5.6 Combined Interpretation and Comparison of Results

Based on the results of the thermal property analysis the dark dunes were classified as supposedly movable and supposedly immovable. Note that not every deposit of dark material could be classified due to the lack of THEMIS or TES data or unreliable thermal property results (e.g. missing thermal thickness, conflicting data conclusion, insufficient spatial resolution). As mentioned above, the BTR results were used as tentative indicators whereas the measured TI values governed the classification and interpretation. However, in cases where the measured TI values lay close to the 400 J m^{-2} K^{-1} s$^{-½}$-boundary, helpful additional information could be gained from BTR difference analyses (Sect. 5.5.2). Thus, for example, a dune field with an apparent thermal inertia of 395 J m^{-2} K^{-1} s$^{-½}$ can be classified as 'immovable' due to its high night-time BTR in comparison to its surroundings. Moreover, THEMIS images revealed in some cases that obviously night-time cold dunes were superimposed on a night-time warm and high thermal inertia crater floor (see Fig. 64). Due to the inadequate spatial resolution of 3 km, the TES data (Fig 64b) point to high TIs for the dunes in these cases although these high values are derived from the crater floor. Such misleading conclusions from TES data may be set right by THEMIS images with their higher spatial resolution of 100 m (Fig. 64c & 64d). The proportion of dunes, which might actually be immovable, is therefore much smaller than the number of localities with higher thermal inertia values.

