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Thermal stress weathering on airless, terrestrial bodies

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Abstract

Thermal stress weathering plays a significant role in desert landscape evolution on Earth, and is likely an active process on other inner solar system bodies that lack atmospheres, as they will experience higher rates of heating and cooling. We will use a heat-conduction model to calculate surface temperatures of airless, inner solar system landscapes in order to explore the optimal parameters for high thermal stresses. Damage accumulated over geologic time scales from thermal stress could play an important role in setting the lifetime of surface boulders and the overall evolution of these landscapes.

1. Introduction

Thermal stress weathering (thermal fracture) is the mechanical breakdown of a rock from expansion and contraction caused by changes in temperature. Together with aeolian, fluvial, and chemical weathering, it plays a role in the evolution of Earth's landscapes. In most Earth environments, processes such as freeze-thaw and salt weathering dominate rock breakdown. However, in those that lack significant amounts of water, thermal fracture plays a key role in processes such as exfoliation, large crack formation, and granular disintegration [4, 2].

The rate of temperature change, dT/dt, is the primary control on whether or not damage is caused by thermal stress. The presence of an atmosphere dampens heating and cooling rates experienced by rocks through sensible heat exchange and radiative effects, thus surfaces that lack atmospheres may experience greater thermal stresses than otherwise. A dT/dt value of 2 ^{o}C /min is typically used as the threshold above which damage is assumed to occur [6, 2]. While this value is not well constrained and varies depending on rock size and properties [1, 7], it will act as an approximation in order to determine if thermal stress weathering may be occurring on various solar system bodies.

Thermal stress is typically divided into two broad categories: thermal fatigue and thermal shock. Thermal fatigue is progressive damage caused by thermal cycling, which over time accumulates to cause failure [4]. Microcracks form preferentially at grain boundaries due to thermal expansion differences between adjacent mineral grains. Thermal shock is the formation of cracks due to rapid changes in temperature, causing immediate catastrophic failure [3]. In reality, there is a continuum of processes between these two regimes, operating at a variety of scales and a history of thermal fatigue likely increases a material's susceptibility to cracking from thermal shock. Our model results (discussed below) suggest that thermal stress shocks from sudden shadowing on airless bodies are enough to cause microfractures to form, but not great enough to cause catastrophic failure. Damage would be slow and progressive, and contribute to dust and regolith production, boulder breakdown, and crater degradation. In this study, we will compare the strengths of shadow-induced thermal stresses by modeling temperature changes of landscapes on airless inner solar system surfaces.

2. Thermal Modeling

A one-dimensional heat conduction model can indicate under what conditions a surface experiences the highest dT/dt values, and thus where we expect thermal stress weathering to be most effective [5]. We calculated the solar flux on a point surface over one complete insolation cycle, with variable latitude, slope, and aspect angle. We artificially shadowed the surface for a brief period in the afternoon to simulate a sudden shadowing event. The trends were the same for model runs for both Mercury and the Moon, though only Mercury cases showed shocks that exceeded 2 ^{o}C/min. These were found at all latitudes, an example of which is shown in Figure 1.

We found that shock strength is primarily dependent on surface temperature. In each case, cold (tensional) shocks tend to be stronger than hot shocks, significant because the tensile strengths of most

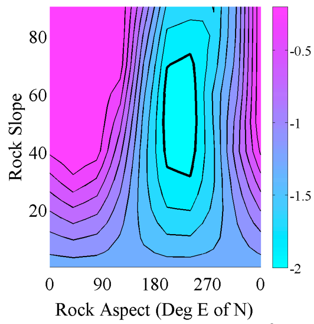

Figure 1: Contour plot of dT/dt in ^{o}C /min for the strongest cold shocks at 45°N on Mercury as a function of surface slope and aspect (measured in degrees East of North). The bold, center contour line corresponds to the threshold of -2 ^{o}C /min.

materials are lower than compressional strengths. Optimal slopes for cold shocks are those that receive the most direct sunlight just before shadowing occurs. Optimal aspect angles for cold shocks to occur are those that are warmest when the shadowing occurs. This means that the strongest cold shocks will occur on south- and west-facing slopes, in the afternoon and evening. While these trends are valuable clues to understanding optimal parameters for thermal weathering, a more sophisticated model is required to simulate the efficiency of this process in realistic landscapes.

We model surface temperature changes of a three-dimensional landscape using spacecraft data as input topography and calculating terrain slope and aspect at each point. We include the effect of shadowing from surrounding topography, ensuring shadows only occur with realistic frequencies and durations. We balance incident solar flux, emitted longwave radiation with conduction into the rock interior, and solve the thermal diffusion equation using standard forward finite difference methods. Figure 2 shows an example of the solar flux and surface temperatures of a crater (taken from a Mars DEM) and placed on the equator of Mercury.

6. Summary

Our preliminary model results indicate that thermal shocks from sudden shadowing are strong enough on Mercury, and maybe the moon, to cause damage to some rock surfaces. In this study we will use the model described above to explore what parameters are common in realistic landscapes, and within those, what are the optimal conditions for high thermal stresses. Modeling temperatures of realistic surface topography will allow us to examine thermal stress behavior of different types of features, on different solar system objects.

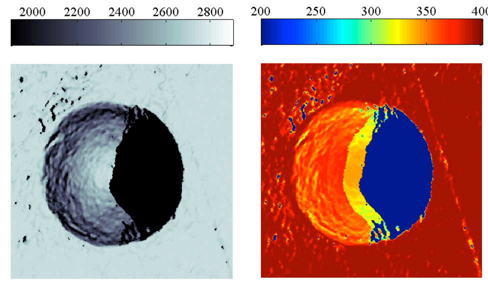

Figure 2: Solar flux in W/m^2 incident on an equatorial crater (left) early in Mercury's insolation cycle, and resulting surface temperatures in K (right). DEM courtesy of the HiRISE team.

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