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1      **TAFFY PULL AND ASSOCIATES: REVIEW AND NEW**  
2      **OBSERVATIONS OF NORTHWESTERN HELLAS**  
3      **PLANITIA**  
4

5      H. Bernhardt, D. Reiss, M. Ivanov, E. Hauber, H. Hiesinger, J. D. Clark, R. Orosei

7      **Abstract**

8      Northwestern Hellas Planitia hosts landforms that are unique on Mars, e.g., the so called  
9      honeycomb and banded (aka “taffy pull”) terrains. Recently, robust formation models for the  
10     ~6 km large honeycomb depressions involving salt or ice diapirism have been formulated.  
11     However, the nature of the banded terrain, a ~30,000 km<sup>2</sup> area characterized by a dm- to km-  
12     scale pattern of curvilinear troughs, has remained elusive. While previous interpretations range  
13     from deep-seated, honeycomb-related outcrops to a younger veneer, recent reports of putative  
14     periglacial features (e.g., potential thermokarst) strongly indicate it to be a relatively thin,  
15     volatile-related surface unit. In order to further constrain the origin and nature of the banded  
16     terrain, we investigated the northwestern Hellas basin floor employing various datasets.  
17     Although neither CRISM nor MARSIS/SHARAD revealed any clear signatures on and beneath  
18     the area, we used a purpose-built CTX mosaic to produce a 1:175,000 morphologic map to  
19     comprehensively characterize the banded terrain in great detail. We mapped the banded  
20     terrain’s extent at high precision, showing that it partially superposes the honeycomb terrain,  
21     likely resulting in certain superposition features, but also occurs up to ~240 km away from it.  
22     Via stratigraphic analyses and crater size-frequency measurements, we bracketed the age of the  
23     banded terrain between ~2.2 and ~3.3 Ga. Furthermore, the banded terrain can be differentiated  
24     into two types, ridged and creviced, with the former predominantly occurring among the lowest

reaches of the terrain's ~2 km topographic extent. We also produced a grid map (2x2 km box size) of the entire banded terrain in order to assess the relation between band shape and local topography. As we identified no large-scale (> 25 km) band pattern and no correlation between local slope and band orientation, regional tectonics or gravity-driven flow down modern topography are unlikely to have played decisive roles for banded terrain formation. Instead, we observed numerous locations, where band slabs appear to have broken off and subsequently rotated, as well as "cusps" that seem to have resulted from buckling. Based on this, we suggest that the banded terrain experienced both, ductile deformation as well as brittle failure on or near the surface. Following this assessment, we investigated formation scenarios involving low viscosity materials, namely salt, lava, and ice/ice-rich/wet layers based on terrestrial analogy. Despite certain similarities, neither salt (as salt glaciers), lava sheets, nor land-based glaciers are in agreement with the extensive curvilinear texture and topographic/geologic setting of the banded terrain. Ice shelf margins, on the other hand, can produce surface textures akin to the banded terrain in both form and scale, even including cusps and broken off, rotated blocks. However, an ice-covered sea between 2.2 and 3.3 Ga ago is not supported by the geologic inventory of the Hellas basin, which previous investigations found to lack any landforms indicative of a standing body of water. Instead, we identified several sinuous ridges terminating at plains covered by smaller, braiding ridges, which we interpret as eskers and glacial sandurs, respectively. As both are embayed and partially covered by the banded terrain, we tentatively propose an alternative model of the banded terrain having formed as wet till that was viscously deformed according to the stress fields created by the ice overburden pressure in conjunction with bed topography. Although this formation model remains inconclusive, it is in agreement with climate models suggesting obliquity excursions and a denser, early Amazonian atmosphere to have caused ice accumulation in the adjacent northwestern Hellas basin rim, thus potentially enabling flow onto the floor entailing subglacial banded terrain formation.

50     **1. Introduction**

51       The northwestern Hellas basin floor on Mars hosts a highly complex landscape containing  
52       several unique landforms in close geographic association, e.g., the “honeycomb” and “banded”  
53       (or “taffy pull”) terrains (e.g., *Diot et al.*, 2015a; *Bernhardt et al.*, 2016a; *Voelker et al.*, 2017).  
54       Both of these terrains have been subject to a wide range of conflicting interpretations with  
55       profoundly different implications (*Moore and Wilhelms*, 2001, 2007; *Mangold and Allemand*,  
56       2003; *Kite et al.*, 2009; *Diot et al.*, 2015a,b; *Bernhardt et al.*, 2016b). One detriment for  
57       investigations is the physiographic setting of the area within Mars’ largest and deepest  
58       topographically well-defined impact basin (e.g., *Andrews-Hanna and Zuber*, 2010), resulting  
59       in remote sensing observations often being compromised by atmospheric opacity and a high  
60       surface dust abundance amongst others (*Ruff and Christensen*, 2002; *Basu et al.*, 2004). This  
61       caused previous studies of the western Hellas basin floor to focus exclusively on specific  
62       landform types and/or to rely on comprehensive low-resolution datasets and only selective high-  
63       resolution observations (e.g., *Moore and Wilhelms*, 2007; *Diot et al.*, 2015a,b; *Bernhardt et al.*,  
64       2016a,b; *Voelker et al.*, 2017). Nevertheless, these studies yielded crucial insights and  
65       concluded the honeycomb terrain to be the surface expression of diapirs, possibly of salt or ice  
66       (*Bernhardt et al.*, 2016b; *Weiss and Head*, 2017), and the banded terrain to be some form of  
67       volatile-rich veneer (*Diot et al.*, 2014, 2015a). However, profound ambiguities remain that  
68       greatly limit our understanding of these enigmatic landforms, their role in the history of water  
69       in the Hellas region, and the resulting implications for the climatic evolution of Mars.

70       By assembling a comprehensive, high-resolution morphologic map (on a purpose-built,  
71       seamless Context Camera mosaic), as well as a fine-scale grid mapping and further analyses  
72       based on all available datasets (including radar and hyperspectral), this investigation provides  
73       a refined assessment of northwestern Hellas Planitia with the aim of shedding more light on its  
74       enigmatic landforms.

75      **2. Physiographic and geologic setting**

76      The study area covers an ~670 x ~445 km large portion of northwestern Hellas Planitia  
77      ([Fig. 1A](#)), the floor of the deepest and largest (~1700 x ~1300 km) topographically well-defined  
78      impact basin on Mars (e.g., *Wood and Head, 1976; Andrews-Hanna and Zuber, 2010*). The  
79      study area was defined to encompass the honeycomb and banded terrains as mapped by  
80      *Bernhardt et al. (2016b)*, who also provided detailed descriptions of the basin's general  
81      physiography and geology. To the north, the study area reaches into central Peneus Palus, a  
82      wrinkle-ridged plain hosting the deepest area of the Hellas basin containing the lowest point on  
83      Mars at -8204 m (within Badwater crater ~65 m northeast of the study area's extent) (*Bernhardt*  
84      *et al., 2016a*). Displaying a high kilometer-scale roughness, Peneus Palus is partially covered  
85      by prominent ejecta, e.g., around Kufstein crater, but also by weakly consolidated materials  
86      similar to those of the hummocky basin center (*Bernhardt et al., 2016a*). Peneus Palus lies at  
87      an average elevation of ~ -7,500 m and forms the northern half of an annular, ~1,500 km long,  
88      and up to ~330 km wide depression along the western Hellas basin floor outline previously  
89      called "Hellas Planitia trough" (HPT; *Howard et al., 2012*). The western edge of the study area  
90      roughly follows the HPT, whose average elevation rises to ~ -6,800 m in its southern half, where  
91      its floor is characterized by a high 1 – 10 kilometer-scale roughness. The center portion of the  
92      floor of the HPT is dissected by a basin rim-parallel chain of ~20 – 77 km long, ~11 – 33 km  
93      wide, and up to ~200 m deep, irregularly-shaped depressions. To the east, the HPT is bound by  
94      a ~600 – ~1,000 m high scarp leading up to a central, hummocky portion of the basin previously  
95      referred to as "Alpheus Colles plateau" (*Moore and Wilhelms, 2001*). The study area  
96      encompasses the westernmost reaches of this more elevated, hummocky region, which is  
97      characterized by a high, 10 – 20 kilometer-scale roughness and includes Beloha crater ( $\varnothing \sim 27$   
98      km) as well as a nameless, highly degraded crater ( $\varnothing \sim 90$  km) ~160 km southwest of it.

99     **3. State of research**

100       **Banded terrain:** After the Mars Orbiter Near Angle Camera (MOC-NA) first revealed the  
101       texture of the banded terrain, it was interpreted as sediment layers that were viscously deformed  
102       by icebergs floating on a receding Hellas sea, thereby leaving behind the honeycombs as  
103       imprints (*Moore and Wilhelms, 2001*). Later investigations maintained a genetic link between  
104       the banded and honeycomb terrains, but interpreted the observed textures to suggest multiple  
105       overturns caused by convective processes, e.g., diapirism (*Mangold and Allemand, 2003; Kite*  
106       *et al., 2009*). Despite the banded terrain's textural similarity to halokinetic sequences (layers  
107       viscously deformed by salt tectonics; e.g., *Jackson et al., 1990; Wilson et al., 2010; Bernhardt*  
108       *et al., 2016b*), batholithic diapirism (*Mangold and Allemand., 2003*) and impact melt  
109       convection (*Kite et al., 2009*) were tentatively favored over salt diapirism as formation  
110       scenarios for the honeycomb-banded terrain assemblage.

111       After *Thomas et al. (2010)* first differentiated between the honeycomb and banded terrains,  
112       *Diot et al. (2013)*, outlined the banded terrain's approximate extent and noted that, despite a  
113       close geographic association, its textures can occur separately from the honeycomb depressions.  
114       This crucial observation was followed by several investigations suggesting the banded terrain  
115       to be a relatively thin, volatile-rich surface layer that is unlikely to be genetically related to the  
116       honeycomb terrain (*Diot et al., 2014, 2015a,b*). *Diot et al. (2014)* modelled the banded terrain's  
117       crater retention age to be ~3 Ga and made several important observations, noting the presence  
118       of thermokarst-like depressions, patterned ground, pit chains, pingo-like fractured mounds, as  
119       well as individual "bands" transitioning into textures similar to other martian landforms likely  
120       resulting from periglacial processes, e.g., the brain terrain (*Levy et al., 2009*). It was also  
121       inferred that, in an ice-flow scenario, the banded terrain's average slopes of ~6° and band  
122       depths, i.e., assumed thickness, of ~12 to ~30 m could produce basal stresses of up to ~28 kPa  
123       (*Diot et al., 2014*). As this is close to the minimum value of ~30 kPa calculated for martian

lobate debris aprons/viscous flow features (VFF; *Mangold and Allemand, 2001*), a formation involving downslope creep was deemed conceivable (*Diot et al., 2014*). Furthermore, *Diot et al. (2015a)* suggested that the orientation and geometry of some selected bands appear to be a result of viscous flow across the surface, although this assessment was not based on a comprehensive, statistical analysis. Likening them to glacial crevasses, several locations were pointed out, where the bands are perpendicular to the local slope, often forming tongue-like arrangements with notable deviations mostly occurring where there are interferences between adjacent bands (*Diot et al., 2015a*). Additionally, *Bernhardt et al. (2016b)* observed apparent “slabs” detaching from a banded terrain zone of turbulent texture as well as band-perpendicular, meter-scale furrows that are much more reminiscent of glacial crevasses than the actual bands themselves and visible on almost all high-resolution images of the banded terrain. It was also pointed out that the small-scale morphology of the banded terrain (smooth surface dissected by curvilinear, crevice-like troughs) is different from that of halokinetic sequences sometimes found around terrestrial salt diapirs. While halokinetic, curvilinear patterns are reminiscent of the banded terrain, they are, in fact the result of ridges formed by steeply dipping layers of different erosion resistances and not crevice-like troughs (*Jackson et al., 1990; Bernhardt et al., 2016b*).

**Honeycomb terrain:** The honeycomb terrain was first identified as “reticulate floor unit” and interpreted as differentially eroded Amazonian mantle material, possibly of eolian origin (*Greeley and Guest, 1987*). A tentative eolian interpretation, albeit as compound crescentic dunes, was maintained (*Tanaka and Leonard, 1995; Leonard and Tanaka, 2001*) until high resolution MOC-NA images revealed the honeycombs’ and banded terrain’s details, leading to both landforms being interpreted as a single unit that is the result of wet, viscous sediments having been imprinted by icebergs floating on a receding Hellas sea (*Moore and Wilhelms, 2001, 2007*). Later, observations of highly convoluted textures (wavelengths 10s of meters) within the banded terrain motivated an interpretation of the honeycombs as upwelling

150 structures, either due to “lower crust vertical tectonism”, i.e., batholithic diapirism (*Mangold and*  
151 *Allemand, 2003*), or impact melt convection (*Kite et al., 2009*). Although similarities to  
152 terrestrial salt provinces were noted, salt diapirism was not favored as formation model due to  
153 the large amount of required salt (*Kite et al., 2009*) and the lack of brittle deformation structures  
154 (*Mangold and Allemand, 2003*). However, it was later found that neither of these arguments  
155 prevent a salt scenario and that diapirism by salt, or alternatively ice, appears to be more likely  
156 than the alternative models, which face certain plausibility issues and/or whose analogs in  
157 nature, if existent at all, bear little similarities to the honeycombs (*Diot et al., 2015b; Bernhardt*  
158 *et al., 2016b*). Mostly depending on the weight of overburden, physical models of diapirism  
159 suggest that the spacing, size, and extent of the honeycombs would have required either ~22,000  
160 to 130,000 km<sup>3</sup> of salt, or ~3,600 to 112,000 km<sup>3</sup> of ice (*Bernhardt et al., 2016b; Weiss and*  
161 *Head, 2017*). As the adjacent wrinkle ridged plains were found to partially superpose it, a  
162 Noachian age (>3.8 Ga) is implied for the honeycomb terrain, whose very low crater density  
163 was interpreted as a result of relatively recent excavation, likely by deflation (*Bernhardt et al.*,  
164 *2016b*). The morphometry and potential volume of the honeycomb terrain was found to be  
165 similar to terrestrial salt provinces, e.g., the Great Kavir in Iran or the Gulf of Mexico  
166 (*Bernhardt et al., 2016b*), and numerous channels leading into the Hellas basin might have  
167 supplied potentially salty water from the adjacent, chloride-bearing highlands (*Osterloo et al.*,  
168 *2008, 2010; Bernhardt et al., 2016a*). This underlines the viability of a salt diapirism scenario,  
169 thus implying climatic conditions during honeycomb formation in the Noachian that permitted  
170 at least episodic surface water runoff as well as subsequent evaporation and/or  
171 freezing/sublimation over extended time periods accumulating to no less than 3.5 m global  
172 equivalence layer (GEL) of salt-saturated water (*Bernhardt et al., 2016b*). *Weiss and Head*  
173 (*2017*) on the other hand emphasized the more modest prerequisites of an ice diapirism  
174 scenario, which would require no liquid water and only ~0.05 to ~0.5 m GEL worth of ice.  
175 Furthermore, preliminary model results indicate that in a denser atmosphere and with higher

176 obliquities (e.g., 600 mbar CO<sub>2</sub> and 45°), ice could have accumulated around the Hellas basin  
177 and subsequently flowed onto its floor before being buried by later deposits (*Fastook et al.*,  
178 2017). At this point, both salt as well as ice diapirism remain viable formation mechanisms for  
179 the honeycomb terrain, albeit with drastically different climatic implications.

