when meltwater fills frost cracks, a process that occurs almost every summer. These cracks are caused by thermal contraction of ice within the ground during cold spells, a process that results in polygonal patterned networks of cracks at the surface when stress exceeds the soils shear strength (Lachenbruch, 1962). Massive bodies of ice can also originate from, e.g., buried glacier ice (ice-cored moraines).

4.1. Introduction to Spitsbergen, Svalbard

4.1.1. Svalbard climate and periglacial context

The present climate of Svalbard is arctic (Fig 19A and B). The mean annual air temperature ranges between about –6 °C at sea level and –15 °C in the high mountains. In Longyearbyen (78°13′0″N, 15°38′0″E), which is located near the study area in Adventdalen (Fig. 19C), the coldest (February) and warmest (July) months have mean temperatures of –15.2 °C and 6.2 °C, respectively. The mean annual air temperature is –5.8 °C (average 1975–2000), but it can get as low as -15 °C in mountain areas. Precipitation is low and reaches only ~180 mm in central Spitsbergen. At the coasts of Svalbard, the precipitation is ~400–600 mm. The central part of Spitsbergen can therefore be considered to be a polar (semi)desert, which is defined as an area with annual precipitation less than 250 mm and a mean temperature during the warmest month of less than 10 °C (Walker, 1997). Inter-annual differences in mean precipitation and temperatures can be very high. Heavy snowfalls can occur in December and January in some years, and snow is the dominant type of precipitation. Snow avalanches are frequent, especially on downwind slopes. Svalbard lies at the border zone between cold arctic air in the north and mild maritime air in the south. This border zone can be meteorologically very active, with cyclones generating unstable and often stormy weather. Strong winds can occur in winter and redistribute the snowpack, so that wind-exposed sites, particularly in the more arid regions of central Spitsbergen, can be more or less snow-free even in high winter, enhancing heat loss from the ground (Humlum et al., 2003). At the more maritime western coast, the thicker snowpack in winter acts as an effective insulator (Winther et al., 2003). About 60% of Svalbard is covered by glaciers and ice caps. The remaining part (~25,000 km2) is characterized by continuous permafrost (Brown et al., 1997). Permafrost thickness is 10–40 m in coastal regions and ~100 m in the major valleys, but it can increase to more than 450 m in the highlands (Liestøl, 1976; Isaksen et al., 2001; Sollid et al., 2000). The age of the permafrost on Svalbard is Weichselian in the mountains and late Holocene in the coastal areas and in the valleys (Humlum et al., 2003). Permafrost temperature is between –2.3 °C and –5.6 °C, with a trend toward warming (Christiansen et al., 2010).

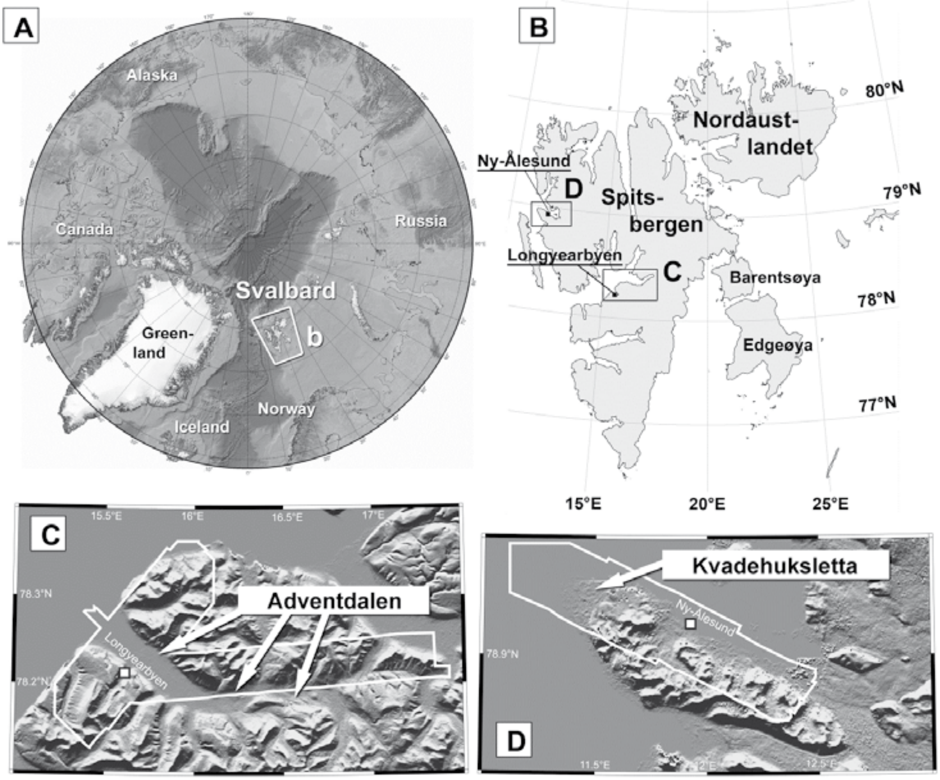


Figure 19. Context maps of study areas. (A) Map of the Arctic, with location of Svalbard highlighted. (B) Map of Svalbard with study areas highlighted. (C) Study area in Adventdalen (cf. Fig. 3A). White outline shows coverage by High-Resolution Stereo Camera (HRSC-AX) (base map: hillshaded version of Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) digital elevation model [DEM]). (D) Brøgger peninsula with white outline showing the coverage by HRSC-AX (base map: hillshaded version of ASTER DEM). The study area, Kvadehuksletta, is located at the northwestern tip of the peninsula.

4.1.2. Geology

The geology of Svalbard is extremely diverse, given the limited size of the archipelago. A comprehensive description is available from Harland (1997). For the purpose of this thesis, a brief description of the overall geography and geology of the study sites is sufficient.

At the largest scale, the topography of central Spitsbergen (Nordenskjøld Land) is dominated by mountain massifs that are separated from each other by valleys, which are in some cases interconnected. The glacial valley, Adventdalen, the site where most of the terrestrial features discussed in this study are located, has been ice free since ~10,000 yr ago (Mangerud et al., 1992). It is ~40 km long and hosts many periglacial landforms. The bedrock of the massifs bordering Adventdalen consists of Jurassic and Cretaceous sediments (Dallmann et al., 2002). Most of the bedrock in the study area belongs to the Helvetiafjellet and Carolinefjellet Formations (Dallmann et al., 2001). Their lithology is characterized by sandstones, siltstones, shales, and some thin coal seams (Parker, 1967; Major and Nagy 1972). The rocks are thinly layered (centimeters to tens of centimeters), and the layering is generally subhorizontal. The rocks are heavily fractured by frost-shattering and, particularly near the coast, salt weathered. Most of the periglacial landforms in Adventdalen (e.g., pingos, ice-wedge polygons) were formed in the late Holocene and are ~3000 yr old (Svensson, 1971; Jeppesen, 2001; Humlum, 2005), but some ice wedges at high elevations might have survived the Weichselian ice age under cold-based glaciers (Sørbel and Tolgensbakk, 2002).

The second study site is located on the outermost part of the Brøggerhalvøya (Fig 19D). The lithology of the mountains in the hinterland is predominantly dolomitic (Challinor, 1967). The study area at Kvadehuksletta is an abrasion platform (Fig. 20) with well-developed raised beach ridges up to an elevation of 80 m above sea level. The sediments covering the strandflat have a calcitic and dolomitic composition (Dallmann et al., 2002). The reader is referred to Svendsen et al. (2002) for an in-depth description of the physical environment of the Kongsfjord region.

Figure 20. Photo of the abrasion platform at Kvadehuksletta. Sorted stone circles are visible in the background. Photo taken during the 2011 field campaign. Photo credit: Matthew Balme.

5. Mars cryosphere

Since Mars is a cold planet with a mean global temperature of -53°C, and only reaches temperatures above 0°C skin-depth in the equatorial regions, all of the available water is currently locked up in frozen reservoirs, such as the polar caps, polar layered deposits, as mid-to-high latitude ground-ice and as debris covered glacier ice (Fig. 21). These are the currently known reservoirs, but while there are no direct measurements, the subsurface reservoir may be substantially larger (Carr, 2006). The thickness of the cryolitosphere (global permafrost shell) has been estimated to be in the order of 1-3 km in the equatorial zone and 3-7 km in the Polar Regions (Kuzmin, 2005; Forget, 2007). To date, radar sounding has found no evidence for aquifers or deep occurring ground ice. Thus, their presence or possible characteristics remain poorly constrained. In the following chapter the known near-surface reservoirs will be presented.

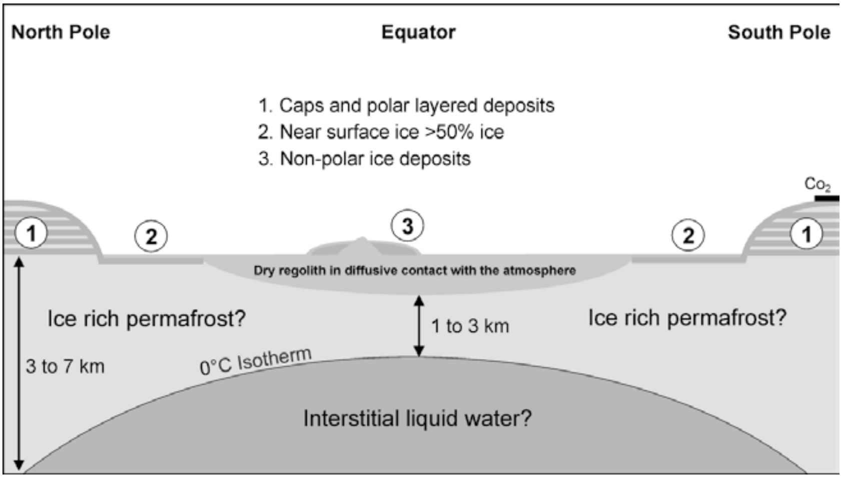


Figure 21. Schematic profile with the largest known reservoirs of frozen water on Mars. These include (1) caps and the polar layered deposits, (2) near-surface ice, (3) non-polar deposits (modified from Forget, 2007).

5.1. Polar caps and polar layered deposits

The most easily recognizable ice deposits on Mars are the polar caps. These permanent polar caps are a mixture of solid phase carbon dioxide (CO_2 ice) and water ice. Since the measurement by the Viking Orbiter Infrared Thermal Mapper in the 1980's the northern cap (Fig. 22) has been known to mainly consist of water ice with a residual cap of CO_2 ice (Kieffer et al., 1976). In the winter, the cap gains a seasonal coating of solid phase carbon dioxide about one meter thick. The perennial cap is approximately 1100 km across in summertime and about 2 km thick if the total amount of ice was spread evenly (Carr, 2003).

The southern cap is smaller and 350 km across, with a slight offset from the geographical south. It is approximately 3 km thick and almost completely covered by perennial CO_2 ice. For a long time the blanket of CO_2 ice made observations of the bulk cap composition impossible. It was not until the advent of the Mars Express spacecraft and the *Observatoire pour la Mine´ralogie, l'Eau, les Glaces et l'Activite´* (OMEGA) instrument that it could be confirmed that also the southern cap consists of water ice (Bibring et al., 2004).

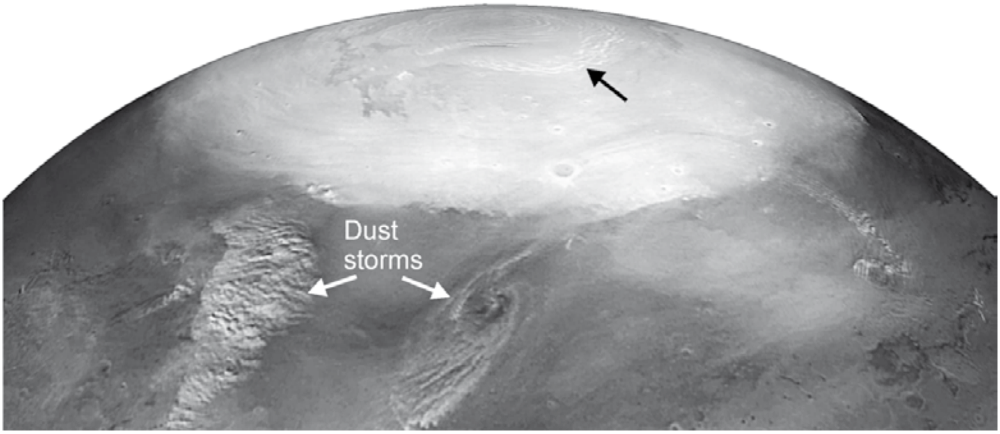


Figure 22. Image mosaic of northern polar cap of Mars. Images were taken by the Mars Global Surveyor spacecraft in 2002. Mosaic shows the extent of the CO_2 ice during the northern winter and some seasonal dust storms. Outlines of the perennial H_20 cap are vaguely visible (black arrow). Image credit: NASA/JPL/Malin Space Science Systems.

