CHAPTER VII: SUMMARY AND OUTLOOK

The aim of this study, as described in Chapter I, was to analyze the properties and features of dark material and the dunes themselves. Joined together, these jigsaw pieces would then be used to create an image of well-founded knowledge about dark material, which should preferably answer the question about the origin and genesis of the dark material in Martian craters.

Following the brief overview of the geology and climate on Mars (Chapter II), Chapter III provided a comprehensive introduction to the background of aeolian processes and material transport. Furthermore, it described the fundamentals of aeolian bed forms, sand sources, and the current state of dark material distribution on Mars. It reviewed existing knowledge about the 'difficulties' of sand transport on Mars due to the fact that the physical requirements for the initiation of saltation are rarely fulfilled under current atmospheric conditions (inadequate friction threshold velocity mainly due to low atmospheric pressure). The current knowledge about aeolian processes on Mars was presented as well. Evidence for both particle transport and dune immobility has been uncovered during recent years of observation. Relevant dune types as well as the requirements for their formation were introduced by means of terrestrial analogous. A disquisition on the distribution of dark material on Mars showed its virtually global appearance at multiple different topographic sites, such as impact craters, valleys and chasmata, polar regions, and volcanic calderas.

Chapter IV introduced the various data sets used in this study, including image and spectral data as well as thermal data products. Gathered over many years, and differing in spatial resolution and information content, a great variety of data from different Mars missions was used. All data sets used have been summarised in Table 5 Moreover, data derivation and processing was described in detail.

Chapter V described various analyses of dark material properties, including morphological, spectroscopic, and thermophysical investigations. A number of properties and facts have emerged from this work:

1. The dark material has not primarily been blown into the craters, as formerly assumed by many authors, but seems to originate in the craters themselves in many cases. The lack of convincing evidence of distinct material input into the craters and many examples of dark material emerging from craters support this interpretation.
2. Dark layers exposed in the crater walls and beneath some crater floors may be assumed to be the local source of dark intra-crater aeolian deposits. Obvious sediment transport pathways from the source layer to the dunes and a mineralogical composition similar to the intra-crater dune material corroborate this conclusion.

3. Insolation seems to be a mechanism supporting layer exposure in crater walls if they are covered by regolith.
4. The compositional mixture of unweathered pyroxenes and olivines formerly reported by many authors was confirmed by spectral analysis. The mineralogical composition of the bulk of the dark dunes and sand sheets is consistent and shows no correlation with the geographical location in terms of mafic minerals. However, the hydrated minerals detected in small parts of some dark deposits form clusters in Arabia Terra. This is interpreted to be founded on the former activity of water-related processes in this particular region.
5. The presence of olivine in dunes and dark layers indicates a low level of weathering and thus relatively fresh material.
6. It is impossible to assess dune activity in terms of differentiation between active and non-active dunes by comparison with current modelled MCD wind data sets. It cannot be assumed that the model data reflect current dune-influencing forces because the modelled wind speeds are too low to initiate saltation under current Martian atmospheric conditions.
7. Thermophysical analyses using surface brightness temperature and thermal inertia point to the existence of both unconsolidated movable dunes and immovable dunes probably having indurated surfaces. Whereas the movable deposits are primarily located in the southern highlands, a certain correlation between immovable deposits and the lowland-highland boundary is obvious. Water-related processes formerly occurring in these regions as well as mechanical compaction are considered as mechanisms causing the immobility of these deposits.
8. Induration of a proportion of dunes was furthermore proven by the existence of several morphological dune surface features.
9. No convincing correlation between dune surface condition and mineralogical composition could be ascertained.

Many of these properties discovered serve to diagnose specific conditions relating to the origin and evolution of the dark material, as discussed in Chapter VI. The generally consistent mafic composition of dark material without any geographical correlation points to a similar origin of every dark deposit. Thus, the dark material was probably developed during similar formation processes with a regional or global reach. Indications of the nature of this formation process came from the mineralogical composition itself. Olivine and pyroxene minerals, detected as the major components of the dark material, might be indicative of a volcanic origin analogues to Earth. Furthermore, these minerals must have been protected during times of active fluvial processes on Mars; otherwise, they would have been altered by chemical weathering. Morphological aspects of the dark layers found in several craters disclose that they were buried after deposition and later exposed by impact erosion. The layered nature of the material and its mineralogical composition strengthens the concept that it was generated by time-restricted events, such as volcanic eruptions leading to the deposition of thick ash layers. The geological history of Mars suggests a time range of genesis from the Early to the Middle Noachian period (4.5 to

