INVESTIGATING THE TOPOGRAPHIC EXPRESSION OF VALENTINE CAVE WITH 3D AND 2D MODELS. E. A. Williams[1], L. G. J. Montési[1], P. L. Whelley[2], and E. R. Bell[2,3]. [1]University of Maryland, College Park, MD, USA, ewilli17@umd.edu, [2]NASA/GSFC, Greenbelt, MD 20771, [3]University of Maryland, Department of Astronomy, CRESST II, 8000 Regents Dr., College Park, MD 20742

Introduction: Lava tubes are volcanic features created within some lava flows. If a lava flow forms a crust of solidified rock over its surface that is strong enough to support its own weight, lava can drain producing a lava tube. Lava tubes are being evaluated as potential shelters for astronauts enabling long-term exploration of a planet. For this idea to become reality, it is important to be able to detect and characterize lava tubes before use. We evaluate various approaches by studying terrestrial examples of lava tubes such as, here, Valentine Cave, in the Lava Beds National Monument (LBNM), California.

The LBNM is a volcanic region on the flank of Medicine Lake shield volcano that contains nine major lava tube systems including Valentine Cave, a 500-meter-long tube [1, 2] that formed between 10,500 and 65,000 years ago [3]. LiDAR scans taken inside this cave captured its internal geometry [4] and LiDAR data at the surface reveal a ridge over the center of the tube with a height varying from 0.5 to 2 m (Figure 1). No such ridge is expected above the tube under the sole influence of gravity but it might form if a lava tube was inflated by internal lava pressure and kept its shape after the interior lava drained out.

In this project, we verify the applicability of idealized 2D lava tube deformation models in light of the three-dimensional complexity of Valentine Cave and evaluate how much internal pressure would be required in this tube to produce the observed surface ridge.

Methods: Elastic finite-element models of lava tubes were created and analyzed using COMSOL Multiphysics®. These models assume the tubes are embedded in solid basalt. The models were allowed to deform under their weight, and in some cases, pressures on the inner walls of the tube were added. We discuss the deformation field and stresses that develop around the tube.

In a prior project, we modeled lava tubes with idealized 2D shapes and reported relationships connecting their dimensions with surface features that they cause [5]. These idealized tube shapes were half-ellipses with a 3:1 width-to-height ratio and rounded corners. Here, we consider a short section of Valentine Cave using the LiDAR-derived 3D model. The results were compared with the 2D model results to confirm that the idealized models produced similar results and were therefore applicable to this tube.

After this comparison, we apply a range of internal pressures to the simplified 2D shape to simulate inflation. For each pressure we report the height of the resulting ridge to find what pressure would be needed to create the observed ridge.

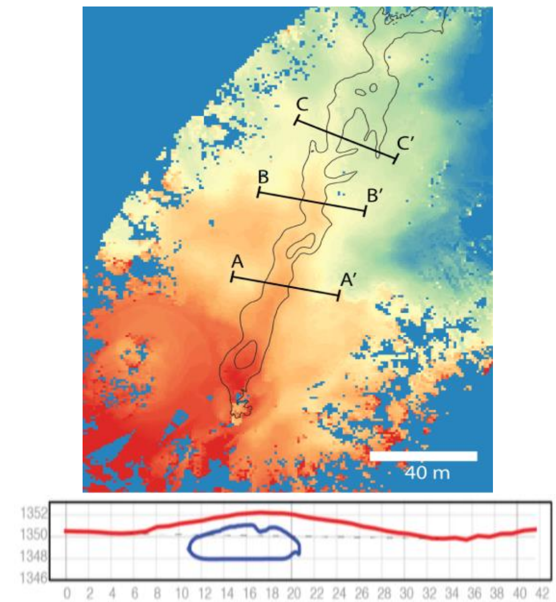

Figure 1: Surface elevation above Valentine cave (black outline) and cross-section A-A', where the ridge height is 2 m, tube width is 11.8 m, roof thickness is 1 m, and tube height is 3 m.

Results:

Models with only gravity loading: Prior work using 2D lava tube models with idealized shapes predicted two types of surface features near lava tubes: areas of high tensile stress, possibly highlighted by tensile cracking, and faint topographic bulges above the edges of the tube. These features are expected to occur symmetrically on either side of the tubes, at predictable distances away from the tubes. However, the surface immediately above the tube develops a depression as the roof sinks slightly into the void space, in marked contrast to the observations from Valentine cave.

