AN ATLAS OF MARS SEDIMENTARY ROCKS AS SEEN BY HIRISE

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"*There are no foreign lands. It is only the traveler who is foreign*"
—Robert Louis Stevenson

INTRODUCTION

Images of distant and unknown places have long stimulated the imaginations of both explorers and scientists. The atlas of photographs collected during the Hayden (1872) expedition to the Yellowstone region was essential to its successful advocacy and selection in 1872 as America's first national park. Photographer William Henry Jackson of the Hayden expedition captured the public's imagination and support, returning home with a treasure of images that confirmed the existence of western landmarks previously regarded as glorified myths: the Grand Tetons, Old Faithful, and strange pools of boiling hot mud. Fifty years later, photographer Ansel Adams began his long legacy of providing the public with compilations of iconic images of natural wonders that many only see in prints.

Photography in space has provided its own bounty. Who can forget the first image of Earthrise taken by astronaut William Anders in 1968 from *Apollo 8*; the solemnity of the first photos of the surface of the Moon from the *Apollo 11* astronauts; and the startling discovery of the tallest mountain in the solar system (Olympus Mons) on the surface of Mars in images sent from *Mariner 9*? The images from *Mariner 9* also allowed for a game-changing discovery. Earlier, based on very limited *Mariner 4* data that covered less than 10% of the planet's surface, Chapman et al. (1968) speculated that "If substantial aqueous erosion features—such as river valleys—were produced during earlier epochs of Mars, we should not expect any trace of them to be visible on the *Mariner IV* photographs unless they were of greater extent than typical features on Earth." Mapping a much greater part of the planet, *Mariner 9* provided the first evidence of such spectacular features and ushered in the modern era of understanding Mars in the context of its aqueous history. Our understanding of the ways in which terrestrial planetary surfaces evolve through time was transformed by the notion that Mars may have been warmer or wetter at some point in the past.

Almost three decades later, this first evidence for aqueous erosion of bedrock on Mars was finally matched by evidence for deposition of aqueous sedimentary materials (Malin and Edgett 2000). The identification of "layered terrains" thought to be of sedimentary origin on Mars is regarded as a major discovery. Observations of erosion in one place require, naturally, that deposition of the eroded materials occurs elsewhere, so this discovery was not so much surprising as exciting. Unlike erosion, deposition records a time series of past events and can thus be analyzed as a record of environmental history. Furthermore, the state of preservation of these outcrops suggests a past cycle of erosion and deposition, followed by erosion of the deposited sediments. Evaluation and understanding of the Martian "rock cycle," which is very different from Earth's, are some of the major objectives of the next decade of Mars research, and the study of sedimentary rocks is central to this theme (McLennan and Grotzinger 2008, Grotzinger et al. 2011).

The most recent image data of the surface of Mars show that there are at least several types of distinct layered deposits that are consistent with a sedimentary origin. In some cases, they form vast, laterally extensive sheets that cover the ancient cratered terrains and fill topographic depressions such as impact craters. The spectacular images in this atlas present just a tiny fraction of the material that exists for further study and examination. This atlas is not intended to capture all of this diversity, but rather to illustrate some of the most important

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TABLE 1.—Classification of sedimentary deposits on Mars.

Category	Subcategory	Example locations
Underfilled crater interior	Preserved depositional system	Eberswalde crater delta Holden crater alluvial deposits Xanthe Terra terraced fans Melas Chasma sublacustrine fans
	No observed depositional system	Columbus crater deposits
Overfilled crater interior		Gale crater layered mound Terby crater layered mesas Galle crater layers Becquerel crater layered mound
Chasm/canyon	Undeformed layered deposits	Ophir Chasma Juventae Chasma Ganges Mensa Melas Chasma
	Fractured and faulted layered deposits	West Candor Chasma
Plains-covering deposits	Plains surrounding Valles Marineris	West of Juventae Chasma Near Ganges Chasma South of Ius and Melas Chasmata
	Stratified plains	Meridiani Planum layers
Ancient terrain		Mawrth Vallis Nili Fossae
	Central uplift	Oudemans crater central uplift
Polar deposits		North polar layered deposits and basal unit South polar layered deposits

end members defined by representative exposures, some of which might be viewed as key "reference" sections (see Grotzinger and Milliken this volume). Our selections of sedimentary deposits fall into several very broad categories based on the environment in which these outcrops are found today (Table 1). These categories include: (1) underfilled crater interiors, (2) overfilled crater interiors, (3) chasm/canyon units, (4) plains-covering deposits, (5) very ancient terrain, and (6) polar deposits.

Determining the ages of rocks and units on Mars is problematic due to our inability to age-date samples. However, Scott and Carr (1978) were the first to establish three general time-stratigraphic periods, Noachian, Hesperian, and Amazonian, which were further refined into eight epochs and assigned relative ages based on the traditional principles of superposition and intersection, as well as the size-frequency distribution of impact craters (Tanaka 1986, Tanaka et al. 1992). The connection to absolute ages was further refined by Hartmann and Neukum (2001): the Noachian Period stretches from the beginning of Martian time to 3.6 ± 0.1 Ga, the Hesperian Period from 3.6 to 3.1 ± 0.6 Ga, and the Amazonian from 3.1 Ga to the present (Hartmann 2005, Fassett and Head 2008, Tanaka and Hartmann 2008). More details on the Martian time scale can be found in Grotzinger and Milliken (this volume).

Underfilled crater interiors contain sediments that are interpreted not to have exceeded the volume of their host crater. This category is further subdivided into deposits that exhibit distinct fan morphologies (e.g., Eberswalde crater delta, Holden crater alluvial deposits, and the Xanthe Terra terraced fans), and those that do not (e.g., Columbus crater deposits). Although the putative sublacustrine fans in Melas Chasma (Metz et al. 2009) are within the Valles Marineris and not a crater, they are better grouped in this category, which includes other fan morphologies, because the fluvial system that created the Melas deposits is well expressed.

Overfilled crater interiors are those with stratified deposits that reside primarily within a crater but rise close to or above the current elevation of the crater's rim. While there is no straightforward explanation for these deposits, they may be remnants of once-larger deposits that both filled the craters and extended beyond to blanket the surrounding plateaus. Many of these deposits occur as tall mounds near the center of the crater, surrounded by a lower elevation "moat." The specific erosional processes that would have scoured away the surrounding deposits and denuded nearly down to the crater floor while allowing an isolated mound to be preserved are currently unknown. The Gale crater mound, the layered deposits in Terby crater, the Henry crater layered mound, and the stratified deposits in Galle crater all exhibit this remnant high-standing topography and may provide evidence for formerly extensive deposits that had greater lateral extent than that currently preserved.

Chasmata and canyons on Mars provide topographic lows and often closed basins in which sediments can accumulate, and their deposits are often similar to those found in craters. The Martian chasmata of Valles Marineris are very large and extensive, providing a vast setting to test a variety of sedimentary hypotheses. Tectonics have played a role in the geologic history here, from the activity that may have formed the chasmata themselves, to other tectonic forces that caused deformation of the sedimentary deposits observed within those chasmata. We divide the sedimentary deposits in the Valles Marineris into those that have not been tectonically disrupted (deposits in Ophir, Melas, Juventae, and Ganges Chasmata) and those that have, like the west Candor Chasma deformed layered deposits (Metz et al. 2010, Okubo 2010).

Plains-covering deposits include complex sequences of stratified units that vary widely from place to place over the surface of Mars. Volcanism, sedimentation, and fluvial action have all played a role in the formation of these terrains. Unique features among these terrain units are the plateaus surrounding the large canyons of Valles Marineris, which exhibit layered exposures not seen elsewhere (Milliken et al. 2008, Weitz et al. 2010). These sediments might be the evidence of fluvial systems that either existed prior to the chasma openings or those that acted as overland flows for systems (e.g., Mangold et al. 2004) that ultimately drained into these giant cavities.

Other very ancient terrains consist of the oldest identifiable portions of the Martian crust (from the Martian Noachian Period), which, in many cases, have been altered by a variety of chemical and physical processes. This ancient crust contains numerous deposits with clay minerals (e.g., Bibring et al. 2006, Murchie et al. 2009b), the presence of which indicates water–rock interaction either on the surface or in the subsurface. Although the specific timing and duration of this alteration are unknown, our knowledge of the diversity of clay minerals on Mars has increased dramatically over the past several years, and it is beginning to rival that of Earth. The ancient terrain consists of layered rocks, many of which are presumably sedimentary in origin, but it also hosts many deposits that lack clear stratification. These deposits may represent primary crust, thick deposits of crater ejecta, or regions that have been heavily altered by hydrothermal processes. The ancient crust on Mars is complex in both its morphology and mineralogy, but it is clear that sedimentary processes are recorded in the Martian rock record to at least 4 billion years before present, and likely longer. This makes Mars a particularly interesting and possibly unique place for understanding the role of aqueous and sedimentary processes in the earliest history of the Solar System.

In addition to areally extensive sequences of stratified deposits, very ancient terrains on Mars are also characterized by craters in which central uplifts occasionally exhibit large, layered structural blocks brought up from depth during the crater formation process. These deep layers may be a way to sample Martian geologic history from the distant past that would otherwise remain buried. In the Southern Highlands, many of these central uplifts contain clay minerals that are indicative of aqueous alteration of primary crust, possibly as a result of deep alteration within the ancient crust (Murchie et al. 2009a).

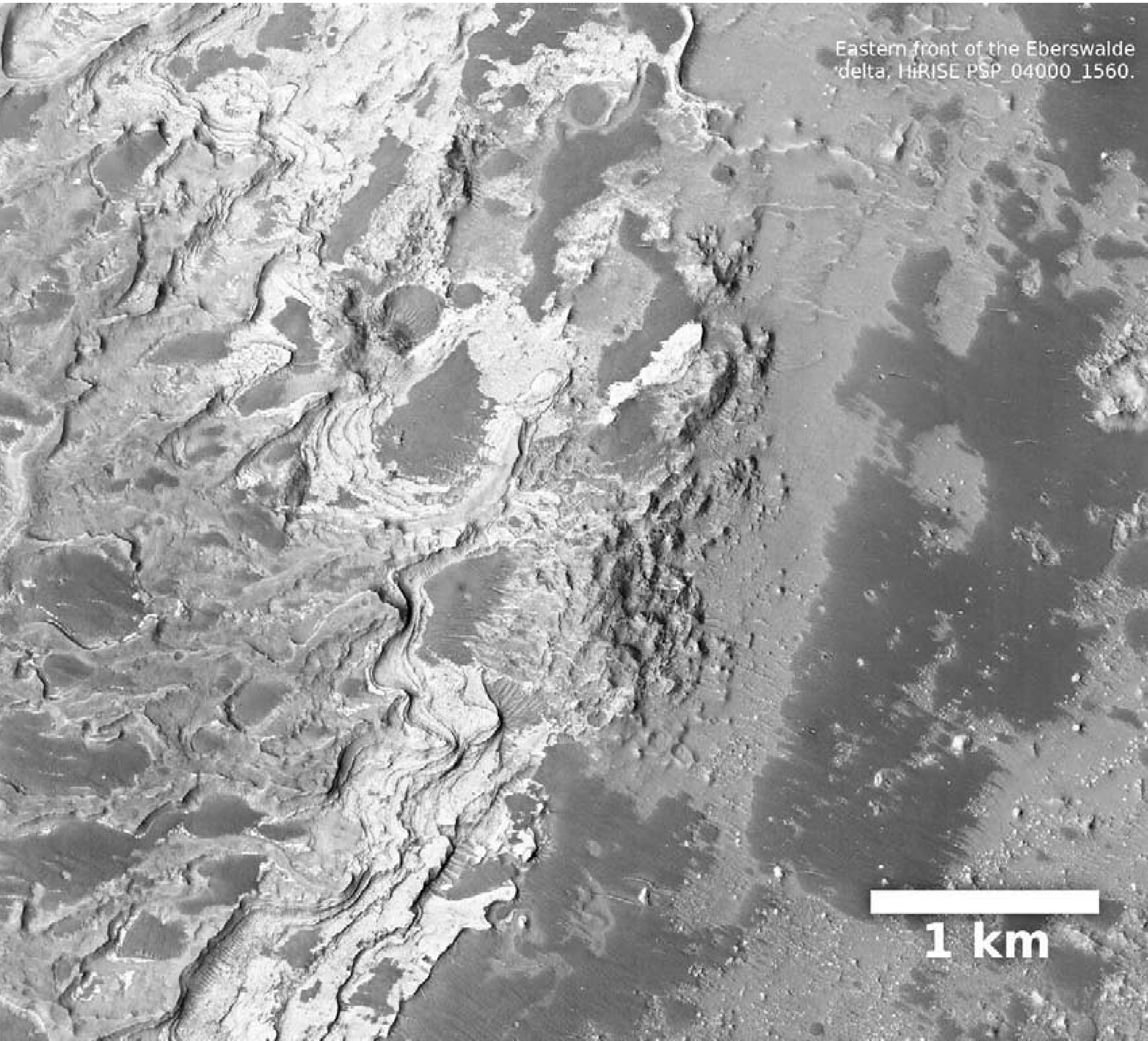
Polar deposits at both the north and south Martian poles exhibit a variety of ice and dust layering sequences that likely encode the recent variability of Martian climate. Polar layered deposits were first recognized in *Mariner 9* images (Murray et al. 1972) and motivated theoretical studies of climate changes on Mars (Ward 1974, 1979; Bills 1990; Touma and Wisdom 1993). The tilt of the rotational axis and eccentricity of the orbits of both Earth and Mars have undergone periodic variations due to gravitational interactions with the other planets, but the amplitude of these variations is much greater on Mars. Because these orbital/axial changes are known to cause climate changes (ice ages) on Earth, they are expected to cause even greater climate variability on Mars (e.g., Head et al. 2003). More recent observations have shown that the polar layered deposits are ice-rich, with less sediment than previously thought (Byrne 2009).

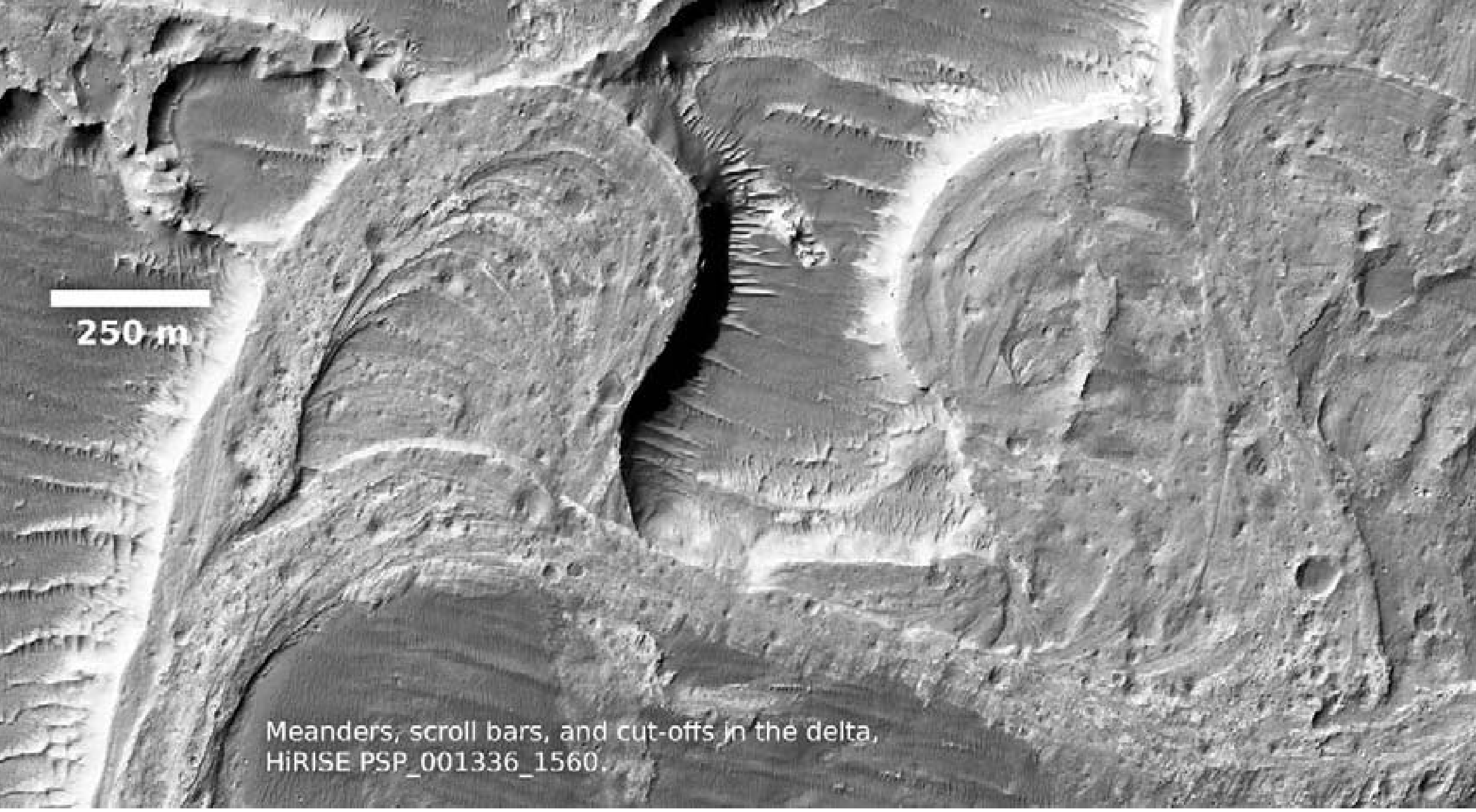
This atlas is largely based on image data obtained by the High Resolution Imaging Science Experiment (HiRISE; McEwen et al. 2007) on board the *Mars Reconnaissance Orbiter* (MRO). This camera has allowed for a more detailed examination of the Martian surface than previous imagers, providing images at 25 cm/pixel scale, with a swath width of about 6 km. HiRISE images and digital terrain models (DTMs) can be obtained from http://hirise.lpl.arizona.edu. In addition, other image data for Mars can be found at National Aeronautics and Space Administration's (NASA) Planetary Data System (PDS) at http://pds.jpl.nasa.gov. This atlas includes some images from the Context Camera (CTX; Malin et al. 2007) on MRO. CTX acquires grayscale images of Mars with a spatial scale of approximately 6 m/pixel, and a swath width of about 30 km. There are also data from the Shallow Radar (SHARAD; Seu et al. 2007) instrument on MRO. This atlas discusses mineralogical data from hyperspectral mapping instruments such as the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM; Murchie et al. 2007) and the Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité (OMEGA; Bibring et al. 2004). These hyperspectral imaging systems measure the sunlight reflected off of the surface over visible and near-infrared wavelengths, providing important information about the types and distributions of primary and secondary minerals across the Martian surface.

The goal of this atlas is to provide a pictorial sampling of the diversity of Martian "layered terrains," which are increasingly regarded to have formed through the action of sedimentary processes. Our hope is that these images will motivate the reader to further pursue their own investigations.

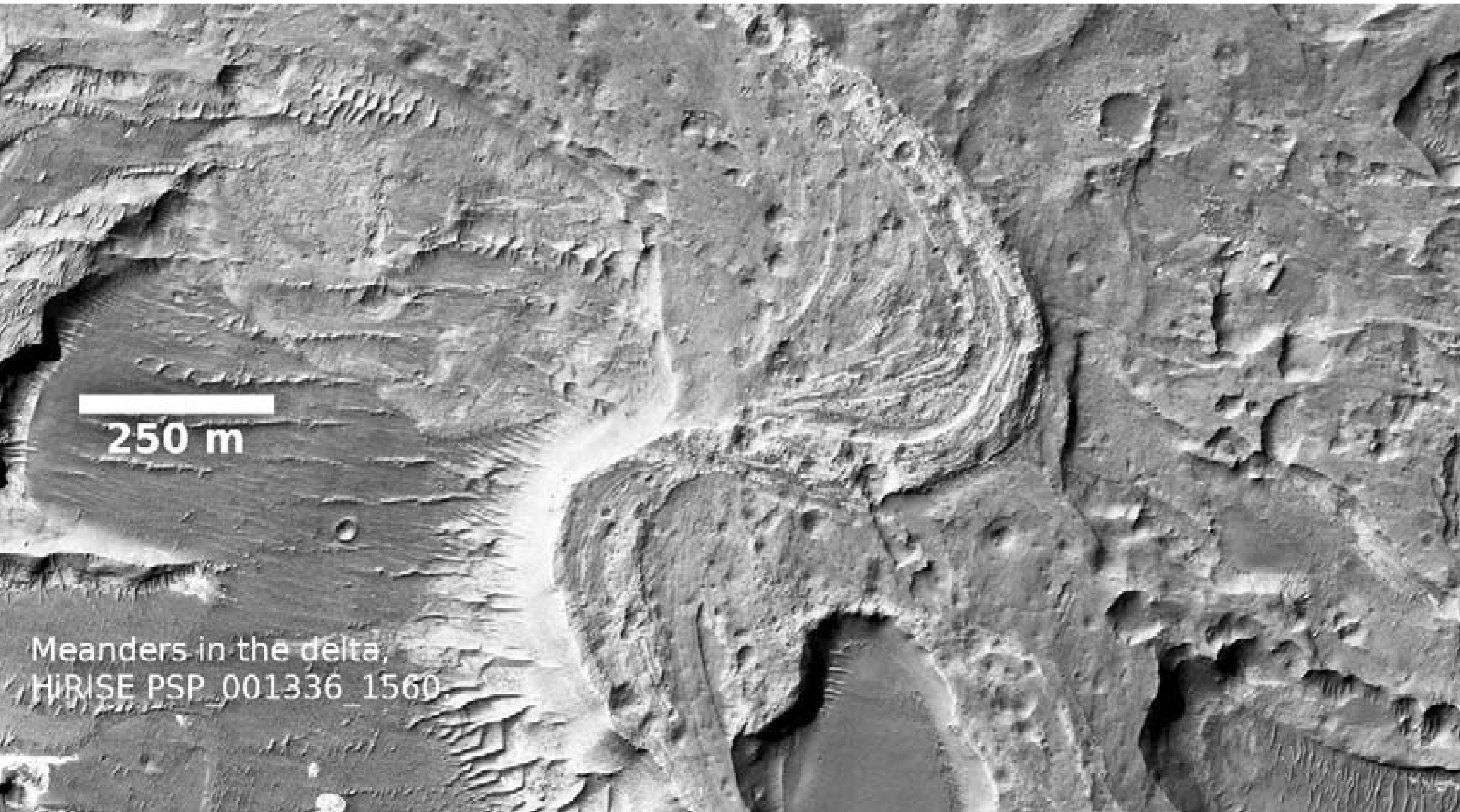

Eberswalde Crater Delta
Overview of delta complex in
Eberswalde crater, north is to the right,
CTX P01_001336_1560_XI_24S033W.
3 km


Potential down-lapping of layered deposits at toe of Eberswalde delta, perspective view of terrain model created from HiRISE PSP_001534_1560 and PSP_001336_1560.

