Thermoelastic grain-scale stresses on airless bodies and implications for rock breakdown

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Quick Summary

Thermal fatigue processes may have a significant contribution to regolith production on airless bodies that experience extreme temperatures or high cycling rates. Here we present modeling results of grain-scale stresses induced in microstructures on the Moon, and elsewhere in the solar system. We also investigate the relationship between stresses and spatiotemporal temperature gradients, which are often used as proxies.

Molaro et al. (2015), *JGR: Planets 120*, 255-277.

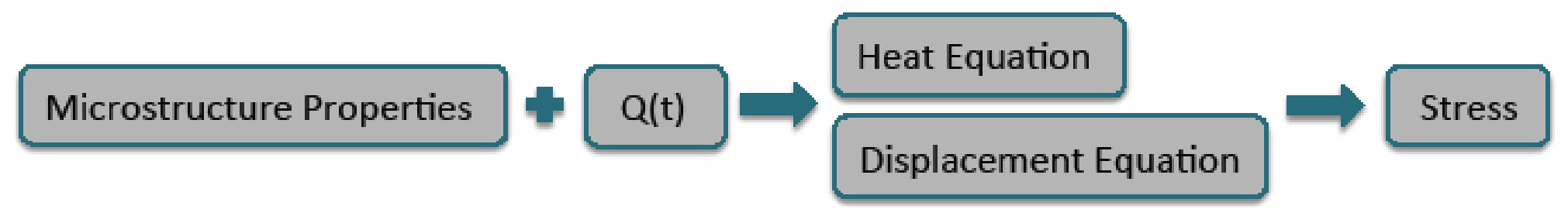
Background

Thermally induced fatigue and shock processes are thought to contribute to rock breakdown on Earth, especially in environments where other weathering processes are slow. Stresses are induced from expansion and contraction caused by changes in temperature, and by mismatches in elastic properties between mineral grains. Airless bodies may provide an environment uniquely suited to thermal stress weathering, as they experience more dramatic diurnal temperatures and temperature ranges than Earth, and many have high cycling rates.

Understanding regolith production processes on these bodies may have a significant impact on our understanding of their evolution. This study represents the first attempt to understand and quantify the contribution of thermal processes to breakdown rates on these bodies.

Model

Finite Element Analysis of Microstructures (OOF2) is a 2D finite element modeling program developed by NIST to help scientists simulate the behavior of microstructures.


Microstructure Properties + Q(t) → Heat Equation / Displacement Equation → Stress

