THE FIRST FIELD GEOLOGIC MAPS ON ANOTHER PLANET. L. S. Crumpler, New Mexico Museum of Natural History & Science, 1801 Mountain Rd NW Albuquerque, NM, 87104, USA, larry.crumpler@state.nm.us

Introduction: Field geologic maps have been prepared from in situ ("field") observations during the traverse of Mars Exploration Rovers Spirit and Opportunity [*1,2,3*]. These maps are *the first tests of field geologic mapping methods at the human scale on another planet.* Now in its 13th year of operation on Mars, Opportunity's current mapping campaign on the rim of the 22-km-diameter Noachian Endeavour impact crater [*4, 5*] is also *the first in situ geologic traverse on the rim of large (complex morphology) impact crater.* Prior to this traverse the most basic outcrop-scale geologic, structural, lthologic, and petrologic characteristics and associated outcrop land forms of preserved large impact craters were unknown.

Field Geologic Mapping Method on Mars. A decade ago the *MER Science Team* established the methods for efficient rover operation by codifying field geologic methods. Based on experience in geologic mapping from Mars Exploration Rovers Spirit and Opportunity over the past decade, and based on personal experience in terrestrial 1:24000-scale field geologic quadrangle mapping, *we conclude that the methods of geologic mapping on foot in the field on Earth and in situ with a rover on Mars are comparable.* Throughout Spirit and Opportunity's traverse's in the Columbia Hills and on the rim of Endeavour crater rim the textures, structures, mineralogy, chemistry, and petrography of outcrops were systematically examined in situ at each end-of-sol position. Similarities and differences between examined rocks and outcrops were noted and the rock types and relative stratigraphic positions of separated outcrops were compared, correlated, and mapped along the traverse on a MRO/HiRISE image base out to a radius of 20 m, resulting in an along-traverse mapping swath 40 meters wide [**Fig. 1**]. The 20-m limit is based on experience in ability to detecting differing lithologies wuth increasing distance from MER Navcam images. Unlike previous planetary maps, the high resolution image base, in this case MRO/HiRISE, is used only to record and assist in locating contacts, while the contact itself is detected from in situ observations. This is similar to the use of air photos on Earth during a field mapping campaign: air photosa are used as assistance, not as a source of the information recorded on the map.

A true geologic map that merges lithology and stratigraphy was developed by (1) plotting the observed positions of exposures within each lithologic unit, (2) correlating exposures from site to site, (3) identification of their contacts, respective overlapping characteristics and time series of emplacement, and (4) compilation of the attitudes of structures and foliations. The availability of topographic relief data from Nvcam ranging and from HiRISE DTMs enabled construction of simple geologic sections that permit further tests of proposed stratigraphic and structural field interpretations. In many locations, the attitude of bedding has been determined from simple field methods such as along-strike and down-dip viewing and plotting contacts on geologic sections. The ultimate result is a record of field observations in a map format of the lithology and history of the area traversed.

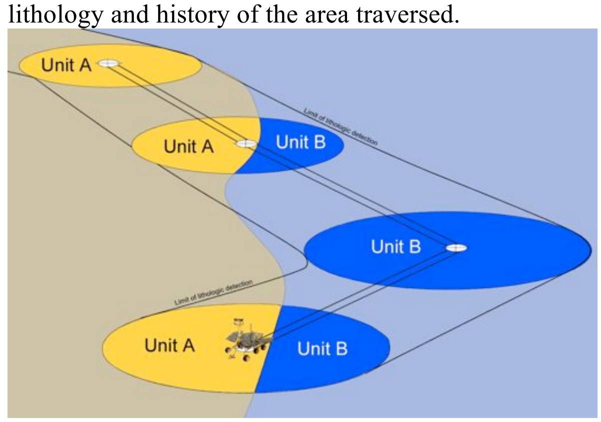

Figure 1. Field geologic mapping on Mars is comparable to mapping in an area of extensive cover: lithology, structure, and contacts are compared between stations and continuity derived from correlation of petrography. Elemental correlations are frequently confusing or distracting.

Spirit and Opportunity. The rovers were designed to replicate the capabilities of a field geologist: 20-20 color vision (Pancam), a rock hammer (Rock Abrasion Tool), a hand lens (Microscopic Imager), the ability to test for basic minerals (mini-TES, Mossbauer), and "lab analysis of elemental abundances" (APXS). The design goals were achieved: As with a field geologist, these tool more than suffice for detailed mapping at sub-meter length scales.

Several kilometers of geomorphically diverse but lithologically monotonic terrain were traverse initially by both rovers. Ultimately Spirit mapped **0.05 km^2** along its 4.3 km traverse within the lithologically diverse Noachian Columbia Hills. Likewise, Opportunity has mapped **0.2 km^2** to date (sol 4376) along its 9.2 km trek on the rim of a complex Noachian impact crater.

Spirit in the Columbia Hills: The Common case of Up-hill is Down-stratigraphy on Mars. The varied geochemistry and diverse morphology of outcrop exposure as Spirit ssummited the Columbia Hills rendered obvious correlations and stratigraphic determinations between outcrops difficult. Extremely variable alteration and deep erosion renders quantitative correlations perilous. The petrologic and lithologic protolith of many outcrops however remains and serve as a basis for recognizing similar units at widely separated locations. Ultimately the Columbia Hills was determined from basic stratigraphic correlation and from the pattern of bedding attitudes form to be a succession of layered materials draping a precusor massif [**Fig. 2**]. We believe this "up-hill is down-stratigraphy" arrangement of the Columbia Hills is common on Mars.