180       **Other landforms:** The first Viking-based map covering the area characterized  
181 northwestern Hellas Planitia as transition zone between the higher-standing deposits in the basin  
182 interior and a smoother peripheral zone, now identified as HPT (*Peterson, 1977*). Due to the  
183 relatively small volume of material eroded from the then known channels leading into the Hellas  
184 basin and the apparent friability of the interior deposits, later investigations interpreted them as  
185 well as the HPT floor as different erosional states of mainly eolian materials superposing  
186 wrinkle-ridged lava plains (*Greeley and Guest, 1987; Tanaka and Leonard, 1995; Leonard and*  
187 *Tanaka, 2001*). Contrasting this, a mainly glacial origin of many landforms in our study area  
188 was emphasized by *Kargel and Strom (1992)*. They proposed a Noachian glacier entering the  
189 Hellas basin from the south, interpreted several wrinkle ridges as well as elongate erosional  
190 remnants in the HPT as terminal moraines, and knobs within the interior deposits as drumlins.  
191 In order to explain the honeycomb terrain as iceberg imprints, *Moore and Wilhelms (2001,*  
192 *2007)* then suggested a large-scale glacio-fluvial scenario, in which an ice-covered sea filled  
193 the Hellas basin up to ~ -3,100 m. The interior deposits (called “Alpheus Colles plateau”) were  
194 proposed to be sediments of that sea, whereas 100s of meters to few kilometers wide and up to  
195 ~100 km long, sinuous ridges perpendicular to the scarp delimiting the interior deposits to the  
196 southwest were tentatively interpreted as eskers laid down by meltwater beneath an ice-rich  
197 overburden after the Hellas sea had completely frozen (*Moore and Wilhelms; 2001, 2007*).  
198 However, comprehensive studies of the Hellas basin floor based on post-Viking datasets  
199 showed the morphometries and detailed morphologies of the honeycombs, as well as the afore  
200 mentioned wrinkle ridges and knobs to be unsuited for their respective glacial interpretations  
201 (*Wilson et al., 2010; Diot et al., 2015a; Bernhardt et al., 2016a*). Instead, *Greeley and Guest’s*

202 (1987) initial interpretation of the plains north of the honeycombs as tectonically modified (i.e.,  
203 wrinkle-ridged) volcanic deposits was largely affirmed, albeit with a Noachian model age (~3.8  
204 Ga) and variable overlay by remnants of the hummocky interior deposits, for which a Hesperian  
205 model age (~3.7 Ga) was derived (*Bernhardt et al., 2016a*). Hesperia as well as Malea Plana  
206 east and south of Hellas Planitia were identified as potential sources of the estimated  $\sim 10^6 \text{ km}^3$   
207 of initial Hellas interior deposits, as similarly-aged erosional landforms there suggest the  
208 removal and transport of that volume down to the basin, likely triggered by large-scale volcano-  
209 ice interactions (*Ivanov et al., 2005; Bernhardt et al., 2016a; Cassanelli and Head, 2016*).  
210 However, no clear morphological or textural indications for a past body of water or ice filling  
211 the Hellas basin, e.g., wide-scale layering or unambiguous shoreline-like terraces, have been  
212 found (*Bernhardt et al., 2016a*).

## 213 **4. Data and techniques**

214 The centerpiece of our investigation is a 1:175,000 morphologic map (Fig. 2A)  
215 encompassing an area of 159,856 km<sup>2</sup> between 50°E 33.4°S and 61.3°E 44.3°S on the  
216 northwestern Hellas basin floor. The mapping process was carried out on a purpose-built,  
217 seamless Context Camera (CTX; e.g., *Malin et al., 2007*) mosaic (Fig. 1B). For this mosaic,  
218 177 CTX images (~6 m/px) were co-registered and seamlessly stitched using Photoshop, after  
219 which we applied a high-pass filter at the average CTX swath width to reduce brightness  
220 variations along the individual image margins. For better manageability in ArcMap regarding  
221 the mosaic's large size, we reduced its resolution by 50% (i.e., to ~12 m/px) and then  
222 geographically aligned it to version 12 of the THEMIS-IR Day Global Mosaic (*Edwards et al.,*  
223 *2011*). Stereo CTX pairs were also used to create digital elevation models (DEMs) via the Ames  
224 Stereo Pipeline (e.g., *Moratto et al., 2010*) for local topographic analyses alongside the global  
225 DEM by the Mars Orbiter Laser Altimeter (MOLA; *Smith et al., 2001*). Local-scale  
226 observations including multi-temporal investigations were made using images by the High-

227 Resolution Imaging Science Experiment (HiRISE; 25–50 cm/px; *McEwen et al.*, 2007) as well  
228 as the Mars Orbiter Near-Angle Camera (MOC-NA; 1.4 to ~3 m/px; *Malin and Edgett*, 2010).  
229 Within this context, our investigation was greatly enhanced by the multi-temporal database of  
230 planetary image data (MUTED; *Heyer et al.*, 2017), which provided swift access to zoom- and  
231 scrollable, full-resolution MOC-NA as well as HiRISE data including highlighted areas of  
232 overlap within and beyond the designated mapping area. In order to assess the correlation  
233 between the banded terrain’s texture and the local slope, we also performed a CTX mosaic-  
234 based grid mapping covering its entire extent ([Fig. 3](#)). At a grid box size of 2x2 km, the banded  
235 terrain encompasses 9920 boxes, each of which was assigned to one of ten categories according  
236 to the general type (“creviced” or “ridged”) as well as five dominant orientations of the  
237 contained bands ([Fig. 4](#)): slope-perpendicular, slope-parallel, circular, lobate, and random. Also  
238 using our CTX mosaic, we conducted crater size-frequency distribution (CSFD) measurements  
239 on one of our morphologic units to derive an absolute model age via CraterStats (*Michael and*  
240 *Neukum*, 2010).

241 We supplemented our visual and morphologic analyses with nine full- as well as three half-  
242 resolution targeted (FRT and HRL/HRS) observations by the Compact Reconnaissance  
243 Imaging Spectrometer for Mars (CRISM; *Murchie et al.*, 2007). Using the CRISM Analysis  
244 Toolkit (CAT) version 7.3.1 for ENVI to apply photometric and atmospheric corrections  
245 (empirically determined “volcano scans”; *McGuire et al.*, 2009), we also employed revised  
246 spectral parameters by *Viviano-Beck et al.* (2014) to identify potential regions of interest whose  
247 spectra were then “ratioed”, i.e., divided by a nearby “spectrally bland” area, to reduce  
248 ubiquitous atmospheric effects.

249 In addition to our photogeological studies, we investigated the subsurface of the Hellas  
250 basin, e.g., to test diapiric (salt or ice) formation models for the honeycomb terrain. We  
251 analyzed radargrams of ground penetrating radar (GPR) tracks traversing our study area, five  
252 by the Mars Advanced Radar for Subsurface and Ionospheric Sounding (MARSIS; *Picardi et*

253 *al., 2004; Orosei et al., 2015*) as well as three by the Mars Shallow Radar Sounder (SHARAD;  
254 *Seu et al., 2007*). We combined observations by both GPRs in order to exploit MARSIS'  
255 superior penetration depth (>3.7 km in ice-rich material) as well as SHARAD's finer horizontal  
256 and vertical resolutions (0.3-1 km and ~15 m) (*Seu et al., 2007*). Measured and simulated  
257 radargrams by MARSIS were generated using the algorithm by *Nouvel et al. (2004)*  
258 implemented as described in *Cantini et al. (2014)*. Those of SHARAD were generated using  
259 the Colorado Shallow Radar Processing System (Co-SHARPS) by the Planetary Science  
260 Institute (*Putzig et al., 2016*). Each radargram was correlated with its simulated counterpart to  
261 prevent “clutter”, i.e., echoes from surface reflections, being mistaken for signals by potential  
262 subsurface reflectors.

## 263 **5. Descriptions and interpretations of morphologic units**

264 In this section we briefly describe all units of our morphologic map (in order of their  
265 stratigraphic positions) and offer interpretations for each unit group as shown in Fig. 2B. All  
266 mapped units, along with their type locality coordinates and areal extents, are listed in Table 1.  
267 Standardized pictures of each unit's type locality as seen in our CTX mosaic are shown in Fig.  
268 8. For a general photogeologic overview of the Hellas basin floor including this study's working  
269 area, as well as more in-depth descriptions and interpretations of units *Hih*, *Hik*, and *HNila*  
270 please see *Bernhardt et al. (2016a)*.

### 271 **5.1. Amazonian veneers**

272 **TARs** – Fields of up to few 10s of meters wide “transverse aeolian ridges” (*Bourke et al.,  
273 2003*). Often occur within local depressions. Orientations are variable, with dune fields on the  
274 floor of the HPT occurring perpendicular as well as parallel with respect to the HPT's  
275 topographic outlines. Within some occurrences, dunes tend to bend towards topographic  
276 obstacles.

277 **Scalloped** – Fields of rimless, often elongate, and shallow depressions with diameters

278 between few 10s of meters and ~6.6 km. Occur mostly within craters > ~2 km diameter, but  
279 also within other local depressions. Orientations vary, but steepest slopes tend to occur on the  
280 northwestern inner walls. Often associated with *smooth* terrain.

281        ***Skeleton terrain*** – Relatively small patches of terrain characterized by 10s of meters to few  
282 100s of meter large enclosures formed by irregularly shaped ridges. Mostly occurring within  
283 craters < 10 km diameter; often associated with *scalloped* terrain or *concentric crater fill*.

284        ***Concentric crater fill*** – Terrain exclusively occurring within craters and characterized by  
285 crater-concentric, often lobate lineations often manifested by small, meter-scale ridges.  
286 Average spacing of lineations is 50-100 m. Often associated with *scalloped* and *brain terrains*.

287        ***Brain terrain*** – Rough terrain characterized by up to 10s of meters wide knobs often  
288 forming a brain or coral-like texture. Mostly occurring within local topographic lows, e.g.,  
289 between the hills of the hummocky interior formation. Often associated with *smooth* terrain.

290        ***Smooth*** – Surface appearing mostly featureless at scale of CTX mosaic (12 m/px). Often,  
291 but not exclusively, within local topographic lows. Often associated with *scalloped* and *brain*  
292 *terrains*.

293        **Interpretation:** The Amazonian veneers group within our mapping area consists of thin  
294 (< few 10s of meters) units formed by atmospheric outfall/redistributions driven by persistent  
295 winds moving through the Hellas basin in a clockwise pattern (*Siili et al., 1999; Ogohara and*  
296 *Satomura, 2008; Howard et al., 2012*). While large eolian constructs are absent, volatile-poorer  
297 materials accumulate as small *TARs* or settle down to form up to few 10s of meters thick *smooth*  
298 layers also referred to as “latitude-dependent mantle” (e.g., *Schon et al., 2012*). Volatile-richer  
299 materials, which might have been mobilized during past obliquity excursions (e.g., *Laskar et*  
300 *al., 2004*), tend to be preserved in wind traps, e.g., craters, and later become characterized by  
301 desiccation (*scalloped*, *skeleton terrain*, *brain terrain*) (e.g., *Zanetti et al., 2010; Levy et al.,*  
302 *2010*) and slope creep features (*concentric crater fill*) (*Levy et al., 2009, 2010*).

303        **5.2. Crater materials**

304        ***Fluidized ejecta*** – Concentric, mostly comprehensive deposit around craters extending up  
305        to ~2 crater diameters beyond the rim. Often with finger-like extensions, lobate onlaps, and  
306        radial lineations formed by decameter-scale striations, i.e., furrows and ridges (Fig. 6). Five  
307        craters (diameters ~1.5 to ~6 km; randomly scattered over mapping area) are surrounded by  
308        double- or multiple-layered fluidized ejecta. Smallest crater with mapped fluidized ejecta is ~1  
309        km in diameter and located on interior formation close to northern map limit. One ~1.5 km  
310        crater with fluidized ejecta occurs on floor of Peneus Palus.

311        ***Non-fluidized ejecta*** – All circum-crater deposits that generally lack distinctive  
312        characteristics of fluidized ejecta as described above.

313        ***Crater material (undivided)*** – Morphologically distinct and sufficiently extensive (at  
314        mapping scale) crater rims as well as remnant central mounds/peaks, e.g., in Beloha crater.

315        **Interpretation:** Crater ejecta with a fluidized appearance are attributed to melting of  
316        subsurface ice by the energy released during the impact (e.g., Mouginis-Mark, 1981). Double-  
317        or multiple-layer ejecta specifically indicate target layers of different volatile-contents, either  
318        as permafrost (e.g., Barlow and Perez, 2003), and/or as surface ice (Weiss and Head, 2013).  
319        The occurrence of small craters (~1 km diameter) with fluidized ejecta suggests a target that  
320        was relatively ice-rich up to a depth of ~100 m or less at the time of impact (e.g., Melosh, 1989).

### 321        **5.3. Thick mantling**

322        ***Mantle*** – Corresponds to “mantle material (dark)” as mapped by Bernhardt *et al.* (2016a).  
323        Outline often appears as a padded drop-off of up to ~100 m. Nearly featureless at scale of CTX-  
324        mosaic (12m/px); dissected by several kilometer-scale, shallow, elongate depressions that are  
325        aligned mostly parallel to the HPT outline. Often associated with *polygonal ridges*.

326        ***Polygonal ridges*** – Corresponds to “reticulate terrain 2” and “polygonal member” as  
327        mapped by Diot *et al.* (2015) and Bernhardt *et al.* (2016a), respectively. Consists of up to ~8  
328        km wide, but mostly less than ~2 km wide polygons formed by up to ~100 m high and few 10s

329 of meters wide linear to slightly curvilinear ridges.

330       **Interpretation:** The thick mantling is an order of magnitude thicker than the *smooth*  
331 material (latitude-dependent mantling; e.g., Schon *et al.*, 2012; Willmes *et al.*, 2012) and also  
332 appears to be distinctly older due to several km-sized, superposing craters. Mostly along its  
333 northeastern limit, the thick mantle transitions into the polygonal ridges, thereby indicating  
334 them to be clastic dikes previously contained in, and now being eroded out of, the once volatile-  
335 rich mantle (Bernhardt *et al.*, 2016a). This, as well as deflation pit-like depressions suggest the  
336 thick mantling to currently undergo eolian erosion and possibly be mostly or entirely desiccated.  
337 As was proposed for similarly or even much thicker mantle deposits elsewhere, the thick  
338 mantling in the HPT might have been emplaced by snowfall during obliquity excursions within  
339 the Amazonian (e.g., Head *et al.*, 2006; Pedersen and Head, 2010). This is in agreement with  
340 the absolute model age of 2.2 to 3.3 Ga we derived for the main occurrence of the *mantle*  
341 material (see [supplementary online material 1](#)).

#### 342       **5.4. Banded terrain**

343       **Banded terrain (BT) (ridged/cusp/convoluted/creviced)** – The characteristics of the  
344 banded terrain have been described in detail in previous studies (e.g., Diot *et al.*, 2015;  
345 Bernhardt *et al.*, 2016b, Voelker *et al.*, 2017) and can be summarized as follows: The banded  
346 terrain is a unique landform covering over 30,000 km<sup>2</sup> of the northwestern Hellas basin floor  
347 that consists of a smooth surface (at meter-scale) dissected by up to ~30 m deep, crevice-like,  
348 curvilinear troughs (“inter-bands”) at a median spacing of few 100s of m. These troughs form  
349 various patterns, e.g., lobate/lamella-like or circular arrangements, but also confined zones of  
350 convolution with decameter-scale folding.

351       In our map ([Fig. 2A](#)), the banded terrain covers 30,071 km<sup>2</sup> and is divided into two  
352 subtypes: The creviced type (light blue/grey; 20,277 km<sup>2</sup>), which expresses the characteristics  
353 described above; and the ridged type (navy blue; 8,405 km<sup>2</sup>), which has a somewhat rougher

354 surface (at meter-scale) but shows the same general texture, albeit produced by ridges with the  
355 same dimensions as the curvilinear troughs of the creviced type ([Fig. 5A](#)). In some locations,  
356 ridged type areas appear to superpose creviced type areas ([Fig. 5B](#), white arrows). The  
357 remainder of the banded terrain includes separately mapped zones of convolution (1,351 km<sup>2</sup>),  
358 which mostly occur as triangle- or wedge-shaped areas among the creviced type. Lastly, 382  
359 km<sup>2</sup> constitute 11 small areas, which we refer to as “cusps” - apparently upthrust slabs and/or  
360 textures of intense, local-scale displacement sufficient to leave a topographic signature (as  
361 determined by shadows; [Fig. 5D,E](#)).

