CHAPTER VI: ORIGIN AND EVOLUTION OF DARK MATERIAL

In the following chapter, the results of the analyses presented will be discussed with respect to possible hypotheses on the origin and evolution of the dark material on Mars.

Morphological conditions show that the material is distributed almost all over Mars. This is barely indicative because the material is obviously distributed by globally acting aeolian processes. At first sight, no obvious geologic unit can be distinguished as the source of the dark materials (except for the dark deposits of the north polar erg, which probably have their local origin in the Planum Boreum cavi unit [*Tanaka et al.*, 2008], cf. Sect. 3.4). Although dark material is predominantly found on impact crater floors, there is no convincing evidence that it is predominantly blown into the craters. This suggests that the occurrence of such material in the craters might be directly associated with the crater localities themselves. Further morphological analyses of the impact crater walls revealed dark layers exposed in the walls and evidence of transport of the dark layer material into the crater interiors (Sect. 5.2). However, these layers could not be localised everywhere, not even in the majority of the craters. Therefore, it is problematic to draw conclusions from the small body of evidence for the entire set of study localities. Nevertheless, the small number of dark layer exposures in crater walls could be explained by the fact that these layers were covered by weathered regolith or dust (see Fig. 39) in many places. Further probable sources of dark materials could be identified beneath the floors of some craters in eastern Arabia Terra for example. These dark layers might be located just beneath the crater floors and were cut by smaller craters superimposed onto the larger crater floors (see Sect. 5.2, cf. Fig. 31 and 36). But how to explain the irregularities in the elevation of craters that exhibit probable dark material sources underneath their floors or in their crater walls, or the fact that craters, located at the same level nearby, do not exhibit any signs of dark material at all? These questions will be discussed in Sect. 6.2. What other diagnostic facts about dark material did the analyses reveal?

The mineralogical composition of the dark material (pyroxenes and olivines) points to unweathered material which did not undergo chemical alteration and, consequently, did not have contact with liquid water for a relatively long time [*Jaumann et al.*, 2006]. Otherwise, the mafic minerals would have changed into hydrated minerals [*Matthes*, 2001] which, however, were only found in a few places in Arabia Terra (see Sect. 5.3). This is another indicator that the material might have been buried and protected in times when liquid water occurred on the Martian surface. If the material has its primary genesis in a time before liquid water existed on the surface, this hypothesis would imply that the material is older than the Late Noachian and was buried from the Middle Noachian to the Late Amazonian period. This age is drawn from the dating of the oldest fluvial events, e.g. the beginning of the formation of extensive valley networks around 3.8 to 4.0 Ga (cf. Table 3, Sect. 2.1, and Fig. 73, Sect. 6.1) [*Masursky et al.*, 1977; *Neukum and Hiller*, 1981; *Scott and Tanaka*, 1986; *Greeley and Guest*, 1987; *Marchenko et al.*, 1998; *Jaumann*, 2003; *Werner*, 2006]. Alternatively, the material could be much younger, originating after the wet periods on Mars. This would imply a genesis starting in the Late Amazonian (around 0.1 to 0.05 Ga), inferred from the age of the youngest fluvial features (cf. Table 3, Sect. 2.1, and Fig. 73, Sect. 6.1) [*Head et al.*, 2001; *Jaumann*, 2003; *Werner*, 2006]. The specific implications of the material age question will be discussed in the next section.

Further results of the analyses presented, such as dune induration, are of minor diagnostic importance for the material itself. However, consolidation and crusting processes take a certain time to develop (e.g. crust formation on Mars is estimated to take 10^5 to 10^6 years [*Jakosky and Christensen*, 1986], cf. Sect. 5.7). Thus, this fact helps in proposing a minimum age for the respective dune fields.

