GROUND PENETRATING RADAR FIELD STUDIES OF LUNAR-ANALOG GEOLOGIC SETTINGS: IMPACT EJECTA AND VOLCANIC MATERIALS. P. S. Russell[1], J. A. Grant[1], K. K. Williams[2], L. M. Carter[3], W. B. Garry[4], G. Morgan[1], I. Daubar[5], and D.B.J. Bussey[6] [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]U. Arizona, Tucson, AZ 85721 [6]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 the nature of subsurface properties encountered 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, thereby 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 at terrestrial sites where geologic processes, settings, and/or materials may be similar to those encountered on the Moon, especially volcanic deposits and impact ejecta. Our study focuses on GPR-based interpretation of the subsurface geology. The challenge we seek to address is to constrain whether and how different geologic scenarios can be uniquely distinguished and characterized with GPR. Our approach is to conduct side-by-side comparisons of GPR measurements and corresponding "ground-truth" outcrop exposures of the subsurface. Here, data and associated interpretations are presented from GPR surveys at Barringer Meteor Crater, SP Volcano cinder cone, Sunset Crater Volcano National Monument, and Columbia River flood basalts.

Methods: Several sites were chosen in each field area based on accessibility, visual access to the subsurface, and presence of particular geologic features of interest. Multiple transects were acquired at most sites, usually with both 200 MHz and 400 MHz GSSI® impulse tranceivers, in conjunction with a GSSI SIR-3000 GPR system. Transects were repeated at multiple depth-ranges, typically 40-160 ns and 20-80 ns two-way travel time with the respective antennas. Multiple measurements allow an assessment of the dependence of GPR detections on depth and wavelength. At most sites, measurement of a metal plate buried at a known depth (~30-50 cm) served to empirically estimate the local radar wave velocity and dielectric constant, from which a length scale can be applied to the vertical radargram axis. Dielectric values at Meteor Crater (~3.5-6.1) were consistent with the range of values obtained from ejecta materials (4.0-5.3) by [1]. In places, data collection was complicated by rough ground surfaces, making it difficult to maintain constant orientation and ground coupling of the GPR antenna.

Data processing employed GSSI's RADAN® software. Both original and migrated versions of the data were used in estimating the number of subsurface blocks. In unmigrated radargrams, isolated blocks in a uniform matrix appear as hyperbolas. The arc of the nose of the hyperbola and the extended tails are helpful in denoting a block. Radargrams become very complex due to scattering when the density of blocks is high and a range of sizes is present, such that the distinction between blocks and matrix is less clear. In this case, hyperbolas become incomplete and masked, and the many overlapping tails, multiple reflections, and 3-D nature of the sampling volume make it very challenging to determine the presence of specific individual blocks. Migration of the data often helps clean up the data, but presents new challenges in distinguishing true "collapsed" reflectors from other variations in the recorded radar signal. Estimates of subsurface dielectric values derived by fitting hyperbolas during migration spanned a range generally in agreement with those made using metal-plate target reflectors.

Meteor Crater: The ejecta deposits of Meteor Crater have been mapped and studied extensively [eg 2]. Existing excavations (eg old mine workings) enable characterization of the number and density of blocks in the ejecta subsurface against which to compare observed radar returns. This work builds on prior GPR-derived relationships of ejecta and surrounding sediments used by [1] to derive local post-impact erosion rates. In this study, 11 sites within 1 crater radius (~500 m) of the crater rim were surveyed.

An existing ~2.5 m-deep pit in Kaibab limestone-dominated ejecta and a ~2 m-high wall of an old quarry in fractured and pulverized Coconino sandstone-dominated ejecta provided the "ground-truth" exposures. The number, size, and depth of blocks were measured in digital photographs of these exposures. The measured size-frequency distribution of blocks in the outcrop [3] is consistent with counts made at the Viking Lander 2 site [4,5] and around small craters explored by the Spirit rover [6], consistent with a dominating influence of fragmentation processes.

Interpretation of 400 MHz radargrams of the top 2-5 m of the subsurface always yielded more blocks than 200 MHz data. This likely reflects differences in radar resolution with wavelength, compounded by the real deficiency of larger blocks. However, interpreted 200 MHz data did not typically reveal blocks at depths greater than ~1.5-2 m, thereby yielding a similar limit to the depth of useful data as for the 400 MHz data. Thus, even the 200 MHz data suggest that the number density blocks in the upper near-surface effectively limits penetration of radar signal, similar to results. from beneath highly scattering impact-crater breccias at Haughton Crater [7].

The typical number density of blocks interpreted from the 400 MHz data is 2-3 blocks per m^3. How does this reconcile with the "ground-truth" block counts? Based on visually determined size-frequency distributions of blocks [3], a number density of 2-3 blocks per m^3 is expected to represent that portion of the block population composed of blocks larger than 0.25 to 0.30 m. This is also roughly the limit to be expected from the $\lambda/3$ approximation of resolution at radar wavelength λ. Thus, these results indicate that the 400 MHz GPR is capturing the ≥~0.3 m population of blocks.

