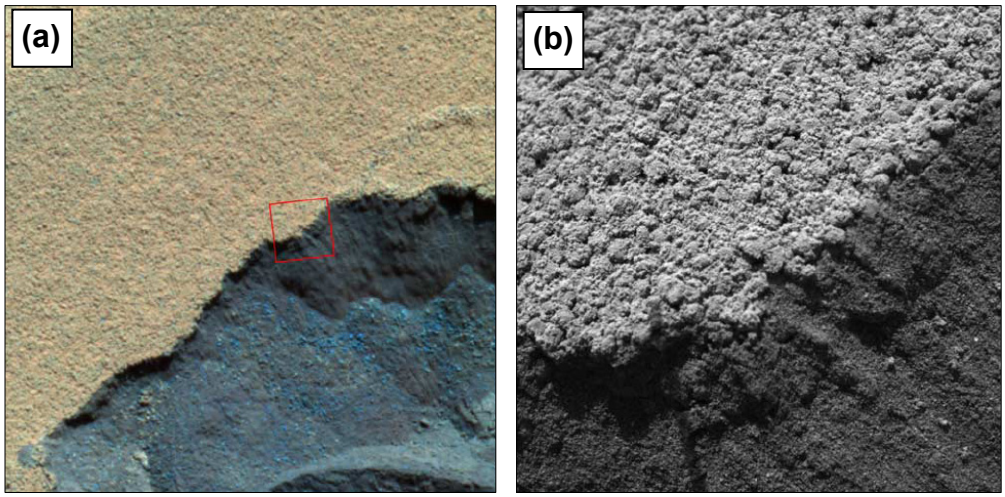
5.7 The Immobilization of Dunes - Possible Types of Consolidation

Higher thermal inertia values measured at several dunes are caused by a higher heat transfer in consolidated material. Thus, a certain induration process must have taken place.

Induration of Martian surfaces is a well-known phenomenon. In 1976, superficial crusts and hardpans on Mars were first observed by the Viking landers. Since then, crusting and induration of originally fine-grained surface material has been observed at all five Martian landing sites [e.g. *Jakosky and Christensen*, 1986; *Arvidson et al.*, 2004; *Thomas et al.*, 2005; *Richter et al.*, 2006]. Moreover, dunes may be immobilised to a certain extent by surface consolidation because small Martian dunes do not appear to have moved during time scales of 4 - 15 Martian years, as shown by multi-temporal analyses of remote sensing data [*Schatz et al.*, 2006]. Some of the latest images showing surface crusting in aeolian bed forms have been acquired by the MER rover Spirit at the Gusev Crater landing site. Fig. 69 shows a crusted bright ripple surface built by dust aggregates and a soil profile of El Dorado deposit revealing a ~3 mm-thick superficial crust.



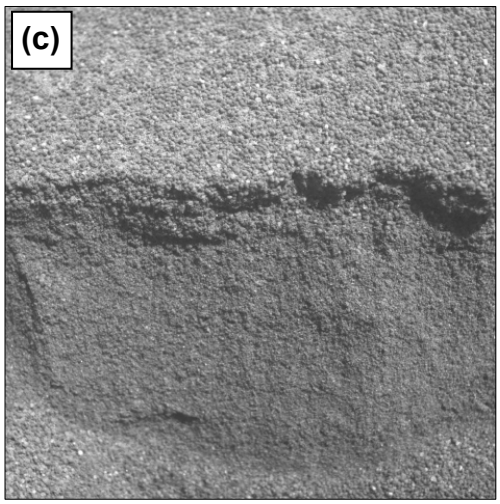


Figure 69: Crusting of aeolian bed forms observed at MER Spirit landing site.
(a) Rover wheel scuff in light-toned coarse-grained ripple named "Serpent", revealing a dusty, crusted, coarse-gained surface (reddish) and finer interior material (purplish), (Pancam false colour image L257). **(b)** Close-up of Fig. (a) marked by the red quadrangle showing dust aggregates on the undisturbed ripple forming coarse grains (700-1800 µm) and a sudden transition to finer ≤300 µm sand grains underneath (MI image, ~31 mm across). The albedo difference is caused by the grain size difference and correlates with the colour difference in Fig. (a). **(c)** 2cm soil profile named "Gallant Knight" in dark material of the El Dorado deposit showing 3 mm thick crust dominated by 200-300 µm rounded sand grains. Particles beneath are dominated by grain sizes ≤100µm (MI image, 31mm across). All images were obtained from *Sullivan et al.* (2008a).

