GROUND PENETRATING RADAR FIELD STUDIES OF LUNAR-ANALOG GEOLOGIC SETTINGS AND PROCESSES: BARRINGER METEOR CRATER AND NORTHERN ARIZONA VOLCANICS. P. S. Russell[1], J. A. Grant[1], K. K. Williams[2], L. M. Carter[3], W. B. Garry[4], and D.B.J. Bussey[5] [1]Cent. Earth & Planet. Studies, Smithsonian Inst., Washington DC 20013, russellp@si.edu [2]Dept. Earth Sci., Buffalo St. College, Buffalo NY 14222 [3]NASA-GSFC, Greenbelt MD 20771 [4]Planet Sci. Inst., Tucson, AZ 85719 [5]JHU/APL, Laurel MD 20723.

Introduction: Ground-Penetrating Radar (GPR) data from terrestrial analog environments can help constrain models for evolution of the lunar surface, aid in interpretation of orbital SAR data, and help predict what might be encountered in the subsurface during future landed scientific or engineering operations on the Moon. GPR can yield insight into the physical properties, clast-size distribution, and layering of the subsurface, granting a three-dimensional view of the processes affecting an area over geologic time.

The purpose of our work is to demonstrate the usefulness and capabilities of GPR in geologic investigations of sites at which geologic processes, settings, and/or materials are similar to those that may be encountered on the Moon, especially lava flows, impact-crater ejecta, and layered materials with varying properties. We show how physical characteristics of the subsurface gleaned from GPR data allow for geologic interpretations of these sites to be made. This study design focuses on GPR-based geologic interpretation, which differs slightly from studies that seek specific terrestrial conditions that most exactly and fully replicate a particular planetary environment (or aspects thereof) [eg 1], and from studies that aim to determine geophysical parameters of various subsurface materials or conditions [eg 2]. The challenge in using GPR in geologic investigations is the degree to which different geologic scenarios can be distinguished in the data. Our approach to constraining this is to qualitatively and quantitatively characterize GPR signatures of different geological environments and to compare them with "ground-truth" observations of subsurface exposures (Fig. 1).

We present GPR surveys performed at Barringer Meteor Crater, SP Volcano cinder cone, and Sunset Crater Volcano National Monument, all in northern Arizona. We focus on the Meteor Crater results, and discuss preliminary results from the volcanoes.

Methods: The ejecta deposits of Meteor Crater have been mapped and studied extensively eg [3]. Our primary focus of investigation here is characterizing the number and density of blocks in the ejecta subsurface that produce a radar return. Secondarily, we survey subsurface locations and relationships of ejecta lobes/material with overlying, embaying sediments deposited since the impact (by alluvial, colluvial, and aeolian processes). GPR-derived relationships of ejecta and surrounding sediments were used by [4] to derive local post-impact erosion rates. Nine sites, all within < 1 crater radius, (~500 m), of the crater rim were surveyed and plotted on ~50 cm/pixel WorldView-2 imagery. At some sites, multiple transects were taken. Each transect was measured with both 200 MHz and 400 MHz GSSI® tranceivers in conjunction with a SIR-3000 GPR system. With each antenna, transects were repeated at multiple depth-ranges, typically 40-160 ns and 20-80 ns two-way travel time, respectively. Measurement at two frequencies and at multiple depths allows an assessment of how GPR detections vary with depth and the antenna employed. At most sites, measurement of a metal plate buried at a known depth (~30-50 cm) served to empirically estimate the local radar velocity and dielectric constant. Dielectric values (~3.5-6.1) were consistent with the range of values obtained from ejecta materials (4.0-5.3) by [4].

Fig. 1. Pre-existing ~2.5 m-deep pit exposing Meteor Crater ejecta blocks, providing for ground-truth of block size-frequency distribution for comparison to GPR data.

Meteor Crater Results & Analysis: An existing ~2.5 m-deep pit in Kaibab limestone-dominated ejecta (Fig. 1) and the > 2 m-high wall of an old quarry in fractured and pulverized Coconino sandstone-dominated ejecta provided the exposures in which the number, size, and depth of blocks were measured as our "ground-truth" picture of the subsurface against which we compare nearby GPR transects. All 4 walls of the pit produced similar block size-frequency distributions. Also, the block count per unit area within each of 3 meter-high depth bins indicates the block distribution is fairly uniform with depth. Plotted as cumulative size-frequency per unit area, our results compare reasonably well with both a power-law fit [5] and an exponential fit [6] to counts at the Viking Lander 2 site, over the size range of 0.1 – 0.5 m. This suggests that this population has been dominated by fragmentation processes, although the slightly lower exponent values in our fit may indicate less advanced fragmentation, likely due to protection by burial since the ejection event.