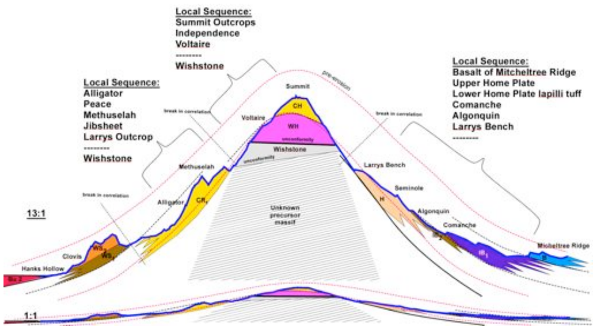

Figure 2. Structural section of the Columbia Hills from field observations Spirit's traverse across the flanks and summit.

Opportunity on Endeavour crater: Field Geology on a Complex Impact crater. The structure and stratigraphy of complex impact craters is beginning to emerge from Opportinity's traverse along the west rim of the 22 km-diameter Endeavour crater. Evidence for up to several hundred meters of degradation of the crater rim [*6*] is supported in outcrop by exposure of the steep monoclinal dip (22°) of bedrock layers unconformable with outward rim slopes (~10°) at *Pillinger Point* and near the *Cape Tribulation* summit.

With few exceptions, variably altered impact breccias ("*Shoemaker formation*") account for most of the outcrops visited along the rim, including distinct upper and lower units. Locally pre-impact substrate materials are exposed at a strong unconformity. These rocks are the oldest voisited by any rover on Mars and represent surfaces exposed to and eroded in the Martian environment during the Noachian. Details of the breccias vary, but generally consist of darker clasts up to several centimeters embedded in a matrix of altered fine-grained material and coarse agglomerations of both. While individual outcrops rarely show bedding, slab-like foliation of consistent orientation is locally prominent, resulting in a general sense of the arrangement of deposition planes within the ejecta.

Evidence for up to several hundred meters of degradation of the crater rim [*6*] is supported in outcrop by exposure of the steep monoclinal dip (22°) of bedrock layers unconformable with outward rim slopes (~10°) at *Pillinger Point* and near the *Cape Tribulation* summit.

Bedrock exposures on the floor of *Marathon* Valley are planar layering surfaces consisting of *lower Shoemaker fm*: relatively clast-poor breccias broken by layering sheets dipping N60E at approximately 14 to 15 degrees (**Fig. 3**) and a set of roughly vertical joints or fractures. The structure arrangement of permeability together with the prevalence of vertical joints and dippingly foliation may be fundamental to the original control of groundwater movement and the corespondiung location of smectites at this site.

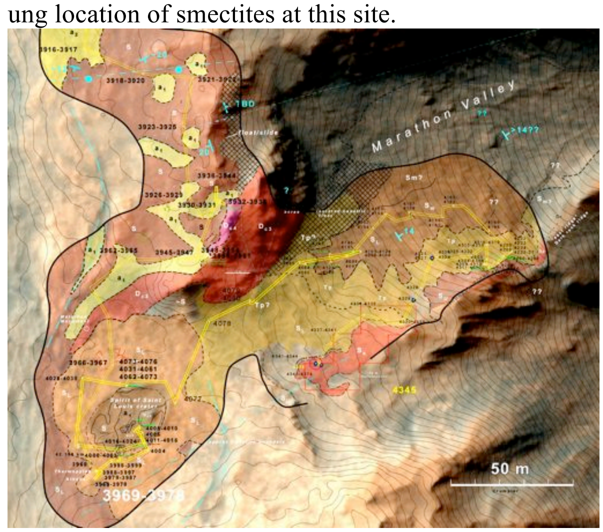

Figure 3. The most recent few hundred meters of Opportunity's traverse address the structure and stratigraphy within a deep valley cross the west rim of Endeavour crater. Contrary to typical complex crater cross sections, the structure is anticlinal and consistently sequenced.

Summary. *First*, the construction of a geologic map from field geologic observations is an important development in Mars science, expanding the geologic characterization of Mars from photogeologic to actual in situ ("ground truth") measurements of petrologic, structural, stratigraphic, and geomorphic information of surface materials in a local lithologic context over kilometers of traverse. For the foreseeable future "in situ" maps are likely to be confined to the vicinity of actual traverse. The opportunity to expand the area of these maps somewhat may be supplemented in the future with aerial surveys from automamous UAVs, but detailed outcrop mapping will continue to rely on surface traverses of one sort or another.

Second, no geologist has ever examined the geology in situ on the rim of a large crater, so Opportunity' s investigations are now developing the science of large craters. There is no template for expectation about this new terraim, nor the new science and the structure and stratigraphy of complex impact craters is beginning to emerge. The discoveries are now sol by sol.

References: [1] Crumpler, L.S. et al. (2011) *J. Geophys. Res.,* 116; [2] Crumpler, L.S. et al. (2015) J. Geophys. Res., 120; [3] McSween, (2014) GSA Today, 25; [4] Arvidson et al. (2015), AGU; [5] Crumpler et al (2016) LPSC 47 abstract 2272; [6] Grant et al (2016) Icarus, doi:10.1016/ j.icarus. 2015.08.019