At the base of the caps and also surrounding them, are finely layered deposit, so called *polar layer deposits* (PLD). At a regional scale, the surface of the PLD's is generally smooth and gently rolling. The smooth, relatively uncratered surface, stratigraphic relationships (Tanaka, 2005) and climate modeling (Levrard et al., 2007) suggest an age of less than 5 Ma. The PLD's are approximately 3 km thick and the individual layers range from 10–30 m in thickness. The alternating dark and bright layers are interpreted as the relative proportions of dust and ice in each layer. Individual layers can be traced for 100' of kilometers in some cases, and some layers show unconformity. The North and South PLD's of Mars are believed to be of fundamental climatological importance because they represent the largest actively-exchanging reservoir of Martian water. It is thought that the PLD's are produced by cycles in the Martian orbit, driving climate change through insolation variations affecting the ice/dust ratio of the accumulating layer (e.g., Squyres, 1979; Toon et al., 1980). As such, the PLD's are important climate archives (e.g., Milkovic et al., 2008). The global-equivalent-water-depth locked up in the north polar cap is approximately 5 m (Phillips et al., 2008) and 11 m in the south polar cap and layered deposits (Plaut et al, 2007)

5.2. Non-polar ice deposits

The amount of preserved non-polar ice is poorly constrained on Mars, but morphologic evidence for its presence and past actions is ubiquitous (Carr, 2006). Studies have revealed evidence for ice related deposits in non-polar regions, including tropical mountain glaciers (e.g., Head and Marchant, 2003) and mid-latitude glacier-like flows (e.g., Lucchitta, 1981; Squyres and Carr, 1986; Pierce and Crown, 2003). Along some parts of the crustal dichotomy there is evidence for valley-like glaciations. Estimates on glacial thickness suggest a maximum thickness of 2.5 km in this area (Dickson et al., 2008). Though, the timing of major glaciations is currently not well-constrained. Modeling suggests that obliquity exceeding 45° is needed (e,g., Forget et al., 2006), conditions that was reached before ~5 Ma ago (Laskar et al., 2002).

5.3. Ground-ice

At latitudes 60° and poleward on both hemispheres the surface looks relatively smooth in high-resolution imagery. At lower latitudes, to about 30°, the upper surface layer appears dissected (Mustard et al., 2001). Both the smooth and dissected surfaces are part of the meters thick latitude-dependent-mantle which is hypothesized to be an air-fall deposited sediment layer that drapes the underlying topography (Kreslavsky and Head, 2000). The characteristics of this particular geologic unit will be discussed in the section 6.1. Interestingly though is that this unit contains significant amounts of ground ice. Until recently, we had only models of the distribution of ice in the near-surface materials (e.g., Mellon and Jakosky, 1995), but measurements made by the Gamma Ray and Neutron Spectrometers (GRS/NS) onboard the Mars Odyssey spacecraft showed that this mantle unit may be saturated by ice (Fig. 23.) (Boynton et al., 2002; Feldman et al., 2002; Feldman et al., 2004). Later, the Phoenix Lander confirmed the presence of significant quantities of ice beneath a dry, centimeter thick, sediment layer in the high northern latitudes (Mellon et al, 2009; Smith et al., 2009). Moreover, findings at the Phoenix landing site of relatively pure ice deposits may point to ice segregation, similar to needle ice and ice lens formation on Earth (Mellon et al., 2009). In addition, spectral analyses of water ice excavated from impact craters in a mid-latitude region show that ice is clearly available at other locations in mid-and-high latitudes as well (Byrne et al., 2009. These findings is in agreement with ice-stability models that suggest stable ground ice can exist near the surface only at higher latitudes (>50–60°N and S) under the current Martian climate, but ice could generally be stable at depths below 1 m at latitudes down to ~40–45°N and S (e.g., Mellon and Jakosky, 1995; Mellon et al., 2004). Therefore, the depth of the ground-ice table varies in relation to the geographic distribution. The models also suggest that the stability of near- surface ground ice on Mars depends on the variations of Martian orbital parameters. If Mars' obliquity exceeds 32° (today ~25°) ground-ice becomes globally stable (Mellon and Jakosky, 1995). Since the orbital parameters change chaotically and the value of the mean obliquity in the Martian past was probably higher than today (Laskar et al., 2004), ground ice is believed to have exerted a significant influence on Martian landscape evolution. The estimated global-equivalent-water-depth of this near-surface ground ice is ~5 m (Feldman et al., 2004).

Although, several lines of evidence confirm the wide-spread distribution of ice-rich near-surface material, the origin of the ground ice is still not conclusive. Most of the studies concerning landforms with ground-ice affinity have focused on their formation in young Late Amazonian-aged units of the mid-and-high latitudes. These observations are in agreement with hypotheses of obliquity-driven air-fall deposition of ice-rich material during recent geological times (e.g., Head et al., 2003; Levrard et al., 2004; Madeleine et al., 2009). Other authors have discussed climatic and latitude-dependent water exchange by vapor diffusion into and out of the subsurface regolith (e.g., Mellon et al., 2004; Schorghofer and Aharonson, 2005; Schorghofer, 2007). The hypothesis of Martian ice-ages will be dealt with in more detail in section 6.

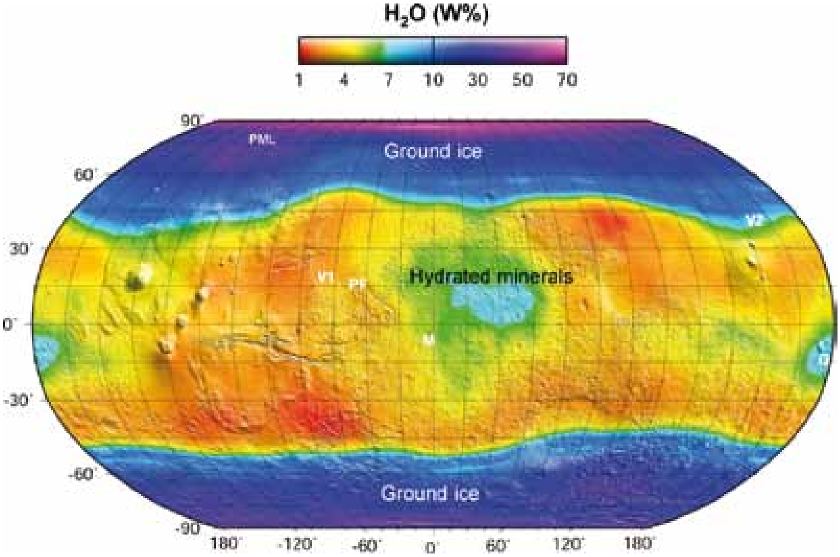


Figure 23. Global map based on gamma-ray signals from hydrogen within the upper meter of Mars surface as measured by the GRS instrument Odyssey Spacecraft. The high hydrogen concentration has been interpreted to be sediments supersaturated by ground ice. Letters denotes landing sites by rovers and landers: (PML) Mars Phoenix Lander, (V1 and V) Vikinglander 1 and 2, (PF) Pathfinder, (M) Meridiani Planum where MER Opportunity is roving, (G) Gusev Crater, the landing site for MER Spirit. Image credit: NASA/JPL/UA.

6. Obliquity driven climate change on Mars

Our current understanding about Mars geological evolution implies a dramatic shift in climate at the end of the Noachian, to account for the end of valley network formation and the drastic decrease in erosion rates (e.g., Carr, 2006; Carr and Head, 2010). What was not understood until fairly recently was the dynamic behavior of Mars climate in recent geologic history. The discovery of glacial deposits, and latitude dependence of terrain smoothening (Kreslavsky and Head, 2000), youthful gullies (e.g., Milliken et al., 2003) and pristine-looking periglacial landforms such as polygonal patterns (e.g., Mangold, 2005; Levy et al., 2009b), rock glacier-like features (Milliken et al., 2003) suggested that something more recent had happened on Mars. Latitude is the single variable with which all of these diverse observations correlate, and climate is the only process known to be latitude-dependent (Head et al., 2003). As previously been mentioned, Mars experience extreme variations in its orbital parameters (Laskar et al, 2002), and obliquity may reach 45° or more on a timescale of millions to tens of millions of years (Laskar et al., 2004). During periods of high obliquity (>30°), increased summer insolation on the polar regions results in greater water vapor release from the polar caps, increasing the atmospheric water vapor content and thus the humidity (e.g., Jakosky and Carr, 1985), as such the obliquity is the major climate forcing on Mars (Laskar et al., 2002).

6.1. Latitude-dependent mantle deposits

One particular consequence of the cyclic climate is the latitude dependent mantle. Mid-and-high latitudes on both hemispheres are dominated by a surficial, meters thick, mantle deposit that drapes the underlying topography (Kreslavsky and Head, 2000). The mantle has been proposed to have formed by fine-grained subaerial sediments which have been cemented by atmospherically deposited ice. The mantle has been traced equatorward to ~30°N and S latitude. The mantle has been recognized to be geologically recent (Mustard et al., 2001; Milliken et al., 2003) and its formation driven primarily by Mars obliquity excursions (Head et al., 2003), but it is not clear how much of this thickness is deposited during one obliquity cycle. As mentioned in the above section, mean polar insolation will increase when obliquity is higher and volatiles located at the poles will sublimate and redistribute to lower latitudes which acts like cold sinks under these insolation conditions (Head et al., 2003; Levrard et al., 2004; Madeleine et al., 2009). Furthermore, at latitudes between ~30° and ~60° on both hemispheres the mantle appears dissected (Fig. 24A and B) which has been interpreted as a current loss of ground-ice by sublimation (i.e. cryocarst) and loss of sediments by wind erosion (Mustard et al., 2001). The layered nature of the mantle has been interpreted as cyclical episodes of deposition (Fig. 24C), and could be an argument against the diffusion model (Schon et al., 2009b). The sublimation of the mantle has been linked to changing ice-stability conditions, so that at the present less obliquity, the zone of ice-stability has moved more poleward, thus leaving near-surface ice in the latitude band between 30° to 60° exposed to sublimation (Fig. 25) (Mustard et al., 2001). Recognizing the relationship between obliquity variability and climate has led to the hypothesis of a recent ice age during a period of enhanced obliquity variation from 2.1 to 0.4 Ma (Head et al., 2003). Many young landforms show the same latitudinal dependence, such as gullies (Milliken et al., 2003; Kneissl et al., 2010), polygonal ground (Mangold, 2005; Levy et al., 2009b), solifluction (paper III). Thus, they are clearly linked to the dynamics within the ice-rich mantle. The appended papers deal with conditions that have taken place within the last 5 Ma on Mars, which represent a dynamic period of accumulation and redistribution of water ice, sublimation of water ice and possible transient melting of snow and ice.

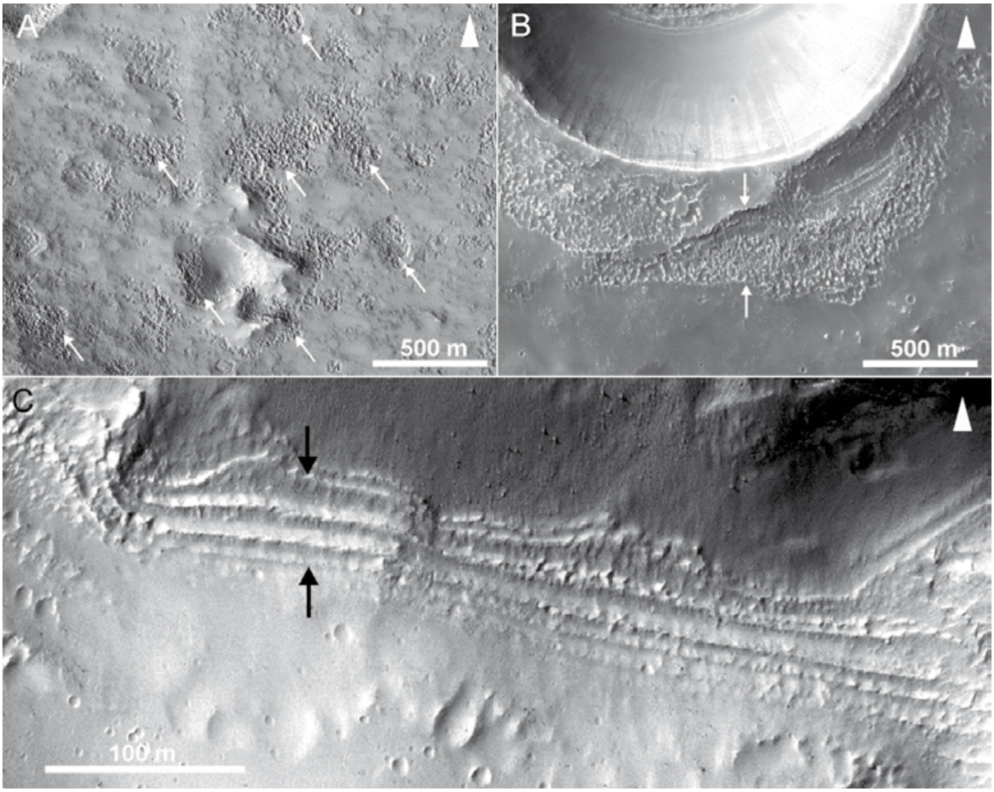


Figure 24. Compilation of dissected mantle terrain which forms due to sublimation of interstitial ice and removal of dust by wind. (A)HiRISE image ESP_011870_2145 (34.31°N/4.128°E) showing partially dissected mantle and smooth intact areas. (B) HiRISE image PSP_005804_1490 (30.64°S/ 35.89°E) of partially dissected mantle at an exterior crater wall. (C) HiRISE image PSP_001507_1400 (39.58°S/343.7°E) showing layering within the mantle terrain (black arrows). These layers support the notion of an air-fall deposited mantle of ice, snow, and dust related to geologically recent obliquity excursions (Schon et al., 2009).

