STRETCH MARKS ON PHOBOS. T. A. Hurford[1], E. Asphaug[2], J. N. Spitale[3], D. Hemingway[4], A. R. Rhoden[2,5], W. G. Henning[1,6], B. G. Bills[7], S. A. Kattenhorn[8] and M. Walker[9], [1]NASA Goddard Space Flight Center, Greenbelt, MD 20771, [2]Arizona State University, School of Earth and Space Exploration, Tempe, AZ 85287, [3]Planetary Science Institute, 1700 E. Ft Lowell, Tucson, AZ 85719, [4]University of California, Santa Cruz, Department of Earth and Planetary Sciences, Santa Cruz, CA 95064, [5]Johns Hopkins Applied Physics Laboratory, Laurel, MD 20723, [6]University of Maryland, Center for Research and Exploration in Space Science and Technology, College Park, MD 20742, [7]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, [8]Conoco Phillips Company, Geological Technology, Houston, TX 77079, [9]University of California, Los Angeles, Earth, Planetary and Space Sciences, Los Angeles, CA 90095

Introduction: Phobos' surface is covered with a global network of ~10–100 m wide, kilometers-long linear features ('grooves'). Some resemble pit chains or graben while others resemble secondary crater chains. Differing morphologies suggest that more than one mechanism is responsible for groove formation. Parallel grooves overprint all of Phobos' major craters, crossing their ejecta deposits, so groove formation has occurred over a timescale shorter than major crater formation, and takes place in regolith.

Tidal Stress and Groove Formation: We treat Phobos as a spherical, two-layered body made up of a homogeneous interior and a discrete outer layer. Surface stresses are computed using a thin-shell spherical approximation [1,2]. The horizontal strain of this shell, as global shape evolves due to orbital decay, produces stresses on the surface given by

$$\sigma_{\theta\theta} = \frac{9M\mu h_2}{88\pi\rho_{av}}\left(\frac{1}{a_f^3} - \frac{1}{a_i^3}\right)(5 + 3cos2\theta) \qquad (1)$$

$$\sigma_{\phi\phi} = -\frac{9M\mu h_2}{88\pi\rho_{av}}\left(\frac{1}{a_f^3} - \frac{1}{a_i^3}\right)(1 - 9cos2\theta) \qquad (2)$$

where θ is the colatitude measured with respect to the axis through the center of the tidal bulge (i.e., $\theta = 0°$ corresponds to the sub-Mars point on Phobos' surface). We define tension as positive and compression as negative. The surface stress $\sigma_{\theta\theta}$ is along the surface in the θ-direction, while $\sigma_{\phi\phi}$ is along the surface orthogonal to $\sigma_{\theta\theta}$. Here M is the mass of Mars, and a_i and a_f are the starting and final semi-major axes during any span of orbital decay.

The magnitude of the tidal stress on the surface is proportional to the displacement Love number h_2, which describes Phobos' global tidal response. The value of h_2 depends on internal structure and material properties of our incompressible two-layer model. Both layers have ρ_{av} = 1880 kg/m^3 in our model. The inner layer has a rigidity $\mu = 10^3$ Pa, which approximates a strengthless material, and a total radius of 11.1 km. The outer, stiffer layer is modeled as 100 m thick based on the thickness implied by the drainage of regolith through the grooves [3]. This layer is modeled with $\mu = 10^8$ Pa, based on the assumed regolith density and knowledge of s-wave velocities that are found to be uniformly ~200 m/s in Lunar regolith [4]. For these model parameters h_2 = 0.062, which corresponds to a tidal bulge height of ~70 m at the sub-Mars point.

Our hypothesis, that de-orbiting tidal stress is causing surface failure on Phobos, means that to first order the principal tensile stress should be normal to the grooves. To test this, we mapped ~200 of the most prominent linear surface features. Using the latitude, longitude, and strike for multiple points along these fractures, we calculated the principal tidal stress tensor experienced along each fracture in response to orbital decay, including the normal and shear stresses across each fracture. The magnitudes of the computed stresses, as well as the correlation between principal stress orientations and the azimuths of observed fractures, provide the critical tests of the tidal fracturing model.

Figure 1 shows the stress field predicted on Phobos from orbital migration starting at 3 R_{Mars} to the current orbital radius (2.77 R_{Mars}). Tensile tidal stresses ~150 kPa near the sub-/anti-Mars regions to ~30 kPa at points in between. In the sub-/anti-Mars regions, both principal stresses are tensile whereas in the inter-bulge regions, stresses radial to the tidal axis are tensile and stresses concentric about the tidal axis are compressive. There is a strong correlation between the surface stress field and the geometry of Phobos' grooves. The majority of grooves (non-purple) experience a tensile stress normal to the strike of the fault, indicating that they could have formed (or are still forming) by tensile failure of the surface. Note that we do not model failure explicitly, nor the stress perturbation associated with the opening of a fracture.

