Imaging lava tubes using ground penetrating radar

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1. ABSTRACT

Craters of the Moon National Monument is a large lava field on the Snake River Plain in southern Idaho, with lava flows ranging between 15,000 and 2,000 years old.

At 2100 years old, and covering approximately 280 square kilometres, the 'Blue Dragon' flow is one of the largest and youngest flows at this site. This flow was fed by a system of lava tubes, which provide an important means of transporting lava over large distances.

Ground penetrating radar (GPR) images were acquired over known lava tubes in order to determine the usefulness of the method for detecting lava tubes and other lava flow features. The images were processed with standard GPR processing techniques, as well as the more advanced methods of migration and deconvolution. Lava tubes were imaged to depths of at least 10 m in the processed sections.

2. CRATERS OF THE MOON

Blue Dragon lava flow
Older layers of cinders and lava
Known lava tube system

FIG. 1. Schematic map of area surrounding Blue Dragon vents. The spatter cones mark the location of the lava source vents.

FIG. 2. Interior of Indian Tunnel lava tube. It is approximately 18 metres wide and 8 metres tall in this area.

3. GROUND PENETRATING RADAR

GPR builds images of the near surface by transmitting electromagnetic waves into the ground, and measuring the amplitude and return time of reflected waves. With increasing antenna frequency, depth of imaging is traded for better resolution.

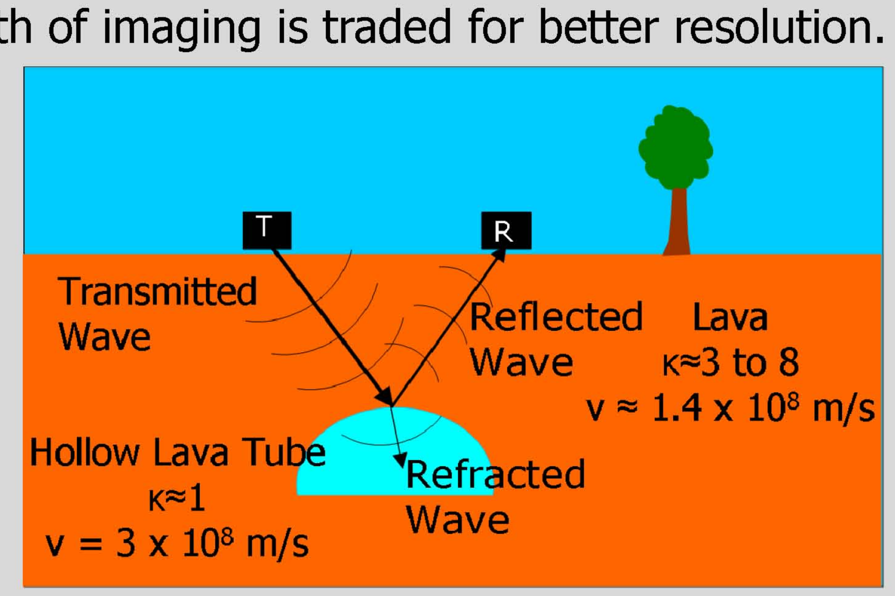

FIG. 3. Schematic of a GPR survey over a lava tube. EM waves are sent from a transmitting antenna, reflect from a sub-surface boundary to return to the receiving antenna. Propagation of GPR signals in the earth is primarily governed by the dielectric constant, κ (Jol, 2009).

4. LAVA TUBES

GPR images were acquired over known tubes to establish the resolution limits of the method. These surveys employed 100 MHz antennas with antenna separation of 1 metre.

