3.2.3 Limitations for Mapping Subsurface Voids

Many factors limit the success of GPR during field surveys with local geology playing a significant role. Electromagnetic waves attenuate rapidly in soils that are electrically conductive (i.e. high in clay content or saline conditions), making GPR an ineffective method in these areas when the target lies within or below clay layers. If saline conditions occur, thus making the subsurface electrically conductive, then penetration depths will be severely limited. If the dielectric constant between the layers is similar, insufficient energy may be reflected at the boundary and the receiver will not detect the boundary change. Cultural noise such as radio towers, power lines, and cellular phones may also lower the quality of data.

3.2.4 Case Studies for Mapping Subsurface Voids

The use of GPR to locate lava tubes has already occurred worldwide. In a case study titled *Ground Penetrating Radar to detect lava tubes: preliminary results of a GPR application to Fuji volcano, Japan* (*11*), a GPR survey was conducted over a paved road that bisects a well mapped lava tube, the Komoriana cave in the Aokigahara flow. The subsurface consisted of a basaltic lava flow. A Subsurface Interface Radar (SIR) 2 was utilized in the survey coupled with a 200 MHz antenna produced by Geophysical Survey Systems, Inc (GSSI). One two-dimensional profile was collected approximately perpendicular to the cave orientation. The raw data showed two distinct anomalies in the data that were interpreted to be the top and the bottom of the cave. The report did not list the extent, depth, and size of the cave. The preliminary results, however, suggests that GPR is an effective method in locating lava tubes.

Hot and Cold Lava Tube Characterization with Ground Penetrating Radar (12) is an additional study involving lava tube detection performed by the Department of Geophysics, Colorado School of Mines. The study was conducted on the island of Hawaii in Hawaii Volcanoes National Park. Two types of GPR equipment were utilized during this survey: the Sensors and Software PulseEKKO 1000 and the GSSI SIR-8 radar systems. The data were processed and modeled using GRORADAR and custom software written by M. Lagmanson. The results from two locations were discussed in the paper.

The first location was the south side of the Kilauea volcano over an active lava tube in a shatter ring. Data were collected at multiple frequencies with both systems, with the purpose of locating structural defects around the lava tubes. It was determined that GPR could detect, but not characterize, the hot lava tubes due to the fact that "…molten lava is conductive and makes the surrounding material highly lossy (producing an attenuation shadow in the image). There is not a clear image from a hot tube as the temperature gradient produces a gradual dielectric contrast gradient."

The second site was located south of the Mauna Ulu crater near Chain of Craters Road. The surveys were conducted over cold lava tubes. Data were collected over an area with two known lava tubes. The first time the data were collected, the ground was dry and the tubes were not located. After a night of rain, the data were recollected and the lava tubes were easily identified because the lava tubes were draining water, which has a high dielectric contrast with basalt.

In general, lava tubes as deep as 6 m (19.7 ft) were interpreted in the data. In addition to the 2 known tubes, many lava tubes less than 1.5 m (4.9 ft) in diameter and less than 0.4 m (1.3 ft) in depth were located. Although not presented in the referenced paper, processing and modeling successfully derived the size, shape and orientation of the lava tubes.

3.2.5 Application of the GPR Method at LBNM

Based on the previous successes of GPR applications, the GPR method was selected as one of the methods to be tested at LBNM. The GSSI SIR-2000 instrument was selected along with the 100 MHz, 200MHz, and 400 MHz antennas. A photograph of the 400 MHz antenna and the 100 MHz antenna (shown in the background) utilized during the LBNM survey is illustrated in figure 7.

Figure 7. Photo. GPR data collection with the 400 MHz antenna at LBNM.

3.3 MAGNETIC METHOD

3.3.1 General Background and Data Acquisition

Measurements of the natural magnetic field strength can be used to interpret the subsurface distribution of magnetic minerals, usually magnetite. If a lava tube occurs near the ground surface, it may be detected using the magnetic method because it provides a region in the subsurface where no magnetic minerals are present. If the host rocks contain magnetite, then the lava tube may create an anomaly that can be measured by a magnetometer on the ground surface.