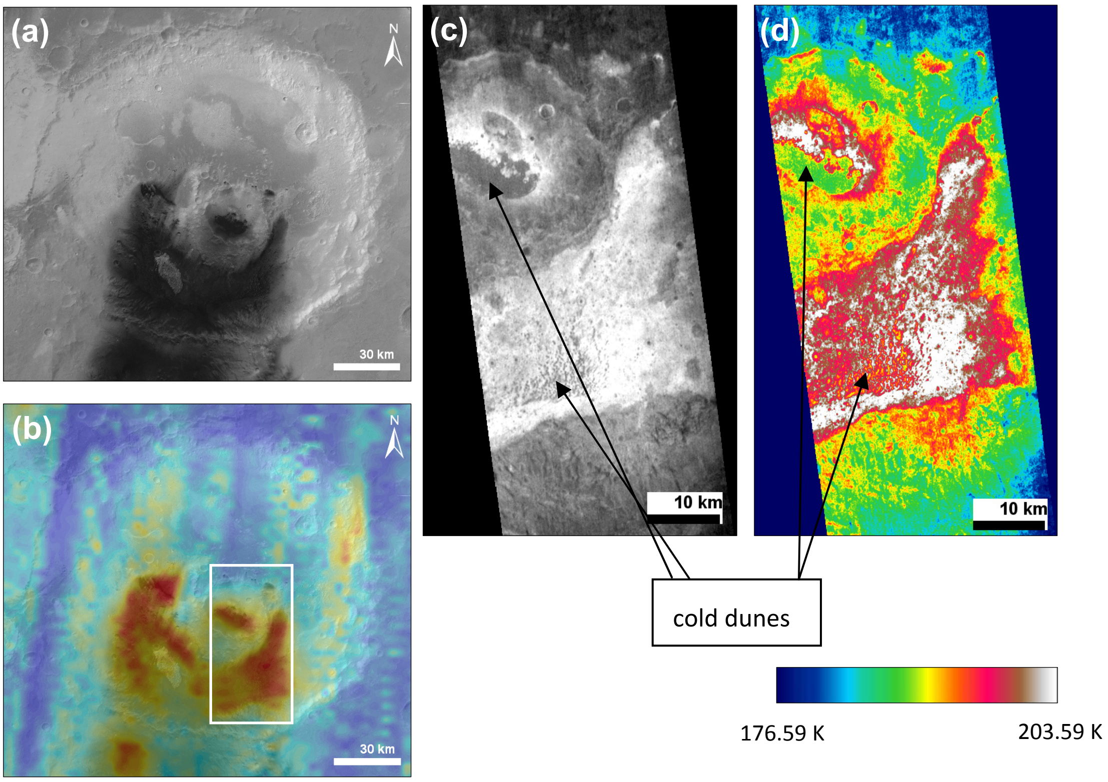

Figure 64: Validation of thermal inertia interpretation by means of brightness temperature results in Trouvelot Crater (16.3°N, 346.5°E).
(a) HRSC nadir mosaic of 3286_0000 and 3275_0000. **(b)** TES overlaid on HRSC showing high TI values (around 432 - 543 J m^{-2} K^{-1} s^{½}) in the dune areas, indicating immovable dunes. White quadrangle marks the position of Fig. c & d. **(c)** THEMIS BTR grey-scale image revealing cold dunes relative to a warm crater floor thanks to higher spatial resolution **(d)** THEMIS BTR colour-coded image of the same area as image (c). For temperatures see the legend below. (see text for discussion)

For a combined interpretation, the results of the previous analyses were compared. Dark deposits for which a cold night-time temperature as well as a low TI was measured are interpreted to consist of loose material and are thus assumed to be movable (Fig 65a). Warm night-time BTRs in combination with elevated TI values are a sure sign of immovable dunes (Fig. 65b). There are a number of localities showing conflicting BTR and TI data (e.g., night-time warm dune with low TI and vice versa, see example in Fig. 65c). For these localities, no assured interpretation is possible. Thus, they are marked as 'unclear material condition'.

