CHAPTER V: ANALYSIS OF DARK MATERIAL – THE INTRA-CRATER DEPOSITS

The aim of this work is to gain as much information as possible about the dark material in Martian craters. Many properties of a certain subject of interest can be analyzed by using satellite data. The following analyses of the dark material are supposed to answer a set of questions, such as: What is the dune morphology? How is the material distributed over Mars? What are the material sources? What is the mineralogical composition? Are the dunes still active? Are there any correlations among these properties or between them and the geographical location? All this information is used as puzzle pieces from which a complete picture of the nature and origin of this material will be composed.

Analyses cover morphological aspects such as dune shape and distribution (Sect. 5.1), an investigation of dark layers exposed in crater walls (Sect. 5.2), and a spectral analysis of mineralogical compositions (Sect. 5.3). The mobility or otherwise of a dune depends on whether its sands can be transported by the winds that are currently blowing. The surfaces of active dunes consist of loose material, while inactive dunes should have consolidated surfaces. Thus, the active status of dunes can be detected by analyzing the relation of dune slip face orientation to current wind fields (Sect. 5.4) as well as the grain size and compaction of the dune sands (Sect. 5.5). The following describes the nature and appearance of the dark dunes and its material and presents analyses of its properties. It characterizes the analyses mentioned and introduces the utilization of thermal property information. It provides the results of these analyses and, finally, includes some conclusions, which may be drawn from them.

5.1 Morphology of Dark Intra-Crater Material

The morphology of the dark material deposits is diverse. Next to a great variety of dune types, the material forms dark wind streaks and sand sheets of varying size and thickness. This chapter addresses the differences in the appearance of the dark material accumulations on Martian crater floors.

The general appearance of dark material in Martian craters can be divided into four categories: small clusters of single dunes, dunes associated with sand sheets aligned around obstacles such as central peaks, spacious huge compound or complex dune fields, and thin sand sheets. Examples of these categories are shown in Fig 24 a-d.

