**TRACE-ELEMENT SYSTEMATICS OF FAN CLASTS WITHIN APOLLO 16 REGOLITH BRECCIAS: IMPLICATIONS FOR UNDERSTANDING THE EVOLUTION OF THE LUNAR HIGHLANDS CRUST.**

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**Introduction:** In recent years, a wealth of mineral trace-element chemistry for lunar highland lithologies have been reported for lunar meteorites (e.g., [1, 2]), however, relatively few trace-element analyses have been reported from the Apollo collections [3, 4]. In this study, we present plagioclase trace-element systematics from Ferroan Anorthosite (FAN) clasts hosted within a suite of Apollo 16 regolith breccias, to explore the extent to which Apollo FANs display chemical heterogeneities, and test to what extent small (< 1 cm) clasts can be used to gain information about their parent lithologies

**Compositional heterogeneity of lunar primary crustal rocks:** Studies have noted that some chemical differences are present between the Fe-richer Apollo FANs and Mg-richer anorthosite (MAN) clasts in lunar meteorites, that are thought to have originated from the lunar farside [2, 5, 6]. This led workers to challenge the idea of a signal plagioclase flotation event during the crystallization of the lunar magma ocean (LMO) (e.g., [5, 7, 8]). However, some have questioned the extent to which the modal mineralogy of small clasts within breccias represent their parent lithologies, further questioning the role that small clasts can play in identifying new highland rock types such as the MANs [9]. Trace-elements have the potential to circumvent these issues, due to their generally incompatible nature within the main rock-forming minerals. Not only can trace-elements distinguish between source lithologies [2], but also reveal the extent of geochemical diversity within lithological groups [1, 2, 4]. Here, we used extended mineral trace-element abundances (including HFS, LILE, REE), combined with reported mineral trace-element chemistry from the Apollo 16 FAN hand samples to fully investigate the extent of chemical variability within FAN clasts, enabling the assessment of LMO crystallisation models.

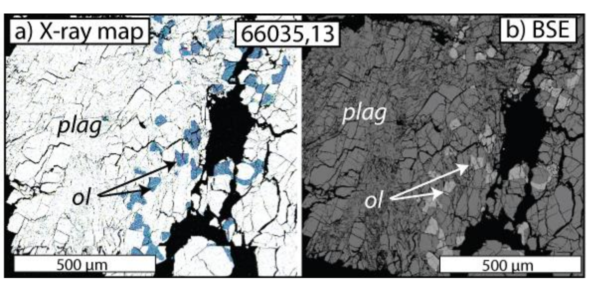


**Fig. 1**: Representative combined element X-ray map (a) and BSE image (b) of an FAN clast from regolith breccia 66035,13. White represents plagioclase and blue olivine.

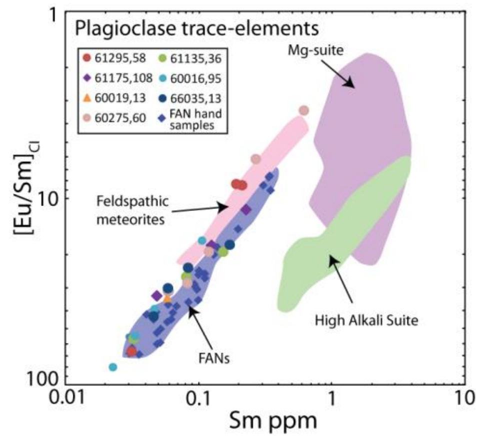


**Fig. 2:** Plots of plagioclase Eu/Sm vs. Sm for clasts in this study compared with lunar highland lithologies [1- 3, 16].

**Methods and Results:** Major-elements were obtaining using a Camaca SX100 EMP using the methods described in [11], and X-ray element maps were determined on a Phillips FEI XL30 Environmental Scanning Electron Microscope-Field Electron Gun (ESEM-FEG) at the University of Manchester. Trace-element abundances were determined on an ASI RESOlution excimer laser ablation system (64 µm spot size) coupled to an Analytic Jena Plasma Quant MS Elite ICP-MS at the University of Portsmouth.

Polymineralic clasts investigated here range in size from ~ 1 cm to ~250 µm, and consist of plagioclase, clinopyroxene, and/or olivine of varying size and proportions (**Fig. 1**). Clasts with clear igneous textures (i.e., minerals meeting triple junctions) and lacking Fe-metal blebs were preferentially targeted, however, in some cases, particularly for the smallest clasts, textures are ambiguous to distinguish from the poikiloblastic texture typically associated with granulites or phyric impact melts. Plagioclase major-element (e.g., An% vs. Mg#, [11]) and trace-element (e.g., Sm/Eu vs. Eu; [2]) systematics can be used to identify the parent lithologies of the smallest clasts and mineral fragments (**Fig. 2**). All samples investigated here, regardless of their petrographic classification (i.e., mafic minerals > 5 modal %), are most similar to the anorthosite field in terms of plagioclase trace-elements (**Fig. 2**). The An% content of the plagioclase investigated ranges from 94 to 98, whereas MgO and FeO range from 0.03 to 0.50 wt. % and 0.06 to 1.45 wt. % respectively, falling within range of reported pristine FAN hand specimen samples [2, 12]. The REE abundances encompass the range reported for the Apollo 16 FAN hand samples

[4], however, **Fig. 2** illustrates the incompatible element ratios bridge the gap between the Apollo 16 FAN hand samples and the anorthite clasts sampled from lunar meteorites. Clasts range in $La/Sm_{CI}$ from 0.7 to 5.4, Eu/Eu* range from 4.79 to 119.