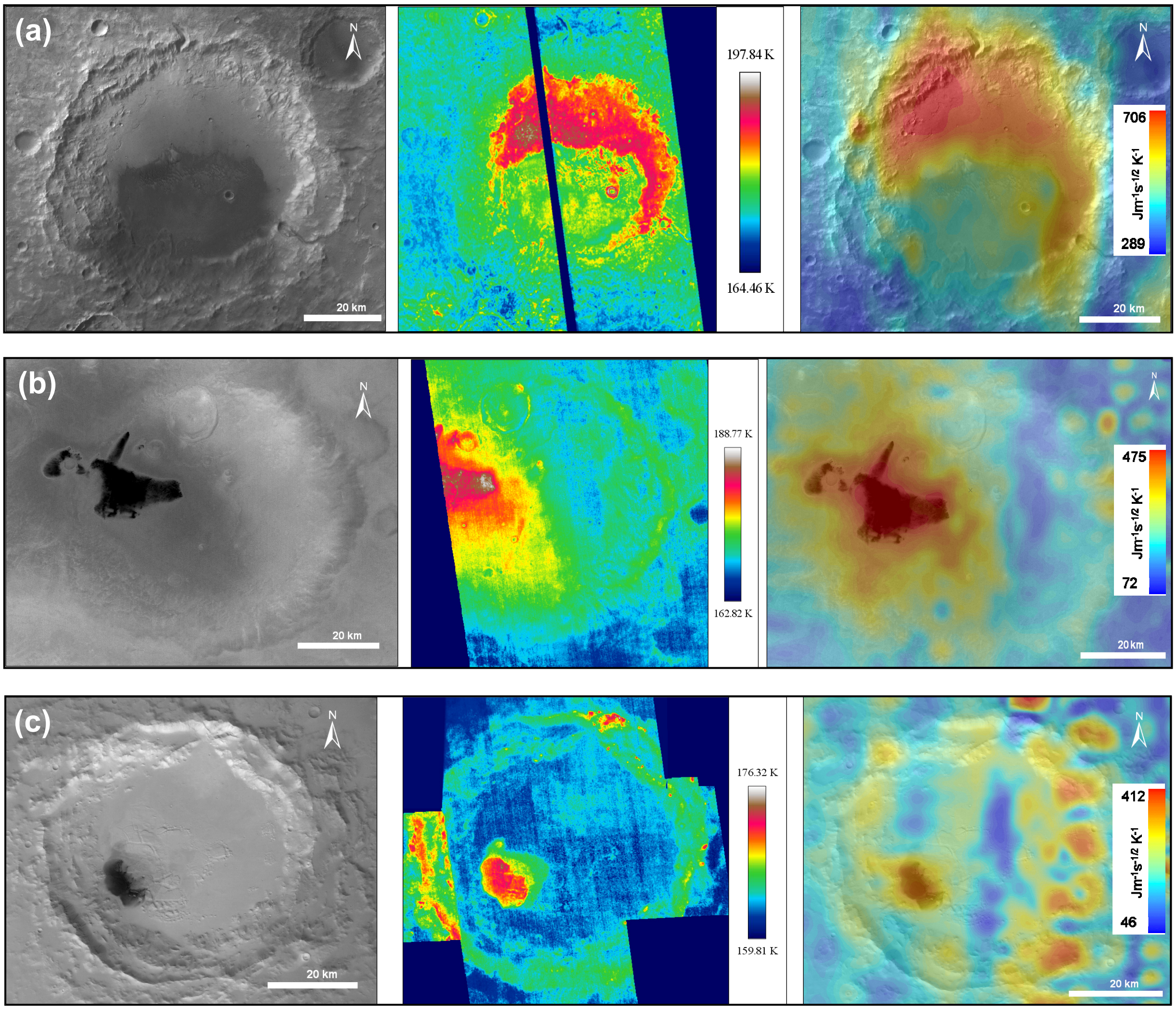

Figure 65: Combined interpretation of thermal property analyses.
(a) Dune field in a crater in western Arabia Terra (8.5°N, 344.3°E) interpreted to be movable. Left: HRSC nadir mosaic of orbits 0912_0000 and 0901_0000. Centre: Colour-coded BTR mosaic showing a night-time cold dune field relative to its surroundings. Left: TI result image showing lower TI values for the dune field around 388 $J\,m^{-2}\,K^{-1}\,s^{½}$. (b) Dune field in a crater in central Arabia Terra (17.2°N, 5.9°E) interpreted to be immovable. Left: HRSC nadir image 1366_0000. Centre: Colour-coded BTR mosaic showing a night-time warm dune field relative to its surroundings. Left: TI result image showing higher TI values for the dune field around 450 $J\,m^{-2}\,K^{-1}\,s^{½}$. (c) Dune field in a crater near Marte Vallis (15.6°N, 181.6°E) with conflicting BTR and TI values, interpreted as unclear material condition. Left: HRSC nadir image 2205_0001. Centre: Colour-coded BTR mosaic showing a night-time warm dune field relative to its surroundings. Left: TI result image showing higher TI values for the dune field than for its surroundings. However, the absolute TI values for the dune field are only around 257 $J\,m^{-2}\,K^{-1}\,s^{½}$ indicating movable sands and contrasting with the BTR results, which point to consolidated dunes retaining heat at night.

Localities with missing or unsatisfactory TES TI data (e.g. insufficient spatial resolution to show individual dunes) were labelled as 'no or no clear TES data'. Because interpretation is governed by TES TI results and only assisted by THEMIS BTR, the condition of dark deposits was interpreted even in the absence of BTR data as long as reliable TI data were available. The albedo of the dunes relative to their surroundings furnishes another indication for the status of the material, because it may point to a dust cover resulting in a higher albedo. Immovable dunes may be covered by dust, whereas a dust cover on movable dunes is not to be expected. However, a dust cover is not an obligatory criterion for a dune to be interpreted as immovable. Moreover, if a dune field shows a slightly higher albedo (pointing to dust) but low BTR and TI values, it is interpreted to be movable despite the deviant albedo indication, because the strength of these thermal parameters overrides the albedo.

Following the aspects and principles discussed above, all dark deposits are classified as 'movable', 'immovable', 'unclear material condition' or 'no or no clear TES data'. A tabular overview including the differential BTR results and the mean TI values for every dark deposit is given in Table 11. Additionally, the following diagram (Fig. 66) presents a statistical overview of the results of the mobility analysis derived from the combined interpretation of BTR and TI. More than half the localities analyzed (38) contain dark deposits which are assumed to be mobile under current Martian atmospheric conditions. In 18 dune fields, the thermal properties indicate that the material is able to retain heat at night, and the thermal inertia measured points to coarse grains, which are not movable under current atmospheric conditions. Furthermore, it can be assumed that the thermal behaviour of these dunes is caused by dune surfaces consisting of agglomerated or cemented sand grains, which raise their thermal inertia and heat retention ability (see Sect. 5.7 for further discussion). To lower the percentage of localities without an assured interpretation (15 due to unreliable data or conflicting results; 8 due to missing data or insufficient spatial resolution), it is advisable to use higher-resolution thermal inertia data (e.g. THEMIS) (see Chapter VII).