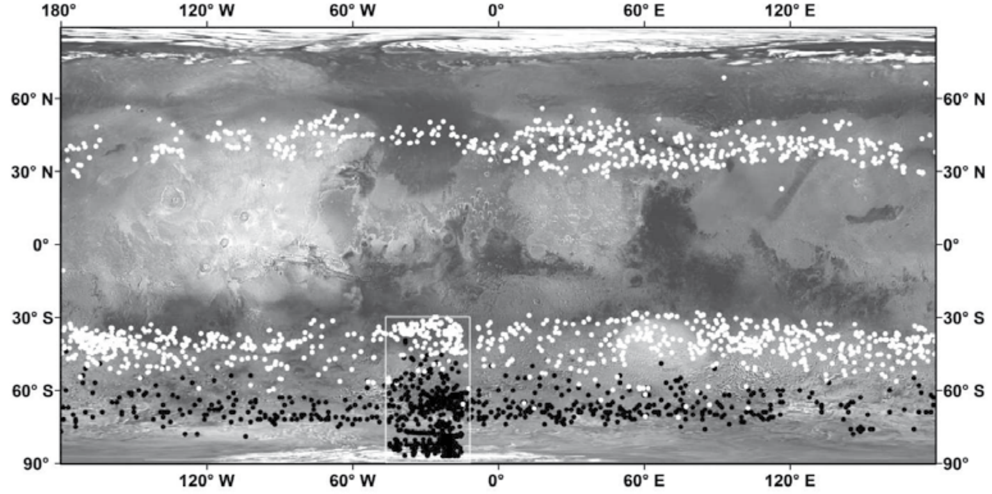


Figure 25. Global equidistant cylindrical projection of Mars showing the spatial relationship between dissected mantle (white dots) and data on polygonal patterned ground from the southern hemisphere (Johnsson et al, 2008) (black dots). Polygonal patterned ground forms by thermal contraction of an ice-rich substrate (Mangold, 2005). The white box contains polygonal and dissected landforms data from all available narrow angle Mars Orbiter Camera images (Johnsson et al., 2010). Note the striking latitude dependence (courtesy by J.F., Mustard)

7. Data and Methods

A number of datasets have been used within this thesis and these will be described in the following sections. Data include orbiter image data in the visible wavelengths at different ground resolutions and spatial coverage. Additional datasets such as infrared images to derive surface characteristics and elevation data for topography has been used as well. Together these datasets are powerful tools for landscape analysis. Image data has been used for morphologic interpretations and for putting detailed studies in a geologic context. For comparison to Svalbard, an instrument with the same properties as HRSC was used, called HRSC-AX. The benefits of using HRSC-AX instead of normal aerial photos are the ability to render detailed digital terrain models (DTM). The instrument also has a similar ground resolution as HiRISE which eliminates problems of scaling. Image analyses have been accompanied by field work aimed at validating image interpretations and increase ground resolution by field photos. Field works also aimed at acquiring soil samples and perform low-altitude imaging (in preparation).

7.1. Remote sensing data used for Mars

Key data sets for Mars include those obtained by the Mars Reconnaissance Orbiter (MRO) Context Imager (CTX) (Malin et al., 2007) and High Resolution Imaging Science Experiment (HiRISE) (McEwen et al., 2007). Mars Global Surveyor Mars Orbiter Laser Altimeter points (MOLA) (Smith et al., 2001) were also included in the analyses.

For comparative analysis the HiRISE camera were used. HiRISE operates in visible wavelengths, with a telescopic lens that produces images at resolutions of ~25 cm/pixel. These high-resolution images make it possible to distinguish 1-meter-size objects on Mars and to study the landforms in a much more detailed manner than ever before. HiRISE also makes observations at near-infrared wavelengths to obtain information on the mineral groups present (McEwen et al., 2007). HiRISE images has been the primary data source for image interpretations of small-scale landforms in this thesis (Papers I to V).

As a complement to HiRISE the Context Camera (CTX) were used. CTX is currently orbiting Mars and acquiring panchromatic images at 6 meters per pixel scale over a swath 30 kilometers wide. CTX provides context images for the HiRISE instrument. As of February 2010, CTX had covered more than 50% of the planet. CTX provided valuable context images for paper I, III, IV and V.

To be able to identify young craters on Mars (rayed crater) the Mars Odyssey's Thermal Emission Imaging System (THEMIS) were used. THEMIS is an instrument on board the Mars 2001 Odyssey spacecraft. It combines a 5-band visual imaging system (VIS) with a 10-band infrared imaging system (IR). The IR subsystem has a resolution of 100 m/pixel and VIS subsystem has a resolution of 19 m/pixel. The IR data was used to distinguish between porous and solid material as well as sandy and blocky material (e.g., Zimbelman and Leshin, 1987). THEMIS nighttime IR images were used for surveying rayed craters in paper IV.

The Mars Orbiter Laser Altimeter (MOLA) provided topographic data for paper III and IV. MOLA is an instrument onboard the late Mars Global Surveyor spacecraft (1997–2006). The MOLA instrument has obtained 588 million individual topographic measurements of the Martian surface. Altimetry was acquired by a pulsed laser every 300 m along-track with a footprint coverage of about 120 m across. Absolute vertical precision is ~30 m and 2 m on a relative scale. Horizontal precision is about 400 m (Smith et al., 2001).

7.2. Remote sensing data used for Svalbard

The High Resolution Stereo Camera Airborne Extended (HRSC-AX) was used for analysis of landforms in Svalbard (Neukum et al., 2001b). HRSC-AX is a multi-sensor push broom instrument with 9 CCD line sensors mounted in parallel. It simultaneously obtains high-resolution stereo, multicolor and multi- phase images. Like HRSC, the particular value of HRSC-AX is the stereo capability, which allows to systematically producing high-resolution Digital Elevation Models (DEM) with grid sizes between 50 cm and 1 m (e.g., Scholten & Gwinner 2004). The HRSC-AX flight campaign in July/August 2008 covered a total of seven regions in Svalbard. Areas covered in this thesis include: (1) Longyearbyen and the surroundings of Adventfjorden, (2) large parts of Adventdalen, (3) large parts of the Brøggerhalvøya in western Spitsbergen (cf. Fig. 3 *in* paper I).

7.3. Methods

7.3.1. Image processing

In order to compare landforms on Mars to morphologic analogues on Earth both Martian and terrestrial data sets where used. HiRISE and CTX images have been processed using ISIS3 software (Integrated Software for Imagers and Spectrometers) (Anderson et al., 2004). Morphometry and DTM analyses of both Svalbard and Mars were done in the ESRI software's ArcGIS 9.3. and ArcMap 10.

7.3.2. Crater size-frequency distribution analysis

Crater size-frequency distribution measurements are a well-established technique to determine relative and absolute surface ages using remote sensing images. Relative ages can be determined on the basis of stratigraphic relationships, state of erosion and frequency and size of impact craters (e.g., Hartmann, 1973; Hartmann and Neukum, 2001; Hartmann, 2005). The crater production function for the Moon is well-constrained and chronology models have been developed for the Moon on the basis of the Apollo sample radiometric ages. Using scaling laws these models were adapted for Mars (e.g., Hartmann and Neukum, 2001; Ivanov, 2001; Neukum et al., 2001a).

In paper IV the technique was used to date the surface age of the rayed crater's ejecta. The software used was CraterTools, an ArcGIS toolbar for map-projection-independent crater size-frequency determinations (Kneissl et al., 2011). Using HiRISE image PSP_006837_1345 a crater inventory of the homogenous parts of the study crater's ejecta blanket (~40 km^2) resulted in about 500 impacts of which all are less than 25 m in diameter (for results see Fig. 5 *in* paper IV). Graphs were produced in CraterStats2, a program for plotting crater counts and determining surface ages.

7.3.3. Field work and ground truth

In five field campaigns, conducted during the summers of 2007, 2008, 2009, 2011 and 2012 selected landforms were investigated in situ. The first campaign was reconnaissance and the following campaigns objectives were the acquisition of ground truth data (Fig. 26A to D) for HRSC-AX measurements, e.g., morphometry with laser range meters and manual measurements that had been observed with HRSC-AX. Field photographs helped to increase the range of scales for which textural information was available from airborne images.

In July and early August 2007, two base camps were set up. The first camp was located at Hjorthamn, at the northeastern shore of Adventfjorden, opposite to Longyearbyen. The second camp was at Diabasodden, northeast of Adventfjorden. The objective of the field work was primarily reconnaissance to find suitable gully landforms and periglacial landforms to investigate further, such as thermal contraction polygons and pingos. First results are reported as extended abstract for two conferences (Carlsson et al., 2008a; Carlsson et al., 2008b).

In July and early August 2008, the base camp was located in Hjorthamn as in the previous year. The main purpose was to further study gullies and gully-fans resembling the young gullies on Mars that had been detected in MOC (Mars Orbiter Camera) images (Malin and Edgett, 2000). First results of these investigations are reported in and paper II.

The second study area was Kvadehuksletta, a strand flat at the northwestern most part of Brøggerhalvøya in western Spitsbergen. The site is renowned for its well-developed sorted stone circles and was visited in July 2009. Another objective at this site was the exploration of protalus ramparts, a class of rock glaciers, which are prominent landforms at a nearby location called Stuphallet. A third study area (July–August 2009) was the Adventdalen in central Spitsbergen. It offered a variety of periglacial landforms in close spatial proximity, such as polygons and other types of patterned ground, rock glaciers, and pingos. First results of these investigations are reported in paper I and V. Results on unsorted stripes have been reported in an extended abstract (Johnsson et al., 2010)

The fourth field visit (July–August 2011) included a revisit to Kvadehuksletta to further investigate the sorted stone circles, the Zeppelinerfjellet close to Ny-Ålesund to study degrading ice-cored moraines, the Shetelingfellet at Brøggerhalvøya, Operafjellet and Louisfjellet in Adventdalen. The objectives were to find analogues for possibly degrading ice-debris, i.e. thermokarst, landforms on Mars (degrading ice-cored moraines) and slope landforms that reflect the action of freeze-thaw activity (solifluction landforms). First results from the study on solifluction are presented in paper IV. The study on ice-cored moraines is in preparation.

The fifth and most recent visit (July–August 2012) included further work on stone-circles on Kvadehuksletta using stereo photography to make detailed digital terrain models of sorted borders. We also performed thermal conductivity measurements, low-altitude kite-photography at selected sites. A second site was the Kongsvegen ice-cored lateral moraines, where detailed morphometry, stereo photography and kite-camera imaging was performed on active thaw slumping of the moraine (in preparation). In Longyearbyen I visited selected debris flow sites in Endalen for ground truth. Results from the Endalen investigation is presented in paper IV.

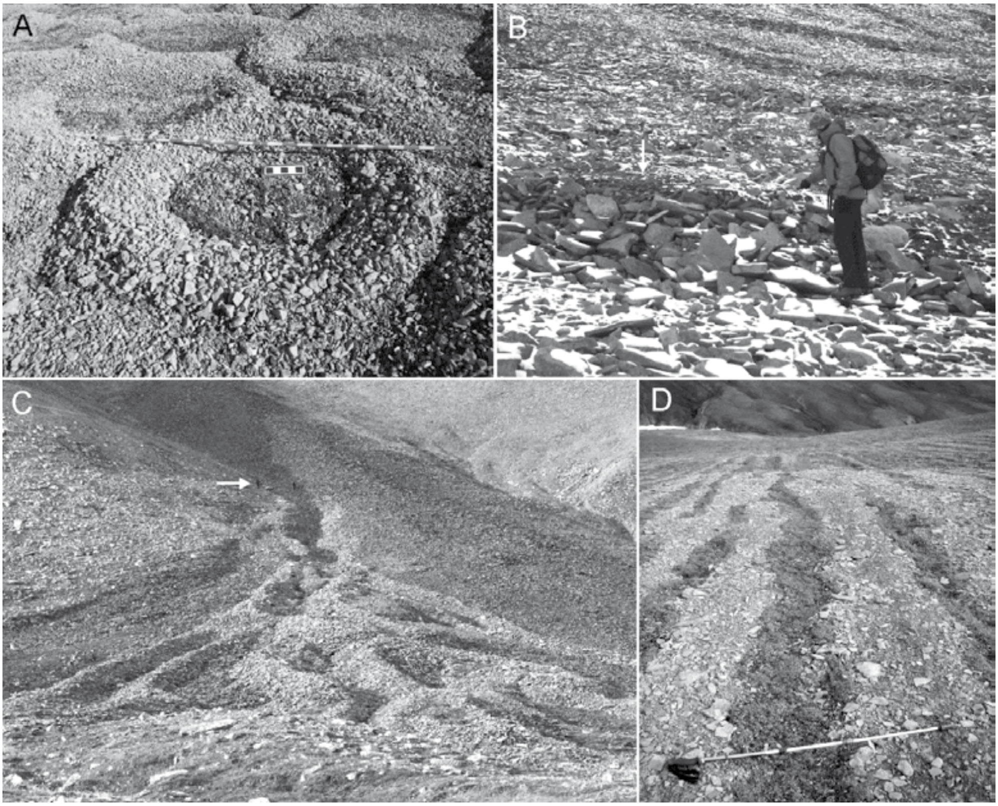


Figure 26. Ground images of several different landforms that has been the focus of the field works campaigns. (A) Sorted stone circles at the Kvadehuksletta abrasion platform. Circle diameter is approximately 2 m. (B) Stone-banked solifluction lobes at Operafjellet. Person for scale. White arrow marks the rim of the lobe front. (D) Debris flow dominated fan in Hanaskogdalen close to Adventdalen. Note the well-developed levées. White arrow marks a person for scale. (D) Sorted stone stripes within Louisdalen.

