CHARACTERISTIC TIME SCALES OF DUNE-RELATED PROCESSES IN POLAR REGIONS OF MARS. ***M. A. Kreslavsky***[1], [1]Earth and Planetary Sciences, University of California - Santa Cruz, 1156 High Street, Santa Cruz, CA, 95064, USA, mkreslav@ucsc.edu

Introduction: Dark sand dunes are abundant in high-latitude areas of Mars [e.g., 1, 2]. They are indicators of surface-atmosphere interaction and potentially record details of the recent climate changes on Mars. Recent studies of dune morphology and observations of actual changes [e.g., 3, 4] indicate that sand movement does occur in the present epoch, but the overall rate of sand migration is significantly lower than for active dune fields on the Earth.

One of the recognized factors potentially responsible for the low activity levels is induration of the sand by ground ice [e.g., 4]: at high latitudes on Mars, H_2O ice is known to be stable against diffusive exchange of H_2O vapor with the atmosphere [e.g., 5, 6], which means that H_2O vapor would diffusively migrate from the atmosphere into sand and condense as ice at some depth.

Here I consider an independent observational constraint on dune activity time scales from the population of small impact craters in Olympia Undae, the largest sand sea on Mars located at high northern latitudes. Then I analyze characteristic time scales related to diffusive H_2O exchange between sand, the atmosphere and the substrate and use these considerations to explain some observed phenomena.

Impact crater population in Olympia Undae: I visually searched HiRISE images of Olympia Undae dunes for small impact craters superposed over the dark sand. I surveyed all full-resolution summer-time (no seasonal frost) images released by March 2010, totally 24 images. Their total area was 1640 km^2, and the area covered with dark sand was estimated to be 1340 km^2. My experience with searches of this kind shows that craters larger than ~5 m can be reliably identified. Only one crater was found (Fig. 1); its diameter is about 7 m. The formal error bar for statistics of one crater is wide: at 90% confidence level, the expected number of craters (related to the crater retention age) is bracketed within 0.1 - 3.9 interval.

I use the accumulation population of small craters on ejecta of a young 10-km crater Zunil as a proxy for production function of small craters [7]. Found single crater means that the crater retention age on Olympia Undae is bracketed between $2.7\times10^{-5}\,T_Z$ and $1.0\times10^{-3}\,T_Z$, where T_Z is the age of Zunil. This estimate is biased on two reasons. (1) Thicker atmosphere (due to lower elevation in comparison to Zunil) and seasonal frost (especially because it is present during the aphelion season, when impact rate is higher [8, 9]) make crater production rate in Olympia Undae lower than for Zunil. (2) All other condition being the same, an impact into loose or slightly indurated sand produces a larger crater than the same impact into rocky Zunil ejecta. These two biases partly compensate each other.

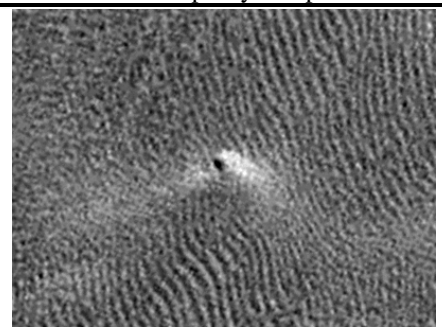

Fig. 1. Impact crater in Olympia Undae. Portion of HiRISE image PSP_009728_2620. The scene is 100 m wide, north is on the top, solar illumination is from lower left.

The absolute calibration of ages obtained from small craters is also highly uncertain. The observed present-day cratering rate of 5.3×10^{-7} km^{-2} a^{-1} has been reported in [9], and 5 m is close to the observed diameter cut-off of the new craters. Two observations indicate that the true rate is probably a factor of a few higher. (1) New impacts are unevenly distributed in the dusty region of Mars, which indicates that impacts in some places in these region do not produce large dark halos and hence cannot be spotted [10]. (2) The size-frequency distribution of the new craters is shallower than that of the production population on Zunil ejecta.

Taking in account all uncertainties, the age constraints from the impact crater population can be summarized in the following statements:

- During a thousand of martian summers (or quicker), any 5-10-m size crater would be completely obliterated.
- Crater in Fig. 1 certainly survived at least a few martian summers.

