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WATER IN THE POLES AND PERMAFROST REGIONS OF MARS

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ABSTRACT

The poles and mid-latitudes of Mars contain a large reservoir of water in ice caps, thick sequences of ice-rich layers, and mantles of snow. This reservoir is $\geq 5 \times 10^6$ km^3 in volume, corresponding to a layer ~130 m thick over the planet. Hydrogen in water ice has been detected at the surface at latitudes poleward of 50°. Morphologic features show downslope flow of ice-rich sediment, and recent gullies have been produced from sub-surface aquifers or melting snowpacks. Variations in Mars' orbit on 50,000 to 2M year timescales produce significant changes in climate, transporting water between the poles where it currently resides, and the lower-latitudes, where it may play a critical role in surface evolution.

INTRODUCTION

Water has long been recognized as a major morphologic agent on Mars (see review by Baker, this issue), but its present abundance and location remains enigmatic. A possible reservoir for a substantial amount of water is surface and sub-surface ice at the poles and mid-latitudes. Recent observations have substantially improved our knowledge of this reservoir, but major questions remain as to its volume, age, and history. Oscillations in the axial tilt, eccentricity, and timing of closest approach to the Sun cause major changes in surface heating that produce cyclic changes in martian climate on timescales of 10^5 to 10^6 years [e.g. *Ward*, 1974; *Pollack and Toon*, 1982]. These changes redistribute the polar ices, transferring it to lower latitudes as snow and ice during martian "ice ages" [e.g. *Toon et al.*, 1980; *Jakosky et al.*, 1995; *Haberle et al.*, 2001; *Head et al.*, 2003].

Today the major ice-bearing elements are the polar ice caps, the layered units that surround them at both poles, and the mid-latitude permafrost zones that contain morphologies strongly suggestive of sub-surface ice. Each have unique properties, water abundances, and histories, and contribute to the water cycle in varying ways.

POLAR CAPS

Overview

The polar caps of Mars have been observed since the 17th century, and assumed to be composed of some combination of water and CO_2 ice [see review by *James et al.*, 1992]. The martian atmosphere was determined from Earthbased observations and early Mariner spacecraft to be composed of >95% CO_2 with a pressure of only a few mbar [*Kaplan et al.*, 1964; *Kaplan et al.*, 1969], which led to the prediction that CO_2 would accumulate in the poles during winter [*Leighton and Murray*, 1966]. This prediction was confirmed by temperature measurements [e.g. *Neugebauer et al.*, 1971; *Kieffer et al.*, 1977; *Kieffer*, 1979], and global mapping has shown that seasonal CO_2 caps grow well into the mid-latitudes during winter, with perennial ice caps surviving the summer at both poles [e.g. *Kieffer et al.*, 1976; *Briggs et al.*, 1977; *Kieffer*, 1979; *James et al.*, 1992; *Kieffer et al.*, 2000; *James and Cantor*, 2001; *Kieffer and Titus*, 2001].

Seasonal Caps

The size of the north and south seasonal CO_2 ice caps differ significantly due to differences in the length of the respective winter seasons caused by Mars' eccentric orbit around the Sun. The southern seasonal cap grows to ~40°S in the long southern winter, whereas the northern cap only extends to ~65°N. Portions of the southern seasonal cap have been suggested to form an impermeable, translucent slab of CO_2 ice [*Kieffer et al.*, 2000]. As this cap retreats it displays unusual spots, fans, and 'spiders' [*Malin and Edgett*, 2001; *Cantor et al.*, 2002; *Edgett et al.*, 2000; *Piqueux et al.*, 2003; *Kieffer*, submitted; *Christensen et al.*, submitted] that may result from vents and jets through the CO_2 slab in ways that are unlike any process found on Earth [*Kieffer*, 2000; *Kieffer*, 2003; *Kieffer*, submitted; *Christensen et al.*, submitted].

The thickness of this seasonal CO_2 ice has been estimated from Mars Global Surveyor (MGS) MOLA observations to reach approximately 1.5 m near the pole in both hemispheres, with total estimated mass values of 3.1×10^{15} kg in the north and 3.3×10^{15} kg in the south [*Smith et al.*, 2001a]. This mass of condensed CO_2 is ~25% of the total mass of the Mars atmosphere [*Hess et al.*, 1977; *Hess et al.*, 1979; *Tillman et al.*, 1993].

As the seasonal caps condense they incorporate minor amounts of dust and water ice that significantly affect the sublimation rates the following spring [e.g. *Paige and Ingersoll*, 1985; *James et al.*, 1992]. Assuming a water vapor mass fraction of 1×10^{-5} in the condensing atmosphere gives an estimate of ~3×10^{10} kg (~3×10^{-2} km^3) of water stored in the seasonal caps (the Mars atmosphere contains ~10^{-1} km^3 of water). As the southern cap shrinks in the spring an annulus of brightening has been observed immediately poleward of the retreating cap edge that may be due to the recondensation of this water as it is released from the subliming CO_2 ice. Overall, however, the water within the seasonal cap plays a relatively minor role in the global inventory or annual cycle of water on Mars.

Perennial Caps

In their pioneering work Leighton and Murray predicted that CO_2 would condense at the poles to sufficient depth that CO_2 would remain throughout the following summer. Spacecraft temperature observations show that CO_2 ice does survive the summer in the south [*Neugebauer et al.*, 1971; *Kieffer*, 1979], but is completely removed from the northern perennial cap to expose water ice [*Kieffer et al.*, 1976]. Sublimation of this ice releases water vapor into the atmosphere, which was initially detected by groundbased observations over 40 years ago [*Jakosky and Barker*, 1984], and has been observed by subsequent groundbased observations [*Clancy et al.*, 1992; *Clancy et al.*, 1996; *Sprague et al.*, 2001] and IR spectrometers aboard the Mariner 9, Viking, Phobos, MGS, and Mars Express orbiters [e.g. *Hanel et al.*, 1972; *Farmer and Doms*, 1979; *Jakosky and Farmer*, 1982; *Rodin et al.*, 1997; *Rosenqvist et al.*, 1992; *Smith et al.*, 2001b; *Smith*, 2004; *Smith et al.*, 2001c].