362 Boudinage-like band segmentations can be observed within creviced type areas ([Fig. 5B](#),  
363 black arrows) and individual bands of the banded terrain appear to interact in both, brittle and  
364 ductile manners (e.g., [Fig. 5C](#)). Comparisons of MOC-NA with HiRISE images taken up to 14  
365 years apart (e.g., E2001405 and ESP\_045349\_1405) show no discernible change within the  
366 banded terrain (e.g., collapse by de-volatilization or slope processes). The banded terrain  
367 superposes the honeycomb terrain (e.g., partially filling several honeycomb cells) as well as the  
368 hummocky, more elevated interior formation of the Hellas basin. Along its transition to the  
369 lower HPT in the northwestern basin, the material of the interior formation appears as elongate  
370 mesas (dark blue in [Fig. 2A](#)) embayed by banded terrain. In many locations, band orientations  
371 are aligned to the mesas, or terminate on one side and continue on the other ([Fig. 5F](#)). Several  
372 large crater ejecta (yellow in [Fig 2A](#); e.g., around craters Beloha and Kufstein) superpose the  
373 banded terrain. In certain locations, e.g., north of Kufstein crater at 57.66°E, 35.67°S, ejecta  
374 appears to be dissected by bands of the underlying banded terrain ([Fig. 6](#)).

375 According to our grid mapping ([Fig. 3](#)) the orientation of bands does not seem to correlate  
376 with the local slope. All grid box categories ([Fig. 3 and 4](#)) are nearly equally abundant and  
377 distributed randomly, except within the honeycomb cells (circular arrangements dominant) and  
378 in the northernmost extents (lobate/slope-perpendicular arrangements dominant). In general,  
379 the banded terrain occurs across an elevation spectrum of over 2 km, from -7667 m up to -5548

380 m (Fig. 7B). Within this spectrum (Fig. 7B *inlet*), the creviced type follows a quasi-Gaussian  
381 distribution (mode at ~ -6765 m), whereas the ridged type occurs mostly below ~ -7,000 m  
382 (mode at ~ -7285 m).

383       **Interpretation:** See sections 6.3 and 6.4.

384       **5.5. Interior formation**

385       **Hih** – Corresponds to “hummocky member of the interior formation” (Hih) as mapped by  
386 *Bernhardt et al. (2016a)*. Characterized by 5-10 km wavelength roughness created by rounded  
387 hills and undulating mesas with padded rims. Widespread coverage by Amazonian veneers.

388       **Hik** – Corresponds to “knobby member of the interior formation” (Hik) as mapped by  
389 *Bernhardt et al. (2016a)*. Fields of 100s of meters to few kilometers wide knobs; often  
390 associated with Hih.

391       **Fan-shaped** – Four occurrences of roughly semicircular areas characterized by few 10s of  
392 meters-scale roughness created by radial lineations. Largest measures ~20 x 20 km, other three  
393 are less than ~5 x 10 km and ~4 x 4 km. On two largest occurrences, decameter-scale ridges  
394 forming braided patterns are visible. *Fan-shaped* landforms have little relief, but are always  
395 situated on top of *mesas* at distal (topographically lower) terminus of a sinuous ridge (Fig. 9).

396       **Mesa/deformed mesa** – Roughly based on “etched material” (He) as mapped by *Bernhardt*  
397 *et al. (2016a)*. Elevated, flat-topped areas with relatively sharp edges dropping ~100 to ~200 m  
398 down to surroundings. Mostly around highly degraded ~90 km wide crater in southern mapping  
399 area. Here, a system of braided, decameter-scale ridges can be seen on a ~19 x 11 km large  
400 *mesa* at 54.03°E; 40.12°S. *Mesas* often occur as few 100s of meters to few kilometers wide  
401 ridges, mostly radial to said crater (Fig. 9). Can appear “deformed”, i.e., streamlined or striated  
402 in curvilinear patterns conforming to surrounding banded terrain. Contrary to stratigraphic  
403 interpretation of etched material by *Bernhardt et al. (2016a)*, *mesas/deformed mesas* do not  
404 superpose *Hih*, but are superposed by it (Fig. 10A).

405        ***HNila*** – Corresponds to “arcuate, layered member of the interior formation” (***HNila***) as  
406        mapped by *Bernhardt et al. (2016a)*. Flat-topped, step-like, up to ~150 m thick outcrops of  
407        light-toned, horizontal, decameter-scale layers. CRISM data, e.g., FRT0000978A,  
408        compromised by atmospheric effects. Within mapping area, occurs in two highly degraded  
409        craters at similar elevation of ~ -7,000 m; largest occurrence close to Hellas basin center  
410        (*Bernhardt et al., 2016a*). Superposed by all adjacent units.

411        **Interpretation:** Following the interpretation offered by *Bernhardt et al. (2016a)*, we  
412        suggest the interior formation of the Hellas basin, mainly units *Hih* and *Hik*, but possibly also  
413        the *mesas/deformed mesas*, to represent different erosional stages of Hesperian (~3.7 Ga  
414        absolute model age) deposits derived from Hesperia Planum and the “Hesperia-Hellas trough”,  
415        where they might have been mobilized by hydrovolcanic processes. *HNila* might either be a  
416        more pristine member of these deposits, or is a remnant of materials laid down earlier by  
417        different, more localized processes, e.g., as sediments in a glacio-lacustrine environment that  
418        was confined to the Hellas basin center as well as the two craters in western Hellas in which  
419        *HNila* is found in (*Bernhardt et al., 2016a; Voelker et al., 2017*). Such a scenario would also  
420        be in agreement with an interpretation of the sinuous ridges consisting of *mesa* material around  
421        a partially *HNila*-filled, degraded crater ([Fig. 9](#)) as glaciofluvial or fluvial features, i.e., eskers  
422        or inverted stream deposits. The *fan-shaped* deposits located at the distal termini of four of these  
423        sinuous ridges are strongly reminiscent of terrestrial sandurs/outwash plains (braided ridge  
424        system on largest two occurrences as well as directly on *mesa* superposed by smaller two  
425        occurrences; e.g., *Benn and Evans, 2010*) and alluvial fans (radial striations on smaller two  
426        occurrences, possibly remnants of tributary systems; e.g., *Ritter and Ten Brink, 1986*). This  
427        indicates that glaciofluvial deposition might have taken place both, in subglacial as well as  
428        proglacial settings, possibly as a sequence due to glacial retreat, with hydraulic drainage  
429        transporting meltwater from a body of ice occupying (parts of) the floor of the degraded crater  
430        amongst others. Furthermore, we suggest that such glacial activity might have been responsible

431 for the formation of the banded terrain (see section 6.4).

## 432 5.6. Plains materials

433      ***Etched (western)*** – Variable unit characterized by rough to knobby materials (100s of  
434 meters to kilometer-scale roughness) exclusively occurring on the southern floor of the HPT.  
435 Superposes *etched* and *fractured* units, superposed by all other adjacent units.

436      ***Etched*** – Similar to *etched (western)*, albeit with larger topographic variations (up to ~400  
437 m). Exclusively occurs on northern floor of HPT; superposes *rough* and *HC rim* units;  
438 superposed by all other adjacent units.

439      ***Rough (undivided)*** – Variable unit including low-relief, hummocky surfaces with several  
440 100s of meters-scale roughness, as well as plains with ~50-200 meters-scale roughness. At least  
441 five occurrences of up to ~35 km long, ~400 m wide, degraded, flat-topped, sinuous ridges  
442 forming braided pattern in one location (56.98°E; 34.34°S). Ridges reside on *rough (undivided)*  
443 unit of northern HPT floor, but appear to emerge out of *etched* materials. Unit *rough (undivided)*  
444 exposed in various locations across the entire HPT floor; superposes *fractured* (Fig. 10B) and  
445 *HC rim* units, superposed by all other adjacent units.

446      ***Fractured*** – Smooth plains characterized by up to ~300 m wide, shallow, graben-like,  
447 solitary fractures often forming zig-zag patterns. Exclusively occurs on southern floor of HPT;  
448 superposed by all adjacent units (Fig. 10B).

449      **Interpretation:** The plains materials of this study's map largely correspond to the units  
450 HNpr (southern HPT) and Npwr<sub>1/r</sub> (northern HPT) of the photogeologic map by Bernhardt *et*  
451 *al.* (2016a). Accordingly, we interpret them as Noachian (~3.8 Ga absolute model age) basalt  
452 plains that are covered by relatively friable materials, which are likely to be remnants of  
453 *Hih/mesa material* and/or Hellas rim deposits (Bernhardt *et al.*, 2016a). Missed by previous  
454 investigations but revealed by comprehensive CTX data, some of these remnants form sinuous  
455 ridges on the northern floor of the HPT, which might have been laid down as stream deposits

456 (fluvial) or eskers (subglacial). In any case, they postdate potential fluvial sediments and  
457 landforms along the inner wall of the nearby northern Hellas basin rim (units Nli and Nld by  
458 *Bernhardt et al. (2016a)*), as these rim deposits are superposed by the floor of the HPT. Instead,  
459 the sinuous ridges might be associated with the later formation of the interior formation (*Hih*,  
460 *Hik*, *mesas*, *HNila*), thereby indicating that its deposition involved (glacio-) fluvial activity.

461 **5.7. Honeycomb terrain**

462 ***Honeycomb rims (HC rims)*** – Approximately 1-2 km wide, up to ~170 m high ridges  
463 arranged in honeycomb-like pattern, i.e., forming edge-on-edge assemblage of circular to  
464 kidney/cell-shaped enclosures with a median diameter of ~7 km. Subdivided into three  
465 categories based on different morphologies. 1) *Furrowed*: Ridges are covered with ~80-400 m  
466 wide, up to few km long secondary ridges at a spacing of several 100s of meters. Areas between  
467 secondary ridges are *lineated*. Predominantly occur in central portion of honeycomb terrain. 2)  
468 *Bulged*: Ridges have rounded crests and steeper walls than other two categories. Occasionally  
469 dissected by up to 1 km wide, shallow, ridge-parallel troughs. Exclusively occur in northeastern  
470 honeycomb terrain. 3) *Lineated*: Ridges are flat-topped with slightly raised edges; meter to  
471 decameter-scale lineations (small ridges and troughs) occur on their tops, mostly parallel to  
472 ridge outlines, but can have turbulent texture at junction of three ridges (e.g., at 53.97°E;  
473 37.97°S). Exclusively occur in southwestern honeycomb terrain.

474 **Interpretation:** In general, we adapt the interpretation of the so called honeycomb terrain  
475 as the surface expression of a diapir canopy, specifically withdrawal basins created by ridges  
476 of upwelling material (e.g., *Bernhardt et al., 2016b; Weiss et al., 2017*), which was elaborated  
477 on in further detail in [section 3](#). The honeycomb terrain is manifested as mostly flat-floored  
478 enclosures bound by ridges. Both, the floors as well as the ridges show different morphologies,  
479 with the former being covered by different types of units also occurring outside the honeycomb  
480 terrain, e.g., *rough*, *etched*, *Hik*, and banded terrain ([Fig. 10C](#)). This was interpreted as filling

481 of the cells, thereby implying the honeycomb terrain to predate the plains material, for which  
482 an absolute model age of ~3.8 Ga was derived (*Bernhardt et al., 2016a,b*). The apparent  
483 geographic sequence of different HC rim categories (*linedated-furrowed-bulged* from SW to NE)  
484 might be caused by differential erosion across the honeycomb terrain, likely by persistent winds  
485 moving clockwise through the Hellas basin (*Howard et al., 2012*). Alternatively, the rim  
486 categories might be the surface expressions of different regimes of honeycomb formation, i.e.,  
487 changing displacement kinematics between the honeycomb cells, possibly due to different  
488 rheologies within the overburden material (e.g., basalt vs. sandstone). This interpretation would  
489 be in agreement with turbulent textures on *linedated* HC rims, which occur at triple-junctions of  
490 honeycomb cells, which is also where turbulent displacement textures are seen in overburden  
491 materials of terrestrial salt or batholith diapir provinces (*Ramsay, 1989; Bouhallier et al., 1995;*  
492 *Jackson et al., 1990*). While the distinct basin-range landscape of the honeycomb terrain occurs  
493 only on Peneus Palus (i.e., the northern floor of the HPT), its general surface pattern (quasi-  
494 circular, ~5-10 km wide cells) extends beyond the ~1 km high scarp leading onto the interior  
495 formation. Here, the pattern is not expressed morphologically, but merely by the arrangement  
496 of convoluted zones within the banded terrain ([Fig. 11](#)). As already suggested by *Bernhardt et*  
497 *al. (2016b)* and further explained in [section 6.4](#), we interpret this as a superposition effect  
498 caused by zones of convolution having preferentially formed above topographic rises, e.g.,  
499 buried honeycomb rims, during the formation of the banded terrain.

## 500 **6. Discussion**

### 501 **6.1. GPR and hyperspectral investigations**

502 **MARSIS/SHARAD:** Neither MARSIS nor SHARAD revealed any definite reflectors  
503 beneath the Hellas basin (see [supplementary online material 2](#)). Several MARSIS tracks, e.g.,  
504 R\_10934\_SS3, traverse the Hellas basin including the HPT and show horizontal reflectors  
505 further to the south, beneath the well-known south polar layered deposits (SPLD; e.g., *Plaut et*

506 *al., 2007*), but also beneath adjacent Promethei Planum. Beneath the honeycomb terrain,  
507 SHARAD radargram QDA\_7470010000 shows at least four slanted, several km long echoes at  
508 depths between 1 and 2 km that are not seen in the respective simulation. However, as the  
509 simulations are based on relatively low-resolution topography data by MOLA, these signals are  
510 more likely to be surface clutter missed by the simulated radargram than actual reflectors. If the  
511 signals are true reflectors, they would be in agreement with a salt or ice diapir-interpretation of  
512 the honeycombs as they could represent reflections of well-developed, slanted diapir flanks.  
513 Their depths of 1-2 km would accommodate either material scenario, salt as well as ice, for  
514 which overburden thicknesses in that range have been predicted (*Bernhardt et al., 2016b, Weiss*  
515 *and Head, 2017*).

516 While GPRs have been successfully used to detect halite and water ice interfaces in the  
517 subsurfaces of Earth and Mars (e.g., *Stewart and Unterberger, 1976; Annan et al., 1988; Plaut*  
518 *et al., 2007; Orosei et al., 2015*), the lack of detectable, definite reflectors beneath the  
519 honeycomb terrain can have various reasons: 1) Hellas' rough surface creates intense radar  
520 clutter, thus greatly reducing GPR sensitivity (*Seu et al., 2007; Orosei et al., 2015*). 2) An  
521 upwelling layer can develop diapirs with near-vertical flanks (e.g., *Diegel et al., 1995*), i.e.,  
522 non-horizontal reflectors that are very difficult to detect from orbit. 3) Certain interfaces, e.g.,  
523 between dry halite and sandstone, have small dielectric contrasts resulting in very weak  
524 reflections (*National Research Council, 2000*).

525 **CRISM:** Despite atmospheric corrections (see Data and techniques), all 12 analyzed  
526 CRISM scenes (nine FRTs including one new pre-projected/processed MTRDR image + three  
527 HRL/HRS; all covering the banded terrain, *HC rims*, or unit *HNila*) are characterized by a  
528 ubiquitous CO<sub>2</sub> signature. A very weak, ubiquitous H<sub>2</sub>O ice signature can be seen in certain  
529 images (e.g., HRS00010EF1) alongside strong CO<sub>2</sub> absorption features. Certain spectral  
530 parameters, e.g., “D2300” defined by a 2.3 μm drop-off, which can be indicative of  
531 hydroxylated silicates (*Viviano-Beck et al., 2014*) but also of CO<sub>2</sub> (*Hansen, 1997*), do show a

532 spatial correlation with outcrops within the banded terrain (e.g., on FRT0000AAD1; see  
533 [supplementary online material 3](#)). However, averaged spectra of these “signatures” only show  
534 the afore mentioned CO<sub>2</sub> features and become virtually flat when ratioed with a nearby,  
535 spectrally bland reference area, which, in turn, indicates an atmospheric signal. Thus, we  
536 explain the spatial correlation with the fact that outcrops, i.e., steep slopes, are usually  
537 associated with shadows, where an increased fraction of the CRISM signal comes from the  
538 atmosphere instead of the surface, thereby intensifying the atmospheric signature (including the  
539 relatively weak 2.3 μm drop-off for CO<sub>2</sub>).

