CHAPTER 5

# Pingo Landforms and Frost Mounds

Observations of putative pingo landforms on the Martian surface have been described since the early Viking days. Generally small sizes and various morphologies (topographic moulds or mounds) make these feature almost indistinguishable from other, similar-looking landforms on Mars. Most observations on Mars lack descriptions of other landforms indicative of periglacial environments and which are found in association with possible frost mounds. For such ambiguity reasons, pingos have been excluded from in-depth investigations in the course of this work but the main processes involved in their formation as well as the current research status on Mars is summarized in the following sections to conclude the chapter on periglacial landforms. Due to the absence of organic matter in the Martian environment, development of other frost-mounds, such as thufurs and palsas (*Schunke*, 1973), are not discussed in the following sections although their development is comparable to that of pingos. The reader is therefore referred to literature covering these morphologies in more detail.

## 5.1. Terrestrial Landforms

The term *pingo* (also frost mound, ice-cored mound, bulgunnyakh (russ.)) dates back to the first half of the 20th century when it was introduced in literature by *Porsild* (1938). Pingos are dome-like bulges in sediments of periglacial environments and usually have a solid ice core if they are not fossil (figures 5.1a-e). There are different types of pingos which are distinguished on the basis of their structure and the nature of hydrology (*French*, 1996).

Depending on the exact type, pingos have sizes in the range of a few meters up to 600 m and heights of up to 70 m (*Embleton and King*, 1975); several observations report on pingos with a size of 1,200 m (*Ehlers*, 1994). The bulged sedimentary cover has a general thickness of 1-10 m (*French*, 1996). Terrestrial pingos occur predominantly in the arctic regions of Alaska, Canada, Greenland and Siberia.

Although pingos are typical landforms of the periglacial zone, they are not frequently observed: several associated geomorphologic and hydrologic factors are required for their development and growth (*French*, 1996). According to a proposal by *Müller* (1959), pingos are grouped either as pingos of *hydrologically open* system (*artesian or open-system pingos*) and as pingos of *hydrologically closed* systems (*cryostatic or closed-system pingos*) (table 5.1).

### 5.1.1. Theories on Formation and Types

Characteristics of the two main types of pingos, i.e., hydrologically open- and closed systems, are shortly discussed hereafter because these features have been mentioned also in literature covering Martian analogues (section 5.2).

#### 5.1.1.1. Open-System Pingos

*Open-system pingos*, or hydro-lakkoliths (*Maarleveld*, 1965), also East-Greenland type pingos, comprise several landforms related to the result of a high hydraulic potential of water that is derived from upland areas; they are therefore hydrological phenom-