The orientations of most grooves on Phobos are closely aligned with the modeled tidal stress field. In regions of anisotropic horizontal stress, we expect the surface to fail perpendicular to the direction of maximum tension. Indeed, many of the grooves experiencing tension in these regions are aligned almost perfectly perpendicular to the direction of maximum tidal tensile stress (redder colors in Figure 1). In the sub-/anti-Mars equatorial regions, both principal stresses are tensile; however, failure will still occur perpendicular to the maximum tension as soon as the tensile strength of the surface layer is reached. Where the

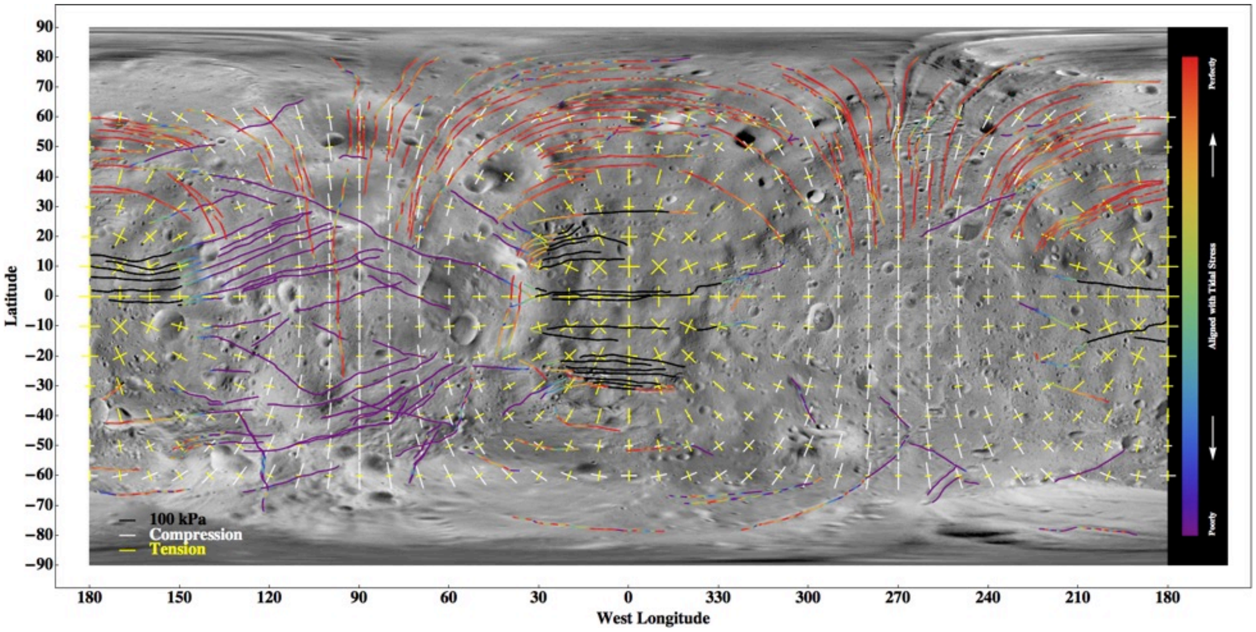

Figure 1 Stresses in a thin elastic shell computed for the last 10% of orbital decay, for a spherical Phobos with a nearly strengthless interior. The sub-/anti-Mars regions experience tension in both principal stress directions. Over the rest of Phobos' surface, stresses radial to the tidal axis are tensile while stresses concentric about the tidal axis are compressional. A majority of the observed fractures experience tensile stress normal to their strike (non-purple colors) while a cluster of fractures in the leading hemisphere are oriented such that the normal stress would be compressional across them (purple). The orientation of each fracture can be compared to the tidal principal stress field to assess goodness of fit. Most fractures in tension and in regions with clear large asymmetry in principal stresses are aligned nearly perfectly with the tidal stress field (warmer colors). The orientation fits of fractures in the sub-/anti-Mars regions (gray) are difficult to assess since the tidal stress is almost isotropically tensile. Any preferred formation orientations in these areas may be influenced by local stress anisotropy.

principal stresses have nearly equal magnitudes (i.e., approaching an isotropic stress field), no preferred formation orientation is predicted.

Conclusions: Our model results applied to surface observations imply that Phobos is a rubble pile overlain by a lunar-like cohesive regolith layer. This layer is developing fissures as the global body deforms due to increasing tides related to orbital decay. Our results confirm that grooves form in response to tidal stress [5]. More detailed study by an orbiter or lander will provide better constraints on the satellite's past and near-term geologic evolution, and its suitability for human exploration given what may be an active and evolving surface.

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