3.8 Ga), when global volcanism reached its peak, and fluvial processes just began to act. It is plausible that the material was deposited and subsequently buried during this time and fluvial processes did not alter or clear out the buried dark layers completely. An alternative later genesis after the wet period would imply a young material age, with genesis starting at 0.1 to 0.05 Ga before present. However, this hypothesis is relatively untrustworthy because it is more plausible that the layers were buried during times of higher erosion rates on Mars, such as the Noachian period, indicating an earlier layer deposition. The alternative approach suggested by *Schultz and Mustard* (2004), according to which the dark material originated from impact bombardments, was discussed as well. Following this hypothesis, the dark material represents impact glasses or melts produced during multiple impact events. However, its explanation of compositions, source regions, and distributions is uncertain. Yet there are no distinct reasons for rejecting or accepting one of the hypotheses described. As far as the origin of the material is concerned, therefore, both approaches mentioned must be taken into consideration. Based on the morphological characteristics of the dark layers, it can be assumed that the material has to be generated by several origin events rather than by a single one. Consequently, it cannot be ruled out that several layers of dark material produced by several periodic events exist beneath the surface of Mars.

The picture of the evolution of the material after its genesis is less blurred. As shown in Fig. 76, layers might have experienced several stages of modification after their deposition and burial. Related factors include impact erosion of the upper layers, chemical alteration, and material removal by groundwater from beneath, and probably displacement of layers by tectonic processes, resulting in a highly fragmented nature of each layer. Evidence of this layer fragmentation might be provided by the various cases of layer exposure, as revealed by the morphological analysis of crater-layer relationship shown in Fig. 76 III. The last stage of layer development is clearly inferable from the current material appearance on Mars. Mechanical weathering of dark material sources provides sediments for intra-crater dunes and sand sheets of various types and sizes. These aeolian bed forms frequently experience deflation by wind, thus forming the source of the dark crater-related wind streaks on Mars. The immobility of several dune surfaces may indicate dune surface induration and, possibly, an older age relative to movable and unconsolidated dunes. Hydrated minerals were found in a small proportion of dunes clustered in western Arabia Terra but do not correlate well with consolidated dunes. It is likely that the occurrence of hydrated minerals in this region is associated with the geographical location because this region experienced a long history of aquatic processes, such as groundwater upwelling and the outflow of water in channels and valleys. It is assumed that these water-related processes have supported the formation of hydrated minerals. In some places, it cannot be ruled out that the spectral signature of hydrated minerals comes from the subsurfaces underneath the dark material and does not point to an alteration of the dark material. Only in two localities, the hydrated signature originates probably from the dark material itself, suggesting a local chemical alteration of the deposits. The negative correlation between immovable and thus possibly indurated dunes and their mineralogical composition in terms of hydrated minerals points to the conclusion that the induration process did not cause a specific mineral alteration that is typical of indurated surfaces. Alternatively, indurated dunes could exhibit newly-generated minerals that could not yet be detected by the spectral analysis technique applied to the OMEGA data. The type of induration process has not been specified yet, although crust formation in association with mobilised salt ions as cementing agents in connection with absorbed atmospheric water is likely.

Further studies should be concerned with a detailed analysis of the exposed dark layers. Searching for a higher number of exposure sites would be especially important because it might permit generating regional layer extent maps. The results may yield significant insights into the large-scale source of the material. Additional CRISM spectral data of these layers may corroborate the identification of the mineralogical consistence of layers and dunes. More high-resolution data of the walls may yield further insights into the nature of layer erosion processes by revealing residual morphological evidence and might even disclose interbedded strata or the like. High-resolution DTMs of crater walls would allow determining the thickness of the exposed dark layers, their relative depth, and the thickness of the covering regolith layer. This information could be used to better specify the minimum duration of the time needed to deposit and bury the dark layers. HiRISE data and complex computer models of possible deposition scenarios would be useful tools in this context. Estimates of these durations might help to better specify the possible time range of genesis and deposition, resulting in more assured statements. Together with the mapping results indicating either a global or a regional source, a specific time range, might permit identifying the type of genesis and origin and confirming it by substantive evidence. Detailed case studies of selected dunes and dune fields in which all local influences and parameters are carefully measure and considered may fundamentally prove the classification of consolidated and unconsolidated dunes. Data with a higher spatial resolution, e.g. THEMIS thermal inertial data, are an essential must for these analyses.

Although there have been many previous studies of dark material addressing the mineralogy, the morphology, and thermal behaviour of the dunes, a number of open questions concerning the dark material could be answered by this study. Contrary to most previous studies, it was designed on a global scale. Thus, it was possible to compare local information with regional to global aspects, leading to significant new conclusions. The study sheds light on the globally homogeneous mineralogical nature of the dark material, leading to the assumption that this homogeneity might be due to a consistent history of genesis. The study discovered sources of dark material on a local to regional scale, proved by mineralogical consistency. Furthermore, it provided initial evidence for a mechanical rather than a chemical cementation of dune surfaces.

If once, based on very high-resolution orbit observations and in-situ studies, individual dark layers could be correlated to individual volcanic eruptions, the dark layers might serve as stratigraphic levels for the geological history of Mars, i.e. analogues to the Laacher See Tephra on Earth.