The Viking orbiter MAWD instrument provided the first global map of water vapor, and confirmed high abundances (~100 pr. μm) coming from the northern perennial cap [e.g. *Farmer and Doms*, 1979; *Jakosky and Farmer*, 1982; *Jakosky and Barker*, 1984]. The MGS TES instrument has provided detailed global maps of water vapor over three Mars years (1997-2004), confirming high vapor abundances equatorward of the cap in the north that rise rapidly to ~100 pr μm in late spring once the CO_2 ice has disappeared [*Smith et al.*, 2001b; *Smith*, 2004; *Smith et al.*, 2001c].

The MAWD data showed no indication of water vapor coming from the perennial south polar cap [*Farmer and Doms*, 1979; *Jakosky and Farmer*, 1982], consistent with measured temperatures that correspond to CO_2 ice [*Kieffer et al.*, 2000]. A notable exception to this pattern was the groundbased water vapor measurements in 1969 that showed a significant increase in water vapor compared to other seasons or other years that has been interpreted to indicate that water ice was exposed that year in the south [*Barker et al.*, 1970; *Barker*, 1976; *Jakosky and Barker*, 1984]. TES observations have confirmed the release of water vapor (~45 pr μm) along the southern cap edge, providing conclusive evidence that water ice is now being exposed on the southern perennial cap [*Smith et al.*, 2001b; *Smith*, 2002; *Smith*, 2004]. The presence of this exposed ice has been confirmed by direct temperature measurements from the Mars Odyssey THEMIS infrared imager [*Titus et al.*, 2003], and by near-IR spectral measurements from the Mars Express OMEGA spectrometer [*Langevin et al.*, 2004].

A remarkable finding from the high resolution (1.5-3 m/pixel) MGS MOC camera was the discovery of quasi-circular depressions in the perennial south polar cap that are up to 1 km diameter and uniformly ~8 m deep [*Thomas et al.*, 2000; *Malin et al.*, 2001] (**Figure 2**). Some depressions are expanding at rates of 1-3 m per year [*Malin et al.*, 2001], and have been modeled as layer of CO_2 ice over a substrate of either water ice or high albedo (dust free) CO_2 ice [*Byrne and Ingersoll*, 2003]. This thin layer of CO_2 may be relatively young [*Thomas et al.*, 2000], and, even if completed sublimated, would be a minor contributor to the atmospheric CO_2 inventory [*Byrne and Ingersoll*, 2003]. In this case the atmospheric CO_2 partial pressure, and therefore the atmospheric temperature, cannot be much higher than its current value [*Byrne and Ingersoll*, 2003].

POLAR LAYERED DEPOSITS

Thick stacks of sedimentary deposits extend up to 600 km outward from the poles in both hemispheres [e.g. *Sharp et al.*, 1971; *Murray et al.*, 1972; *Soderblom et al.*, 1973; *Cutts*, 1973; *Howard et al.*, 1982; *Tanaka and Scott*, 1987; *Plaut et al.*, 1988; *Thomas et al.*, 1992; *Herkenhoff and Plaut*, 2000; *Koutnik et al.*, 2002]. These units are ~3 km thick at both poles [*Smith et al.*, 1999; *Zuber et al.*, 1998], and are layered down to the resolution of the MOC camera [*Malin and Edgett*, 2001]. These layers may be produced by differences in the amount of airfall dust incorporated into the ice that may vary with orbit-driven cyclic changes in climate Mars orbit [e.g. *Ward*, 1974; *Toon et al.*, 1980; *Pollack and Toon*, 1982; *Milkovich and Head*, 2005].

The volume of the north polar layered deposits is estimated to be ~1.2 to 1.6 10^6 km^3 [*Zuber et al.*, 1998; *Johnson et al.*, 2000]. Attempts have been made to determine the density, and thus the ice/sediment ratio, of the layered materials using gravity and topography [*Malin*, 1986; *Zuber et al.*, 1998; *Johnson et al.*, 2000], but this value has been difficult to constrain. The topographic slopes and gently undulating surface of the north layered materials are consistent with the slow radial flow velocities for water, but not CO_2, ice rheology [*Zuber et al.*, 1998]. Assuming a composition of pure water for the layered deposits gives an upper limit of ~$1.6\text{x}10^{18}$ kg (~$1.6\text{x}10^6$ km^3) of water in the northern layered terrains, corresponding to an equivalent global layer of water ~12 m deep [*Zuber et al.*, 1998; *Johnson et al.*, 2000]. The areal extent of the southern deposits is roughly twice that of the north with a similar average the thickness, suggesting a water inventory, again assuming pure ice, that is roughly twice that in the north.

Units within these deposits can be traced 100's of km at both poles, suggesting a regional formation process [*Byrne and Murray*, 2002; *Byrne and Ivanov*, 2004; *Milkovich and Head*, 2005]. A stratigraphic horizon near the base of the northern units is interpreted to have been an extensive sand sea that formed during a period when no icy cap was present [*Byrne and Murray*, 2002]. The lack of an ice cap would require a dramatic climate change and would represent a major event in martian history [*Byrne and Murray*, 2002]. Analysis of layers within the upper units of the northern layered terrain shows the existence of ~30-m periodicity, possibly associated with the 50,000 year obliquity cycle [*Milkovich and Head*, 2005]; a 100-m unit within this sequence lacks this layering and may represent a recent (0.5-2 My) period of ice removal and the formation of a sediment-rich lag [*Milkovich and Head*, 2005]. Crater counts also suggest an active process, with ages for the upper surfaces of these deposits of ~30-100 My for the southern and <0.1 My for the southern deposits [e.g. *Plaut et al.*, 1988; *Herkenhoff and Plaut*, 2000; *Koutnik et al.*, 2002]. These ages likely only reflect the most recent cycle in this process, and cyclic deposition and erosion may have been occurring in the polar regions throughout martian history.