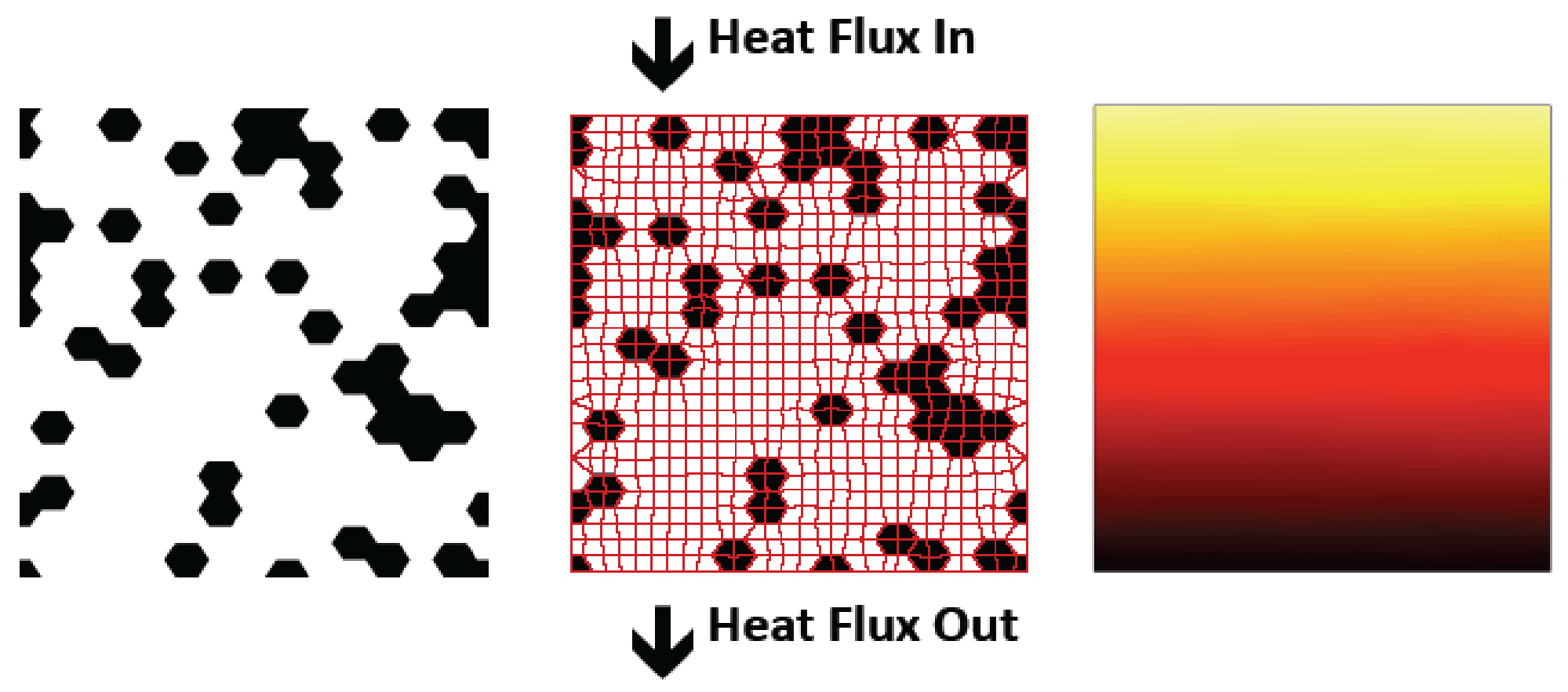
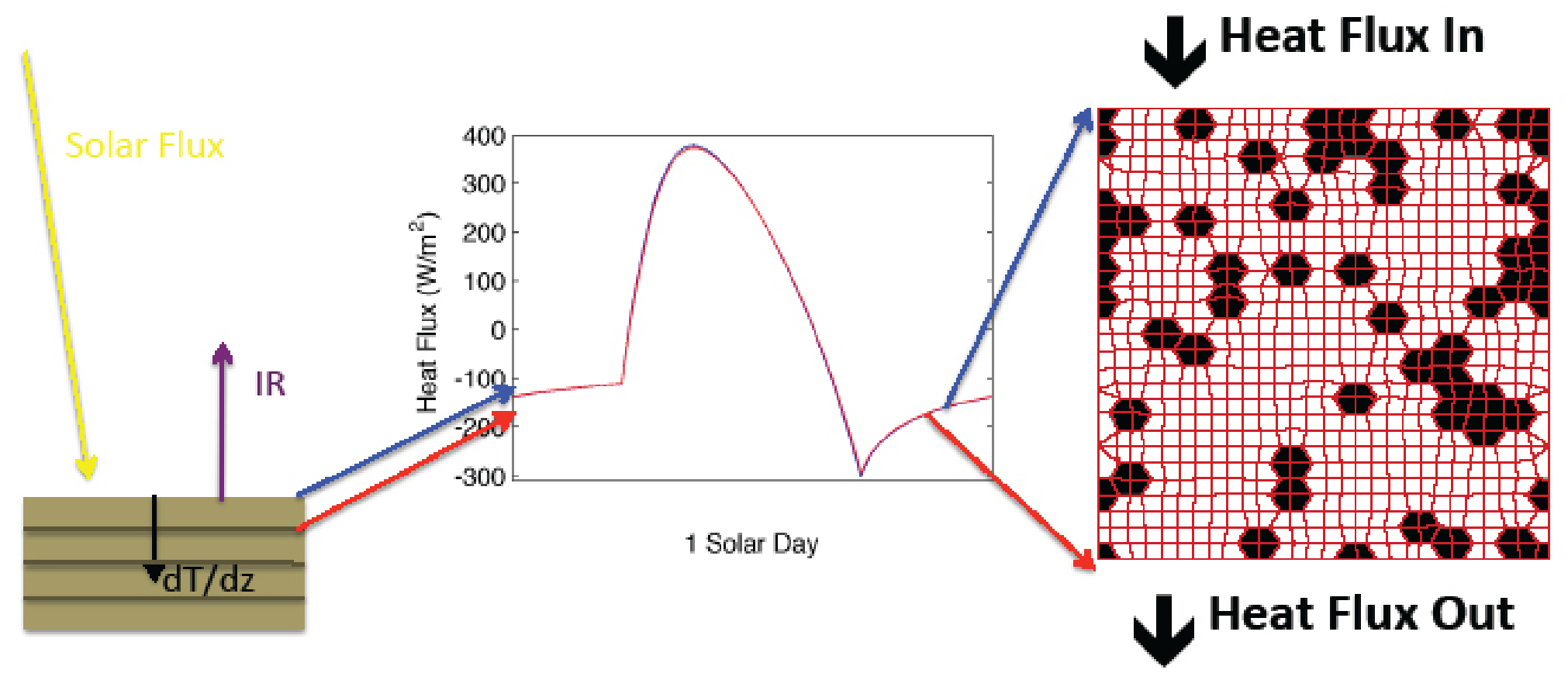