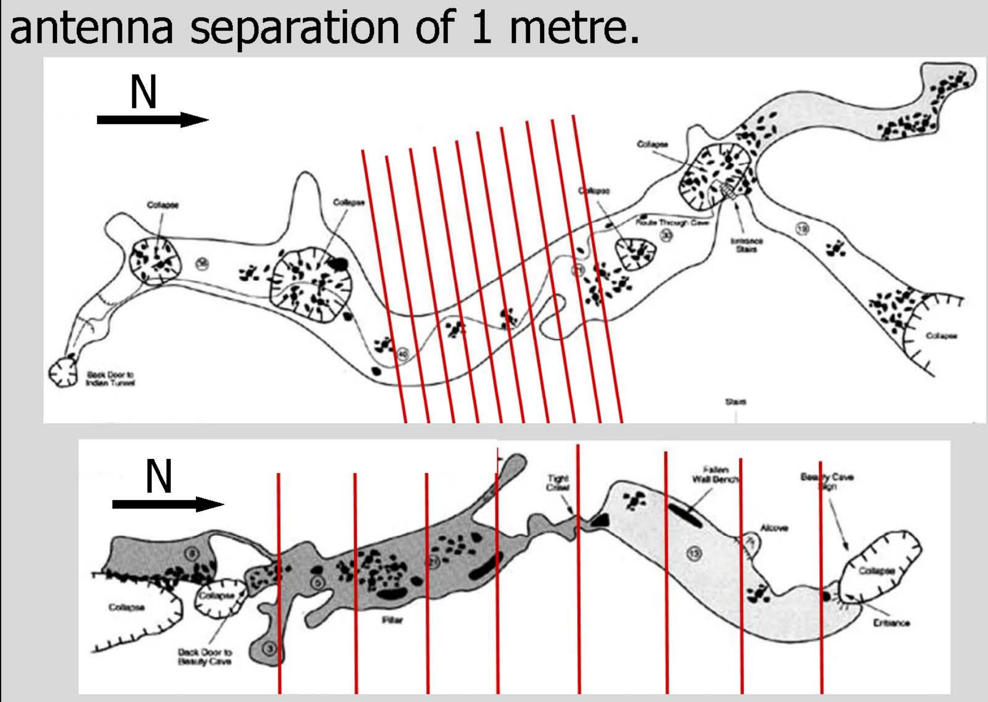

FIG. 7. **(a)** Schematic of Indian Tunnel. Red lines indicate the approximate locations of ten 2D GPR lines run over top of the tube. **(b)** Schematic of Beauty Cave. Red lines again represent locations of GPR lines, eight in all. Figures modified from the US National Park Service website (www.nps.gov/crmo/planyourvisit/caves-trail.htm).

5. FORWARD MODELLING

We want a picture of what we expect a lava tube to look like in a GPR section.

So we build a computer model, which becomes the input for a MATLAB code that models 2D GPR images. This code was written by Irving et al., (2006). This code solves Maxwell's Equations in 2D.

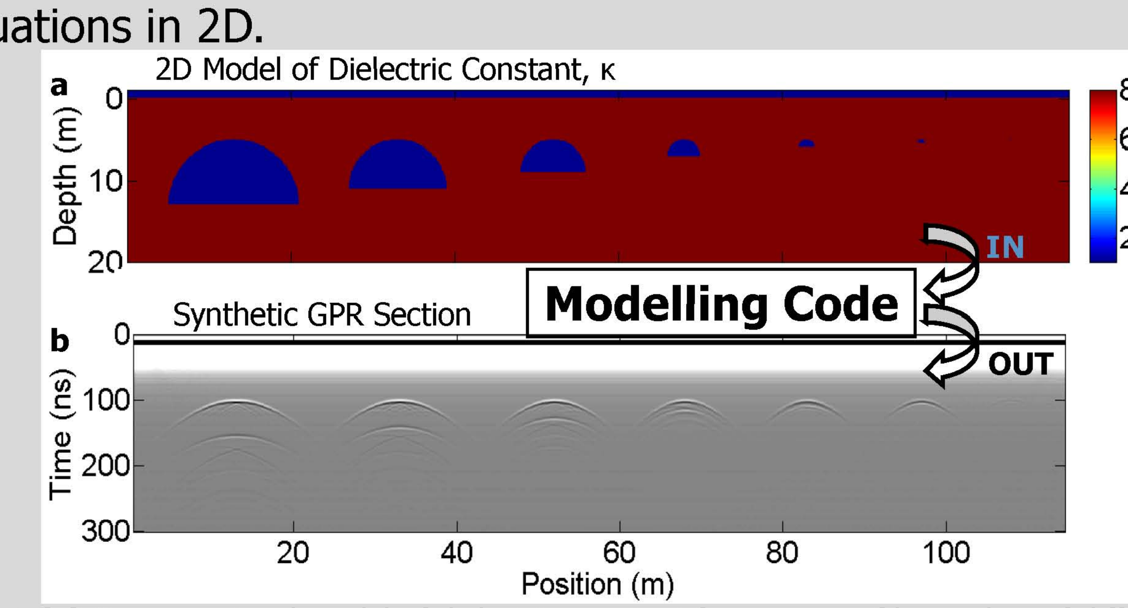

FIG. 5. **(a)** Cross-sectional model of dielectric constant for a series of lava tubes of different sizes. This model is used as input for the GPR modelling code.

(b) Simulated GPR section result from 2D finite-difference time domain modelling code. The modelled tubes appear as sets of diffraction hyperbola.

6. PROCESSING FLOW

Raw GPR data are put through a series of processing steps to create images. The final processed image shows the shape of the lava tube roof much more clearly (green arrow). This gives a more accurate estimate of location and depth of the tube and other features.