The Earth's magnetic field is often thought of as similar to that which would result from a large magnet placed in the interior of the Earth. The magnetic north pole is close to, but not coincident with, the geographic North Pole. Thus, the lines of force due to the Earth's magnetic field can be thought of as emanating from the magnetic South Pole and "returning" to the magnetic North

Pole. This field is a vector and has a direction and a magnitude. The field is thought to result from large-scale movements of magma within the earth. Superimposed on top of this field are time varying pulsations caused by the movement of electrical charges at distances of many km above the earth. One of the causes of these charge movements is sun spot activity. These time varying fields have a wide range of periods (or frequencies) varying from fractions of a second to hours. Generally, however, the amplitude of these variations has a daily cycle, and they are therefore called Diurnal variations. During magnetic surveys, the Diurnal variations in the magnetic field are accounted for by having a base station collect data at a fixed location as the survey progresses. During processing, the Diurnal variations are removed from the survey data.

When the Earth's magnetic field interacts with magnetic mineral in a rock, a "secondary" magnetic field is created. It is these secondary magnetic fields that give rise to anomalies that can be detected with a magnetometer.

3.3.2 Advantages for Mapping Subsurface Voids

The magnetic method was successful at detecting the presence of lava tubes. The field data acquisition is rapid and therefore large areas can be efficiently surveyed, thus making it a good reconnaissance method. Although magnetic anomalies are seen over most of the known lava tubes, their shapes are complex. However, detailed computer modeling may be used to obtain more information about the lava tube, such as the depth to its top and possibly its dimensions.

3.3.3 Limitations for Mapping Subsurface Voids

The complexity of the geologic setting of most lava tubes makes anomaly prediction and interpretation difficult. The basalt surrounding the lava tube is often comprised of lava from different flows, cooling over different periods of time and at different rates. Thus, the magnetic properties of the basalt could vary greatly from flow to flow, causing the magnetic properties of the basalt to vary greatly. Interpretation of magnetic data can be ambiguous, in that several different geologic and dimensional models can be constructed, each of which may produce a similar anomaly. Therefore, magnetic data interpretation is usually verified with the results from other geophysical methods.

3.3.4 Case Studies for Mapping Subsurface Voids

No publicly published work related to the detection of lava tubes exists for review.

3.3.5 Application of the Magnetic Method at LBNM

Although magnetic methods were not initially proposed for this project, the Geometrics G-858 cesium-vapor magnetometer system was tested at LBNM. This instrument is carried manually, with the magnetometer strapped to a harness worn around the shoulders and the control panel worn around the waist of the operator. Data were collected at walking speed, with sensor positioning accomplished with a Differential Global Positioning System (DGPS) unit also worn by the operator. Figure 8 is a photograph of the magnetometer system and DGPS system in use at LBNM.

3.4 ELECTRICAL CONDUCTIVITY

3.4.1 General Background and Data Acquisition

Electrical conductivity is the ability of a material to transport electrical charge. Conductivity is the inverse of resistivity, although some geophysical instruments are designed to specifically measure conductivity, rather than resistivity. The conductivity, or resistivity, of rocks spans a wide range, and depends significantly on the degree of rock pore saturation and the conductivity of the saturating fluids. There are various types of instruments that measure the bulk conductivity of the subsurface down to a particular depth, depending on the instrument and its mode of use. In the case of lava tubes, the air within a lava tube will have a very low electrical conductivity. The conductivity of the surrounding lava will depend on the fluids, if any, within the pore spaces of the lava. If the pore spaces are filled with air then the lava will have a low conductivity, although probably not as low as that of air.

Figure 8. Photo. Data collection with the Geometrics G-858 Magnetometer at LBNM.

3.4.2 Advantages for Mapping Subsurface Voids

Instruments using inductive techniques to measure electrical conductivity do not require ground contact. Thus, data can be recorded quickly. In addition, different instruments could be used in different modes allowing different depths of investigation.

