RECONNAISSANCE ELEMENT MAPPING OF LUNAR REGOLITH BRECCIAS. K. H. Joy[1,2], D. K. Ross[3,4], M. E. Zolensky[2,3], D. A. Kring[1,2]. [1]CLSE, LPI/USRA, 3600 Bay Area Blvd., Houston, Texas 77058, USA (joy@lpi.usra.edu). [2]NASA Lunar Science Institute. [3]ARES, NASA Johnson Space Center, Houston, TX 77058, USA. [4]ESCG-Jacobs Technology, 2224 Bay Area Blvd. Houston TX 77058, USA.

Introduction: The lunar surface is covered with a regolith produced by impact comminution of underlying rock [1,2]. This boundary layer with space preserves a record both of the Moon's geological history and its collisional evolution with impacting asteroids and comets (*e.g.,* [3]). Regolith breccias are lithified samples of regolith that has been fused together by impact shock and thermal metamorphism. These complex samples, and the rock fragments they contain, can be used to investigate a range of geological processes.

We are studying Apollo and lunar meteorite regolith breccias. These samples include the Apollo 16 regolith breccias that formed across 4 billion years of lunar history [4,5]. We have also been studying the Dhofar 925 and 961 stones that have been postulated to originate from the South Pole-Aitken Basin [6].

With these samples we aim to (1) identify and classify meteorite fragments to temporally constrain the sources of projectiles hitting the Moon, with the aim to better understand the lunar impact record and provide constraints for models of Solar System evolution; (2) identify phases in impact melts and melt breccias that can be age dated using *in situ* U-Pb age dating techniques, with the aim to investigate the lunar impact flux; (3) Petrographically characterise the samples, and identify unusual or unique lunar rock types to constrain the heterogeneity and geological history of the lunar crust.

We have employed innovative analytical element mapping techniques to chemically fingerprint rock-types and phases of interest.

Method: We studied 30 µm thin sections of several Apollo 16 regolith breccia samples, and 100 µm thick sections of the Dhofar 925 and 961 stones. Each section was carbon coated and mapped completely, or in part, using the NASA JSC JEOL 7600f Field Emission Gun Scanning Electron Microscope (FEG-SEM) using a beam current of 15 nA, and an accelerating voltage of 25 to 30 nA. Our instrument has a faraday cup, so we can set the sample current at a known value, and check at the end of runs to gauge beam stability.

Images were collected at a magnification of ×150. The system was coupled to a Thermo Scientific EDS (electron dispersive spectrometer) with NSS software to derive <1 µm per pixel back-scatter electron (BSE) images (Fig. 1b) and spatially resolved element data (~2-3 µm per pixel). Each pixel of data that is collected retains a complete 0-20 KeV energy spectrum and, therefore, we were able to extract maps of C, O, Na, Mg, Al, Si, P, S, Cl, K, Ca, Ti, Cr, Mn, Fe, Co and Ni data.

Element distribution and concentration maps were then processed using the ImageJ software package to normalise each element to the same brightness scale, assign each element a colour, and recombine the colourised images to make qualitative false-colour element maps. These typically have large file sizes on the order of 10s to 100s mb of data, and contain a wealth of compositional information.

Identification of lunar lithologies and meteorite fragments: To investigate the distribution of rock-forming elements we use a colour scheme where Mg=green, Al=white, Si=blue, K=cyan, Ca = yellow, Ti = pink and Fe = red (modified from [7-10]). This colour scheme (Fig. 1c) is useful for initial reconnaissance petrographic characterisation and rapid identification of different lunar rock types: for example, (i) evolved lithologies, like granites, stand out in blue and cyan colours; (ii) lunar Mg-Suite lithologies (dunites, troctolites etc.) and magnesian (primitive) projectile fragments appear in green colours; (iii) mare basaltic material appears in red, purple and pink colours, (iv) lunar and meteoritic metal and sulphides appear bright red; (v) anorthositic fragments are dominated by white; (vi) impact melt breccias, which are composed of a mixture of mineral and glass phases, typically range from greenish-white to reddish white.

Identification of mineral phases suitable for in situ dating: To locate phases of interest for U-Pb dating studies (*i.e.,* phosphate and Zr-rich phases), we used a colour scheme of P = green, Ca = blue and Fe = red. These three elements were selected because there are EDS peak overlaps between P (K-α 2.015 keV), Zr (L-α 2.042 keV) and S (K-α 2.308 keV) that make it challenging to distinguish between phosphate, Zr-bearing, and sulphide phases. In this colour scheme, however, phosphate minerals will appear cyan as they contain P and Ca; sulphide minerals will appear yellow as they contain S and Fe; and zircon will appear green as it is not associated with either Ca or Fe (Fig. 1d).

Summary: These element maps are a valuable time-saving resource when studying complex brecciated samples. Examples are shown in Figure 1. We study these maps in detail and combine these data with optical and BSE images, electron microprobe and ion microprobe studies. So far we have used these techniques to identify potential extralunar material in

Apollo 16 regolith breccias [11], and characterise the petrography of lunar meteorites Dhofar 925 and 961 [12]; locating apatites, merrillites and zircons for U-Pb age dating (analysis in progress).

When we have finished studying the Apollo samples, we plan to make these element maps available to other lunar researchers who may be interested in investigating a particular phase or clast type to address their own lunar science goals. The maps will be a data resource that can be mined repeatedly to reveal new insights about the geological history of the Moon.