Figure 1. Example microstructure (left) and finite element mesh (center) used to calculate stress (right).

Figure 2. To define the time dependent heat flux boundary conditions, we imposed the solar and conductive fluxes calculated by a separate 1D thermal model at the surface and at a depth of 0.005 m on a microstructure. Each microstructure is made of randomly distributed pyroxene and plagioclase grains in given proportions. The material parameters used in the 1D model were equal to the bulk properties of each microstructure.



We present effective (von Mises) stresses, as given by:

$$\sigma_e = \sqrt{\frac{(\sigma_1-\sigma_2)^2 + (\sigma_2-\sigma_3)^2 + (\sigma_1-\sigma_3)^2}{2}}$$

Note that because tensile stresses are more likely to cause damage, a sign correction has been applied to visually separate results.

Material Property	Pyroxene	Plagioclase
Thermal Conductivity (W/m*K)	4.6	2
Heat Capacity*Density (J/kg*K)*(kg/m^3)	2.7x10^6	2.9 x10^6
Young's Modulus (GPa)	175	85
Possion's Ratio	0.23	0.33
Linear Coefficient of Thermal Expansion (K^{-1})	0.8x10^{-5}	0.4x10^{-5}

Table 1. Properties applied to grains in microstructures.

Results

Heterogeneous versus Homogeneous Microstructures

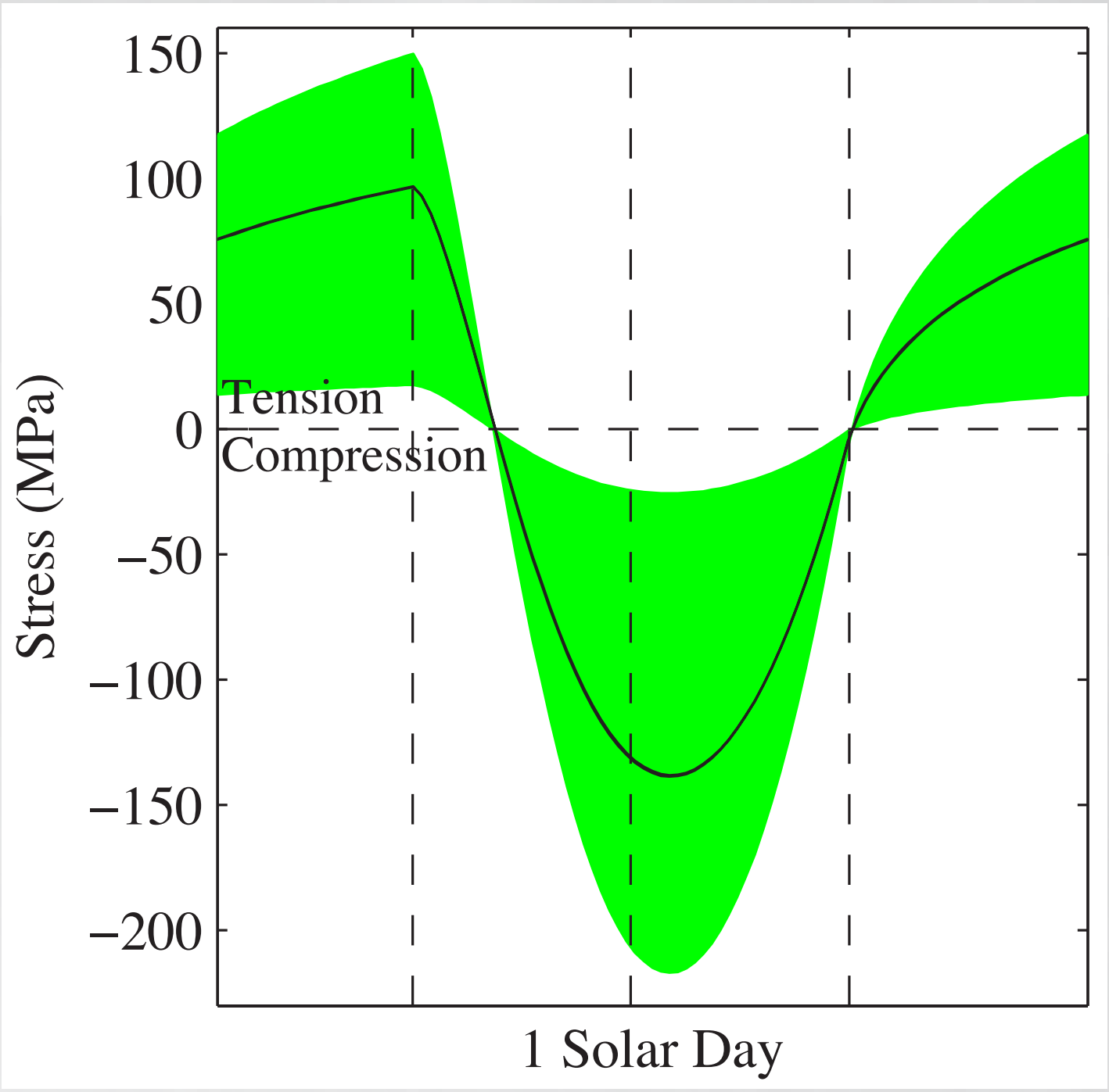


Figure 3. Profile of the range of effective stresses within a microstructure over one solar day for a flat, equatorial Lunar surface. The black envelope represents a homogeneous pyroxene microstructure and the green, a microstructure with 25% plagioclase and 75% pyroxene grains. The vertical dotted lines represent the time at which sunrise, noon, and sunset occur.