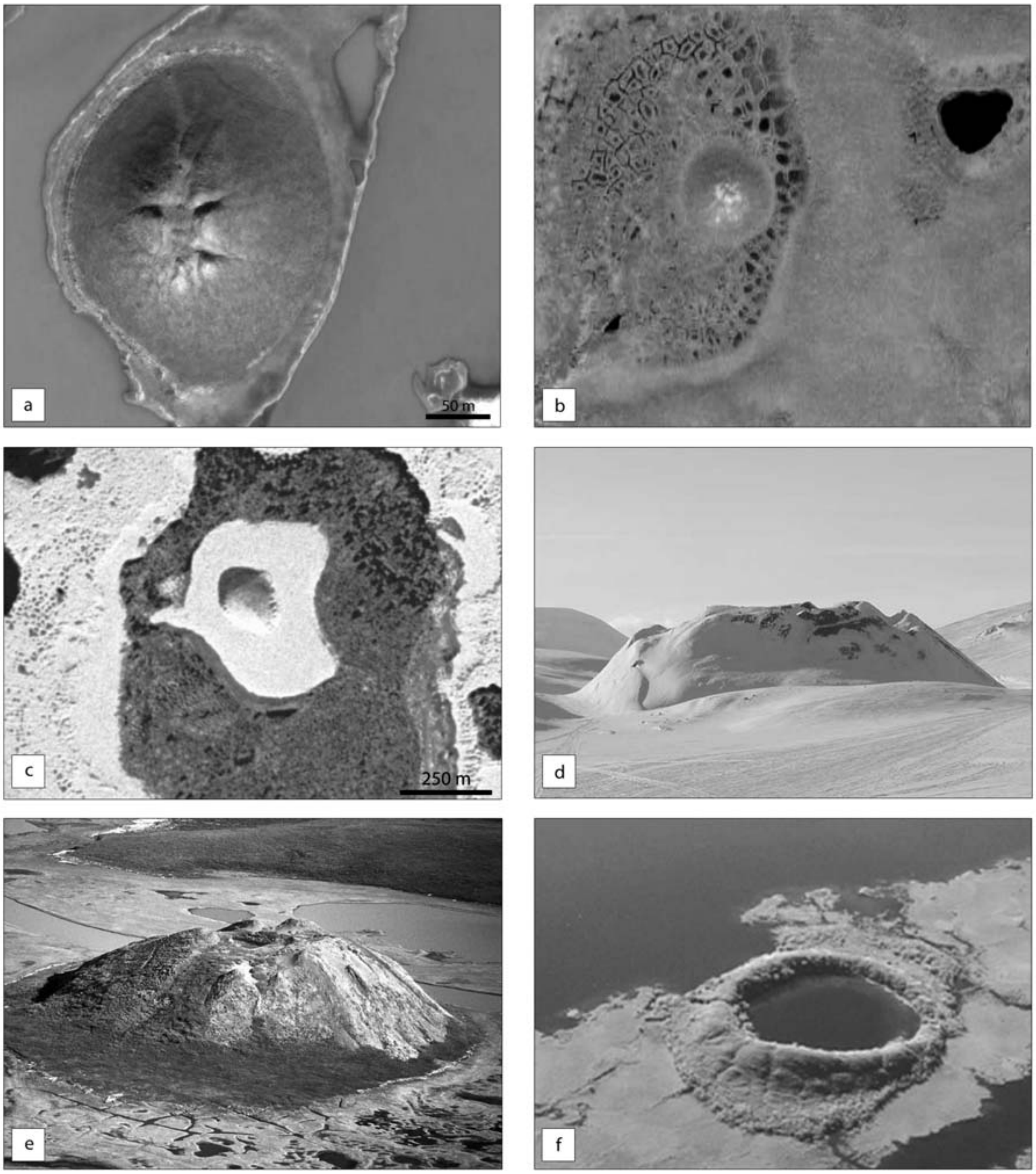

**Figure 5.1.:** Examples of terrestrial pingos, [a-b] pingos in the Tuktoyaktuk area, Mackenzie delta, Canada (Quickbird), [b] pingo in close relationship to polygonal fracture patterns; [c] Siberian Arctic, (Corona satellite, image courtesy of G. Grosse, University of Fairbanks, Alaska); [d] open-system pingo, upper Eskerdalen, Longyearbyen (Dept. Geology, UNIS); [e] 50-m high pingo, Mackenzie Delta, Canada (image courtesy of H. J. A. Berendsen); [f] degraded pingo in the Canadian arctic, Canada (*Herbert*, 2002).

ena (*French*, 1996) and formed predominantly by artesian groundwater in areas of discontinuous permafrost (e.g., *Mackay*, 1978, 1994) (figures 5.1d and 5.1.1.1, table 5.1). In a seasonal context and precursory to pingo formation, *frost blisters* form when, e.g., freezing of the active layer prohibits water discharge from intra- or sub-permafrost. Water below the frozen layer builds up high pressures leading subsequently to injection of water and ice into the covering frozen ground (*injection ice*). When

**Table 5.1.:** Characteristics of frost mounds in hydrologically open and closed systems (modified after *Karte*, 1979).

| type | Mackenzie | East-Greenland |
|---|---|---|
| hydrology | hydrologically closed system | hydrologically open system |
| permafrost connection | thick continuous permafrost | discontinuous permafrost |
| mean annual temperatures | below -6°C | between -1°C to -6°C |
| shape | circular to elliptical | elliptical to elongated |
| occurrence | solitary | often grouped |
| topography | plains, former lake/river beds | shallow valley flanks |
| exposition | no preference | preferred SE to S on northern hemisphere |

pressure builds up, it can eventually exceed the tensile strength of frozen ground (mostly sand fraction (*Mackay*, 1962)) and form dome-like circular to elliptically shaped mounds. For continuous growth, a steady supply of ground water and formation of injection ice is required according to *Müller* (1959). If hydraulic pressure exceeds the overburden pressure, seasonal ruptures in the overlying sediments can form. Blisters usually have sizes in the range of few meters only as they normally decay by slumping of the active layer and melting of accumulated ice during thawing seasons. When repeated formation of seasonal blisters at the same location leads to formation of perennially frost mounds, they are termed *open-system pingos*. Naturally, open-system pingos occur predominantly below slopes where artesian ground water pressure can build up; their occurrence is also preferably connected to southward-facing slopes on the northern hemisphere where freezing is prevented due to insolation conditions (*Brown*, 1973; *French*, 1996).

Other requirements for formation of open-system pingos are (a) restricted ground-water flow, i.e., slow flow rates of water that allow freezing of groundwater, and (b) temperatures close to 0°C, so that a minimum tensile strength of the ground is maintained and immediate freezing of ground water is prevented (*French*, 1996). Most artesian pressures, however, are not high enough to overcome the tensile strength of the overburden and maintain a pingo several meters high over long periods of time (*Holmes et al.* (1968) as cited in *French* (1996)). As a consequence, a pingo might collapse in connection with melting of the ice core. According to *Mackay* (1973), formation by injection-ice only, as previously stated by *Müller* (1959), is not the only mechanism: factors controlling formation and growth of open-system pingos are (a) water pressure conditions in areas outside of the pingo system, (b) varying strength of overburden sediments, and (c) ambient temperatures. For pingo development and growth, formation of injection ice as well as segregation ice would be necessary (*Mackay*, 1973) and the ratio of both could make the difference between small meter-scale pingos formed by segregation and large pingos formed by injection ice (*Soloviev*, 1973). High-pressure injection of water would cause immediate fracturing and spring formation whereas a slow water supply would result in immediate freezing; consequently pingo growth would cease (figure 5.1.1.1).

