A GPR SURVEY OF KILBOURNE HOLE, SOUTHERN NEW MEXICO: IMPLICATIONS FOR NEAR SURFACE GEOPHYSICAL EXPORATION OF MARS AND THE MOON

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Introduction: Features such as the Home Plate plateau on Mars, a suspected remnant of a phreatomagmatic eruption [1], can reveal important information about paleohydrologic conditions. The types and sizes of pyroclastic rocks produced by a phreatomagmatic eruption are indicative of the behavior of the explosion and the characteristics of the groundwater reservoir [2]. For example, analysis of the pyroclast size distribution can be used to determine magma volatile content [3]. We conduct an analysis of pyroclast size distribution using Ground Penetrating Radar (GPR) to make a quantitative estimate of the presence of past groundwate at Kilbourne Hole, NM (Fig. 1).

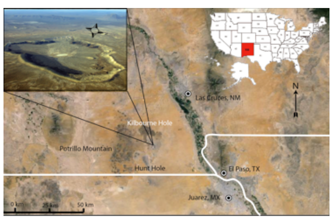

Figure 1. *Kilbourne Hole, NM.*

Study Area: Kilbourne Hole is a well-known [4] phreatomagmatic crater, located in southern Dona Ana County, New Mexico. It is a 2-km wide depression that is approximately 200-m deep. As basaltic magma intruded the groundwater reservoir in the mid-Pleistocene, the water vaporized and caused the phreatomagmatic explosion that excavated Kilbourne Hole [5]. Kilbourne Hole serves as a convenient and scientifically interesting planetary analog site for similar features on Mars and on the Moon [6].

The stratigraphy of the Kilbourne Hole area comprises 5 units [7]. The pre-eruption units are: the Plio-Pliestocene Camp Rice formation which includes 150-500 m of lacustrine, fluvial, and alluvial sediments; and the 100-300 ka Aden and Afton basaltic lava flows which are each approximately 2-3 m thick in the vicinity of Kilbourne Hole. The eruptive units associated with the Kilbourne Hole explosion include: pyroclastic base surge deposits that form an up to 50-m thick tuff ring around the crater rim containing cross-bedded ash, lapilli, and bombs; and pyroclastic deposits that fill the crater interior. The youngest geologic units comprise post-eruption aeolian and fluvial sediments, much of which include reworked Camp Rice, basalt, and pyroclastic materials that are deposited both inside and outside of the crater.

Hydrology of Phreatomagmatic Eruptions: The thickness of the pyroclastic units produced during a phreatomagmatic explosion is proportional to the size and the duration of the explosion and the size of the groundwater reservoir [8]. The wetter the eruption, the stronger is the explosion [4].

Experiments indicate a linear relationship between explosion intensity (released kinetic energy, E_k) and surface area of deposited pyroclastic ejecta [9]. We can derive E_k if we know the surface area. Furthermore, a quantitative relationship between the amounts of water and pyroclastic material involved in an eruption and E_k is given by [10]:

$$E_k = \frac{(M_f + M_w)V_e^2}{2} \quad (1),$$

where M_f is the mass of ejected pyroclastic fragments, M_w is the mass of water injected into the melt, and V_e is the expansion velocity. To explain equation (1), in a violent volcanic eruption, magma changes from a liquid state into solid fragments while also releasing liquid water and water vapor [10]. The magma transfers its heat to the water and transforms water into vapor. Water vapor pressure releases and accelerates masses of ejectas, and ash [10]. The masses of ejectas were released with the kinetic energy E_k, In order to determine M_w in Equation (1), we must know gas expansion velocity, V_e. The relationship between the expansion velocity of the gas (V_e) and the distance from center of eruption(R) is given by [11]:

$$V_e = V_0\left(\frac{R_0}{R}\right)^2 e^{-\frac{t}{\tau}} \quad (2),$$

where V_0 is the gas maximum velocity at time zero at radial distance R_0 from the center of the explosion; R is radial distance from the vent; over time t maximum velocity would decay to V_e; in which τ is a time constant defined as the duration of the entire gas expansion phase [11]. Equation (2) shows that the gas expansion velocity exponentially decreases with time and distance. Based on a semi-numerical model relating pyroclast size and the velocity of pyroclasts ejected in Hawaiian and Plinian eruption [3], clast size also exponentially increased in response to the decreasing of expansion velocity