SUB-SURFACE ICE

Ice Stability Models

The stability of sub-surface depends strongly on the porosity, tortuosity, and thermal conductivity of the surface [*Mellon and Jakosky*, 1995]. These models predict that water ice will be stable at all latitudes for obliquities >32°, but will diffuse outward from the upper 1-2 m in the equatorial and mid-latitude regions when the obliquity decreases [*Mellon and Jakosky*, 1993; *Mellon and Jakosky*, 1995; *Mellon et al.*, 1997; *Hecht*, 2002]. Mars is currently in an "interglacial" period at an obliquity of ~25° [*Mellon and Jakosky*, 1995; *Mustard et al.*, 2001; *Christensen*, 2003; *Head et al.*, 2003], and the near-surface ice is predicted to only be stable poleward of ~50° [*Mellon and Jakosky*, 1995].

This prediction is in excellent agreement with the mapping of water ice abundances by the Odyssey Neutron Spectrometer, HEND, and Gamma Ray instruments. These instruments discovered high hydrogen abundances in the uppermost meter extending from the poles to 50° in both hemispheres [*Feldman et al.*, 2002; *Boynton et al.*, 2002; *Mitrofanov et al.*, 2002] (**Figure 3**). Assuming that the hydrogen is in water ice, the ice content of the upper meter is >70% by volume over large regions on the high latitudes [e.g. *Boynton et al.*, 2002]. This high abundance is unlikely to have been formed by gas diffusion into soil pores, but instead represents accumulation as surface snow or frost [e.g. *Tokar et al.*, 2002; *Christensen*, 2003].

Morphologic Evidence for Sub-surface Ice

Ice-rich materials in the mid-latitudes have long been postulated [see recent review by *Clifford et al.*, 2000] on the basis of: (1) lobate, grooved, and ridged textures suggestive of flow on channel, crater, and mesa walls [e.g. *Rossbacher and Judson*, 1981; *Squyres and Carr*, 1986; *Carr and Schaber*, 1977; *Lucchitta*, 1981; *Tanaka*, 2000; *Garvin et al.*, 2000] (**Figure 4**); (2) unusual lobate crater ejecta suggested to form by fluidization of ground ice [e.g. *Carr et al.*, 1977; *Barlow and Perez*, 2003]; (3) evidence for volcano-ice interactions [e.g. *Allen*, 1979; *Squyres et al.*, 1987]; and (4) possible evidence for glacial landforms and processes [*Baker et al.*, 1991; *Kargel and Strom*, 1992; *Kargel et al.*, 1995].

Additional evidence for of ground ice comes from a pervasive "basketball" surface texture found from 30-50° in both hemispheres [*Mustard et al.*, 2001]. This unit is 1-10 m thick and interpreted to result from the desiccation and erosion of once ice-rich soils that formed through diffusion of water vapor into the soil pore space [*Mustard et al.*, 2001]. This material does not have a hydrogen signature [*Tokar et al.*, 2002], in agreement with the predicted desiccation of the upper 1-2 m for these latitudes [e.g. *Mellon and Jakosky*, 1995]. However, it transitions poleward to a smooth mantle that does have a high hydrogen abundance [*Tokar et al.*, 2002], suggesting that it may also have formed by direct condensation of snow or frost. In this case this unit may contain substantially more water than the 1.5-6.0 x 10^4 km^3 initially suggested [*Mustard et al.*, 2001]. The number of small fresh craters on these mantling units is low, suggesting that these mantles are possibly as young as 0.15 Myr but most certainly less than 10 Myr [*Mustard et al.*, 2001; *Kreslavsky and Head*, 2002; *Head et al.*, 2003].

Further evidence for ice-rich mantles is found in 1-10 m thick deposits that preferentially occur on pole-facing slopes, have features suggestive of flow, and have a distinct, rounded edge marking the upslope boundary (**Figure 5)** [*Carr*, 2001; *Malin and Edgett*, 2001; *Christensen*, 2003; *Milliken*, 2003]. These characteristics suggest an ice-rich mantle that was once more extensive but has been removed from all but the cold, pole-facing slopes where near-surface ice is stable under solar illumination.

Modern Gullies

Recent gullies are also found in the 30-50° latitude range in both hemispheres [e.g. *Malin and Edgett*, 2000; *Malin and Edgett*, 2001], and their origin is the topic of a vigorous, on-going discussion. They have been proposed to form from a range of processes, but discharge of liquid water from sub-surface aquifers [*Malin and Edgett*, 2001; *Mellon and Phillips*, 2001; *Gaidos*, 2001; *Gilmore and Phillips*, 2002; *Heldmann and Mellon*, 2004], the melting of pore ice that diffused inward from the atmosphere during periods of colder temperatures [*Costard et al.*, 2002], or melting of a snow layer [*Lee et al.*, 2001; *Hartmann*, 2002; *Christensen*, 2003] deposited during periods of higher obliquity when surface ice was stable at these latitudes are the most plausible [see review by *Heldmann and Mellon*, 2004].

Of these models, the melting of pore ice does not account for the fact that as the surface and sub-surface temperatures warm, the upper soil layer will become desiccated before significant liquid water can be produced [*Mellon and Phillips*, 2001; *Christensen*, 2003; *Heldmann and Mellon*, 2004]; if ice formed by vapor diffusion, it will dissipate by the same mechanism. Water released from sub-surface aquifers works to explain gully morphology, latitudinal distribution, and slope position [*Heldmann and Mellon*, 2004]. However, this model does not account for the presence of gullies on isolated knobs and dunes where with no obvious aquifer source, the survival and recharge mechanism that would allow these aquifers to persist to the present, their formation only at latitudes poleward of 30°. This model also requires high flow rates (>30 m^3/s [*Heldmann et al.*, 2005]) for water to remain liquid long enough to carve the 1-2 km long gullies under current conditions.