6.1 Possible Scenarios of Origin

What could be the cause of layer deposition? What is the origin of the material?
On Earth, mafic minerals as detected by spectroscopic analyses (Sect. 5.3) usually develop as a result of volcanic activity [*Matthes*, 2001; *Markl*, 2004]. Analogously, the mafic material on Mars is of magmatic origin [e.g. *Edgett and Lancaster*, 1993; *Edgett and Christensen*, 1994; *Ruff and Christensen*, 2002; *Fenton and Bandfield*, 2003; *Rogers and Christensen*, 2003; *Fenton*, 2005b; *Hayward et al.*, 2007a]. Thus, the dark deposits might have their origin in the deposition of a thick layer of volcanic ash after one or more volcanic eruptions. These hypothetic volcanic eruptions probably led to the deposition of several different ash layers that are located at different depths today. Chronologically, these eruptions should have occurred in the Early to Middle Noachian period, when global volcanism, especially the widespread highland volcanism, had its main activity phase and significant fluvial processes had not yet started on Mars [*Neukum and Hiller*, 1981; *Head et al.*, 2001; *Werner*, 2006]. This scenario would also correlate with an old age of the material, implying an era of genesis approximately between 4.2 and 3.8 Ga before present. The global distribution of the ash material produced by several highland volcanoes might have been easily accomplished because eruption material was thrown to high altitudes in the atmosphere and distributed widely by aeolian processes. The alternative approach of a young age (around 0.1 to 0.05 Ga, see above) associated with a volcanic origin would imply the building of ash deposits mainly caused by the Tharsis volcanism in the Late Amazonian period after the decline of fluvial activities (see Fig. 73). However, this scenario is less likely because the volcanic activity was less intense and locally restricted to the Tharsis region at that time, and it is questionable whether this volcanic activity might have endured long enough to produce an ash layer of such thickness. Although the huge Tharsis volcanoes were active until 100,000 years before present [*Neukum et al.*, 2004a] the time since might not be sufficient to deposit the layers and cover them globally with regolith and dust. The deposit of regolith covering the dark layers has a thickness of at least 20 - 30 m in some places (measured from HRSC DTMs). Erosion rates on Mars show a dramatic drop of 4 - 6 magnitudes between the Noachian (10^2 - 10^4 nm/y) and the Hesperian/Amazonian period (10^{-2} - 10^{-1} nm/y) [*Golombek and Bridges*, 2000]. Recent calculations of *Golombek* (2007) result in long-term erosion rates of 0.01 - 10 nm/y since the Hesperian. Such low erosion rates make it unlikely that such a thick layer of regolith should have accumulated above the dark layer in the Late Amazonian period. In turn, the high Noachian erosion rates support the idea of an old age because the burial and coverage of the dark layer by regolith seems reasonable.

Subsequent developments, such as the exposure of the dark material, the building of the dunes, and even the induration of some of these dunes (see Sect. 5.5 and 5.7) need along time. It is more reasonable to assume that the re-exposure and global distribution of the material began much earlier than this latter hypothesis of a young age would allow. Chronological placement is visualised in Fig. 73, which is derived from *Werner* (2006), modified so that the two hypothetical epochs when dark material was generated by volcanic activity are added in the form of black bars. The early and late-genesis hypotheses are designated as 1a and 1b, respectively.

