THE EFFECTS OF GIANT IMPACT INTO A DIFFERENTIATED VESTA: IMPLICATIONS FOR LARGE-SCALE TROUGH FORMATION. A. M. Stickle1, P.H. Schultz2, D.L. Buczkowski2, and K.A. Iyer3. 1Johns Hopkins University Applied Physics Laboratory, Laurel MD, angela.stickle@jhuapl.edu; 2Brown University Geological Sciences, Providence, RI.

Introduction: The Dawn mission observed two sets of linear faults on the surface of the asteroid 4 Vesta [1-3]. Observations indicate that these features are likely related to the two large impact basins on the south pole of Vesta: Rheasilvia and Veneneia; though they appear to be slightly offset from the basin centers [2]. Our experimental and numerical results show that this is a natural consequence of oblique impacts into a spherical, differentiated target. Initial experiments and models show that large impacts result in different patterns of tensile stress and pressure for differentiated v. undifferentiated targets, and that sets of shear planes develop within the subsurface of the body following impact [4-5]. These subsurface features can propagate to the surface under combined tensile-shear loading to create sets of approximately linear faults on the surface.

Experimental Details and Model Setup: Impact experiments into spherical PMMA were performed at the NASA Ames Vertical Gun Range (AVGR) to track the time evolution of subsurface damage in spherical targets [e.g., 5]. For this study, a 6.35-mm Pyrex projectile impacted the spherical target at angles ranging from 40°-65° at 5 km/s. High-speed imaging allowed tracking the damage within the spheres at a high time resolution, which was then compared with three-dimensional CTH calculations [6].

For the direct comparison, the CTH calculations were done with identical impact conditions to the experiments to identify observed failure conditions observed inside the targets. Adaptive Mesh Refinement was used to track high-pressure regions in detail [6-7]. Pyrex was assumed to behave as a geologic material with a pressure-dependent yield surface; the PMMA spheres assume a von Mises plasticity model coupled to the Johnson-Cook Fracture damage model (JCF), which is used here to track shear deformation [8]. Tensile failure is considered separately.

While laboratory simulations provide important information about the processes occurring following oblique impacts, these direct comparisons also provide confidence for interpreting large-scale models. Specifically, we considered impacts into the asteroid 4 Vesta. To provide constraints on the formation of the trough systems, we examined the effects of impact angle (15°, 30°, 45°, and 90°), projectile size, internal structure of Vesta (e.g., un-, partially-, and fully- differentiated, as well as varying the core size), and material properties of the asteroid itself. Fully differentiated models included an iron core, dunite mantle and either basalt or basalt-analog crusts. The basalt-analog materials have fully described equation of state (EOS) and strength models known to undergo brittle fracture and have densities similar to the modeled basalt crusts. All impacts were at 5 km/s. Oblique impacts examined the effects of a 100-km dunite projectile into a fully differentiated Vesta, with structure after [9], and the calculation included self-gravity for the asteroid and the impactor. Normal impacts were simulated into three structures representing ancient Vesta: undifferentiated Vesta, and a two- or three-layer Vesta [after 10]. All models are of a ~530 km sphere, with core sizes ranging from 164-220 km.

Results and Discussion: The combination of laboratory experiments and numerical models allow us to track the state of the material, the modes of deformation, and the damage and fracture growth following impact (at both small and large scales).

Laboratory Experiments and Small-Scale CTH. Direct comparisons were made between observations of damage growth in the AVGR experiments and corresponding CTH models. A typical failure pattern from the AVGR experiment is shown in Figure 1B. Observation of damage evolution coupled with CTH models of these experiments indicate that the near-surface failure haze is the result of incipient spallation at the farside of the target, the central damage stalk is a result of tensile strain, while the sub-parallel failure planes form due to high magnitudes of shear stress (Figure 1A). The orientation of these damage structures depends on impact angle and velocity, but they all evolve in the same manner.

Figure 1. Comparison of lab-scale CTH simulations with AVGR experiment showing shear failure planes. (left) CTH simulation showing damage from both shear and spallation overlain onto each other, (right) Final damage from the AVGR experiment, with failure planes shown by white dotted lines. After [5].

Large-scale CTH models of Vesta. Large-scale CTH simulations, in conjunction with insights gained from laboratory experiments, provide new clues into the formation of the troughs on Vesta. Exploring a...
large parameter space allows examination of the effects of impact parameters on subsurface damage and possible formation scenarios for the large-scale fracture systems.

Models examining the effect of differentiation on internal damage and fracture indicate that Vesta was likely differentiated at the time when Rheasilvia and Veneneia formed. The results of these models show that different patterns of fracture (Fig. 2) and pressure (Fig. 3) develop in a differentiated sphere (Fig. 2 center and right; Fig. 3, right) compared to an undifferentiated sphere of the same material and diameter (Figs. 2, 3, left). While these first-order models have yet to fully mimic the observations of troughs on Vesta, they do demonstrate that the density contrast in Vesta’s differentiated interior affects the stresses resulting from the Rheasilvia and Veneneia impacts. It is this impedance mismatch that is suggested to be responsible for the development of Vesta’s planet-like troughs [2]. Similar differences between differentiated and undifferentiated targets are seen for models of oblique impacts.

![Figure 2](image1.png)

Figure 2. CTH hydrocode models of giant impact into Vesta showing materials following impact. Red is iron, green is dunite, brown is higher-density basalt analog and grey is lower-density basalt analog. Fracture due to tensile stresses changes depending on the amount of differentiation [4].

![Figure 3](image2.png)

Figure 3. CTH models of a giant impact into an undifferentiated (left) and differentiated (right) Vesta yield very different pressure profiles depending on the presence or absence of a core. Though pressure values are not given in this image, changes in patterns of pressure can be observed [4].

In both normal and oblique impact cases, large regions of Vesta are subjected to tensile stresses great enough for fracture and failure. Because they are coupled to a damage model tracking shear deformation, the oblique impact 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, as the shock, rarefaction, and shear waves reflect and coalesce throughout the body (Figure 4). The combination of 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 (Figure 4). 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 from deep in the interior, similar to what is seen in laboratory experiments.

![Figure 4](image3.png)

Figure 4. Large-scale time sequence of CTH simulation results showing maximum tensile stress (left) and the magnitude of shear stress (right) within Vesta. (top) center plane of Vesta on a plane perpendicular to the impact trajectory; (bottom) center plane parallel to the impact trajectory. The initial impactor size (100 km) and trajectory (30°) are shown for scale. Note here that the south pole of Vesta would be at the top of these images. After [5].

These general results are true for varying impact angle (30-45°) as well as impactor and core size (50-100 km and 164-220 km, respectively). At 15°, a large portion of the projectile decapitates and decouples from the impact, significantly reducing subsurface stress and damage formation. The results from differing impact angles also may allow constraints to be placed on impact trajectory. If the subsurface shear planes observed in the laboratory experiments are small-scale analogs to the trough features on Vesta, then the orientation of the damage region might also be used to constrain the impact trajectory and location by comparing the angle of the damage offset from the impact crater antipode.