Lee, Rice, and Hartmann [*Lee et al.*, 2001; *Hartmann*, 2002] suggested that melting snow might carve martian gullies based on analogies with similar gulley morphologies in cold regions on Earth. This model has been developed [*Christensen*, 2003] by noting the association of gullies with the ice-rich slope mantles (**Figure 5**), and by incorporating the models for snow formation at high obliquity [e.g. *Jakosky and Carr*, 1985; *Jakosky et al.*, 1995; *Haberle et al.*, 2001] and Clow's [*Clow*, 1987] model of melting within dusty martian snow. In the snowmelt model: (1) Water is transported from the poles to mid-latitudes during periods of high obliquity, forming a water-rich snow layer. (2) Melting occurs at low obliquity as mid-latitude temperatures increase, producing liquid water that is stable beneath an insulating layer of overlying snow; (3) Gullies form within and beneath the snow as meltwater seeps into the loose slope materials and destabilizes them; (4) Patches of snow remain today where they are protected against sublimation by a layer of desiccated dust/sediment; and (5) Melting could be occurring at the present time in favorable locations in these snowpacks [*Christensen*, 2003]. Unlike the pore ice model, dusty snow can produce liquid water that remains stable in the solid-state greenhouse environment within the snow [*Clow*, 1987; *Christensen*, 2003]. The primary arguments against snowmelt are the presence of gullies on all slope azimuths and the elevation below the slope crest where gullies originate [*Heldmann and Mellon*, 2004].

SUMMARY AND OUTSTANDING QUESTIONS

The poles and mid-latitudes of Mars contain a large reservoir of water ice, with ~$5x10^6$ km^3 in polar layered materials, >$6x10^4$ km^3 in mid-latitude mantles and ice-rich sediments, and ~$3x10^{-2}$ km^3 in the seasonal ice caps and atmosphere. This reservoir, if melted, would form a layer of water ~35 m deep over the entire planet. Portions of this reservoir appear to exchange with lower latitudes on 10^5-10^6 year timescales. Aquifers and/or melting snow have produced liquid water at the surface in the very recent past, and these areas hold exciting promise for future exploration for past or present life. Many questions remain, among the most intriguing are: (1) What is the age and history of the polar layered deposits? (2) Have the polar ice caps ever been completely removed, and what produced the significant climate change that this would imply? (3) What is the total inventory of sub-surface ice? and (4) What are the source(s) of water for modern gullies?

Figure Captions

Figure 1. The north polar cap of Mars as seen by Viking. This mosaic of images was acquired during northern summer when the ice had retreated to its perennial size. The

relatively bright material is water ice. The cap has shrunk to essentially this same location each year that it has been imaged by spacecraft (1971-present) [*James*, 1982; *James and Cantor*, 2001].

Figure 2. Quasi-circular "swiss cheese" terrain located near 86.9°S, 352.4°E. These pits are several hundred meters across and have a remarkably uniform depth of ~8 m wherever they are observed [*Thomas et al.*, 2000; *Malin et al.*, 2001]. Some pits have been observed to increase in size over one Mars year [*Malin et al.*, 2001]. A possible explanation is that the upper ~8 m layer is CO_2 ice which is gradually disappearing, exposing a stable layer of water ice beneath it [*Byrne and Ingersoll*, 2003]. MOC Image R1303615; MGS MOC Release No. MOC2-695, 13 April 2004. Image width is ~3 km.

Figure 3. The distribution of sub-surface water ice. This global map was made using data from the Neutron Spectrometer that is part of the Odyssey Gamma Ray Spectrometer suite. Data are adapted from Feldman et al. [*Feldman et al.*, 2002]. Hydrogen in the form of water ice occurs in abundances >30% poleward of ~60° in both hemispheres.

Figure 4a. Ice-rich terrains in the northern mid-latitude region. Ice-rich soils have flowed down the wall of this valley centered near 37.6°N, 15.8°E. This image is a mosaic of THEMIS VIS images (18-m per pixel) that has been colorized using the daytime temperatures from the THEMIS IR camera. Bands of bright material can be traced more than 10 km downslope, and show the flow reaching the bottom of the local slope and turning northeast to continue to flow down the valley. The temperatures range from –40° C to –34°, with the colder temperatures (blue-toned) being darker or rockier than the warmer surfaces (reddish-toned).

Figure 4b. Lobes of ice-rich material flowing off of mesas in the northern hemisphere. This mosaic shows THEMIS VIS 18-m per pixel images colorized with nighttime temperatures from the THEMIS IR camera. Lobes of material are colder at night, and therefore finer grained and less rocky than the substrate over which they are flowing. These distinct differences in surface properties between the lobes and the substrate provide strong evidence that this process is youthful, and possibly active, because there hasn't been sufficient time for the properties of these different surfaces to have been homogenized. Mosaic of THEMIS images is centered near 43° N, 27.5° E.

Figure 5. Ice-rich mantles and associated gullies on poleward facing slopes in the southern hemisphere. This collage shows MOC images from the northwest wall of Dao Valles, between 33° and 35°S. These images show well developed flow features with compressive ridges that are strongly suggestive of ice (left panel), mantles of ice-rich material with gullies that are only present where the mantles are lacking (center panel), and depressions with associated gullies, some of which still have mantles, whereas others are free of mantling material (right panel). These landforms could be explained by the melting of a snow mantle to form gullies, which are only visible in those locations where the snow has completely disappeared. MOC images left to right: M03-04950; M09-02885, and M0-3-6266.

