CONSTRAINING THE COMPOSITIONAL VARIETY OF IMPACTORS AT 1AU OVER THE LAST ~3.5 GA: IN SITU IDENTIFICATION AND ANALYSIS OF >200 METEORITIC GRAINS IN A LUNAR SOIL

L. V. Forman[1], P. A. Bland[1], K. A. Dyl[1], L. Daly[1], C. G. Ryan[2] & J. Paxman[3]. [1]Dept. of Applied Geology, Curtin University, GPO Box U1987, Perth, WA, 6845, email: lucy.forman@postgrad.curtin.edu.au [2]Earth Science and Resource Engineering, Commonwealth Scientific and Industrial Research Organisation (CSIRO), Clayton, Victoria, Australia [3]Dept. of Mechanical Engineering, Curtin University, GPO Box U1987, Perth, WA, 6845.

Introduction: On their return from the moon, bulk chemistry of Apollo soil samples revealed an extralunar component, evidenced by an excess of siderophile and volatile elements consistent with primitive meteoritic material [1, 2]. Meteoritic material has been found *in situ* in regolith breccias [3, 4]. The most recent study involved a detailed analysis of 8 lunar regolith breccias and a lunar meteorite. 30 anomalous particles (identified by authors as ultramagnesian chondrule fragments) were identified by optical microscopy and SEM in older regolith samples; 5 more diverse projectile relics were found in younger breccias. But given its abundance in soils (in the case of Apollo 14 soil 14163, bulk chemistry indicated 2.5wt% of extralunar material is present) it is surprising that no detailed *in situ* characteristion of the meteoritic component in soils has been attempted. Aside from the Bench Crater [5] and Hadley Rille [6] meteorites, the collection of studied exogenous materials found within lunar settings, consists of a mesosiderite fragment [7] and iron meteorite fragments [8, 9]. The range of meteoritic hosts for the anomalous signature elements observed in bulk chemical analyses has not been determined.

In this study we apply a range of microanalytical techniques to the detection and characterisation of extralunar material in Apollo 14 soil 14163. It has been recording impacts for an extended period based on regolith grain size distribution [10], much longer than the expected half-life of asteroid families. As such, within the 2.5wt% extralunar component that is known to be present, we might expect to find fragments of meteorites derived from asteroids that are not currently delivering material to the Earth- Moon system.

Materials and Methods: Fine and coarse portions of 14163 were mounted onto cylindrical epoxy resin stubs of 25mm diameter. Fines were set in wells of approximately 50μm depth and both 3mm and 12mm diameters, whilst coarse seperates were mounted into wells 15mm in diameter and one grain deep.

For the purposes of initial analysis, a range of scanning electron microscopy (SEM) instrumentation was employed (Zeiss 1555 VP-FESEM, TESCAN VEGA3 & Phillips XL30 ESEM) at the Centre for Microscopy, Characterisation and Analysis (CMCA) at the University of Western Australia (UWA), and secondary electron, backscatter electron and energy dis-

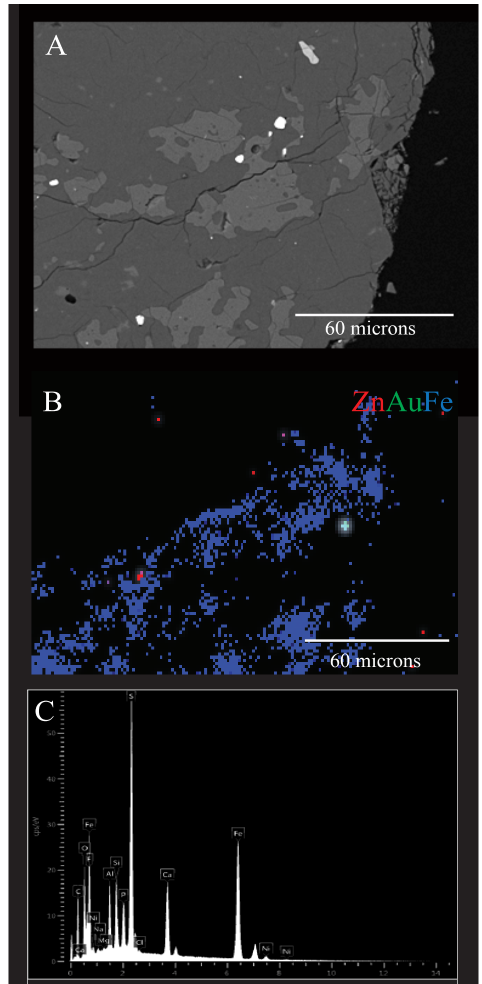

Figure 1- A: BSE image of suspect extralunar grains (CMCA)
B: Synchrotron image highlighting zinc-enriched and gold-enriched particles within the larger grain (Aus. Sync.)
C: EDS data of the same region showing an iron sulphide particle within the grain (CMCA)