The 3D model of a short section of Valentine Cave's actual geometry yielded similar surface features to those predicted by the idealized 2D models. The 3D model predicted areas of high tensile stress and surface bulges to either side of the tube center; the average horizontal distance between bulges and the center of the tube was $D_b = 8.4$ m and the average horizontal distance between the maximum tensile stress point and the center of the tube was $D_s = 4.2$ m. The 2D models in [5] predicted $D_b = 10.8$ m based on tube width or 7.1 m based on tube height. These models also predicted $D_s =$ 6.3 or 4.1 m based on tube width or height. The 2D model values bracket the predictions from the 3D model. Considering models with the same tube height leads to better approximations to the 3D models. Note that the vertical amplitude of the bulges is so small that it would not be detectable unless the preexisting surface had less than a few microns roughness.

Determining pressure needed to produce a ridge: At this location along Valentine Cave, the topographic ridge was approximately two meters high (Figure 1). Assuming that the basalt is completely solid requires an unrealistically high pressure of several hundreds of MPa to produce this ridge. If inflation took place at an early stage in the tube's formation when the crust had not yet fully solidified, Young's modulus would be approximately only 5 GPa, and the effective thickness of the tube's roof that can resist deformation would only be ~0.1 m [6]. Using these parameters, a ridge height of 2 m can be obtained with a lava pressure of 4.3 MPa (Figure 2). As the lava cools, the effective roof thickness will increase with time [7, 8]. For effective thicknesses of 0.2 m and 0.4 m, pressures of 9.5 MPa and 21.3 MPa would be needed to produce the ridge.

Discussion: Results from idealized 2D and more realistic 3D models give similar results for this section of Valentine Cave, especially if models with similar tube heights are compared. This suggests that the 2D models are a good approximation for the behavior of the tube and the differences in shape do not have a significant impact on results. This supports the use of the more cost-effective 2D models as a useful approximation.

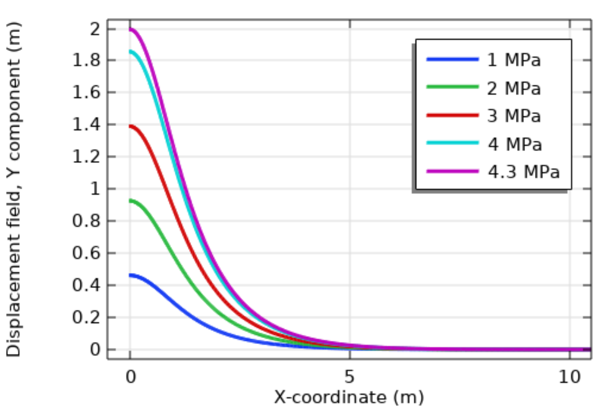

Figure 2: Vertical surface displacement for a 2D idealized Valentine Cave model with varying internal pressures. The effective roof thickness is 0.1 m. Zero on the x-axis is above the tube center. The y-axis is vertically exaggerated.

Uncertainty was introduced into the measurements of D_b and D_s in the 3D models by the nonuniform tube shape used. As it was difficult to determine the exact center of the tube, the distance from the tube center to each surface feature was made less precise. Additionally, the relationships derived from the 2D models were found from models with a 3:1 width-to-height ratio; relationships found using a suite of models with aspect ratios more similar to Valentine Cave may have given more exactly applicable relationships and reduced error.

Forming the observed ridge using completely solid basalt requires unrealistically high pressures. It can therefore be assumed that inflation took place at a relatively early stage of the tube's development, when the rock of the roof had not yet cooled completely. At this point, the roof of the tube must have been effectively thinner and more deformable. Using appropriate parameters for the lava at this time, reasonable minimum pressures can produce the observed ridge.

Inflation taking place early in tube development would also allow the uplifted roof to be held in place as it cools and solidifies. If the roof were completely solid as the flow inflated, it would return to its initial position when the overpressure is removed.

The ridge height that the tube inflates to is affected by both the effective crustal thickness at the time and the internal pressure. If an approximate value for tube pressure at the time could be found, the effective crustal thickness could be determined and used with the relationship in Hon et al. [7] and Deschamps et al. [8] to determine the time of inflation.

Conclusions: Our results imply that Valentine Cave was inflated at an early point in its development, when the effective thickness of the crust was small and the rock had not fully solidified. Under these conditions, it is possible to obtain the observed ridge by pressurizing the tube. If this process is active at other locations, the presence of a linear topographic ridge may be a suitable way to detect lava tubes on other planets.

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