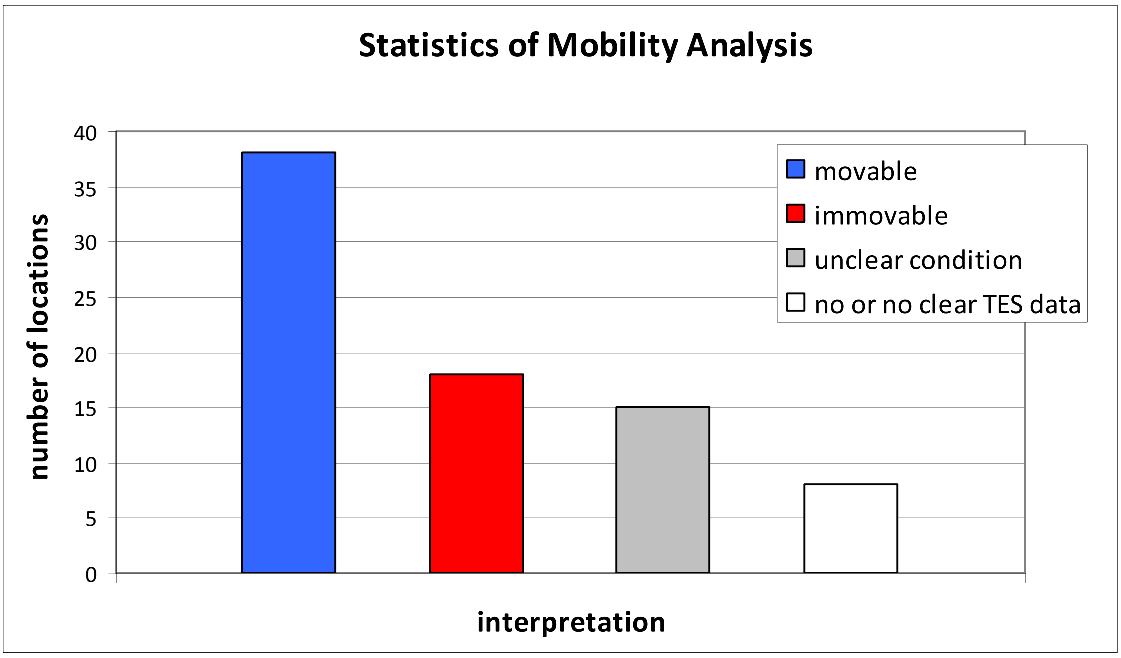

Figure 66: Statistics of the mobility analysis showing the number of locations classified by interpretation results.

Fig. 67 presents a global view of supposedly movable and immovable dunes. The global result image permits identifying possible correlations between the geographical location of dark deposits and their specific surface condition.

It is obvious that the number of dunes interpreted as immovable is smaller than the number of localities exhibiting higher TI values (cf. Fig. 63 and 67) as evidenced by the decreasing incidence of red marks around Oxia Palus. Serving as an example for these locations, the case of Trouvelot Crater (Fig. 64) demonstrates that the dunes are small and the thermal inertia measured is highly influenced by the inter-dune crater floor. Consequently, TI values are interpreted to reflect the condition of the crater floor, not the dune properties. Finally, the number of localities for which unambiguous predictions could be made is much lower than the number of localities for which TI and BTR data were acquired. This is because localities comprising sand sheets, or for which conflicting conclusions were drawn from the relevant data (e.g. night-time cold dune with a very high TI) do not permit determining a material condition. In some of the localities marked as 'unclear material condition', consolidation is probable but not certain (e.g. 'Fesenkov', 'Marte Vallis', see comments in Table 11).