540 **6.2. Stratigraphic model**

541 Based on our 1:175,000 morphologic map ([Fig. 2A](#)) and MOLA data, we derived  
542 stratigraphic profiles along three traverses ([Fig. 12](#)). The map unit groups *honeycomb terrain*  
543 and *plains materials* as well as the units *mesa/deformed mesa* ([Fig. 2B](#)) are represented by a  
544 single stratigraphic unit, respectively.

545 Our self-consistent stratigraphic model is based on interpretations of the honeycomb terrain  
546 as the surface expression of a diapir canopy as well as the banded terrain as a partially  
547 superposing thin veneer. It is consistent with the models by *Bernhardt et al. (2016a,b)* based  
548 on those studies’ 1:2,000,000 map with one exception: Our comprehensive CTX observations  
549 showed the *mesa/deformed mesa* units to be superposed by the hummocky interior unit *Hih*  
550 ([Fig. 10A](#)). Based on THEMIS observations, *Bernhardt et al. (2016a)* interpreted this  
551 relationship to be inverted, i.e., *Hih* to underlie the “etched material”, which corresponds to the  
552 *mesa* units. It is thus possible that a large volume of the westernmost Hellas interior formation  
553 is in fact composed of *mesa* material and not *Hih*. Based on the unconsolidated and rounded  
554 appearance of *Hih*, it might represent a reworked form (deflation/mass wasting) of the *mesa*  
555 material, which is exposed only along the erosive environment of the HPT (*Howard et al.,*  
556 *2012; Bernhardt et al., 2016a*).

557       **Timing of the banded terrain:** The banded terrain is superposed on the *honeycomb*  
558       *terrain*, the *plains materials* and on the *interior formation*, for which model ages between 3.8  
559       and 3.7 Ga were derived (*Bernhardt et al., 2016a*). It is superposed by the *thick mantling, crater*  
560       *materials* and *Amazonian veneers*. While the latter two did not lend themselves to reliable crater  
561       size-frequency measurements, we derived an absolute model age of 2.2 to 3.3 Ga for the main  
562       occurrence of the *mantle* material (see [supplementary online material](#)). This implies that banded terrain  
563       formation took place between ~3.7 and ~2.2 Ga, which is in agreement with *Diot et al.*'s  
564       (2014) derived crater retention age of ~3 Ga. However, it is noteworthy that banded terrain  
565       activity/deformation appears to have persisted or recurred, at least locally, after crater  
566       accumulation had begun, as it dissected otherwise well-preserved, superposing crater ejecta,  
567       e.g., north of Kufstein crater ([Fig. 6](#)).

568       **6.3. What is the banded terrain?**

569       As already mentioned in [section 3](#), interpretations of the banded terrain have been diverse,  
570       yet always implied some form of viscous deformation to explain its curvilinear, folded patterns.  
571       Earlier studies equated or associated the banded and honeycomb terrains, suggesting the former  
572       to be deeply rooted material that was viscously displaced by compressive stresses during  
573       honeycomb formation (e.g., *Moore and Wilhelms, 2001; Mangold and Allemand., 2003; Kite*  
574       *et al., 2009*). However, *Diot et al. (2014, 2015a,b)* and *Bernhardt et al., (2016b)* observed  
575       potential (peri)-glacial features on the banded terrain's surface such as pingo-/sublimation pit-  
576       like landforms, disintegration into brain terrain, and “slabs” detaching from its main body ([see](#)  
577       [section 3](#)). These features, as well as the banded terrain occurring up to 100s of kilometers away  
578       from the honeycombs, cast an immediate genetic association (i.e., a joint formation by the same  
579       process) into doubt. Instead, they seemed to imply a thin veneer scenario of gravity-driven,  
580       ductile deformation of volatile-rich material postdating the honeycombs. The new findings of  
581       our investigation are in agreement with an interpretation of the banded terrain as a relatively

thin layer that underwent ductile deformation at or near the surface: 1) Cusps indicating thin layer buckling ([Fig. 5D,E](#)); 2) the banded terrain’s spread over an elevation spectrum of ~2 km ([Fig. 7](#)); as well as 3) its occurrence on the flanks of intact, non-deformed ridges of likely glacio-([Fig. 9](#)). However, based on our observations, we offer further refinements of the banded terrain’s nature and origin, arguing against deformation by gravity-driven, downslope flow.

The ubiquitous, curvilinear, decameter to kilometer-scale folding of the banded terrain implies a relatively uniform, viscous behavior in the past. Furthermore, while our investigation of CRISM data did not reveal any clear surface signatures, three observations tentatively indicate the current banded terrain to consist of relatively volatile-poor, heterogeneous material: 1) Outcrops and fresh crater ejecta containing up to decameter-scale blocks (*Diot et al., 2015b*) but lacking any fluidization features; 2) a generally elevated, yet variable THEMIS-based thermal inertia; and 3) a lack of detectable surface change (e.g., collapse or mass wasting) on MOC-NA-HiRISE image pairs taken up to 14 years (~7.4 Mars years) apart. Shallow, i.e., not deeply-rooted, terrestrial materials known to form and preserve (via cooling or desiccation/cementation) ductile, decameter- as well as kilometer-scale, curvilinear deformation patterns at or near the surface include low viscous materials like salt, lava, and ice/ice-rich material (e.g., *Talbot, 1979; Lockwood et al., 1987; Bevington and Copland, 2014*).

**Salt:** As was previously elaborated, deeply-rooted halokinetic sequences exposed around many salt diapirs on Earth (e.g., *Jackson et al., 1990*) contradict the observation-based thin veneer-interpretation of the banded terrain. Nevertheless, so called “salt glaciers” ([Fig. 12A](#)), i.e., several 10s to few 100s of meters thick, downslope creeping sheets of salt originating from diapirs are common in terrestrial salt provinces (*Talbot, 1979; Jackson et al., 1990; Fletcher et al., 1995*) and can even contain water dissolution features reminiscent of certain thermokarst landforms observed on the banded terrain (*Talbot, 1979; Jackson et al., 1990*). Furthermore, assuming them to be the result of salt diapirs, the adjacent honeycombs would be suitable

sources of salt. However, while subaerial salt glaciers can produce up to decameter-scale curvilinear patterns (e.g., *Talbot*, 1979), neither them nor submarine salt glaciers (*Fletcher et al.*, 1995) are known to create kilometer-scale patterns even remotely similar to the banded terrain. Moreover, fold patterns within salt glaciers develop according to downslope creep (*Talbot*, 1979), which is not in agreement with our grid map showing no correlation between slope and band orientation (Fig. 3).

**Lava:** Curvilinear patterns are occasionally formed on solidifying lava sheets, e.g., the up to kilometer-scale pattern formed by meter-scale flow fronts during the 1984 fissure eruption in the central caldera of Mauna Loa, Hawai'i (Fig. 13B; *Lockwood et al.*, 1987). Although these textures can be reminiscent of the ridged type banded terrain (e.g., Fig 4D), we argue against such an interpretation as no volcanic landforms, e.g., potential vents/fissures, flows, or calderas, have been identified anywhere on the Hellas basin floor (e.g., *Williams et al.*, 2010, *Bernhardt et al.*, 2016a). Moreover, unlike flow fronts on lava sheets/flows, the orientations of bands in most locations of the banded terrain does neither conform to the outlines of apparently embayed materials nor correlate to the local topography. Lastly, the dominant creviced type (characterized by curvilinear troughs; Fig. 3, 4C, 5C,D), as well as potential (peri-)glacial features of the banded terrain (e.g., thermokarst-like depressions and disintegration into brain terrain), lack any correspondence on the surfaces of terrestrial or martian lava sheets.

**Ice/ice-rich material:** On Earth, curvilinear, decameter- to kilometer-scale surface patterns including isoclinal folds can be found on ice shelves (e.g., *Crabtree and Doake*, 1980) and on surge glaciers (e.g., *Bevington and Copland*, 2014). In both cases, they occur in recurrently fast-moving ice at junctions of interacting stress fields, e.g., along the edge of the Ross ice shelf, Antarctica (Fig. 13C), or at the confluence of a tributary glacier and the main ice tongue of Dusty Glacier in Kluane National Park, Yukon/Canada (Fig. 13D). Unlike Dusty Glacier, whose curvilinear texture is spatially confined and directly determined by gravity-driven flow, ice shelf patterns are only indirectly created by gravity-driven flow of their source

634   glaciers on land (*Casassa et al., 1991*). They can extend over several 10s of kilometers as they  
635   are an immediate result of ductile deformation along shear- and compaction zones at the shelf  
636   margin (*Crabtree and Doake, 1980; Rignot et al., 2011*). The result can be surface patterns and  
637   morphologies that are very reminiscent of the banded terrain, e.g., kilometer-scale, tapering,  
638   crevice-like troughs, isoclinal folds, cusp-forming buckling ([Fig. 13C](#), black arrow), and  
639   confined zones of intense, smaller-scale deformation. Moreover, ice shelf margins produce  
640   ductile as well as brittle deformation in close geographic association, e.g., slab break-off and  
641   rotation ([Fig. 13C](#), white arrow), or one slab breaking through another slab, which itself is being  
642   flexed. Such arrangements are also common in the banded terrain, where intact slabs apparently  
643   broke through other slabs ([Fig. 5C](#), white arrow) or folding was partially accommodated by  
644   brittle failure and flexural slip ([Fig. 5C](#), black arrow). In ice shelves, these phenomena are  
645   enabled by multiple stress fields that result in spatially varied strain rates acting on a decoupled  
646   lid, which might, thus, imply a similar setup during the deformation of what today is the banded  
647   terrain. However, if the banded terrain had also been decoupled due to floatation on a past body  
648   of water, we would not expect its fine-scale texture to be preserved while it settled down on a  
649   rugged landscape across an elevation spectrum of over 2 km during the recession of an ice- and  
650   debris-covered sea. Furthermore, while the banded terrain is a prominent landscape with a  
651   relatively fresh appearance, no other landforms indicative of a past, standing body of water on  
652   the Hellas basin floor have been identified (*Bernhardt et al., 2016a; Voelker et al., 2017*), thus  
653   further casting an ice shelf model into doubt.

#### 654   **6.4. A glacial formation model**

655   Despite the inadequacy of an ice shelf model, we submit that a formation of the banded  
656   terrain's texture due to ice/ice-rich material being deformed by multiple local-scale stress fields  
657   remains a promising concept. The general pattern of bands in the banded terrain implies  
658   numerous, small-scale, slope-independent stress fields (<10s of km) of different orientations.

659 As no regional pattern (>10s of km) can be identified within the banded terrain, we suggest that  
660 large/regional-scale stress fields, either by tectonics or long-wavelength topography, had little  
661 or no effect on its deformation. One terrestrial analog setting with local stress fields deforming  
662 a wet/ice-rich layer is a wet-based, subglacial environment, in which low viscous, ice/water-  
663 rich till is deformed in stress fields caused by the ice overburden pressure (Fig. 14; e.g., *Boulton*  
664 *et al.*, 1974; *Alley et al.*, 1986). Various different strain rates can result from the overburden  
665 pressure acting in conjunction with bed topography, as well as from zones of variable surging  
666 and basal decoupling created by ice flow patterns primarily governed by regional bed  
667 topography but also by the hydraulic transmissibility of the bed as determined by its geology  
668 (*Brennand*, 2000; *Margold et al.*, 2015). Such variable strain rates might account for the  
669 different curvatures and spacings of bands in the banded terrain, and could potentially explain  
670 its zones of convolution. Due to their often “curly” appearance, we interpret these zones to be  
671 indicative of intense compression and shearing, which, in a subglacial scenario, would be  
672 expected in association with topographic obstacles as well as a low hydraulic transmissibility  
673 of the glacier bed (e.g., *Boulton et al.*, 1974; *Margold et al.*, 2015). Thus, as the zones of  
674 convolution are often arranged in patterns mimicking the adjacent honeycombs (Fig. 11), it is  
675 possible that they are located above buried honeycomb-cell rims, which affected the stress field  
676 applied to the glacial substrate. Such a causal relationship between bed topography and banded  
677 terrain deformation would explain several locations, where band orientations conform to  
678 embayed, elongate *mesas* (Fig. 5F) and/or appear to have deformed/streamlined (partially)  
679 superposed *mesas*. The two sections of the banded terrain, where band orientations correlate  
680 more with modern topography (its northernmost extents as well as within most honeycombs;  
681 Fig. 3), might, in turn, indicate a locally stronger contribution of gravity-driven flow, possibly  
682 due to their location close to the northern ice sheet margin, i.e., beneath a much thinner ice  
683 overburden. A glacial formation model for the banded terrain might also be in agreement with  
684 the sinuous ridges we identified in the southern part of our morphologic map and that are always

located on broader rises being unconformably superposed by banded terrain (Fig. 9). As larger-scale topographic rises of the glacier bed are often associated with a reduced ice thickness, i.e., smaller overburden pressure resulting in a negative hydraulic gradient, they are a preferred location of terrestrial esker-forming drainage tunnels (*Shreve, 1985; Ashley et al., 1991*). Thus, we prefer an interpretation of the sinuous ridges as deposits by subglacial drainage. Moreover, the braided ridges on elevated areas often occurring at the distal termini of the sinuous ridges (Fig. 9B, lower left) constitutes a landform sequence also found on Earth, and might have formed as sandurs/outwash plains immediately beyond the glacier margin (*Shreve, 1985; Brennand, 2000; Benn and Evans, 2010*).

In order to preserve the intricate banded patterns in its substrate, the glacier had to retreat in a mostly stagnant fashion, potentially due to sublimation. This might have been driven by katabatic winds, which models suggest to descend from Malea Planum and be pervasive throughout the HPT (*Sili, 1999; Howard et al., 2012*), therefore also explaining the banded terrain's apparent desiccation. Hence, we interpret the ridged type of the banded terrain as wind-degraded version of the creviced type, with the ridges being clastic dikes of material that once filled the crevices (Fig. 5A). This is in agreement with the ridged type predominantly occurring in the lowest elevations of the unit's extent (Fig. 7), where deflation is expected to be more intense, possibly including saltation and abrasion (*Sili, 1999; Howard et al., 2012*). Lastly, it was noted that intense deflation over few 10s of millions of years by such winds could be responsible for the exposure of the deep lying, ancient honeycombs, thus offering an explanation for the geographic association between the unique banded and honeycomb terrains (*Bernhardt et al., 2016a,b*).

However, a remaining problem of such a subglacial formation model is the lack of kilometer-scale, curvilinear textures in respective terrestrial analog environments (*Boulton et al., 1974*). Therefore, we cannot conclusively demonstrate its suitability to explain the origin of the banded terrain.

711       **Climatic considerations:** Due to its low elevation and relatively low latitude on the  
712 southern hemisphere, the Mars Climate Database (MCD; *Forget et al.* 1999; *Millour et al.*  
713 2015) predicts that no other location on Mars experiences temperatures and pressures as high  
714 and for as long (per Mars year) as the HPT. Daily maximum temperatures of at least 273 K are  
715 maintained throughout a third of the year, while pressures are above 10 mbar for more than half  
716 the day during this time. However, without decisive atmospheric changes, even obliquity  
717 excursions to 45° only predict increased dust lifting in Hellas and ice precipitation for the  
718 eastern Hellas basin rim, but no decisive changes in mean ground temperature and pressure that  
719 would enable ice accumulation in the HPT (*Haberle et al.*, 2003; *Forget et al.*, 2006;  
720 *Wordsworth*, 2016). Nevertheless, as it is likely that atmospheric pressures were still higher  
721 during the early Amazonian (*Madeleine et al.*, 2009; *Read et al.*, 2015), ice sheets on the Hellas  
722 basin floor might have been sustainable, e.g., as distal reaches of glaciers originating in  
723 accumulation zones within the adjacent basin rim. This specific topographic setup might also  
724 explain why the banded terrain is unique on Mars, while HPT-like climatic conditions are and  
725 have been occurring elsewhere, yet in much more confined areas, e.g., in Lyot crater, lacking  
726 comparable potential ice accumulation zones.