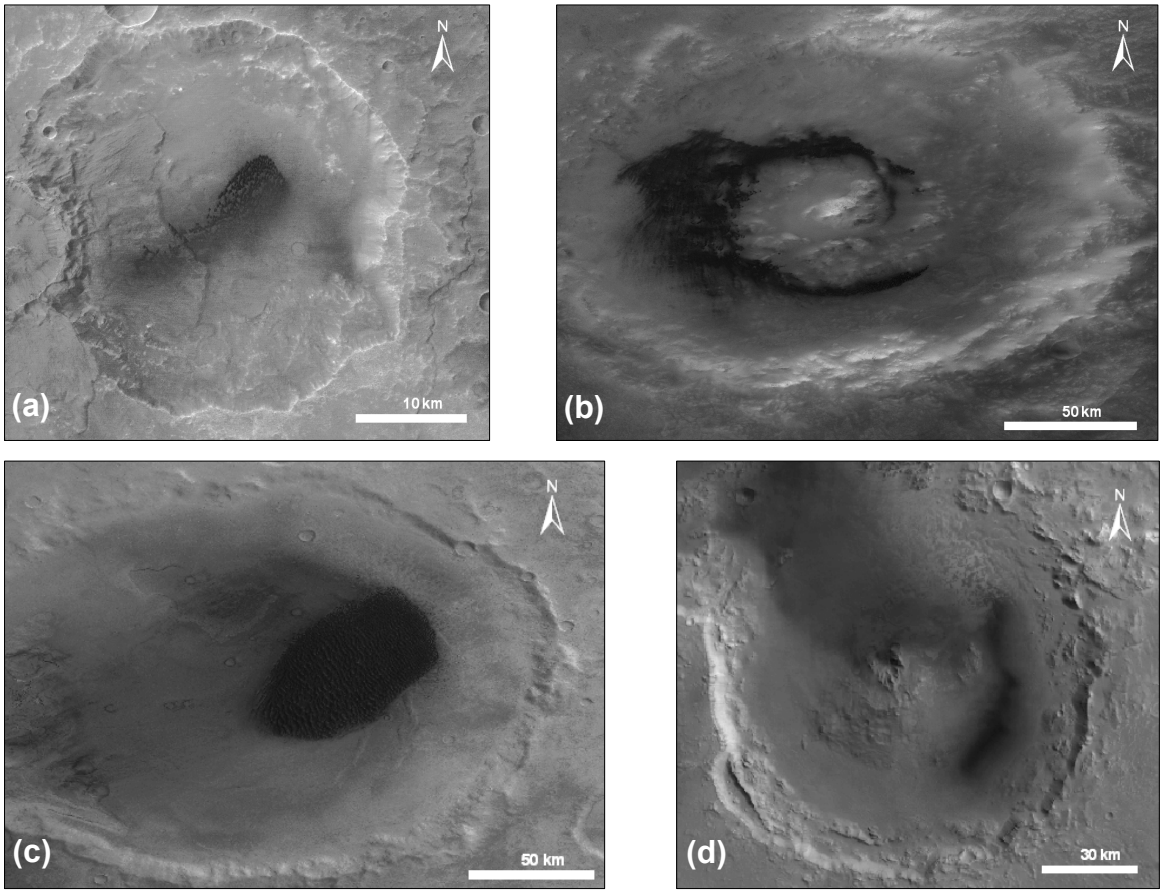


Figure 24: Different types of dark material deposits in Martian craters.
(a) Barchan dune field in a crater in Tyrrhena Terra (14.3°S, 95.8°E; HRSC 0038_0000). **(b)** Circular dune field in Liu Hsin Crater associated with a sand sheet (53.5°S, 188.4°E; HRSC mosaic of 4381_0009, 4370_0000, and 4359_0000). **(c)** Complex dune field in Proctor Crater (47.9°S, 29.5°E; HRSC mosaic of 2529_0000 and 2496_0000). **(d)** Sand sheet in Oudemans Crater (9.8°S, 268.2°E; HRSC 0442_0008).

Ten out of the 70 localities analyzed consist of intra-crater sand sheets without dunes. Such flat deposits develop where the amount of available sand and the local wind regime are not adequate for the formation of dunes, while the presence of hardly transportable coarse grains appears to be a supporting factor [*Pye and Tsoar*, 1990]. The thickness of the sand sheets cannot be determined clearly from the available data sets. However, because the sand sheets are distinct from brighter surrounding materials their thickness should be at least equivalent to the optical thickness of dark sand, which is no less than a few microns (cf. Sect. 5.5.1), depending on composition, grain size, grain shape, and packing. Furthermore, individual sand sheet thicknesses can be derived from the grain size of the sheet material. If the density of the sand sheet does not permit identifying the underlying surface, the sand sheet should consists of at least two grain layers. Thus, its thickness should be at least twice the grain size. A sand sheet of 100 µm-sized grains would therefore have a minimum thickness of 200 µm. Due to the lack of slip faces or wind streaks, no morphology-deduced wind direction could be determined for sand sheets. Sand sheets are often found to cover the centre of a crater (Fig.25a). However, their distribution may also depend closely on the crater morphology if local winds distribute

the material around central peaks, as in Oudemans Crater (Fig. 24d). The sand sheet in Perrotin Crater shows a dichotomy in material distribution probably caused by local winds (Fig. 25b).