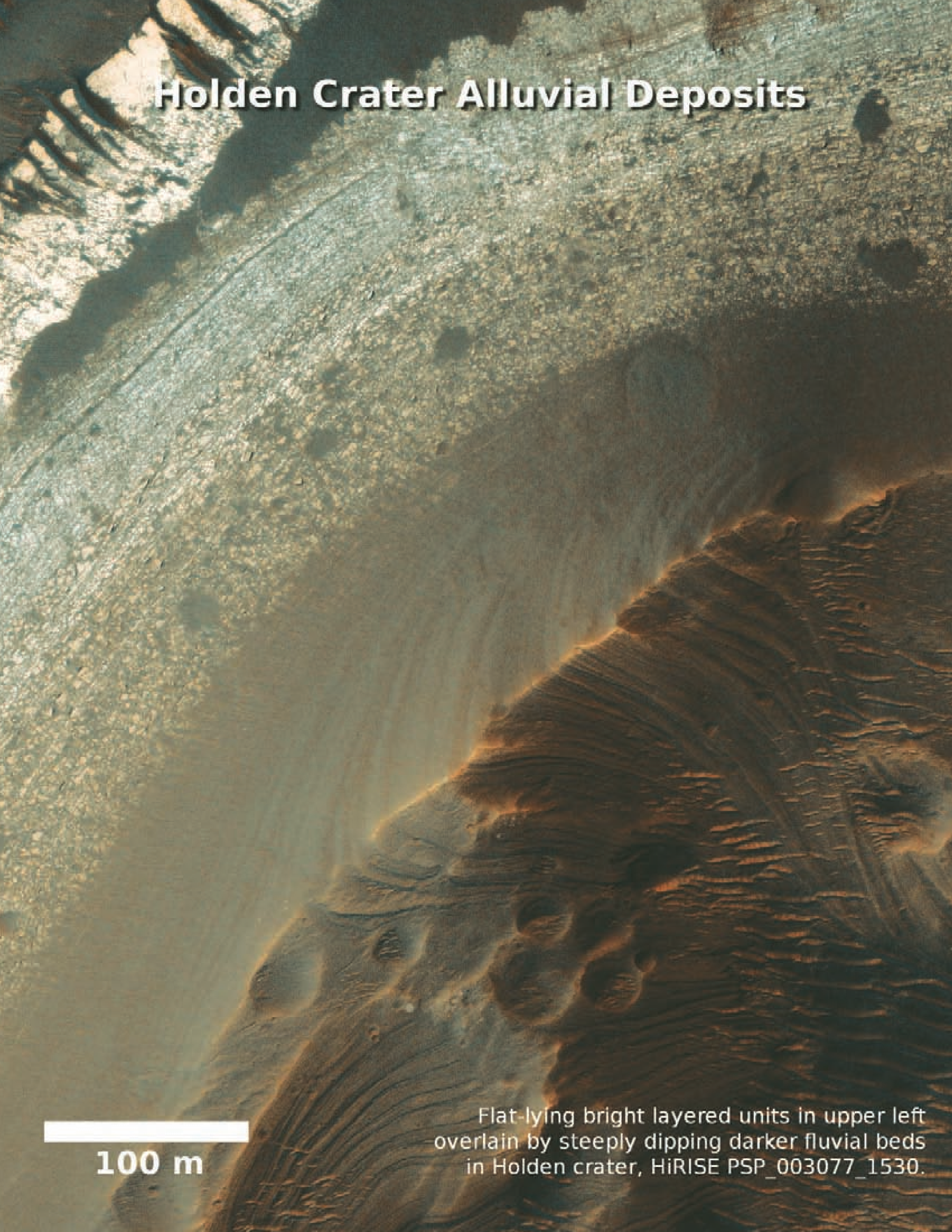

Eastern front of the Eberswalde delta. HiRISE PSP_04000_1560.
1 km



Eberswalde crater contains ~100 m of strata exposed at the terminus of a well-preserved delta form (Malin and Edgett 2003, Moore et al. 2003), most likely dating from the Hesperian Period (Irwin 2011), although it may be as old as Late Noachian (Moore et al. 2003) or as young as Early Amazonian (Grant and Wilson 2011). This sedimentary deposit contains dozens of shallowly dipping (~2°), alternating bright and dark layers of varying thickness (~1–10 m). HiRISE terrain models reveal topset, foreset, and bottomset strata, and these bottomset beds are interpreted as lake-floor deposits (Lewis and Aharonson 2006, Pondrelli et al. 2008). This delta is distinguished from other fan-shaped deposits on Mars by the presence of a preserved distributary network including lobes, inverted channels, and meander cutoffs. Another example of a fan with a distributary network can be found in Jezero crater, which may represent a more degraded version of the same kind of system.

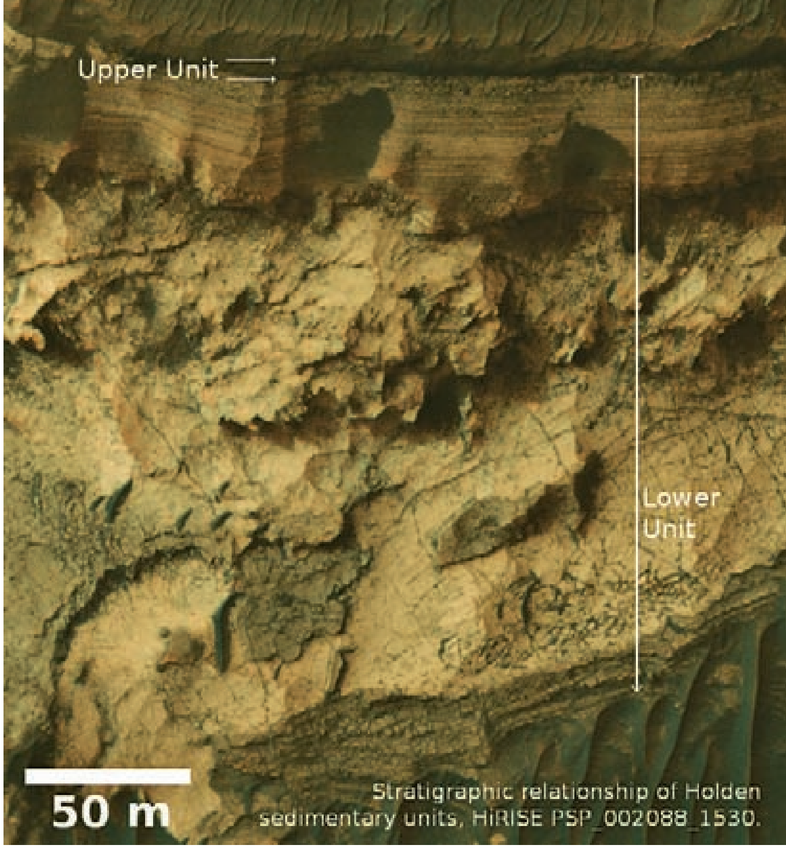


Holden Crater Alluvial Deposits



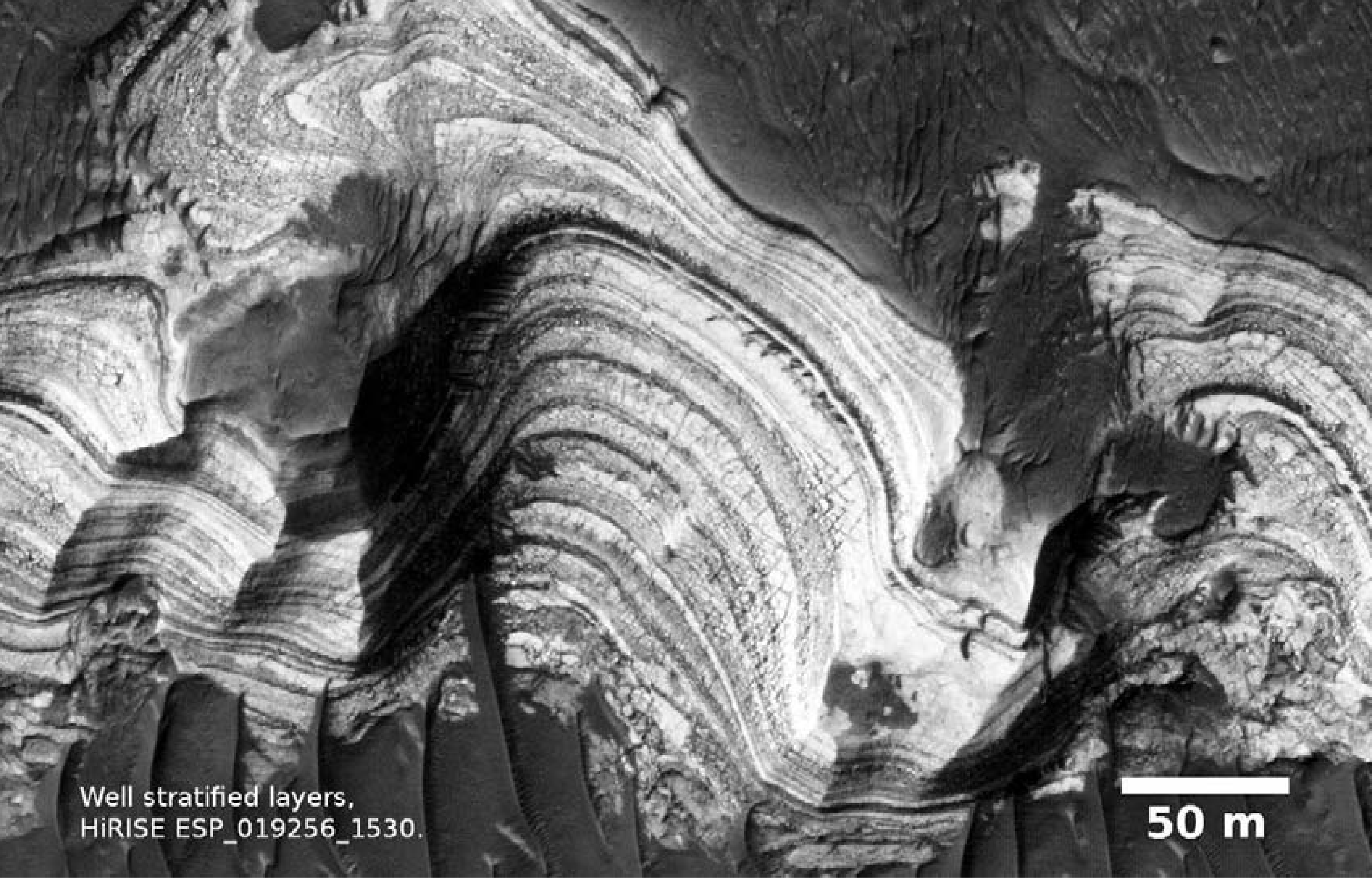
Flat-lying bright layered units in upper left overlain by steeply dipping darker fluvial beds in Holden crater, HiRISE PSP_003077_1530.

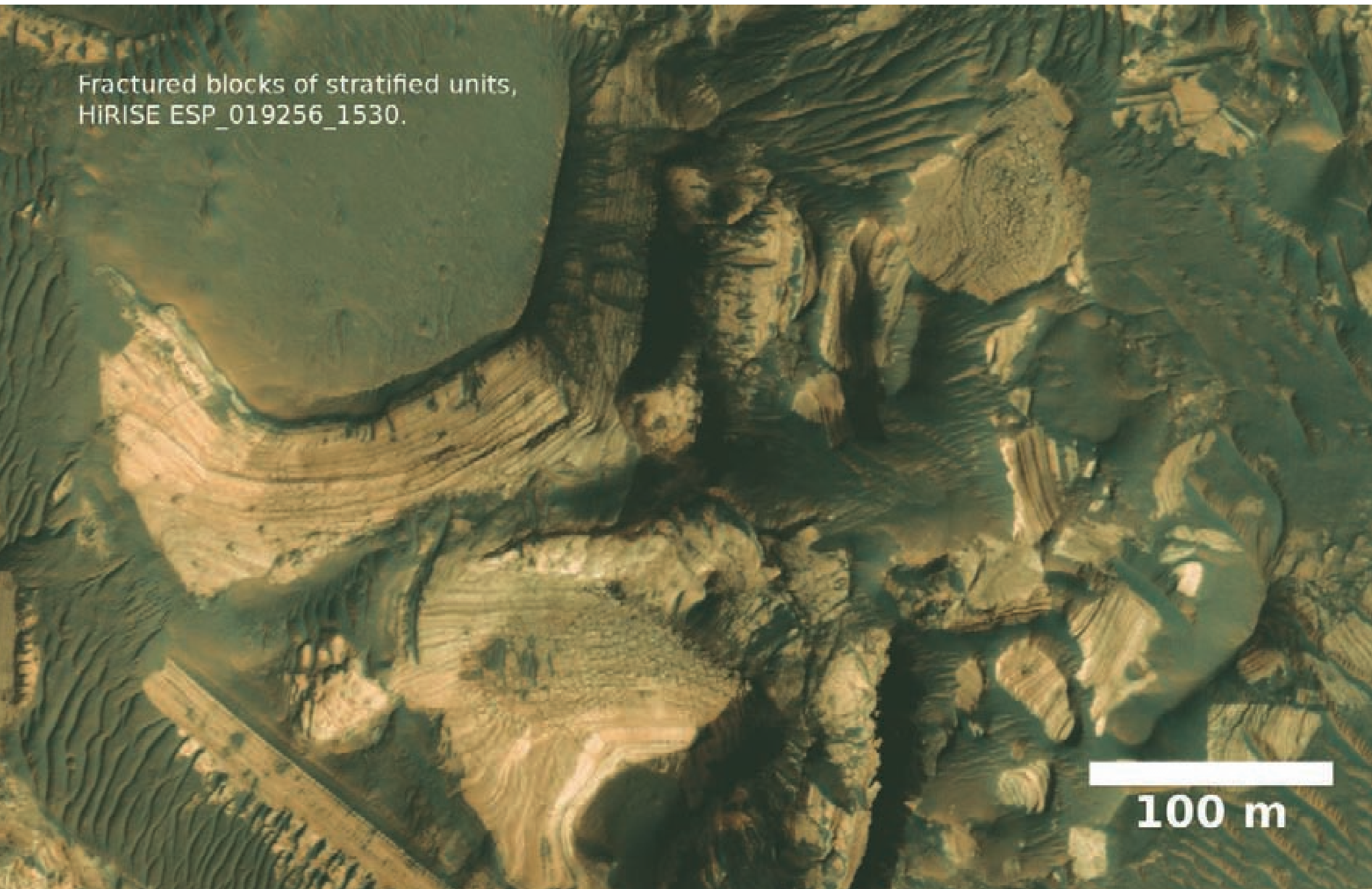
The brighter layers in Holden crater are exposed as rounded slopes and buttes that underlie alluvial-fan deposits distributed along the interior rim of the crater. These relatively flat-lying strata are interpreted as distal alluvial or lacustrine deposits, although no obvious time-equivalent fan delta is preserved. The well-stratified deposits are traceable for hundreds of meters and define the lower unit of Grant et al.'s (2008) Holden lithostratigraphy emplaced during Hesperian or Early Amazonian wet phases (Grant et al. 2010, Grant and Wilson 2011). The lower unit overlies a basal megabreccia composed of poorly sorted blocks tens of meters in diameter, and it underlies a dark-toned, crudely layered upper unit. Fe/Mg smectite clay minerals and possibly mixed-layer smectite–chlorite phyllosilicates have been observed within the Holden crater stratigraphy (Milliken and Bish 2010). Moore and Howard (2005) discuss a number of other alluvial-fan locations on Mars.



Stratigraphic relationship of Holden sedimentary units, HiRISE PSP_002088_1530.

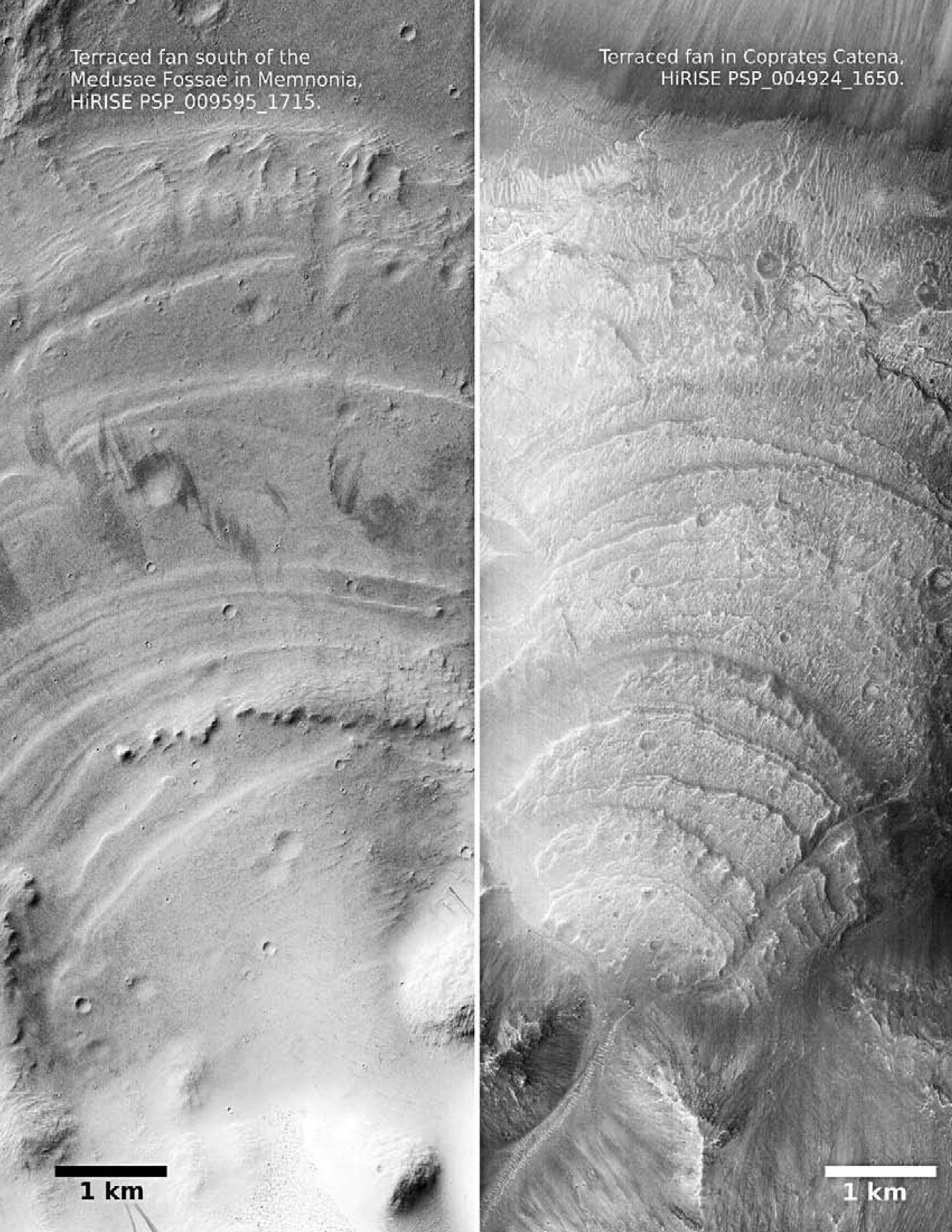
Layered units, HiRISE PSP_009841_1530.


Well stratified layers,
HiRISE ESP_019256_1530.
50 m


Fractured blocks of stratified units,
HiRISE ESP_019256_1530.
100 m

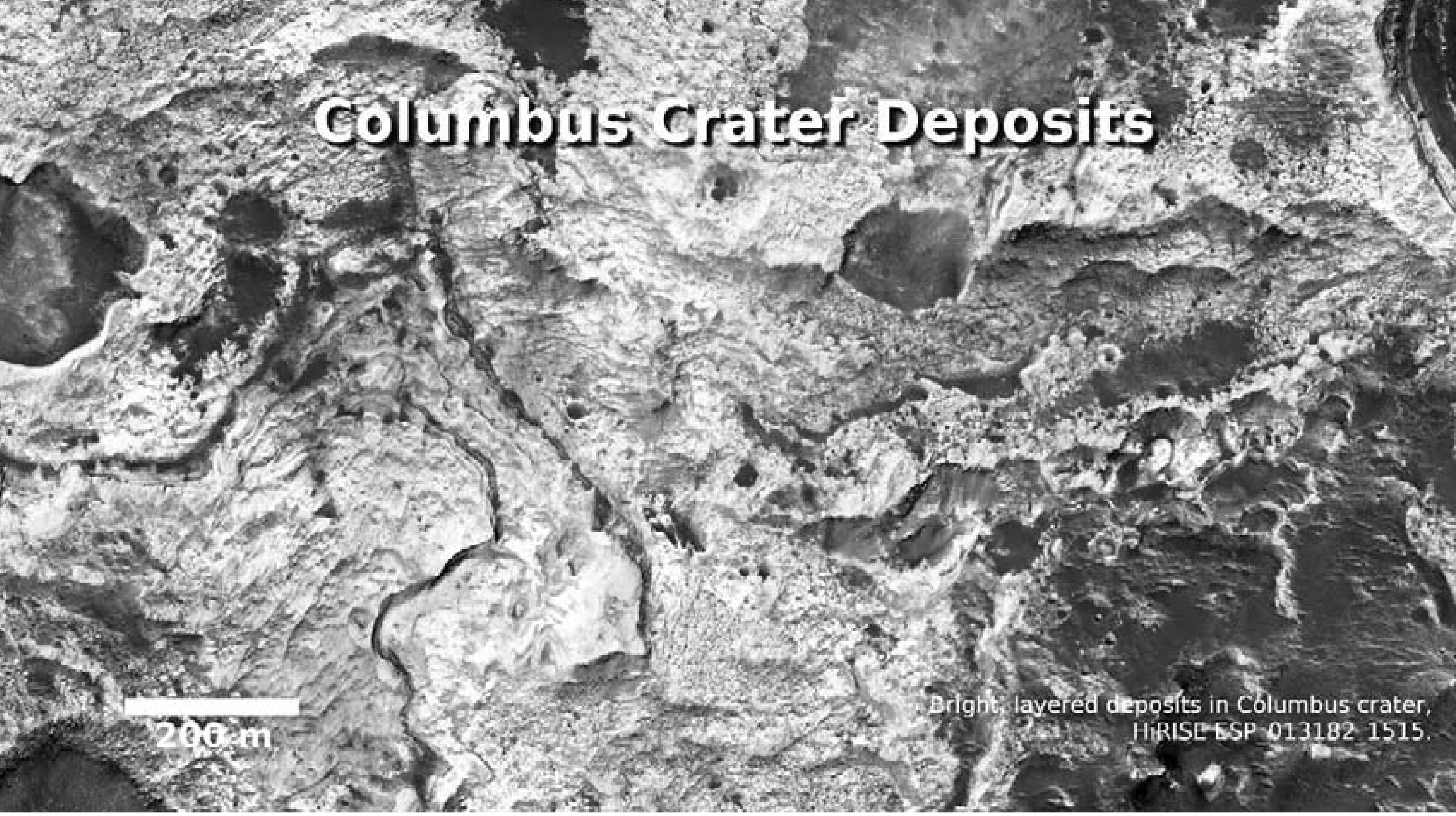
Xanthe Terra Terraced Fans

The Xanthe Terra region is host to several fan-shaped deposits that occur where deeply entrenched channels intersect crater walls. These fans are distinguished from alluvial fans or deltas on Mars because they are composed of distinctive concentric terraces, they lack lobes or evidence for distributary channels, and little to no incision has occurred on the surfaces of the fans. The upper part of these fans usually consist of a flat plain and a steep front (Hauber et al. 2009), and they are assumed to be Late Noachian in age. The terraces are present at distal parts of the deposit and are hypothesized to be erosional scarps from wave action or resedimentation processes (Hauber et al. 2009). There are many hypotheses for the origin of these fans in Xanthe Terra and similar features in the Memnonia region, including formation from a single outflow event (Kraal et al. 2008), or interpretation as Gilbert-type deltas (Ori et al. 2000, Hauber et al. 2009). Alternately, it seems possible that these fans could be viscous debris-flow deposits that spread laterally at the mouth of the canyon and crater walls. Similar terraced-fan features are also found in Aeolis Mensae and Coprates Catena.