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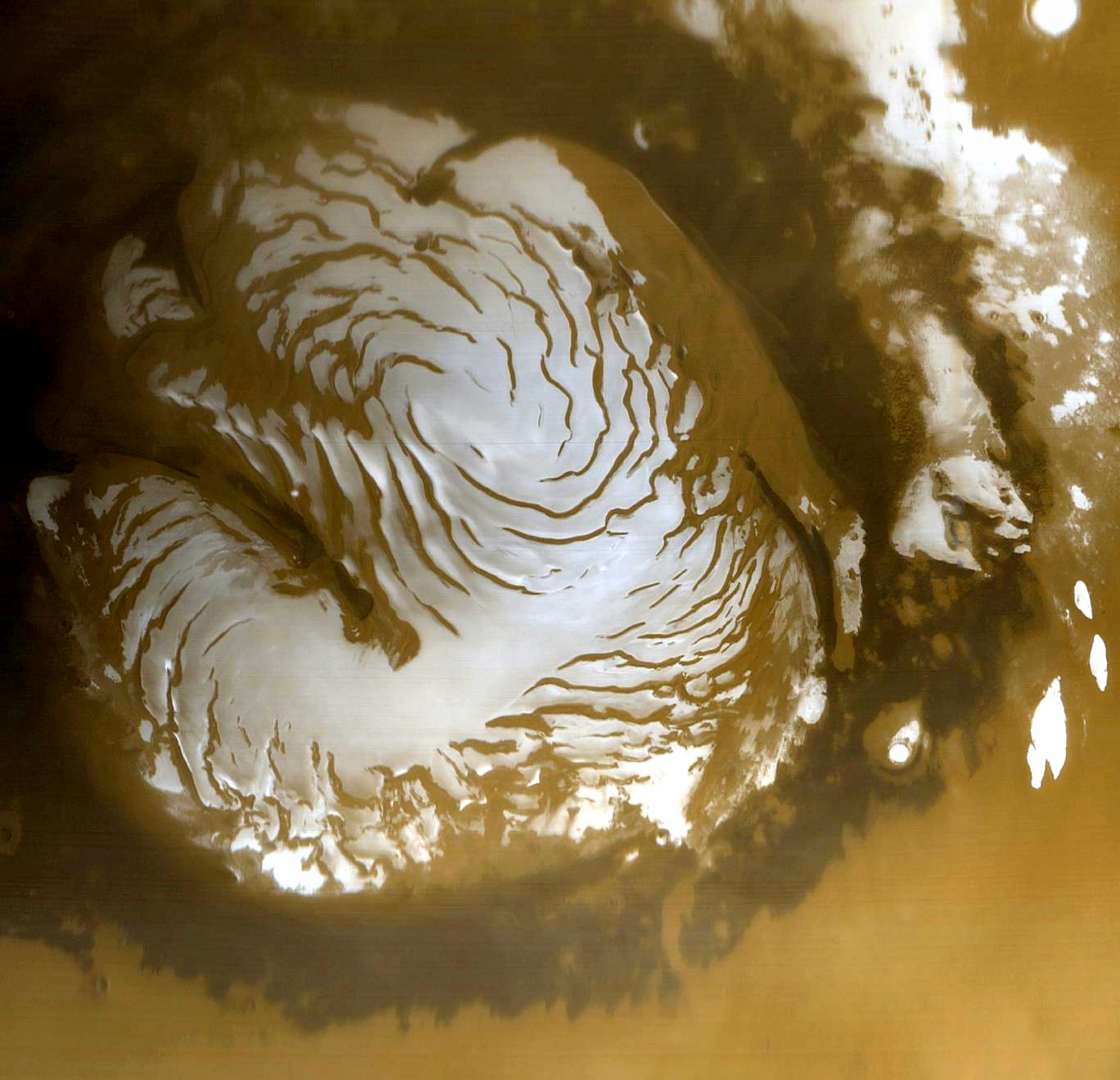

