**CONSTRAINING APOLLO GRANULITE PROTOLITHS USING PLAGIOCLASE TRACE ELEMENT CHEMISTRY.** J. F. Pernet-Fisher[1*], K. H. Joy[1], M. Hartley[1], and R. Tartèse[1]. Department of Earth and Environmental Sciences, University of Manchester, M13 9PL, UK. (*john.pernet-fisher@manchester.ac.uk).

**Introduction:** The lunar granulite suite represents the product of high temperature (> 1000 ºC) re-equilibration of crustal rocks. Potential heat sources are argued to be associated with impact melts sheets, magmatic bodies, or from geothermal gradients within the lunar crust [e.g., 1-3].

Elevated siderophile element abundances reported for the granulite suite indicate that the protolith likely represents impact modified highland lithologies such as impact-melt breccias found around impact craters/basins or within ejecta blankets, impact melt sheets themselves, or impact contaminated mega-regolith [2,3]. The mineral and bulk rock major element compositional similarity of the granulite suite with pristine highland rocks have been used as an indicator of which crustal lithologies contributed to the granulite protolith [e.g., 4-6]. On this basis, Apollo granulites are divided into ferroan and magnesian sub-types. The Apollo ferroan anorthosite suite (FAN) is believed to contribute to the ferroan granulite protoliths [4], whereas a Mg-suite-like plutonic lithology [4] or a magnesian anorthosite [5] have been suggested to contribute to the magnesian granulite protoliths. Magnesian anorthosites are not very well represented by the existing sample collections; thus, constraining which highland lithologies contribute to the granulite protoliths is important as they provide additional data on the compositional diversity of the lunar crust. In turn, this enables modeling of lunar differentiation and crust building to be better constrained [2,4]. To further establish the range of highland lithologies that contributed to the Apollo granulite protoliths, we report here plagioclase trace element chemistry from Apollo 15, 16, and 17 granulites.

**Methods:** Plagioclase major element chemistry was obtained using a Cameca SX100 electron microprobe at the University of Bristol. Trace-element abundances were obtained using a Teledyne Analyte Excite+ excimer laser coupled to an Agilent 8900 ICP-MS at the University of Manchester. Samples were ablated using a circular spot size ranging from 40 to 85 µm.

**Results:** The samples investigated here include both ferroan and magnesian subtypes. Ferroan granulites (77017, 78155, 67749, 67615, 67485, 15418) display a limited range of plagioclase An values (94 to 96) and relatively ferroan pyroxene Mg# (63 to 65), overlapping FAN plagioclase compositions, whereas the magnesian granulites (79215, 67415, 67955, 76235, 72559) display a larger range of An values (90 to 95)

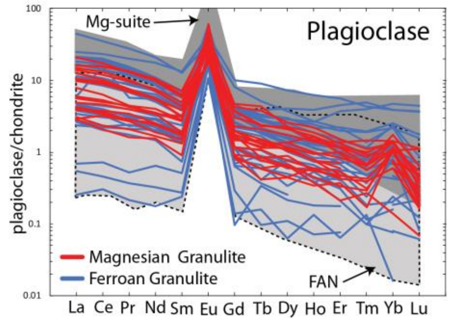


**Figure 1:** Plagioclase chondrite-normalised REE profiles for ferroan (blue) and magnesian (red) granulites. Comparative data for Mg-suite (dark-grey) and FAN (light grey with dashed outline) rocks are plotted. Data from [9, 11].

and display higher Mg# in pyroxene (75 to 81) overlapping Mg-suite-like compositions.

Plagioclase in ferroan granulites are characterized by large variations of REE abundances and display chondrite-normalised REE profiles that range from broadly flat profiles (i.e., La/Sm ~1) to slight LREE enrichments (La/Sm ~ 4.9) (Fig. 1). Plagioclase in magnesian granulites have more restricted REE abundance, display LREE enrichment, with La/Sm ranging from 1.5 to 4.1 (Fig. 1). Ferroan and magnesian granulite plagioclase REE profiles overlap the range of values reported for plagioclase from both Apollo/lunar meteorite FAN samples [9,10] and Mg-suite lithologies [11]. We find no systematic differences between samples from different Apollo landing sites.