Terraced fan south of the
Medusae Fossae in Memnonia,
HiRISE PSP_009595_1715.
1 km
Terraced fan in Coprates Catena,
HiRISE PSP_004924_1650.
1 km

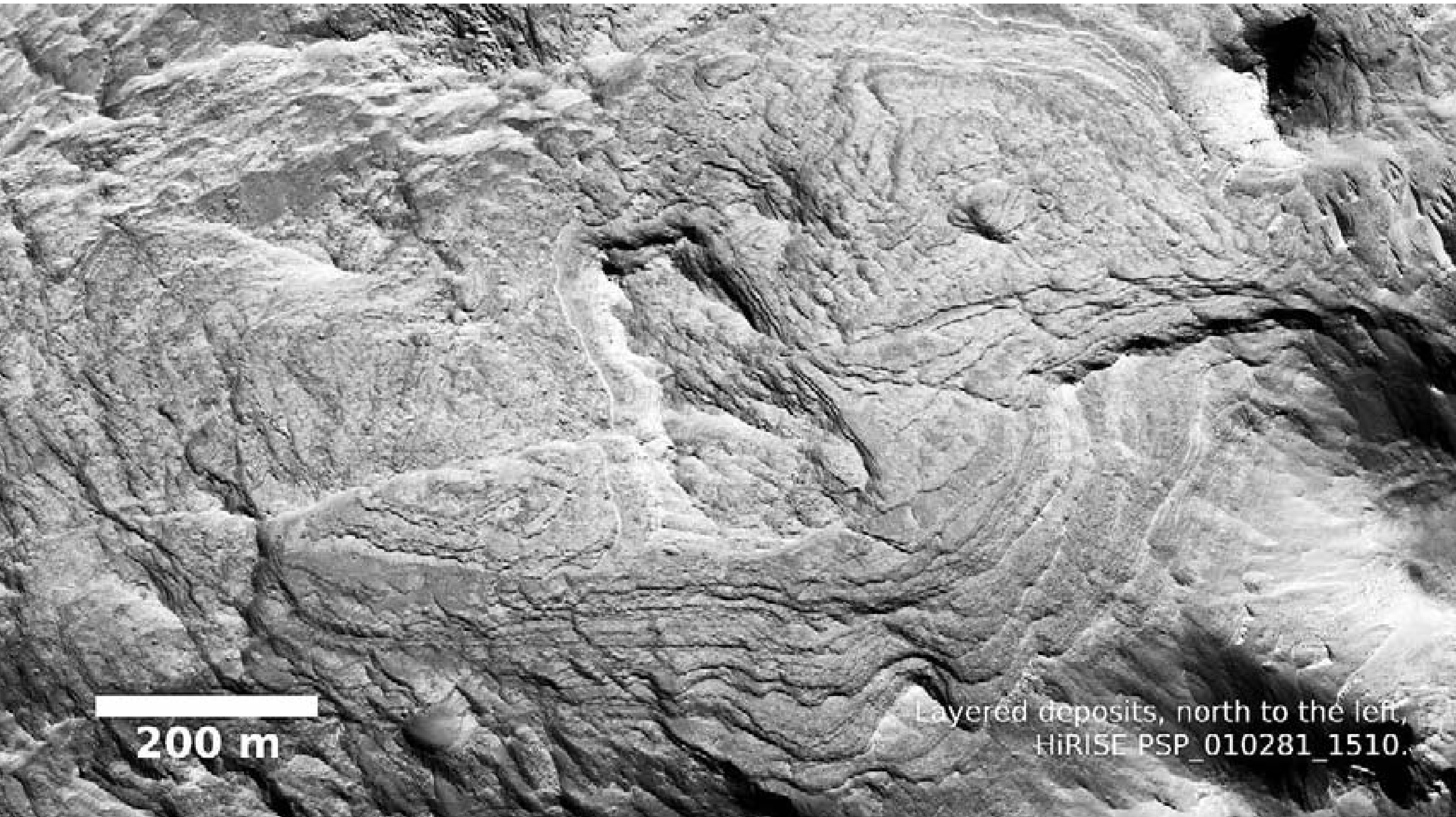
These Noachian- or Hesperian-aged fans, located at the center of the Melas Chasma topographic basin, are unique amongst the undeformed layered deposits in Valles Marineris because they suggest a sublacustrine origin (Metz et al. 2009). Layers observed in the fans are characterized by their low slope, and they preserve evidence of channel-branching geometry and dendritic small-scale lobes. Mono- and polyhydrated sulfates, Fe-oxides, opaline silica, and jarosite have been detected in the vicinity of the Melas fan (Metz et al. 2009). There are no other confirmed sublacustrine fan deposits outside of Melas Chasma.


500 m
Better preserved
sublacustrine fans
within layered deposits
in Melas Chasma,
HiRISE PS_007667_1700.



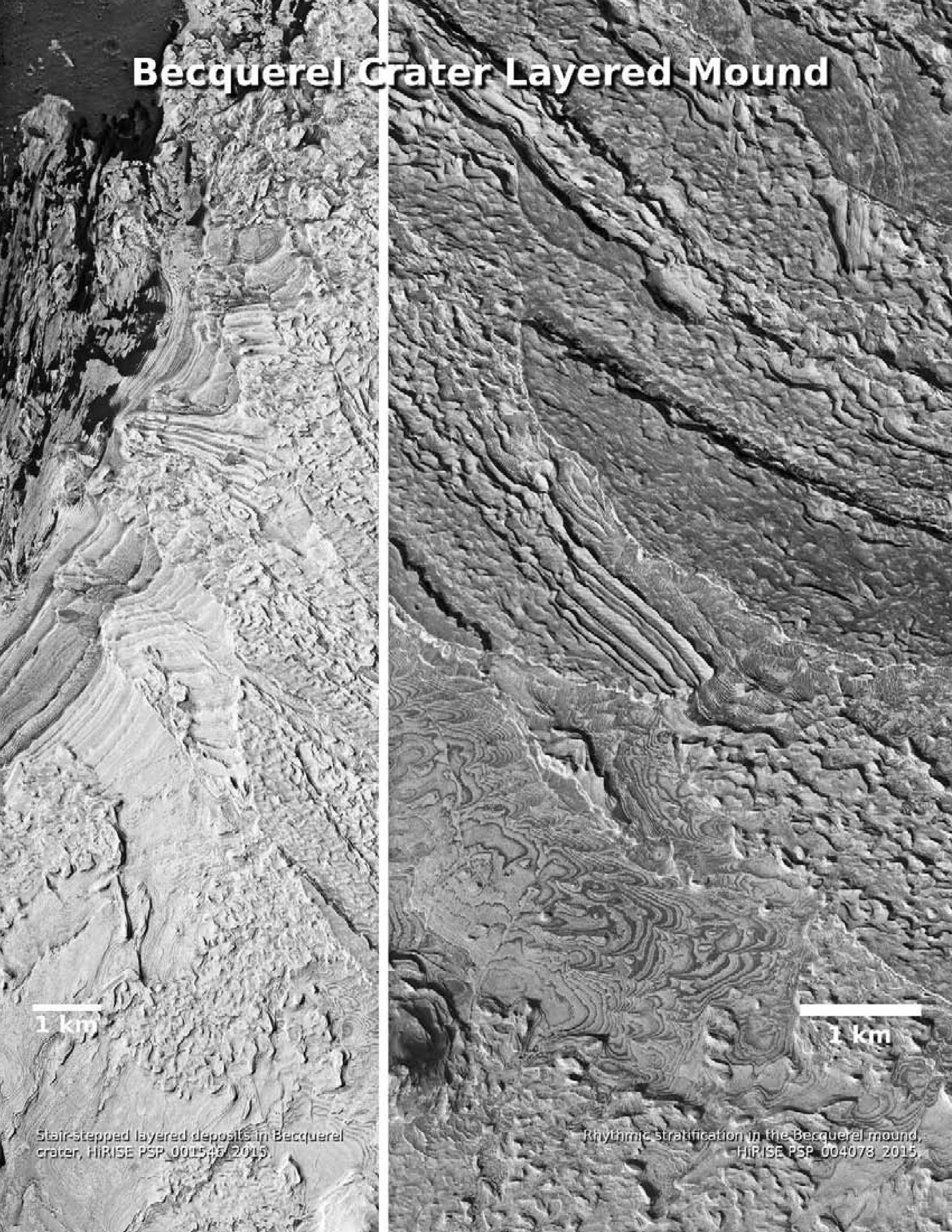
Bright, layered deposits in Columbus crater, HiRISE ESP_013182_1515.

Layered deposits are found on the floor and inner walls of Columbus crater. Because no fluvial networks have been identified in the region, a groundwater-fed playa lake environment has been hypothesized to explain the layered deposits and observed mineralogy within the crater (Wray et al. 2011). Polyhydrated sulfates (gypsum and Mg-sulfate) interbedded with kaolinite have been detected in these layers, and jarosite and Fe/Mg smectites have also been observed and are assumed to have formed in the Late Noachian (Wray et al. 2011). The layered material consists of polygonally fractured bright layers that can be traced around the circumference of the crater. Other locations of similar deposits can be found in Terra Sirenum, and the *Opportunity* rover site in Meridiani Planum.



Layered deposits, north to the left, HiRISE PSP_010281_1510.

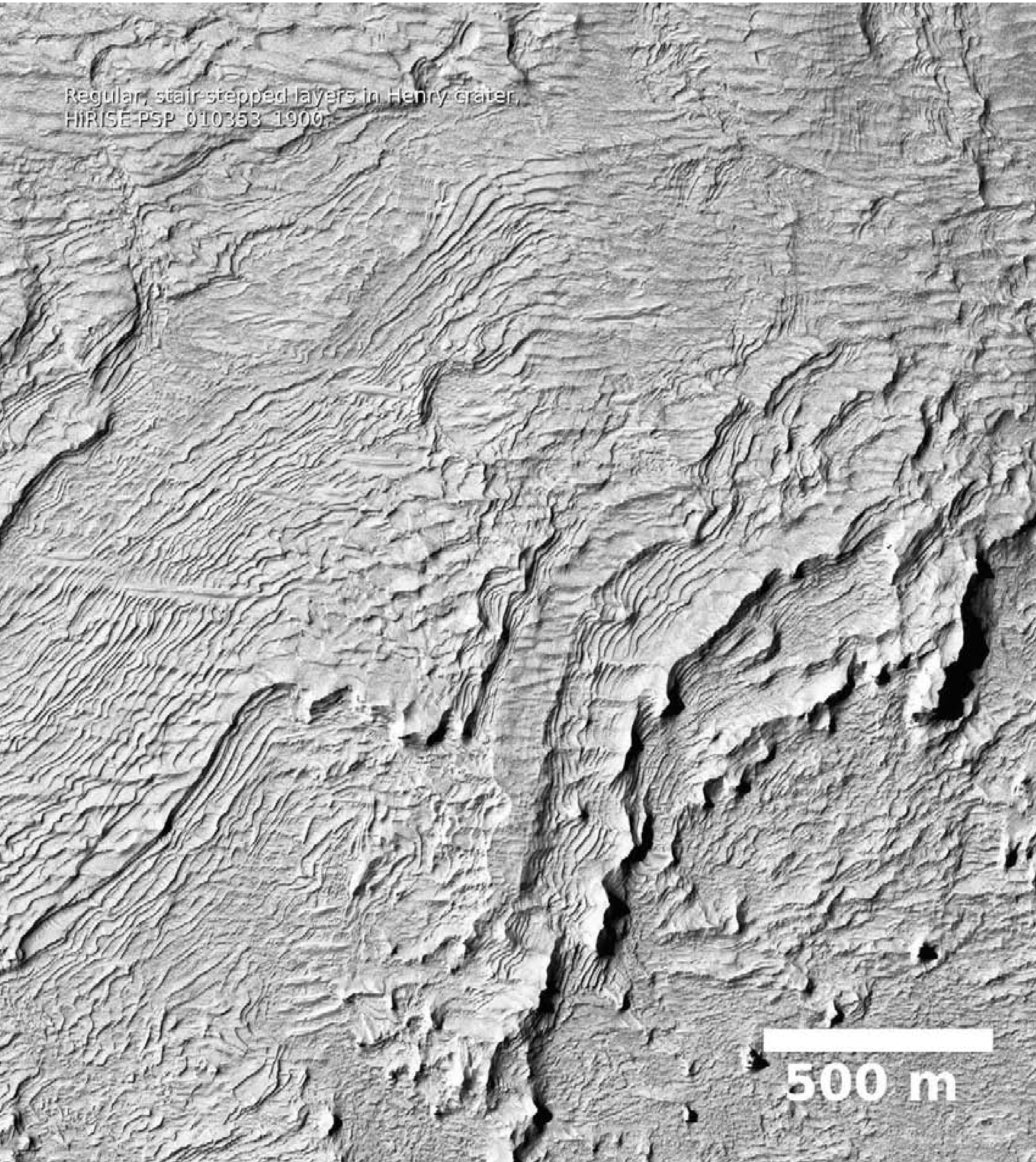
Becquerel Crater Layered Mound



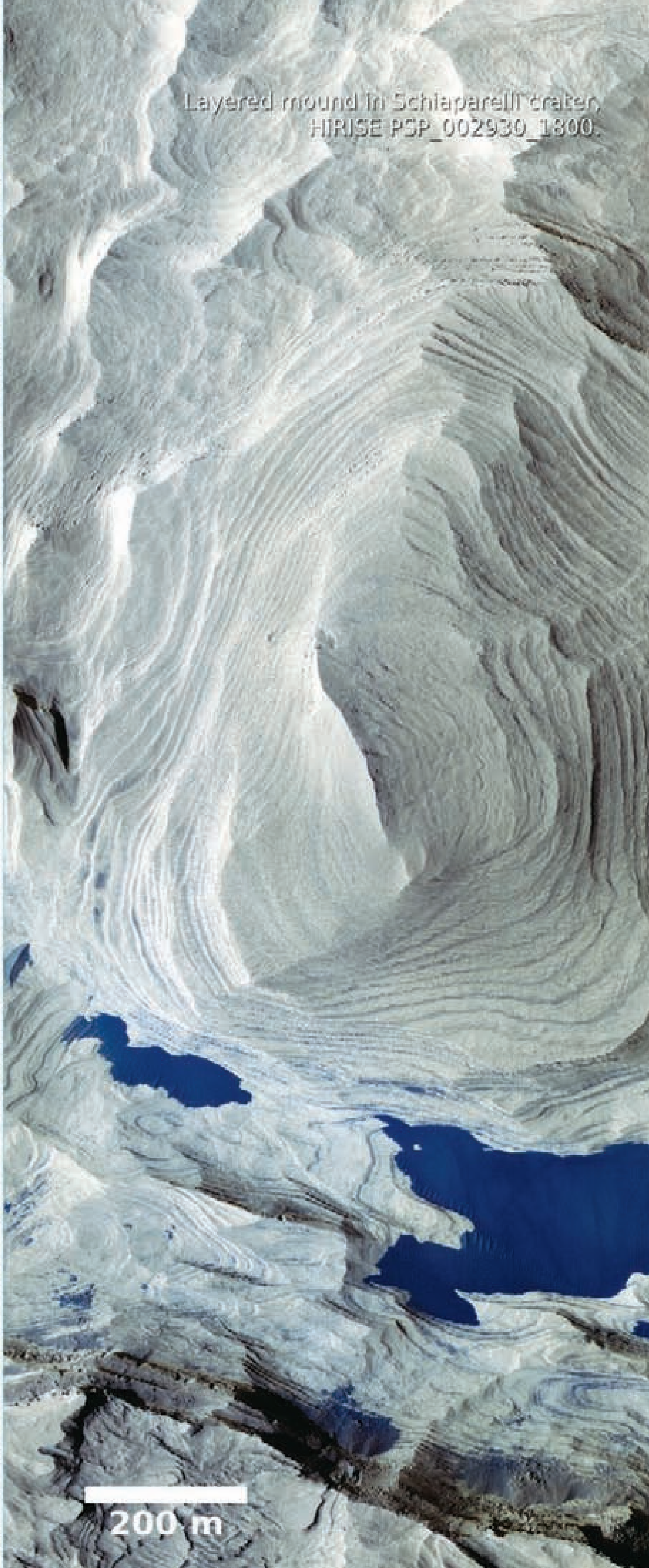
Stair-stepped layered deposits in Becquerel crater, HiRISE PSP_001546_2015.

Rhythmic stratification in the Becquerel mound, HiRISE PSP_004078_2015.

The layered mound in Becquerel crater contains repetitive indurated beds exhibiting nearly uniform thickness that appear to be expressed in rhythmic bundles (Lewis et al. 2008). The strata are generally of uniform tone and are often fractured and faulted, resulting in the structural offset of layers throughout the section. Several interpretations have been put forward to explain the origin of the Becquerel mound, including air-fall dust, lacustrine deposition, or polar layered deposits (Bridges et al. 2008, Lewis et al. 2008). Similar exposures can be found elsewhere in the Arabia Terra region, for example, in Henry crater, Schiaparelli crater, Vernal crater, and Crommelin crater, and they are thought to be Noachian in age (Malin and Edgett 2000). At Henry crater, the layered mound is at a higher elevation than the rim of the crater, suggesting deposition in an overfilled basin. At Becquerel crater, the highest point on the mound is below the crater rim, making it difficult to determine whether these strata represent deposition in an underfilled basin, or are the degraded remnant of a more extensive overfilled basin deposit.




Layered mound in Schiaparelli crater,
HiRISE PSP_005897_1790.
200 m


Layered mound in Schiaparelli crater,
HiRISE PSP_002930_1800.
200 m

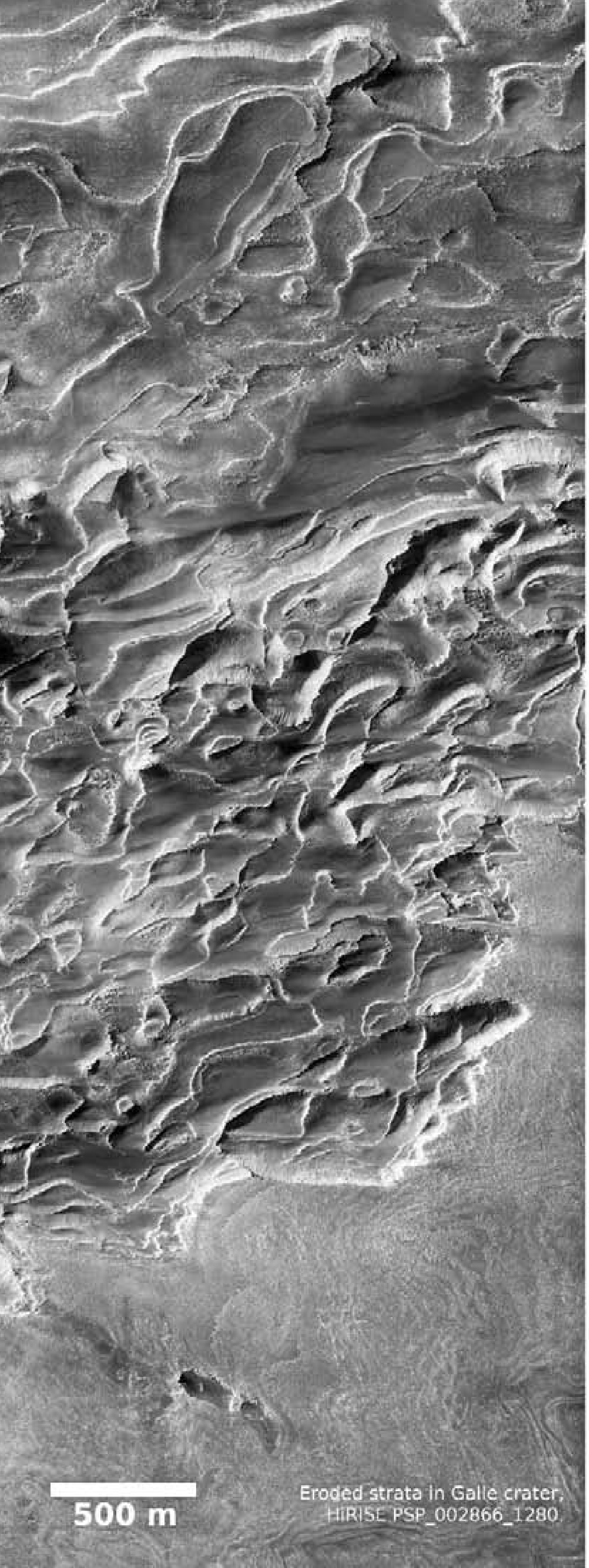
Galle Crater Layers

Finely-bedded layers in Galle crater mound, HiRISE PSP_003934_1275.

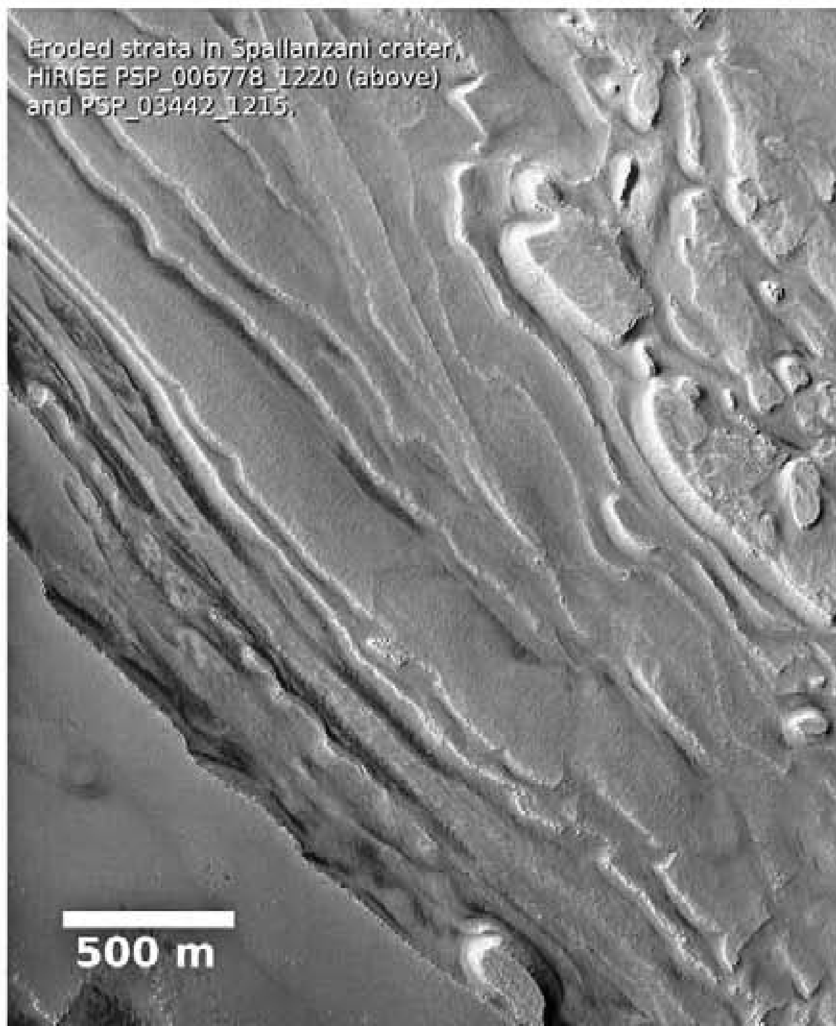
The southern part of Galle crater hosts a 600-m-thick stack of layered deposits. The lower portion of the deposit consists of thin layers with unconformable contacts and numerous truncation surfaces. This layered mound has been interpreted as lacustrine (Reiss et al. 2006), but because the style of layering in Galle is reminiscent of stratigraphy observed in polar layered deposits, this mound and similar outcrops in Spallanzani crater have been interpreted as ancient polar layered deposits (Ansan and Mangold 2003). The ages of these deposits are unknown.

Truncated layers in the Galle crater mound, HiRISE PSP_003934_1275.