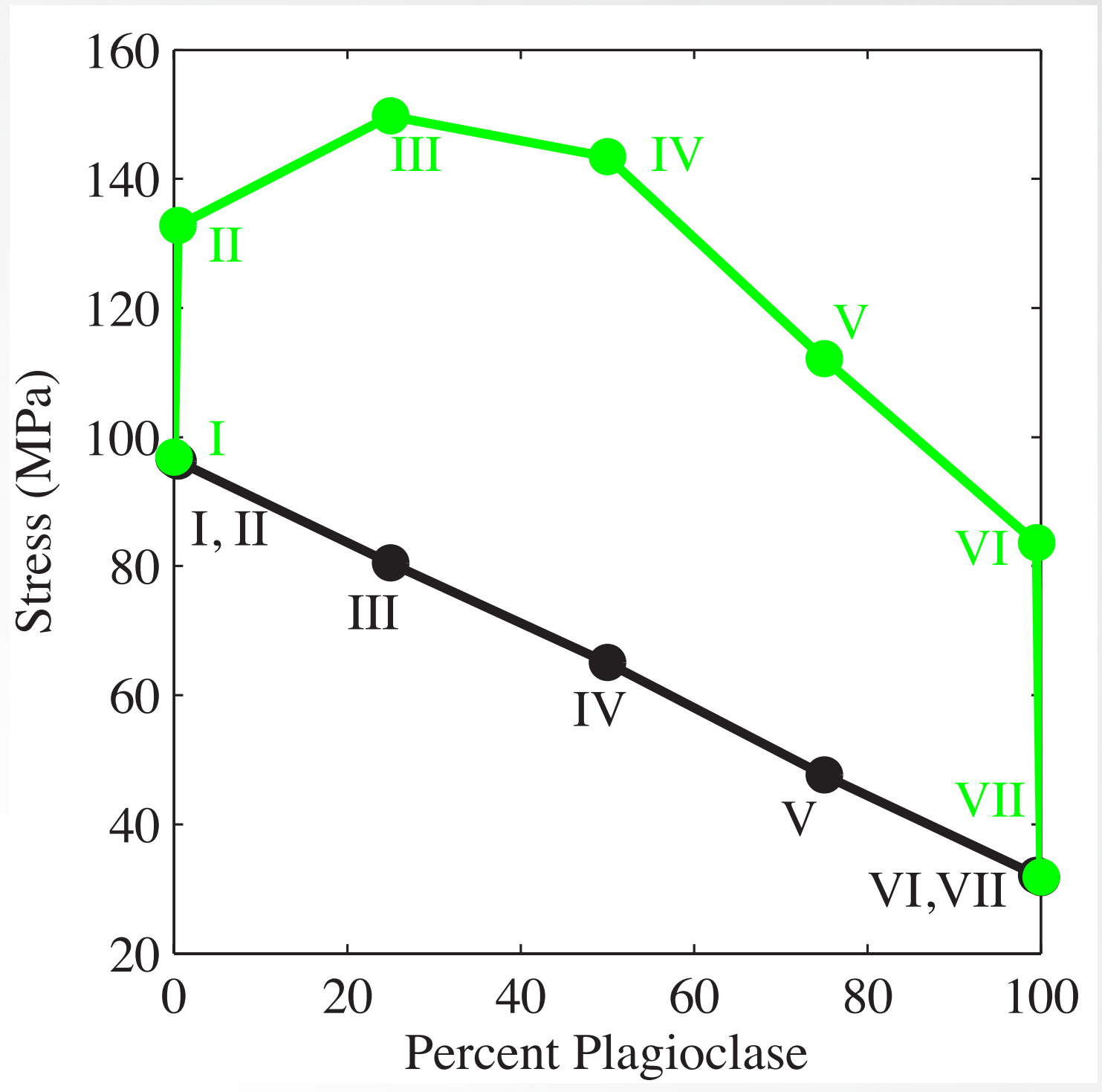


Figure 4. The average (black) and maximum (green) stresses induced during the state of peak tension in a Lunar microstructure with a given volume of pyroxene and plagioclase grains.

The average stress induced in a microstructure decreases as you increase the amount of plagioclase. Due to their lower Young's modulus, plagioclase grains experience more strain and take up some of the stress that would otherwise be induced.