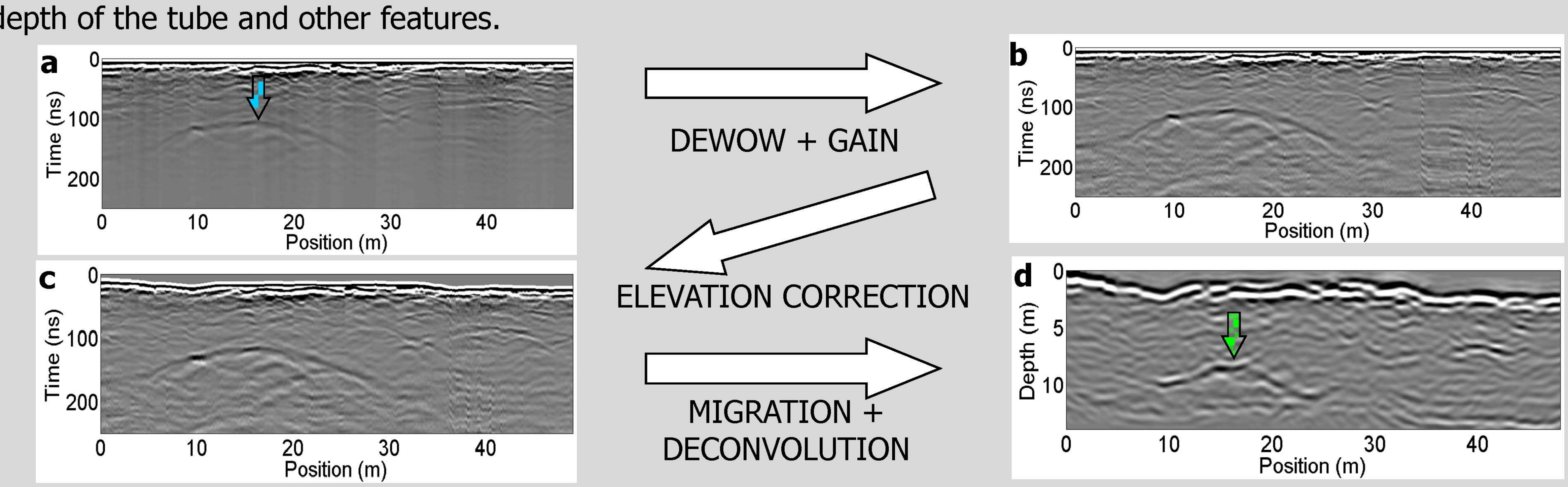

FIG.6. **(a)** Raw GPR section over Beauty Cave. Lava tube appears as a broad diffraction hyperbola (blue arrow). **(b)** Antenna coupling effects cause a DC-bias in GPR signals, meaning the amplitudes are not centered around zero. The dewow filter removes this effect. The next step is to apply a gain function, which adjusts the relative signal amplitudes to make deep features visible. **(c)** GPS data is then used to adjust trace elevations to reflect topography. **(d)** Migration then collapses the diffraction hyperbola to their true position in space, producing an image that more closely reflects true sub-surface structure. Deconvolution sharpens the image to bring out small features. The migration and deconvolution algorithms used were designed for use with GPR data. Migration and deconvolution for this data set were performed by Ferguson (2010).

7. INTERPRETATION IN 3D

The Kingdom Suite, a seismic interpretation software package, was used to interpret the GPR lines in 3D. Using GPS data acquired simultaneously with the GPR images, each line can be placed relative to its neighbours in 3D space.