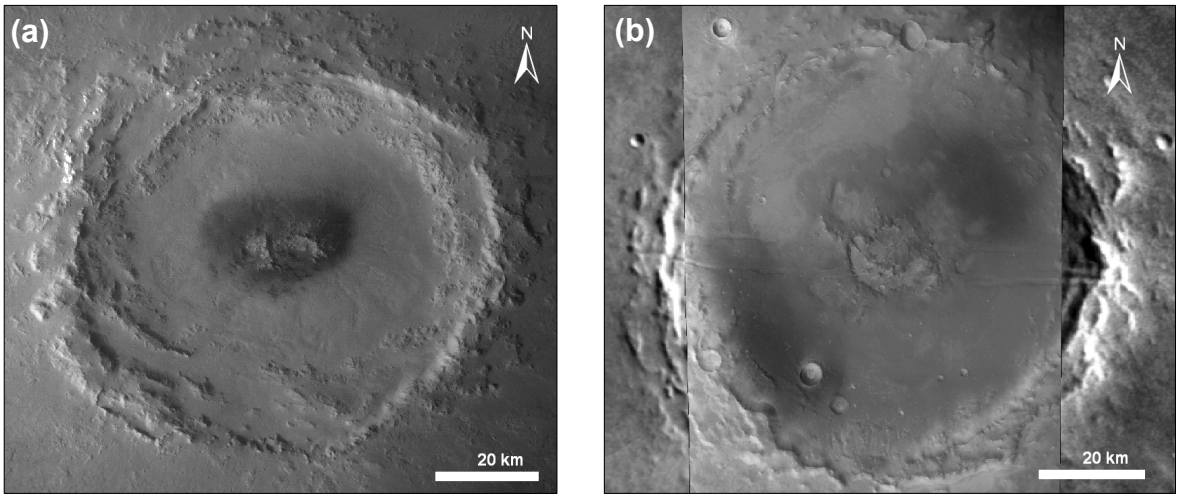


Figure 25: Differences in the appearance of sand sheets.
(a) Sand sheet in a small crater in Hesperia Planum showing a central sand sheet (31.6°S, 108.7°E; HRSC 1909_0000). (b) Sand sheet in Perrotin Crater showing a dichotomy in material distribution (2.9°S, 282.0°E; HRSC 2149_0000).

The remaining localities comprise dunes or dune fields of different types and sizes, frequently surrounded by sand sheets produced by the deflation of dune material. Craters with separate dunes often feature barchan dunes (Fig. 24a and 26a), the most common dune type on Mars [*Breed et al.*, 1979]. Their number varies widely, ranging from a few individual dunes to clusters of several 10s to 100s. A larger amount of dark sand promotes the development of bigger fields of interconnected and merged dunes up to huge compound or complex dune fields (Fig 24c). Flat but spacious dune fields are primarily found on big degraded crater floors, such as those of Lyot Crater (50.6°N, 29.4°E), Moreux Crater (42.1°N, 44.5°E), Gale Crater (5.4°S, 137.8°E), and Liu Hsin Crater (53.5°S, 188.4°E; Fig. 24b) (for localities see Fig. 2 and Appendix). The material is often aligned along the irregular crater topography or accumulates in a circular shape around a central peak. The dune types found in these localities are barchans (Fig. 26a) and barchanoid ridges (Fig. 26b). In addition, sand sheets surround the dunes and cover small knobs, hills, and ridges on the crater floor.

Compound dune fields comprise multiple dunes of the same type coalesced into a huge aeolian bed form [*McKee*, 1979]. Often, smaller dunes climb up the windward and leeward side of the main dune complex [*Silvestro et al.*, 2008]. Complex dunes fields consist of patterns of different dune types, which have grown together or are superimposed onto each other [*McKee*, 1979; *Kocurek and Ewing*, 2005]. Compound and complex dune fields are mostly found in great ancient craters of Noachis Terra, such as Russell, Kaiser, Proctor (Fig. 24c), and Rabe Crater (for locations see Fig. 2 and Appendix). Common dune types are barchans (Fig. 26a), barchanoid ridges (Fig. 26b), and transverse

dunes (Fig. 26c). The latter often arise from barchanoid dunes and are characterised by asymmetric ridges with one slip face [*Hayward et al.*, 2007a]. Linear dunes (Fig. 26d) may develop where a continuous bi-directional wind regime prevails. Some few circular dome dunes (Fig. 26e) were found in the vicinity of bigger dune fields, often aligned along their margins where they can be influenced by winds coming from various directions. Star dunes (Fig. 26f) were found in just two localities, both medium-sized to huge dune fields in the southern lowlands. This pyramid-shaped dune type develops under multidirectional wind conditions [*Edgett and Blumberg*, 1994]. Like dome dunes, star dunes are located at the outer margin of dune fields, an area which might be more exposed to different winds than the inner regions of a dune field. Linear, dome, and star dunes are very rare on Mars [*Edgett and Blumberg*, 1994; *Lee and Thomas*, 1995]. Unclassified dunes were found in a total of 28 localities. In most of these cases, bad image quality is the reason why classification was impossible. Unusual dune morphology can be another reason for unclassified dunes. Examples of their diverse appearance are described by *Haywards et al.* (2007a).