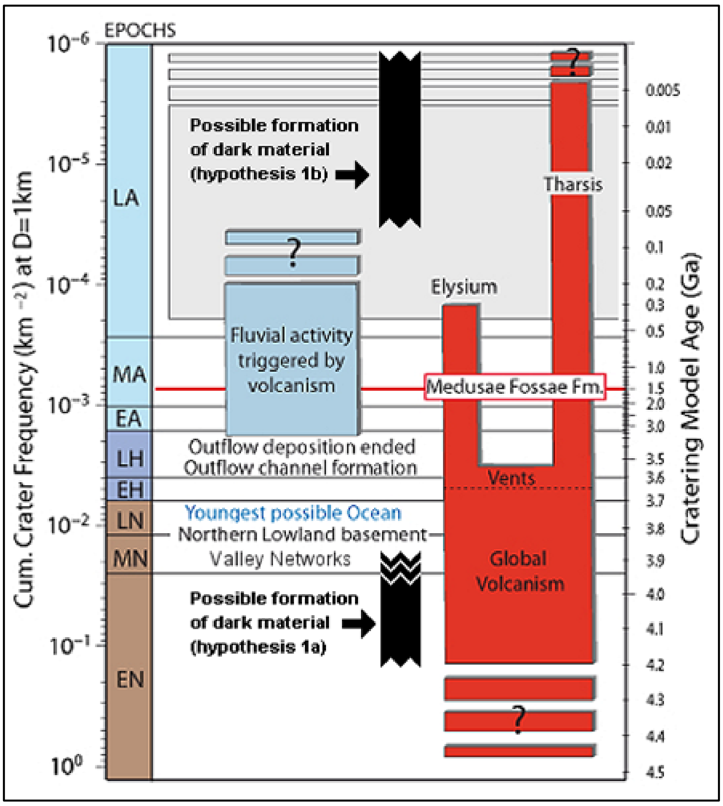

Figure 73: Possible periods of dark material formation incorporated in the sequence of the global geological evolution of Mars (adopted from *Werner* (2006), modified).
The two hypothetical periods for the formation of dark material (hypotheses 1a and 1b) following the volcanic ash theory are represented by black bars. Ages were determined by *Werner* (2006) and are here given in terms of cumulative crater frequency (left axis) and in absolute figures (right axis). Geological epochs are abbreviated as follows: EN, MN, and LN for Early, Middle, and Late Noachian; EH, MH, and LH for Early, Middle, and Late Hesperian; and EA, MA, and LA for Early, Middle, and Late Amazonian (boundaries following *Tanaka et al.* (1992)).

An alternative approach concerning the origin of the dark material on Mars was proposed by *Schultz and Mustard* (2004) and further investigated by *Wrobel and Schultz* (2006) and *Wrobel and Schultz* (2007). They propose that the dark material on Mars could be the product of well-preserved impact-related materials, i.e. impact glasses or impact melts, accumulated since the Hesperian and generated by the huge number of impact bombardments on Mars. To support this suggestion, they name various indicators: (1) the absence of a mafic spectral signature of certain dark deposits on Mars; (2) the feldspathic composition of several blocks found at the Pathfinder landing site pointing to andesites rather than basalts; (3) indications based on terrestrial analogues in Argentina pointing to the formation of global distal melts caused by impacts into soft loess deposits, which they call the prime terrestrial analogue for Martian sediments; and (4) the possibility of a global dispersal of impact material driven by the Coriolis force, as evidenced by terrestrial observations [*Schultz and Mustard*, 2004; *Wrobel and Schultz*, 2004]. *Wrobel & Schultz* (2007) performed a quantitative study using computer simulations incorporating hydrocode models and ballistic ejecta delivery calculations to predict the distribution of distal impact melts across Mars since post-Noachian times generated by impacts producing >100-km diameter craters. They compared the results with an albedo map of Mars (Fig. 74 A & B) and recognised correlations between areas of extensive impact melt coverage and low-albedo regions. For example, they identified the huge amounts of dark material depositions at Oxia Palus (Fig. 74 C) (previously classified as Surface Type I by *Bandfield* (2000) and *Christensen et al.