Migration of ground penetrating radar (GPR) data to image the floor of lava tubes; TubeX project

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Abstract

Ground Penetrating Radar (GPR) is shown to be a successful tool in detecting tunnels and voids. Lava tubes are tunnel-like features in volcanic terrains that can be potential safe places for human crews and equipment on the Moon and Mars. We utilize GPR to detect and map lava tubes (Valentines cave, Skull cave and Hercules Leg cave) in Lava Beds National Monument, CA. Our preliminary results show that the ceiling of the lava tubes are readily detectable by GPR. However, due to the strong radar velocity contrast between lava and the air-filled tubes, accurate recovery of the position of the lava tube floor is much more challenging. Careful migration of the GPR data is required to resolve the floor signature and create an image with the tube floor restored to its correct depth. We are developing an optimal workflow for recovering complete lava tube geometries. We can do this because we have collected centimeter-scale LiDAR data from the interior of tubes as well as on the surface along GPR transect lines. Thus we can test the accuracy of GPR migration methods against the LiDAR-measured tube geometry. We are testing conventional 2D migration techniques as well as topographic migration. At selected field sites we have limited 3D 'grids' of data. We expect to compare the results of different migration techniques to identify optimal methods for this problem. As a part of this project, we also seek to develop a library of different lava tube geometries and their corresponding GPR image from their migrated sections. The GPR image library will encompass a range lava tube geometries, including tubes of different heights, widths, shapes, and structures (e.g., pillars), plus a variety of floor textures (e.g., smooth, ropey, rubble) and overhead thickness. This library will be an asset for determining the utility of deploying GPR technology in mapping a tube-rich environment.

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Abstract

Ground Penetrating Radar (GPR) is shown to be a successful tool in detecting tunnels and voids. Lava tubes are tunnel-like features in volcanic terrains that can be potential safe places for human crews and equipment on the Moon and Mars. We utilize GPR to detect and map lava tubes in Lava Beds National Monument, CA. Our preliminary results show that the ceiling of the lava tubes are readily detectable by GPR. However, due to the strong radar velocity contrast between lava and the air-filled tubes, accurate recovery of the position of the lava tube floor is much more challenging. Careful migration of the GPR data is required to resolve the floor signature and create an image with the tube floor restored to its correct depth.

We have collected centimeter-scale LiDAR data from the interior of tubes as well as on the surface along GPR transect lines. So we can create 2D geometry model of the tube and surface at the same place as GPR line and make a 2D velocity model for 2D migration. For the exploration scenario where no LiDAR data are available, we test the method defining the velocity model simply by picking GPR arrivals from of the ceiling.. Thus we can test the accuracy of GPR migration methods against the LiDAR-measured tube geometry.

Site, data acquisition and methods

Data were acquired with two campaigns, one in April-May 2017 and the second in October 2018.

We used:

- PulseEKKO 100 GPR system from Sensors and Software with 100 MHz antennas and the Ultra receiver in the 2018 campaign
- Trimble R10 RTK GPS positioning

In both years' data collections we mapped Valentine, Skull, Hercules Leg, Indian Well, Natural Bridge, Incline, Ship & Dinghy caves. Here we only show the result of a line crossing over Skull Cave.

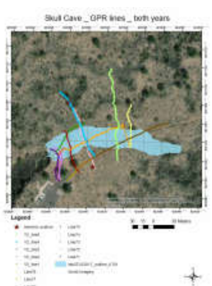
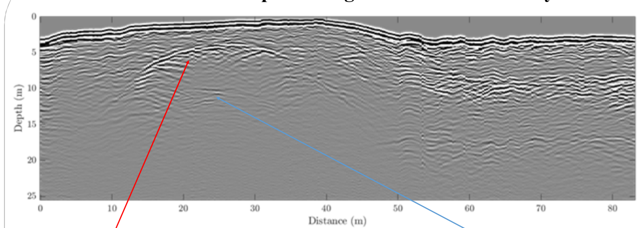
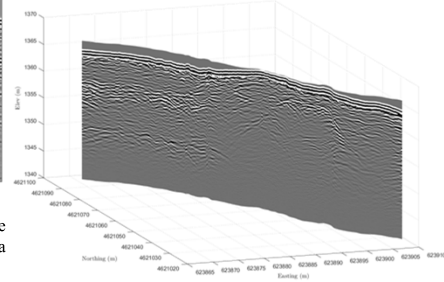
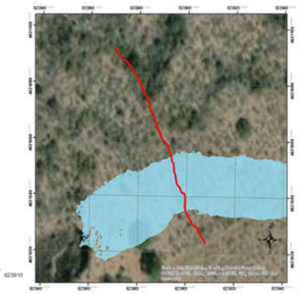


Figure 1- Top Left: Map of all collected GPR lines over the Skull cave. The line presented here is Y2_line4, shown in light blue. Top Right: Site surface view of Skull Cave and GPR data collection; Bottom small box: Lidar cross section view of Skull cave containing the alignment of 10 scans all represented in different colors; Bottom Gray figure: Identical cross section view of Skull Cave as small one with a reflectance view type [Special Thanks to Frankie Enriquez for preparing the LiDAR images].