**Discussion:** The plagioclase siderophile element abundances of the clasts investigated here overlap reported pristine FAN hand samples, indicating they are 'pristine' clasts [12], and are not impact melts. The suite of plagioclase crystals investigated here display correlations between ratios that are controlled by fractionation crystallisation (Sr/Y, Eu/Y) indicating this suite samples the crystallised products of the LMO at different crystallisation %. Samples also display variations in incompatible element ratios (e.g., La/Sm, Th/Sm, Zr/Y). Such ratios are not modified by crystallisation, which is reflected by the lack of correlation with compatible elements or Sr/Y. To account for this variation, the composition of the melts in equilibrium with individual plagioclase can be calculated. To achieve this, the plagioclase-melt partition coefficients were derived for relevant An% values using the formulations of [13].

Reconstructed incompatible element ratios do not display correlations with compatible elements, suggesting the variations observed are not the result of combined assimilation (of material chemical very difference to the FAN parent melts, e.g., KREEP) and fractional crystallisation (AFC). Trace-element ratios that are typical used to track KREEP (e.g., Th/Sm) display weak correlations with LREE enrichments (**Fig. 3**). Due to the very elevated incompatible element abundances of KREEP relative to the FANs (KREEP Th/Sm ~0.45 vs. FAN Th/Sm <0.001) and overlapping La/Sm ratios, bulk mixing between KREEP and FANs have very step (near vertical) trajectories. Bulk-mixing models (black line, **Fig. 3**) indicate that < 0.5% contribution from a KREEP (using the KREEP composition of [14], and assuming the lowest Th/Sm reported from the suite best represents a 'pristine' chemically unmodified FAN parent melt (61135,36)) can account for the range of Th/Sm values. However, the occurrence of a shallower trend with respect to the KREEP mixing trend, together with the general lack of correlations between incompatible element ratios suggests that these variations could reflect intrinsic source heterogeneities. Alternatively, impact related thermal resetting/re-equilibration can be difficult to rule out, some trace-elements (such as Mg and Fe) are known to have been affected by diffusion [1]. The lack of correlation between these elements and ratios such as Th/Sm or La/Sm indicates that the ratios investigated here may not have been significantly affected by sub-solidus thermal diffusion effects.

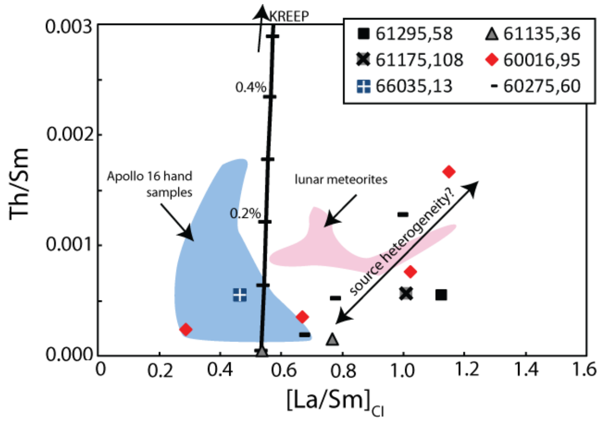


**Fig. 3:** Reconstructed Th/Sm vs $[La/Sm]_{CI}$ for plagioclase in anorthositic clasts (this study), hand specimen FAN rocks and in feldspathic lunar meteorites.

**Implications and summary:** The identification of potential source heterogeneities within the Apollo FAN suite clasts (here) and hand specimen samples [4] have implications for containing LMO crystallisation models. Modification of the 'classic' single event plagioclase flotation model has been proposed over the past few years. These include serial magmatism of discrete plagioclase plutons [5], and asymmetric plagioclase flotation [3, 7], both of which account of chemically diversity of anorthites lithologies on a global scale. The identification of source heterogeneities within the Apollo 16 FAN suite could support the suggestion indicate that the nearside LMO was chemically heterogeneous on localised scales (i.e., within the source region that contributed material to the Apollo 16 landing site), potentially reflecting incomplete equilibration of the magma ocean following overturn events (e.g., [15]).

Overall, investigations FAN clasts within Apollo 16 regolith breccias greatly expand the trace-element systematics of Apollo 16 FANs available within the literature, and highlight the value of trace-element for investing the petrochemical history of the FAN samples, particularly in cases were only small clasts/mineral fragments are available. Furthermore, variations of trace-element systematics provide an important opportunity to test LMO crystallisation models [2].

**References:** [1] Cahill et al., (2004) *MaPS, 39*, 503-529. [2] Russell et al., (2014) *Phil. Trans. R. Soc. 372*, 20130241. [3] Floss et al., (1998) *GCA, 62*, 1255-1283. [4] Papike et al., (1997) *GCA, 61*, 2343-2350. [5] Gross et al., (2014) *EPSL, 388*, 318-328. [6] Takeda et al., (2006) *EPSL, 247*, 171- 184. [7] Arai et al., (2008*) Earth, Plan. Space, 60*, 433-444. [8] Ohtake et al., (2013) *Nat. Geo. 5*, 384. [9] Warren (2012) *2nd Lunar Highlands Conference* abstract #9034. [10] Joy et al., (2015) *MaPS*, *50*, 1157-1172. [11] Warren (1993) *Am. Min., 78*, 360. [12] Warren & Wasson (1977) *LPSC, 8*, 2215-2235. [13] Aigner-Torres et al., (2007) *Contrib. Min. Pet., 153*, 647-667. [14] Warren & Wasson (1979) *Rev. Geophys. 17*, 73-88. [15] Hallis et al., (2014) *GCA, 134*, 289-316. [16] Shervais & McGee (1999) *Am. Min., 84*, 806-820.