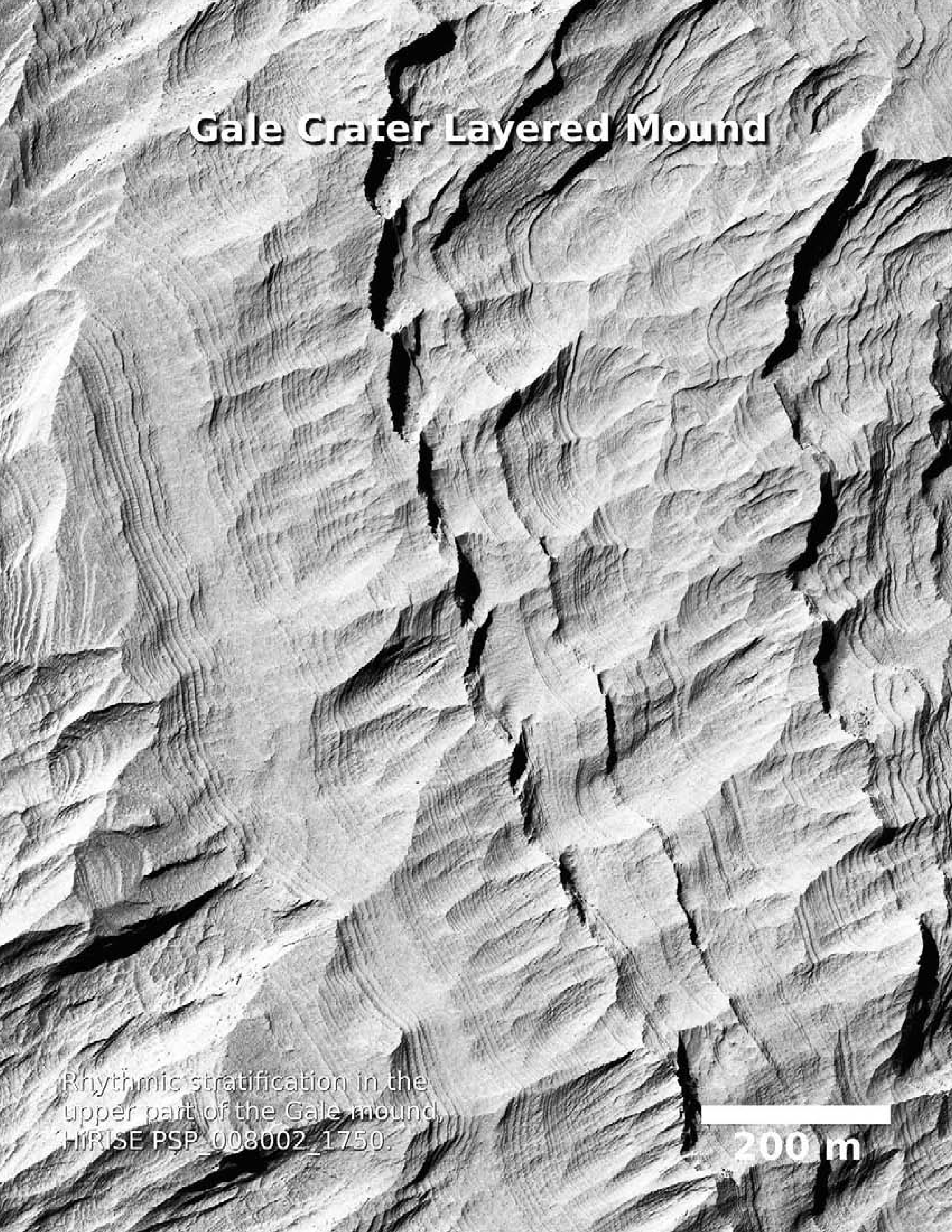
Mesa-forming strata in the Galle crater mound, HIIRSE PSP_002655_1280.

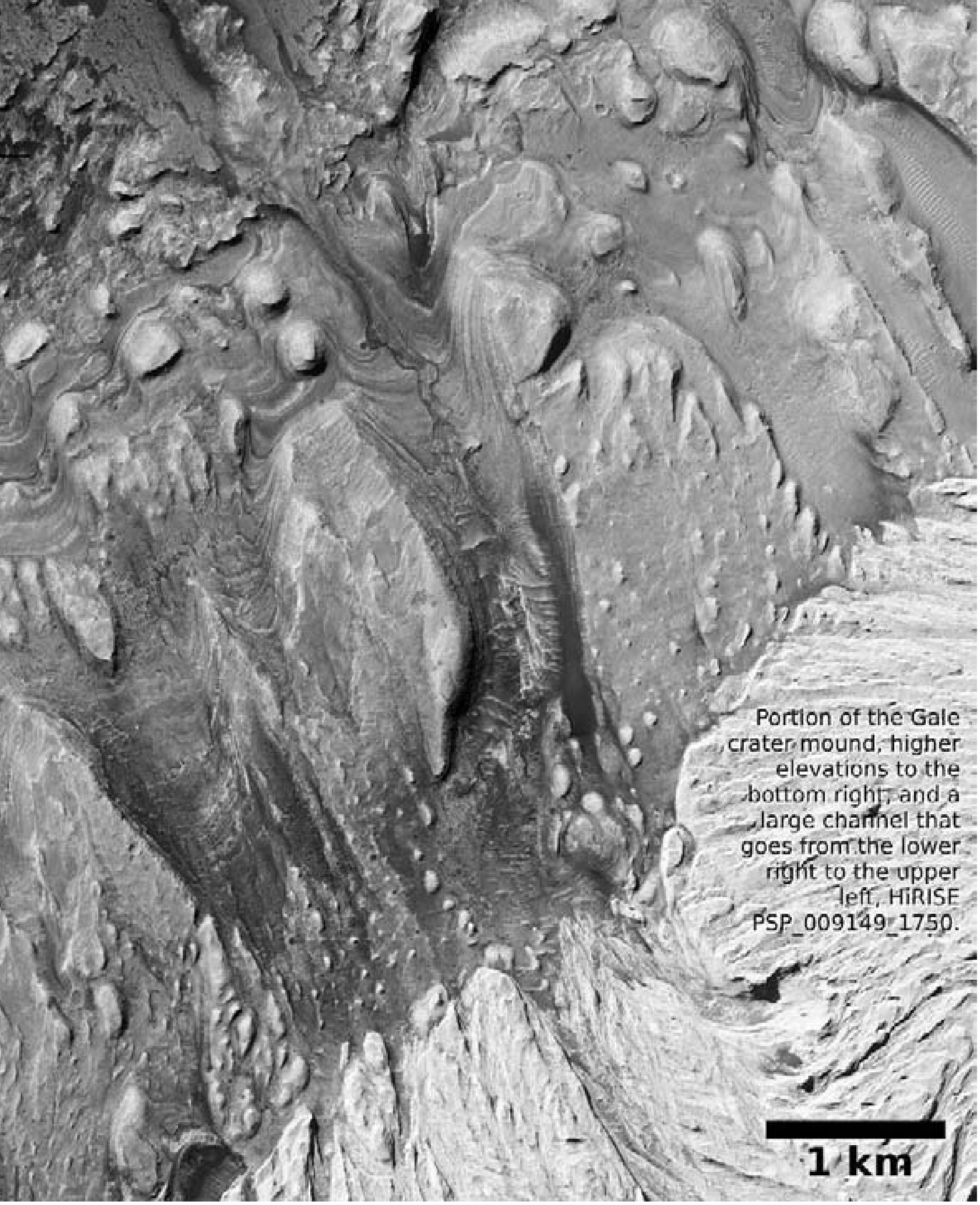


Eroded strata in Galle crater, HiRISE PSP_002866_1280.



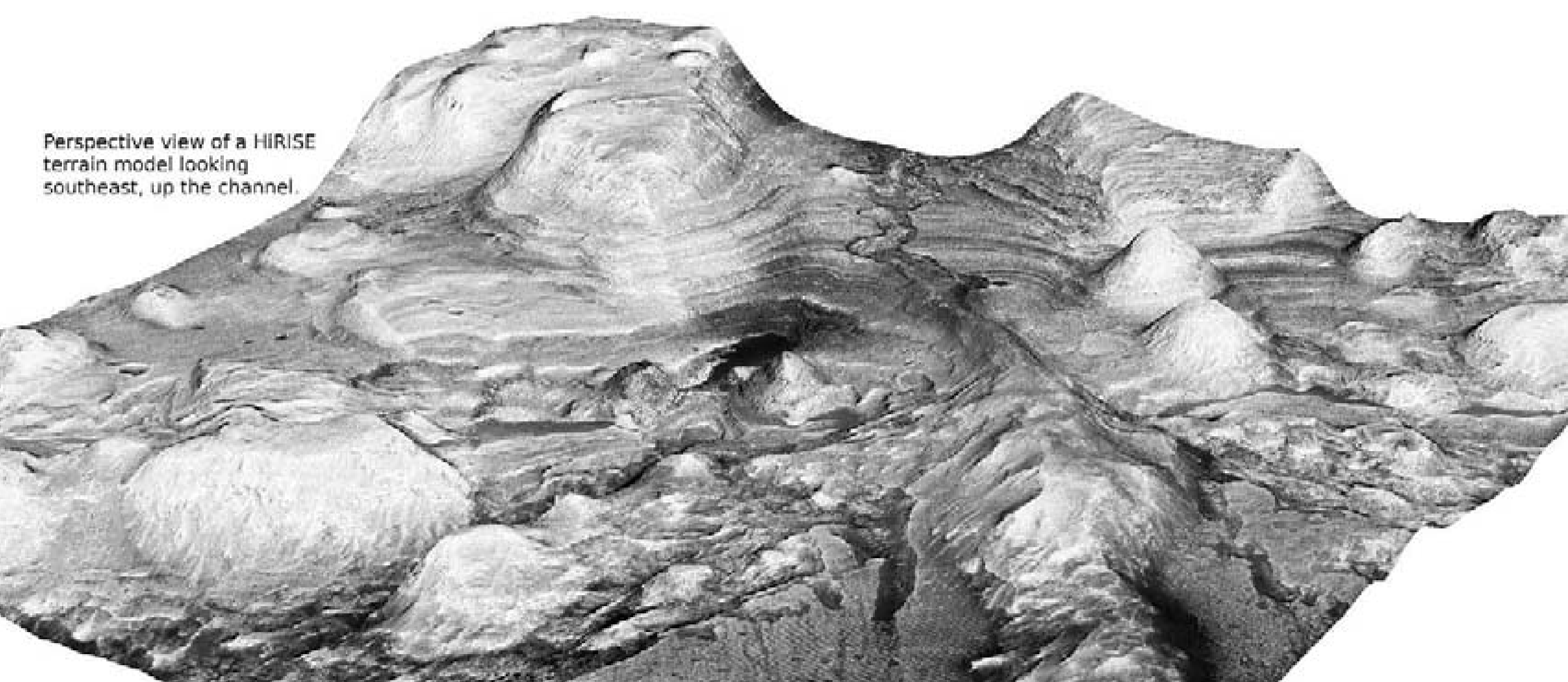
Eroded strata in Spallanzani crater, HiRISE PSP_006778_1220 (above) and PSP_03442_1215.


Gale Crater Layered Mound
Rhythmic stratification in the upper part of the Gale mound, HiRISE PSP_008002_1750.
200 m

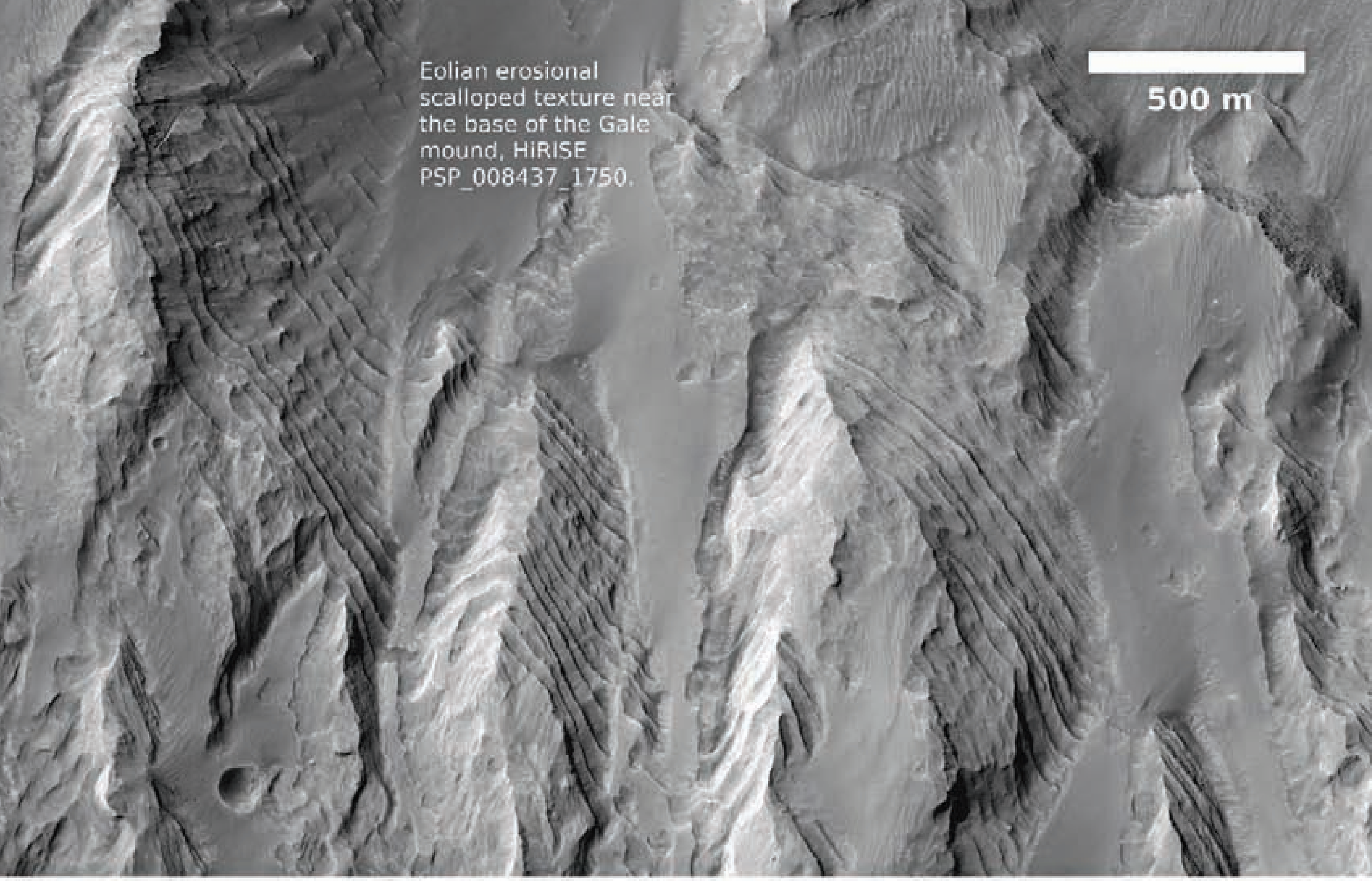


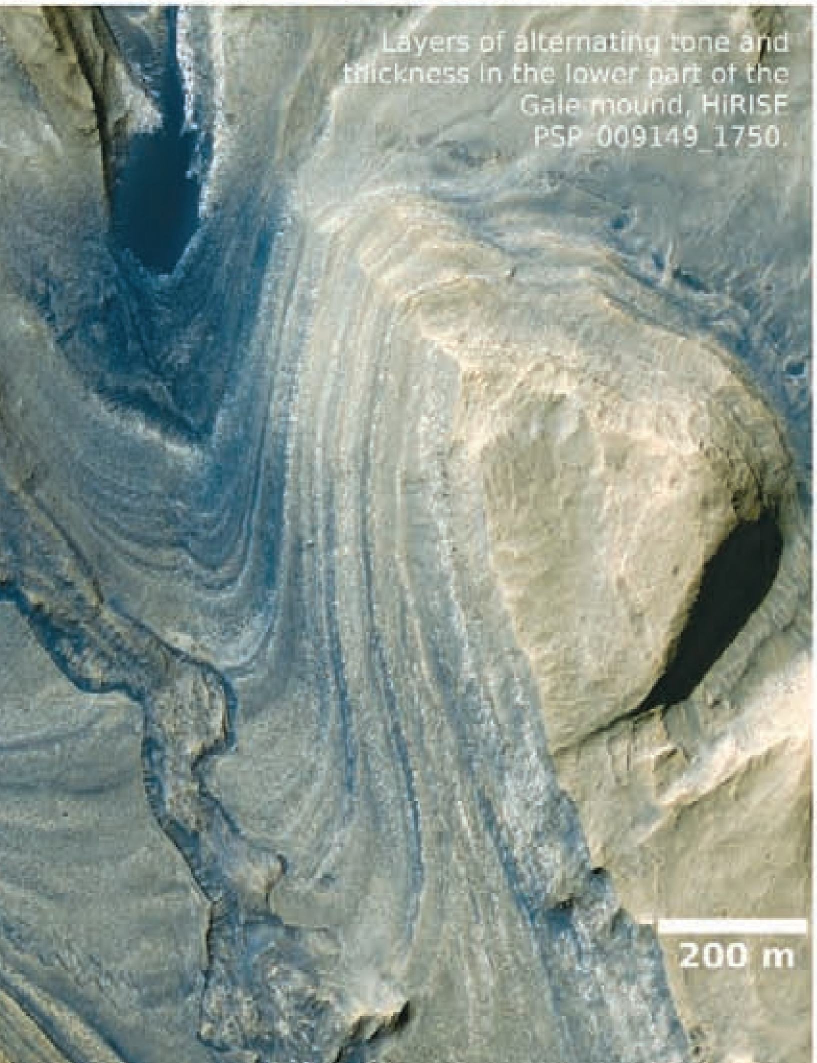
Portion of the Gale crater mound, higher elevations to the bottom right, and a large channel that goes from the lower right to the upper left, HiRISE PSP_009149_1750.

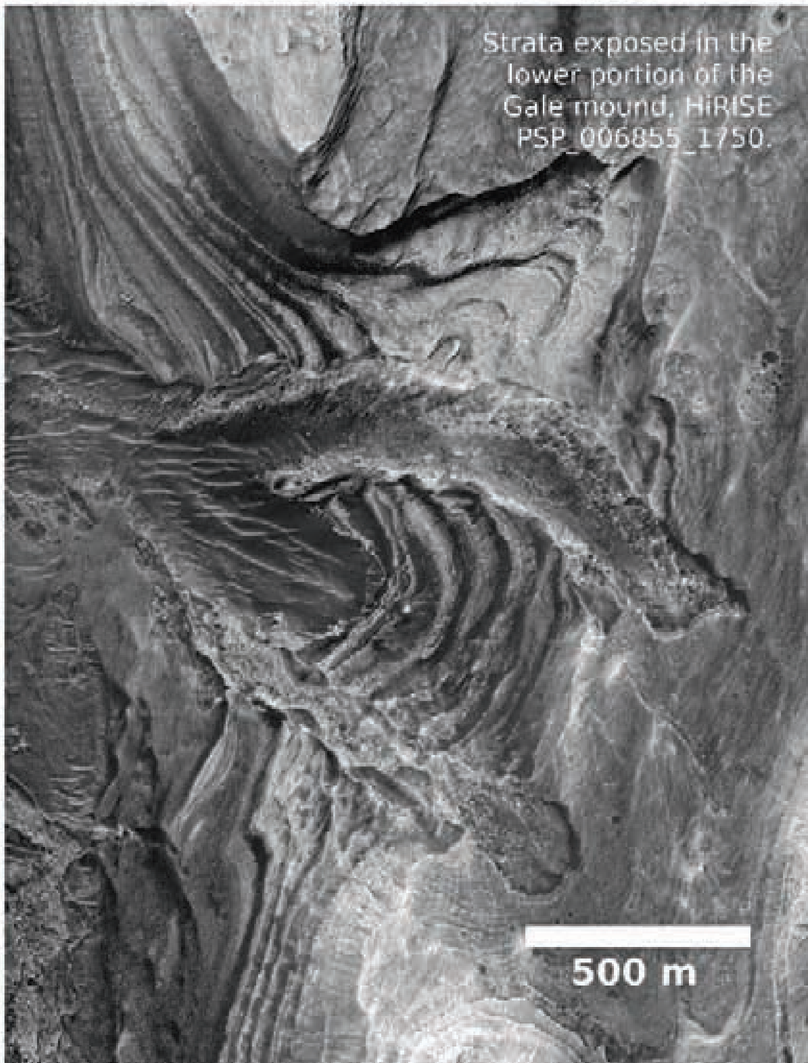
Gale crater contains a layered mound exhibiting diverse mineral signatures and layer morphologies. At ~5 km in thickness, the Gale mound is one of the most substantial continuous sections on Mars. A clearly expressed mineral stratigraphy is observed throughout the mound. The layered deposits at the base of the mound are sulfate- and clay-bearing, whereas the middle section is clay-poor but rich in mono- and polyhydrated sulfates. The upper portion of the mound appears to be spectrally neutral (Milliken et al. 2010), consistent with the composition of Martian dust. The Gale crater mound may record a large section of Martian time, from the Noachian to Hesperian age of its lower units to a Hesperian to Amazonian age of its upper formation (Milliken et al. 2010). These mineralogical changes are coupled with morphological changes. The clay- and sulfate-rich layers appear to vary in thickness, albedo, and texture, whereas the spectrally neutral layers of the upper mound exhibit a stair-stepped morphology with uniform layer thickness, homogeneity in tone, and a lack of impact craters. These rhythmic strata near the top of the mound are comparable to those observed in Arabia at Becquerel crater. Many hypotheses have been invoked to explain the origin of this stack of sedimentary layers, including volcanic ash, lacustrine (Cabrol et al. 1999), eolian, spring mound (Rossi et al. 2008), or ancient polar deposits (Schultz and Lutz 1988).