#### 5.1.1.2. Closed-system pingos

*Closed-system pingos* or Mackenzie-type pingos form in hydrologically closed systems and are characterized by a cryostatic development (figure 5.1.1.1, table 5.1). There are currently several explanations regarding formation and development of open-system pingos, however, prerequisites remain similar: pingos form by doming of the frozen ground caused by freezing of water which was expulsed from pores during permafrost aggradation (*French*, 1996). This process requires either locally or regionally unfrozen ground which is saturated by water. Lateral or vertical narrowing of that unfrozen layer and increase of pore wa-

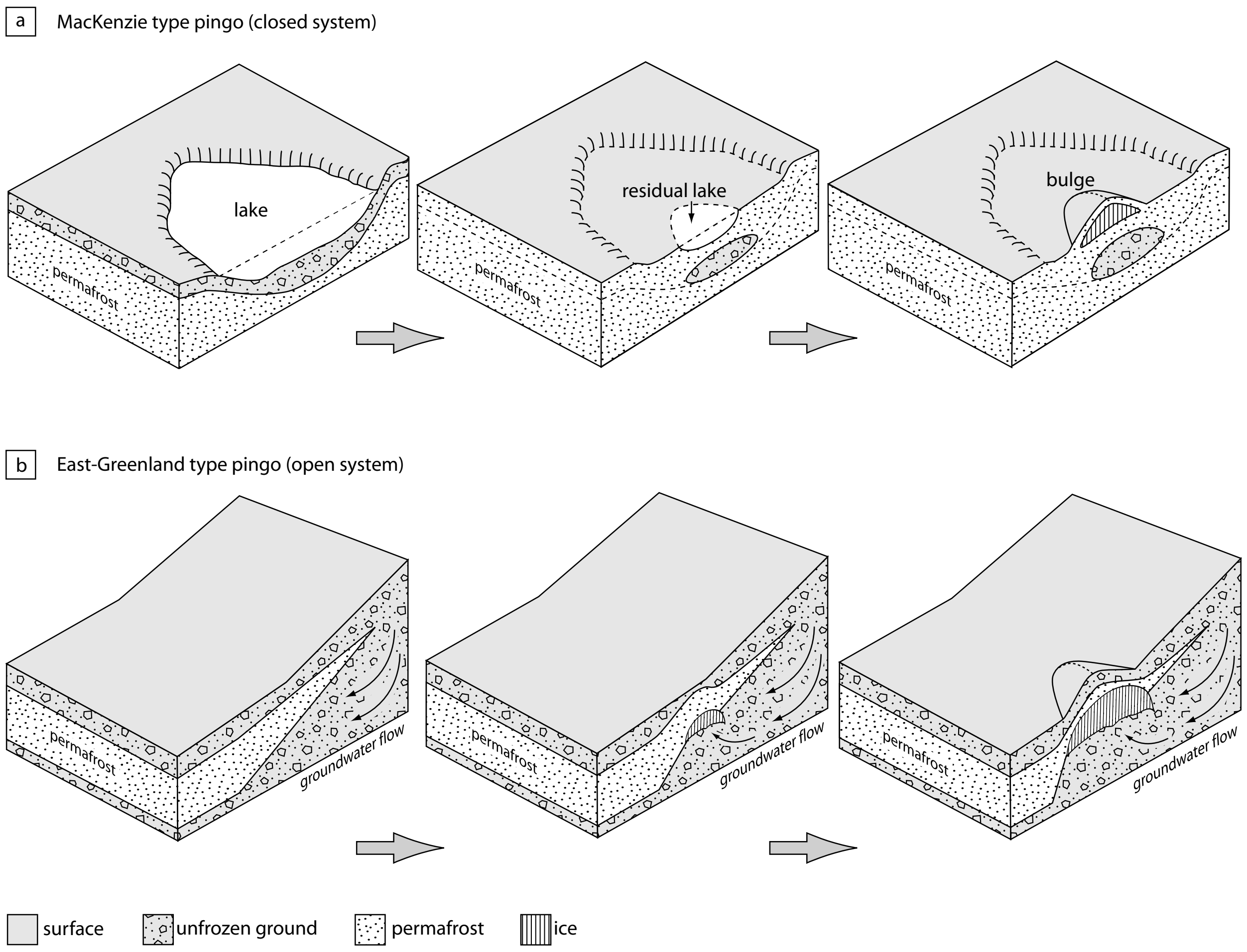

**Figure 5.2.:** Development of hydrologically open- and closed-system pingos; representation by author.

ter pressure occurs as a result of either seasonal freezing of top layers (*Ahnert*, 2003) or as a result of loss of an isolating upper layer, e.g., if a lake drains or is filled by sediments (*Ehlers*, 1994; *Embleton and King*, 1975; *Weise*, 1983; *French*, 1996). The cryostatic pressure raises as a consequence of increased pore-water pressures and eventually, cover sediments are lifted and bulged. As a result, water freezes and forms an ice core which can grow larger over the years (figure 5.1.1.1).

Mackenzie-type pingos occur almost exclusively in continuous permafrost on alluvial and low-relief plains (*Mackay*, 1962; *French*, 1996). Although such features form more or less isolated features, groups of closed-system pingos are frequently observed in dry lake beds (table 5.1, *Mackay* (1973),*Mackay* (1979)). Growth rates depend on the environmental conditions and are in the range of 2 m/a during the initial stadium of a closed-system pingo and no higher than 2 cm/a if the pingo is more mature (*MacKay*, 1986).