727       **7. Main results and conclusions**

728       Based on our 1:175,000 map (159,856 km<sup>2</sup>) of northwest Hellas Planitia, we assessed the  
729 morphologic inventory and stratigraphy of the area at a resolution that resolves the constituents  
730 of the banded and honeycomb terrains. Amazonian deposits are widespread, with recent  
731 veneers, e.g., smooth and brain terrain, covering ~23% and superposing different types of crater  
732 materials (e.g., ejecta) 8% of the map area. Late Hesperian to Amazonian thick mantling,  
733 covering 14% including associated degradation products, are superposed by several craters and  
734 show a CSFD-derived absolute model age range of 2.2 to 3.3 Ga. The banded terrain covers  
735 19% and is partially superposed by thick mantling, crater ejecta, as well as Amazonian veneers,

736 while it superposes the interior formation (16%), plains materials (17%), and honeycomb  
737 terrain. Based on our analyses, as well as previous investigations (*Bernhardt et al., 2016a,b;*  
738 *Voelker et al., 2017*), we laid out a comprehensive, self-consistent stratigraphic model, which  
739 incorporates the banded terrain as relatively thin surface layer and the honeycomb terrain as the  
740 surface expression of evolved diapirs.

741       **Honeycomb terrain:** In agreement with previous studies, we conclude the honeycombs to  
742 be ancient structures, as they are partially filled and/or covered by different materials of the  
743 adjacent plains and interior formation (absolute model ages ~3.8 Ga and ~3.7 Ga; *Bernhardt et*  
744 *al. 2016a*). Within the honeycomb terrain, we differentiated three rim categories (lineated-  
745 furrowed-bulged from SW to NE). Following their interpretation as surface expressions of salt  
746 or ice diapirs (*Bernhardt et al., 2016b; Weiss and Head, 2017*), these categories might reflect a  
747 transition of formation regimes, e.g., displacement kinematics during diapir ascent due to  
748 variable overburden geology. As radar (MARSIS/SHARAD) and hyperspectral data (CRISM)  
749 did not reveal any definite reflectors and surface signatures beneath and on it, respectively, we  
750 were not able to characterize the honeycomb terrain in further detail.

751       **Banded terrain:** The banded terrain covers 30,071 km<sup>2</sup> across an elevation spectrum of  
752 over 2 km, from -7667 m up to -5548 m. It can be subdivided into two types, creviced and  
753 ridged. Since it dominates the lowest areas, where deflation is expected to be more intense (e.g.,  
754 *Howard et al., 2012*), we interpret the ridged type as degraded version of the creviced type. The  
755 banded terrain partially fills several honeycombs, but also occurs up to ~240 km away from the  
756 honeycomb terrain, e.g., on ridges of likely (glacio-)fluvial origin. Based on these observations  
757 and those by previous investigations (see section 3), we conclude the banded terrain cannot be  
758 a deeply rooted unit but has to be a relatively thin surface layer. As it superposes the interior  
759 formation of the Hellas basin (~3.7 Ga, *Bernhardt et al., 2016a*), but is partially covered by  
760 thick mantling, for which we derived an absolute model age range between 2.2 and 3.3 Ga, a  
761 Hesperian/early Amazonian age is implied for the banded terrain. Our grid mapping of the

762 banded terrain showed no regional band pattern or correlation between band orientations and  
763 local topography, and we conclude that neither regional-scale tectonics nor gravity-driven  
764 downslope flow played a major role during its formation. While CRISM data revealed no  
765 distinct surface signatures for the entire region, HiRISE, MOC-NA, and THEMIS observations  
766 indicate the modern banded terrain to consist of relatively volatile-poor, heterogeneous material  
767 containing decameter-scale blocks. Based on regional geomorphology and terrestrial analogs,  
768 we argue against salt or volcanic deposits as its main constituents. Instead we tentatively  
769 propose a subglacial formation, involving viscous deformation of wet/ice-rich till by small-  
770 scale stress fields created by an interplay of ice overburden pressure on local topography.  
771 Models and observations indicate persistent katabatic winds in the area, which might later have  
772 removed the glacier and desiccated the exposed substrate. While terrestrial analogs of such  
773 settings are not known to produce kilometer-scale, curvilinear textures, a scenario like this  
774 would be in agreement with sinuous, esker-like ridges and sandur-like, elevated plains, whose  
775 flanks are partially superposed by the banded terrain, and, thus, might indicate an involvement  
776 of glacial activity during its emplacement. Although the validity of the proposed formation  
777 model cannot be conclusively demonstrated, we submit that potential future CRISM  
778 observations detecting unambiguous signatures, e.g., of chlorides (salts?) or phyllosilicates  
779 (sediments?), on the cusps and convoluted zones of the banded terrain, would be the most  
780 promising, currently feasible contribution to understand this enigmatic landscape.

781 **8. Table**

<b>Group</b>	<b>Unit</b>	<b>Type locality (°E; °S)</b>	<b>Area (km<sup>2</sup>)</b>
Amazonian veneers (23%)	1) TARs	59.31; 34.08	705
	2) Scalloped	55.00; 41.42	2804
	3) Skeleton terrain	58.07; 35.98	75
	4) Concentric crater fill	53.45; 37.00	187
	5) Brain terrain	59.21; 36.36	5916
	6) Smooth	53.28; 43.52	26623
Crater materials (8%)	7) Fluidized ejecta	57.36; 38.77	8433
	8) Non-fluidized ejecta	58.01; 33.78	2886
	9) Crater material	51.29; 40.65	1055
Thick mantling (14%)	10) Mantle	52.21; 38.58	18368
	11) Polygonal ridges	58.02; 36.61	4312
Banded terrain (19%)	12) BT (ridged)	52.04; 41.73	8405
	13) BT (cusps)	53.51; 39.13	38
	14) BT (convoluted)	56.15; 37.84	1351
	15) BT (creviced)	52.26; 40.39	20277
Interior formation (16%)	16) Hih*	60.69; 35.66	7220
	17) Hik*	60.75; 36.01	3139
	18) Fan-shaped	54.10; 40.19	244
	19) Mesa (deformed)	57.28; 37.81	3795
	20) Mesa	58.24; 37.43	10766
	21) Hnila*	53.15; 41.15	541
Plains materials (17%)	22) Etched (western)	50.80; 41.17	4566
	23) Etched	57.98; 34.01	7072
	24) Rough (undivided)	51.78; 36.99	14421
	25) Fractured	52.48; 42.87	645
Honeycomb terrain (4%)	26) HC rim (furrowed)	56.65; 36.45	2954
	27) HC rim (bulged)	58.16; 34.99	2304
	28) HC rim (ridged)	53.90; 37.95	758

782

783 **Table 1:** Unit groups (and map area percentage), unit names, type localities, and areal extents  
 784 of all units of our morphologic map ([Fig. 2](#)). Standardized images of each type locality are  
 785 shown in [Fig. 8](#). \* unit labels adopted from *Bernhardt et al. (2016a)*.

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## 10. Figures

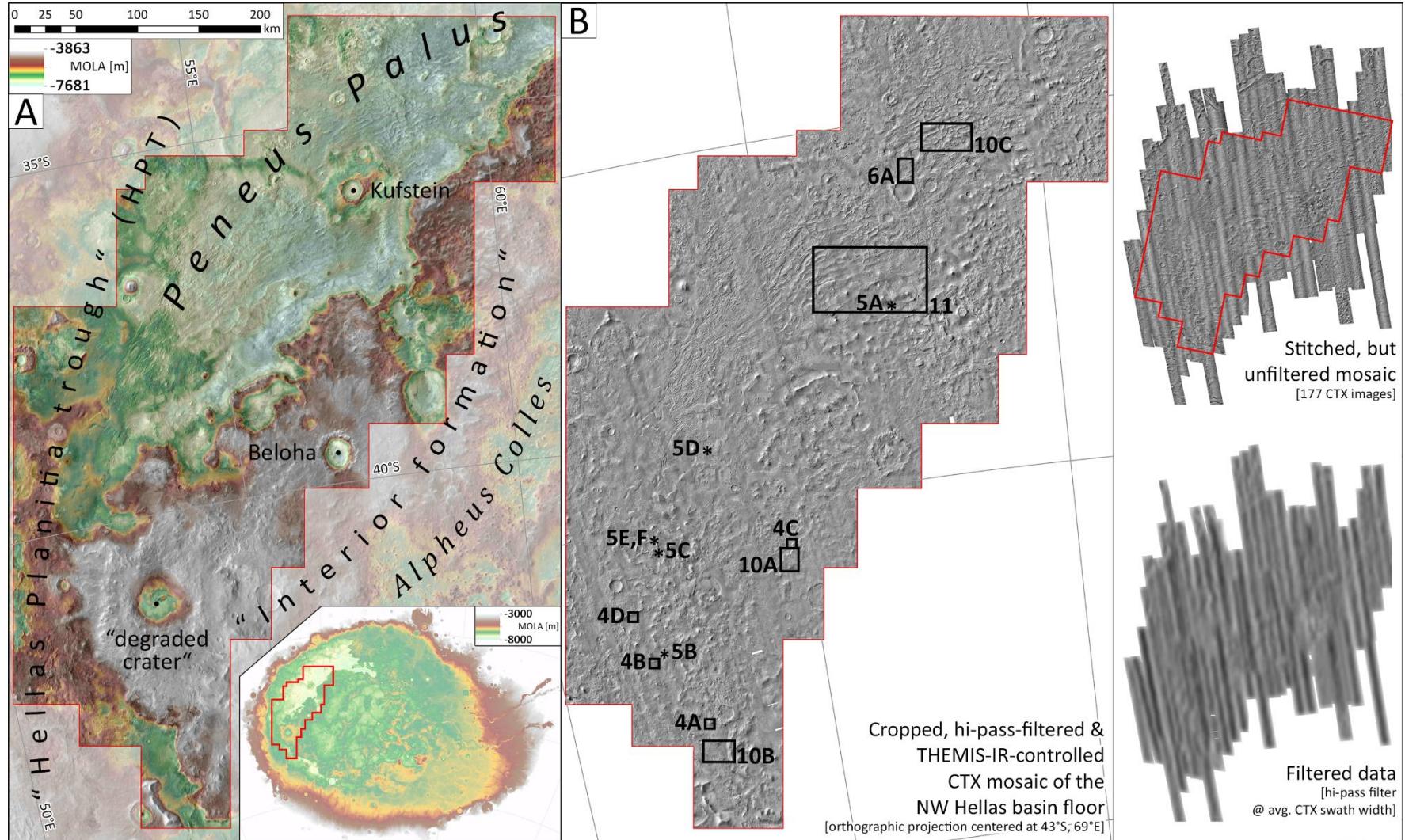


Figure 1: A) Physiographic overview of our mapping area on northwestern Hellas Planitia. MOLA DTM superposed on THEMIS-IR daytime mosaic (version 12). Inlet shows MOLA DTM of the entire Hellas basin floor; red outline indicates mapping area. B) Same scene showing our purpose-built CTX mosaic, which served as basemap for our morphologic map ([Fig. 2](#)), as well as two intermediate processing steps. Numbered asterisks and black boxes indicate locations of following figures.

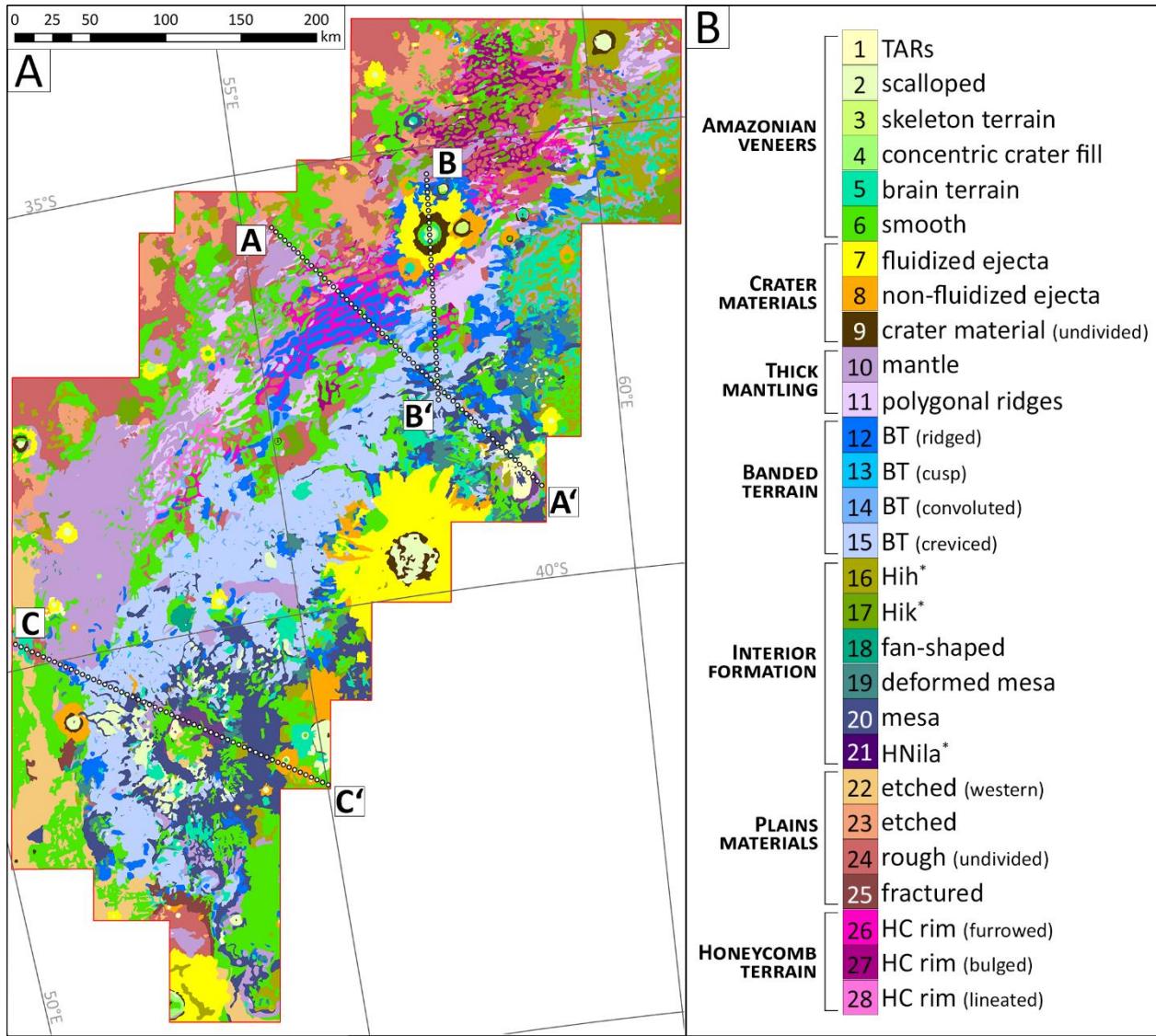


Figure 2: A) CTX-based, morphologic map (1:175,000) of northwestern Hellas Planitia (see Fig. 1A for context). Dotted white lines indicate traverses of stratigraphic profiles shown in Fig. 12. For descriptions and interpretations of all map units see section 5; unit type localities and areal extents are listed in table 1; standardized images of all type localities are shown in Fig. 8. B) Stratigraphically ordered and grouped list of all mapped units. \* unit labels adopted from Bernhardt *et al.* (2016a).

