SUBSURFACE SHEAR FAILURE IN SPHERICAL BODIES: A POSSIBLE FORMATION MECHANISM FOR THE SURFACE TROUGHS ON 4 VESTA. A.M. Stickle[1], P.H. Schultz[2], and D.A Crawford[3], [1]The Johns Hopkins University, Baltimore MD 21218, angela.stickle@jhu.edu, [2]Brown University Geological Sciences, Providence RI, [3]Sandia National Laboratories, Albuquerque NM.

Introduction: The Dawn mission recently observed two sets of linear faults on the surface of the asteroid 4 Vesta [1-2] (Figure 2, bottom). Geologic observations indicate that these features are likely related to two large impact basins at the south pole of Vesta; nevertheless, they appear to be slightly offset [2]. Our experimental and numerical results show that this angle is a natural consequence of oblique impacts into a spherical target. Following impact, a set of shear planes is developed in the subsurface of the body. These subsurface features will propagate to the surface under combined tensile-shear stress fields after the impact to create sets of approximately linear faults on the surface.

Methods and Approach: One-to-one comparisons between laboratory experiments and numerical models provide insight into processes occurring following an impact. Moreover, models illuminate underlying physical processes that may be difficult to determine from experiments alone. Large-scale simulations then provide critical insights into the cratering process, modes of failure, and ways in which such failure could be manifested at large scales.

Impact experiments into spherical PMMA were performed at the NASA Ames Vertical Gun Range (AVGR) to track the evolution of subsurface damage in spherical targets [e.g., 3-4]. For the present study, 6.35-mm Pyrex projectile impacted the target at angles ranging from 40°-65° and 5 km/s. High-speed imaging (250,000-500,000 frames per second using Shimadzu HV-1 cameras) allowed tracking the damage within the spheres, which then could be directly compared with three-dimensional CTH calculations [5].

For direct comparisons to laboratory experiments, three-dimensional CTH simulations were used to identify conditions of failure observed within the impacted spheres. Adaptive Mesh Refinement [5-6] was used to refine the mesh around high-pressure regions. In these models, the Pyrex projectile is assumed to behave as a geologic material with a pressure-dependent yield surface. For the PMMA target, a Von Mises plasticity model is coupled to the Johnson-Cook Fracture model (JCF) [7]. JCF is a scalar damage model used to predict failure of materials, and here damage is assumed to be a function of the local value of plastic strain. Shear failure (defined as damage =1) occurs when the material stresses exceed the yield stress and then the material undergoes a user-specified value of plastic strain (here, strain to failure = 10% [8]). This model only tracks failure due to shear deformation; tensile failure is considered separately.

Laboratory-scale simulations proide important insights into processes occurring following oblique impacts and direct comparisons establish confidence for larger scale applications. Specifically, we considered a 5 km/s impact into a differentiated asteroid, 4 Vesta, with a diameter of 578 km [9]. Its 164-km metallic core was modeled using the ANEOS equation of state [10-11] for iron and a von Mises yield surface with a dunite mantle and basaltic crust (thicknesses of 165 km and 42 km, respectively). The calculation utlitized ANEOS for dunite and a Sesame table for basalt. The impactor was assumed to be an undifferentiated dunite sphere with a 100-km diameter. Dunite and basalt are both modeled as geologic materials with a pressure-dependent yield surface. The calculation included self-gravity for the asteroid and the impactor, with intial conditions consistent with a spherical hydrostatic stress state.

Results and Discussion: A suite of laboratory experiments performed at the AVGR captured the evolution of damage (Figure 1). Directly following impact, failure begins to grow asymmetrically beneath the impact point, concentrated downrange. Approximately 24 μsec after impact, a shallow subsurface haze forms downrange, which grows around the sphere towards the impact point antipode. At ~ 40 μsec after impact, a stalk grows up towards the center of the sphere. Failure planes then begin to grow perpendicular to this central column. These planes grow outward until ~ 100 μsec after impact, when the damage evolution is complete. The final damage can be seen in Figure 2 top-right. The orientation of the final damage structures depends on impact angle and velocity, but the evolution is consistent in all the experiments. Beneath the impact point, a large failure region, centered around a point downrange from first-contact, grows.