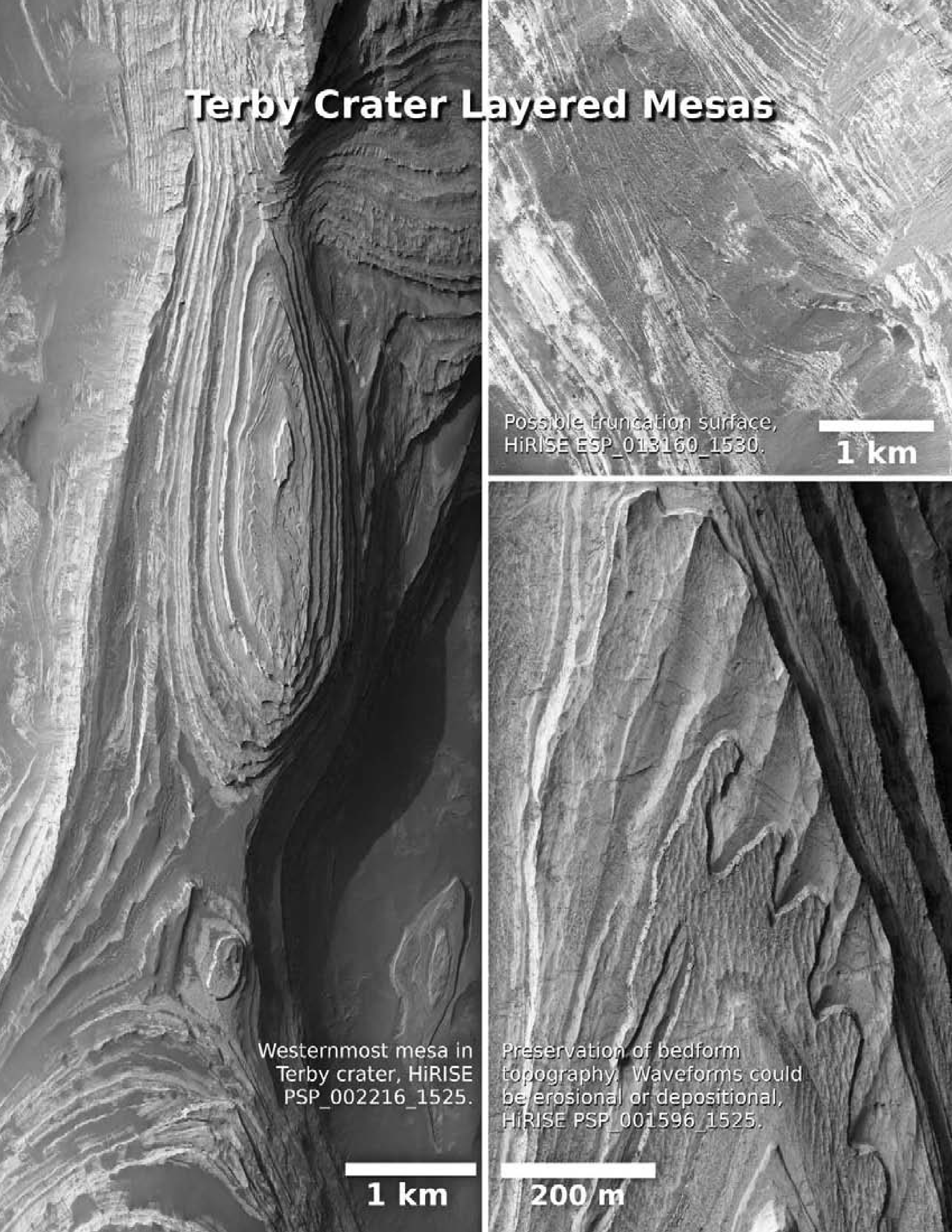


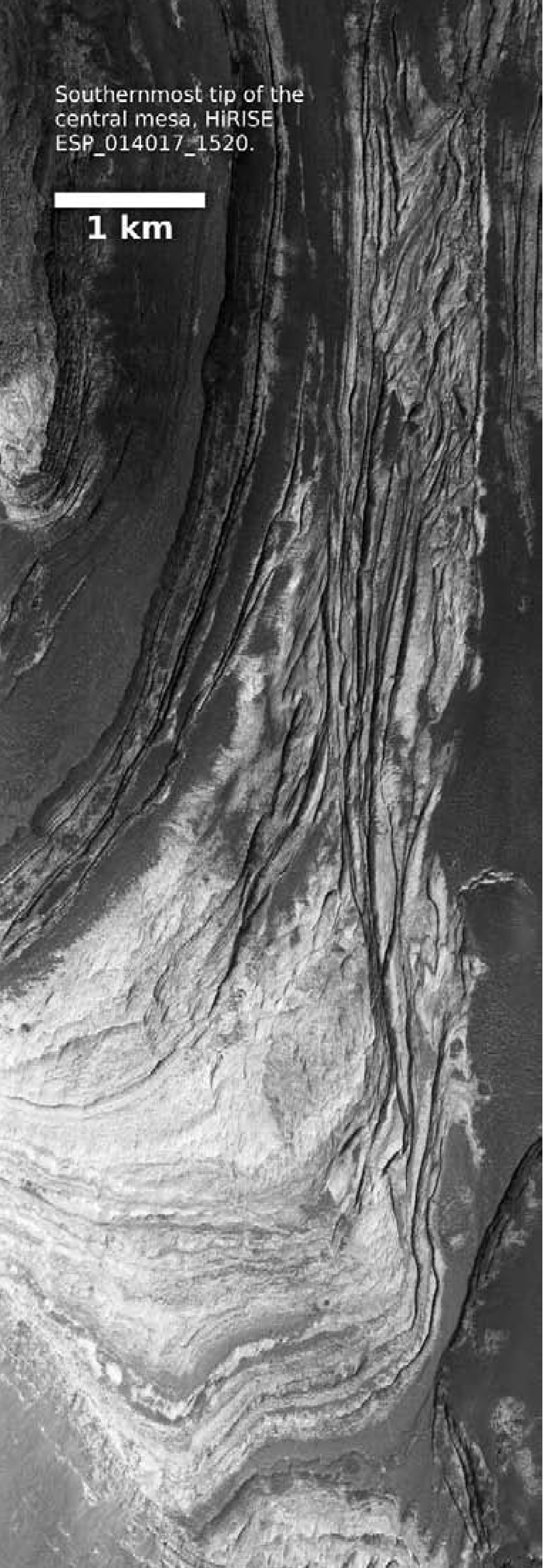
Perspective view of a HiRISE terrain model looking southeast, up the channel.


Eolian erosional scalloped texture near the base of the Gale mound, HiRISE PSP_008437_1750.
500 m

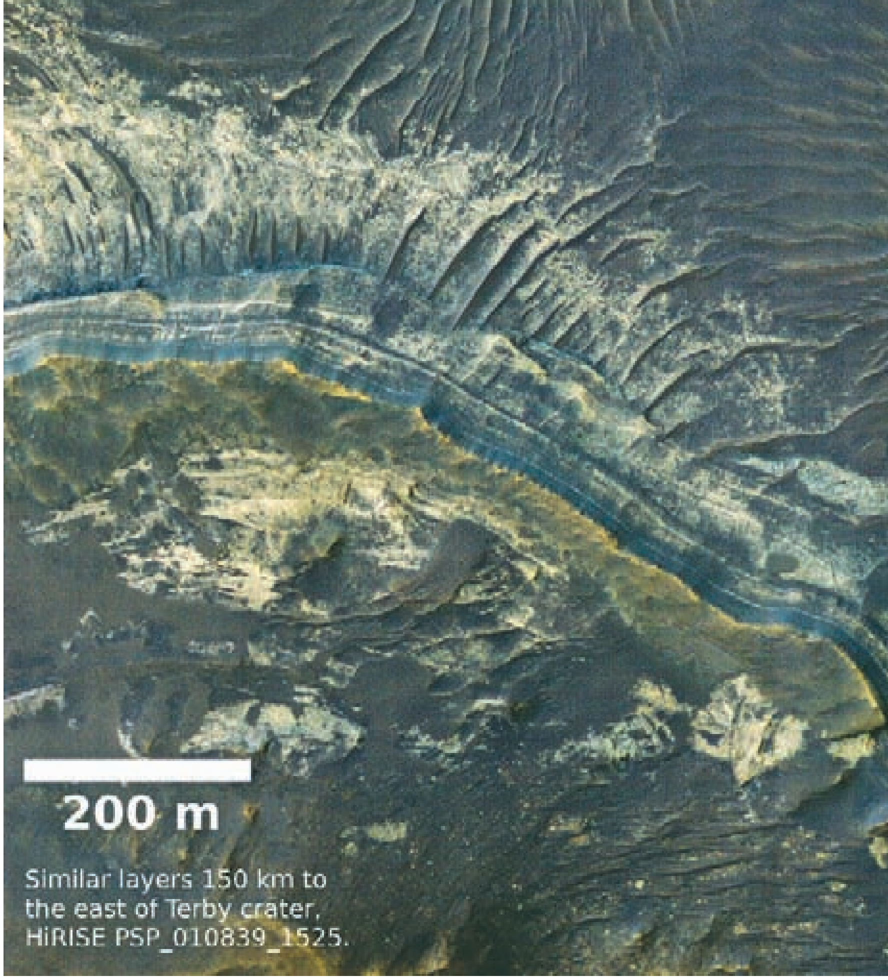

Layers of alternating tone and thickness in the lower part of the Gale mound, HiRISE PSP_009149_1750.
200 m


Strata exposed in the lower portion of the Gale mound, HiRISE PSP_006855_1750.
500 m


Terby Crater Layered Mesas
Westernmost mesa in Terby crater, HiRISE PSP_002216_1525.
1 km
Possible truncation surface, HiRISE ESP_013160_1530.
1 km
Preservation of bedform topography. Waveforms could be erosional or depositional, HiRISE PSP_001596_1525.
200 m

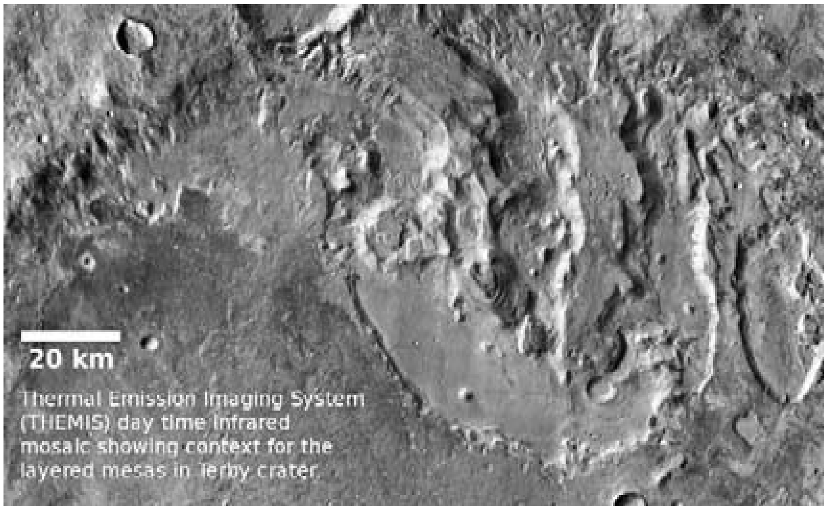


Southernmost tip of the central mesa, HiRISE ESP_014017_1520.



Similar layers 150 km to the east of Terby crater, HiRISE PSP_010839_1525.

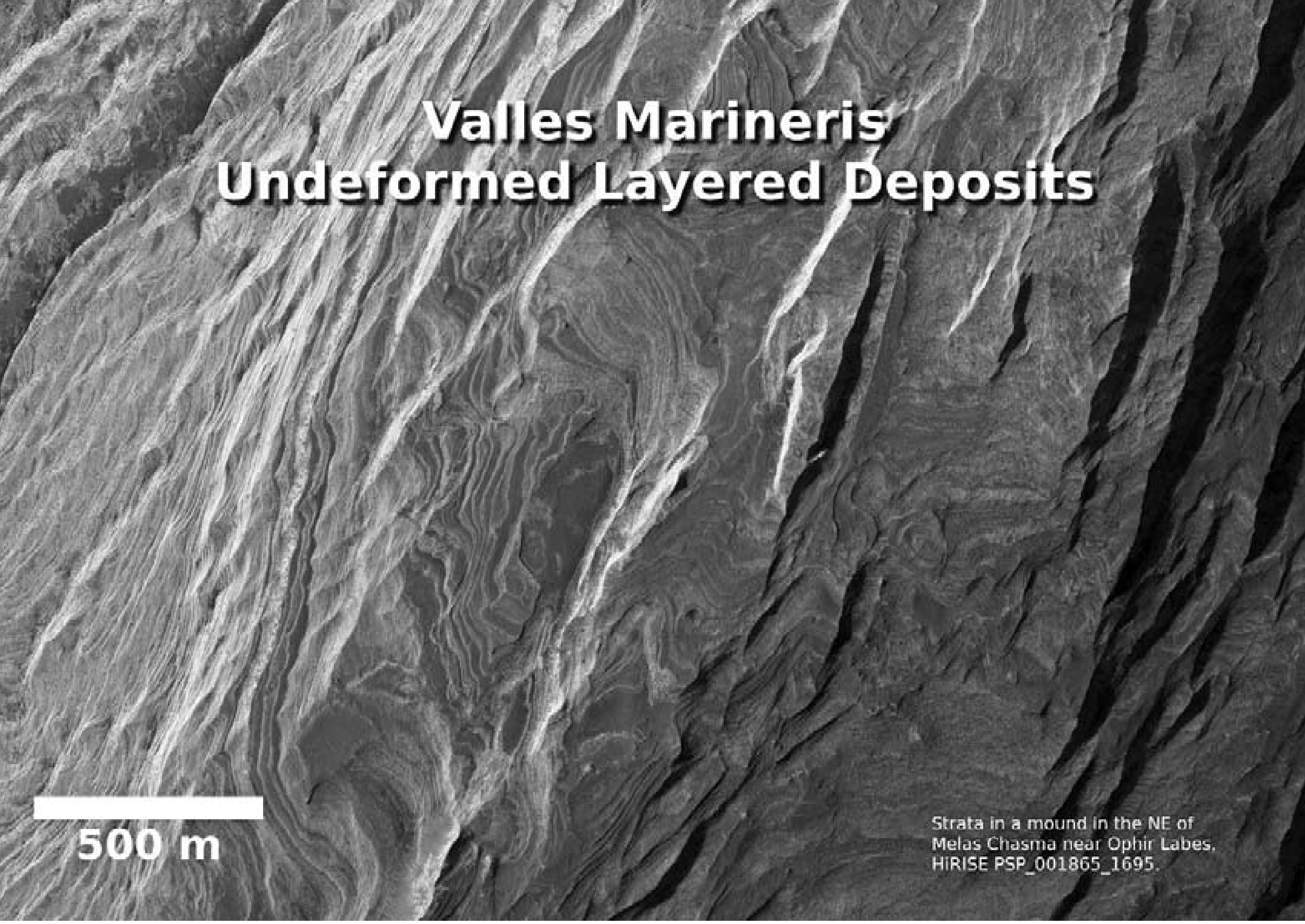
There is a 2.5-km-thick sequence of meter-scale strata exposed in three mesas within Terby crater, located along the north rim of Hellas Basin. Layers in the northern part of the crater are higher in elevation than the degraded southern rim. This deposit has been variously interpreted to be the result of eolian (Lewis et al. 2010), lacustrine (Wilson et al. 2007), volcanic air-fall, and deltaic processes (Ansan et al. 2011). The layered mesas display Fe/Mg smectite clay mineral signatures, and hydrated Mg-sulfates; zeolites or hydrated silicates may be present as well (Ansan et al. 2011). These strata vary in albedo from bright to dark and are laterally continuous for kilometers. Locally, these strata are observed to truncate unconformably. Layers are polygonally fractured in places and exhibit a grooved texture thought to be the result of eolian deflation (Wilson et al. 2007), and they are assumed to have been emplaced during the Noachian. Similar deposits can be observed along the northern rim of Hellas Basin.



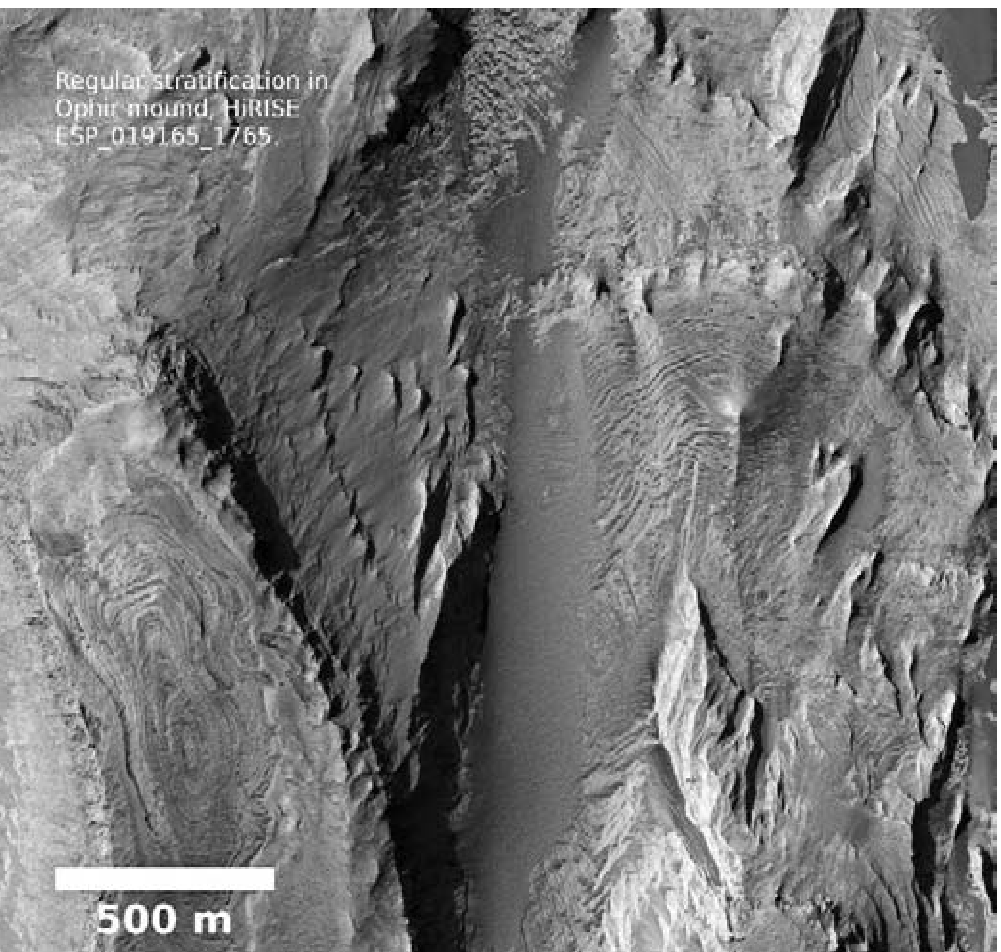
Thermal Emission Imaging System (THEMIS) day time infrared mosaic showing context for the layered mesas in Terby crater.

Steeply dipping layered rocks are exposed in the central uplift of Oudemans crater, located at the western end of Valles Marineris. The strata exposed in Oudemans were likely excavated from a depth of several kilometers below the surface, as a result of the impact-forming process. It is possible that these steeply dipping strata are possibly correlative with strata exposed in the walls of nearby Valles Marineris. Several other craters in the general Tharsis region (e.g., Martin and Mazamba craters) also exhibit well-preserved strata in their central uplifts, suggesting a possible link between these layered deposits and ash fallout from the Tharsis volcanic field. Caudill et al. (2011) identified a number of other layered units in the central peaks of craters. Therefore, these strata may be basaltic pyroclastic deposits rather than deposits of sedimentary origin. These kinds of exposures are found in craters on Hesperian and Amazonian surfaces, but they may well be bringing up rocks formed during the Noachian.

Valles Marineris Undeformed Layered Deposits

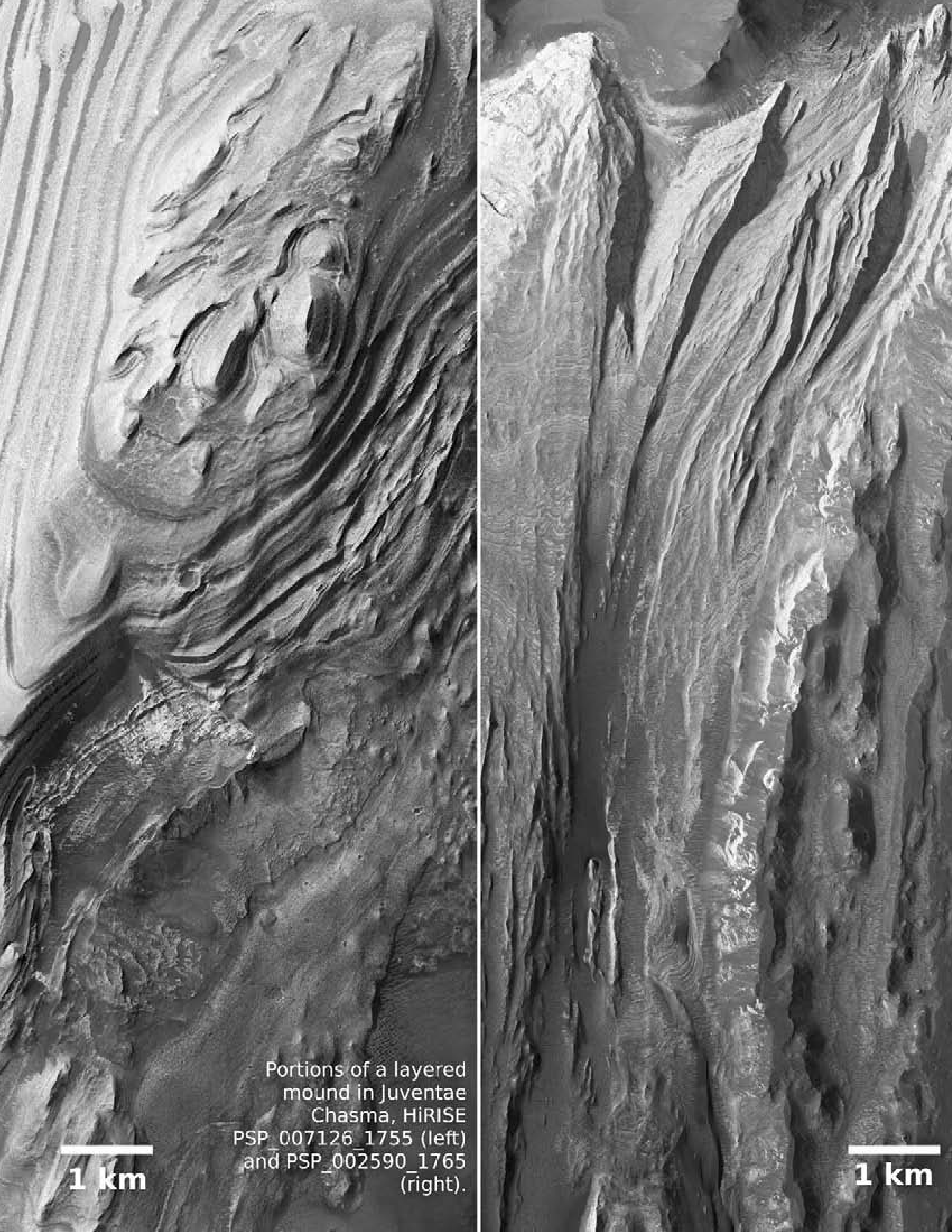


Strata in a mound in the NE of Melas Chasma near Ophir Labes, HiRISE PSP_001865_1695.

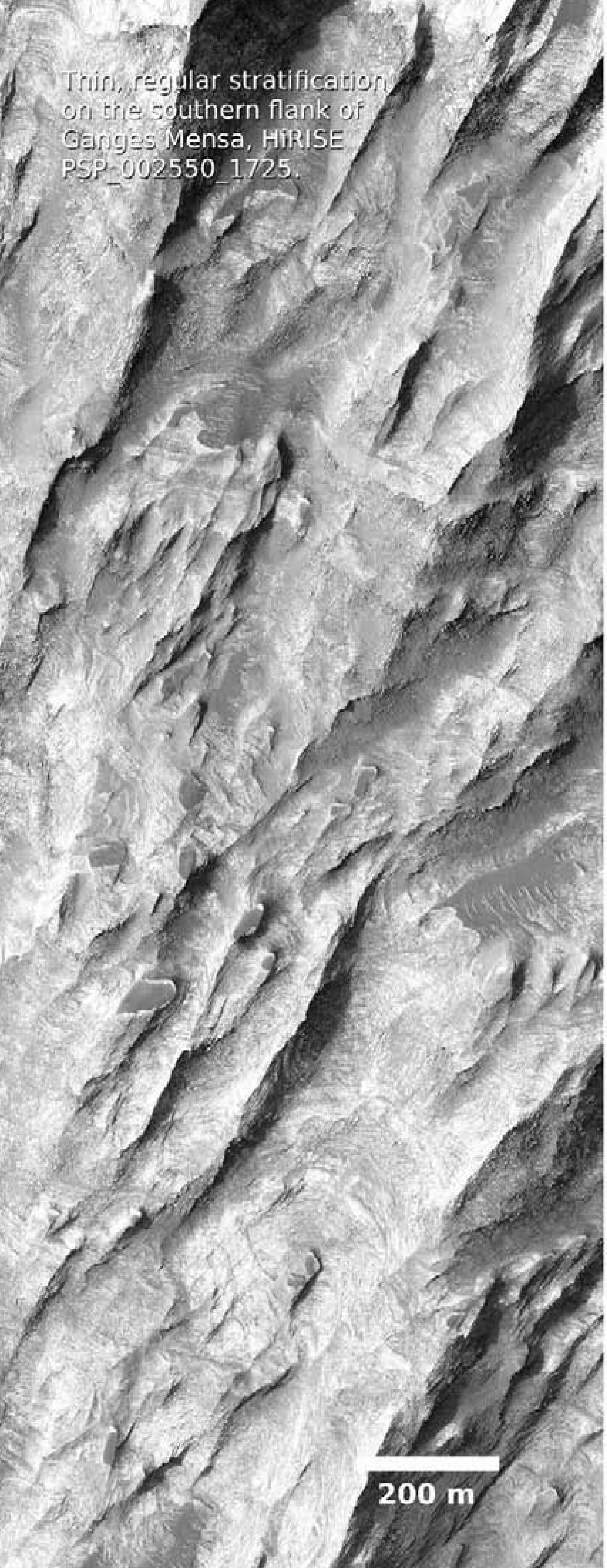


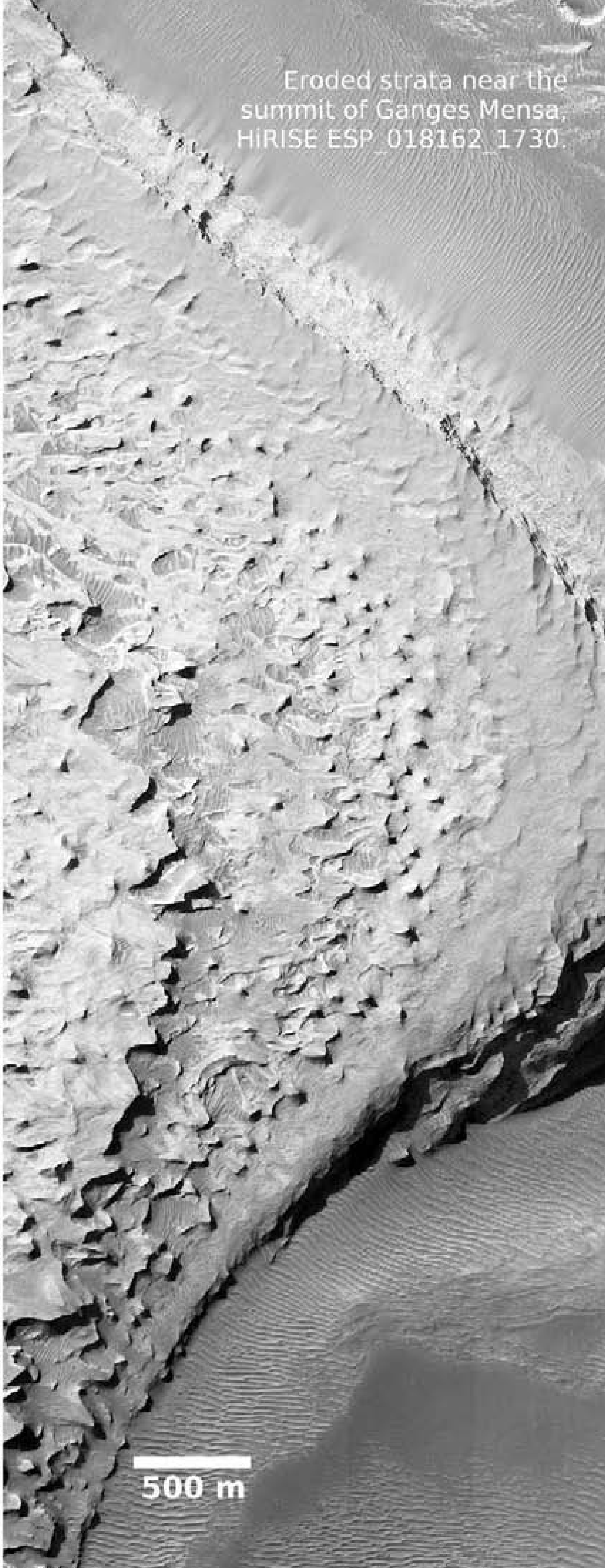
Regular stratification in Ophir mound, HiRISE ESP_019165_1765.