* (2001)) as generated by the massive impact which caused Lyot Crater. According to *Wrobel & Schultz* (2007), parts of the material were transported by aeolian deflation from this source northeast of Oxia Palus to its present-day locations. Furthermore, glasses produced by the Lyot impact were identified as possibly responsible for the dark deposits at Acidalia Planum (classified as Surface Type II by *Bandfield* (2000); *Christensen et al.* (2001), which have undergone a different history of alteration and aeolian re-distribution. Further correlation between predicted impact melt concentrations and low-albedo regions on Mars was found in the Hesperia Planum region (Fig. 74 D), interpreted as mobile glasses weathered out of previously protected sediments [*Wrobel and Schultz*, 2007].

Regarding the preservation of the material within sediment layers, trapped in and emanating from craters, exhumation, mechanical breakdown, and deflation, the authors of the impact glass hypothesis hold views similar to those previously discussed in this work. However, the absence of mafic signatures cannot be confirmed for the dark materials analyzed in the current study. Although *Schultz and Mustard* (2004) cited this fact as an indication of the non-volcanic origin of the dark material, *Wrobel and Schultz* (2007) later admitted that the mafic composition might be due to the predominantly basaltic source material of the impact melts. One further conspicuous point is the difference between the mapped melt concentrations and the low-albedo regions (Fig. 74 A & B), although the authors explain these differences by the existence of dust covers, depositional traps in thick sediments, and aeolian redistribution. Dating the genesis of dark material to Noachian times does not completely exclude the impact glass hypothesis. However, due to the amorphous nature of impact glasses it would not be possible to obtain a mineralogical signature by means of spectroscopy [Pieters, 1977]. It is not until recrystallization takes place that crystal-lattice vibrations in mineral grains produce distinct spectral absorption features. From lunar research it is known that volcanic glasses ('orange glass') have an age of 3.5 to 3.6 Ga and have not recrystallised during that entire period - solely the upper non-covered 'black soil' layer has experienced recrystallization [Stöffler et al., 2006]. Likewise, lunar impact glasses are 3.5 Ga old and have not undergone any recrystallization [Stöffler et al., 2006]. These findings weaken the impact glass hypothesis and strengthen arguments for the volcanic ash theory because the dark material analyzed consists of distinct mineral grains.