8. Results and discussion

In the following sections some of the results from the appended papers will be discussed. Since the papers are comprehensive and touch upon many aspects of the periglacial domain on Earth and Mars, I will present a few results from observations and discuss a couple of new observations that are within the scope of the thesis. The aim is to enlarge the extent to which the appended papers apply on Mars. This will be followed by a discussion on the advantages of an integrated view in landforms on Mars. Finally, some uncertainties will be discussed.

8.1. Martian cold-climate landforms and Earth-analogues

8.1.1. Thermal contraction polygons

In paper I the ambiguity (i.e. equifinality) of landforms is explored. One of the most widespread landforms on Mars is polygonal ground. Polygonal ground in cold climates on Earth is widespread as well. It is caused by thermal contraction cracking (Lachenbruch, 1962), but depending on the temperatures and amount of available liquid water, different formation mechanisms are known. They all involve cooling and cracking of the ground in the winter season and subsequent filling of the cracks by water, sand, or soil. The most common type of thermal contraction polygons are ice-wedge polygons (Leffingwell, 1915; Black, 1976), which form by refreezing of the liquid water that filled the cracks in spring and summer. If there is a lack of liquid water in hyperarid polar deserts (e.g., the ice-free areas of Antarctica or the polar deserts of the Canadian High Arctic), the cracks may be filled by loess or sand (sand-wedge polygons; Pewe, 1959; Sletten et al., 2003), or soil (Black, 1976; French, 2007). Repeated cracking in subsequent years leads to lateral expansion of the ice or sand wedge. A further type of cold-climate polygonal ground has been described by Marchant et al. (2002) from the Antarctic Dry Valleys, where ice buried beneath sediment is cracking by thermal contraction. Fine-grained sediment collects in the cracks, and coarser-grained material (>2 cm) is left at the surface near the cracks, enhancing sublimation due to the relatively higher porosity and permeability. These so called sublimation polygons can be considered to be a special type of sand-wedge polygons (Marchant and Head, 2007).

Polygonal ground is widespread on Mars and has been recognized at different scales, with polygon diameters ranging from meters to tens of kilometers (e.g., Lucchitta, 1981; Lucchitta et al., 1986; Mellon, 1997; Malin and Edgett, 2001; Seibert and Kargel, 2001; van Gasselt et al., 2005). While the giant polygons in the northern lowlands might have a tectonic origin (Hiesinger and Head, 2000), and some very small-scale polygonal patterns might be the result of rock jointing, several classes of polygons with diameters of meters and tens of meters bear a striking resemblance to terrestrial polygons that formed by freeze-thaw processes in cold-climate regions (e.g., Figures 27A, B and C). There seems to be a clear geographic control of their distribution on Mars (Seibert and Kargel, 2001; Mangold, 2005; Johnsson et al., 2008; Levy et al., 2009b). This distribution indicates a possible control by climatic factors, and many workers have inferred that these polygons formed as thermal contraction cracks analogous to terrestrial ice-wedge or sand-wedge polygons (e.g., Seibert and Kargel, 2001; Mangold, 2005; Levy et al., 2009b). Mechanical modeling shows that the maximum size of polygons formed by thermal contraction cracking on Mars is limited, however, and that a formation of many polygons on crater floors by desiccation might be a viable alternative (El Maarry et al., 2010). Recently, detailed comparisons among polygons on Mars, particularly those found at the *Phoenix* landing site and terrestrial polygons in the Antarctic Dry Valleys have led Levy et al. (2008b, 2009b) to conclude that high-latitude Martian polygons are more likely to be sand wedge or sublimation polygons than ice-wedge polygons. Some polygons, however, share the characteristics of the high-centered polygons of the upper Adventdalen (Fig. 27D).

Based on morphology alone, it would appear to be problematic to interpret the Martian small-scale polygons as ice-wedge, sand-wedge, or sublimation polygons. The morphology of different thermal contraction cracks has recently been discussed by Levy et al. (2010, their Fig. 2). For example, polygons on the northern margin of Victoria Valley (Antarctic Dry Valleys) appear morphologically very similar to the examples in Svalbard (with the exception of the trough shoulders, which are slightly elevated with respect to the polygon centers in Victoria Valley), yet they are more likely to be sand-wedge polygons (cf. Fig. 6 *in* Marchant and Head, 2007). On the other hand, sublimation polygons, e.g., in Beacon Valley (Antarctica), can also display an almost identical morphologic expression with high-centered, flat-topped, 10–20-m-wide polygons (cf. fi g. 4 *in* Marchant et al., 2002). A further complication is introduced by the possibility that some varieties of polygonal ground on Mars might be desiccation cracks, resulting from the drying out of ancient crater lakes (El Maarry et al., 2010). Hence, it is concluded (paper I) that an unambiguous interpretation of polygonal ground based on remotely sensed data alone is difficult even on Earth, let alone on Mars. This is even truer because the reconstruction of paleoenvironmental conditions from current-day (ice-wedge) polygons (which are the basis of analog studies) appears to be problematic (e.g., Harry and Godzik, 1988) due to the limited understanding of the constraints on cracking within modern permafrost environments (see Christiansen, 2005). A promising approach is the detailed study of not only polygons, but the entire suite of associated landforms, as was shown by Levy et al. (2009b) in their study of the *Phoenix* landing site, and Ulrich et al, (2012) geomorphometric analysis on polygons on Mars and in Svalbard.

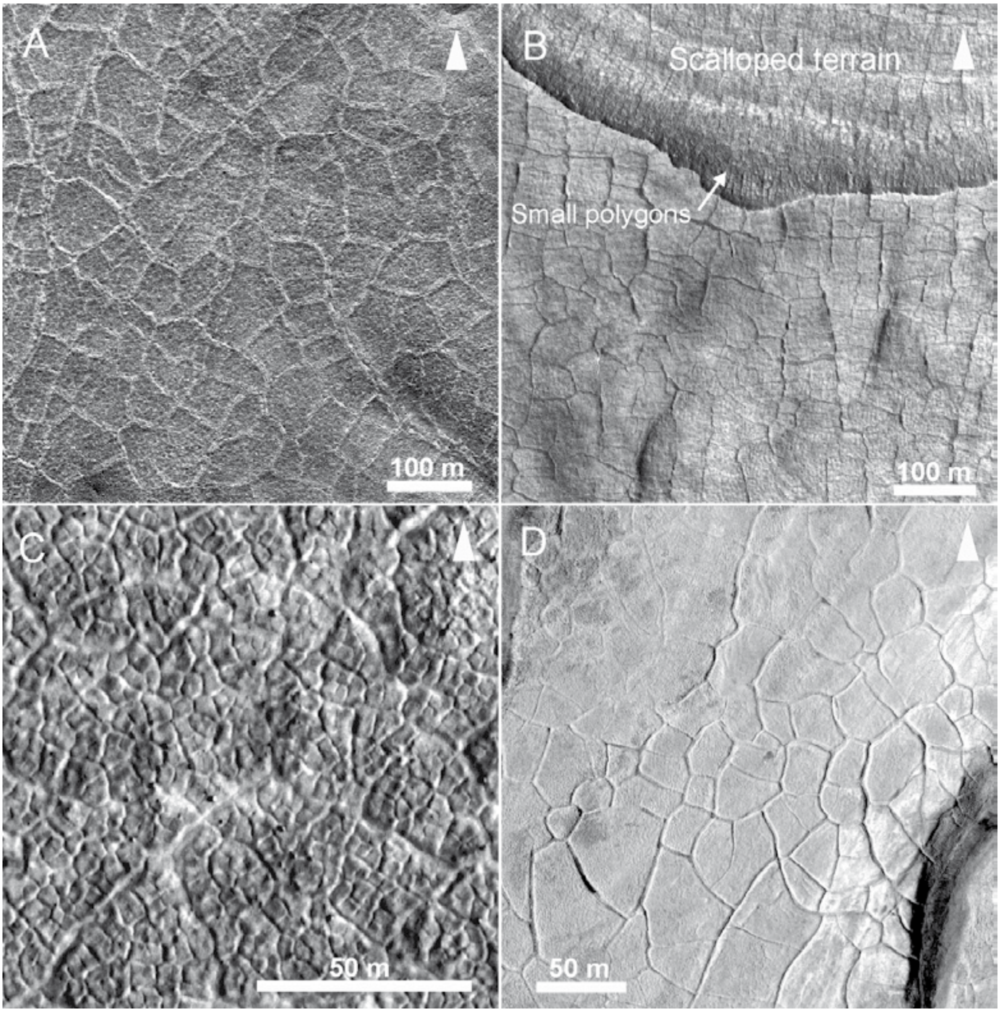


Figure 27. Compilation of thermal contraction crack polygons on Mars and Earth. (A) HiRISE image ESP_017525_2475 of interior crater polygons. (B) HiRISE image PSP_002070_2250 of polygons in Utopia Planitia. Scalloped terrain represents either thermokarst-like features or differential sublimation. (C) HiRISE image PSP_001474_2520 of northern hemisphere plains polygons. (D) Degrading ice-wedge polygons in Adventdalen, Svalbard.

8.1.2. Sorted patterned ground

The term patterned ground was introduced by Washburn (1956) to denote all sorts of “more or less symmetrical forms, such as circles, polygons, nets, steps, and stripes, […].” This definition includes sorts of patterned ground that are not restricted to cold-climate environments (e.g., desiccation polygons), but generally, and in the following, the term is used to refer to cold-climate patterned ground. Patterned ground consists of sorted and non-sorted varieties. The sorted classes of patterned ground commonly exhibit a marginal zone of stones that surround a central area of finer material. The mechanisms thought to form patterned ground include particle sorting, freeze-and-thaw cycles, the deformation of frozen soil, and soil creep (see

Kessler and Werner, 2003, and references therein). There is, however, no consensus whether the range of forms can be explained by a single model (e.g., Kessler and Werner, 2003).

The question whether sorted patterned ground can occur on Mars has important implications for climate and the role of water. Balme et al., (2009) found polygonal structures in Elysium Planitia, Mars, with zones of coarse particles, up to 1 m in size, surrounding interior areas of homogeneous texture. These authors have interpreted these structures as possible sorted stone circles or nets formed due to freeze-thaw. This would imply warmer-than-thought climate in the geologically young history of Mars. Freeze-thaw also relates to slow periglacial mass movements (solifluction) which is reported by Gallagher et al. (2011) and in paper III. With the advent of HiRISE there is growing geomorphologic evidence for freeze-thaw activity on Mars, but the timing of freeze-thaw conditions are still problematic. Kreslavsky et al. (2008) suggested that active-layer processes, as one of several cryoplanation mechanisms, are the cause of the observed decrease of slope at higher Martian latitudes. In an attempt to constrain the timing of the last active-layer formation during which thaw-induced slope modification could occur, they proposed a model based on orbital and insolation parameters (Laskar et al., 2004). The outcome of the model constrains the timing of the last active-layer event to be ~5 Ma ago. Using a similar approach for a specific region (Utopia Planitia), Ulrich et al. (2012) constrained the last period of freeze-thaw activity ~4 Ma ago. Both model results is much older than the 0.5–2 Ma estimate made by Gallagher et al. (2011) on sorted patterned ground near Heimdal crater. Salts, however, can under appropriate conditions, suppress the freezing point of water (Renno et al., 2009).

Sorted stone circles and nets are particularly well developed at Kvadehuksletta on Brøggerhalvøya (cf. Figs. 8A–8C *in* paper I). They are commonly found in shallow depressions dammed by beach ridges (Tolgensbakk and Sollid, 1987). Typical diameters are a few meters (cf. Figs. 8E and 8F *in* paper I), and the raised rims, consisting of stones with diameters of a few centimeters, reach heights of up to 50 cm (Figs. 8A and 8B *in* paper I; Etzelmuller and Sollid, 1991). The plan-form shape and dimensions are significantly different among the polygonal patterns in Elysium Planitia and on Kvadehuksletta. The size of particles in the stone rings, in particular, is much larger on Mars than in Svalbard, but the diameter of the circles is also larger. The mesoscale topography (i.e., the location of the sorted circles in areas behind the beach ridges, where water supply is high) appears also to be different. Nevertheless, larger sorted circles than those on Svalbard are known from the colder and drier Canadian Arctic (e.g., Bjorne Peninsula, Ellesmere Island; see also Goldthwait, 1976) and match in scale the purported Martian examples of Balme et al. (2009). If the polygonal patterns observed by Balme et al. (2009) are indeed sorted circles, this would have interesting implications for the recent Martian climate at equatorial regions. The observed differences between the features in Elysium Planitia and on Svalbard, however, with respect to their morphology (cf. Figs. 8D, 8E, and 8F *in* paper I), geomorphic setting, and clast lithology (i.e., dolomitic at Kvadehuksletta and basaltic on Mars [e.g., Diez et al., 2009], with implications for dissolution processes) require some caution in the interpretation, and careful investigations should identify if some mantling process could preferentially deposit fines (e.g., airborne dust) in the low-lying interior of the polygons, creating a homogeneous texture.