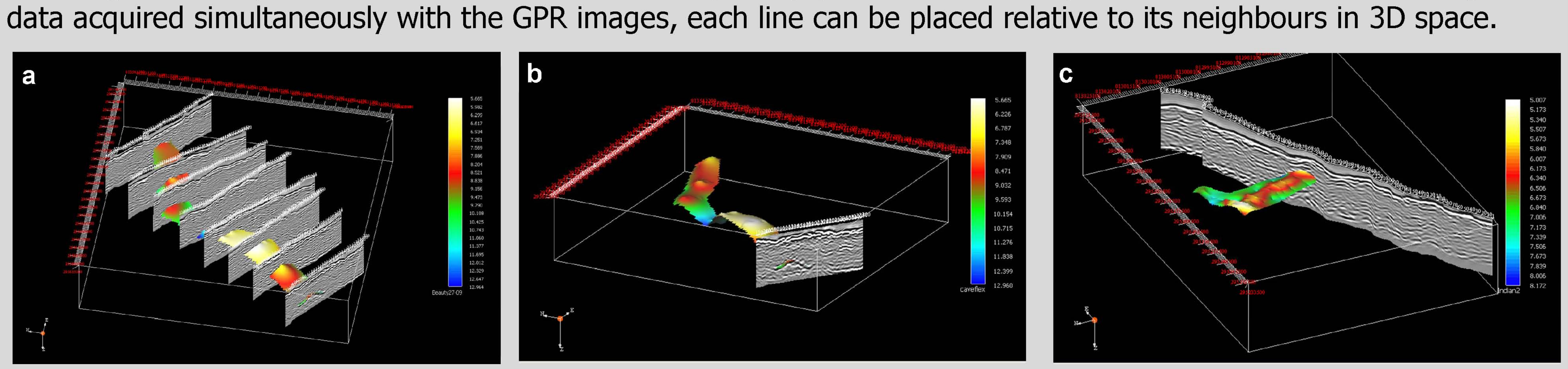

FIG. 8. **(a)** The eight 2D lines over Beauty Cave viewed in a 3D volume. The coloured surface represents the tube roof between lines. Colours represent depth in metres below datum. By tracking the lava tube reflections from line to line, a more robust interpretation of the tube roof can be made. The tube roof is picked in each section. The picks are then interpolated to produce a 3D surface representing the tube roof. **(b)** A view of the interpolated surface of the roof of Beauty Cave, showing only a single GPR section (pictured in Figure 6d.) **(c)** Similar 3D surface of the roof of Indian Tunnel.

8. CONCLUSIONS

Lava tubes have been successfully imaged to depths of at least 10 meters.

As tubes decrease in size or increase in depth, they become more difficult to resolve in GPR images.

The advanced processing steps of migration and deconvolution, when tailored for use with GPR, greatly improved the quality of imaging.

9. ONGOING WORK

The sinkholes in near the vents represent an area where lava tubes are believed to exist.

These tubes would have fed lava from the vents to the tube systems in the rest of the flow.

The lava flow here is confined to a small valley between cinder cones (see Figure 1).

This area is being studied using both GPR and micro-gravity surveys. Correlating the two will provide a more robust interpretation of sub-surface structures.

The goal is to search for lava tubes, and to build an understanding of the lava structures and flow processes that occurred within this valley.

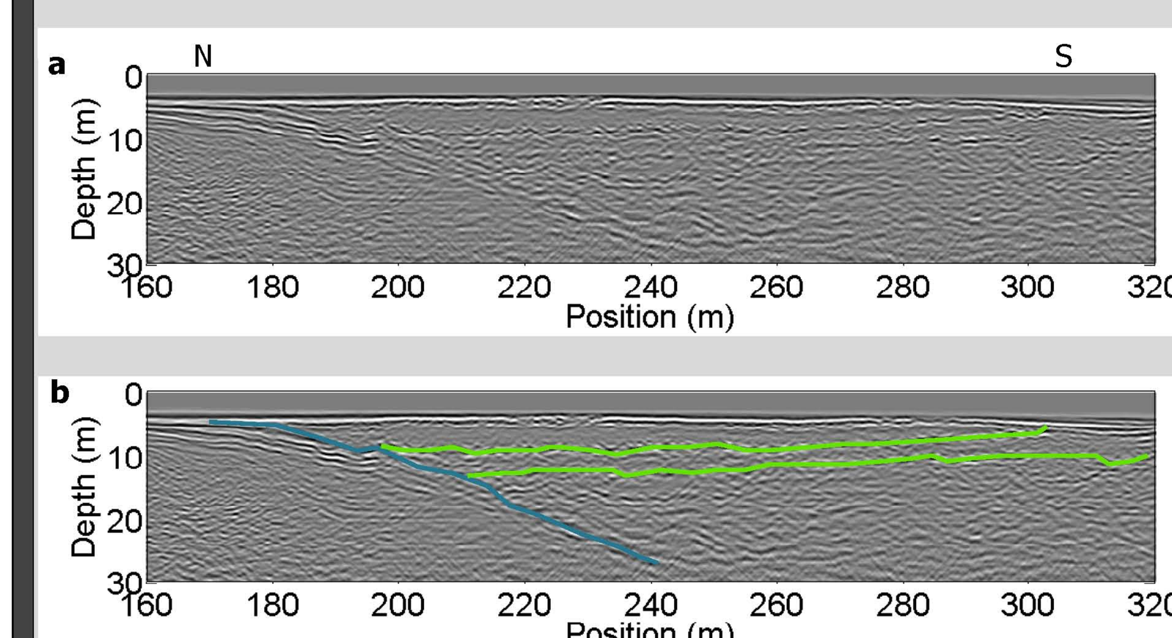

FIG. 8. **(a)** A fully processed section from a 100 MHz line over the road north of the sinkholes (see Figure 1). Structures are imaged to depths of 30 m. **(b)** The same section with features marked. The blue line highlights the dipping limb of an old layer of cinders, which was covered over by the Blue Dragon lava flow. The green lines highlight individual layers of Blue Dragon lava.

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