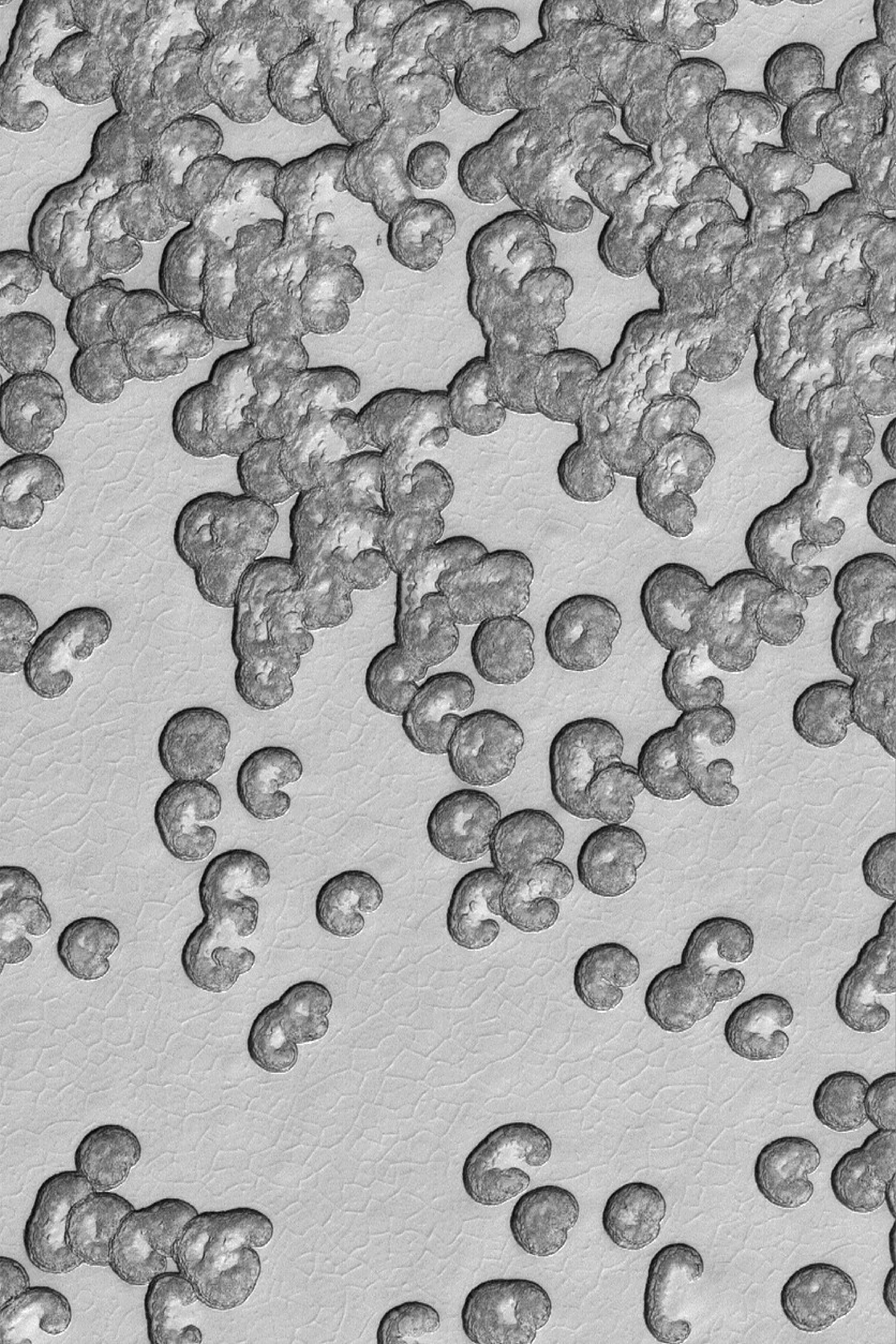

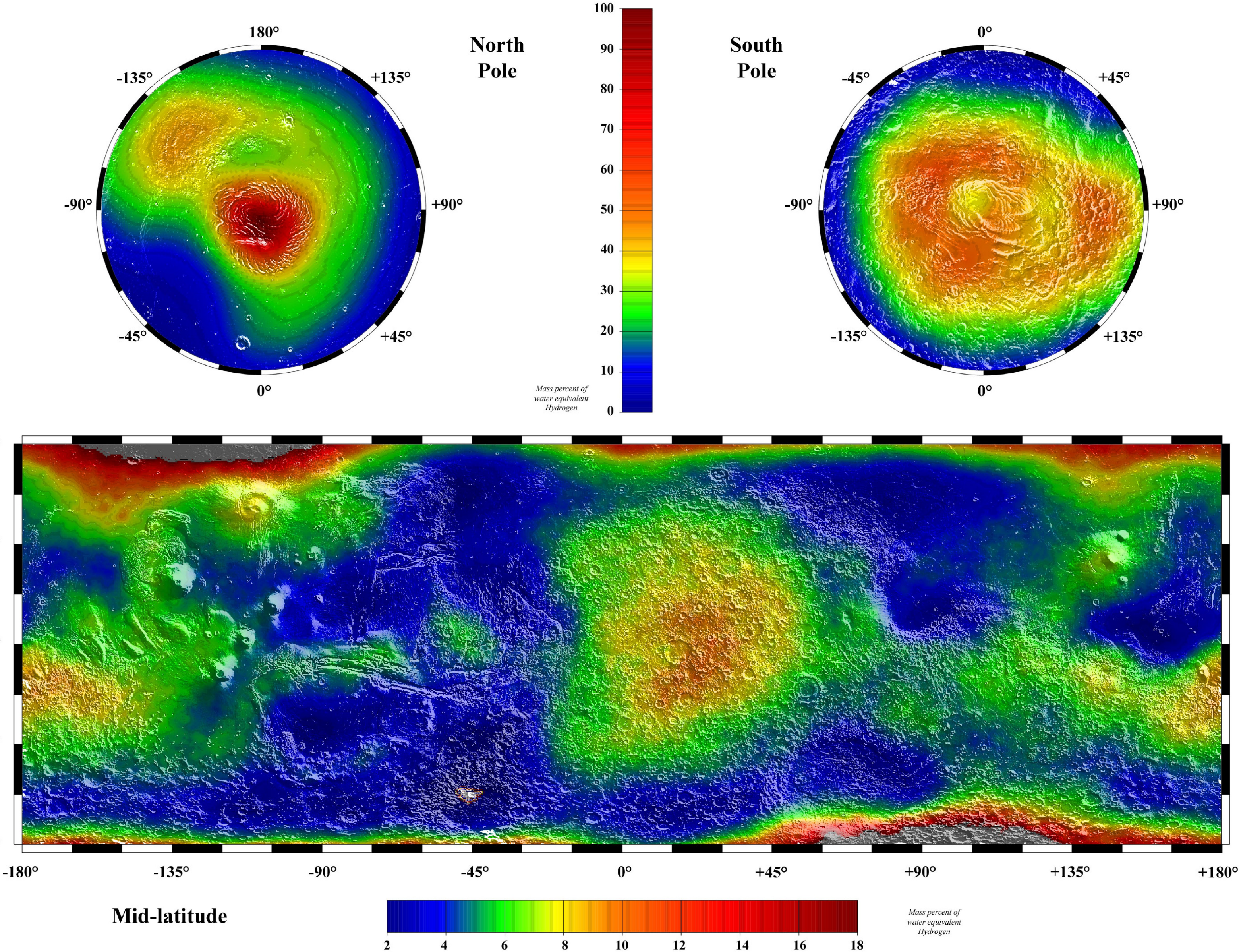
North Pole
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Mass percent of water equivalent Hydrogen