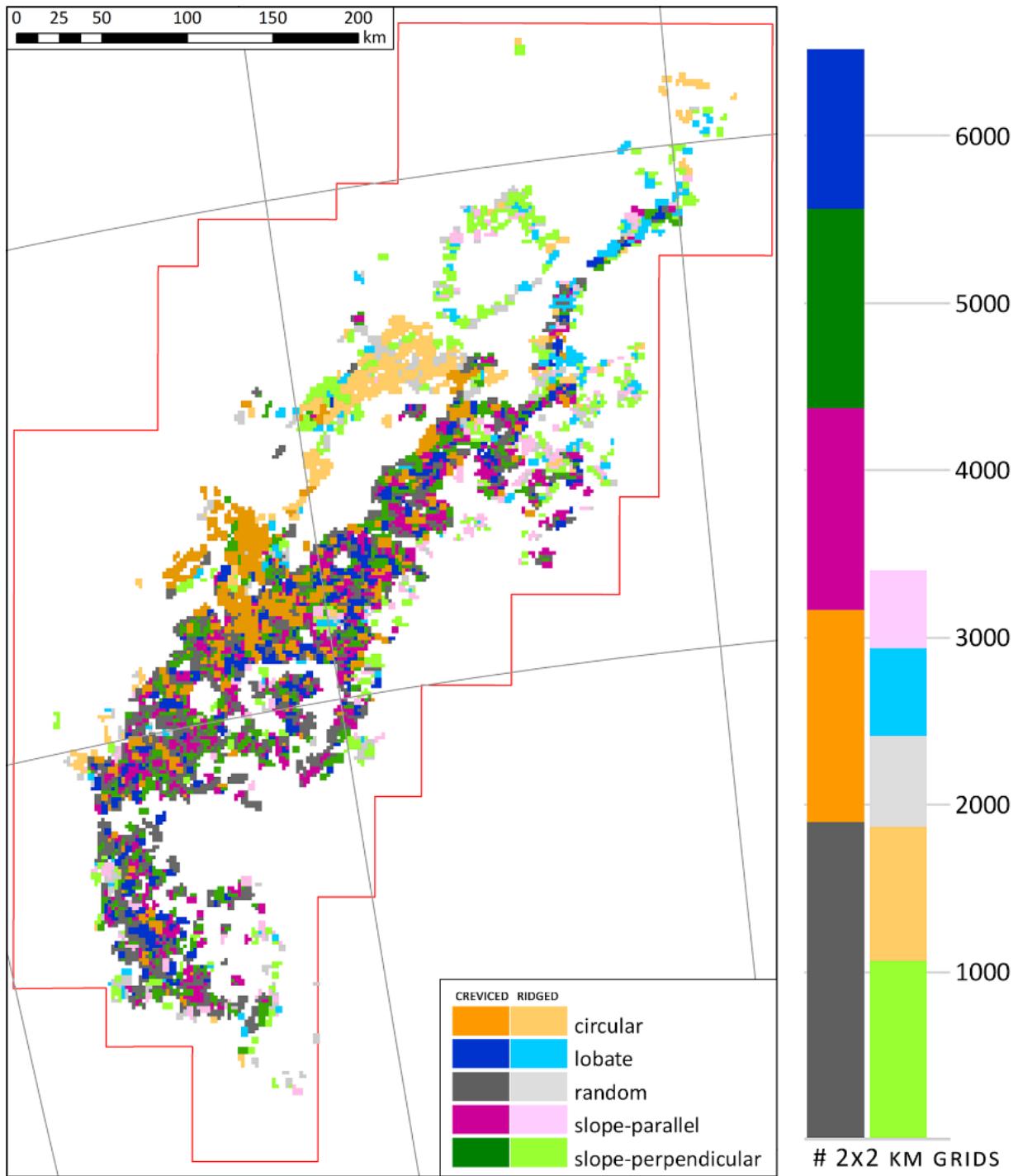


Figure 3: Grid mapping (box size 2x2 km) of the banded terrain as outlined in our morphologic map (Fig. 2). Colors indicate the dominant pattern of bands within a box (see inset); color brightness shows the two different types of banded terrain (creviced and ridged). Bar chart compares absolute number of boxes per type and category. See Fig. 3 for illustrations of different grid categories.

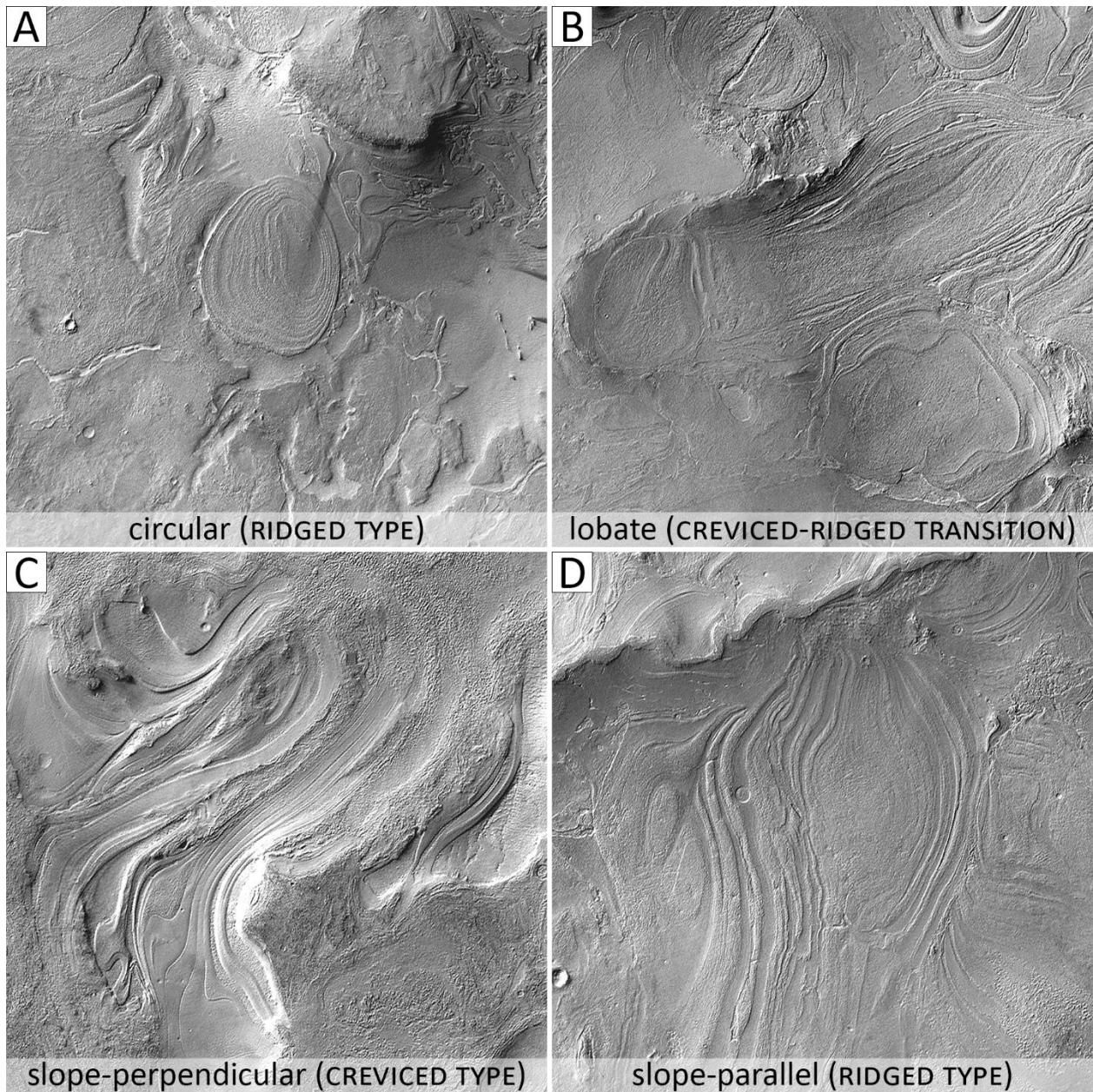


Figure 4: A-D) Collage of crops from our purpose-built CTX mosaic illustrating the four defined types of banded terrain patterns mapped in Fig. 3. Side lengths of images is 10 km; north is up; all image locations indicated in Fig. 1B.

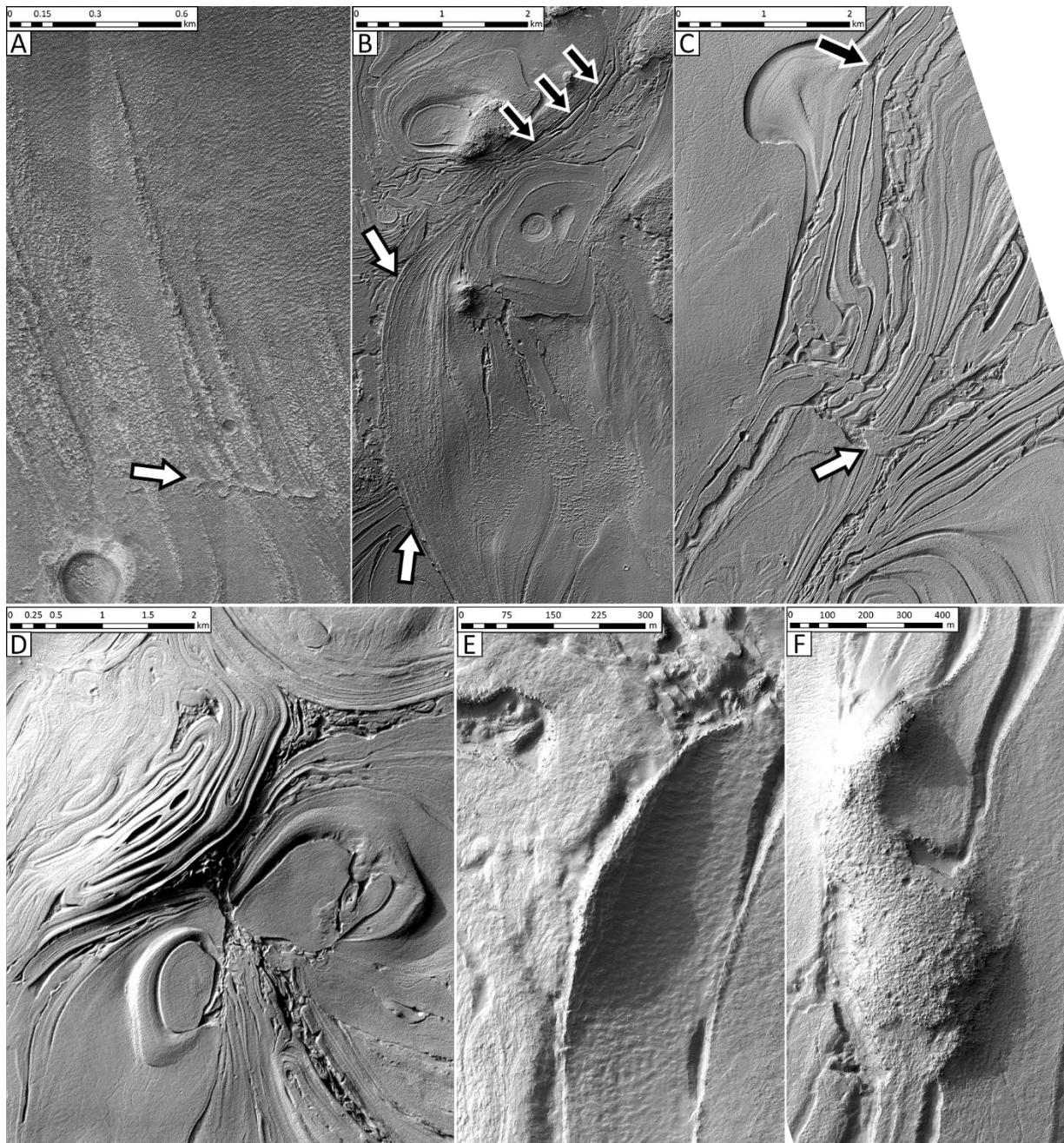


Figure 5: Detail observations of the banded terrain; all image locations indicated in Fig. 1B. A) HiRISE image ESP\_019978\_1420 showing a transition from creviced type banded terrain (south of white arrow) to the ridged type (north of white arrow). B) HiRISE image ESP\_035116\_1380 showing a braid-like portion of ridged type banded terrain apparently overlapping creviced type banded terrain (white arrows). Black arrows mark three boudinage-like segments within creviced typed banded terrain. C) HiRISE image PSP\_008269\_1395 of creviced type banded terrain; the

white arrow indicates one slab apparently breaking through another and causing the adjacent slab to rotate slightly; the black arrow marks band segmentation at a fold hinge, possibly enabling flexural slip. D) CTX image P13\_006199\_1382 showing a butterfly-shaped cusp. E) HiRISE image PSP\_008269\_1395 of a small ridge, probably a buckled slab, at the edge of a band of the creviced type banded terrain. F) HiRISE image PSP\_008269\_1395 of an inselberg-like, elongate mesa, which the surrounding band orientations appear to conform to.

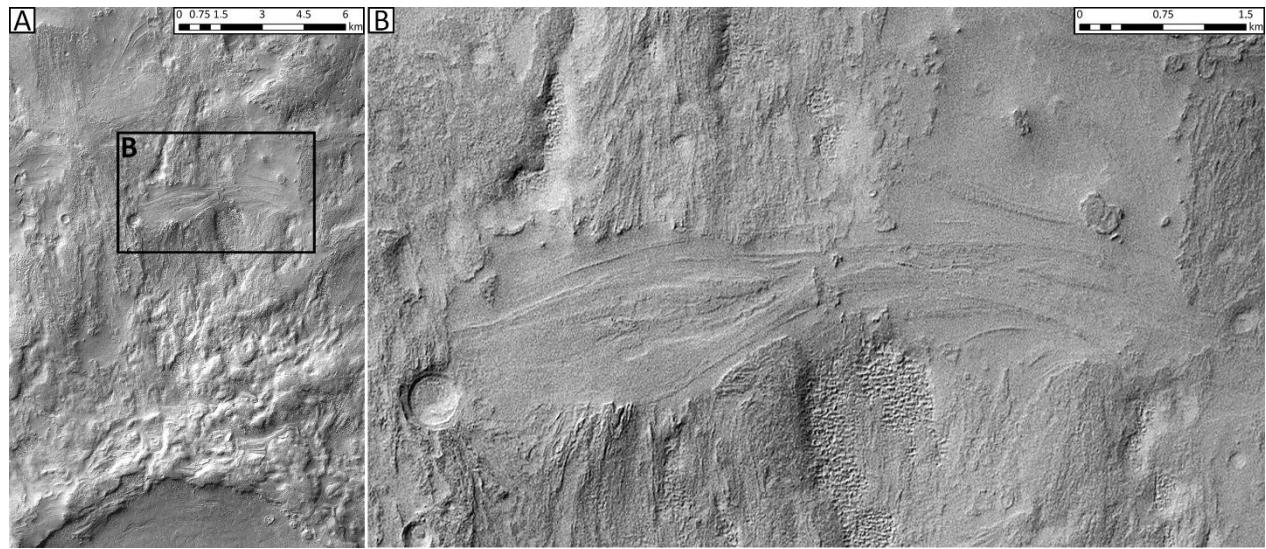


Figure 6: A) Crop of our CTX mosaic showing the northern rim of Kufstein crater (bottom of image) in the northern portion of our mapping area (location indicated in Fig. 1A). North is up. B) CTX image P16\_007425\_1443 showing a zoom on a portion of Kufstein's ejecta, which appears to be dissected by underlying banded terrain.