It thereby appear inconclusive whether frost sorting ever was possible in Mars recent past. The lack of unambiguous evidence may be due to image resolution, that key morphologic attributes of these small-scale landforms are not resolved (e.g., border clasts), making it problematic to test a generic hypothesis of frost sorting by morphology alone (e.g., Zimbelman, 2001). Although, recent freeze-thaw contradict models of surface temperatures within the last 5 Ma (Kreslavsky et al, 2008), there is the possibility that other factors may have played a role. As already mentioned, salts may suppress the freezing point of water (Hecht et al., 2009) which was demonstrated by the liquid drops of water at the Phoenix Mars Lander's struts (Renno et al., 2009). The distribution and likely salt concentrations, however, poorly constrained on a regional level. However, recent results from improved climate models may suggest higher-than-anticipated temperatures may arise at high latitudes when taking to account for cloud formations and release of buried CO_2 deposits (Phillips et al., 2011; Haberle et al., 2012; Madeleine et al., 2012). Nevertheless, if recent synoptic climate did not allow for freeze-thaw conditions, there may have been local environments were conditions for sorting was fulfilled. Figure 28A and C show a site located ~150 km west of the 215-km diameter Lyot crater (50°N, 30°E).

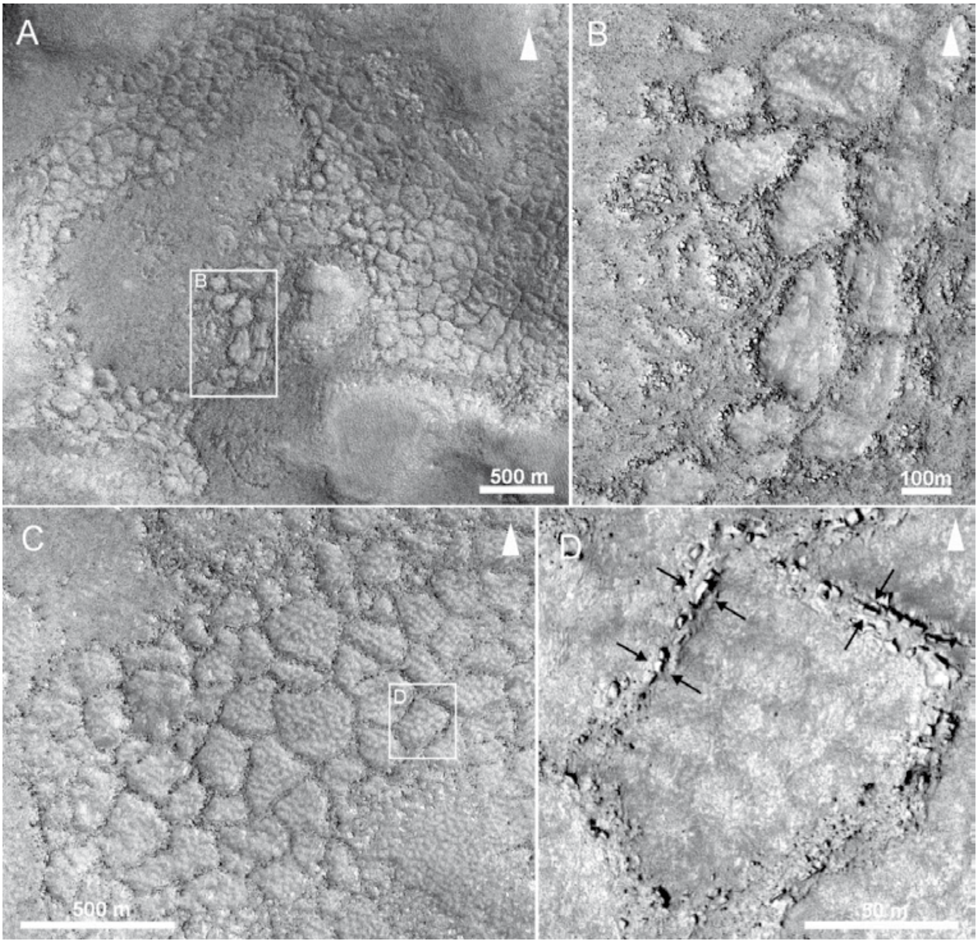


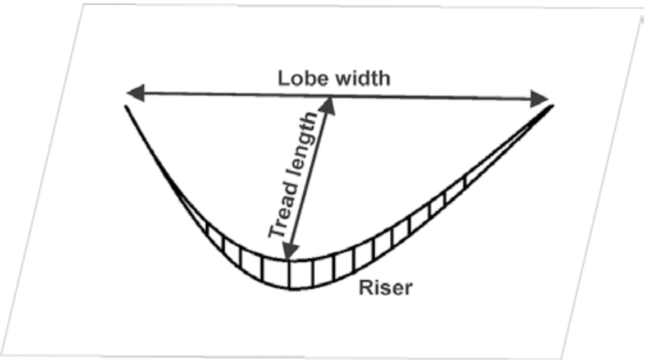
Figure 28. Possibly frost sorted polygons, circles and nets on Mars (HiRISE image ESP_016985_2315 at 51.3°S/ 36.7°E). (A) Image subset showing patterned ground on the northern plain. (B) Border clasts form circles and semi-circles in some places. (C) Clasts form polygonal patterns. (D) Close up view of sorted polygon. Clasts' a-axis is aligned with the borders. The same is typically seen in terrestrial patterned ground. Image credit: NASA/JPL/UoA.

Lyot crater is the youngest basin forming impact, dating to the early Amazonian (e.g., Dickson et al., 2009). Interestingly, the crater and the crater ejecta show evidence for the release of large quantities of groundwater, such as channel systems (e.g., Harrison et al., 2010). Modeling of impact induced geothermal systems for a large crater like Lyot suggest heating for several 100 ka (e.g., Abramov and Kring, 2005). The patterned ground occurs as well-developed circles, semi-circles and polygons are evident, as well as individual clasts. The large scale (10's to 100's m in diameter) (Fig. 28B) would, however, imply a very thick active layer. Within the polygons there is a faint pattern not resolved in the imager, and the borders clasts seem tilted (Fig. 28 D). The question whether structures are linked to the post-impact events, where water and geothermal heating may have sustained an active layer, is obviously hypothetical. It may, however, demonstrate that local events may allow formation of landforms, even under otherwise unsuitable climate conditions.

8.1.3. Small-scale lobes

On Earth solifluction is an integral mass-wasting mechanism in permafrost regions and in environments that undergo seasonal/diurnal freezing, including high altitude mountain environments (Washburn, 1956; Benedict, 1976). The original meaning of solifluction was the slow downslope movement of water saturated soil (Andersson, 1906). As such, it is not only confined to permafrost regions but also include the flow of saturated unfrozen Earth material elsewhere (French, 2007). The term, however, has not yet been defined unequivocally. Paper III, the definition by Matsuoka (2001) is adopted, where *solifluction* is defined collectively as slow mass wasting associated with freeze–thaw action (e.g., Ballantyne and Harris, 1994; French, 2007), the elasto-plastic soil movement over a frozen substrate is designated as *gelifluction* (Washburn, 1979; Harris et al., 1997) and movement associated with basal ice-lens thaw as a *plug-like flow* (Mackay, 1981). *Frost creep* is defined as the downslope movement of soil particles originating from frost heaving normal to the slope followed by nearly vertical thaw consolidation (Washburn, 1979). Periglacial solifluction is restricted to frost-susceptible soils in which pore spaces are sufficiently small to allow ice lenses to form during freezing. The different components (i.e. frost creep, gelifluction and plug-like flow) may act over various freeze and thaw cycles, including diurnal and annual frost creep, annual gelifluction and plug-like flow over frozen ground (Mackay, 1981), and diurnal needle-ice creep (Matsuoka, 2001). On Earth, the source of meltwater is not critical for solifluction to occur; it can be derived from melting snow banks, ground ice, or precipitation (Benedict, 1976) (for a comprehensive review on solifluction see Matsuoka, 2001). The lobe consists of a riser (lobe front) and lobe tread. The lobe front can be either stone-banked (sorted *in* paper III) or non-sorted (Fig. 29).

In paper III For the study, HiRISE images were chosen that show the presence of topographic features such as hills, valleys and craters. Images covering flat areas were excluded from the survey. Following the investigation by Gallagher et al. (2011) we extended our study to include all available HiRISE images between 50°N and 80°N until 01 October 2010 fulfilling the first criteria. In contrast to Gallagher et al. (2011) we only look for lobate landforms. The reason is that sorted patterned ground may be difficult to distinguish from thermal contraction polygons. Lobes, however, are easily distinguished on slopes. Associated landforms included in the survey are clearly defined thermal contraction polygons and gullies, since these landforms may reflect the end members in a freezing and thawing environment, where undeformed polygons superposing lobes may indicate a prolonged cold phase and gullies conditions of excess meltwater. A total of 53 images were catalogued for displaying lobate landforms and also associated landforms such as polygonal patterns and/or gullies. It is shown that small-scale lobate landforms (Fig. 30A to E) are widespread at Mars high-latitudes (cf. Fig. 9 in paper III). In the majority of cases, they occur in close spatial proximity to gullies and polygonal terrain, which is in agreement with the presence of ground ice. Although, polygonal terrain may indicate the dynamical behavior of ground ice under subzero conditions rather than thawing (e.g., Levy et al., 2009b), gullies strongly indicate transient melting of either ground ice or snowpack's (e.g., Costard et al., 2002; Williams et al., 2009). The reported small-scale lobes may imply periods of thawing and slow mass wasting of whole slopes over large regional extents on the northern hemisphere. Superposition relationships of small-scale lobes to polygons and gullies also suggest that they are linked closely in time. The argument against, however, is that Mars has not developed an active layer the last 4–5 Ma (Kreslavsky et al., 2008; Ulrich et al., 2012) based on orbital configurations. By inference from terrestrial conditions in Antarctica, however, it is found that thawing does not necessarily need to be as deep as in the case for sorted stone circles ground, instead the lobe front may act as a break and the lobe accumulate more material by time (e.g., Mori et al., 2006). Other factors, such as the presence of salts (e.g., Hecht et al., 2009) and/or higher-than-expected temperatures in the recent past (e.g., Phillips et al., 2010: Haberle et al., 2012) may have allowed solifluction to occur, despite present day cold temperatures. Salts in solution, so called cryobrines, may be a possible geomorphological agents rather than pure water (e.g., Knauth and Burt, 2002; Möhlmann and Thomsen, 2011). Some brines can exist in a liquid state at temperatures tens of degrees colder than the freezing point of pure water (Knauth and Burt, 2002). McEwen et al. (2011) recently reported equatorial 'wet flows', or *recurring slope lineae*, that are forming in Mars at the present time. This implies activity at cold temperatures and in a thin, dry atmosphere. Therefore, they have been attributed to the action of cryobrines. The alternative hypothesis of polycrystalline flow of ice to explain the small-scale lobes were refuted, amongst other things, due to morphological and morphometric reasons. Flow of ice would not develop the sorting of material which are seen in many cases, where clasts are concentrated at the lobe fronts (Fig. 30A, B, C, and E). The sorting is instead consistent with a higher differential velocity for larger clasts by the effect of frost creep (Benedict, 1976). Also, the thickness of the lobes (<5m) was found inconsistent with the overburden pressure associated with rock-glacier dynamics (>10 m), especially considering Mars' lower gravity. Process rates are for obvious reasons difficult to determine. If low terrestrial values are used and into account the well-development of the lobes, it would suggest a protracted process (thousand to several thousands of years) of freeze–thaw activity at the northern high latitudes on Mars.



Figur 29. Definition of lobe geometry used in paper III.