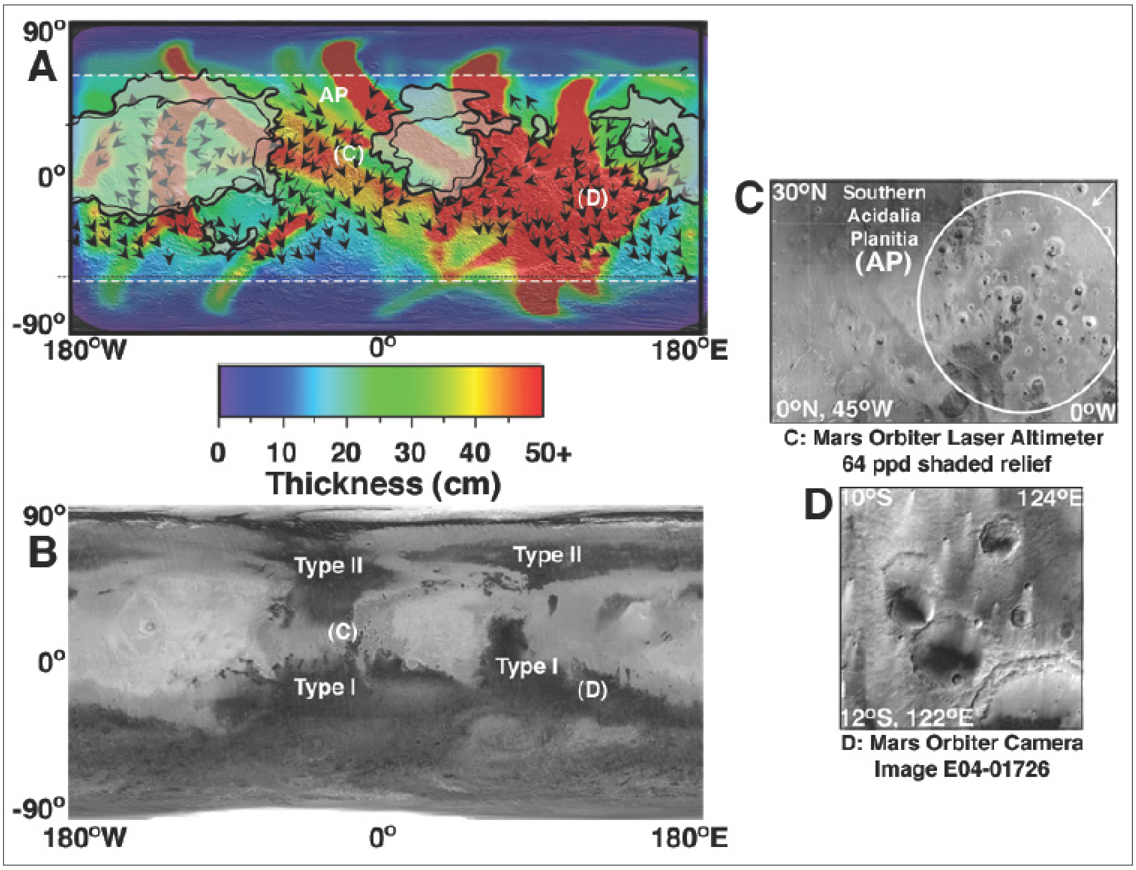

Figure 74: Comparison between calculated impact melt thickness and global albedo map from *Wrobel & Schultz* (2007).
A: Mapped thickness of cumulative ejecta melts across the Martian surface. Highlighted transparent areas represent approximate low TI regions; arrows indicate current wind pattern after *Thomas* (1984); (C) and (D) mark the location of the areas shown in Fig. B and C. **B:** Albedo map of Mars. Type I and Type II designate regions of different surface materials ('Surface Types') classified by *Bandfield* (2000) and *Christensen et al.* (2001) (see text above and Sect. 2.1); (C) and (D) mark the location of the areas shown in Fig. B and C; AP = Acidalia Planum. **C:** Examples of emerging dark layers/dunes/streaks in the Oxia Palus region. **D:** Low albedo Type-I deposits currently being exhumed out of crater floors in Hesperia Planum, the region featuring the greatest accumulation of distal products.

If the impact melts theory is correct, one or more layers or layered patches of dark material should have been generated that may not differ in morphology very much from the situation produced by the volcanic origin scenario discussed before. One could even imagine that not several small but one or two giant impacts might be responsible for the generation of a layer of impact glasses that might represent the dark material on Mars. The Hellas, Argyre, and Isidis Basins would be candidates for these giant impact events. Following the latter theory, the dark materials would be of very old age, because these giant impacts date to 4.0 to 3.8 Ga before present (cf. Fig 73).

The discussion shows that there exist several more or less plausible scenarios for the origin of the dark material on Mars. It is difficult to ascertain the 'one true scenario', but it might be possible to settle the question of whether one single locally restricted event was involved, or multiple regional or global events. This would be possible to determine if the thickness of the layers could be related to their probable origin. For example, if we were dealing with one single volcanic region or one giant impact, the thickness of the layers should correlate with the distance to the source region. Unfortunately, this cannot be investigated yet because of the lack of data sets of exposed layers with a satisfactory spatial resolution. However, the global distribution of the material suggests multiple events with globally distributed sources spread over a long time. The following sketches summarize and visualize the hypotheses of one or multiple origin events, similarly leading to the global distribution (volcanic ashes or impact melts/glasses) and deposition of dark material in one or more layers that were subsequently buried.