persive X-ray spectroscopy (EDS) images were generated to examine the elemental make-up of the grains. In addition, the laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) facility at Curtin University, Western Australia, was evaluated as a trace element mapping tool.

For whole-sample mapping of trace and minor elements at high spatial resolution we employed the X-ray Fluorescence Microscopy (XFM) facility at the Australian Synchrotron, Victoria, Australia. This technique allowed us to create quantitative, micronscale resolution elemental maps from a variety of lunar fine and coarse samples of soil 14163. The Maia detector allows comprehensive and rapid data collection within a large energy range of 4-18 keV [11], detecting elements with Kα peaks within this range (including elements with an atomic number up to that of Zr-40). The 384-array Si-diode detector system is energy dispersive, meaning it allows this large range of minor and trace elements to be detected at high sensitivity, down to the 10s-1000s ppm scale depending upon peak energy [12], which is highly significant with respect to the initial goal of this research: identification and characterization of extralunar material. Post data collection spectral analysis was performed using the GeoPIXE software. GeoPIXE uses a dynamic analysis method allowing for spectral deconvolution and analysis of spatial distribution of trace and major elements [13].

Results: Using the Synchrotron facility and GeoPIXE software, areas and grains were highlighted that were highly enriched in siderophile, chalcophile or volatile elements. From the Synchrotron data alone, fine grained samples show approximately 50-100 anomalous grains per mount. Coarse grains often appear in the samples as microbreccias, and also provide some anomalous grains, with up to 30 grains/ mount.

Broad Classification	*Approximate Proportion*
Metals	60%
Sulphides	20%
Matrix	10%
Other	10%

Table 1- Approximate summary table of types of extralunar grains present within coarse samples of 14163.

'Hotspots' can be identified within the Synchrotron data, containing anomalously high siderophile, chalcophile and volatile elements. Characteristic elements were identified from previous research techniques, such as those outlined in [14-19], and based upon conclusions drawn from [20] a suite of suitable elements for identification of extralunar fragments was generated. These include Fe, Mn, Zn, Cu, Ni, Ge, Au, Ir, As and Pt; images of which can be seen in Figure 1.

Of the grains of the coarse samples examined thus far, Table 1 indicates the proportions of each broad compositional classification, of which the dominant classification is metallic. Fine grained soils contain a greater variety of grains; a study of which is ongoing.

Discussion: Our analytical protocol has detected large numbers of non-lunar fragments. Our preliminary analysis focused on the diagnostic elements listed above, restricting us to metal, sulphide, and volatile materials. Metallic grains are the most common of the extralunar grain types present in the coarse soils, simply due to the ease with which they are identified in the Synchrotron data and under SEM. However, these meteoritic materials will be associated with a larger fraction of silicates. Refining our data reduction protocol will allow us to characterise meteoritic silicates, extending the suite of identified extralunar particles beyond the ~200 grains already seen. This will be aided by the application of a new machine learning approach, which will enable multi-dimensional (25 element) automated identification and classification of grains.

Conclusions: This work has identified and analysed a large number of primarily metallic, sulphide and matrix grains within lunar soil 14163. Our technique, combining whole-sample mapping at high spatial resolution, with high sensitivity for a range of minor and trace elements, facilitates both the identification of anomalous grains and the generation of a detailed classification system. Future work will aim to further classify and characterise grains in terms of their origin, in a range of soils, based on geochemical signature and texture, supplementing Synchrotron analyses with additional techniques such as oxygen isotope analysis; TEM on FIB sections; and LA-ICP-MS mapping. The promising results from this initial study will contribute towards mapping the distribution of impact debris on the lunar surface, and constraining the compositional variety of impactors arriving at 1AU over the last ~3.5 Ga.

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