Crust formation is common in arid and semi-arid regions on Earth. Cementing agents on Earth usually include silicates, gypsum, and calcium carbonate, which can normally be found in semi arid regions. One reason of crustification may be the lack of eluviation of these agents caused by rare precipitation. Thus, carbonates, chlorides, and sulphates become enriched in the soils. The calcium carbonate or calcareous crusts are called calcretes [*Paquet and Clauer [ed.]*, 1997]. Caliche is another term for these crusts, but it is less apt because it is also used for nitrate and gypsum deposits. Crusts made of silicates form the so-called silcretes. Many crusts develop in association with precipitation. They have a very solid upper hardpan and a crumbly capillary zone below. Ascending groundwater causes mineral precipitation at the alluvial horizon. [*Cooke and Warren*, 1973; *Besler*, 1992; *Cooke et al.*, 1993]

The general contributors to the immobilization of dunes on Earth primarily include increased moisture, decreased wind power, and the growth of vegetation. On Mars, immobilization is caused by dunes being buried under or embedded in ice [*Schatz et al.*, 2006] or so-called nivo-aeolian deposits [*Bourke et al.*, 2008b]. For dunes at lower latitudes, embedding in ice is not a likely process, so that other consolidation processes must be taken into consideration. Thus, for example, fine dust particles can be placed into the spaces between coarser particles, causing an increase in coherence [*Thomas et al.*, 2005]. *Schatz et al.* (2006) supposed that crust formation on Mars could be caused by the diffusion of water vapour into and out of fine-grained materials. During this process, salts are deposited as an inter-granular cement [*Clark et al.*, 1982]. Similarly, *Jakosky and Christensen* (1986) consider the mobilization of salt ions within a layer of absorbed water in association with water exchange between regolith and atmosphere to be the trigger for duricrust formation. They suppose that this process might have a duration of about 10^5 to10^6 years. Elementary analyses of Martian soils at different sites yield sulphur contents of up to 4 % [*Rieder et al.*, 2004], providing a basis for the formation of sulphates. Numerous authors have reported on sulphate detection on Mars, [e.g. *Clark et al.*, 1976; *Pelkey et al.*, 2005; *Poulet et al.*, 2005; *Jouglet et al.*, 2007], thus, salts actually can be seen as a cementing agent for crust formation on Martian surfaces [*Clark and van Hart*, 1981]. Furthermore, *Malin* (1974) supposes salt weathering to be a major erosion mechanism on Mars, supposing the availability of salts of volcanic origin. *Landis et al.* (2004) proposed two alternative approaches for the formation of surface crusts based on the fact that water can condense to frost on or between grains (because the atmospheric pressure is above the triple point of pressure of liquid water and night-time temperatures range around -100 °C at MER landing sites). The frost might be melted by day-time temperatures, resulting in a transient liquid water phase, which migrates downwards due to capillary action and dissolves the salts in the soil. Further heating of the soil results in the evaporation of the water, and the remaining salts act as cementing agents and form the duricrust ('top down' model of *Landis et al.* (2004)). In the bottom-up hypothesis, day-time heating draws liquid water from a subsurface brine or ice reservoir by capillary forces. During this process, salts are dissolved, transported upwards, and deposited on the surface as the water evaporates [*Landis et al.*, 2004]. *Richardson and Mischna* (2005) showed that due to the large diurnal

range of surface temperatures, conditions for transient liquid water may still be met on Mars, given current surface pressures and obliquities. Furthermore, the liquid range of water is extended by capillary-pore effects and dissolved salts [*Landis et al.*, 2004]. Thus, the mobilization of salts by temporarily liquid water might be a plausible factor in the induration process on Mars. However, most of the reported induration processes concern Martian soils, not specifically dune surfaces. To what extent these processes might take place on dune surfaces will have to be studied in the future.

There are different morphological indications for indurated dune surfaces on Mars, including dune arrangement, dune shape, and dune surface morphological features. For example, barchan dunes coexisting with straight linear dunes lacking sinuosity indicate different wind regimes (barchans = unidirectional; linear dunes = bidirectional, e.g. in the north polar region (see below) and dunes in Dawes Crater (see Fig. 27, Sect. 5.1)) and thus could not have developed at the same time. Furthermore, one of these dune types is supposed to be immobile or stable because it did not change its shape during the period when the wind regime was different and the second dune type was built. A further indication of indurated dunes is the occurrence of straight linear dunes at the downwind end of rounded barchan or dome dunes, beginning with a knotted structure. *Schatz et al.* (2006), who analyzed such dunes at Chasma Boreale, proved this formation theory by computer simulations (modelling a straight ridge downwind of an unerodable dome dune). They found that the knots develop at an early stage of the simulation, judging that the formation is analogues to the instability of a sand bed under unidirectional winds. This suggests that these sands at Chasma Boreale were recently indurated. Furthermore, they observed that the shapes and morphologies of the rounded elongated slip face-less dunes in Chasma Boreale might be the product of successive indurations of sand at each stage of slip face advancement. Continuing that process, slip faces grow successively smaller until they disappear altogether, and the barchan dunes assume the shape of a dome dune. They proved their findings by comparing these rounded, elongated barchans with the oil-soaked dunes described by *Kerr and Nigra* (1952). Located near an oil field in Saudi Arabia, these dunes were successively sprayed with oil, which indurated their surfaces and finally halted their movement. In the course of this process, the barchans' slip faces shrink successively as new sand arrives. Fig. 70 illustrates this process. The similarity between these terrestrial and the Martian examples is so remarkable that the Marian dunes might have formed in a similar way. Instead of oil, the induration of the dune surface might have been caused by ice, frozen carbon dioxide, or mineral salts [*Schatz et al.*, 2006].