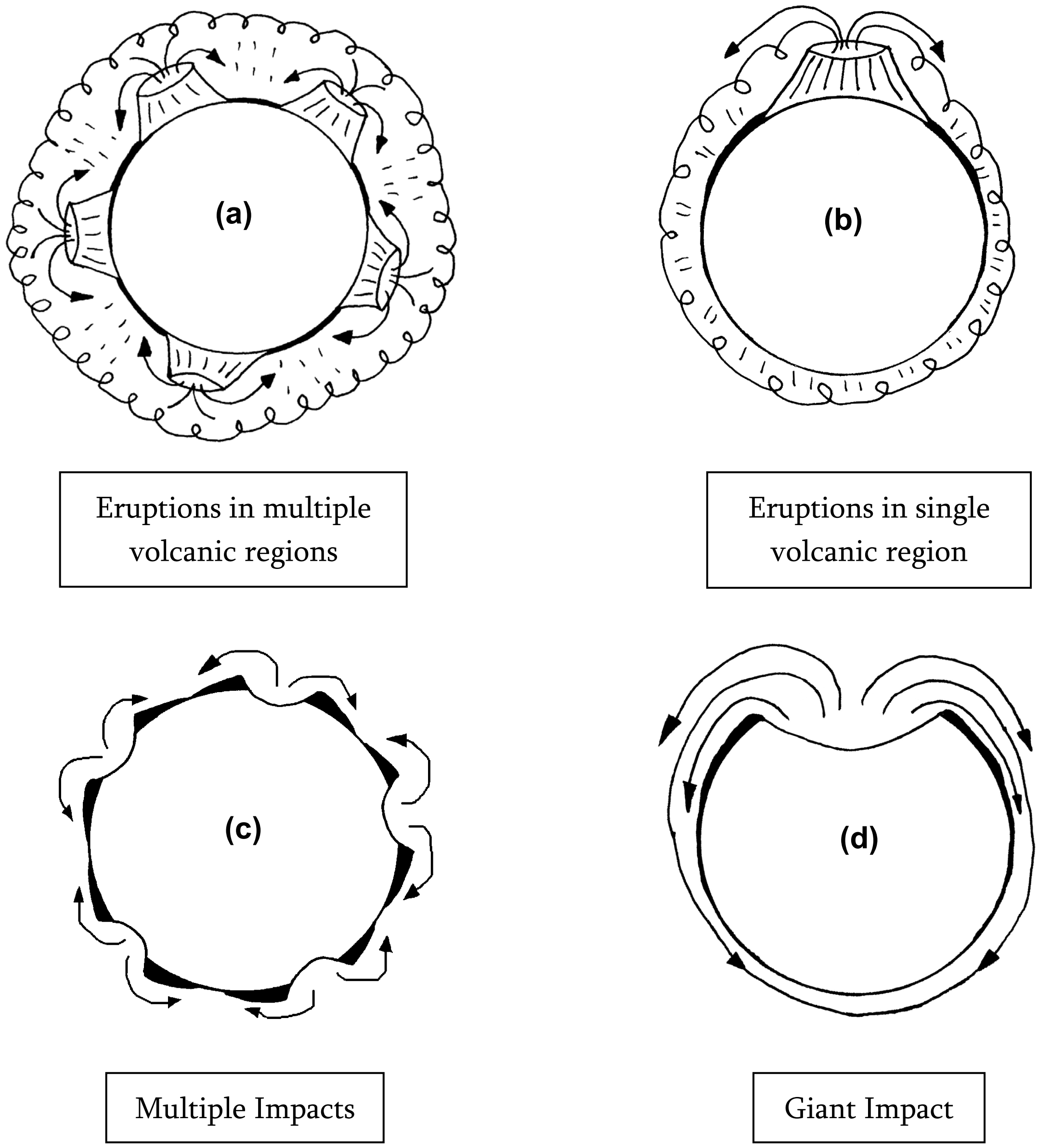

Figure 75: Sketches of scenarios of the volcanic origin hypotheses and the impact melt/glasses theory. The figures show the globe in cross-section and a highly simplified view of the events.
(a) Several eruptions of several volcanic regions (e.g. the highland volcanoes following hypothesis 1a, cf. Fig 73) generate masses of volcanic ash that subsequently are distributed and deposited globally. **(b)** One or more eruptions in a single volcanic region (e.g. the Tharsis region following hypothesis 1b, cf. Fig 73) cause the generation of mafic ash, globally distributed by aeolian processes, thinning out from the source to farther regions. **(c)** Multiple impacts cause the generation and distribution of dark impact melts/glasses. **(d)** One giant impact causes impact melts/glasses and the widespread distribution of the material, thinning out from the source to farther regions.

6.2 Chronology of Evolution – From Deposition to Distribution

What happened after the dark layers were deposited and buried, and what is the layer exposure situation today?

As discussed above, the origin events caused the deposition of one or more layers of dark material. Although there is no evidence of multiple layers in crater walls or other sites of exposure, the existence of several layers cannot be ruled out because the origin events might have gone through several phases with unknown time intervals in between, leading to multiple episodes of material deposition. Of course, if there was only one giant volcanic eruption or impact, only one material layer should have resulted. However, craters with emanating dark material and without any signs for dark material are situated close to each other in some regions (cf. Fig. 40), pointing to the fact that the sources are not continuous and are of different elevations. This indicates multiple layers generated by multiple events as mentioned in the previous section. The following description deals with multiple layers. It must be noted that layers may vary in thicknesses, although this is not indicated in the following sketch. Thus, layer thickness might decrease with decreasing layer depth, and similarly, the thickness of an individual layer might vary across a wide range. The following interpretation describes the evolution of dark material as postulated in hypothesis 1a described in Sect. 6.1 (cf. Fig. 73). Hypothesis 1b can be neglected because it cannot plausibly explain the formation and burial of multiple layers. Thus, this hypothesis is rejected.