During the beginnings of research on closed-system pingos, it was thought that pingo growth is related to injection ice (see also discussion on East-Greenland pingos above), but modern research considers segregation ice as the dominant process for pingo formation although high-pressure injection of ice also plays an important role during the initial stadium and at the end of pingo formation (*French*, 1996). The interrelationship between segregation and injection ice depends on factors such as pore-water pressure

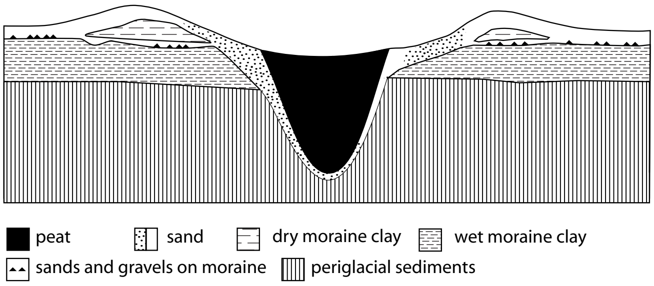

**Figure 5.3:** Cross-profile of a fossil pingo in the Netherlands, after *Jahn* (1975) and *Maarleveld and van den Toorn* (1955).

and overburden pressures, which, again, depend on the height of the pingo (*Mackay*, 1973). *Jahn* (1975) classifies pingos in the Mackenzie delta according to their shape, and he separated *bell-shaped* pingos that might be predominantly connected to injection ice from *disk–shaped* pingos that could be connected to segregation ice.

Earlier discussions on the formation of Mackenzie-type pingos in connection to raising artesian pressure (*Bostrom*, 1967) seem to be settled and such theories have been discarded nowadays. An extensive discussion on this topic can be found in *Embleton and King* (1975).

### 5.1.2. Pingo Degradation and Decay

As a result of the growth of a pingo ice core, the sedimentary top layer can tear open and a star-shaped incisions pattern with a small central crater may form at the top of the pingo (figure 5.1a,d-e). The exposed ice core will consequently slowly melt away and the resulting void then causes collapse of the sedimentary cover. At the end of pingo decay, a near-circular central depression with raised rims and a rampart will remain (figures 5.1f, 5.3). The characteristic shape of a fossil pingo resembles closely that of a small volcanic caldera or that of an impact crater. Characteristic of fossil pingos are upturned strata with outwardly dipping layers.

According to *Jahn* (1975), decay of pingos can generally be subdivided into two phases: First, collapse of the central bulge as a consequence of rupturing and formation of a central crater. This first phase occurs under periglacial conditions and decay cannot continue to the second phase if periglacial conditions are still dominant. The second phase is characterized by complete disintegration of the pingo due to melting of the ice core and formation of a characteristic rampart. That phase can only take place when significant climatic changes occur (*Jahn*, 1975).

Even in terrestrial research there were (and still are) problems related to the morphologic ambiguities of these landforms, e.g., past discussions where fossil pingos were mis-interpreted as small volcanic structures (*Müller*, 1959). *Embleton and King* (1975) also emphasized such problems but considered the characteristic rampart as a feature that helps to distinguish fossil pingos from thermokarst depressions or kettle holes. Notwithstanding such criteria, there have been discussions regarding the nature of similar landforms in France, Belgium, Ireland and Germany (*Embleton and King*, 1975), areas that are usually well-accessible for field investigations.

*French* (1996) does not rule out that there are other non-typical landforms, e.g., in the Canadian Arctic or in Tibet, which could be connected to a development closely comparing to that of a pingo. These forms are relatively small and do not show any indications of growth. They are possibly connected to faults in permafrost through which water can rise and penetrate underneath the surficial layer. *French* (1996) also reports on elongated Arctic morphologies that could be related to freezing of taliks below old river beds. Although mechanisms for pingo development are relatively well known, quantitative work is mainly restricted to growth rates, temperature profiles and derivation of morphometric values, such as widths, lengths, heights, and radii (*Pissart and French*, 1976;