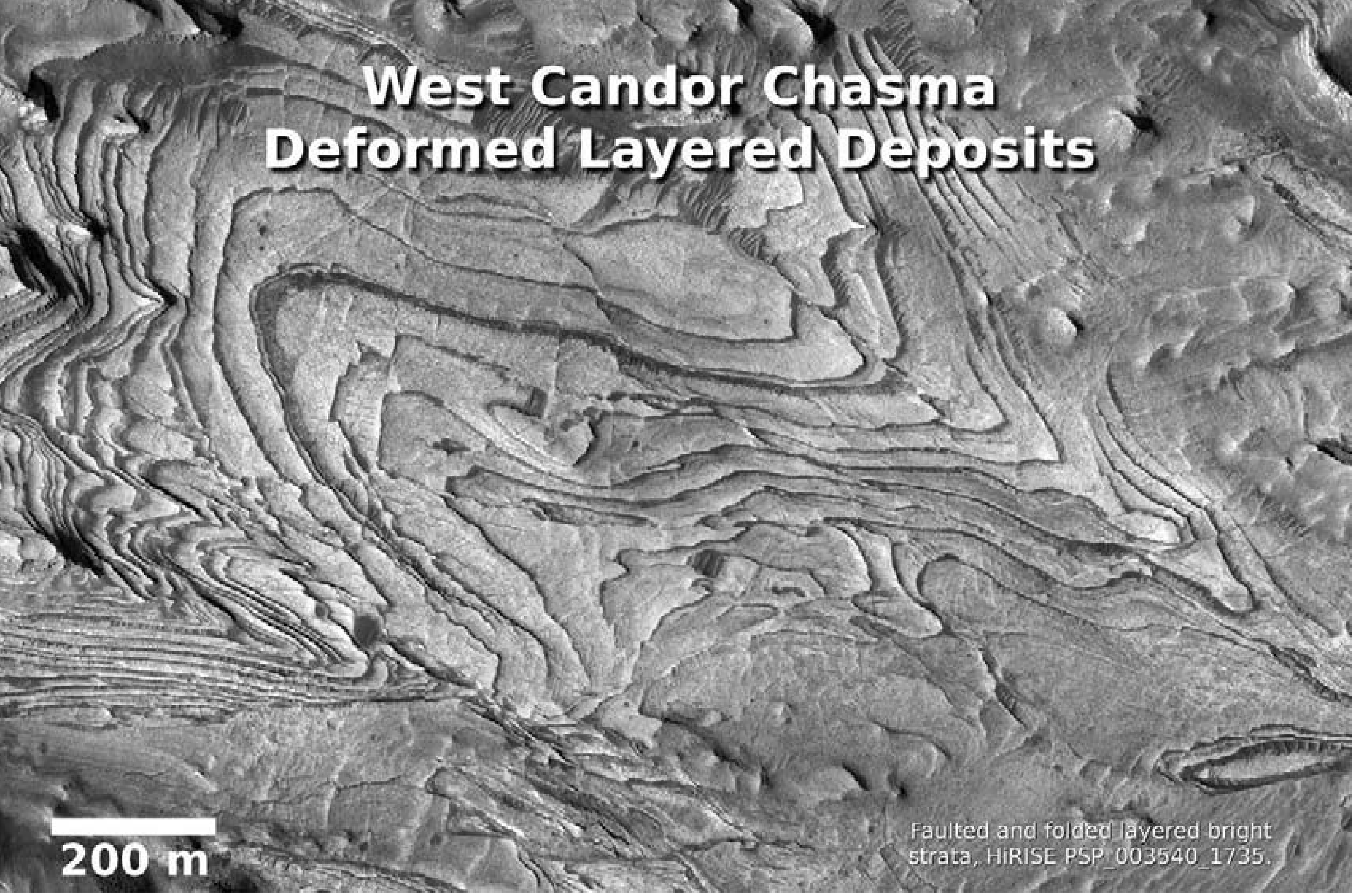
A variety of layered deposits are exposed as isolated plateaus, on the chasm floor, and adjacent to the walls of Valles Marineris. No single origin for these strata has been identified, and various explanations are likely needed to explain the diversity of deposits within the Valles Marineris (Lucchitta 2010), which were likely emplaced in Late Noachian to Hesperian times. In general, these deposits are hundreds-of-meters- to kilometers-thick stacks of undeformed strata that vary in thickness and albedo. Mono- and polyhydrated sulfates, Fe-oxide, and phyllosilicates have been detected in many of these outcrops (Gendrin et al. 2005, Bibring et al. 2007, Le Deit et al. 2007). Layered deposits in Ophir Chasma, Juventae Chasma, Ganges Mensa, and Melas Chasma fall under this broad category.



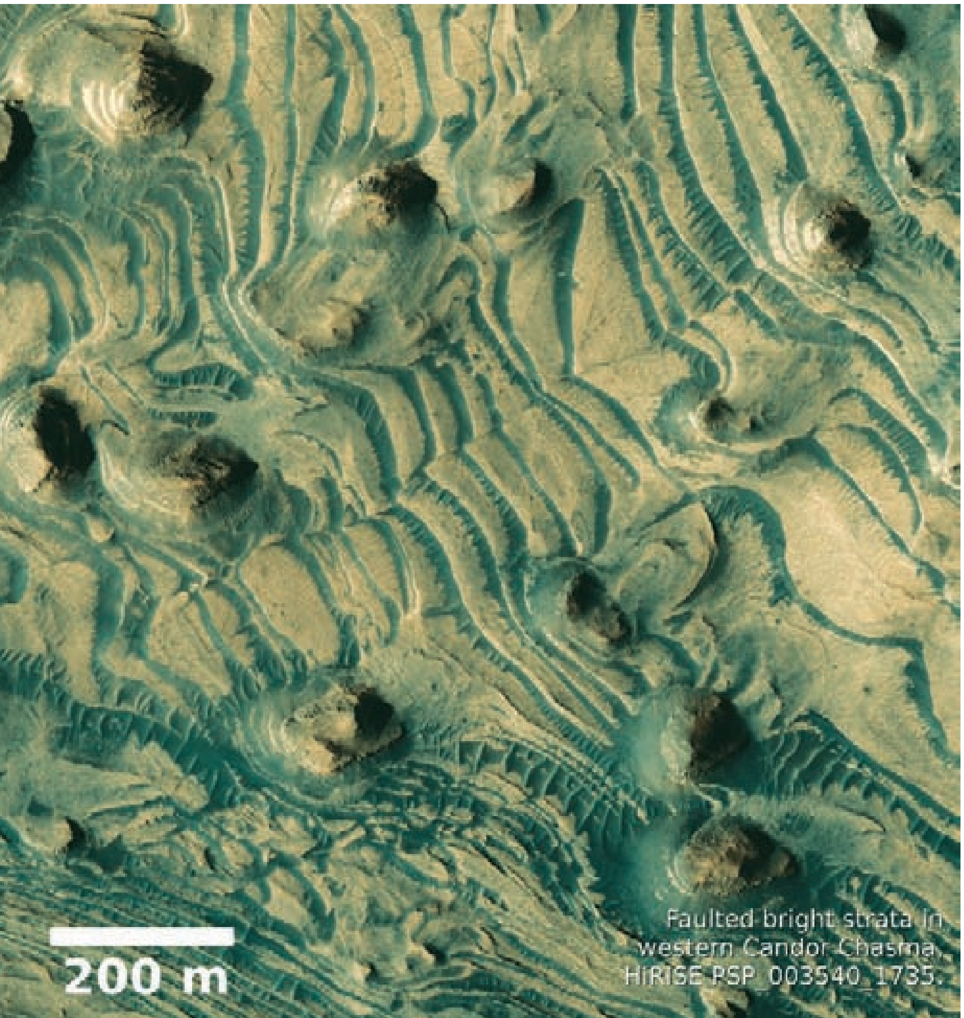
Portions of a layered mound in Juventae Chasma, HiRISE PSP_007126_1755 (left) and PSP_002590_1765 (right).


Thin, regular stratification on the southern flank of Ganges Mensa, HiRISE PSP_002550_1725.
200 m


Eroded strata near the summit of Ganges Mensa, HiRISE ESP_018162_1730.
500 m

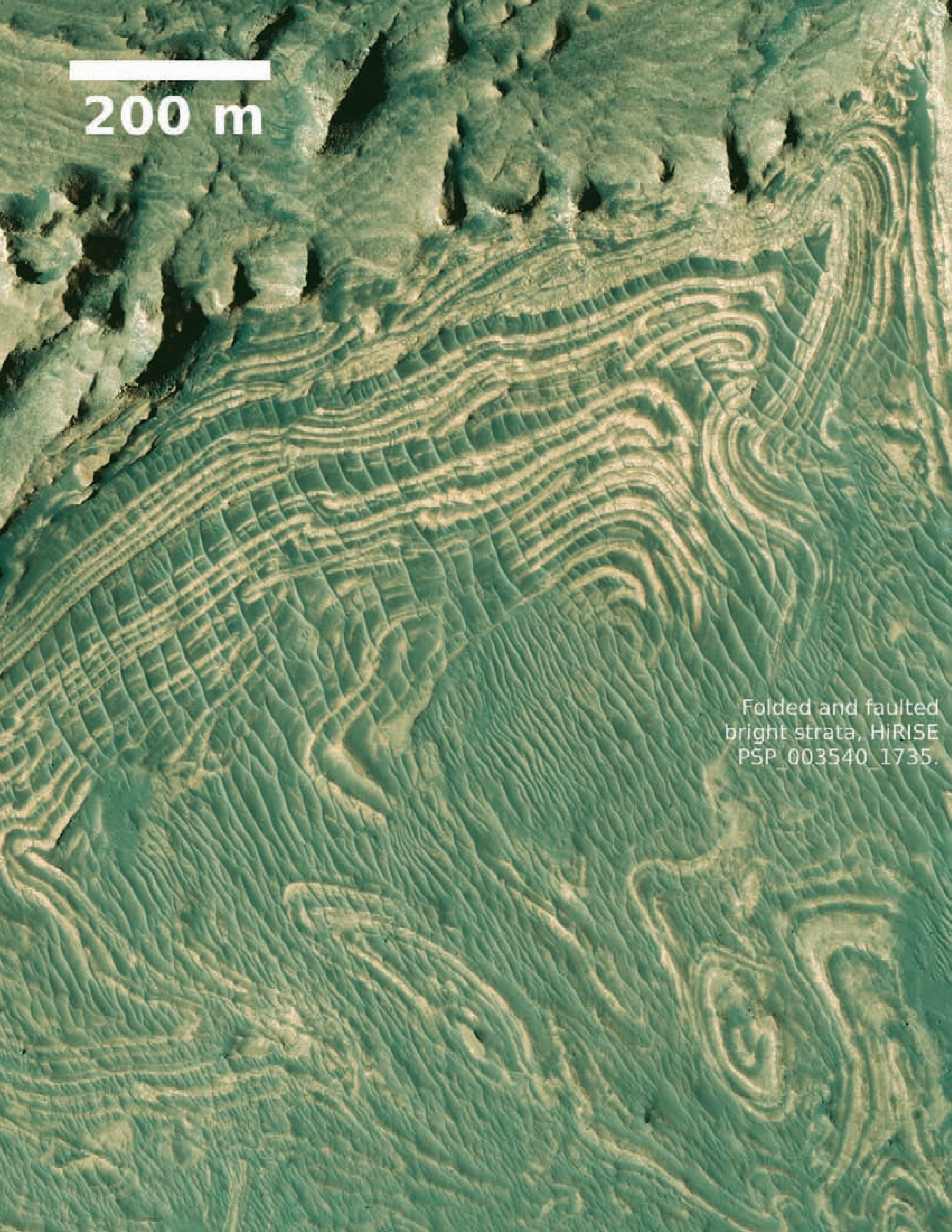


Faulted and folded layered bright strata, HiRISE PSP_003540_1735.



Faulted bright strata in western Candor Chasma, HiRISE PSP_003540_1735.

Although the Valles Marineris system contains many stratified units, there are some locations where those units show evidence of extensive brittle and ductile deformation, making them unique amongst these extensive deposits. This kind of deformation was first detailed in west Candor Chasma (Okubo et al. 2008, Okubo 2010), but it is also observed in Melas and Ius Chasmata (Metz et al. 2010). Kieserite, polyhydrated sulfates, and nanophase ferric oxides and oxyhydroxides have been detected in west Candor Chasma's layered mounds (Mangold et al. 2008, Murchie et al. 2009b). Mangold et al. (2008) observed that strata containing polyhydrated-sulfates have a higher thermal inertia than those containing kieserite, suggesting that these polyhydrated-sulfate-bearing layers may be coarser or better indurated than the kieserite layers (Mangold et al. 2008).

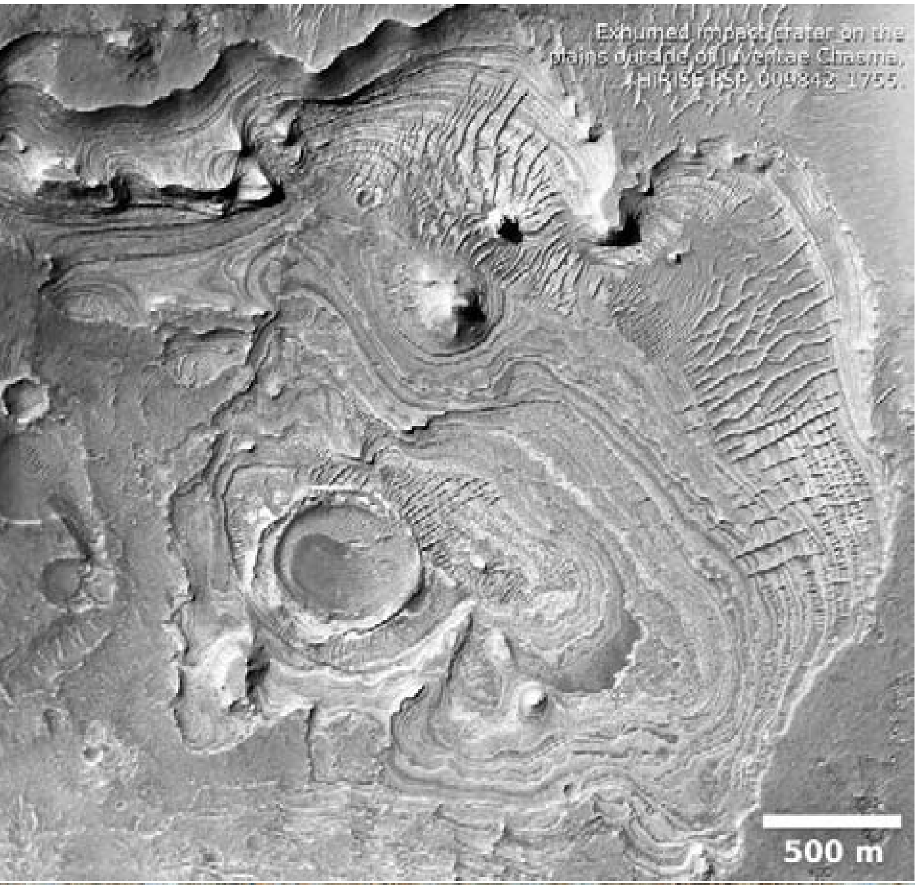


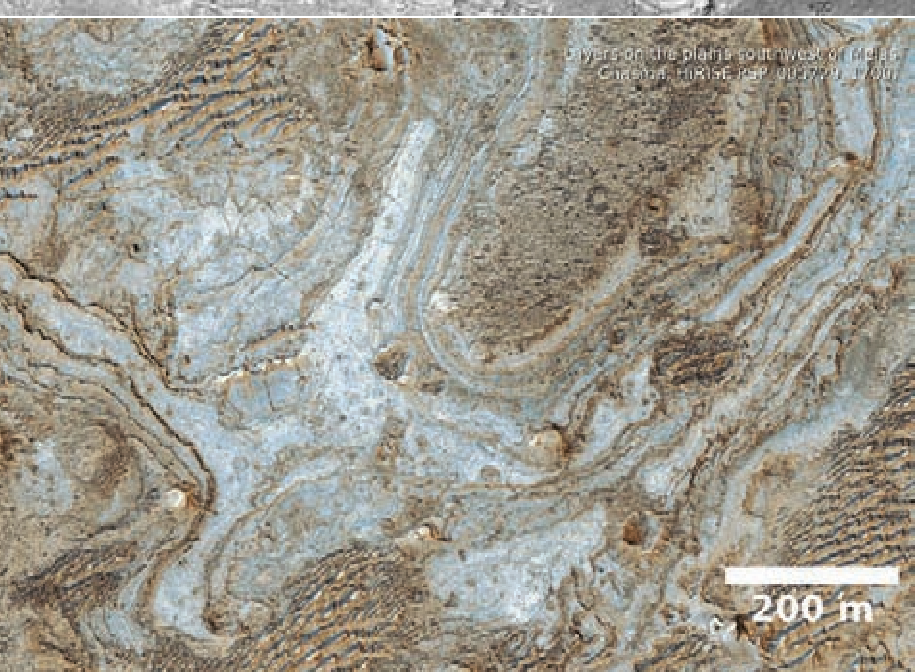
Folded and faulted bright strata, HiRISE PSP_003540_1735.

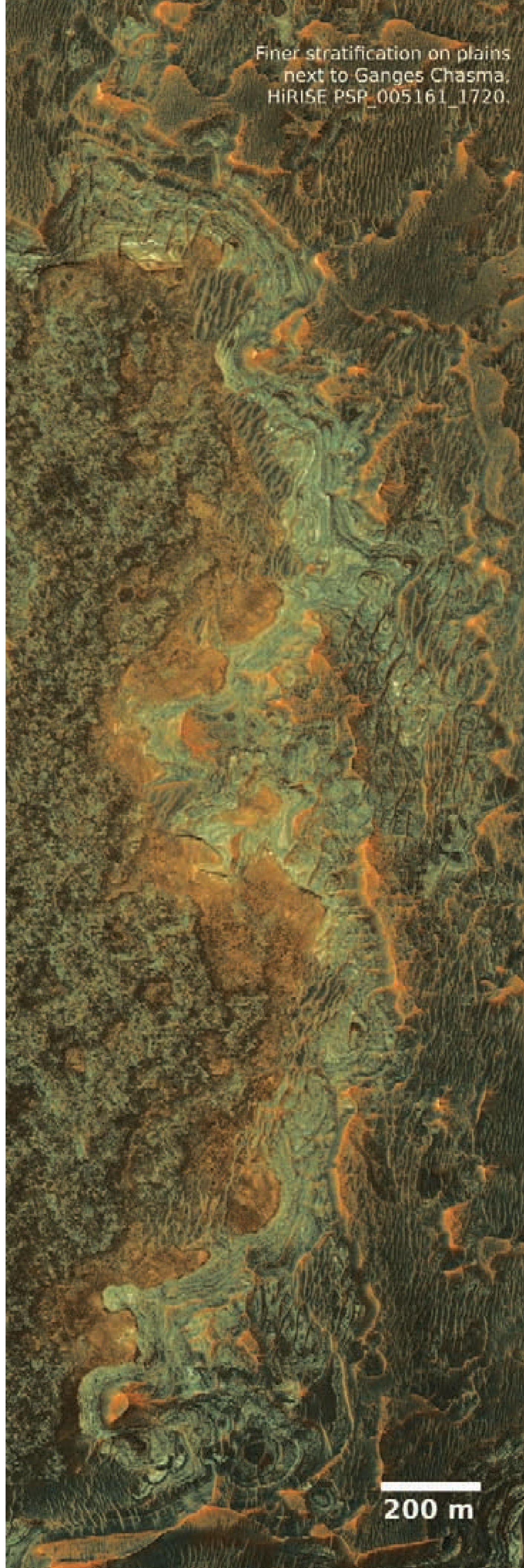
Stratified Plains Surrounding Valles Marineris

Much of the dark material in the scene is loose dark fines, but there are some actual dark layers alternating with the brighter layers here on the plains outside of Juventae Chasma, HiRISE PSP_003434_1755.