The maximum stress induced is controlled by differences in elastic properties between mineral grains (Figure 8). A significant increase in stress over the homogeneous behavior is experienced even by adding a single heterogeneous mineral grain.

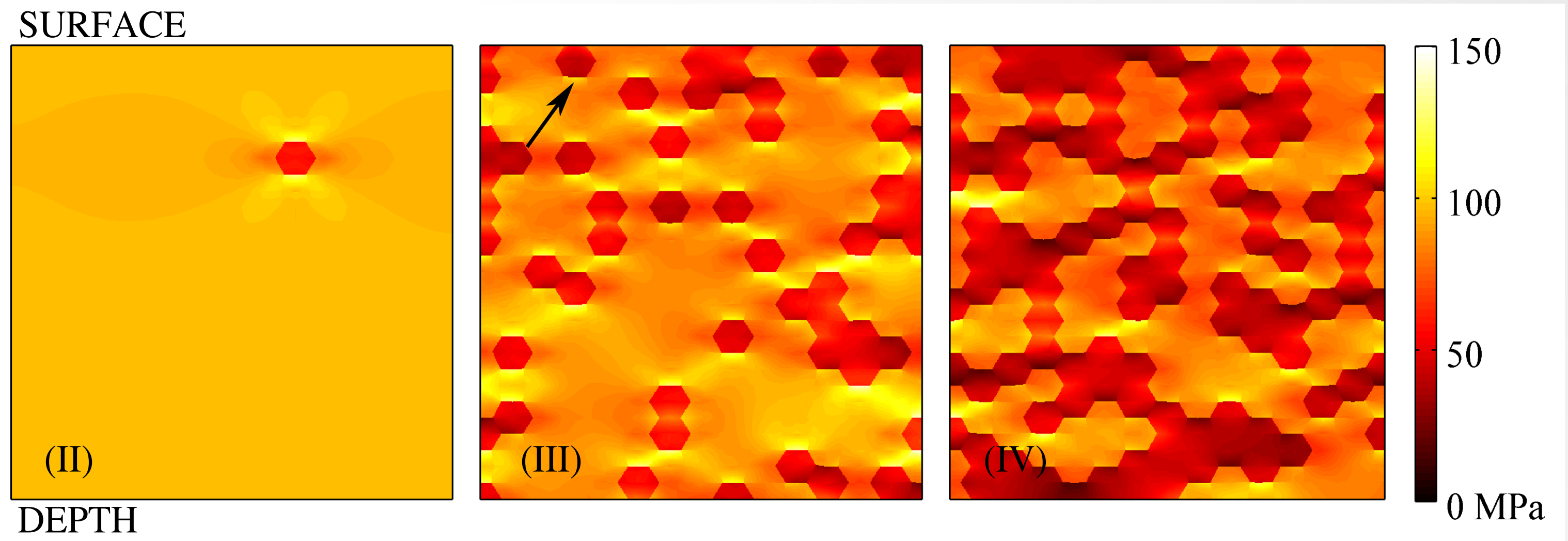


Figure 5. Snapshots of the state of peak tensile stress in microstructures corresponding to II-IV in Figure 4. Stresses are induced along surface parallel boundaries between mineral grains with different properties. Stresses are concentrated in areas where these boundaries are abundant and their stress fields can interact.