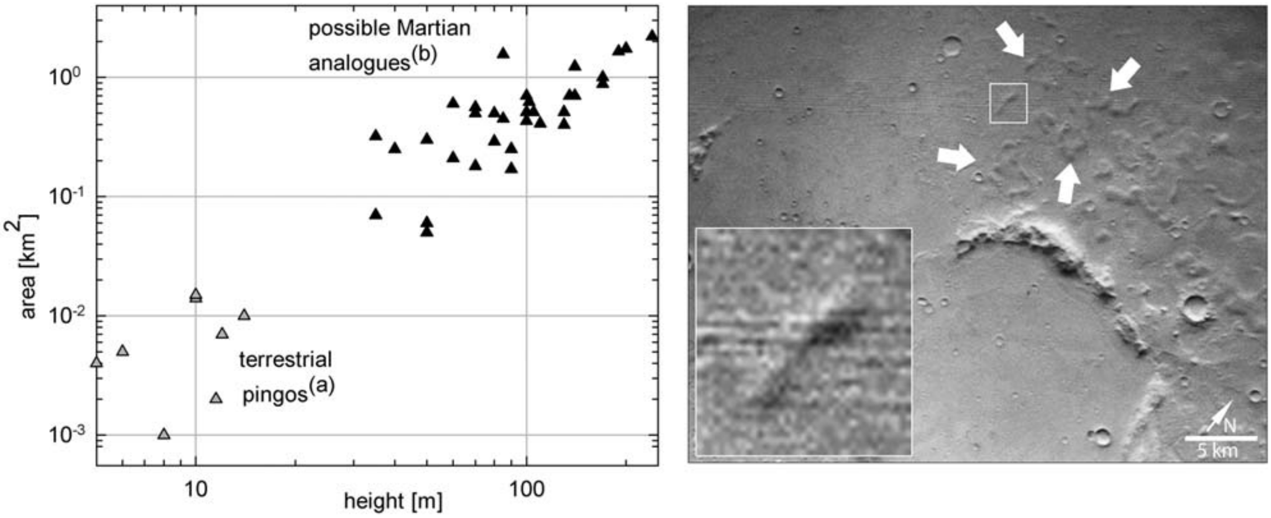

**Figure 5.4.:** Heights and areas of (a) terrestrial pingos (*Pissart and French*, 1976) and (b) possible Martian analogues (*Cabrol et al.*, 2000); Viking scene on the right displays some of the landforms (arrows) interpreted as circular, elongated or composite pingos (Viking frame 434S09, 0.068 km/px at 15.21°S, 183.9°E). Sizes of terrestrial pingos were approximated using average lengths and widths (*Pissart and French*, 1976), data compilation by author.

*Mackay*, 1987; *French*, 1996). Due to a large variety of pingo morphologies observed in the field, these values are nonetheless considered as unrepresentative (*French*, 1996).

## 5.2. Martian Candidate Landforms

In literature on Martian landforms, pingos have been mentioned for the first time in connection with Viking-based observations (*Theilig and Greeley*, 1979; *Lucchitta*, 1981; *Rossbacher and Judson*, 1981). *Rossbacher and Judson* (1981) noticed that although the periglacial environment of Mars could be conducive of pingo formation, even highest-resolution Viking image data would not allow to identify such features unambiguously because of their resemblance to so-called pedestal craters on Mars. *Lucchitta* (1981, 1985) as well as *Squyres et al.* (1993, p. 549f) also doubt that pingo landforms could be easily distinguished from, e.g., volcanic cones, pseudo craters oder secondary crater impacts.

In contrast to this, *Theilig and Greeley* (1979) pointed towards several characteristic pingo morphologies in Chryse Planitia and Lunae Planum and also towards a close relationship of these landforms to other characteristic landforms of the periglacial, such as alasses. The size of these landforms, however, is far larger than that of any terrestrial pingo and therefore the volume of segregation and injection ice must have been much larger. *Coradini and Flamini* (1979), however, showed that on the basis of thermodynamical calculations, the abundance of near-surface water would not suffice to form pingos and that, furthermore, near-surface freezing would not play any significant role in the formation of such landforms.

*Cabrol et al.* (1997, 2000) discussed arguments put forward by *Coradini and Flamini* (1979) and concluded that conditions necessary for release of water and subsequent pingo formation could be favourable in paleolake environments where near-subsurface water could be stored. *Cabrol et al.* (2000) argued on the basis of work by *Lucchitta* (1981); *Rossbacher and Judson* (1981) that fine-grained sediments could be conducive of permafrost accumulation even in equatorial latitudes if a steady supply of groundwater was provided. According to *Cabrol et al.* (2000), such configurations were found in areas that have been discussed as potential sites for Amazonian lakes (e.g., *Goldspiel and Squyres*, 1991; *Scott et al.*, 1995; *Scott and Chapman*, 1995).