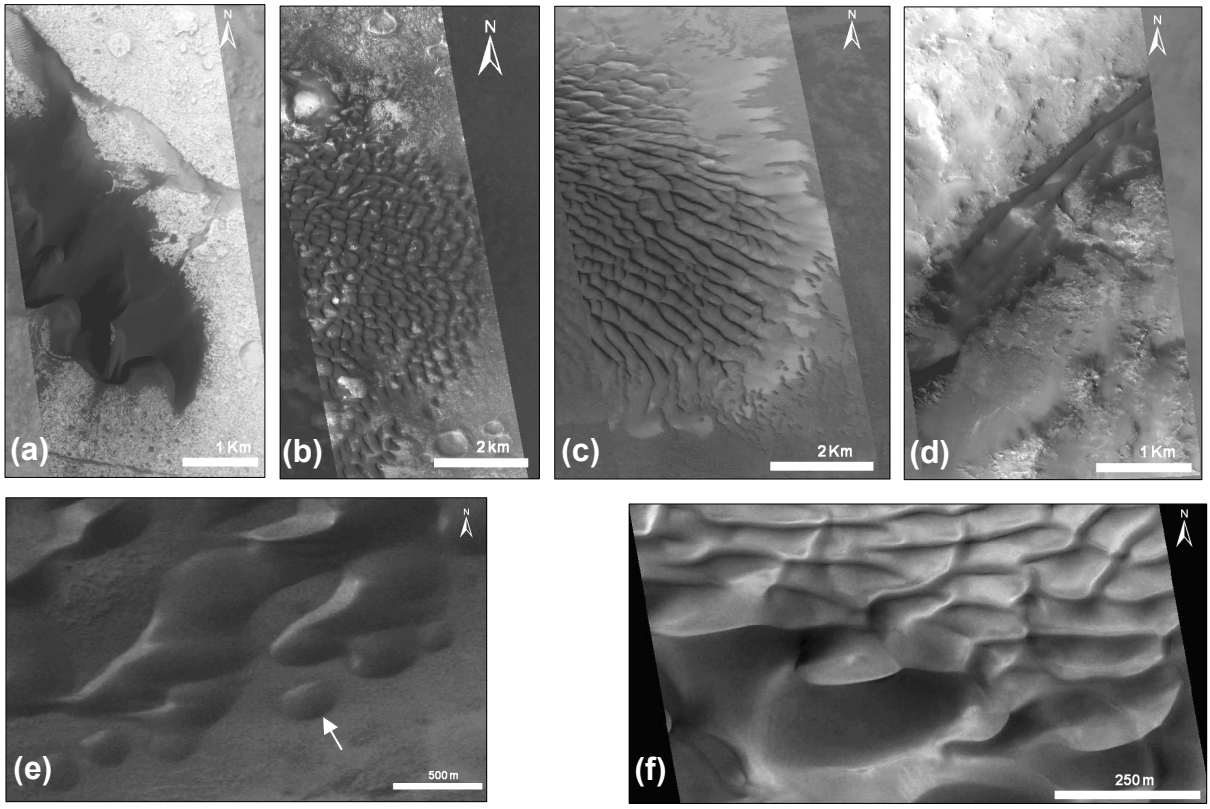


Figure 26: Diverse dark-material dune types.
(a) Barchan dunes in a small crater at Arabia Terra (5.6°S, 343,5°E; MOC E2200514). **(b)** Barchanoid dunes in Moreux Crater (42.1°N, 44.5°E; MOC E0100550). **(c)** Transverse dunes in Lyot Crater (50.6°N, 29.4°E; MOC M1800073). **(d)** Linear dunes in Dawes Crater (9.2°S, 38.0°E; MOC M1101900). **(e)** Dome dunes (see arrow) in Liu Hsin Crater (53.5°S, 188.4°E; MOC R2001248). **(f)** Star dunes associated with barchans in a small crater near Argyre Planitia (42.5°S, 305.1°S; MOC R1501756).