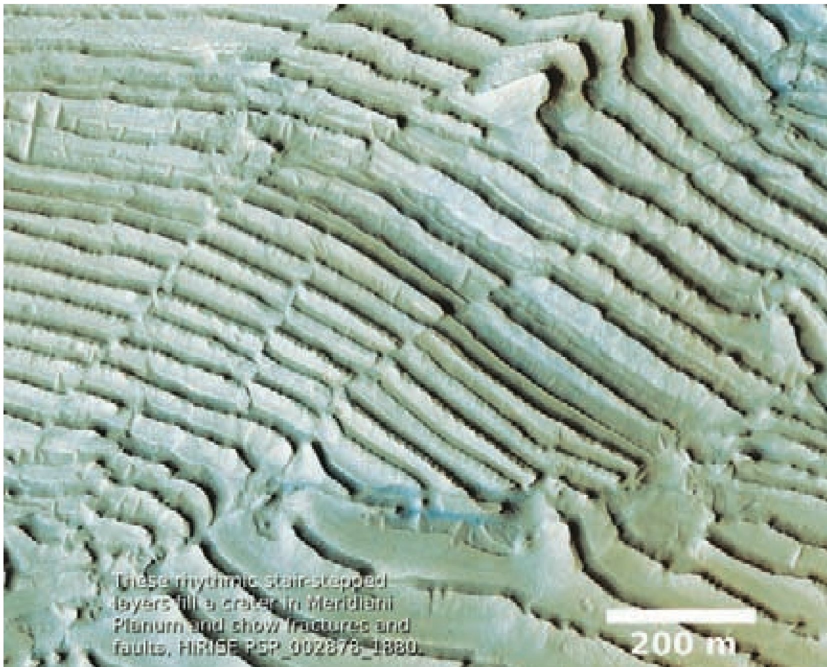
Well-stratified layered deposits have been observed on the plains surrounding Valles Marineris. One of the best examples is located on the plains west of Juventae Chasma, where stratified rocks (<1-m-thick beds) occur beneath preserved crater ejecta and inside inverted channels (Milliken et al. 2008, Weitz et al. 2010). Layers form narrow, sinuous laminations that are continuous for up to tens of kilometers. Hydroxylated ferric sulfate and hydrated silica (opaline silica) have been detected in the deposits (Milliken et al. 2008, Weitz et al. 2010). Several locations on the plains surrounding Valles Marineris also expose layers exhibiting a similar composition and style of stratification to those near Juventae Chasma, including plains around the Louros Valles south of Ius Chasma, Melas Chasma, Candor Chasma, and Ganges Chasma (see Le Deit et al. 2008, Milliken et al. 2008, Weitz et al. 2010). These units are thought to be Late Hesperian in age or younger.



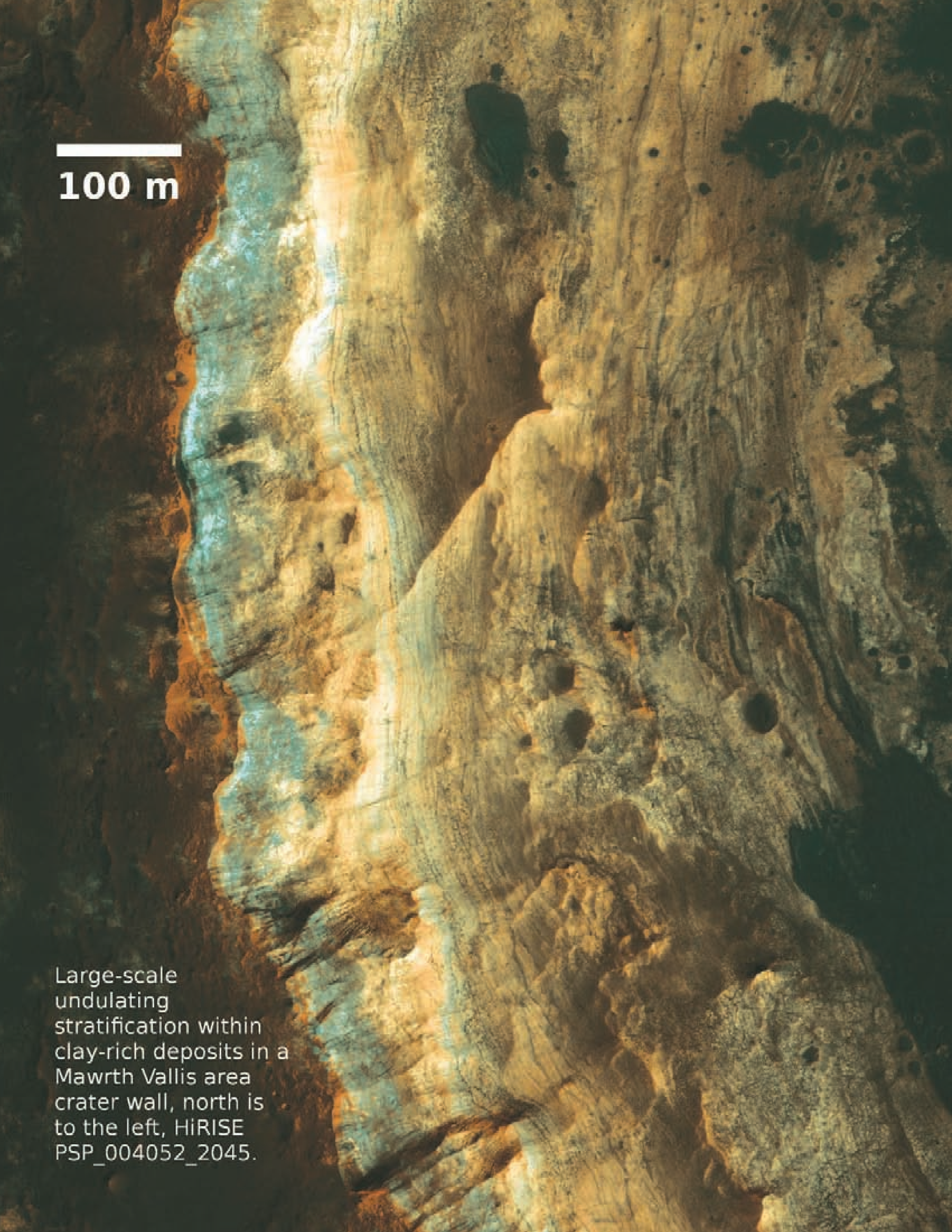




Meridiani Planum is an equatorial region with abundant sedimentary rocks that blanket several hundred thousand square kilometers of the Martian surface. It has a rich diversity of distinct stratigraphic units and mineralogy formed during the Late Noachian to Early Hesperian as mapped by CRISM and OMEGA (Wiseman et al. 2010). The sediments here show evidence for an extensive aqueous history that evolved over time, including deposition, alteration, and repeated erosion. The *Opportunity* rover (Squyres et al. 2004) is currently studying the top of a stratigraphic section (Burns formation) that is composed of dominantly eolian sulfate-rich sandstones, locally reworked by fluvial processes, that were diagenetically altered by groundwater brines (Grotzinger et al. 2005, Edgar et al. this volume, Lamb et al. this volume).

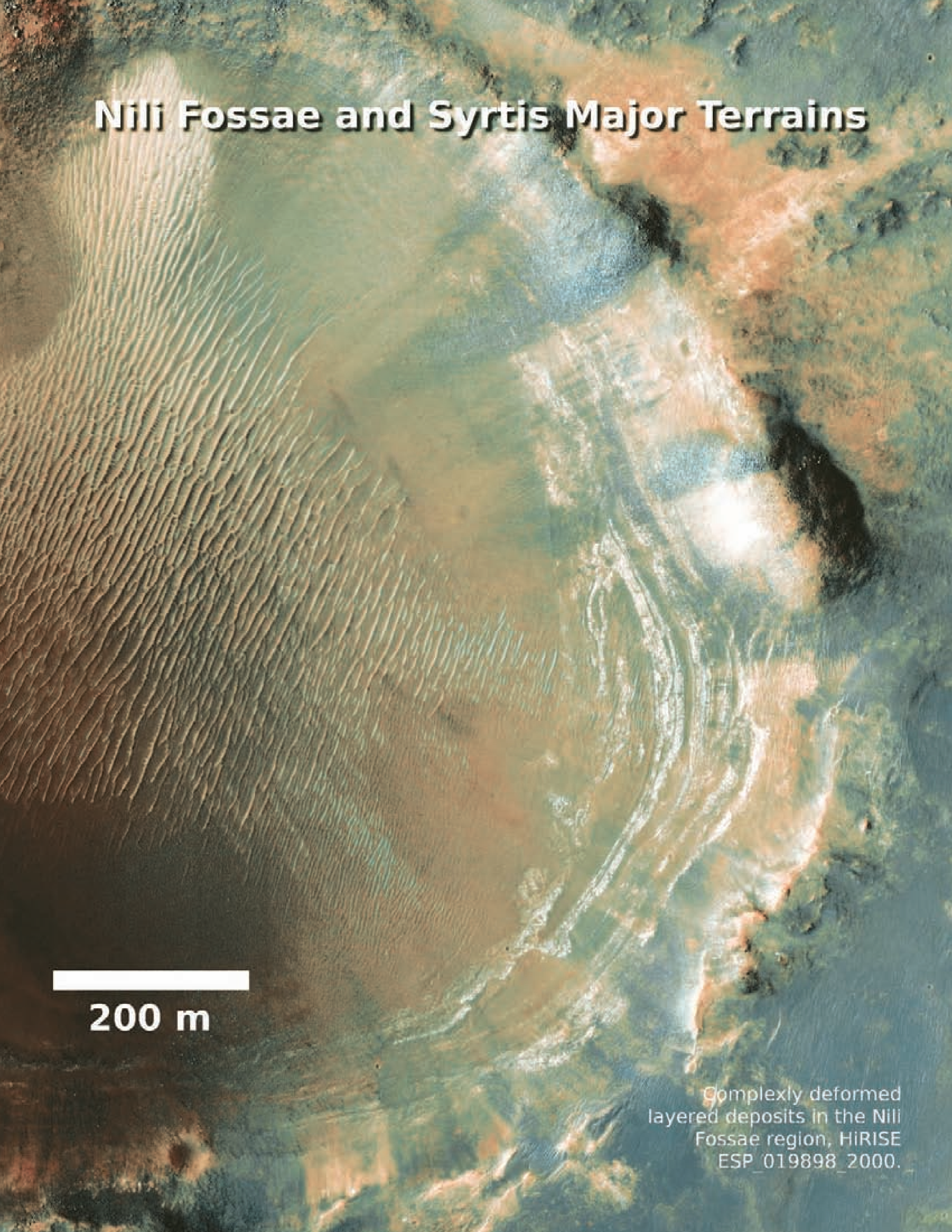


Mawrth Vallis, an ancient outflow channel located at the transition between the Southern Highlands and the Northern Lowlands, is localized within some of the oldest Noachian-aged layered deposits on the planet. Flat plains adjacent to Mawrth Vallis expose Fe, Mg, and Al clay-rich strata covering over 100,000 square kilometers (Poulet et al. 2005, Michalski and Noe Dobrea 2007, Loizeau et al. 2007, Bishop et al. 2008). These rocks are exposed as irregularly shaped and eroded mounds and scarps. While there are a number of depositional interpretations for the layered deposits, including altered volcaniclastic sediments or a lacustrine origin, impact processes likely played an important role in the formation, transport, and distribution of sediments in this location.

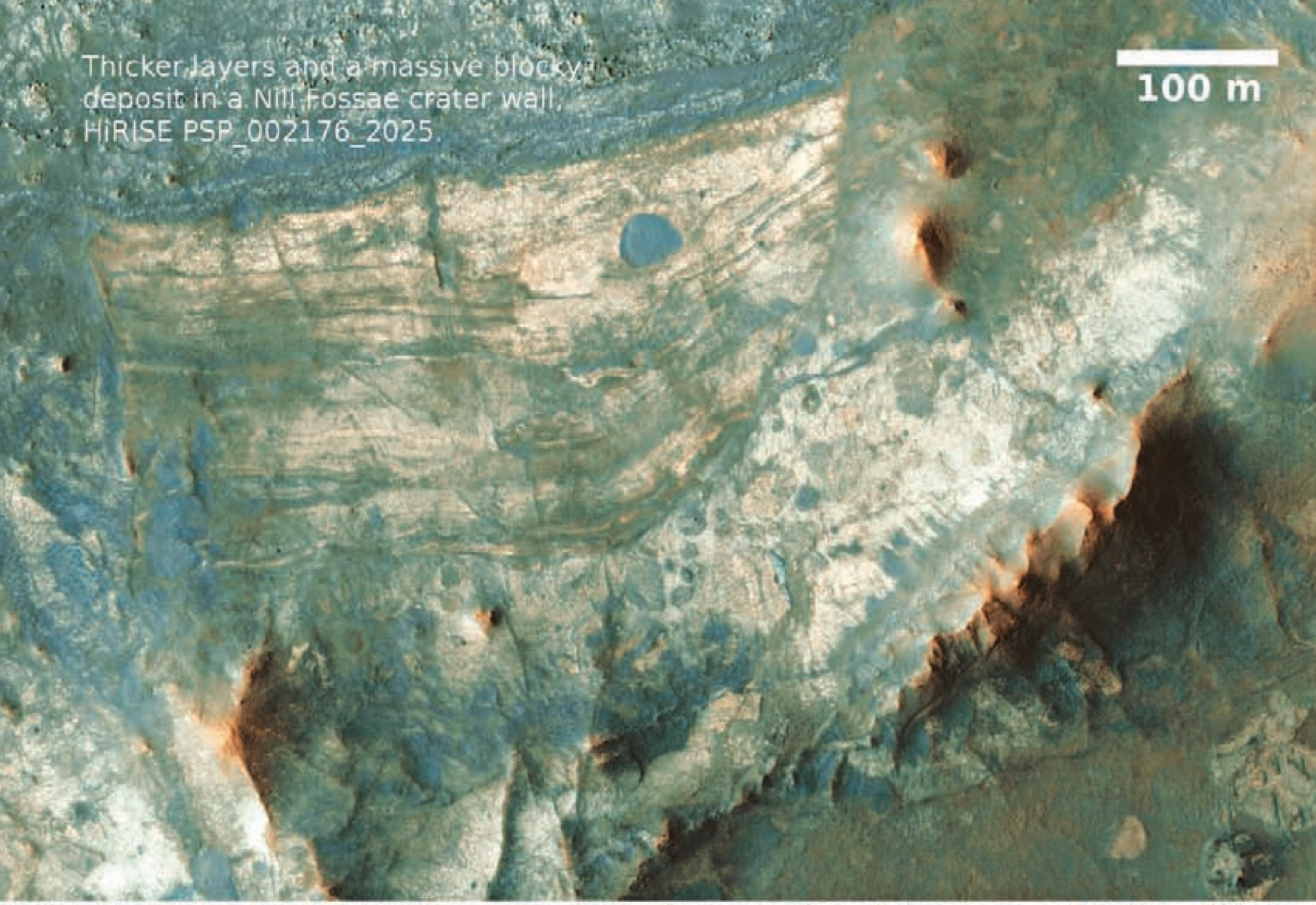


Large-scale undulating stratification within clay-rich deposits in a Mawrth Vallis area crater wall, north is to the left, HiRISE PSP_004052_2045.

Nili Fossae and Syrtis Major Terrains

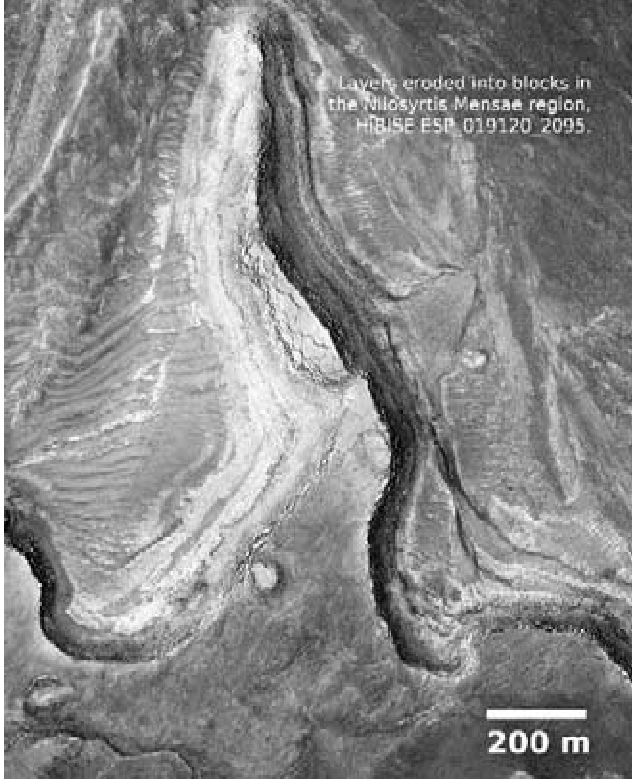


Complexly deformed layered deposits in the Nili Fossae region, HiRISE ESP_019898_2000.

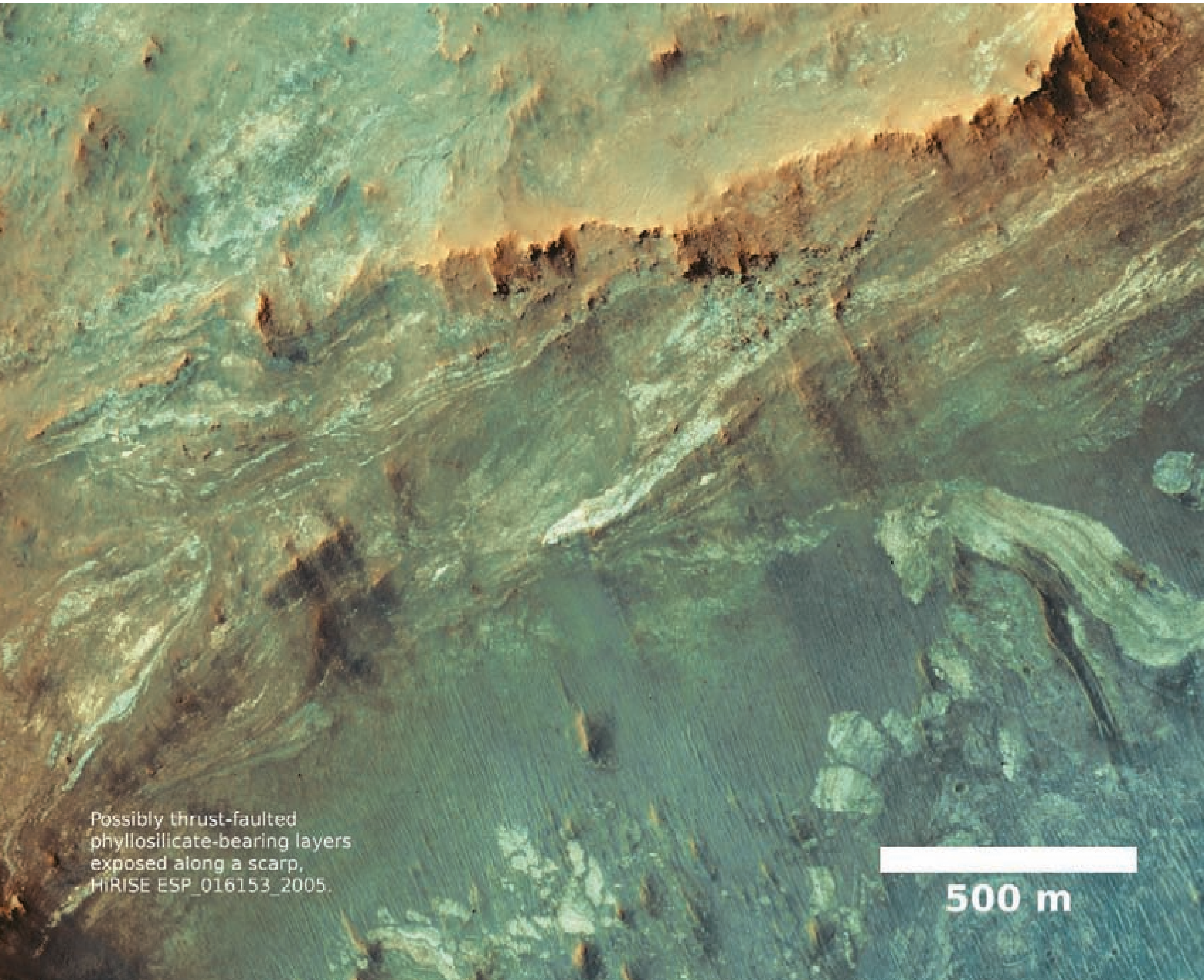

Thicker layers and a massive blocky deposit in a Nili Fossae crater wall, HiRISE PSP_002176_2025.
100 m


Strata NW of Nili Fossae, HiRISE PSP_009626_2020.
200 m

The Nili Fossae and Syrtis Major regions of Mars are on the northwest edge of the large Isidis impact basin. The former are large, concentric grabens that likely formed by tectonic readjustment after the Isidis impact event, whereas the latter are ancient Noachian terrains capped by younger Hesperian lava flows from the Syrtis Major volcanic system (Mangold et al. 2007, Mustard et al. 2007). The layered rocks in this region are among the oldest on Mars, likely dating back to >3.7 Ga. These rocks also host the greatest diversity of minerals observed on Mars, including Fe/Mg smectite, kaolinite, opaline silica, sulfates, carbonates, serpentine, prehnite, and zeolite (analcime) (Ehlmann et al. 2009). Layered deposits in this region have been interpreted as hydrothermally or fluvially altered mafic/ultramafic lava flows and impact breccia deposits, both of which likely comprise much of the ancient Noachian basement. In contrast, the overlying Hesperian-age lava flows likely represent low-temperature, near-surface aqueous alteration (Mustard and Ehlmann 2010). The origin and depositional environments of stratified rocks exposed within Nili Fossae are largely unknown, but their antiquity and mineralogical diversity indicate that aqueous processes were important and widespread on ancient Mars. Indeed, these rocks may provide some of the best examples of altered primary crust that has survived the Late Heavy Bombardment.

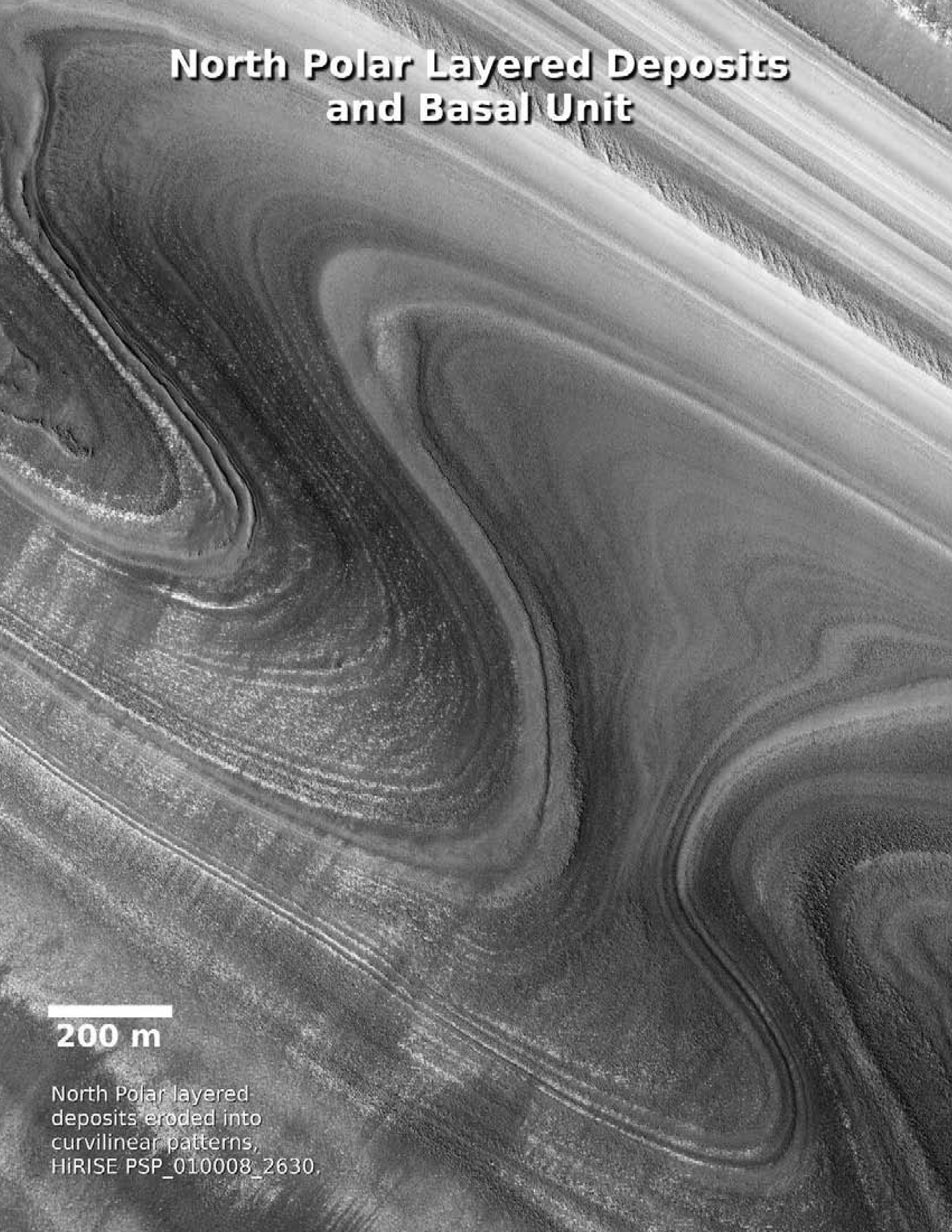


Layers eroded into blocks in the Nilosyrtis Mensae region, HiRISE ESP_019120_2095.