Figure 2 (top-left) shows the results of a companion CTH simulation to compare final damage patterns 108 μsec after impact. Here, the two failure criterion have been overlain to show the complete damage patterns, and a 2D slice of the 3D CTH model reveals the extent of subsurface failure more clearly; a haze created by near-surface microcrack obscures deeper failure in the experiments. The failure haze observed in the experiments is mimicked as a spall zone in a thin region near the surface. The central stalk is revealed to be the re-

sult of tensile failure as the shock waves coalesce and concentrate at the far side of the sphere. The planes perpendicular to the stalk, however, represent shear failure.

Large-scale CTH simulations in conjunction with insights gained from laboratory experiments provide new clues into the formation of the troughs on Vesta. Large regions of Vesta are subjected to tensile stresses great enough for fracture and failure. The models also show that these regions overlap with, or form directly prior to, regions of high shear-stress. Temporally, the combination of these two stress states suggests that the subsurface of Vesta may be damaged or fractured due to tensile stresses but then fail and slide due to high shear-stresses set up behind the shock wave. This pattern is seen even to late times (Figure 3), as the shock, rarefaction, and shear waves reflect and coalesce throughout the body. The combinationof high shear-stress magnitudes overprinting weakened or pre-damaged material lasts for hundreds of seconds, and during this time damaged material is continually subjected to high shear stress. This combination creates localized shear planes that then propagate to the surface. Thus, the linear features observed on Vesta may be the surface expression of large-scale subsurface shear failure and faulting. Such zones should be continuously reactivated through time, thereby retaining their fresh appearance.

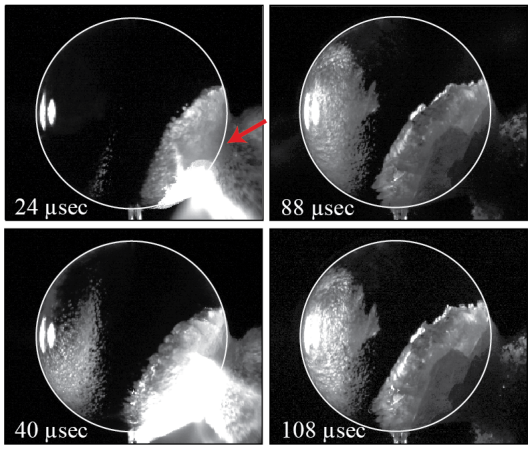

Figure 1 Time-sequence of damage evolution from AVGR experiment. Impact parameters: 0.635-cm Pyrex projectile into a 10-cm sphere, impact angle: 47°, impact velocity: 5.6 km/s.

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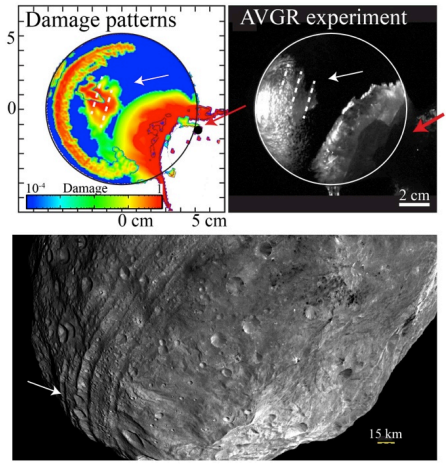

Figure 2. (top) Comparison of lab-scale CTH simulations with AVGR experiment showing shear failure planes. (left) CTH simulation showing damage from both shear and spallation overlain, (eight) Final damge from AVGR experiment shown in Fig. 1; (bottom) equatorial troughs on Vesta observed by the Dawn spacecraft.

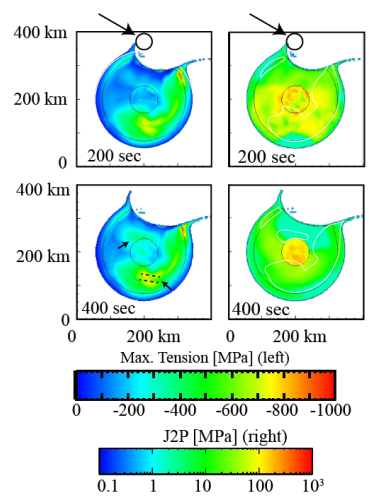

Figure 3. Large-scale CTH calculations showing max-tension (left) and the magnitude of the shear stress (right) 200 and 400 sec after impact. Areas failing in tension (maximum strength at the CMB is ~310 MPa and 180 MPa at the surface [12]) also experience high magnitudes of shear stress.