Lonar Crater, India: Analog for Mars in the field and in the laboratory

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Introduction: "There is no perfect analog for Mars on Earth" (1^{st} line [1]). But with three processes analogous to Mars (basaltic volcanism, aqueous alteration, and shock), the ~1.8 km Lonar Crater in India (Figure 1) has morphological features of cratering and impactite deposits that are excellent analogs for shergottites and for spectrometers that mirror those sent to Mars. Field geology and remote studies that ground-truth the composition of altered ejecta lobes have implications for phyllosilicate detections on Mars (Figure 2). All three scales – sample (Figures 3 and 4), field (Figure 5), and remote data (*e.g.*, Figure 2) – are briefly discussed.

Geologic History from Sample Analyses: Lonar Crater is a young (~570 ka) [3] impact site emplaced in ~65 Ma Deccan basalt, which is an excellent analog material for Mars with ~45-50% labradorite and ~35% augite/pigeonite [4] before lower flows were altered and then shocked. Two geologic histories are possible at Lonar after the initial basaltic volcanism: 1.) the existence of altered basalt protoliths ("pre-impact alteration") (Figure 4) now vitrified as in-situ breccia clasts or float; and 2.) the alteration of impactites/glasses of a range of shock pressures ("post-impact alteration"), which likely increase the rate of alteration where compared to pristine, igneous minerals (Figure 3). Both geologic histories have implications for the discoveries of alteration minerals found solely in Martian ejecta blankets with remote VNIR data [5,6] (*e.g.*, Figure 2). Alteration minerals are briefly listed here, and these mirror those suggested for Mars [7,8]: chlorite, serpentine, zeolites, hematite, palagonite, calcite, silica.

Sample Collection: ~80 kg of "intermediately" (20-80 GPa) shocked basalt, which exist as clasts in the uppermost, suevite breccia layer at Lonar Crater, India [2], along with float that were former breccia clasts, were collected during a 2-month field season. These add to a large collection of unshocked basalts and impact melts (aka Class 5 [2]). Petrography reveals of range of shock pressures (deduced by phases and mineralogies of labradorite and augite), various protoliths such as fresh and altered basalt (Figures 3 & 4) and what is interpreted as a consolidated soil or a sample from weathering horizons in-between individual basalt flows. A shocked hematite-rich sample is likely from a "bake zone" in-between basalt flows. Impact melt veins and pockets are found in some Class 2 impactites. This sample collection is likely the only one of its kind.

Figure 1. Aerial view of Lonar from SW. The town of Lonar on NE rim developed ~1 ka near largest gulley (developed due to pre-impact spring & fault).

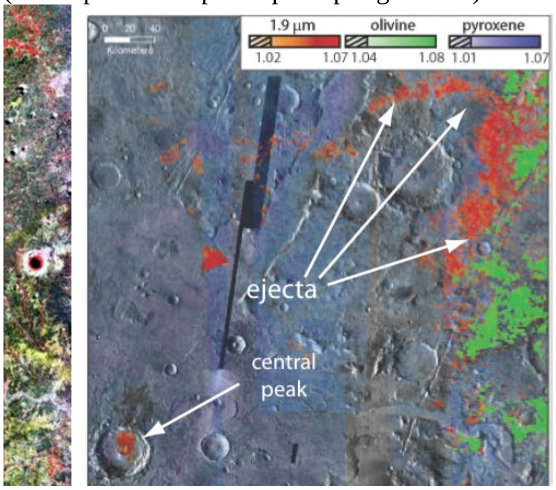

Figure 2. left – Hyperion data of Lonar Crater right – OMEGA spectral index maps of the Nili Fossae region showing the presence of phyllosilicates (in orange) within impact ejecta and the central peak or crater floor of a 40 km-diameter crater [6].

Fieldwork: Both fresh and aqueously-altered basalt are found as impact breccia clasts in a ~8 m thick lithic (relatively unshocked; "throw out") layer and ~1 m suevite (all ranges of shock pressure; "fall out") ejecta deposit. Underlying, altered basalt (by groundwater/aqueous alteration) is only exposed in the ejecta due to impact. "Bake zones" and soils representing boundaries between flows are scattered throughout the ejecta. A benefit to understanding ejecta is the ability to conduct fieldwork and collect samples of these materials undisturbed in the surrounding regions [9].

Spectroscopy & Remote Sensing: As our only samples of Mars are ~55 shocked basalts [10], along with the wealth of spectral data from MER/MSL, orbiters, and future (ExoMars, "cache-2020") instruments, it would be fortuitous to collect and understand the spectra of these samples from techniques and instruments used for Martian meteorites and/or sent to Mars. TIR emission spectroscopy of Lonar basalts provide constraints to Mars data [10]. With a smaller spot size, μFTIR and μRaman data of various slices show new, unique glass end-members [11,12]. Some VNIR data has been acquired [13,14], and these provide spectral end-members to understand remote hyperspectral data of Lonar (Figure 2a) to replicate Mars analyses (Figure 2b) of Lonar ejecta lobes. Mossbauer spectroscopy [15,16] is ongoing to study the behavior of Fe (in glass, pyroxenes, and oxides) at various shock pressures.

