THERMALLY INDUCED STRESSES IN BOULDERS ON THE MOON: IMPLICATIONS FOR BREAKDOWN. J. L. Molaro[1], P. O. Hayne[1], and S. Byrne[2], [1]NASA-Jet Propulsion Laboratory, California Institute of Technology (MS 183-205, 4800 Oak Grove drive, Pasadena, CA 91109; jmolaro@jpl.nasa.gov), [2]University of Arizona

Introduction: Thermally induced stresses are thought to contribute to rock breakdown in the solar system, especially on airless bodies that have large diurnal temperature ranges and/or have high thermal cycling rates [1, 2]. Researchers have suggested it may operate on (among others) the Moon, Mercury, Mars, 433 Eros, 3200 Phaethon, and comet 67P [1-8]. In general, bodies that rotate slowly and/or bodies that have small solar distances have the largest temperature ranges, and thus experience the highest stresses [1], though the nature and extent of damage caused by this process is not well constrained.

Propagation of microcracks in rocks can occur due to grain-scale stresses from expansion and contraction caused by changes in temperature, as well as from mismatches in elastic properties of adjacent mineral grains [9]. However, the interaction of these stresses with those induced at macroscopic scales ultimately determines the overall thermomechanical behavior of a given object. At larger scales, the size and surface curvature of, e.g., a boulder will affect its response to the temporal and directional heating from the sun, and the extent to which stress can be relieved by expansion of its edges [10]. These effects may result in induced stresses and/or temperature gradients at macroscopic scales that impact grain-scale processes. Additionally, thermal interaction with surrounding regolith and topography may also play a role by affecting how quickly a boulder can heat and cool.

Here we model the thermomechanical behavior of boulders of varying size on the surface of the Moon and other solar system bodies. We investigate the magnitude and distribution of stresses induced by diurnal thermal forcing, providing insight into how thermal breakdown may occur, as well as the relative efficacy of this process on different bodies.

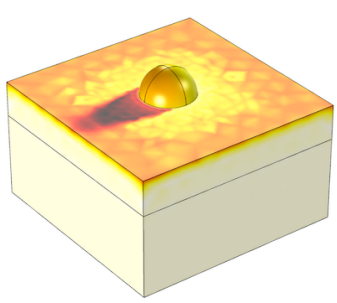

Figure 1. Geometry of a regolith volume and embedded 1 m boulder. This snapshot shows the temperature of the geometry shortly after sunrise.

Model and Results: In this study, we used a 3D finite element modeling program (COMSOL Multiphysics) to model the thermoelastic response of boulders on the lunar surface to diurnal thermal cycling, allowing us to investigate the magnitude and distribution of resulting stresses. We modeled a boulder embedded in a volume of regolith (Fig. 1), imposing the solar flux at the surface and solving the heat and displacement equations over one solar day. The model accounts for the radiative and conductive interaction between the boulder and surrounding regolith.

The sides of the regolith are fixed with respect to displacement, whereas the surface of the regolith and the boundary of the boulder are free, allowing them to expand and contract in response to the thermal cycling. The material properties of the regolith are temperature and depth dependent, following the work of [11]. The boulder is assigned material properties of a typical basalt, all of which are fixed, with the exception of a temperature dependent heat capacity [12].

We compared the maximum principal stress (where tensile stress is always positive) induced in boulders with varying radii. This value represents the maximum idealized energy available for crack propagation at a given time and a given location within the boulder. Preliminary results show that boulders exhibit a bimodal thermoelastic response to diurnal cycling, with

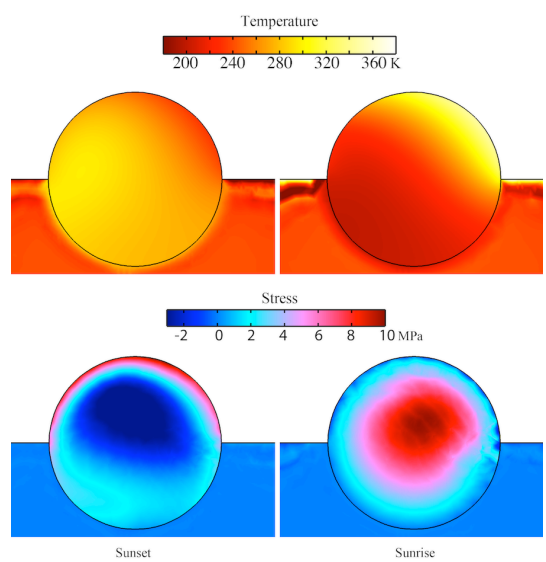

Figure 2. Snapshots of the temperature (top) and stress (bottom) in a 2D cut plane through a boulder 1 m in radius during sunrise (right) and sunset (left).