An interesting example was found in Dawes Crater, where unusual straight linear dunes (unlike their meandering terrestrial counterparts) are aligned along a sort of wind aisle coming down the crater wall (Fig. 27). At the downwind end of the linear dunes, barchan dunes developed. The latter dune type indicates a unidirectional wind regime in contrast to the bi-directional wind regime generally constitutive for the formation of linear dunes. A comparable case to the Dawes Crater dunes was reported by *Schatz et al.* (2006) who found straight linear dunes coexisting with elongated and rounded barchans in the north polar region (see Sect. 5.7). They found the induration of dune surfaces to be the probable cause for this odd dune type and combination.

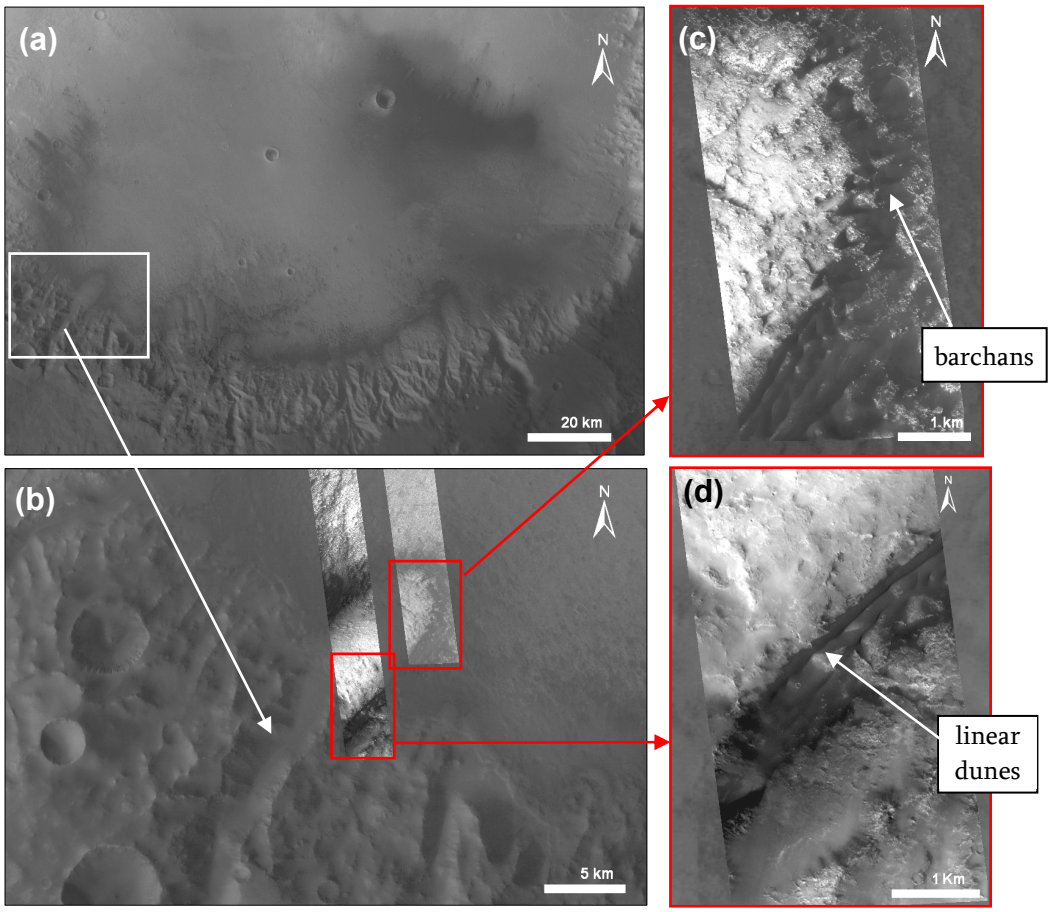


Figure 27: Linear dunes associated with barchans in Dawes Crater (9.2°S, 38.0°E).
(a) Subset of Dawes Crater showing dark material (HRSC mosaic 1961_0000, 1950_0000, 1928_0000 and 1917_0000). **(b)** Detail of Fig. a showing the wind aisle (MOC overlaid on HRSC). **(c)** Barchan dunes at the north-eastern end of the wind aisle (subset of MOC E1200683). **(d)** Linear dunes at the eastern margin of the wind aisle (subset of MOC M1101900).

Table 9 lists localities or craters together with the dune types found there. Note the diversity of dune types found in a singly locality and the frequent association with sand sheets. Some of the abbreviations for the dune types have been adapted from the Mars Digital Dune Database (see Sect. 4.7.2) [*Hayward et al.*, 2007b]. They are: B – barchan dune; Bd - barchanoid dune; T - transverse dune; L - linear dune; D - dome dune; St - star dune; Ss - sand sheet; U - unclassified.

Table 9: List of analyzed localities with corresponding dune types.

Locality ID	dune type	Locality ID	dune type
Arabia1	B, U	Moreux	B, Bd, Ss
Arabia2	B, Ss	Morpheos Rupes	Bd, U
Arcadia	B, U, Ss	Newton2	Ss
Argyre1	Bd	Nier	Ss