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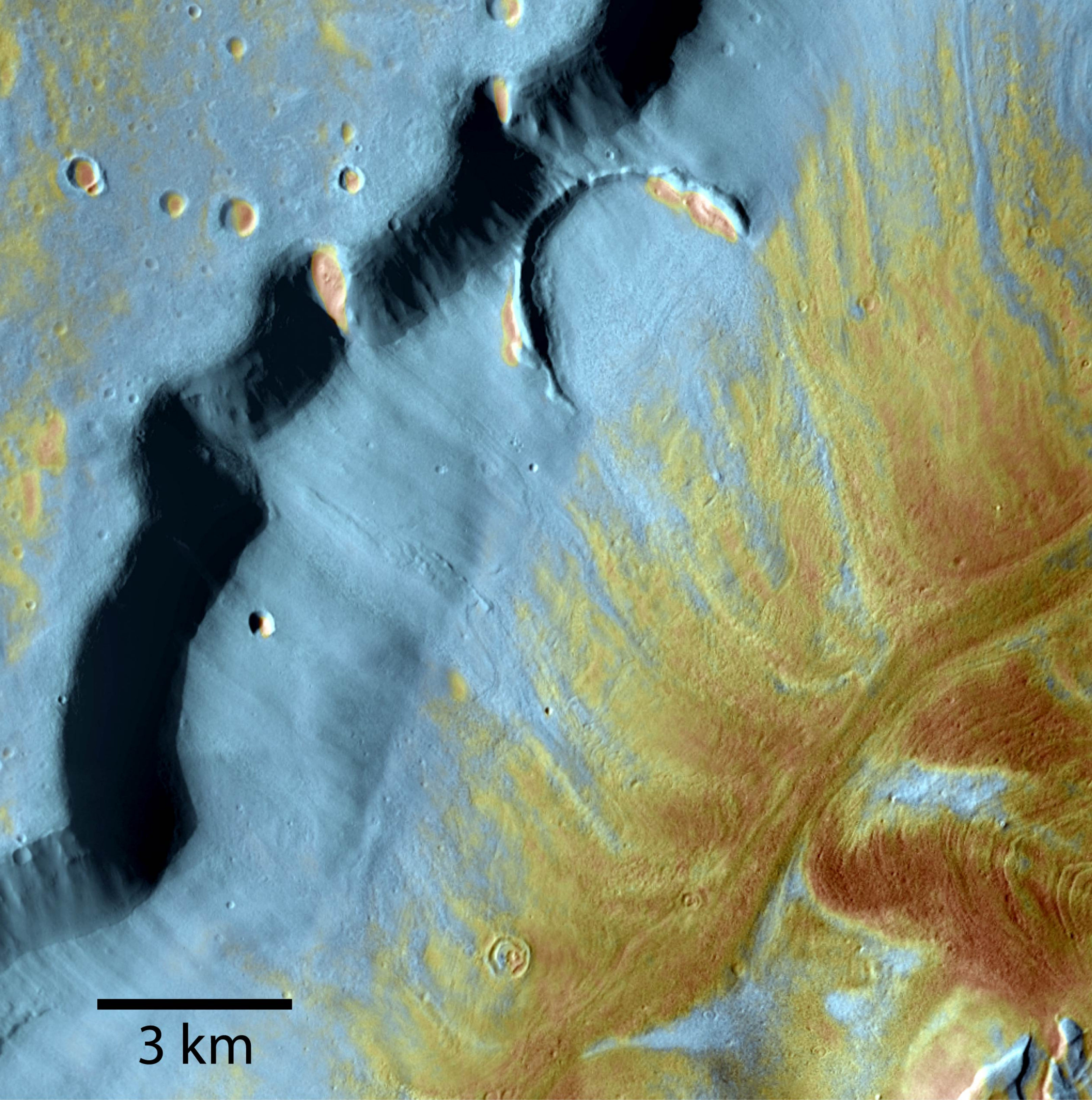
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