Stresses Throughout the Solar System

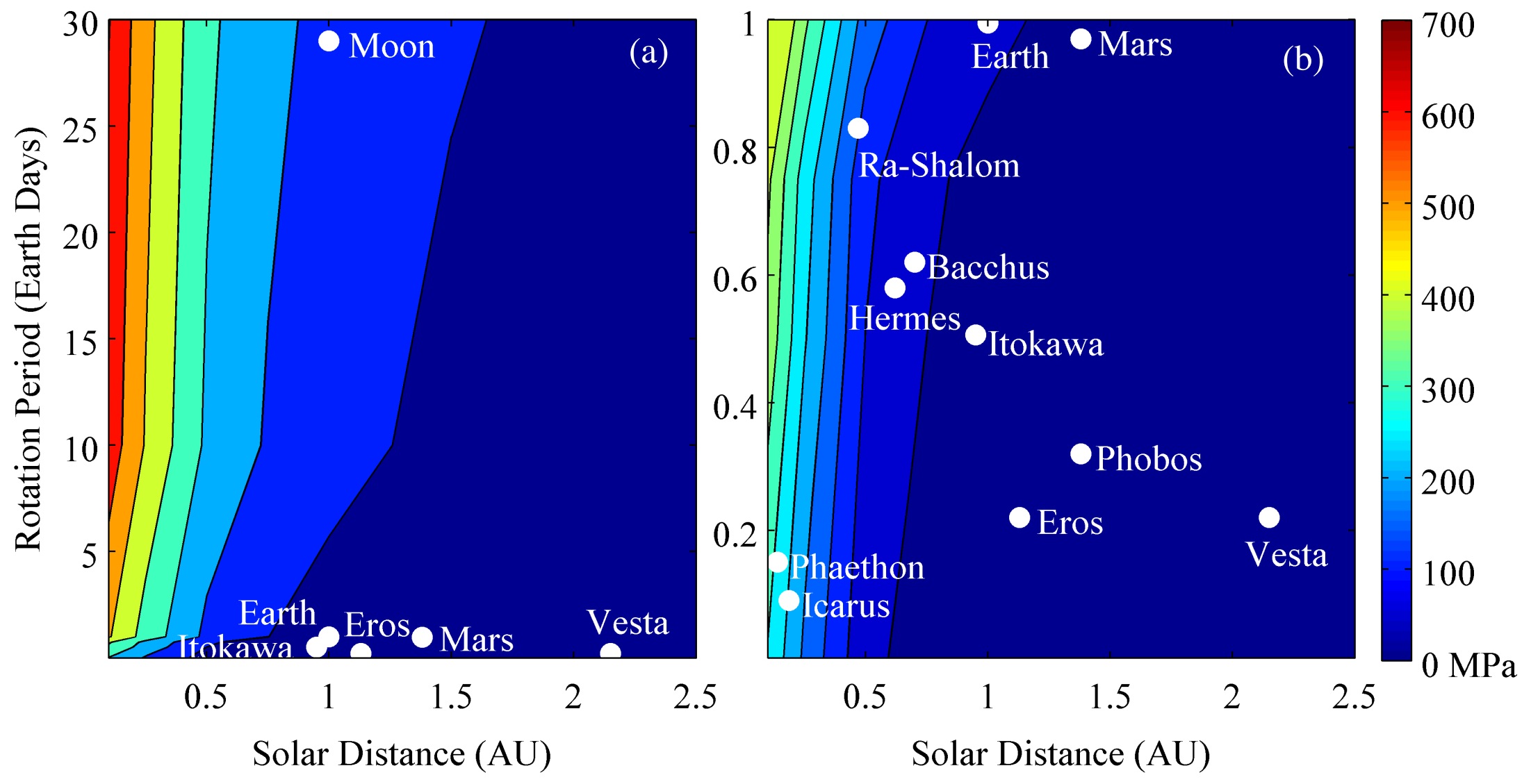


Figure 6. Maximum effective stress during the state of peak tension on arbitrary surfaces of bodies with varying solar distance and solar day length in the inner solar system, with contour lines spaced at 50 MPa intervals. All bodies used for these model runs were assumed to have zero eccentricity and inclination. Various bodies are placed for reference. **Bodies that rotate slowly and/or are close to the sun experience the highest stresses.**