This is consistent with the following:

- Migration of Dunes in Olympia Undae does occur under the present-day climate conditions
- Characteristic sand migration rates are significantly lower than for terrestrial active dunes

Water vapor and ice in sand dunes on Mars: The diffusion coefficients of water vapor in soils under martian conditions has been measured in [11]. For sand (unless its pore space is saturated with ice), the highest measured diffusion coefficient of 5 cm^{2}s^{-1} is appropri-

ate. This high value looks perfectly plausible given high porosity, large pores and low tortuosity of the pore space in sands, as well as low gas pressure. High diffusion coefficient of water vapor in martian soil is consistent with the diurnal atmospheric humidity cycle observed by Phoenix lander [12]. The diffusion coefficient of water vapor can be directly compared with thermal diffusivity of sand. Thermophysical parameters adopted in [4] and consistent with TES temperature observations of Olympia Undae dunes give thermal diffusivity 4×10^{-4} cm^2s^{-1} for ice-free sand and 1×10^{-2} cm^2s^{-1} for ice-saturated sand. Thus, the diffusion coefficient is much higher than the thermal diffusivity. This means that the stable diffusive flux is established instantly in response to temperature changes.

Exchange with the atmosphere. Detailed calculations of ground ice stability against vapor diffusion under the present-day climate conditions [6] show that ice is unstable in the uppermost decimeter(s)-thick layer of the soil and is stable beneath it. For Olympia Undae the model calculations [6] predict the ice table at ~30 cm, deeper than for other surfaces at the same latitude due to lower albedo and higher thermal inertia of the dark sand. This is consistent with neutron flux observations [4]. In the upper secularly dry soil layer, minor amounts of ice can come and go seasonally and diurnally due to vapor exchange with the atmosphere [6]. Typical concentrations of this seasonal ice in models of [6] were on the order of 10^{-6} by weight. These calculations were done for diffusion coefficient on the order of 0.1 cm^2s^{-1}. Significantly higher actual diffusion coefficient would lead to higher ice abundance. In addition to diffusive transport, vapor can be advectively transported into sand due to forced ventilation caused by daily pressure cycle and wind turbulence. Thus, seasonally varying ice amount of 10^{-4} to 10^{-3} of the pore volume can be expected. Laboratory experiments under martian conditions [13] have shown preferential early deposition of ice at grain contact points. This means that sand can get and lose at least some cohesion very quickly, at seasonal or diurnal time scale, due to tiny amount of ice coming and going in response to temperature and humidity changes.

Sand can potentially be mobilized by winds only during certain season and certain hours of a day, when the uppermost millimeters of sand are free of ice. Dunes are "frozen" all other time due to small amounts of ice in sand. This effect contributes to the observed low rate of sand transport. This also explain the puzzling coexistence of apparently fresh slip faces of dunes in Olympia Undae (that are formed by loose non-cohesive sand) and gully-like avalanche scars and other landslide-like features (that need depth-dependent cohesion for their formation).

Insolation conditions and temperature regimes depend on slope orientation, hence the seasonal and diurnal "unfrozen windows" may be different for different slopes. Some slopes can be source of saltating sand, while other slopes can be slightly cohesive and develop small-scale morphology of eolian erosion, which is also observed in Olympia Undae.

Exchange with the substrate. Analysis of images indicates that the dark sand in northern circumpolar areas of Mars and perhaps in other high-latitude locations is deposited over ice-rich substrate. If sand rests on such a substrate for a long time, a vertical temperature gradient due to the geothermal heat flux will be established in the deposit, and water vapor diffusion will cause slow migration of H_2O from the warmer substrate into colder sand. A very rough order of magnitude estimate is 1 Ma time scales for complete filling pore space in 10-m thick sand layer by this process.

The situation is very different for migrating sand masses. Dark sand has lower albedo and hence higher year-average temperature than neighboring exposed surfaces. Thus, in freshly deposited sand beds the temperature gradient will be opposite (until the geothermal flux is reestablished at 100s- and 1000s-year time scales): the substrate will be colder than sand, hence the diffusive water vapor flux will go from sand into the substrate, thus drying the sand. This effect prevents filling the main mass of dunes with ice and helps keeping them dry and mobile. This effect may explain, why in the martian polar areas dunes are made of dark sand.

A similar effect occurs when dark sand beds are exhumed from polar ice deposits (images show numerous cases of this kind). When high-albedo ice cover goes away, the year-average surface temperature dramatically increases, which causes downward diffusive flux of water vapor and removal of ice from upper sand layers. This effect probably contributes to mobilization of freshly exposed sand at high latitudes.

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