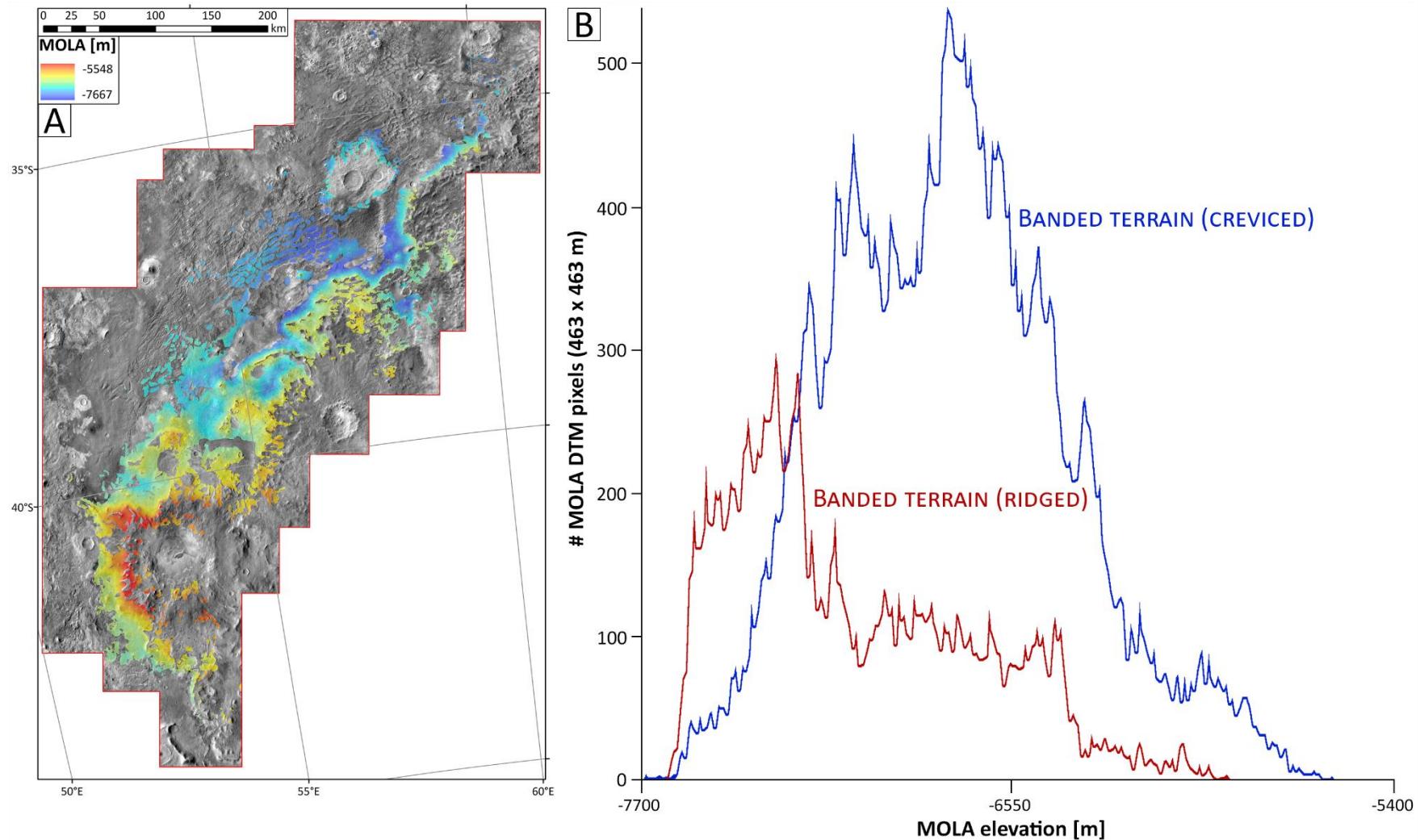


Figure 7: A) THEMIS-IR daytime mosaic overlaid by MOLA DTM cut out according to the banded terrain outline as shown in our morphologic map (Fig. 2). B) Hypsogram of all MOLA DTM pixels ( $463 \times 463$  m) contained within the banded terrain and differentiated

according to its type (creviced and ridged).

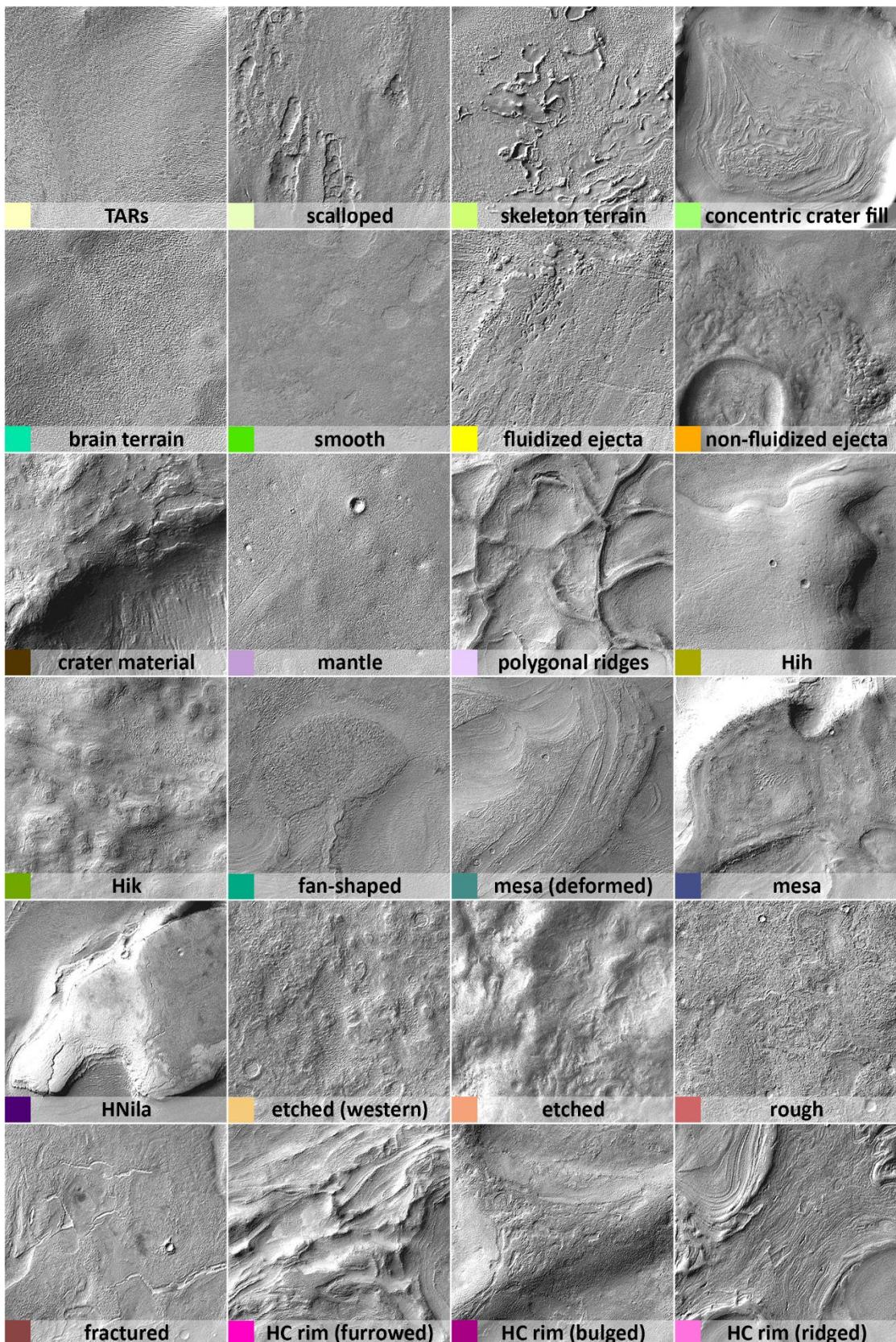


Figure 8: 5 x 5 km crops of our purpose-built CTX mosaic centered on the type localities of all

mapped morphologic units as listed in [table 1](#).

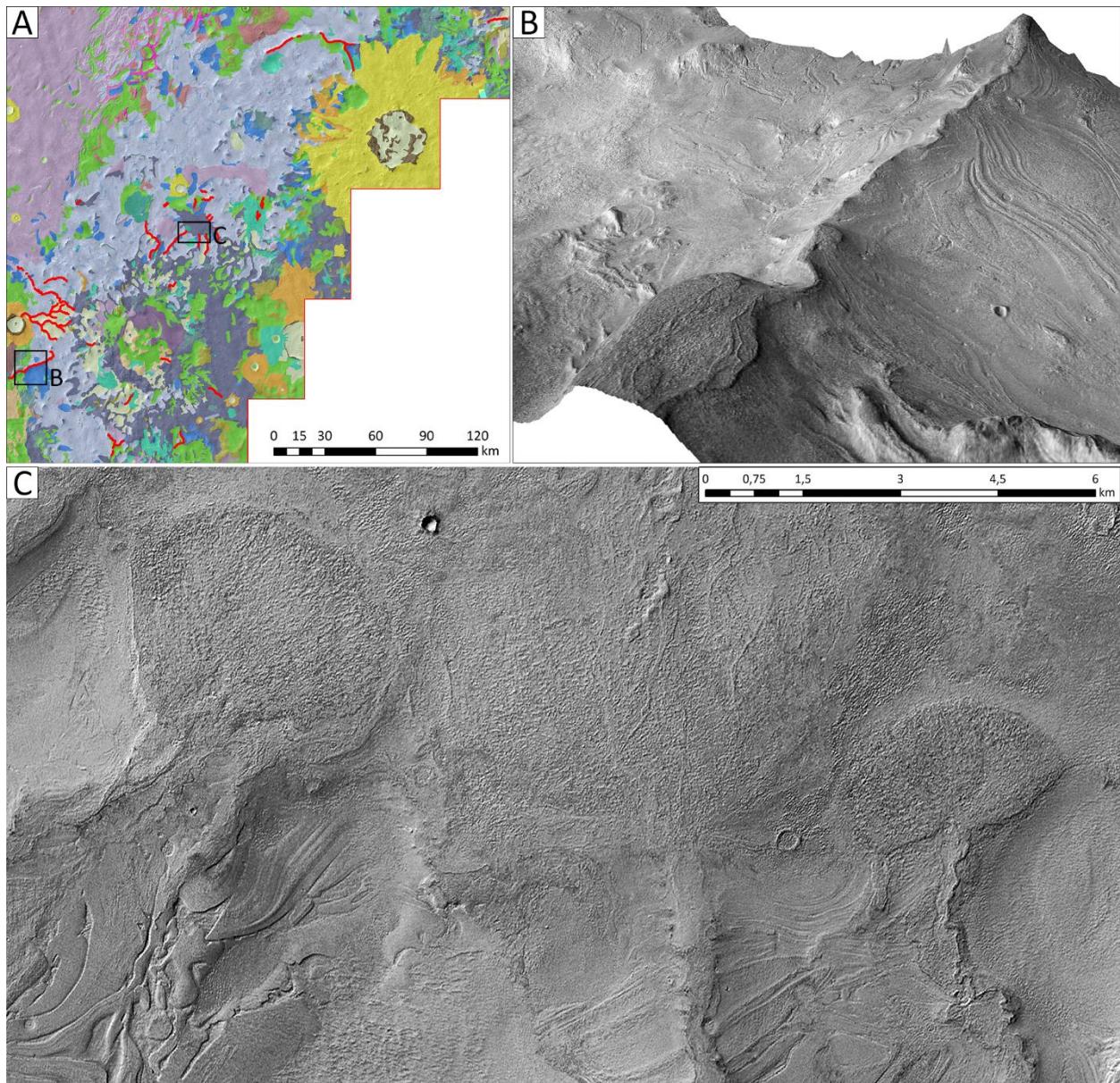


Figure 9: Observations of sinuous ridges surrounding the nameless “degraded crater” on western Hellas Planitia. A) Southeastern portion of our morphologic map (Fig. 2), showing Beloha crater in the upper right and the “degraded crater” in the lower left. Red lines mark sinuous ridges; black boxes indicate locations of (B) and (C). B) CTX image D20\_034905\_1382 projected onto a CTX stereo-DTM created in combination with image F21\_044083\_1382. The scene shows a prominent sinuous ridge terminating at an elevated plain characterized by a braiding system of smaller ridges (lower left). The ridge is located on top of a broader rise and the banded terrain can be seen

extending up on its flanks. C) Crop of our CTX mosaic showing the termini of three sinuous ridges, two of which transition into fan-shaped landforms that, in turn, are superposed on a *mesa* characterized by small, braiding ridges.

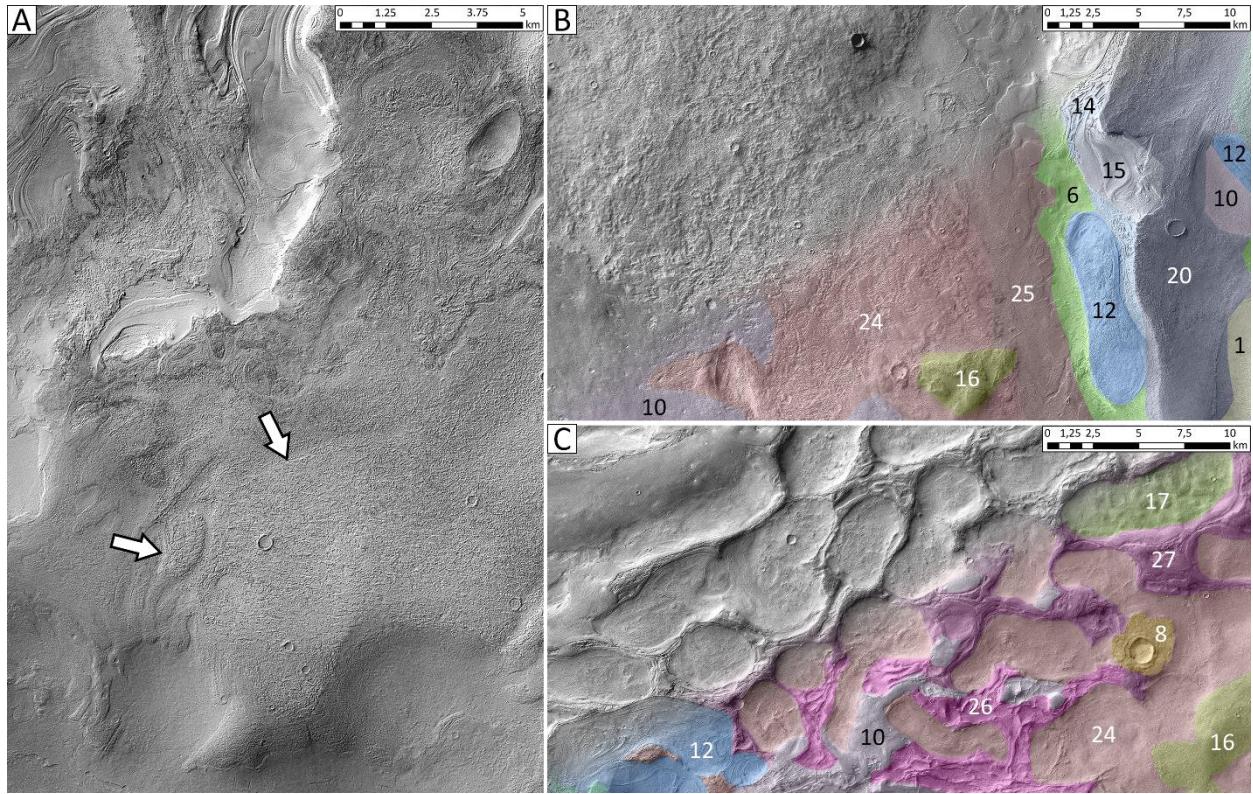


Figure 10: Stratigraphic observations pertaining to our morphologic map; image locations marked in Fig. 1B; all unit labels and numbers listed in Fig. 2B and table 1. A) Crop of our CTX mosaic showing unit *Hih* superposing a mesa (white arrows). B) CTX mosaic crop (lower right superposed by our morphologic map) showing from left to right: *Mantle* (10) superposing *rough* (24) material, which is also superposed by a zeugenbergs of *Hih* (16). *Rough* and *Hih* superpose *fractured* (25) material, which is also superposed by *smooth* (6) material, which in turn is overlain by banded terrain embaying a *mesa*. The latter is also partially covered by TARs (1), *mantle*, and banded terrain. C) CTX mosaic crop (lower right superposed by our morphologic map) showing honeycomb cells being filled by banded terrain, *rough*, and *Hik* (17). The scene also shows the transition from predominantly furrowed honeycomb rims (lower left) to predominantly bulged rims (upper right).