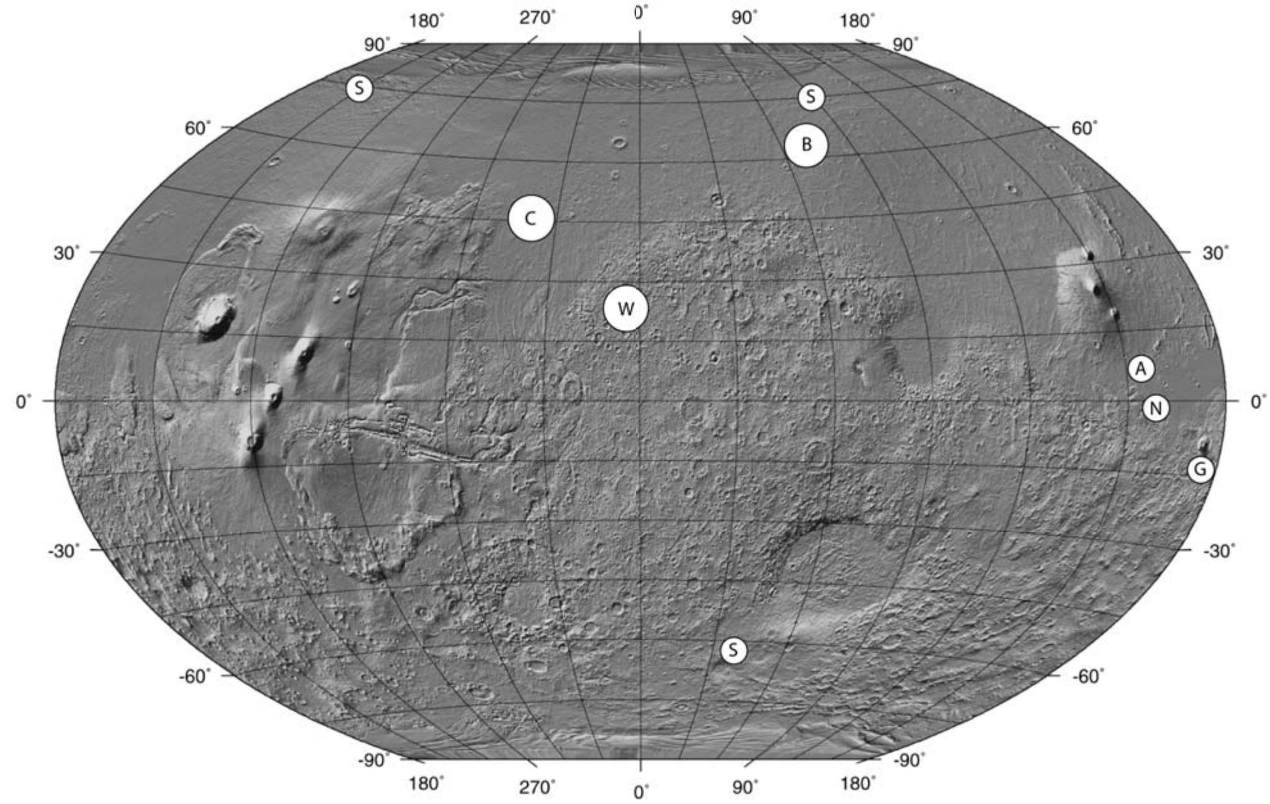

**Figure 5.5.:** Locations of discussed pingo landforms on Mars. (A) Athabasca region (*Burr et al.*, 2005), (G) Gusev impact crater (*Cabrol et al.*, 1997, 2000), (N) southeastern Elysium region (*Nussbaumer et al.*, 2000), (S) high-latitude regions (*Sakimoto*, 2005; *Sakimoto*, 2005), (W) Cydonia region (*Wood*, 1982), (B) northwestern Utopia Planitia region (*Soare et al.*, 2005; *Soare et al.*, 2005), (C) Chryse Planitia (*Theilig and Greeley*, 1979) (compilation by author).

*Cabrol et al.* (2000) furthermore compared morphometric values derived from pixel counting on Viking-based maps with terrestrial values by *Pissart and French* (1976) and obtained a number of values for heights and areas. Individual mounds on Mars are more than 10 times taller and areas are more than 100 times larger when compared to terrestrial pingo landforms (figure 5.4).

*Cabrol et al.* (2000) furthermore distinguished elliptical, circular and and composite pingo landforms (figure 5.4) and also picked up suggestions by *Scott* (1983) who mentioned meandering landforms. Based on the proposed morphologic similarities, *Cabrol et al.* (2000) ruled out volcanic or thermokarst landforms and argued that the generally characteristic incisions at the top of pingos is missing because pingos on Mars might not have reached a mature phase yet. Consequently, a pingo ice-core could theoretically still be intact. A separation of cryostatic and hydraulic pingos could not be made due to limitations in image resolution (*Cabrol et al.*, 2000) . A paleolake environment for Gusev Crater was proposed in numerous contributions by, e.g., *Grin and Cabrol* (1997); *Cabrol et al.* (2000) but it could not be confirmed by observations of the MER Spirit rover. The possibility of limited aqueous processes were, however, not excluded completely (*Cabrol et al.*, 2006).

Apart from a few conference contributions in which some resemblance of terrestrial pingos and certain Martian landforms were shortly mentioned (*Wood*, 1982; *Jöns*, 1985; *Lucchitta*, 1985; *Squyres and Carr*, 1986; *Cave*, 1993; *Chapman*, 1993; *Lucchitta*, 1993; *Mellon and Jakosky*, 1995), no significant contributions on the topic of pingo landforms on Mars were published