Argyre2	Bd, St	Nili Fossae	B, Bd, Ss
Barnard	U	Nili Patera	B, Bd, L
Chaos1	B	Ophir1	B, Bd, Ss
Chaos2	B, Ss	Ophir2	U
Chaos3	U	Oudemans	Ss
Chaos4	B, Bd, U, Ss	Peridier	B, Ss
Cimmeria1	B, Bd, U	Perrotin	Ss
Cimmeria2	B, Bd, U, Ss	Porter2	Bd, B, U
Cimmeria_Sirenum	Ss	Proctor	B, Bd, T
Dawes	B, L, Ss	Rabe	B, Bd, T
Elysium	B, Bd, Ss	Rabe2	B, Bd
Fesenkov	B, Ss	Richardson	Bd, T
Gale	B, Bd, L, Ss	Rossby2	U
Gill2	U, Ss	Renaudot	B, Ss
Gill	U, Ss	Reuyl	U, Ss
Hellas	U, Ss	Russell	B, Bd, D, L, T
Hesperia	Ss	Sagan	B, Ss
Holden	B, Bd	Sinus_Meridiani	B, U
Liu Hsin	B, Bd, D	Sirenum1	U
Lyot	B, Bd, T	Sirenum2	B, Bd, U
Kaiser	B, Bd, T, St	Thaumasia1	U, Ss
Kunowsky	Ss	Thaumasia2	Ss
Ma'adim Vallis	Ss	Tolstoy2	U
Mamers Valles	Ss	Trouvelot	B, Bd, D, U, Ss
Maja Valles	U, Ss	Tyrrhena1	B
Maraldi2	U, Ss	Tyrrhena2	B
Marte Vallis	U, Ss	Tyrrhena3	B
Mawrth Vallis	B, U, Ss	Vastitas	B, Bd
Melas Dorsa	Ss	Verrier2	B, Ss
Meridiani	B, Ss	Xante1	U, Ss
Molesworth	B, Bd	Xante2	U, Ss

Total No° of localities comprising the different dune types:

Barchan dunes:	35	Linear dunes:	4
Barchanoid ridges:	25	Star dunes:	2
Transverse dunes:	6	Dome dunes:	2
Unclassified dunes:	28		

Fig. 28 summarizes the results of Table 9, presenting a global view of the distribution of dune types observable at the localities analyzed. Note that although designated as one dune type, transverse dunes, dome dunes, and star dunes coexist with barchans or barchanoid ridges in most cases. The distribution of dune types on Mars is irregular and does not correlate with any geographical location because their formation follows no specific geographic aspects but is governed by local topography, wind regime, and sediment supply [*Tirsch and Jaumann*, 2008]. Barchan and barchanoid dunes are the most common dunes observed, followed by transverse dunes. Linear dunes, star dunes, and dome dunes are rare on Mars. Like transverse dunes, they are frequently located in huge dune fields together with other dune types and sand sheets.