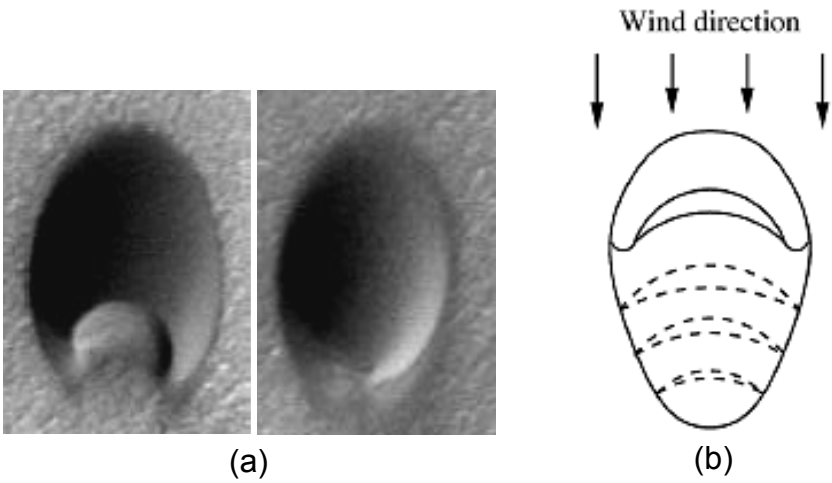


Figure 70: Dune shape as evidence of induration.
(a) Subset of MOC image M02-00783: Rounded barchan dunes located near 85°N, 27°W. Both dunes are about 200 m wide, north is to the right. **(b)** Sketch of the development of a rounded barchan showing the deposition of sand to the lee of the initial barchan. Solid lines show the initial and final shape. Dotted lines show slip face positions in intermediate stages. [*Schatz et al.* (2006) after *Kerr and Nigra* (1952)].

Additionally, the texture of a dune surface may reveal surface consolidation. Grooves, gullies, and steep-walled avalanches at the dune surface mainly develop in more or less solid material and are thus indicators that the dune surface does not consist of loose unconsolidated grains [*Schatz et al.*, 2006]. One example is provided by dunes in Kaiser Crater (46.5°S, 18.8°E). Fig. 71 shows gully formation on a dark barchan located at the margin of this dune field. Besides the gullies, the steep wall of this dune also indicates an induration of the dune surface [*Bourke*, 2005]. As shown in Fig. 59, the thermal inertia of these dunes indicates immovable and indurated material, proving the suggestions based on morphological aspects.