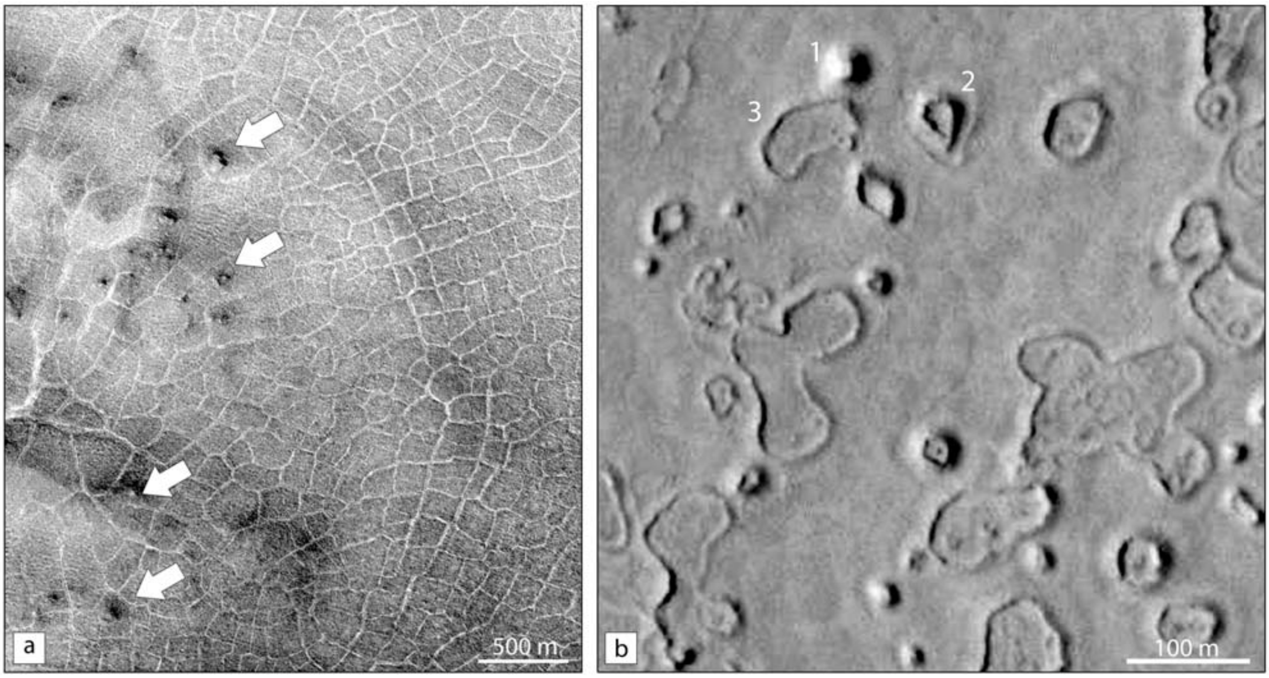

**Figure 5.6.:** Putative pingo landforms on Mars, MOC-NA scenes; [a] E03/00299, pingos (arrows) as proposed by *Soare et al.* (2005) and oriented orthogonal polygonal patterns in Utopia Planitia, 67.0°E/64.7°N; [b] R01/00745, various degradation phases (1) intact pingo, (2) collapsing pingo, (3) pingo scars, classification after *Burr et al.* (2005), faint polygonal pattern indicative of thermal contraction processes visible on the plains, Athabasca region, 156.0°E/9.7°N.

until 2005 in connection with data obtained from Mars Global Surveyor. In these publications, two regions were investigated in more detail: the Athabasca Valles area (*Burr et al.*, 2005) and the northwestern Utopia Planitia region (*Soare et al.*, 2005) (figure 5.5).

*Soare et al.* (2005) analyzed small mounds in an impact crater in Utopia Planitia and considered the close proximity to other periglacial landforms, such as polygonal patterns and possible thermokarstic pits and moulds, as convincing argument for interpreting these mounds as pingo landforms. The morphologies were, however, not discussed in the paper by *Soare et al.* (2005). They suggested that the water needed for pingo formation might have been redeposited in that area (figure 5.5) during periods of high obliquities of the planet's spin axis. During subsequent lower obliquity periods, four phases were proposed which have led to pingo formation: (1) dissipation, evaporation or sublimation of near-surface water, (2) permafrost aggradation, (3) formation of an ice core, and (4) bulging of the sediment cover and formation of a pingo. They compared mounds and morphologic assemblies to the Canadian Tuktoyaktuk area and concluded that the proposed mounds are hydrostatic pingos. The authors, however, did not believe that the amount of water in that impact crater would have been sufficient to aid pingo formation but they suggested also that water which might once have covered large areas of the northern lowlands and which was derived from late Hesperian outflow activity, could have been sufficient for permafrost aggradation. Based upon estimates of the planet's obliquities, pingos were considered to be as young as ~100 ka (*Soare et al.*, 2005).

*Burr et al.* (2005) described on the basis of three MOC scenes (one of which being a cPROTO scene with 50 cm/px) possible pingo morphologies in the Athabasca region of Mars, an area known for its fluvial and volcanic history (e.g., *Burr et al.*, 2002; *Berman and Hartmann*, 2002; *Werner et al.*, 2003; *Werner*, 2005). To account for ambiguities regarding pingo morphologies, *Burr et al.* (2005) pointed also