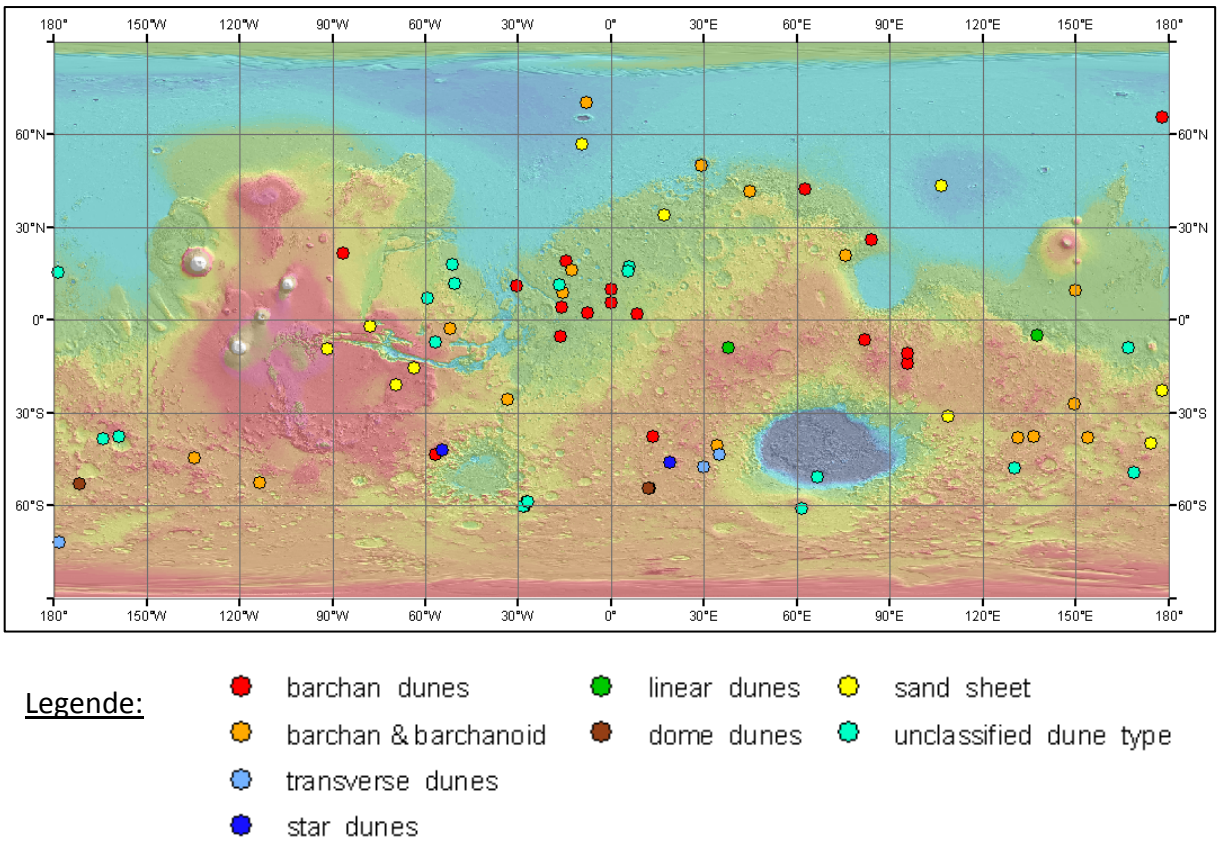
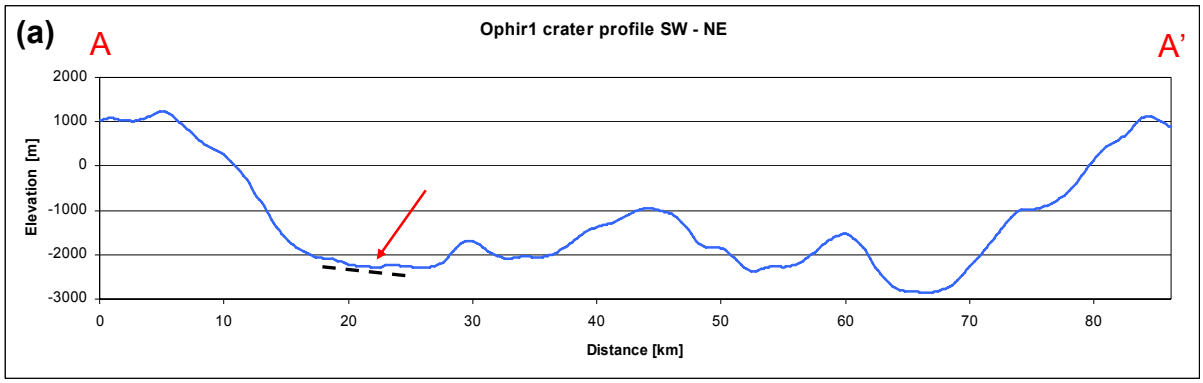


