EXOTIC LITHOLOGIES AT THE APOLLO 12 SITE: EXAMINATION OF FINES FROM THE LUNAR SOIL SAMPLES 12023 AND 12003.

L. Alexander[1,2], J. F. Snape[2,3], K. H. Joy[2,4], I. A. Crawford[1,2], H. Downes[1,2] [1]Department of Earth and Planetary Science, Birkbeck College, University of London, UK, [2]Centre for Planetary Sciences, UCL-Birkbeck, London, [3]Planetary and Space Sciences, The Open University, Milton Keynes, UK, [4]SEAES, University of Manchester, Manchester, UK (l.alexander@bbk.ac.uk).

Introduction: The Apollo 12 mission landed in the Eastern region of Oceanus Procellarum (Mare Cognitum). Crater size-frequency distribution measurements by [1] indicate that some of the youngest lava flows on the Moon occur within the Oceanus Procellarum region and it is, therefore, possible that some younger, exotic fragments have been sampled by the Apollo 12 mission. Most basalts from the Apollo 12 site can be grouped into three main basaltic suites: olivine, ilmenite and pigeonite, based on their mineralogy and bulk composition [2,3,4]. An additional suite of feldspathic basalts consists of one sample only [4]. However, care needs to be taken with classification based on bulk chemical properties as many small samples are not representative of their parent rocks [4].

As part of a larger study of the diversity of basalts at the Apollo 12 site, we present petrological and geochemical results for basaltic chips from the Apollo 12 soil samples 12003 and 12023 with an emphasis on variations in major, minor and trace element mineral chemistry in order to identify samples which are representative of local flows and samples which are likely to be exotic material introduced by impacts.

Methods: All samples were cut in half for radioisotope dating and mounted in epoxy resin. Samples 12003,308 and 12023, 155 consisted of a variety of chips which were labelled accordingly (e.g. 12023,155_1A, 2A etc). Samples were analysed with a JEOL JXA-8100 electron microprobe with an Oxford Instrument INCA energy dispersive system (EDS) to produce back scattered electron (BSE) images and elemental maps (Fig. 1). Bulk chemical compositions were calculated from multiple EDS raster beam analyses (RBA) and corrected for differences in phase densities in accordance with [5]. This method has been previously tested on known compositions and found to be in good agreement [6].

Results:

Bulk Chemistry. With the exception of 3 coarse-grained, possibly non-representative, fines, all samples are low-Ti basalts (bulk rock 1-6 wt% TiO_2), which are typical of lava flows sampled at the Apollo 12 site [7]. The bulk compositions of most of the samples are consistent with those of olivine, pigeonite and ilmenite basalts. Four samples (12023, 155_4A and 5A, and 12003, 308_1A and 314_D) are compositionally similar to feldspathic basalts given the high concentrations of Al_2O_3.

Chemistry of mineral phases. The pyroxene grains show a range of compositions ($En_{0-67}Fs_{15-90}Wo_{3.7-41}$) with zoning from Mg-rich cores to progressively Fe-richer rims, with extreme Fe-rich pyroxferroite rims in some samples. Plagioclase feldspar is mostly anorthitic (An_{77-94}). Olivine compositions typically range from Fo_{34-74}, but the widest range and the lowest Fo contents are seen in 12003,308_2A (Fo_{3-73}). Olivine Ti/V ratios are similar for most samples (2 to 3), although higher values are seen for coarser grained samples due to generally lower V contents. Spinel compositions range from chromite to ulvöspinel ($2Ti_{10-97}Al_{2-29}Cr_{0.4-69}$) following a typical mare basalt fractionation trend [8].