Possibly thrust-faulted phyllosilicate-bearing layers exposed along a scarp, HiRISE ESP_016153_2005.

North Polar Layered Deposits and Basal Unit

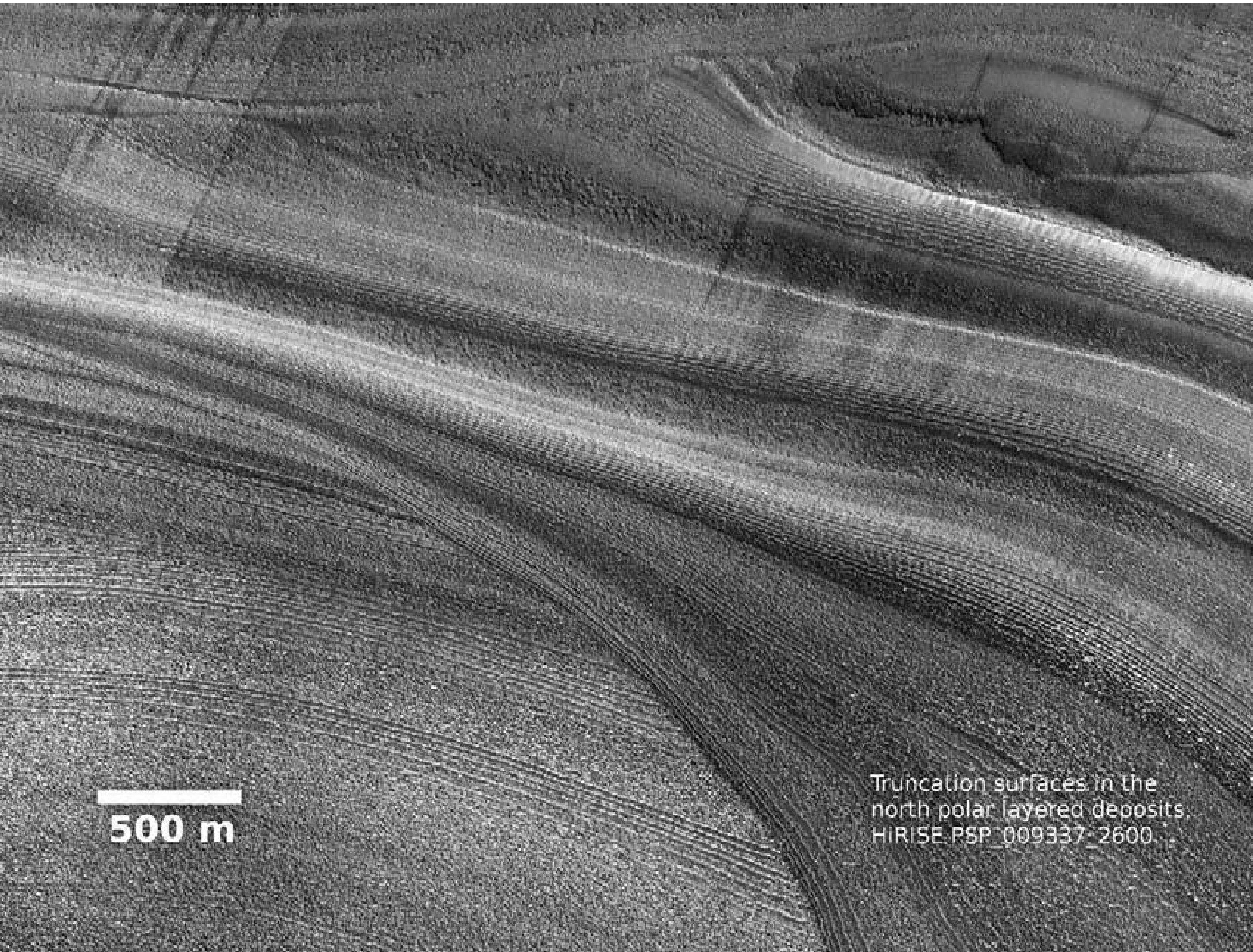


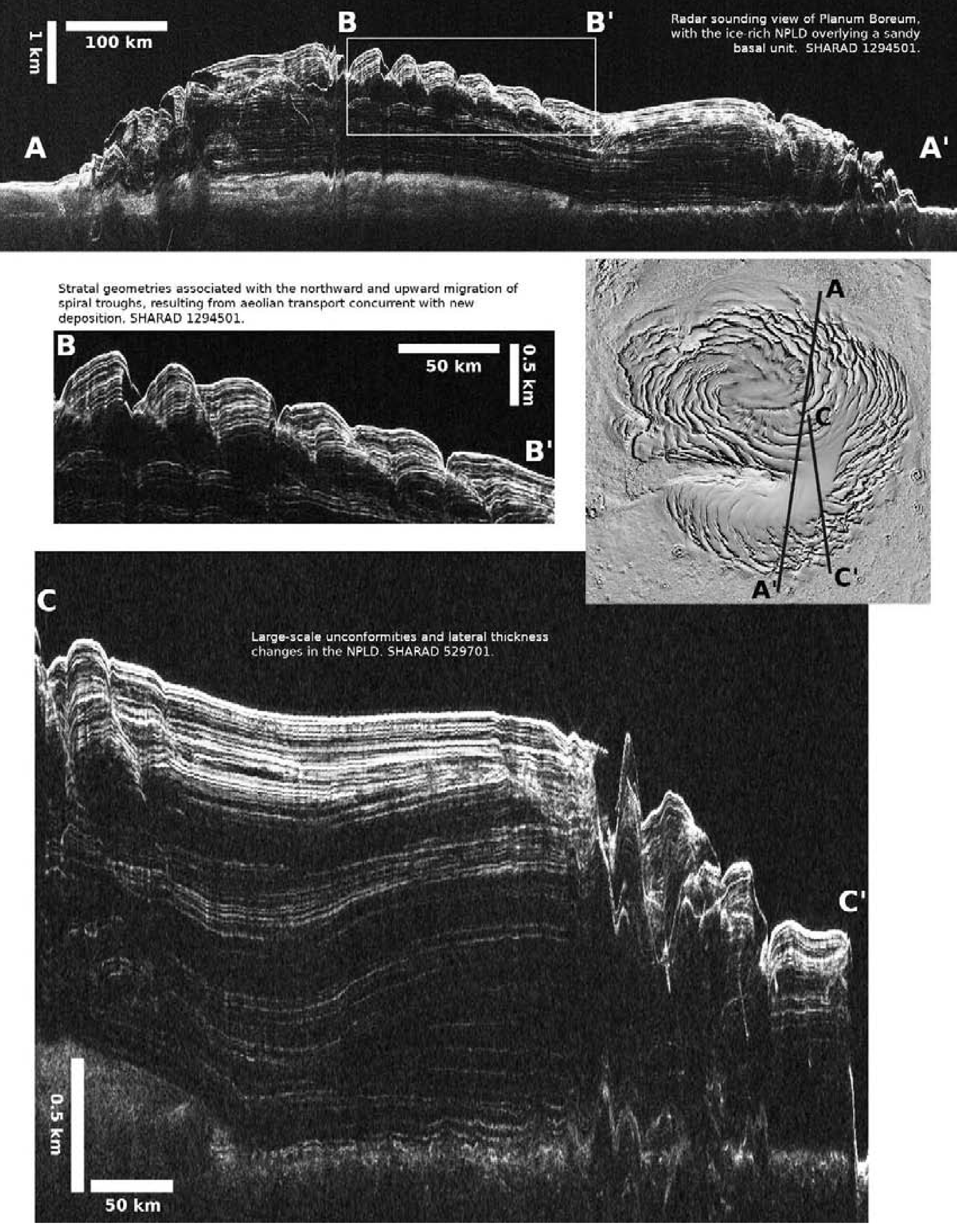
North Polar layered deposits eroded into curvilinear patterns, HiRISE PSP_010008_2630.


100 m
Dune-scale cross-stratification or clinoforms within the north polar basal cavi unit, HiRISE PSP_001334_2645.


200 m
Undulating dune-forms in north polar basal unit, HiRISE ESP_019047_2640.

The north polar layered deposits (NPLDs) form an ~3-km-thick stack of young strata exposed in the walls of troughs and scarps in the north polar regions of Mars (Byrne 2009). The NPLDs are composed primarily of water-ice, based on radar penetration to their base, and are thought to record recent climate variations. Craters are sparse, but their population statistics suggest ongoing deposition over the past few thousands of years. Layers of the NPLD are laterally continuous over scales of hundreds of kilometers, and they exhibit variable brightness, roughness, and slope where exposed. The thinnest layers detected by HiRISE are ~10 cm, but most observable layers are of meter-scale thickness (Fishbaugh et al. 2010). Morphological differences between the lower and upper layers within the NPLDs have been identified; the lower layers are steeply exposed and exhibit extensive polygonal fracturing, while upper layers are often exposed in troughs with gentle slopes, and lack polygonal fracturing (Herkenhoff et al. 2007). Radar reflectors within the NPLDs identified from orbit are generally subhorizontal and exhibit vertical variations in brightness, resulting in distinct packets (Philips et al. 2008). Radar-layer unconformities and lateral thickness changes have been observed and indicate accumulation rates that vary in both space and time, including the early formation of two accumulation centers that later partially merged (Holt et al. 2010). Radar stratigraphy also indicates the more recent, constructional formation of large-scale spiral troughs and ridges within the NPLDs via deposition concurrent with eolian transport (Smith and Holt 2010). One of two basal units identified beneath the NPLDs (Byrne and Murray 2002, Fishbaugh and Head 2005, Tanaka et al. 2008) appears to have alternating layers of ice and sand-sized material organized into successions dominated by low-angle clinoforms. Erosion of this unit supplies sand-sized material to the current circumpolar sand sea. Langevin et al. (2005) found that calcium-rich sulfates (gypsum) comprised a minor constituent of the dune material. The gypsum is concentrated at 240°E, decreases slowly to the west, and locally appears most abundant at dune crests (Roach et al. 2007). Hydrous alteration of material comprising the dunes (Fishbaugh et al. 2007) or within dikes radiating from Alba Patera (Tanaka 2006) has been suggested as a possible source; however, CRISM data show that trace amounts of gypsum also exist within the NPLDs and are concentrated as a sublimation lag in places before being transported to the dunes (Massé et al. 2010). Thus, where, when, and how this mineral formed remain unknown.





Radar sounding view of Planum Boreum, with the ice-rich NPLD overlying a sandy basal unit. SHARAD 1294501.

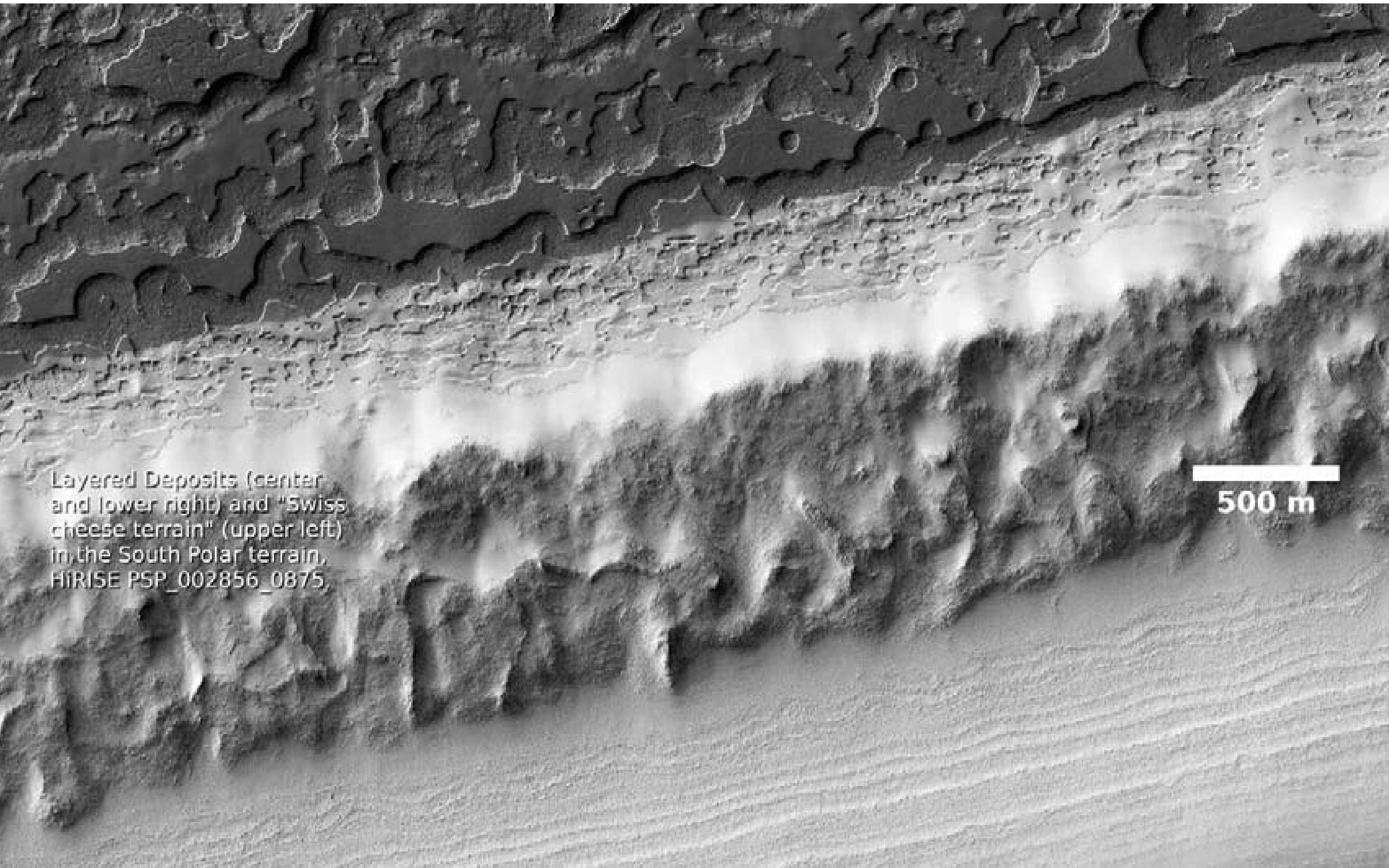
Stratal geometries associated with the northward and upward migration of spiral troughs, resulting from aeolian transport concurrent with new deposition. SHARAD 1294501.

Large-scale unconformities and lateral thickness changes in the NPLD. SHARAD 529701.

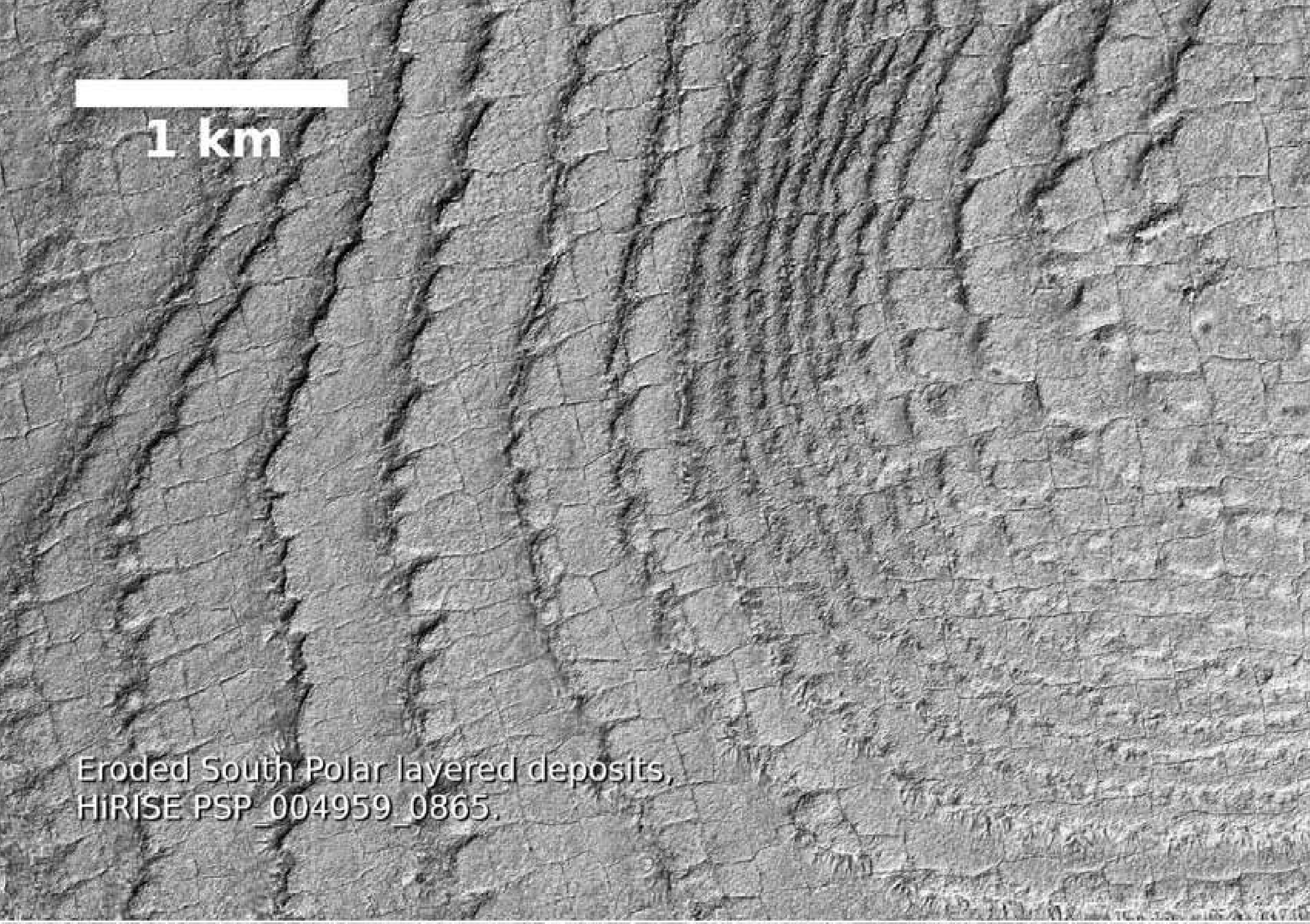
South Polar Layered Deposits

Folded and faulted layers in the South Polar layered deposits. HiRISE PSP_004708_1000.

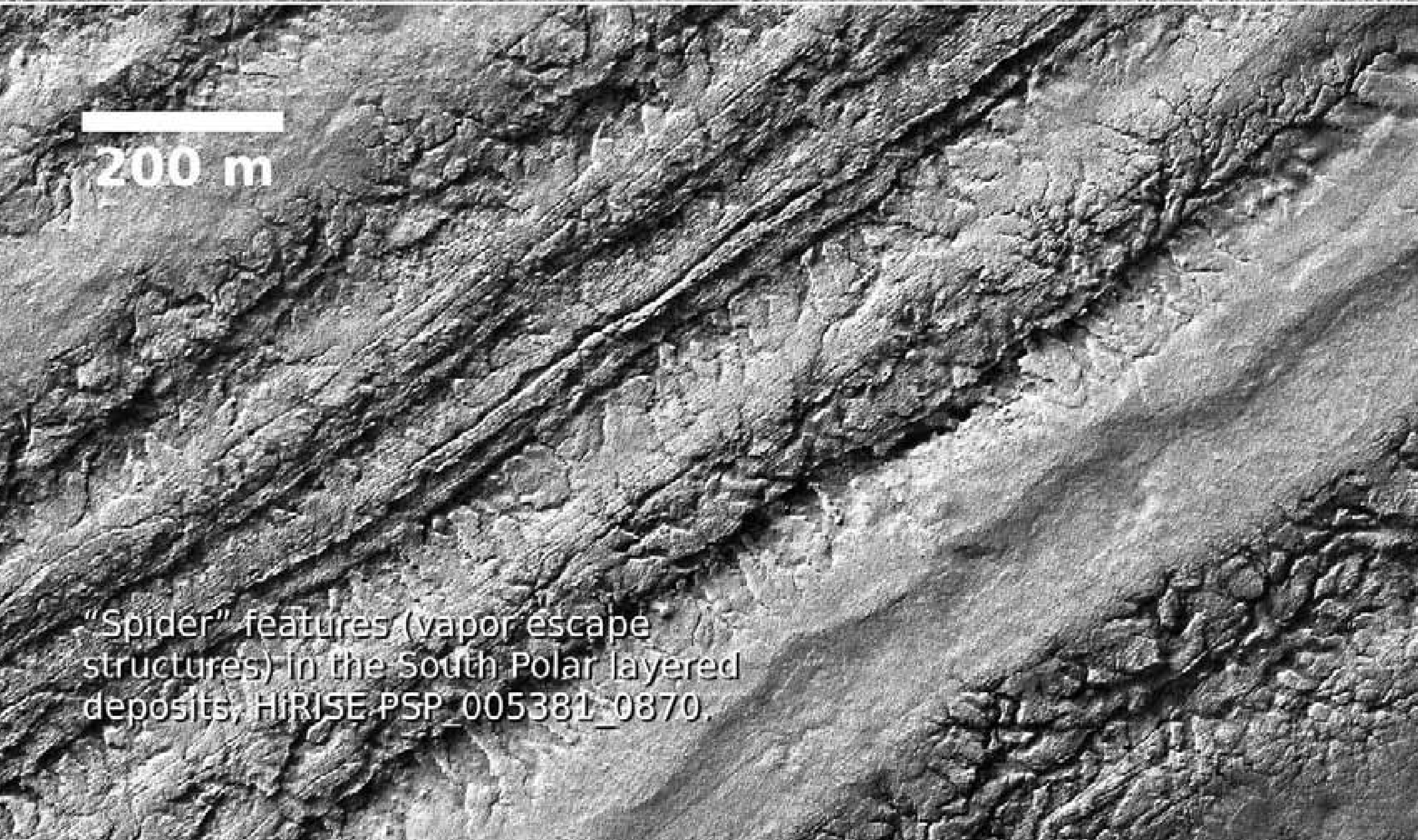
The south polar layered deposits (SPLDs) form a stack of strata up to 3 km thick observed in the walls of troughs and scarps in the south polar regions (e.g., Chasma Australe, Promethei Chasma, Ultimum Chasma; Byrne 2009). The SPLDs are composed of varying amounts of water-ice and dust, with gravity data indicating concentrations of the latter at ~15%. Impact craters are more common on the SPLDs, indicating that their surface is older than the surface of the NPLDs, with age estimates ranging from 30–100 Ma. The SPLDs have been broken out into three main units, although each of these units may be subdivided into rhythmic strata formed of smaller-scale bedding. The smallest-scale bedding observed in the SPLDs is typically thicker as compared to the NPLDs, and subsurface relationships are less evident in orbiter-based radar observations of the SPLDs. However, it is likely that the SPLDs also record climate variations on Mars (Byrne 2009). Orbiter-based surface-penetrating radar data reveal pervasive volume scattering that obscures layering in many locations and that may be due to fracturing at the scale of the radar wavelength. The surface of the SPLDs appears to be a low-thermal-inertia material consistent with a dust lag.



Layered Deposits (center and lower right) and "Swiss cheese terrain" (upper left) in the South Polar terrain, HiRISE PSP_002856_0875.



Eroded South Polar layered deposits,
HiRISE PSP_004959_0865.



"Spider" features (vapor escape
structures) in the South Polar layered
deposits, HiRISE PSP_005381_0870.

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