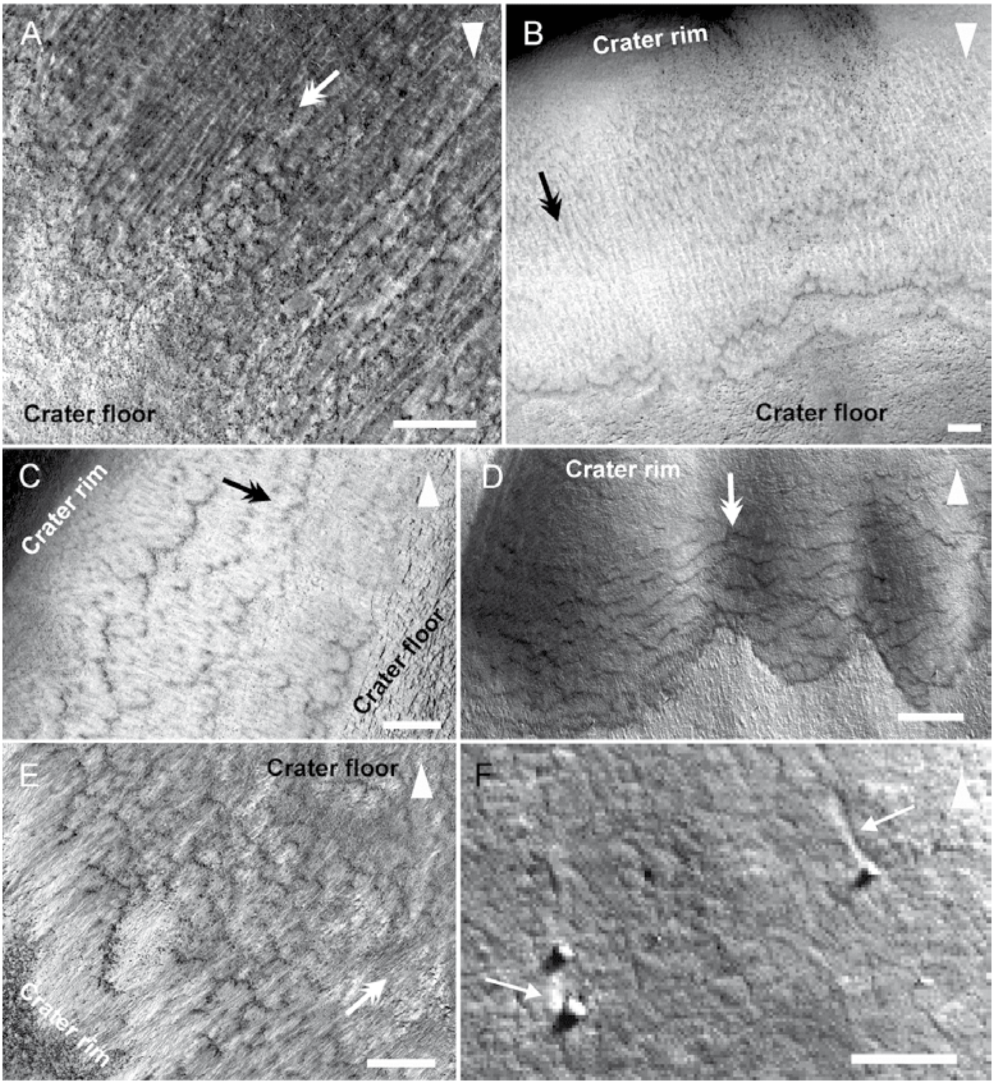


Figure 30. HiRISE compilation of observations of small-scale lobes on the northern hemisphere (double arrow marks the slope and each scale bar is approximately 100 m except for F [10 m]). (A) Clast-banked lobes forming stripes as debris is laterally sorted (HiRISE image PSP_008052_2410 at 60.6°N/ 202.8°E). (B) Lobes coalesce to form sheet-like features with clast-banked risers (PSP_010053_2455 at 65.5°N/284.1°E). (C) Well-defined clast-banked lobes (PSP_008200_2475 at 67.3°N/120.1°E). (D) Homogenous lobes with no clasts (ESP_017626_2825). (E) Clast-banked lobes within Heimdal crater (PSP_009580_2485 at 68.3°N/235.5°E). Gallagher et al. (2011) interpreted these to be formed by freeze-thaw processes within ice-rich permafrost. (F). Ploughing boulders with furrows upslope (white arrows). The site is located at the same crater as figure 28 D (ESP_017626_2825). 39 observations were made at the same slope. White bar is 10 m. Image credit: NASA/JPL/UoA.

Observations of ploughing boulders may add further support for solifluction (Fig. 30F). Ploughing boulders are strongly associated to solifluction on Earth and are hypothesized to form by the liquefaction of soil beneath the boulder during a thawing episode (Ballantyne, 2001). On Mars, the close proximity to small-scale lobes may suggest a similar origin. Though not firmly proven, the small-scale lobes are likely latitude-dependent like many other periglacial landforms are on Mars (e.g., Milliken 2003; Mangold, 2005; Levy et al., 2009).

Although, it appears that thawing may have modified slopes in the northern hemisphere in recent geologic history on Mars, no studies have yet confirmed the presence of similar features on the southern hemisphere. Here, two craters are presented that show similar looking small-scale lobes in the southern hemisphere. Figure 31 represents an unnamed 8.5-km diameter crater in Terra Sirenum region at the southern mid-latitudes (43.8°S/222.5°E). The topography has been blanketed by dust-ice mantle material and the crater floor show moraine-like ridges (Fig. 31A) (Arfstrom and Hartman, 2005). The northeastern crater wall is incised by gullies and outcrops are visible. More interestingly, three very pristine-looking gullies are incised on the northwestern interior wall, where the dust-ice mantle appears thicker (Fig. 31B). The gullies lack the typical theatre-shaped source alcove, and appear to have developed by retrogressive erosion within the mantle material. Similar-looking gullies have been reported by Schon and Head (2011) elsewhere and interpret this type of gullying formed due to melting of the ice-rich mantle material. Adjacent to the gullies are surficial "scars" (Fig. 31C). Whether these "scars" represent early stage gully development or represent another process is difficult to determine. In terrestrial periglacial environments shallow slide scars may represent active-layer detachment slides (Fig. 32), where the top of the permafrost table act like a slip plane (French, 2007). Alternatively, these shallow slides may represent mass wasting of a “dry” lag-deposit on top of an ice-rich substrate. Also, at the foot of the slope, lobe-like features are seen (Fig. 31D). These lobes are similar-looking to the small-scale lobes reported in paper III for the northern hemisphere. Also, within the gully troughs, smaller slide scars are present (Fig. 31E). They cut the polygonal pattern and are therefore younger. On Earth, similar-looking thaw slumps are seen on degrading ice-cored moraines (e.g., Bennet et al, 2000). It requires some caution since thaw slumps involve large amount of water from the ablation of top of the body of ice (Bennet et al., 2000).

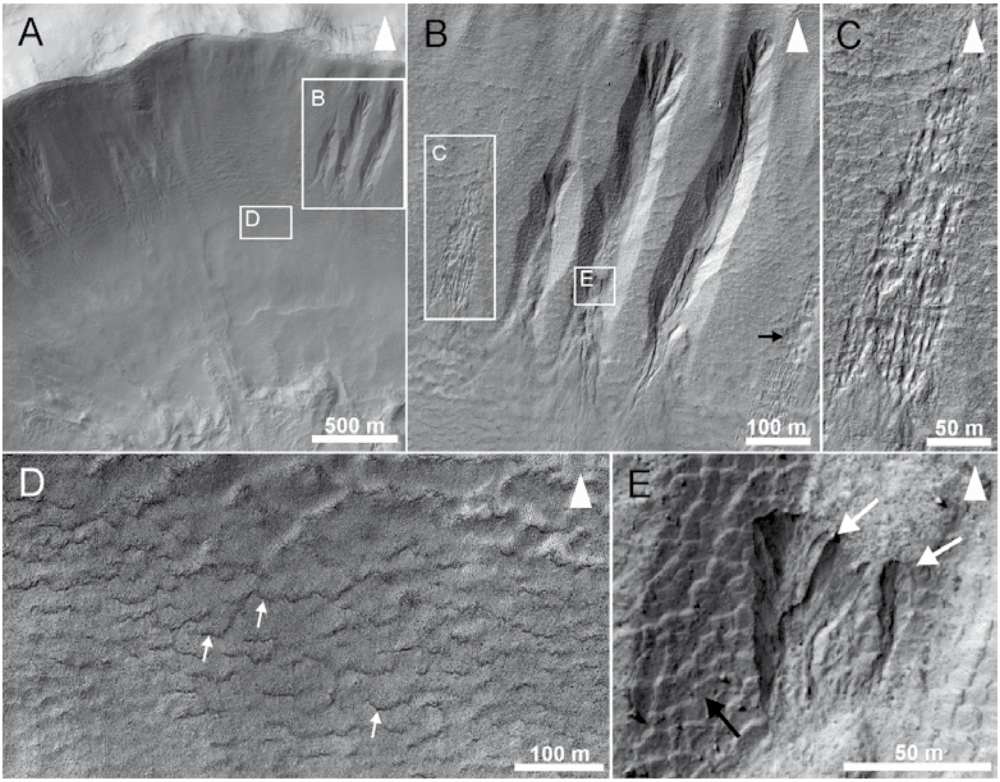


Figure 31. Examples of possible freeze-thaw induced landforms within a southern hemisphere crater (HiRISE image PSP_005850_1360 at 43.8°S/222.5°E). (A) Overview of pole-facing interior crater wall. (B) Gully systems incised in the mantle deposits. Shallow mass wasting, resembling terrestrial active- layer detachment slides can be seen adjacent to the gullies (black arrows). (C) Clast-banked small-scale lobes near the foot of the slope (white arrows). (D) Features resembling retrogressive thaw slumps within the gullies (white arrows). Image credit: NASA/JPL/UoA

Figure 32. Example on shallow slide on top of the permafrost table in Adventdalen, Svalbard. The distance between the arrow is a few meter. Photo credit: Ernst Hauber

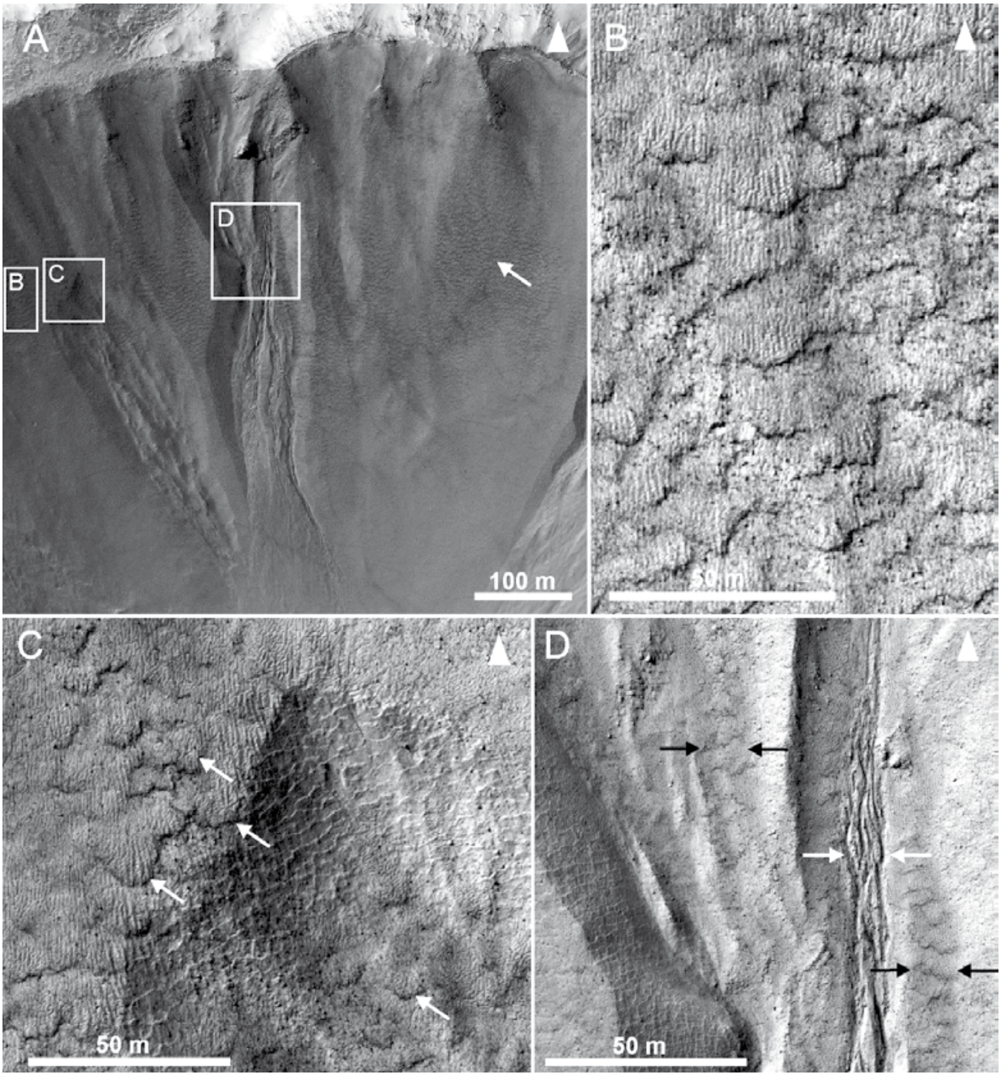


Figure 33. A second example of a southern hemisphere crater (HiRISE image ESP_023679_1365 at 43.2°S/173.1°E). (A) Small-scale lobes occur on the pole-facing slope within the dotted lines, in close proximity to braided gully systems. White arrows show the location of additional patches of lobes. (B) Clearly defined lobes adjacent to a polygonal patterned gully alcove. Note that lobes are seen with the alcove as well. (C) Braided gully channel (white arrows) and nearby lobes (black arrows).

Figure 33 represents a second unnamed crater in the southern mid-latitudes on Mars. The crater is 7 km in diameters and, as the previous crater it is covered dust-ice mantle material. A fresh-looking gully is seen on the pole-facing slope (Fig. 33A). The gully in the center of the image is well-developed and the gully-fan appears to superpose the more degraded gully on the right. On the walls adjacent to both gullies, numerous small-scale lobes are seen (Fig. 33B). The lobe fronts overlap each other and are between 10 to 30 meters wide. Lobe fronts appear to be a couple meters in height. Interestingly, the surfaces of the lobes display a striped pattern (compare to Fig. 7E *in* paper I). At the top of the alcove of the degraded gully (Fig. 33C); lobes appear to move over the rim. Lobes are also present within the alcove. The channel of the fresh-looking gully is braided and may indicate of liquid flow (Gallagher et al., 2011). Moreover, interior alcove walls display polygonal patterns which are associated to ice-rich sediments. Weather these small-scale lobes are formed by similar processes as in the northern hemisphere is too early to determine, but they fulfill the morphological and morphometric criteria used in paper III. In addition, the assemblage of landforms, such as gullies, polygons and an ice-rich mantle unit, would point to a process of thawing and slow periglacial mass wasting (solifluction).

In summary, the two southern hemisphere craters presented here may serve as instructive examples on how inference on governing processes can be made by the spatial relationships among landforms.