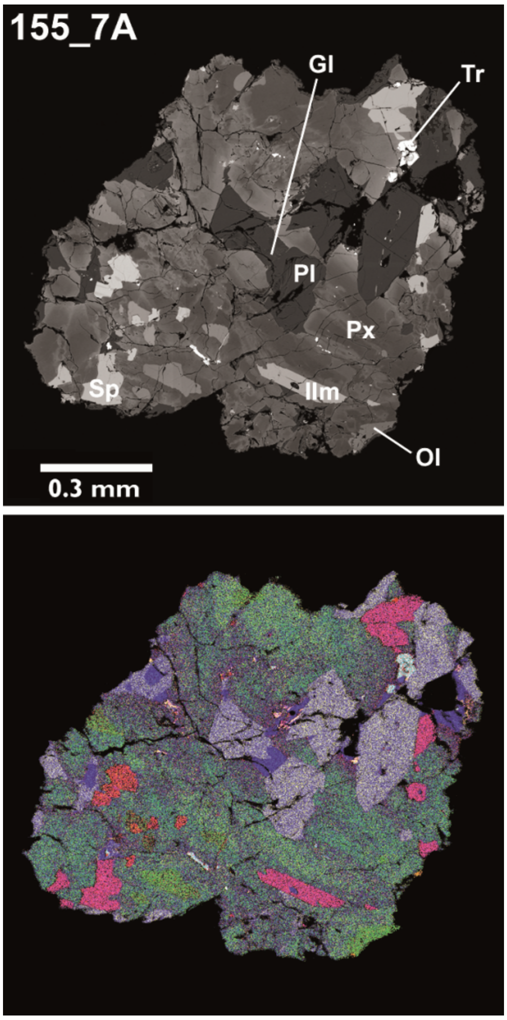

Figure 1: Back-scattered electron (BSE) image and false colour element map of sample 12023,155_7A, one of the samples which may be exotic to lava flows at the Apollo 12 site. Colours represent concentrations of different elements: Si = blue, Fe = red, Mg = green, Ca = yellow, Al = white, Ti = pink and Cr= orange. Annotations are: Px

= pyroxene, Ol = Olivine, Ilm = ilmenite, Pl = plagioclase, Sp = spinel, and Gl = glass.

Discussion: The small sizes of the samples means that they may not be representative of their parent rock and their bulk chemical properties cannot be relied on for classification or comparison, particularly in the case of the coarse grained samples. Where samples are fine-grained or vitrophyric, we can reconstruct the equilibrium parent melt Mg# using the composition of the most primitive olivine [9, 10, 11] and appropriate mineral-melt Kd values [12]. Other methods can help to categorise the samples. It has been suggested [13] that olivine trace element compositions, and particularly Ti/V ratios discriminate between the basalt groups . While most samples have bulk compositions, modal mineralogies and mineral chemistries consistent with the previously identified olivine, pigeonite or ilmenite Apollo 12 basalt lithological groups, there are several notable exceptions:

Samples 12003,308_3A, 12003_316 and 12003_311 have high modal abundances of olivine and low modal abundances of pyroxene, although the coarse grain size (up to ~0.8 mm) indicates that they may not be representative. However, in addition these samples have olivine with higher Ti/V ratios and lower Co concentrations than other Apollo 12 samples and may represent material contributed by a separate lava flow.

Sample 12023,155_1A has unique mineral compositions in olivine and spinel which indicates that it is not related to the other samples. The olivine grains analysed have lower concentrations of Cr_2O_3 at high Mg#, with low Ni and Mn concentrations (41 to 55 ppm Ni, 2400 to 2556 ppm Mn). Plagioclase compositions are less anorthitic and the spinel grains have higher Al_2O_3 concentrations. Ti/V ratios in olivines are high (Fig. 1), which indicate that this sample is similar to Apollo 12 ilmenite basalts [13]. However, compositional equilibration is believed to have affected the chemistry in this coarser-grained sample. Given the differences in mineral composition, we believe that 155_1A may originate from a different parent melt to other Apollo 12 basalts.