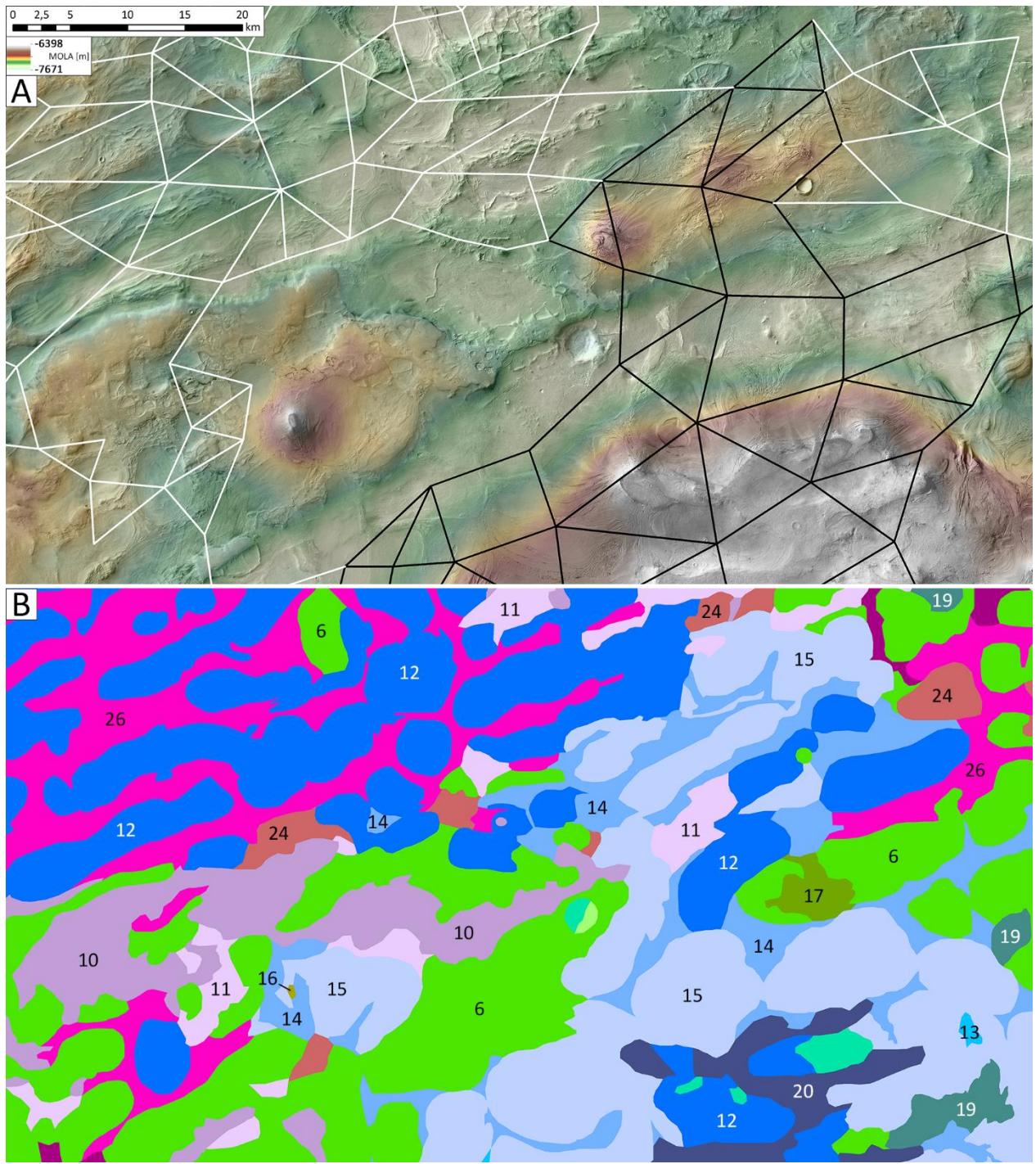


Figure 11: A) MOLA DTM superposing crop of our CTX mosaic; location shown in [Fig. 1B](#); north is up. The scene is centered on the southern edge of the honeycomb terrain; a portion of the elevated interior formation can be seen in the lower right. The white lines connect the centers of adjacent honeycombs (here defined as kidney/cell-like depression confined by unit *HC rim*). The black lines

connect adjacent kidney/cell-shaped arrangements of convoluted banded terrain, i.e., *BT* (*convoluted*), or by *mesas*. B) Portion of our morphologic map showing the same scene. Numbered units are listed in Fig. 2B and table 1.

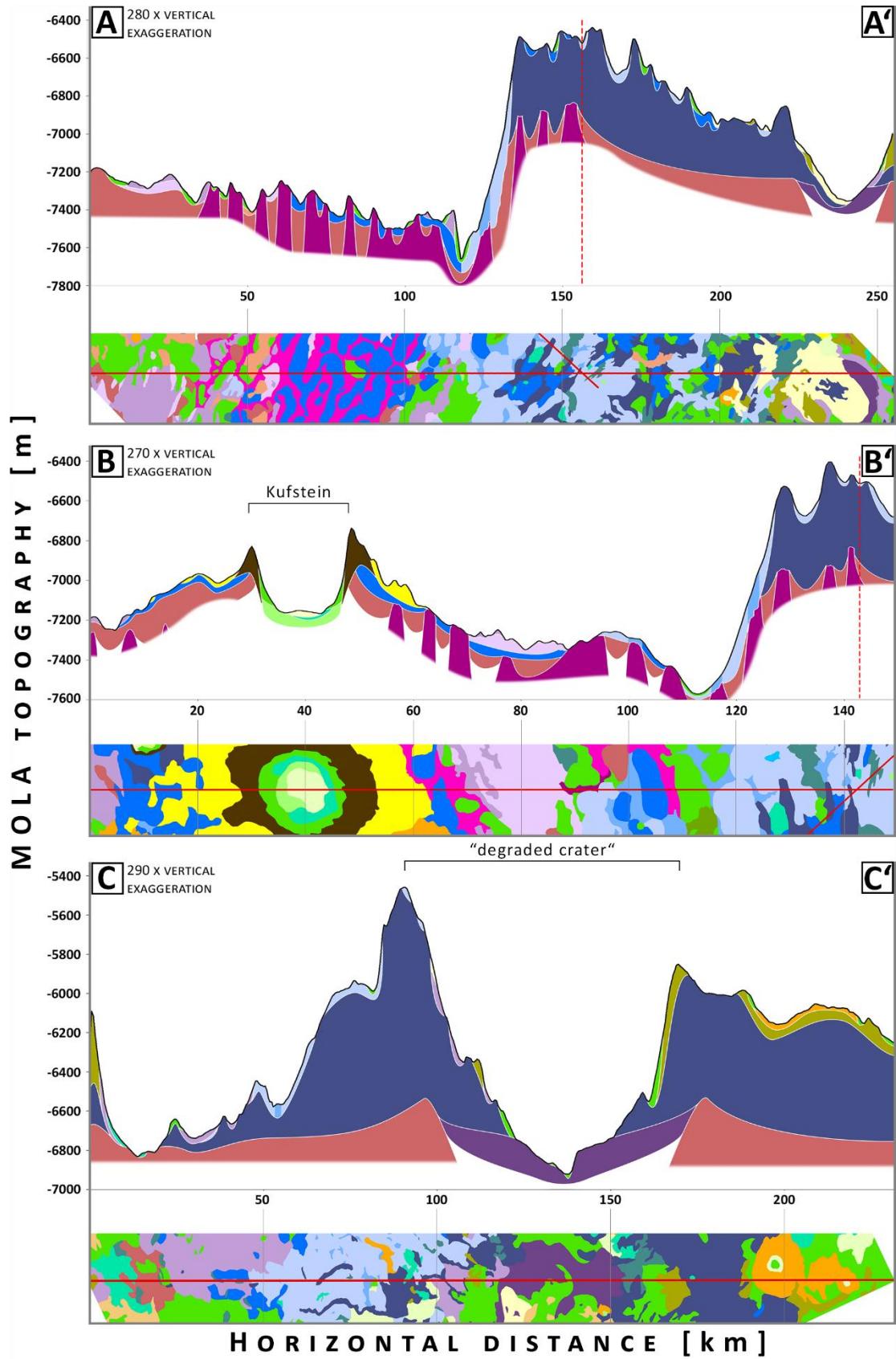


Figure 12: A-C) Cross-sections illustrating our stratigraphic model along three traverses through our morphologic map as shown in Fig. 1B. The model is partially based on that by Bernhardt *et al.* (2016a,b) and was expanded as well as refined based on our observations outlined in section 5 and showcased in Fig. 10 und 11. The red dashed lines in (A) and (B) indicate the intersection of both profiles.

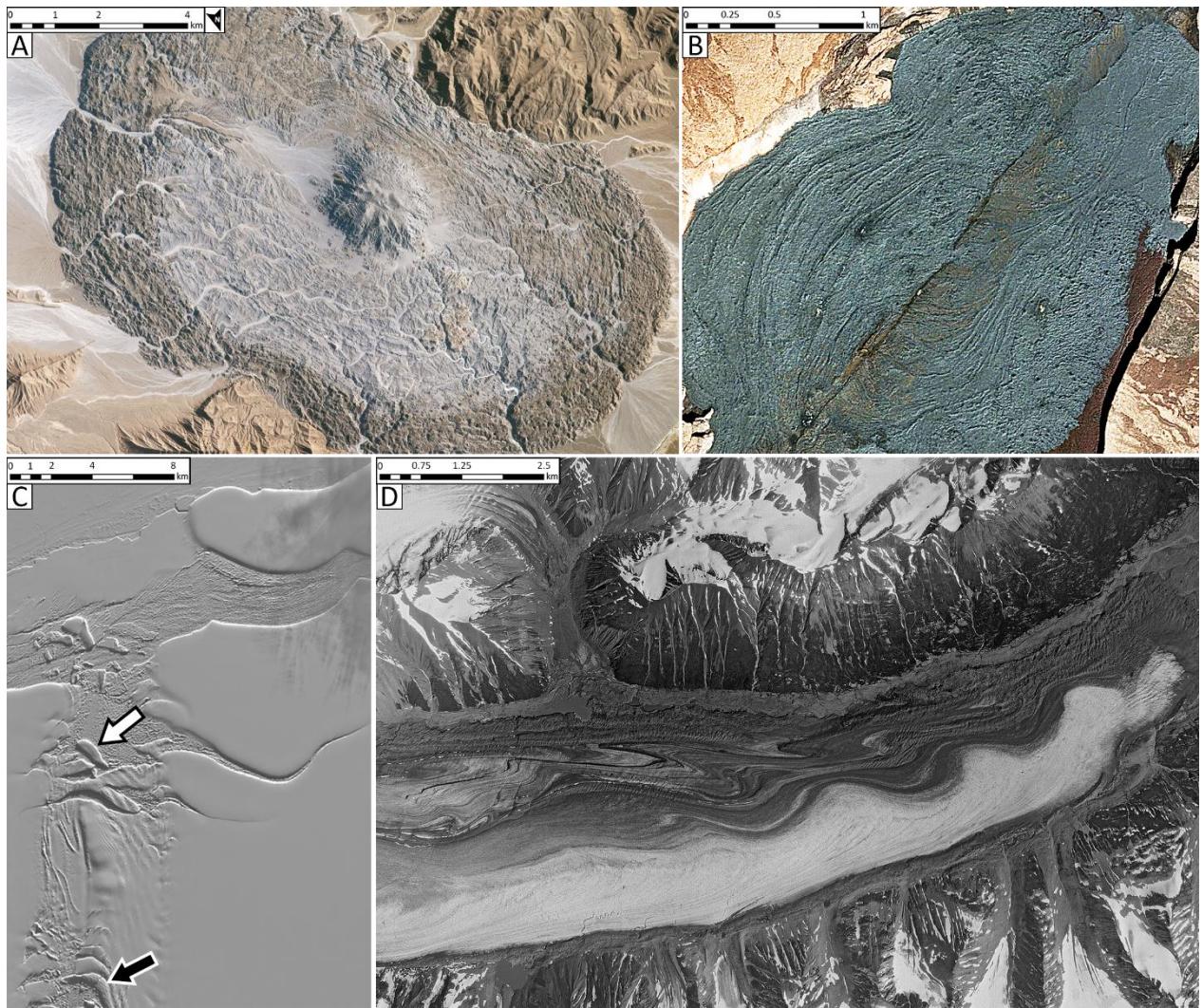
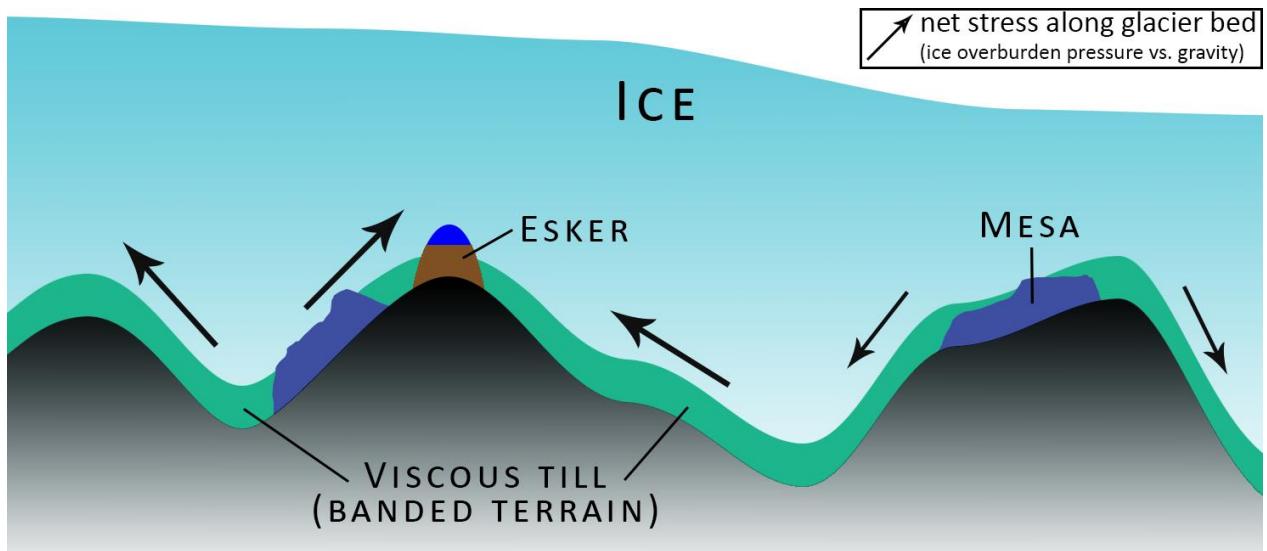


Figure 13: Terrestrial landforms investigated as potential analogs to the banded terrain. North is up in (B), (C), and (D). A) ISS astronaut photo ISS052-E-8401, acquired on 24 June 2017, of a salt dome surrounded by a salt glacier in the Zagros Mountains, southeastern Iran. B) QuickBird image, acquired 27 December 2002, of Mokuaweoweo, the central caldera of Mauna Loa, Hawai'i. It shows curvilinear ridges formed as flow lobes during the 1984 eruption of the fissure diagonally crossing the image. C) Landsat 8 image LC08\_L1GT\_191116 of the northern margin of the Ronne ice shelf at  $48,73^{\circ}\text{W}$  and  $77,76^{\circ}\text{S}$ , close to Berkner island. Interactions of stress fields create curvilinear compressional, and extensional, features. The white arrow points to a broken off, rotated slab; the black arrow show an area of upthrusting/buckling. D) USAF aerial photo acquired

on 22 June 1973 of Dusty Glacier in Kluane National Park, Yukon, Canada. Recurrent surges by a tributary glacier to the north create a curvilinear surface pattern.



1

2 Figure 14: Illustration of our subglacial formation model for the banded terrain (see section  
3 6.4).

4

5