Relationship to Temperature Gradients

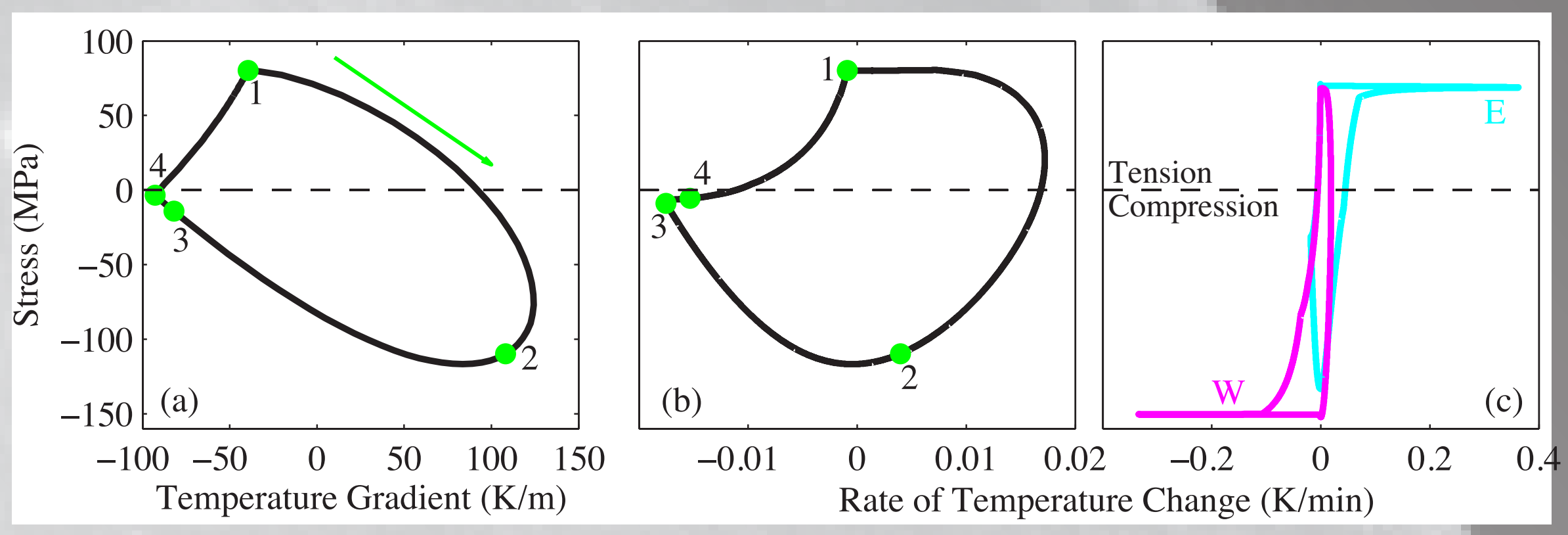


Figure 7. Average stress in a microstructure (III) over one solar day on a Lunar surface with (a) vertical temperature gradient (calculated from the difference in average temperature at the top and bottom of the microstructure), and (b) rate of temperature change (calculated from the 1D thermal model and paired with the 2D results). (c) Same profile as in (b) for an east- (cyan) and west-facing surface (magenta) with a slope of 65°. The panels (a) and (b), point 1 is the beginning of sunrise, 2 is noon, and 3 and 4 are the beginning and end of sunset, respectively.

Neither large temperature gradients nor rapid rates of temperature change correlate with the times of day at which maximum stresses occur.

Dominant Material Properties

The temperature gradient is often used as a proxy for stress. To test the dominant material parameters controlling stress and temperature gradient, we present results for microstructures whose grains have the same material properties, with a single parameter different in each case.