The initial state can be seen as the deposition and burial of the material (Fig. 76 I). As a consequence of the burial, material compaction can be assumed. The degree of compaction is not yet clear. Furthermore, layers might have been modified in different ways (Fig. 76 II). At the surface, multiple impact craters should have cut through the upper layer at least, removing a given amount of material each time. The impact-removed material was transported to the surrounding surface and exposed to weathering, probably leading to chemical alterations in the material. This ongoing process resulted in the fragmentation of the upper layer, probably removing the material completely in many places. In some regions, crustal movement, such as normal or reverse faults or dipping, might have shifted the layers deeper or higher. Furthermore, large- and small-scale erosional events (such the development of the outflow channels [e.g. *Jaumann*, 2003]) might have completely removed large amounts of the material in certain regions. Underground water welling up from beneath the surface (especially in the Meridiani Planum region) [*Andrews-Hanna et al.*, 2007b; *Andrews-Hanna et al.*, 2007a] might have reached the lower layers, so that the material was chemically altered and washed out. Consequently, the lower layers might be extremely fragmented as well. During the wet periods on Mars (Late Noachian until the first half Late Amazonian), the buried material was, if it already existed, protected from superficial fluvial processes. Thus, dark material layers were not exposed to chemical weathering, resulting in the unaltered condition of the material today.

Although huge amounts of the material originally deposited was removed or altered by erosional and weathering processes, large amounts of dark material deposited in fragmented layers still exist on Mars. Some of the layers are probably nothing more than small lenses or elongated patches. Extensive modification, displacement, and removal of these layers explain regional variations occurrence and exposure of dark material. There are various possible explanations for the crater-layer relationship: First, in places where an impact crater cuts through a dark layer deeper than its bottom, the layer will be exposed in the crater wall (situation 1, Fig. 76 III). As discussed in Sect. 5.2, these exposures might be coated by regolith or dust covering the crater wall, whereas insolation effects probably support the exhumation and mobilization of coated dark layers. Second, some impact craters might come close to but not completely reach the depth of the dark layers. Subsequent impacts on the same crater floor might cut into the dark layers lying just beneath the larger crater's floor, exposing the dark material in this second step (situation 2, Fig. 76 III). Third, craters located close to other impacts where dark materials have been exposed may not cut into a dark layer because the dark material was removed from this locality or displaced to greater depths, the impact thus hitting, as it were, a gap in the dark layer (situation 3, Fig. 76 III). Therefore, these craters do not show any indication of dark material although situated in a potential region for dark layer exposure (cf. profile in Fig. 40, Sect. 5.2). Fourth, the crater depth does not reach the depth of the dark layer (situation 4, Fig. 76 III).

Due to the exhumation of the dark material primarily caused by impact cratering, the material was exposed to mechanical weathering. As mentioned above, significant chemical weathering can almost be ruled out because the dark material shows no considerable signs of chemical alteration. Possible disaggregation processes without the influence of water could be thermal weathering (insolation weathering) and aeolian processes (abrasion) [*Thomas et al.*, 2005] (described in section 2.1.2). Material expansion caused by insolation–related temperature increases and material contraction caused by night-time temperature decreases result in the breakup of formerly solid layer material. The predominant erosion process influencing the layers and causing material mobility could be wind abrasion, which results from the impact of windblown grains on a target [*Greeley and Iversen*, 1985]. The comminuted material will be transported into the crater's interior, where it forms dunes, dune fields, or sand sheets. Evidence for such material transport can be seen in gullies filled with dark material that run down-wall below exposed dark layers (cf. Fig. 32 c & d, Sect. 5.2). Furthermore, intra-crater material can be blown out of the craters by wind action. Downwind of these craters, dark wind streaks develop from deflated dune material. Material emerging from dark layers (situation 1 and 2, Fig. 76 III), its mobilization, and the formation of dunes and wind streaks are illustrated in Fig. 76 IV.

Most of the dunes seem not to migrate or shift very much (Sect. 3.1). At the same time, the size of several dune fields indicates great age, and the physical conditions for sand particle movement on Mars support the concept of old stable dune bodies. Signs of dune induration processes (Sect. 5.5.3 & 5.7) might be the first step towards the current and future development of sandstone on Mars.