GPR Profile: Basic processing with constant velocity v = 0.1 m/ns, a) 2D; b) 3D; c) top view







There is a strong reflection from the tube ceiling and a very weak signature of the tube floor. The floor is not at the correct depth as the wave velocity is 3X faster in the lava tube than in surrounding rock.

Migration

Recovering complete lava tube geometries is extremely challenging. With wave velocity 3 x faster in the lava tube than in surrounding rock, recovering the correct floor depth requires 2D velocity migration. Even when the measured cave geometry is specified , as in the left column below, the migrated profile shows strong artifacts, such as improper projection of wave energy along the sides of the cave. Energy return is concentrated from a point at the central trough of the cave.

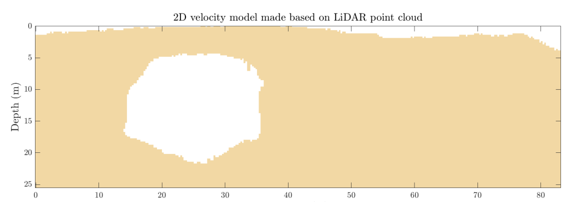


Figure 3 – 2D velocity model used in migration, $V_{soil} = 0.1\frac{m}{ns}$ and $V_{air} = 0.3\frac{m}{ns}$.

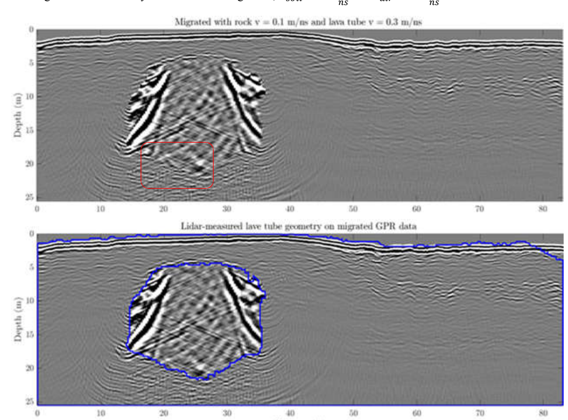


Figure 4 - GPR cross section with 2D phase shift plus interpolation (PSPI) migration followed by topography correction. A small coherent return appears from the center of the tube floor at ~ 21 m depth. (The radar wavelength is much longer in the air than in the rock.) Bottom: Blue line shows the LiDAR-derived tube boundary used to make the velocity model.

In the true exploration scenario without LiDAR data, arrivals from the ceiling of the cave can be used to create a velocity model with rock to air transition at the ceiling.

Migration results vary significantly with migration technique: compare the Kirchhoff migration shown here with the PSPI migration in Figure 4.

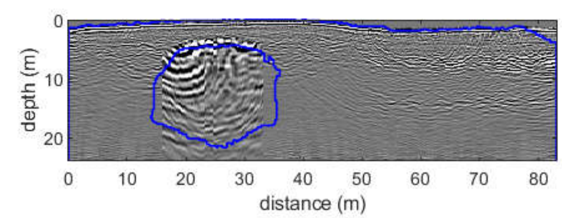


Figure 5 – Kirchhoff migration with rock velocity = 0.1 m/ns followed by topography correction.

Migration is further complicated by rock velocities that decrease significantly with depth, outside the lava tube. The 2-velocity model is too simple. Shown below, a Kirchhoff migration with rock velocity 0.12 m/ns better collapses energy from the upper corners of the cave, but misestimates ceiling location and places the apparent floor at too shallow a depth.

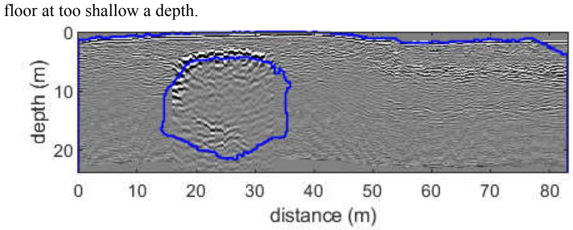


Figure 6 – Kirchhoff migration with rock velocity = 0.12 m/ns followed by topography correction.

Acknowledgements

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