In GPR radargrams, reflections attributed to blocks in the top 2-5 m of the subsurface were counted, and their depth recorded (Fig. 2). The 400 MHz antenna always showed more blocks than the 200 MHz. This is to be expected due to the two-times lower resolution of the 200 MHz, and to the corresponding less frequent occurrence of blocks at the larger sizes detectable by the 200 MHz. However, the 200 MHz did not typically reveal blocks at depths greater than the 400 MHz did, as one might expect from increased penetration of the longer wavelength. Inspection of the radargrams indicates this is probably due to scattering of the radar signal in the near surface by the very dense distribution of blocks in the ejecta. Poor returns have also been recorded from beneath impact-crater breccia, also a highly scattering medium, at Haughton Crater [7]. This suggests that, for a study of a highly-scattering subsurface, the 400 MHz has the advantage of better capturing the near-surface block population, with further analysis needed to determine the cases in which deeper information can be extracted.

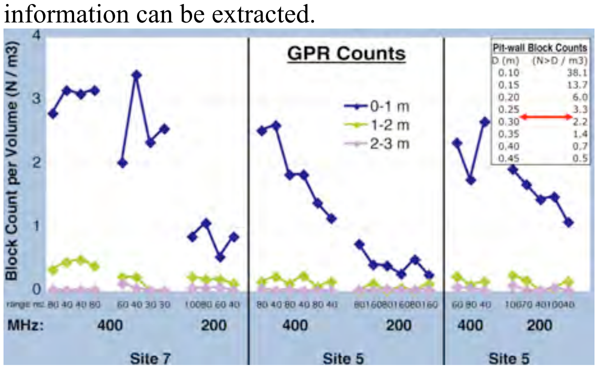

Fig. 2. Block counts for several transects at different sites, radar frequency, and depth range.

The typical distribution density of blocks measured using the 400 MHz was 2-3 blocks per m^3. Comparing this value with the size-frequency distribution per unit volume derived from the "ground-truth" block counts, a distribution density of 2-3 blocks per m^3 is expected to result from that portion of the population composed of blocks larger than 0.25 to 0.30 m. This is roughly the limit to be expected from the $\lambda/3$ approximation of resolution at radar wavelength, λ.

Given the GPR results of the Meteor Crater ejecta block population determined here, GPR investigations of other ejecta deposits for which no ground-truth is available, as on the Moon or Mars, can be compared to this study and interpreted relative to the known Meteor Crater ejecta block population, especially if multiple wavelengths are used. As it develops further, our work aims to contribute to a basis for future GPR-based interpretations of ejecta processes.

SP Volcano: Work at SP Volcano focuses on the northern, lower slopes of the cinder cone, from beneath which a basalt lava flow extends onto surrounding terrain. Layering within cinders is visible in GPR radargrams in the upper ~0.5 m. A small pit reveals that such layering may be due to significant, stratified variation in cinder size, relative moisture content of a fine, loess-like matrix, and fraction of inter-cinder voids (pore space) filled with matrix. The subsurface cinder-lava contact is consistent with a horizontal or dipping surface, or termination, as it is traced southwards beneath the cinders. To the north, the surface of the lava flow descends beneath a loess-rich cover and appears to have significant surface relief, consistent with observations of nearby, non-buried surfaces. Sparse, isolated reflectors (relative to the crater ejecta and to the buried lava flow) are likely large (up to ~1.5 m) lava bombs as observed around the site.

Sunset Crater Volcano: GPR surveys were conducted on cinder-covered portions of the Bonito lava flow, extending to the NE of Sunset Crater cinder cone. In thick sections of cinders, layering can be seen, possibly due to aeolian transport events. The surface of the buried lava flow is easily recognized, and can be correlated with surface outcrops of lava where it rises to the surface. Especially notable are raised ridges delineating individual surges within the flow. GPR can help estimate cinder-cover volume, buried lava surface relief, and intra-flow structures. Two locations at flow margins exposed near-vertical cross-sections of the subsurface flow stratigraphy, dominated by alternating < 2 m-thick, massive, vesicular, lightly fractured basalt and thinner layers (< 0.5 m) of extremely rough, irregular clinkers with significant intervening pore space, corresponding to a temporary one-time surface of the flow. We are currently matching these profiles with deeper sections of the GPR transects to determine how this inter-layering is manifested in GPR data.

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