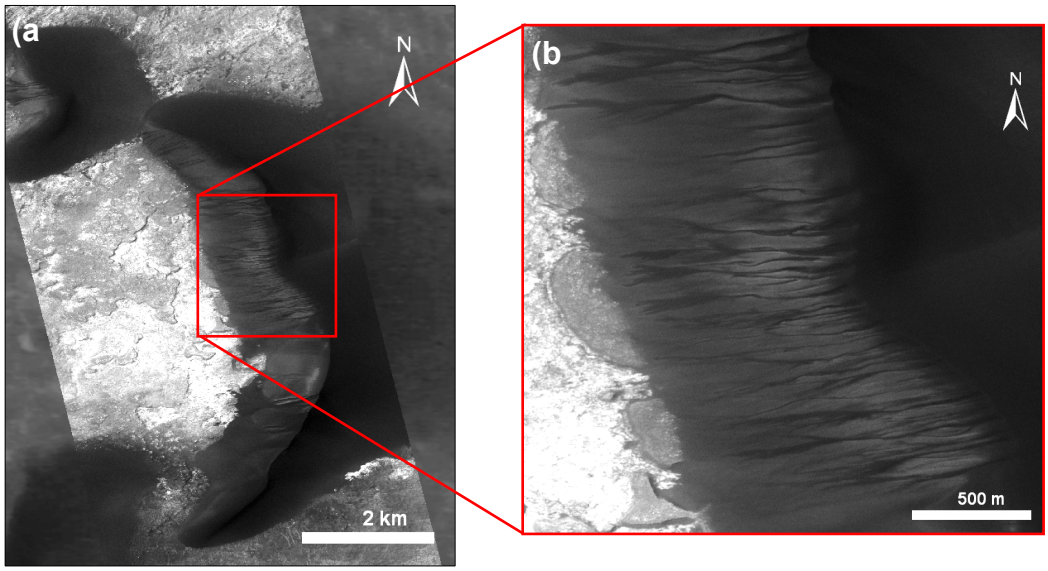


Figure 71: Gullies as indicators of indurated dune surfaces.
(a) Barchan dune in Kaiser Crater (subset of MOC R0600380; centre near 46.7°S, 20.1°E). **(b)** Close-up of Fig. a showing the gullies at the steep dune slip face. (cf. Fig. 59)

Consolidated dune surfaces may be scoured by wind, consequently exhibiting traces of abrasion such as small yardangs. Yardangs are wind-abraded elongated ridge-like landforms with a steep and broader wind-faced front and a lower and narrower end [*Besler,* 1992]. *Edgett and Malin* (2000b) found eroded dark dunes at the eastern floor of Herschel Basin that have a typical ridged and grooved texture (Fig. 72a). This texture is interpreted as yardangs caused by wind erosion on indurated dunes, which are even supposed to have been lithified into sandstone [*Edgett and Malin*, 2000a]. A further indicator of dune inactivity found by *Edgett and Malin* (2000) is a mantle of dust on the surface. They found dunes at the base of a slope in the northern portion of the Olympus Mons aureole whose albedo is indistinguishable from the surrounding terrain (Fig. 72b). Furthermore, dark streaks that have formed on the ancient slope in Fig. 72b appear to have overridden the dust-covered aeolian bed forms at the slope's base, as indicated by the white arrows. This is further evidence of the inactivity of these dunes [*Edgett and Malin*, 2000b].

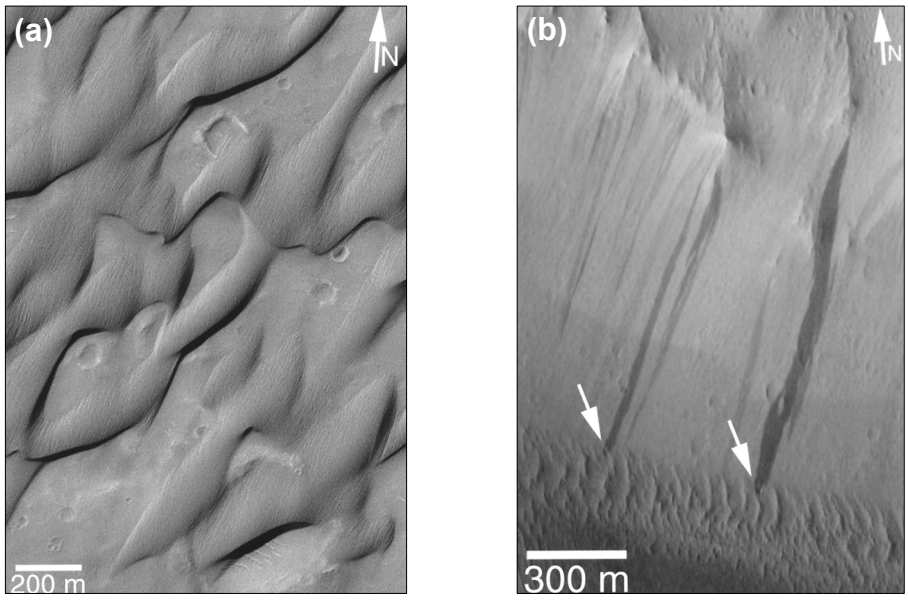


Figure 72: Yardangs and dust mantles as morphological evidence of indurated dune surfaces.
(a) Eroded, low-albedo aeolian dunes on the eastern floor of Herschel Basin (subset of MOC M00-03222; centre near 15.4°S, 228.2°W; illumination is from the upper left). **(b)** Dust-covered aeolian bed forms at the base of a slope in the northern portion of the Olympus Mons aureole, Lycus Sulci (subset of MOC AB1-02403; centre near 31.6°N, 134.1°W; illumination is from the left). White arrows mark regions where dark streaks appear to have overridden the aeolian bed forms (see text for discussion). Both images from *Edgett and Malin* (2000b).