References: [1] Hörz F. et al. (1991) Chapter 4. *The Lunar Sourcebook.* pp. 61-120. [2] McKay D. D. et al. (1991) Chapter 7. *The Lunar Sourcebook.* pp. 265-356. [3] Lucey P. et al. (2006) Chapter 2. *Reviews in Mineralogy & Geochemistry*. 60, 83-219. [4] McKay D. D. et al. (1986) *LPS XVI*, D277-D30.3 [5] Joy K. H. et al. (In Press) *Geochimica et Cosmochimica Acta.* [6] Jolliff B. A. et al. (2008) *LPS XXXIX,* Abstract #2519. [7] Joy K. H. et al. (2008) *Geochimica et Cosmochimica Acta.* 72, 3822 - 3844 [8] Joy K. H. et al. (2011) *Geochimica et Cosmochimica Acta.* 75, 2420-2452. [9] Kearsley A. T. et al. *74th Annual Meeting of the Meteoritical Society*, Abstract #5280. [10] Snape et al. (2011) *Meteoritics and Planetary Science* doi: 10.1111/j.1945-5100.2011.01230.x. [11] Joy K. H. et al. (2011) *LPS XXII*, Abstract #2103. [12] Joy K. H. et al. (2011) *74th Annual Meeting of the Meteoritical Society*, Abstract #5100.

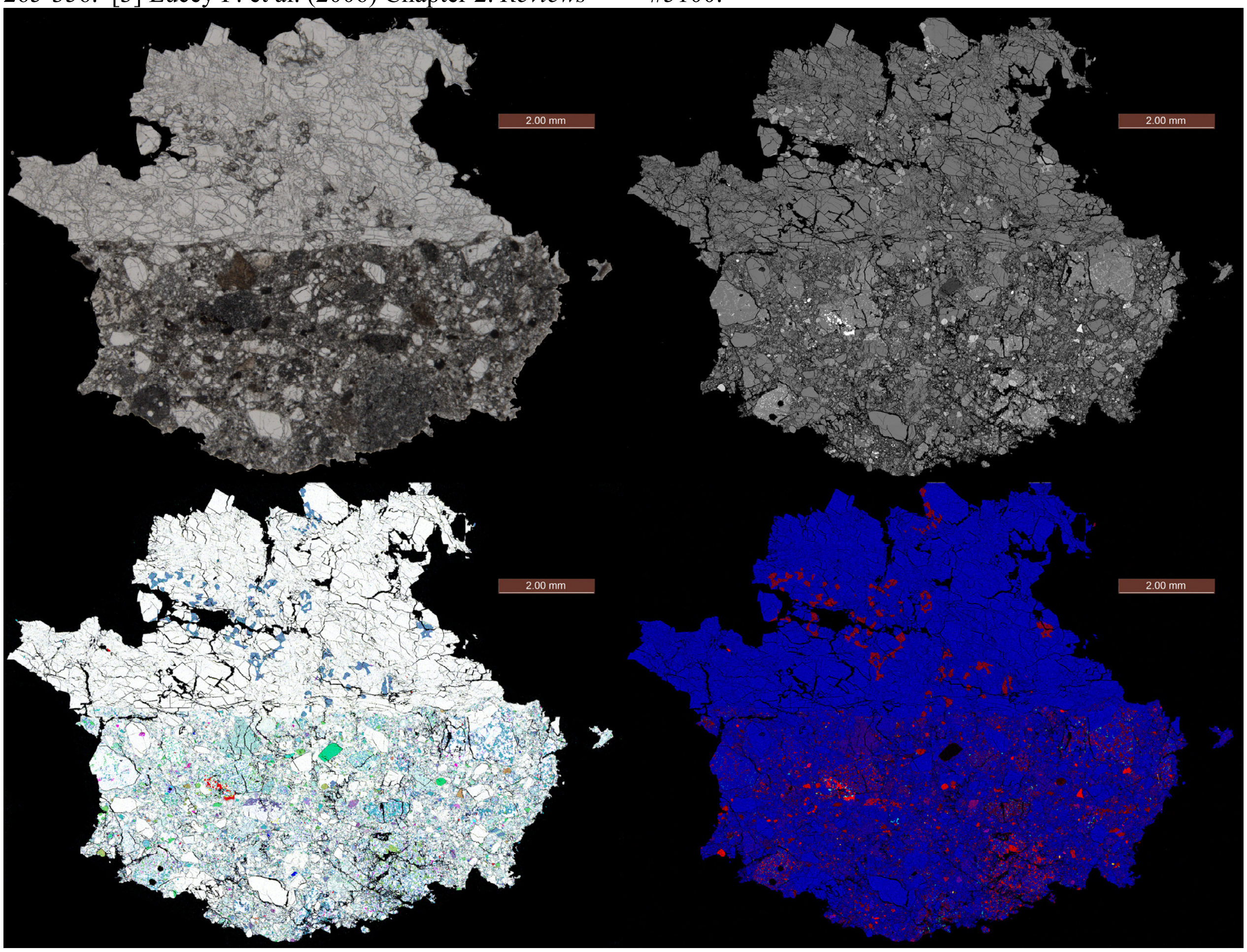

Figure 1. Surface area maps of Apollo 16 regolith breccia 66035,13. The sample is composed of a large ferroan anorthosite clast (top of sample) and a regolith breccia portion (base) of sample with many clasts including impact melts, mineral fragments and igneous lithics. (a) Top left: Optical image scan of the thick section surface. (b) Top right: Montaged area back scatter electron map. (c) Lower left: False colour element map where Al=white, Ca=yellow, Fe=red, Si=blue, Mg=green, Ti = pink and K=cyan (see text for details). The large bright green clast in this image is an ultra-mafic magnesian fragment (UMMF [11]), which is potentially non-lunar (primitive asteroid debris) in origin) (d) Lower right: False colour element map where Ca=blue, Fe=red and P=green. Apatites appear cyan colour, zircons green colour and sulphides are yellow (see text for details). Small apatite grains can be seen to a clast to the lower left of the sample centre.