8.1.4. Martian gullies and debris flow deposits

Martian gullies are young, Late Amazonian landforms. Gullies are known to display a range of different morphologies but typically include a source alcove, chute or channel and a depositional fan (cf. Fig 5 *in* paper II) (Malin and Edgett, 2001). Gullies are suggested to have formed by a combination of processes, including mass wasting, overland flow, and debris flows (Malin and Edgett, 2000). However, morphologic features such as braided channels, multiple terraces, point bars, and cut banks suggests that fluvial processes were involved in their formation (Gulick and the HiRISE team, 2008; McEwen et al., 2007a). Although alternative mechanisms such as dry mass movements (Treiman, 2003) or CO_2-driven processes (Musselwhite et al., 2001) have been proposed, none of these processes is able to form all of the observed morphologic attributes of Martian gullies, and the latter is unlikely due to stability relations of CO_2 on Mars (Stewart and Nimmo, 2002). The origin of gullies was first associated with groundwater seepage (Malin and Edgett, 2000). However, this source is not consistent with the occurrence of a large number of gullies on slopes of central peaks (Baker, 2001), mesas (Balme et al., 2006), and crater rim crests (Dickson et al., 2007), where groundwater availability is unlikely. Costard et al. (2002) suggested accumulation and melting of near-surface ice within the regolith during high-obliquity phases on Mars. A similar model of snow deposition during periods of high obliquity but melting during phases of lower obliquity was proposed by Christensen (2003).

The formation of gullies on Earth depends on several parameters, including rainfall and/or melting of snow, the presence of steep slopes, and sufficient amounts of fine-grained material and debris (e.g., Costa, 1984). The latter two have also been proposed as limiting factors affecting the occurrence of gullies on Mars (Reiss et al., 2009). However, it remains unclear whether fluvial processes or debris flows are dominating the formation of gullies on Mars. Debris flows are non-Newtonian, viscous slurries that have mixed water and fines as the interstitial fluid (Selby, 1993). The flowing mixtures of fines, clastic debris, and water have relatively low water content (<30% water by weight) and show a visco-plastic flow behavior (Costa, 1984). Streamflows and hyper-concentrated flows have a high water content and relatively low sediment supply (>30% water by weight), and they show a Newtonian flow behavior (Costa, 1984; Pierson and Costa, 1987). The morphologies of debris-flow fans show typical features such as levées, lobes, snouts, and debris plugs (Hooke, 1987; Whipple and Dunne, 1992), the combination of which is not observed on fans formed from purely fluvial processes. Fluvial deposits consist of stratified sheets and bars, and they are well sorted in comparison to debris-flow deposits (Costa, 1984; Blair, 1999).

Gullies are investigated in paper II and paper IV. In paper II a survey of several hundred gullies were made to find clues on governing gully forming processes on Mars (see Fig. 3 *in* paper II). Well-developed debris flows were only found in Hale crater (35.7°S, 322.3°E). By comparing periglacial gully-fans in Svalbard to the surveyed gullies on Mars it was found that the more likely processes are by episodic streamflow and that signals of debris flow processes are very rare on Mars. This is contrary to previous results based from slope-area analysis (Conway et al., 2011) and modeling and morphology (inference from sinuous channels) (Mangold et al., 2010), which argues for a dominance of debris flows, despite any clear evidence from depositional fans. It was concluded that episodic melting of snow the best explanation for the source of water for the reported gullies and debris flows.

In paper IV a very young rayed crater was found in mid-latitude Aonia Terra region that contains well-developed debris flows. Mass-wasting within the crater show a strong north-south asymmetry with debris flow deposits on pole-facing slopes and talus cones on the equator-facing slope. The debris flow deposits display a range of details that on Earth are strong indicators for water-bearing debris slurries (i.e. debris flows), such as overlapping terminal lobes, debris tongues and snouts, debris-flow fans, scoured channels with medial deposits (debris plugs), and well-defined levées (see figure 7 *in* paper IV)(Coussot and Meunier, 1996; Johnson and Rodine, 1984). Also, rayed craters represent some of the most recent impacts on Mars since their ejecta have not been reworked by other processes. Rays on Mars can be homogenized with the surrounding environment or obscured from view by multiple processes known to be active on the Martian surface, including: glacial modification, dust deposition, eolian reworking, and volcanic flows (Schon et al., 2012). As previously been discussed, glacial modification and dust-ice deposition is particularly prone in the mid-latitudes and the rare occurrence of rayed craters at these latitudes has been attributed the geologically young dust-ice mantle, which obscure any signals of rays from before dust-ice deposition (Tornabene et al., 2006). Thus, the majority of previously reported rayed craters are located in the lower latitudes (Tornabene et al., 2006), with Gasa crater (35.7°S) as one exception (Schon et al., 2012). The study crater's rays are clearly evident from THEMIS nighttime IR images and are also one of the most poleward rayed craters ever documented (45.11°S). Crater size-frequency measurements of the crater's ejecta gave a best-fit age of ~0.19 ± 0.04 Ma. The young crater age is supported by the pristine appearance, crisp crater rims and very limited aeolian infill. This young age clearly post-dates the latest dust-ice mantle emplacement (> 0.4 Ma ago) (Head et al., 2003; Schon et al., 2012). Thus, it would imply that the debris flow processes have been efficient at modifying the crater wall within the last few hundred thousand years. As such it may represent one of the most recent indications of processes related to water-saturation at or close to the surface. But what was the source of the water? The lack of dust-ice mantle material with the crater precludes melting of ground ice as a water source. The strong north-south asymmetry of landforms within the crater (Fig. 6 *in* paper IV), also suggest that impact induced melting of volatiles and seepage was not a viable mechanism for gullying. If it were, gullying would have occurred radially within the crater and shown no aspect preference. Gullies, which occur radially within the Meteor Crater in Arizona, may have formed by ground water seepage (Kumar et al., 2010). Although other mechanisms for water recharge has been suggested (Palucis et al. (2011). The pole-facing preference is instead consistent with snow accumulation at these sites and melting at higher obliquity. Gully distribution on Mars is mainly limited to the mid-latitudes between 30° and 60° in both hemispheres, and gullies occur preferentially on pole-facing slopes at least in the 30°–45° latitude belts (Balme et al., 2006; Kneissl et al., 2010). Their distribution is consistent with the deposition and subsequent melting of snow and ice during periods of high obliquity in the mid-latitudes (Head et al., 2003).

Why did debris flows develop within the Aonia Terra crater when results from paper II suggests that debris flows are very rare on Mars? One reason for this may be due to the location. The study crater is superposed on rampart ejecta from a much larger, nearby impact. As such, the upper crater rim outcrops of the study crater represent the rampart ejecta. Observations of numerous rock falls and coarse-grained colluvium deposits suggest that crater rims are highly brecciated and unconsolidated (see. Fig. 10A, B and C in paper IV). Studies on two gully fans in Death Valley, USA may be instructive Earth-analogues. Blair (1999) investigated two adjoining gullies, the Anvil and Warm Springs. The Anvil gully is completely dominated by sheet floods and alluvial deposition (well-sorted deposits), whereas the Warm Springs gully is dominated by debris flow deposition (unsorted deposits). Factors such as climate, catchment area, fan area, catchment relief, aspect, vegetation types and density, and neo-tectonic setting are essentially identical for these two fans (Blair, 1999). The diverging factor is the bedrock type, while the Anvil gully is underlain by granite, the Warm Springs gully formed on top of shales, dolomite, and quartzite. The Anvil catchment produces cobble, gravel and sand sized particles with high permeability where saturation of sediments is not reached. Warm Springs produces a wide suite of grain sizes spanning from clay to boulders (Blair, 1999). In the latter case, saturation is possible due to the presence of fine-grained sediments and debris flows dominate. Similarly, the seemingly large variety of grain-sizes within the Aonia Terra crater may favor debris flows. Also, steep slopes in combination with deposits of coarse-grained colluvium the top of slopes may add overburden and consequently increase slope instability.

Finally, what can the debris flows described in paper II tell us about the scarcity of debris flow signals in most other gullies on Mars? The combined results from paper II and paper IV suggest that the lack of positive observations, in contrast to modeling (Mangold et al., 2010) and slope-area analysis results (Conway et al., 2011), may be explained by superposition and melting of more recent dust-ice mantles during the last Martian ice age, which has obscured any preexisting debris flows. In both papers, field work on analogues in Svalbard in combination with aerial images proved to be a useful tool to infer more firm processes on Mars. Importantly, what has been shown with the patterned ground near Lyot crater, the ploughing boulders and the above described debris flows is that some processes, though not absent on Mars, they occur on very limited spatial extents. One explanation may be that HiRISE images cover less than a few percent of the Martian surface, so most of Mars is still unexplored at this scale. Other processes, such as gullying by fluvial incision and deposition and thermal contraction cracking are very common.

8.2. Integrated landscape analysis

With a few notable exceptions (e.g., Soare et al., 2005; Balme et al., 2009; Levy et al., 2009a; Mellon et al., 2009b), the majority of previously reported cold-climate landforms on Mars have been studied in isolation without considering the spatial and geological context. Insights gained from Earth-analogues in Svalbard demonstrate the importance of an integrated approach to landform studies on Mars. Landforms are not isolated entities; instead they form assemblages of landforms that can be related to conditions that are decisive for the dominant process/processes, in this case the existence of ground ice and seasonal thawing. By studying these connections we may gain a more thorough understanding of the landform systems, which is useful for, paleoclimate reconstruction. This will help us to constrain the frequency of freeze/thaw cycles (paper III) and the associated amount of liquid water (paper II, III, IV). The three qualitative scenarios on landform development presented in paper V may help us in understating the links between different geomorphologic features within a spatial and geologic context. Based on terrestrial analogue landforms in similarly close spatial proximity on Svalbard, three scenarios of sequential landscape evolution are presented for Mars (see figure 11 *in* paper V). All scenarios start with initial snowfall and the deposition of a dusty snowpack, and they all end with recent gully and fan formation. These scenarios are qualitative in the sense that none of them is expected to exactly represent the real situation on Mars. In fact, the scenarios are not mutually exclusive, and mixed cases (e.g. the dry and the snow scenarios) are very plausible. Dependent on latitude and insolation, some craters might have been shaped by the dry scenario, while craters at other latitudes might have been shaped by the wet scenario. The different scenarios also have different implications for the interpretation of certain landforms. For example, fractured mounds are unlikely to be open-system pingos in the dry scenario because that does not predict liquid water in the subsurface, a prerequisite for the growth of hydraulic pingos. However, basal melting of snow in the snow scenario could lead to infiltration of liquid water into the subsurface and the formation of a hydraulic pingo as in the wet scenario. It has been shown that despite significant differences in the climates of Mars and Svalbard, a suite of very analogous landforms has developed, although perhaps over enormously different timescales. Attempts to reconstruct paleoclimates on Mars have to take into account the fact that different processes acting in different environments can produce similar results (equifinality). By investigating whole landform assemblages, their spatial and temporal relationships, ambiguity may be reduced (paper V).

8.3. Uncertainties

Even though the combined use of field work on Earth-analogues and remote sensing of equal resolution has been shown promising in studies of cold-climate landforms on Mars, there are still uncertainties that are difficult to overcome. In summary, the comparability of climatic conditions between Mars and Svalbard makes periglacial process rates very difficult (impossible?) to constrain. Inferring formative processes from observations of individual landforms can be difficult even on Earth and is more challenging on Mars where only remote sensing is available. Insights in aeolian research have, however, advanced by multi-year acquisition of imagery of certain areas. These studies have improved our understanding about active dust-devil processes (e.g., Reiss et al., 2011) and migrating dunes (Bridges et al., 2012). This applies also to the recurrent slope lineae (McEwen et al., 2011) and secondary mass-wasting features within gullies under present-day Mars conditions (Malin et al., 2006). We may, however, suspect that periglacial processes act on vastly longer timescales on Mars than on Earth, because liquid water on Mars is probably only available episodically and in limited amounts. Our understanding of Mars cold-climate landforms would, instead benefit from future in-situ robotic or manned explorations. In that way, interpretations could be validated and subsurface properties could be determined, such as salt concentration, ice content and subsurface structures. In perhaps, a similar manner to what was recently done by Mars Phoenix Lander. During the absence of any coming missions to the Martian arctic it is suggested that integrated landscape analysis the best way in helping to understand the processes that shaped Martian landscape.

9. Summary of papers

Paper I. Periglacial landscapes on Svalbard: Terrestrial analogs for cold-climate landforms on Mars.

We present landforms on Svalbard as terrestrial analogs for possible Martian periglacial surface features. While there are closer climatic analogs for Mars, e.g., the Antarctic Dry Valleys, Svalbard has unique advantages that make it a very useful study area. Svalbard is easily accessible and offers a periglacial landscape where many different landforms can be encountered in close spatial proximity. These landforms include thermal contraction cracks, slope stripes, rock glaciers, protalus ramparts, and pingos, all of which have close morphological analogs on Mars. The combination of remote sensing data, in particular images and digital elevation models, with field work is a promising approach in analog studies and facilitates acquisition of first-hand experience with permafrost environments. Based on the morphological ambiguity of certain landforms such as pingos, we recommend that Martian cold-climate landforms should not be investigated in isolation, but as part of a landscape system in a geological context.

Paper II. Terrestrial gullies and debris-flow tracks on Svalbard as planetary analogs for Mars.

We compare the morphology of gully sedimentary fans on Svalbard as possible analogs to gullies on Mars in order to constrain whether fluvial and/or debris-flow processes are predominantly responsible for the formation of Martian gullies. Our analysis is based on high-resolution imagery (High Resolution Stereo Camera [HRSC-AX], ~20 cm/pixel) acquired through a flight campaign in summer 2008 and ground truth during two expeditions in the summers of 2008 and 2009 in Svalbard, compared to high-resolution satellite imagery (High Resolution Imaging Science Experiment [HiRISE], ~25 cm/pixel) from Mars. On Svalbard, fluvial and debris-flow processes are evident in the formation of gullies, but the morphological characteristics clearly show that the transport and sedimentation of eroded material are predominated by debris flows. Most investigated gullies on Mars lack clear evidence for debris-flow processes. The Martian gully fan morphology is more consistent with the deposition of small overlapping fans by multiple fluvial flow events. Clear evidence for debris flows on Mars was only found in one new location, in addition to a few previously published examples. The occurrence of debris flow processes in the formation of Martian gullies seems to be rare and locally limited. If predominantly fluvial processes caused the formation of gullies on Mars, then large amounts of water would have been required for their formation because of the relatively low sediment supply in stream and/or hyper-concentrated flows. Repeated seasonal or episodic snow deposition and melting during periods of higher obliquity in the recent past on Mars can best explain the formation of the gullies.