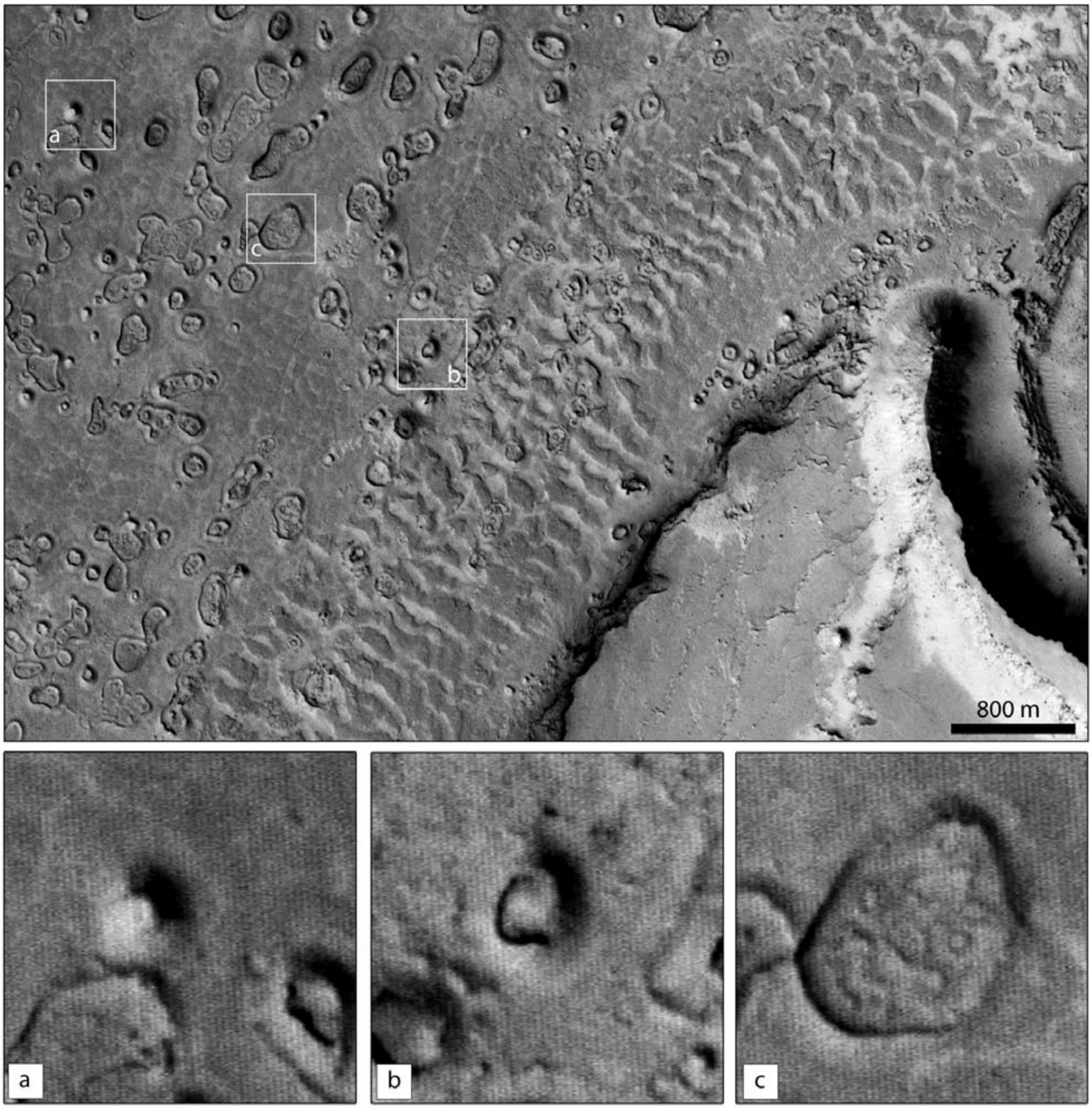

**Figure 5.7.:** MOC-NA cPROTO scene R12/03203 covering an area of the Athabasca Valles at 156.09°, 9.56°N. Rootless cones resemble closely pingo features in different degradational phases as proposed by *Page and Murray* (2006); scenes [a-c] represent different development stages ranging from intact [a], eroded [b] to degraded [c], see also figure 5.6b and similar descriptions by *Burr et al.* (2005).

towards other landforms suggestive of periglacial environments in the vicinity of the proposed pingo morphologies (see also *Soare et al.* (2005)). They distinguished several degradation stages of pingos with diameters in the range of 15-130 m (figure 5.6b) but they did not exclude other formation processes, such as volcanic processes. *Burr et al.* (2005) considered the occurrence of permafrost in the Athabasca region as a local effect because MO-Neutron Spectrometer (NS) data did not show significant amounts of near-surface hydrogen. They connected possible permafrost occurrences to the outflow activity in the Athabasca Valles area. Apart from the putative closed-system pingos, open-system pingos could also develop if groundwater was released hydrothermally from the volcanic region of Elysium Mons. The minimum age for the proposed pingo landforms was consequently connected to the latest outflow activity of Athabasca Valles and was estimates to be in the range of 2-8 Ma or older (*Burr et al.*, 2005).

*Page and Murray* (2006) reported on so-called rootless debris cones in the Athabasca Valles/Cerberus Plains which are generally attributed to explosive magma-ice interaction (e.g., *Lanagan et al.*, 2001; *Fagents et al.*, 2002). They concluded that the superposition relationships of cones and platy deposits in the Athabasca Valles would exclude a magmatic origin of such cones and suggested pingos as an alternative to explain the morphologies; different shapes are attributed to different degradational stages (figure 5.7a-c), similar to the approaches described in *Burr et al.* (2005) (*Page and Murray*, 2006).

A more unusual morphology attributed to pingo formation was suggested by *Sakimoto* (2005); *Sakimoto* (2005). These landforms differ considerably from what has been proposed by other workers and any in-depth attempts to quantify the proposed features or to analyse image data is missing. According to their work, some of the polar impact craters that contain large central mounds and bulges (>10 km) might be pingo landforms as deduced from a missing layering and a central depression at the top (figure 5.5). However, publications and in-depth analysis on this topic were not provided thus far.

## 5.3. Concluding Remarks

For the time being, none of the observations about Martian landforms can be unambigously attributed to frost-mound formation. Restricting factors are a limited image resolution of current space-borne sensors and the close morphological resemblance of fossil pingos to impact crater structures (figures 5.1f, 5.3). Even in much better acessible terrestrial environments, there are many uncertainties when possble pingo landforms are investigated. Because clear observational evidence is missing and none of the landforms discussed above have a close resemblance to terrestrial pingos – they are even missing some of the most characteristic features – a debate on such landforms and the exact formation (open-system or closed-system) seems to be untimely. Mars Reconnaissance Orbiter (MRO) might shed more light onto this debate by providing highest resolution data but considering the modelled ground-ice stability on Mars, intact pingos will be difficult to find. On the basis of spatial relationships to other periglacial landforms, such as polygonal fracture patterns, some of these early observations discussed above seem to be promising and theories might be confirmed in the next years. □