The result of the material mobility analysis (Fig. 67) again shows a correlation between movable dunes and the southern highlands, whereas deposits interpreted as immovable are arranged along the lowland-highland boundary, as could be expected from the distribution of warm and cold dunes (Fig. 62) as well as high and low TI values (Fig. 63). The correlation of immovable dunes with the lowland-highland boundary is obvious. However, what could have caused the larger grain sizes in these dunes or the cementation of the surface grains? Cementation by ice is improbable because most of these dark deposits are located relatively close to the equator, where coverage by ice or freezing is not expected today. At best, this scenario is conceivable for the two northern deposits in craters located close to 60°N (marked by red crosses in Fig. 67). For instance, the dark deposit in Kunowsky Crater (57.1°N, 350.3°E) is supposed to have been cemented by ice because the spectral analysis revealed ice absorptions on the dune surface, proving this suggestion (marked by a red cross (→ immovable) in Fig. 67 and in turquoise (→ ice) in Fig. 68, cf. Table 11). The regions of Xante Terra, the northern margin of Arabia Terra, Meridiani Planum and the lowland-highland boundary in general, where the bulk of immovable deposits are located, have experienced a long history of aquatic processes, such as former rivers draining into the northern lowlands, or upwelling groundwater [*Andrews-Hanna et al.*, 2007b; *Andrews-Hanna et al.*, 2007a]. These water-related erosion processes are evidenced by outflow channels and valley networks (e.g. Maja Vallis, Mamers Valles, Mawrth Valles and Ma'adim Valles) [e.g. *Jaumann*, 2003] and the detection of minerals pointing to the former presence of water [e.g. *Hynek et al.*, 2002; *Loizeau et al.*, 2007a; *Poulet et al.*, 2008] (cf. Sect. 5.3.2). Moreover, the mineralogical analysis presented in Sect. 5.3 revealed the presence of hydrated minerals at least in the surroundings of dunes located in Arabia Terra (Fig. 68). The presence of water could have supported the mobilization of salt ions, which can act as cementing agents in conjunction with absorbed atmospheric water [*Jakosky and Christensen*, 1986] (cf. Sect. 5.7). It cannot be ruled out that these regions held a relatively large amount of residual superficial moisture, which rose to the dune surfaces, by capillary action, resulting in the precipitation of salts cementing the surface (see Sect. 5.7 for a discussion of surface cementation). However, it is not likely that there was a chronological correlation between the unaltered mafic deposits and these water-related processes, which mainly took place in the Upper Noachian and Hesperian periods [*Neukum and Hiller*, 1981; *Head et al.*, 2001; *Jaumann*, 2003], given that the bulk of the dark material is still unaltered today. Nevertheless, the correlation of immovable deposits with these regions is striking. An alternative approach suggests that glacial processes supported the hydration and thus the chemical induration of the material. As mentioned in Sect. 5.3.2 and published by many authors, lineated valley fills or lobate debris aprons prove that Amazonian glacial processes occurred in these regions [e.g. *Mangold et al.*, 2002; *Mangold*, 2003; *Head and Marchant*, 2005; *Dickson et al.*, 2006; *Dickson et al.*, 2007; *Levy et al.*, 2007; *Hauber et al.*, 2008]. This timeframe seems to be a more reasonable explanation for dark material coexisting with glacial processes (see Sect. 6.2 for a further chronological discussion) and might thus have provided the conditions for induration. In particular, this scenario might apply to the crater near Mamers Valles where distinct glacial features dated to the Amazonian are associated with dark material (cf. Sect. 5.3.2). A further alternative explanation for the immobility of the dunes in these regions could be that grains were aggregated or compacted mechanically as pores were filled by small dust particles blown in [*Thomas et al.,* 2005]. This process would enhance grain cohesion, thus immobilizing the dune sands. Further analyses will be needed to see which processes might be the key to the induration of the dunes after the cessation of fluvial processes in these regions (see also Sect. 5.7). Following this discussion, it is impossible to determine whether it was hydration or mechanical compaction that caused the immobility of these deposits. At this stage of research, all of the processes mentioned above might have contributed to the immobilization because reasonable indications can be observed for every one of them.