Paper III. Periglacial mass-wasting landforms on Mars suggestive of transient liquid water in the recent past: Insights from solifluction lobes on Svalbard.

On Earth, periglacial solifluction is a slow mass-wasting process related to freeze–thaw activity. We compare the morphology of small-scale lobate features on Mars to solifluction lobes in Svalbard to constrain their processes of formation. The analysis is based on high-resolution satellite imagery of Mars (HiRISE, ~25 cm/pxl), aerial images of Svalbard with a similar spatial resolution (HRSC–AX, ~20 cm/pxl) acquired through an air campaign in summer 2008, and ground truth obtained during two summer expeditions in 2009 and 2011 on Svalbard. We present a detailed study of two crater environments on Mars displaying two types of lobate forms, characterized as sorted (clast-banked) and non-sorted lobes. On both Svalbard and Mars such lobes typically occur as clusters of overlapping risers (lobe fronts), pointing to differential velocities in the soil. The Martian small-scale lobes have well-defined arcuate risers and lobe treads (surface). Lobe widths range between 14 and 127 m and tread lengths between 13 and 105 m. Riser height is estimated to be approximately 1–5 m. The lobes on Mars share the plan view morphology of solifluction lobes on Svalbard and their morphometry is within the range of values of terrestrial solifluction lobes. The lobes are distinct from permafrost-creep landforms such as rock glaciers. We show the results of a survey of 53 HiRISE images covering latitudes between 59°N and 81°N. Similar to Svalbard, the studied lobate features on Mars occur in close spatial proximity to gullies and thermal contraction polygons. The widespread distribution of the lobate forms in the northern hemisphere and their close association to ground-ice and gullies are best explained by mass-wasting processes related to frost creep, gelifluction and/or plug-like flow. This suggests a protracted process (thousand to several thousands of years) of freeze–thaw activity at the northern high latitudes on Mars. Age constraints on lobe deposits and superposition relationships with gullies and polygons imply a process involving liquid water within the last few million years.

Paper IV. Debris flows in a very young mid-latitude crater, Mars: Insights from Earth-analogues on Spitsbergen, Svalbard.

On Earth, debris flows are mainly studied and monitored because of their hazardous nature, on Mars they may serve as geomorphologic indicators of transient liquid water. We report on well-defined debris flow-like deposits within a young mid-latitude crater on Mars. The crater has rayed ejecta and superposes the rampart ejecta of a larger nearby crater. We compared the morphology of debris flow fans on Svalbard to the debris flow-like deposits within the young crater in order to constrain whether dry mass wasting or water-bearing debris slurries are responsible for the formation of the deposits. We report morphological attributes of the deposits such as overlapping terminal lobes, debris tongues and snouts, debris-flow fans, scoured channels with medial deposits (debris plugs), and clearly defined lateral deposits (levées). These attributes meet the terrestrial morphologic criteria for being water-bearing visco-plastic debris flows. Furthermore, the interior crater walls display a range of aspect-dependent mass wasting, ranging from debris-flow dominated pole-facing slopes, to east-and-west-facing single channel gullies and north-facing talus cones (grain flow). Our findings suggest that the debris flows are not related to impact induced heating and release of meltwater from subsurface reservoirs. Instead, we suggest that the debris flows formed by melting of recent snow deposits during the waning stages of the last Martian ice-age, and that the range of landforms within the crater are controlled by insolation. The north-south asymmetry demonstrates that insolation-controlled slope processes (including gully formation by debris flows) are surprisingly efficient on Mars under very recent climate conditions (< 1 Ma). To our knowledge, the studied flows are the most recent and best preserved debris flows ever documented on Mars and it may represent one of the most recent geomorphological indications of transient liquid water found to date.

Paper V. Landscape evolution in Martian mid-latitude regions: Insights from analogous periglacial landforms in Svalbard.

Periglacial landforms on Spitsbergen are morphologically similar to landforms on Mars that are probably related to the past and/or present existence of ice at or near the surface. Many of these landforms, such as gullies, debris-flow fans, polygonal terrain, fractured mounds and rock-glacier-like features, are observed in close spatial proximity in mid-latitude craters on Mars. On Svalbard, analogous landforms occur in strikingly similar proximity, which makes them useful study cases to infer the spatial and chronological evolution of Martian cold-climate surface processes. The analysis of the morphological inventory of analogous landforms on Svalbard and Mars allows the processes operating on Mars to be constrained. We present tree different qualitative scenarios of landscape evolution on Mars help to better understand the action of periglacial processes on Mars in the recent past. These scenarios may be summarized as: (1) "wet" scenario with the precipitation of snow and formation of warm based "dust glaciers", (2)"snow" scenario with the formation of thick snowpack's and slope modification by denivation, (3) "dry" scenario with the precipitation of snow and formation of cold based "dust glaciers. The landscape evolution scenarios would be controlled by obliquity and/or orbital parameters such as eccentricity or the position of perihelion, and is therefore assumed to be cyclic. It is important to note that not all craters are necessarily expected to be exactly in the same stage of this landscape evolution. Since the scenarios are not meant to be mutually exclusive they may apply to the same crater environment at various times in Mars recent past.

10. Conclusions

Investigate the potential of Svalbard as an analogue environment to Mars cold-climate features (paper I).

In **paper I** it was shown that Svalbard serve as a suitable terrestrial analogue for recent, but not current, processes and climates on Mars. An important insight gained is that any study using morphological features to infer climatic conditions should investigate not a single class of landforms, but a suite of landforms (a landscape) in their geomorphological and spatial context. Furthermore, the use of terrestrial analogues in planetary science benefits from the combined use of remote-sensing data and field work, especially if remote sensing data are of comparable resolution. The latter overcomes the problem of scaling. The former provide an integrated view of the large scale relationships. Field work is the ideal complement as it provides ground truth, increases the spatial resolution of the observations, and allows the subsurface to be sampled.

Explore past and present processes and surface conditions on Mars by inference from morphological counterparts in Svalbard (Paper II, III and IV).

In **paper II** it is shown that gullies on Svalbard are formed by a combination of flow processes with varying sediment contents. Morphologic observations clearly show that the predominant processes in their formation are debris flows. It was further shown that most investigated gullies on Mars do not show clear evidence of debris flows. The detailed morphology of channels and their deposits on Mars is consistent with fluvial-dominated processes. Clear indicators of debris flows have rarely been found on Mars. Thus, by the survey of several hundred gullies on Mars in high-resolution imagery and their comparison with terrestrial analogues suggest that fluvial erosion and deposition is the main process in their formation. This interpretation puts constraints on the amount of water needed for the gully formation process. If predominantly fluvial processes caused the formation of gullies on Mars, then larger amounts of water are required for their formation. Repeated seasonal or episodic snow deposition and melting during periods of higher obliquity in the recent past on Mars might best explain the formation of gullies. Finally, morphological observations of definite debris-flow–dominated characteristics at gully sites on Mars are rare. Their formation might be due to specific microclimates caused by unusually steep slopes in combination with their occurrence on specific slope orientations, which favored higher deposition and melting volumes of water ice at these sites.

In **paper III** it is shown, by inference from solifluction lobes in Svalbard, that small-scale lobate features on high-latitude crater walls are consistent with a slow freeze-thaw induced mass wasting. It is shown that (1) the Martian lobes share several diagnostic morphological attributes with the studied solifluction lobes in Svalbard, (2) a situation similar to the analogous landforms in Svalbard is the close spatial proximity to fluvial and periglacial landforms such as braided gullies and periglacial thermal contraction fractures (polygons), and (3) lobe morphometry is distinct from permafrost creep landforms (i.e. polycrystalline flow of ice) and imply a freeze–thaw origin for the Martian lobes. Furthermore, the presence of lobes implies transient liquid water within numerous crater environments, which might also bear important implications for the habitability of Mars. Finally, the pristine morphology, superposition relationships of other young landforms suggests a very young age of the lobes. This may be linked to recent climate changes or be due to the effects of soil salts that depresses the melting point of water.

In **paper IV** very young debris flows in mid-latitude crater environment was investigated. Based on plan-form morphology, morphometry, the presence of key morphological attributes such as terminal lobes, scoured channels, debris plugs and levées, and by comparison to studied periglacial debris-flow landforms in Svalbard it was concluded that the studied deposits are best explained by water-bearing debris flows. Debris flow activity is linked to the highly unconsolidated rim-outcrops which, in combination with the preserved steep slopes caused an abundant sediment supply of varying grain sizes and slope instability. This makes the conditions particularly favorable for high-energy debris flows. A model of top-down melting of snow packs as the primary source of water is favored for the formation of the Aonia Terra debris flows, since the crater lack dust-ice mantling. Furthermore, the very youthful age of the crater suggest that the debris flows formed during the waning phase of the last Martian ice age (< 0.4 Ma). To our knowledge, the studied debris flows are the best preserved debris flows ever documented on Mars. Finally, the lack of positive observations of debris flows elsewhere, in contrast to modeling and slope-area analysis results, may be explained by a later superposition and melting of more recent dust-ice mantles during the last Martian ice age which has obscured preexisting debris flows.

Explore the potential of modeling landscape evolution on Mars by integrated landscape analysis inferred from Earth analogues in Svalbard (paper V).

In **paper V** it is shown that despite significant differences in the climates of Mars and Svalbard, a suite of strikingly analogous landforms has developed, although perhaps over enormously different timescales. Attempts to reconstruct paleoclimates on Mars have to take into account the fact that different processes acting in different environments can produce similar results (equifinality). The integrated analysis of landscapes can reduce such ambiguities. The landform inventory associated with pole-facing interior walls of impact craters in the Martian mid-latitudes suggests a geologically recent action and interaction of glacial and periglacial processes. Based on Earth-analogue landforms in similarly close spatial proximity in Svalbard, three scenarios of sequential landscape evolution were presented for Mars. All scenarios start with initial snowfall and the deposition of a dusty snowpack, and they all end with recent gully and fan formation. These scenarios are qualitative in the sense that none of them is expected to exactly represent the real situation on Mars. In fact, the scenarios are not mutually exclusive, and mixed cases (e.g. the dry and the snow scenarios) are very plausible. Dependent on latitude and insolation, some craters might have been shaped by the dry scenario, while craters at other latitudes might have been shaped by the wet scenario. The different scenarios also have different implications for the interpretation of certain landforms. For example, fractured mounds are unlikely to be open-system pingos in the dry scenario because that does not predict liquid water in the subsurface, a prerequisite for the growth of hydraulic pingos. However, basal melting of snow in the snow scenario could lead to infiltration of liquid water into the subsurface and the formation of hydraulic pingos as in the wet scenario.

The landscape evolution proposed in **paper V** would be controlled by obliquity and/or orbital parameters such as eccentricity, or the position of perihelion, and is therefore assumed to be cyclic. Several successive episodes of deposition and removal have already been suggested by, for example, Kreslavsky and Head (2002), Schon et al. (2009b) and Morgan et al. (2010). Processes implying an active layer might have operated in the past, although an active layer does not exist today (Kreslavsky et al. 2008; Ulrich et al., 2012). It is thus important to realize that the Martian mid-latitude morphologies do not represent a stable situation over long periods. Instead, this is a dynamic landscape in constant, although perhaps very slow, transition, and patterns of sedimentation and erosion overprint each other repeatedly. Nevertheless, the associated rates of erosion (e.g. in the dry scenario) are likely to be very low, and not all traces of former ice ages are extinguished by later glaciations. Therefore, the spatial extent of former and more widespread glaciations can be identified by careful morphological analysis (Hauber et al. 2008; Dickson et al. 2008, 2010; Head et al. 2010).

11. Outlook

The use of Earth-analogues is a promising approach to understand past processes on Mars. Further field studies applied on other landforms and landform systems in different geological and spatial settings will improve our knowledge about environments on our neighboring planet. Despite the recent advancements on cold-climate landforms on Mars, we have only scratched the surface with respect to understanding the system of periglacial landscapes on Mars so far. The continuous stream of high-resolution images from Mars bear promises for new venues of discovery, as it has been doing so many times in the past. A larger set of landform observations can help decrease the number of hypotheses used to explain various types of landforms. It will widen the scope on the diversity of landforms on Mars, which will help to answer questions whether processes such as, i.e. debris flows are unique local events or just a an effect of poor image coverage. With more years of spatio-temporal imaging, change detection of other aspects of the Martian landscape may be possible. Another important aspect is the fact that analogue research increases our knowledge about Earth's environments too. Some arid regions on Earth, which received limited attention from geomorphologist before, are now important environments to understand and extrapolate to Mars. This is certainly not limited to geomorphology, but also involves astrobiology in Earth's extreme environments to search for the boundaries of life. Since permafrost on Earth is known to host rich habitats containing cold-adapted microbial life, its exploration on Mars is also important for finding environments that potentially could sustain life (e.g., Ulrich et al, 2012b).

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