3.4.3 Limitations for Mapping Subsurface Voids

The instruments used to measure electrical conductivity produce better results in fairly conductive conditions. This is because they need to generate electrical currents (called secondary currents) in the ground inductively. When the ground has a very low conductivity, only very small secondary currents are generated. Therefore, the secondary electromagnetic fields, which these secondary currents generate and which are sensed by the instrument, are also very small. In these cases there is very little signal to measure and the instrument becomes ineffective. This may be the case at LBNM. It is possible that instruments, which inductively measure electrical conductivity, could locate lava tubes filled with salt water or in areas where conductive clays are associated with the lava tubes.

3.4.4 Case Studies for Mapping Subsurface Voids

No publicly published work related to the detection of lava tubes exists for review.

3.4.5 Application of the Conductivity Method at LBNM

Prior to mobilization to the survey site, it was recognized that inductive measurements of electrical conductivity might not be successful. However, it was difficult to accurately estimate all of the possible geologic conditions without on site testing. Since measurements of electrical conductivity using inductive methods are rapidly acquired, this method has the potential to be very useful for locating lava tubes if the geologic conditions are appropriate. Thus the method was tested at the LBNM site. Data was recorded using the EM31, which generates electromagnetic waves oscillating at 9.8 KHz in order to measure bulk conductivity. The instrument was used with the plane of the coils (transmitter and receiver) parallel to the ground surface (figure 9). In this mode the effective exploration depth is about 5 m (16.4 ft). The instrument outputs conductivity data in mmho/m to a data logger.

3.5 SEISMIC REFRACTION

3.5.1 General Background and Data Acquisition

Seismic refraction is a geophysical method that analyzes the time of the first arrival of energy at each geophone. A seismic line, consisting of an array of geophones, is laid out in a straight line. Generally, the length of a seismic refraction spread should be three or four times the expected depth of the refractor, although this depends on the particular geological conditions. Acoustic energy is injected into the subsurface by a seismic source such as explosives or a sledgehammer. The acoustic energy travels through the ground as a wave front of energy. When this wave front encounters a layer with a higher velocity, such as an alluvial/bedrock interface, a portion of the energy is refracted as a head wave along this interface. As this wave travels along this interface, waves are continuously refracted back to the ground surface where they are detected by geophones. Both compression (P-waves) and Shear (S-waves) waves are used in seismic refraction. P-waves and S-waves have different propagation characteristics. P-waves are longitudinal waves and medium displacements are in the direction of motion. S-waves are transverse waves and medium displacements are perpendicular to the direction of motion. Figure 10 is an illustration of the seismic refraction method over a void.

Figure 9. Photo. Data collection with the EM31 at LBNM.

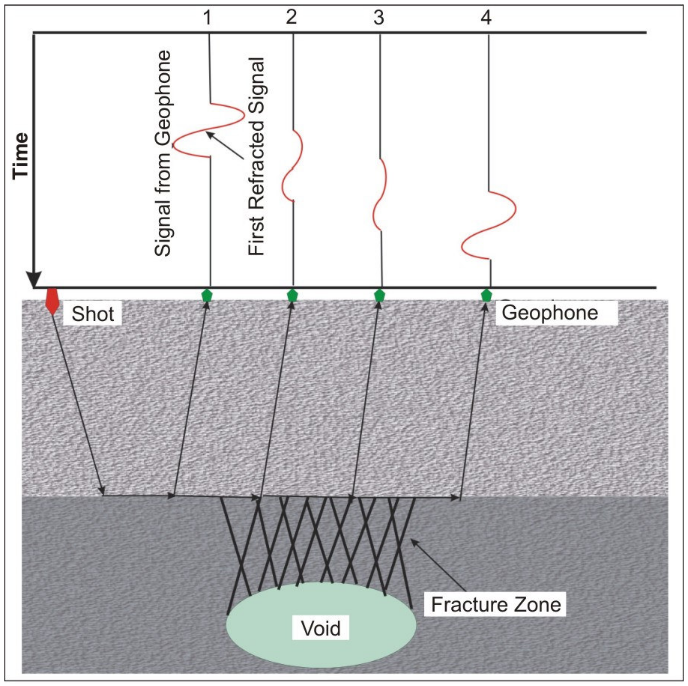

Figure 10. Drawing. Seismic refraction data across a fracture zone. [5]