At the end of this section, the question will be considered whether there is a general correlation between mineralogy and the presumed dune surface condition. A comparison of Fig. 67 and Fig. 68 shows that there is no correlation between material mobility and mineralogical composition in terms of mafic minerals. Olivine was found in dunes interpreted as movable as well as in dark deposits assumed to be immovable. Pyroxene can be found almost everywhere, and can thus not be correlated with a particular thermal property, either. Furthermore, there is no distinct correlation between the detection of hydrated minerals and predicted material conditions. There are only two localities (Mamers Valles, Meridiani) where assumed immovability correlates with the detection of hydrated minerals. Another two localities (Sinus Meridiani, Arabia 1) where hydrated minerals have positively been detected feature deposits interpreted to be movable, whereas the fifth location (Trouvelot Crater) could not be interpreted due to insufficient spatial resolution (see Appendix and Table 11 for more information about the locations mentioned). The miscorrelation between immovable dunes and hydrated minerals can be explained by different theories. It is conceivable that the amount of hydrated material in the unconsolidated dunes was not enough to cause a blinding of pore spaces and thus, to result in dune immovability. Alternatively, there was not enough time for the consolidation process caused by material hydration. Furthermore, if salts (which can act as cementing agents, cf. Sect. 5.7) could be detected on these dune surfaces a mineralogical assignment of immovable dunes, would be more convincing. However, specific salts cannot be detected by the method used in this study. Moreover, in some cases, the dunes are too small to determine accurately whether hydration took place on the dune surfaces themselves or in their surroundings (cf. Sect. 5.3.2). Unfortunately, the insufficient spatial resolution of OMEGA data and the lack of high-resolution CRISM data do not allow any more accurate observations. All that can be said at this stage of research is that consolidated dunes do or do not correlate with altered minerals. However, this merely implies that the supposed consolidation process is not uniquely related to an obvious, visible mineral alteration

In conclusion, it can be stated that the dune fields show significant differences in night-time BTR and TI due to variations in the physical structure and the grain size of the dune material. The results point to immovable and movable dark deposits on Mars. Further evidence to support this assessment comes from distinct morphological features, as discussed in the following section.

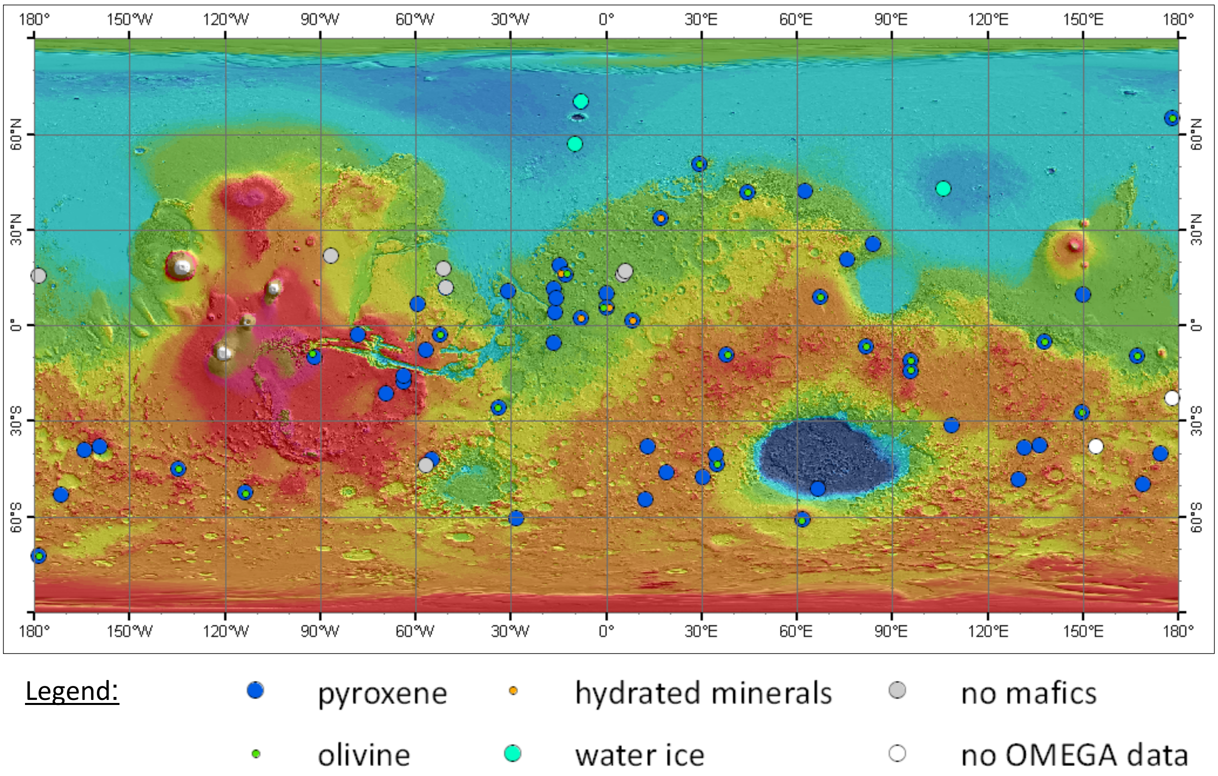

Figure 67: Global distribution of probably movable and immovable dunes as inferred from the thermal property analysis. (cf. Fig. 68, see text for discussion, background: MOLA topography map)