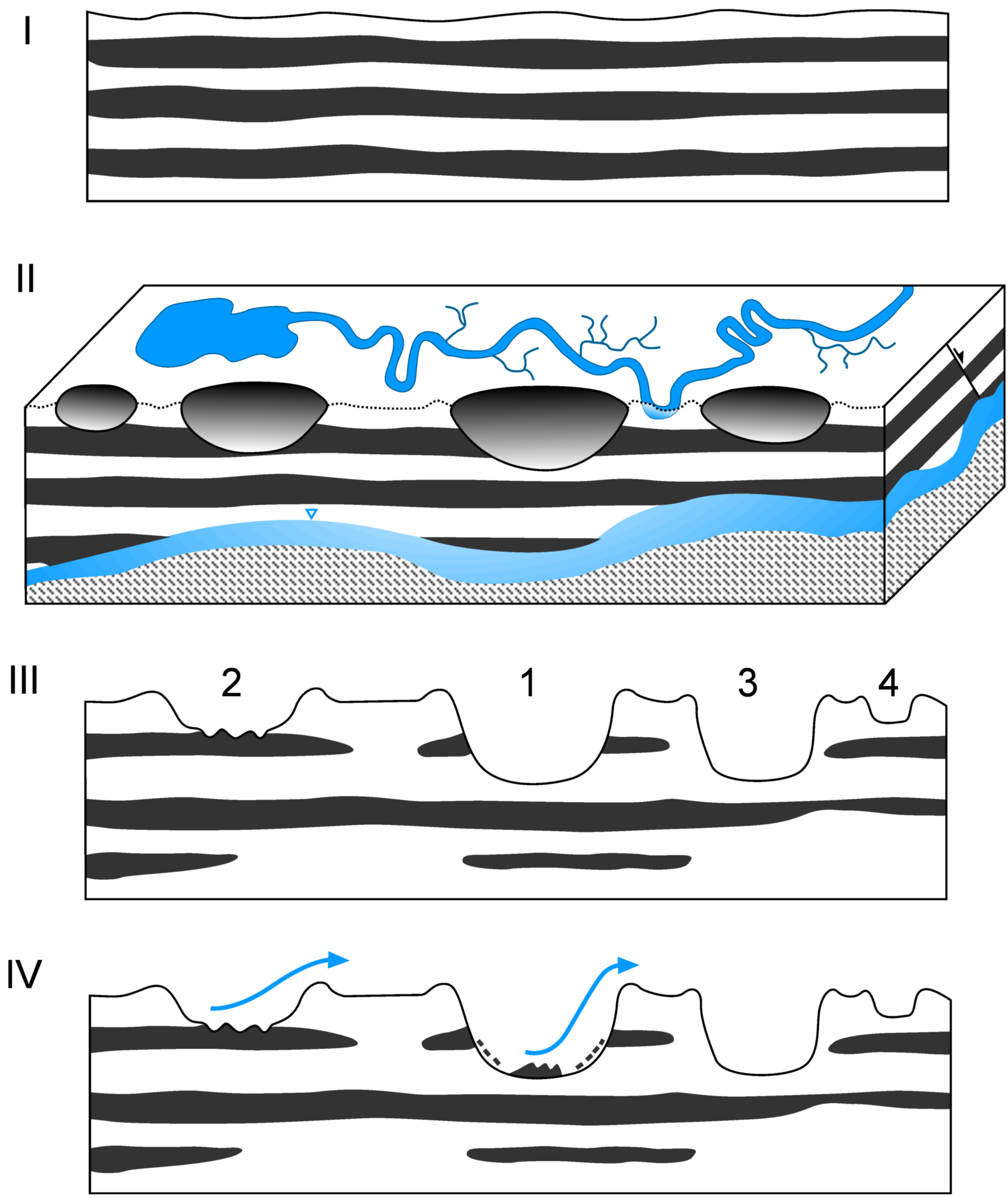

Figure 76: Example of the development of dark layers.
I: Initial state: deposition and burial of dark layers. **II:** Modification of dark layers: impacts from above and groundwater from underneath remove the material piecemeal, resulting in highly fragmented layers. Crustal movement, e.g. normal faults, may cause dislocation of the layers. Superficial fluvial processes do not influence protected dark layers. **III:** Patchy and fragmented layer distribution: Crater-layer-relationship has different characteristics: (1) impact crater cuts layer → dark layers exposed in crater wall; (2) smaller craters on the larger crater's floor cut layer → dark material emerges from smaller craters onto the larger crater's floor; (3) impact crater of similar depth as the crater of situation 1, although close to other layer exposure sites, does not cut into a dark layer because dark layers have been removed in that location; (4) impact crater does not reach the dark layer. **IV:** Final state: mechanical weathering of layer material and aeolian processes result in dune formation on crater floors, building of wind streaks and widespread distribution of dark material.