Figure 28: Global view of dune type and sand sheet distribution in the localities analyzed (background: MOLA topography map).

The location of the dune fields within the craters was analyzed by means of profiles created from HRSC and MOLA DTMs. One point of interest was whether or not the dark material is always deposited at the lowest point in a crater. An analysis of all 70 profiles revealed that the material is not always deposited at the lowest point on a crater floor. Varying material positions in the craters suggest that its deposition is not driven by aspects of topography and wind regime only. Although deposits are often aligned with the downwind side of the crater floor, indicating wind-controlled deposition [cf. *Thomas*, 1984; *Greeley et al.*, 1993; *Christensen et al.*, 1998], there seems to be an additional local parameter that governs the material's position within a crater (see Sect. 5.2, Fig. 33).



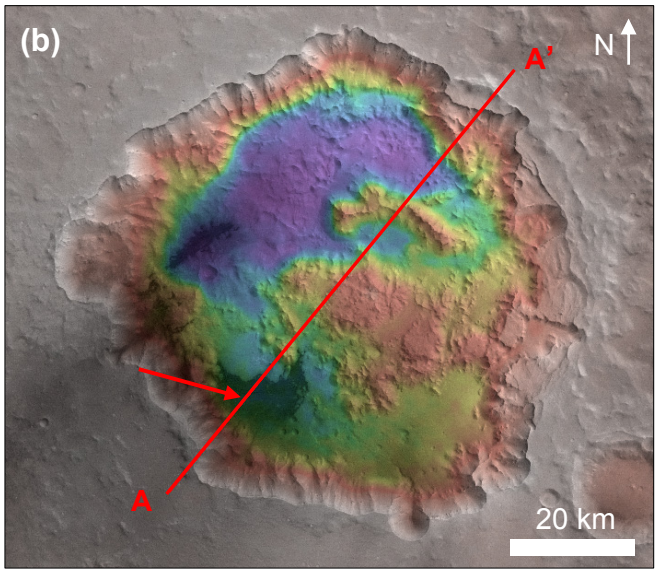


Figure 29: Cross-section of a probable collapse depression in Ophir Planum (3.0°S, 307.8°E). **(a)** Profile from SW to NE (A – A'). The black dotted line indicates the position of dark dunes, the position of the red arrow corresponds to that in Fig. b. Note that the dark material is not accumulated at the lowest point within the depression. **(b)** Colour-coded elevation image. The red line indicates the course of the profile from SW to NE (A to A') shown in Fig. a. (HRSC 0394_0002, DTM overlaid on nadir image).