SP Volcano: Data were collected at the northern, lower slopes of the SP cinder cone, from beneath which a basalt lava flow emerges from the margin of the cone and extends onto surrounding terrain. Layering within cinders is visible in both the 200 and 400 MHz GPR radargrams in the upper ~0.5 m. Stratigraphy viewed in a small excavated pit reveals this layering may be due to significant, stratified variations in cinder size, relative moisture content of a fine, loess-like matrix, and fraction of inter-cinder voids (pore space) filled with matrix (vs. air-filled). The subsurface cinder-lava contact is consistent with a horizontal or slightly dipping interface as it is traced southwards beneath the cinders. To the north, the surface of the lava flow descends beneath a loess-rich cover. Both buried surfaces appear to have significant surface relief, consistent with observations of nearby, non-buried surfaces. More subtle variation in the density of reflectors and scattering may be due to the degree to which the lava flow is broken up vs. relatively intact, variation which is also observed at the surface nearby. Sparse, isolated reflectors are likely large (up to ~1.5 m) lava bombs as observed around the site.

Sunset Crater Volcano: GPR surveys were conducted at two sites on cinder-covered portions of the Bonito lava flow, which extends to the NW of Sunset Crater cinder cone. Radar data reveals layering in the cinders that may reflect redistribution of cinder material aeolian transport events, as has been observed on open cinder surfaces at the site [Paul Whitefield, NPS, pers. comm., 2010]. The surface of the buried lava flow is very rough and easily recognized in radargrams, 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. Thus, results demonstrate the ability to estimate cinder-cover volume, buried lava surface relief, and intra-flow structures from GPR data.

Two outcrops at flow margins expose near-vertical cross-sections of the roughly horizontal 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 one-time surface of the flow. In GPR data, at least one and sometimes two couplets of massive-rough lava layering can be identified, extending down to ~4 m depth. These results illustrate that GPR data enables distinction between volcanic flows and between the interiors and tops of flows, when the lava materials are highly contrasting. Radar penetration is significantly better in these volcanic materials than in the crater ejecta.

Colulmbia River basalts (CRB): All field sites were on the western edge of the CRB: 2 in the area of Frenchman and Echo Coulees just north of where I-90 crosses the Columbia River, and one along Palasades Road in Moses Coulee. Excellent vertical exposures of columnar jointing are plentiful in the area, but few areas have a clear, flat, accessible surface exposing a horizontal cross-section through the polygonal columns. Two scales of columns (of colonnade zones as opposed to entablature zones, [eg 8]) were measured, exhibiting polygons ~15-30 cm and ~60-130 cm across. Interpretation of GPR data of the smaller set reveals little to no signal attributable to real features, likely due to the small scale of the columns relative to the radar wavelengths and the close, tight nature of the fractures in the subsurface that minimizes any dielectric contrast across them. So far, we have found no coherent pattern attributable to interaction of the radar with the network of columnar joints. However, processing of the large-column data has yielded several dipping reflectors consistent with the tracing of joints from their manifestation between polygonal columns at the surface to roughly ~1m depth. The width of these columns is great enough such that individual columns should be resolveable at these wavelengths. However, to be detectible, the joints are likely wider than above and/or contain higher-contrast material such as clay or water to enhance their radar signature. At the surface, gaps filled with fine material are observed between some polygonal columns. This result adds another lava flow-related texture distinguishable with GPR. As columnar jointing is present on Mars on the scale of <1 m - >2 m [8], GPR could be employed on a surface mission to constrain the scale and distribution of buried, near-surface lavas with such jointing, provided the dielectric contrast along joints is enhanced.

Discussion: GPR holds promise for revealing subsurface geological properties. Horizontal interfaces bounding and separating lavas and cinders can be identified, enabling insight into the local history of volcanism. Coherent lavas yield wider, more conformal returns relative to the more irregular and complex interaction of returns from the crater ejecta. We interpret the ejecta data as capable of revealing the population of blocks over a certain size, here determined by visual comparison to the subsurface to be ~0.3 m, also roughly equivalent to $\lambda/3$. This provides a basis for comparison and relative interpretation of remote crater sites surveyed with GPR.

References: [1] Grant, J A and P H Schultz (1994) *Proc. 5th Int. Conf. GPR*, 789-803. [2] Shoemaker, E M and S E Kieffer (1974) *Guidebook to the Geology of Meteor Crater, Arizona,* 66p. [3] Russell et al. (2011) *LPSC 42*, Abstract #2097. [4] Moore, H J and B M Jakosky (1989) *Icarus, 81*, 164-184. [5] Golombek, M and D Rapp (1997) *JGR, 102 E2*, 4117-4129. [6] Grant, J A et al. (2006) *Geophys Res Lett, 33*, L16202. [7] Unrau, T et al. (2010) *AGU Fall,* Abstract #P23A-1619. [8] Milazzo, M et al. (2009) *Geology, 37*, 171-174.