Three samples (12003,314_D; 12023,155_4A and ,155_5A) are identified as potential feldspathic basalts. Given that other feldspathic basalt fragments from the Apollo 12 site have been identified [14, 15], these may represent additions to this lithological group. If this is the case, then it indicates that feldspathic basalts may not be exotic to the Apollo 12 site [4] but may instead represent a local flow, possibly underlying the landing site [15]

Sample 12023,155_7A (Fig. 1) shows a wider range of plagioclase compositions ($An_{76-93}Or_{0-4}$) and a different crystallisation trend of Mg# vs. An# in plagioclase to the other samples. This sample is most similar to the ilmenite basalts in terms of its bulk chemistry (after [4]) and Ti/V ratio of olivine (after [13]) but it has distinctly different plagioclase chemistry and crystallisation trends to the other samples. It shows similarities to Apollo 14 high-Al basalts in terms of An# in plagioclase [16, 17], and Fo#, Ti/V ratios and Sc, Ni and Co concentrations in olivine [13]. This sample is tentatively identified as an exotic fragment which may represent a lithology more similar to the Apollo 14 basalts than the Apollo 12 basalts.

Sample 12023,155_11A contains pyroxene that is compositionally distinct from other samples. Although the pyroxene is zoned ($En_{0-43}Fs_{40-85}Wo_{12-33}$), no Fe-poor pyroxene is present (Mg# <50 in all measurements). Due to the similarity in crystallisation trends and mineral chemistries to those of Fe-rich late-stage minerals in other samples, we conclude that sample 155_11A is likely to represent a more fractionated Apollo 12 basaltic melt, rather than being exotic to the Apollo 12 site.

Future work: Further work, including Ar-Ar dating of the remaining samples (see [18, 19] for initial results) will further help to constrain the origin of these samples and others analysed as part of our wider study.

Acknowledgments: We are grateful to Dr. Andy Beard for his assistance with electron microprobe analyses and to Dr. Martin Rittner for his assistance with LA-ICP-MS analysis.

References: [1] Hiesinger, H. et.al. (2003) *JGR, 108*, E7. [2] James O. B. and Wright T.L. (1972) Bull. *Geol. Soc. Am., 83*, 2357-2382. [3] Rhodes J. M. et al. (1977) *LPS IIX*, 1305-1338. [4] Neal C. R. et al. (1994) *Meteoritics, 29*, 334-348. [5] Warren P.H. (1997) *LPS XXVIII*, Abstract 1497. [6] Snape, J. F. et. al. (2011) *LPS XLII*, Abstract 2011. [7] Neal C. R. and Taylor (1992) *GCA, 56*, 2177-2211. [8] Reid, Jr. J.B. (1971) EPSL 10: 351-356 [9] Roeder, P.L. and Emslie, R.F. (1970) *Contrib. Mineral. Petrol. 29*, 275. [10] Dungan, M. A. and Brown, R. W. (1977) *LPS VIII*, 1339-1381. [11] Joy, K. H. et.al. (2008) *GCA, 72*, 3822-3844. [12] Longhi, J. et. al. (1978) *GCA, 42*, 1545-1548. [13] Fagan, A. L. et. al. (2013) *GCA, 106*, 429-455. [14] Korotev, R.L., Joliff, B.L., Zeigler, R.A., Seddio, S.M., Haskin, L.A. *GCA* 75: 1540-1573, 2011. [15] Snape, J.F., Alexander, L., Crawford, I.A.C., and Joy, K.H. *LPSC XLIV* #1044. [16] Neal, C.R., and Kramer, G.Y. *Am. Mineral. 91*: 1521 – 1535, 2006. [17] Hui, H., Oshrin, J.G., and Neal, C.R. *GCA 75*: 6439 – 6460, 2011. [18] Snape J. F. Burgess R. Joy K. H. Ruzie L. Crawford I. A. *LPSC XLV* #1974. [19] K. H. Joy, R. Burgess, L. Ruzie, P. Clay, J.F. Snape, L. Alexander, I.A. Crawford. (2014) *Goldschmidt 2014* #1429.