Methodology: A GPR survey was performed in January 2012 using a Noggins 250 MHz radar system. We designed the survey to detect volcanic bombs and blocks in the shallow subsurface and to map radial variations in their sizes in order to determine expansion velocity. Basaltic clasts with relatively high Fe contents are common in the ejecta deposits surrounding Kilbourne Hole where they are preserved within surge layers. A total of seven GPR lines were extended radially, in each cardinal direction from the rim of Kilbourne Hole. The lengths of survey lines vary depending on accessibility, but most of the lines extended between 250 m to 500 m. The GPR survey allowed us a penetration depth of about 2.4 m, which was sufficient to detect volcanic bombs and sagged layers in the tephra with very good horizontal resolution. Our surveys provided a 2D cross-section profiling that allowed us to map clast size variation. The resolution of the processed GPR images revealed the object and layer that are between 0.25-25 m in dimension

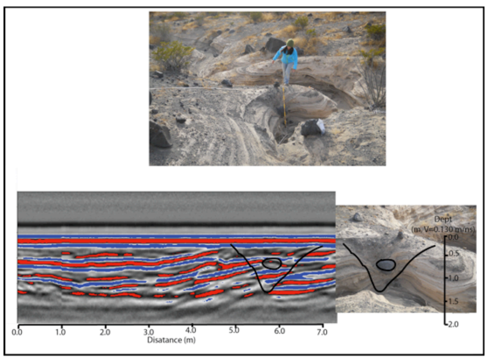

Figure 3. *Example GPR survey result from Kilbourne Hole, revealing the reflectors indicative of bombs and sagged layers.* **(***Image processed with two way travel time v = 1.*30 m/s**)**

Results: The survey successfully allowed us to measure the diameter of bomb influenced sagged layer (Fig. 3). Though the GPR reflectors of the clast may not represent the real clast size but instead the variation of iron content of the clast. We then also performed a ground truth survey over 29 exposed volcanic bombs and sags in the field to obtain the relationship between clast size and sag size. Along the survey line we can measured the size changes in relative to the distance from crater rim. In this abstract, we show here the plot of the clast versus the distance from crater rim along GPR survey line 3 (Fig. 4). Figure 4 shows that clast size is exponentially decreased as the distance from the crater rim increases. Where further away from the center of eruption, ejection velocity is dropped and has to deposit bigger clast closer to the crater.

From the plot, we can delineate an exponential relationship between bomb size and distance from crater rim:

$$y = 48.667 - 5.1647\log(x) \quad (3).$$

Where y is distance from the crater rim equivalence to R in Eq. 2 &4 (y = R) and x is calibrated clast size in cm.

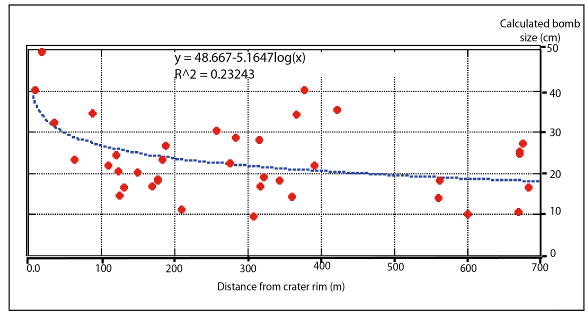

Figure 4. *Calibrated clast size versus distance from crater rim. Data obtained from GPR surveys line 3 at Kilbourne Hole.*

To solve for explosive velocity, Eq. (2) will be rearranged to solve for (R),

$$R^2 = \frac{V_0}{V_e} R_0^2 e^{-\frac{t}{\tau}} \quad (4).$$

$$2\log R = \log\frac{V_0}{V_e} R_0^2 - \frac{t}{\tau} \quad (5).$$

We use least square method to solve for the terminal expansion velocity ($\frac{V_e}{V_0} R_0^2$).

Conclusion: We showed here how to derive expansion velocity (V_e) using clast sizes obtained from GPR surveys. The derived velocity will be ultimately incorporate with the masses of ejecta (M_f) and melt (M_m) from our magnetic and gravity surveys [12] map to calculate the size of the paleo-groundwater reservoir (M_w) responsible for the Kilbourne Hole phreatomagmatic explosion. A GPR survey similar to what we are doing at Kilbourne Hole and conducted on either a robotic or human exploration mission could be used to reveal important paleohydrologic conditions associated with features such as the Home Plate eruption on Mars.

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