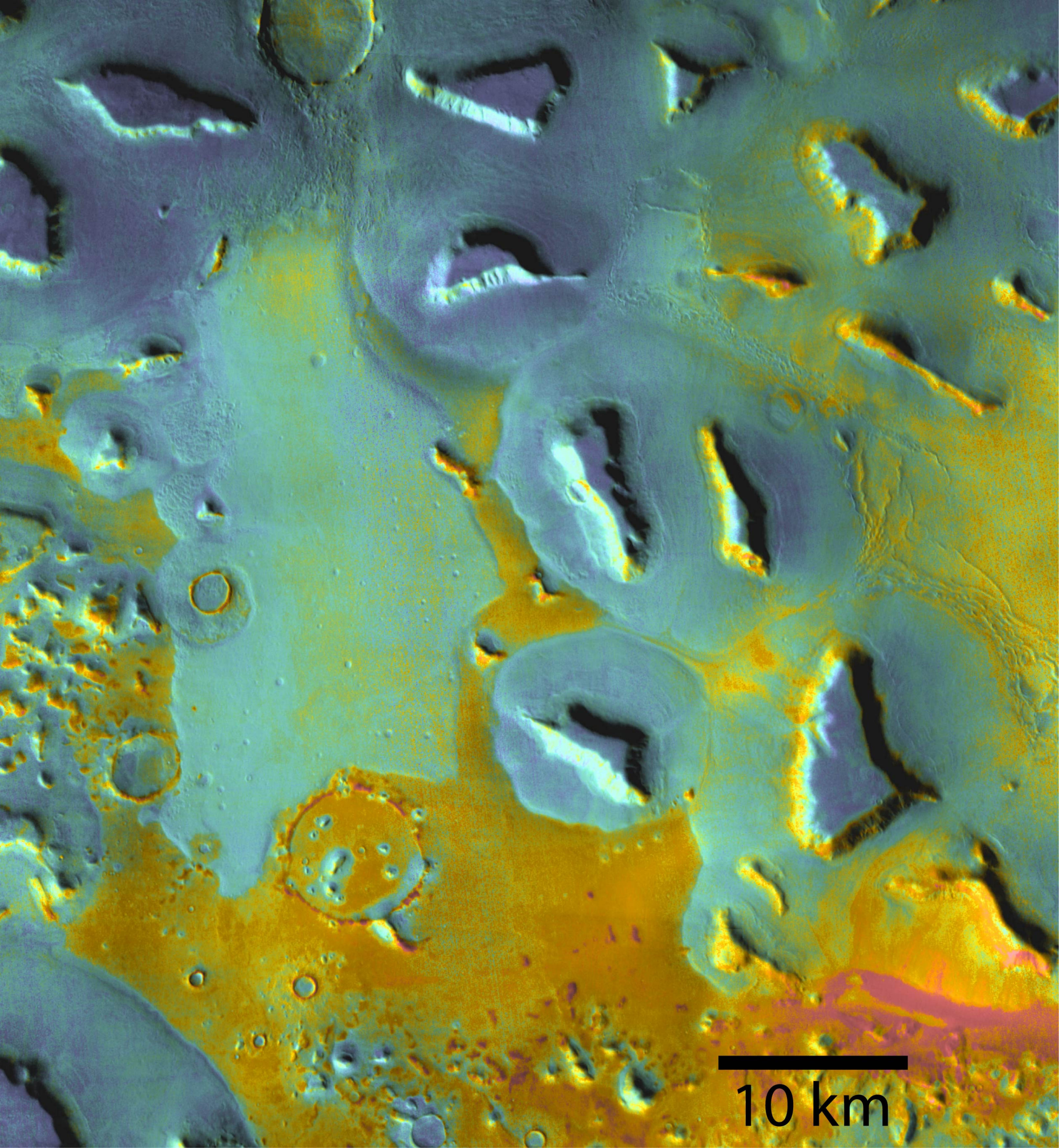
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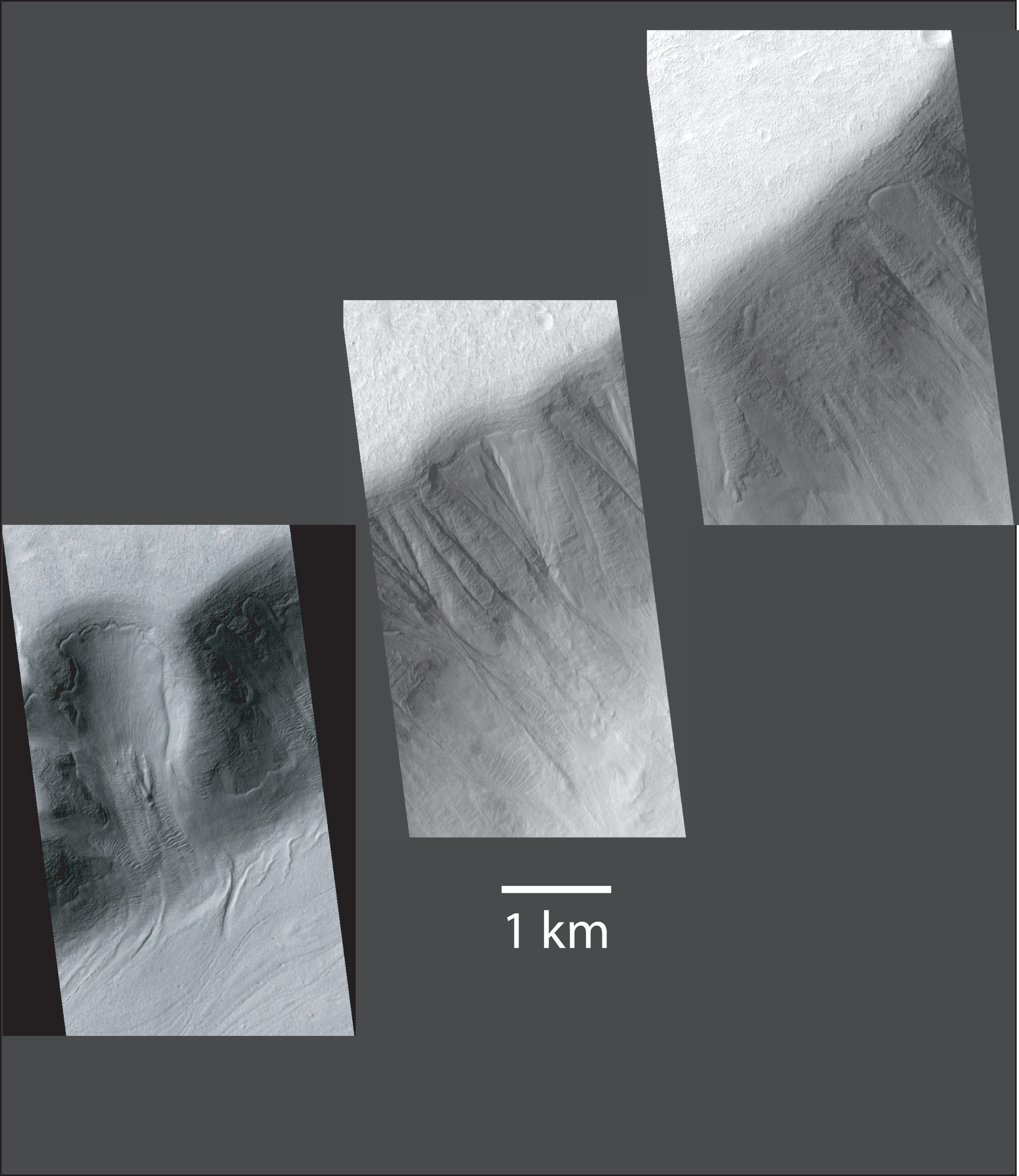
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