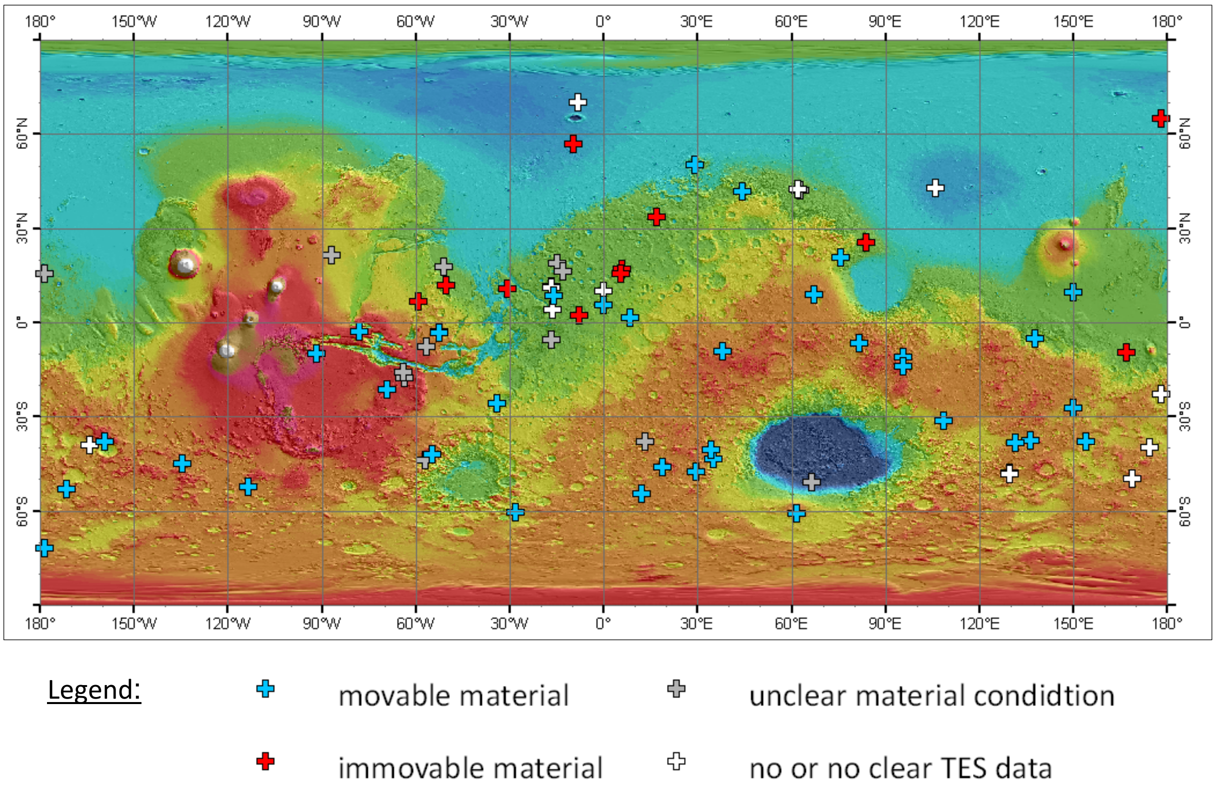

Figure 68: Result image of the mineralogical analysis for comparison with Fig. 67. (background: MOLA topography map)

Table 11: Interpretation of dune surface condition derived from brightness temperature and thermal inertia analysis.
(BTR is given in K; TI is given in J m^{-2} K^{-1} $s^{½}$)