peaks in tensile stress occurring during both sunrise and sunset. Figure 2 shows the temperature (top) and stress (bottom) in a cross-section of a boulder during sunrise (right) and sunset (left). During sunrise, high stresses occur in the boulders' interiors, and are associated with large-scale temperature gradients that develop as a result of overnight cooling of the boulder center. During sunset, high stresses occur at the boulders' exteriors due to the sudden cooling and contraction of the surface.

Stresses on the order of 10 MPa are induced in meter-scale boulders, decreasing to only a few MPa for smaller radii. Figure 3 shows the peak stress over time in boulders with radii ranging from 0.1 to 1 m. Each point in a profile is the peak value of the maximum principal stress from any location within the boulder, which gives us a general sense of relative breakdown potential throughout the day. These profiles illustrate the bimodal response to the diurnal cycle described above, weakening in amplitude with decreasing boulder radius. There appears to be a transition in the thermoelastic behavior of boulders with a radius ≤10 cm, at which size the expansion and contraction of the its surface is able to relieve most of the stress. This size may represent a threshold, below which thermal breakdown does not occur. Another transition in behavior occurs in boulders >1 m (not shown), where peak stresses increase to several 10s of MPa.

The dotted green line in Figure 3 shows the stress response of a boulder 10 cm in radius that is buried by 2.5 cm of regolith. The regolith provides such strong insulation that the boulder experiences a peak stress of only 0.48 MPa, suggesting that even a thin layer of regolith can effectively shield boulders from thermally induced breakdown.

Conclusions: These results show that thermally induced stresses are likely to be most effective in fracturing larger rocks, particularly those > 1 m. This suggests that the process of thermomechanical breakdown is most rapid initially, then slows as the fragments become smaller. This effect is also enhanced by the shielding effects of regolith, as smaller rocks are more likely to accumulate regolith cover and/or become buried. Overall, this suggests that large, very recently exposed rocks, such as at fresh impact craters, are most susceptible to thermally induced breakdown. This may play a significant role in the degredation of impact ejecta, which could have important implications for determining the ages of craters on planetary surfaces. This also has implications for regolith depth and production rates on the Moon and other solar system bodies.

Future Work: Modeling the thermoelastic response of boulders on airless body surfaces to thermal cycling allows us to quantify induced stress. We have investigated the role that boulder size plays on the Moon; however, different thermal environments may reveal differences in thermoelastic behavior and response to cycling. We will model boulders of varying size on different solar system bodies, with a range of solar distances and solar day lengths. This will allow us to investigate the stresses that may be induced on a wide range of solar system bodies, and determine on what surfaces thermally induced breakdown may be most significant. Available lunar datasets, such as Diviner and LROC, may help to contrain this model by providing information about rock abundance, rock size, and regolith depth on the Moon, leading to better constraints on the models.

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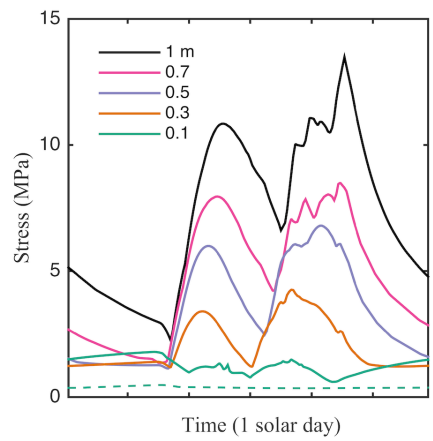

Figure 3. Profiles of the maximum principal stress throughout the diurnal cycle within boulders of varying radius. Each point in a profile is the peak value of the maximum principal stress from any location within the boulder.

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