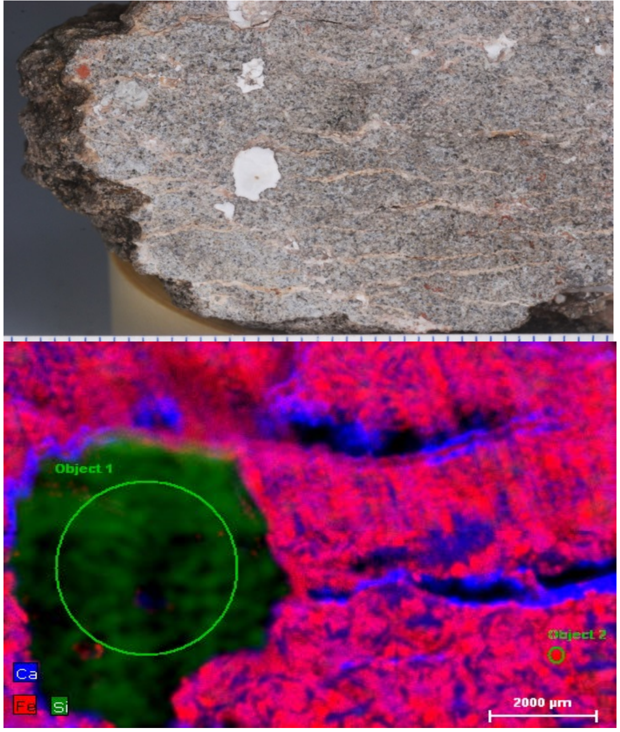

Figure 3. Top: cut surface showing "decompression cracks" [17] in a Class 2 shocked basalt (top). Bottom: in same sample, Bruker element data show a two-stage alteration history: 1.) silica/chert deposited in basalt over ~65 Ma; likely at depth; (bright white on slice; green on element map); 2.) impact/shock ~570 ka produces silica glass and decompression cracks [17], plus sample moved into ejecta; 3.) calcite deposited aqueously in decompression cracks.

Merit: Lonar includes mineralogical signatures of alteration in basaltic ejecta and it's crater-floor breccia deposit. Both alteration and shock potentially create amorphous materials and complex mineralogies, and these must be measured by rovers sent to Mars to characterize the geology. Impactites are found as shocked and melted rocks in a layered ejecta blanket. On Mars, we must be able to unravel the geologic histories of sedimentary rocks, altered rocks, and soils. Evidence for the climate history is reflected in the alteration of materials in the ejecta blanket. The erosion processes producing gullies on crater walls can also be studied on the rim and interior walls at the site. The basaltic lava flows of the target and interflow deposits are analogous to the Martian crust [4]. The engineering merit of the Lonar site includes the preservation of ejecta of a simple impact crater. The site can support tests of drilling into ejecta blankets, fieldwork, and cross sections of ejecta (Figure 5).

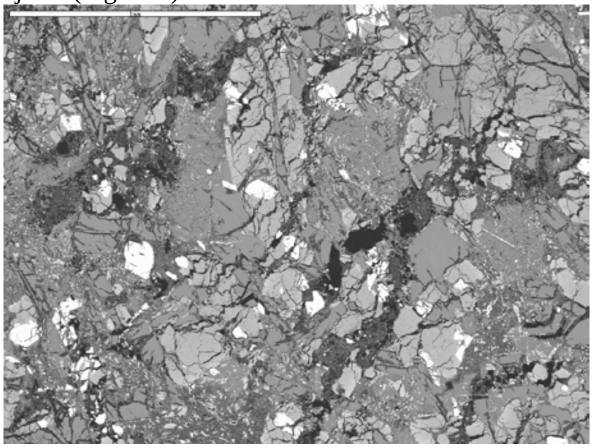

Figure 4. "Feathery" textures in BSE image are phyllosilicates, with needles now maskelynite. Black voids running SW-NE are decompression cracks [17]. Scale bar measures 1 mm.

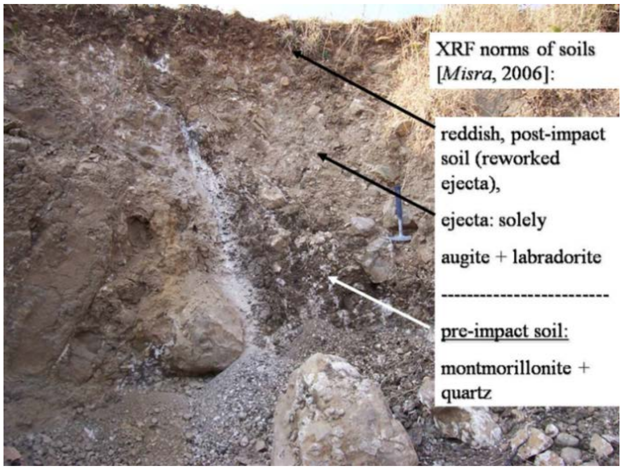

Figure 5. Example of combining field and subsequent laboratory XRF data from [18].

References: [1] Hipkin et al. (2013) *Icarus*, 261-267 [2] Kieffer et al. (1976) *7th LPSC*, 1391-1412 [3] Jourdan et al. (2011) *Geology 39*, 671-674 doi: 10.1130/G31888.1 [4] Bandfield et al. (2000) *Science* [5] Mustard et al. (2008) *Nature*, doi:10.1038/nature07097 [6] Michalski et al. (2010) *Icarus* [7] Ehlmann et al. (2011) *Nature 479*, 53-60 [8] Ehlmann et al. (2011) *Clays & Clay Minerals 59*, 359-377 [9] Maloof et al. (2010) *GSA Bull*, 109-126 [10] Wright et al. (2011) *JGR-Planets*, doi:10.1029/ 2010 JE003785 [11] Jaret et al. (2013) *LPSC 44*, #2881 [12] Jaret et al. (2014) *LPSC 45*, #2151 [13] Ehlmann et al. (2008) *LPSC 39*, #2437 [14] Wright et al. (2004) *2nd Conf. on Early Mars*, #8067 [15] Verma et al. (2009) *ICAME*, 897-904, doi: 10.1007/978-3-540-78697-9_124 [16] Morris et al. (2004) *Science*, 833-836 [17] Wright (2013) *Large Met. Impacts V*, #3049 [18] Misra et al. (2006) *LPSC 37*, #2123