Locality ID	Albedo	BTR difference	mean thermal inertia	interpretation	comments
Arabia 1	dark	no difference	394	movable	
Arabia2	dark	no difference	-	not clear	missing TES data
Arcadia	dark	warm	449	immovable	
Argyre1	medium	no difference	392	not clear	dust in spectrum and albedo
Agyre2	medium/dark	cold	381	movable	
Barnard	dark	-	282	movable	
Chaos 1	medium/dark	cold	562	not clear	conflicting data, movable dunes on high inertia crater floor?
Chaos 2	medium/dark	cold	-	not clear	missing TES data
Chaos 3	dark	cold	-	not clear	insufficent spatial resolution
Chaos 4	dark	cold	388	movable	
Cimmeria 1	dark	-	255	movable	
Cimmeria 2	medium	no difference	248	movable	
Cimmeria/Sirenum	dark	no difference	-	not clear	insufficent spatial resolution
Dawes	medium/dark	cold	271	movable	
Elysium	dark	cold	333	movable	
Fesenkov	dark	warm	341	not clear	conflicting data, probably immovable dune field
Gale	dark	cold	290	movable	
Gill	dark	warm	395	immovable	
Gill2	dark	warm	450	immovable	
Hellas	medium	cold	532	not clear	high TI due to high surface pressure at low elevation?
Hesperia	dark	no difference	260	movable	
Holden	medium	cold	231	movable	
Kaiser	dark	no difference	328	movable	
Kunowsky	dark	-	480	immovable	cemented by ice?
Liu Hsin	dark	no difference	286	movable	
Lyot	dark	no difference	292	movable	
Ma'adim Vallis	dark	-	-	not clear	missing thermal thickness
Maja Valles	dark	warm	428	immovable	
Mamers Valles	dark	warm	437	immovable	thermal thickness ????
Maraldi2	dark	-	243	movable	
Marte Vallis	dark	warm	257	not clear	conflicting data, probably dust covered immovable dune field?
Mawrth Vallis	dark	-	460	not clear	movable material emerging from small craters
Melas Dorsa	dark	no difference	259	movable	
Meridiani	dark	warm	501	immovable	water related processes
Molesworth	medium	cold	286	movable	
Moreux	dark	no difference	310	movable	
Morpheos Rupes	dark	no difference	230	movable	
Newton2	dark	no difference	302	movable	
Nier	dark	no difference	-	not clear	insufficent spatial resolution
Nili Fossae	dark	cold	300	movable	
Nili Patera	dark	cold	230	movable	
Ophir 1	dark	cold	320/530	movable/unclear	two diff. dune fields
Ophir 2	dark	cold	568	not clear	small dunes, TI from crater floor?
Oudemans	dark	no difference	251	movable	
Peridier	dark	warm	444	immovable	
Perrotin	dark	no difference	213	movable	sand sheet disappeared
Porter2	dark	-	318	movable	
Proctor	dark	no difference	277	movable	
Rabe	dark	no difference	327	movable	
Rabe2	dark	no difference	343	movable	
Renaudot	medium/dark	no difference	-	not clear	insufficent spatial resolution
Reuyl	medium	warm	422	immovable	
Richardson	dark	-	279	movable	
Rossby2	dark	-	-	not clear	insufficent spatial resolution
Russell	dark	no difference	326	movable	
Sagan	dark	warm	555	immovable	
Sinus Meridiani	medium	cold	326	movable	
Sirenum1	dark	-	-	not clear	insufficent spatial resolution
Sirenum2	medium/dark	-	240	movable	
Thaumasia 1	dark	cold	577	not clear	thin sand sheet, small dune in centre, TI from crater floor
Thaumasia2	dark	no difference	452	not clear	thin sand sheet, TI from crater floor
Tolstoy2	dark	no difference	-	not clear	insufficent spatial resolution
Trouvelot	dark	cold	469	not clear	small unconsolidated dunes on high TI crater floor? resolution?
Tyrrhena 1	dark	cold	293	movable	
Tyrrhena 2	dark	cold	305	movable	
Tyrrhena 3	dark	-	297	movable	
Vastitas	medium	-	340	not clear	
Verrier2	medium/dark	-	247	not clear	insufficent spatial resolution
Xante1	dark	warm	441	immovable	
Xante 2	dark	no difference	375	not clear	