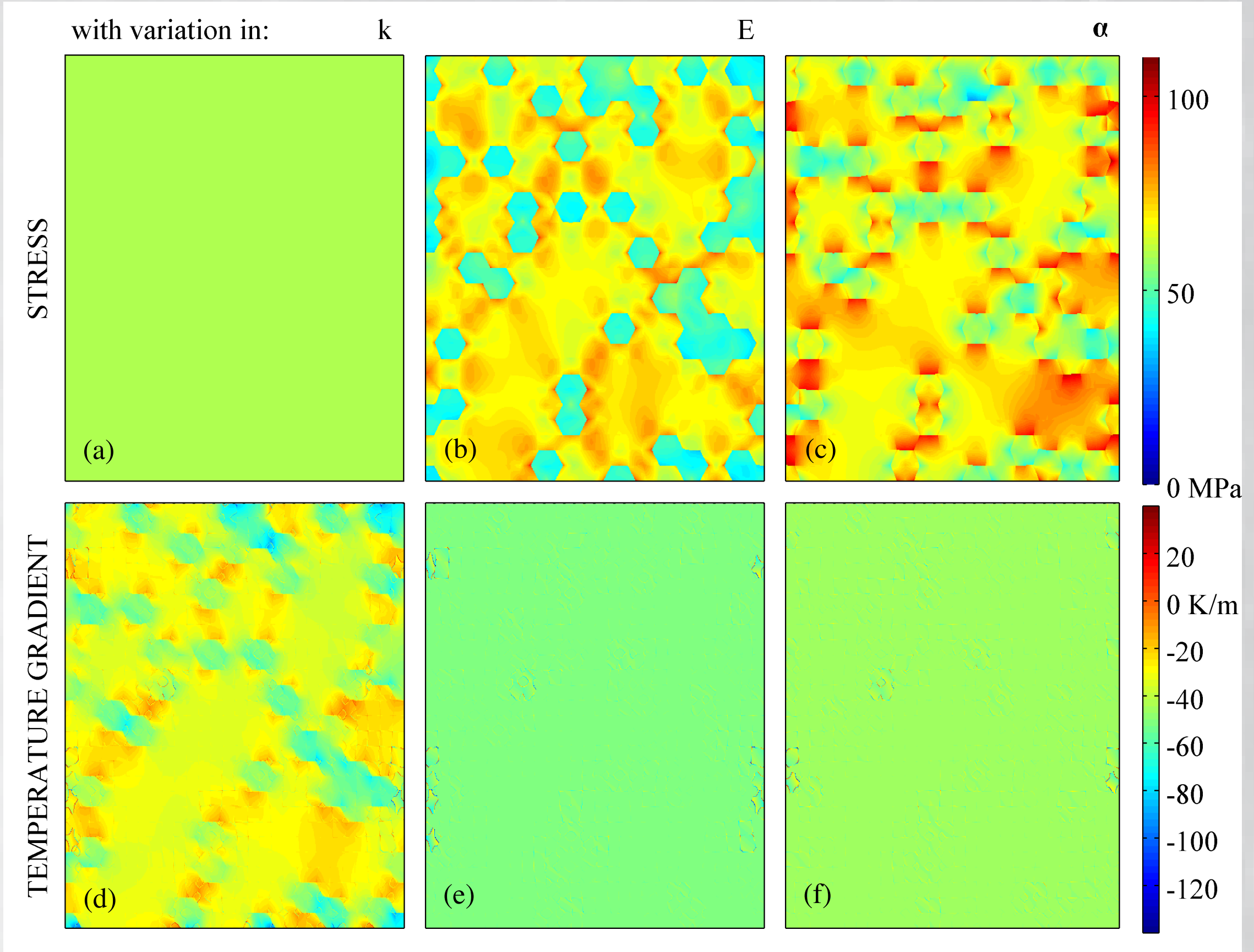


Figure 8. Snapshots of the stress (top row) and temperature gradient (bottom row) during the time of peak tension in a standard microstructure. Average values of all material parameters (Table 1) are assigned to all grains, except thermal conductivity (left), Young's modulus and Poisson's ratio (center), and coefficient of thermal expansion (right).

Grain scale stresses are controlled by a mineral elastic properties. Thermal conductivity plays no role.

Conclusions

1) Heterogeneity, like that expected in natural rocks, will assist in thermal breakdown within the inner solar system.

2) Analyzing the thermoelastic behavior of the mineral constituent with the highest Young's modulus and coefficient of thermal expansion provides the simplest lower limit approximation of expected behavior in a hetergeneous microstructure.

3) Average stresses in a microstructure are controlled by material properties and relative volume of mineral types, but the formation and propagation of cracks is controlled by grain and pore (not shown) distribution.

4) Spatiotemporal temperature gradients are not an appropriate proxy for induced grain scale stresses, however temperature range may be useful.

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