**Metamorphic modification**: Prior to assessing plagioclase mineral chemistry in the context of potential protoliths, the effects of mineral modification during metamorphism must be understood. The high (> 1000 ºC) metamorphic temperatures can act to modify mafic mineral chemistry by element diffusion within grains, and across grain boundaries. Indeed, major element compositional zoning profiles in olivine and pyroxene crystals have been used to estimate re-equilibration timescales (on the order of hundreds to tens of thousands of years) for the granulite suite [1,3]. Plagioclase trace-element mineral chemistry has an advantage over other mineral phases or the bulk chemistry as it is largely unaffected by thermal re-equilibration or by secondary modification (i.e., the impact events that brought the granulites to the lunar surface) [8, 9]. Indeed, major or trace element zoning has not previously been reported for granulite plagioclase, however, complete re-equilibration of pre-existing trace-element zoning is unlikely due the very long (> Myr) timescales of trace-element diffusion in plagioclase [12]. This is reflected by sharp chemical contacts between the plagioclase and surrounding mineral phases [3]. Therefore, plagioclase trace element abundances are likely to still reflect the trace-element systematics of their original protolith.

**Granulite Protolith:** To help constrain which highland rock lithologies potentially contributed to the granulite protoliths, we used plagioclase Eu-anomaly (inferred by Eu/Sm) vs. incompatible trace element abundances (represented by Sm). These are good discriminators of lunar highland rocks, with different rock suites forming distinct sub-parallel linear arrays (Fig. 2; [10,13])

Plagioclase from Apollo ferroan granulites (blue symbols in Fig. 2) and the Apollo magnesian granulites (red symbols in Fig. 2) do not fall on a single sub-parallel trend. Rather, they extend from relatively incompatible element poor compositions (for a given Eu/Sm) similar to crustal anorthosites (grey field in Fig. 2 encompassing Apollo FAN and anorthosite clasts within meteorites), to more incompatible element enriched plagioclase compositions (for a given Eu/Sm) similar to that of the Apollo Mg-suite. By contrast, plagioclase reported from magnesian granulites within lunar meteorites (purple symbols, Fig. 2; [6]) display a smaller range of compositions, with relatively incompatible element poor compositions (for a given Eu/Sm) overlapping the anorthosite field.

Whereas trace-element variation in plagioclase grains is observed between samples (Figs. 1 and 2), ferroan granulite 77017 contains plagioclase that range from FAN-like compositions to Mg-suite-like compositions within a single sample. This clearly highlights the heterogeneous polymict nature of the protolith rocks of some samples in the granulite suite.

Together, our data indicate that Apollo ferroan granulite samples 78155, 15418, 77017, Apollo magnesian granulite samples 76235 and 79215, and lunar meteorite magnesian granulite samples contain plagioclase compositions that are consistent with a protolith that contained a significant contribution from crustal anorthosites, irrespective of their mineral major element defined groups (magnesian vs. ferroan).

The remaining samples contain plagioclase that are more incompatible element enriched (for a given Eu/Sm) than crustal anorthosites, in some cases overlapping Mg-suite compositions (67415, 67955, 67615, 67749). While at face value, Figure 2 indicates that the plagioclase from these sample are more similar in composition to the Mg-suite than crustal anorthosites, reported literature bulk trace element data preclude the involvement of an Apollo Mg-suite contribution. Higher bulk rock Th/Sm ratios relative to the Mg-suite were reported by [4] in similarly incompatible element enriched Apollo magnesian granulites. Such Th/Sm ratios also cannot be accounted for by mixing any known pristine highland lithology with Apollo-like KREEP-rich impact melts. This lead [4] to suggest that the igneous contribution to the magnesian granulite protolith represents an un-sampled highland lithology. On this basis, it is likely that such a lithology is also contributing to the protolith of some of both the ferroan and magnesian granulites that display relative incompatible element enrichments.

**Conclusion:** It is clear from this sample set that the traditional major element groupings alone (i.e., magnesian vs. ferroan) are not sufficient to adequately constrain granulite protolith lithologies. Regardless of the precise highland lithologies that contribute to the granulite protoliths, our plagioclase trace element data indicate that *both* Apollo ferroan and magnesian granulites have impact-related protoliths that source a mixture of highland lithologies from the central region of the lunar nearside. This contrasts with their lunar meteorite equivalents [5, 6] that appear to be dominated by magnesian anorthositic protoliths. It is unclear if this is a result of sampling bias or if this reflects differences in lithological diversity within the lunar crust at different geographic locations across the Moon.

**References:** [1] Cushing et al. (1999) *MaPS*, 34, 185-195. [2] Pernet-Fisher & Joy (2021) *J. Geol. Soc*, 178, 6-16. [3] Hudgins et al. (2011) *Am. Min*. 96, 1673-1685. [4] Korotev et al., (2003) *GCA*. 67, 4895–4923. [5] Treiman et al. (2010) *MaPS*. 45, 163-180. [6] Kent et al., (2017) *MaPS*. 52, 1916-1940. [7] Lindstrom & Lindstrom (1986) *J. Geo. Res*, 91, 263-276. [8] Pernet-Fisher et al. (2017) *Sci. Rep*. 7, 1-12. [9] Pernet-Fisher, et al. (2019) *GCA*, 266, 109-130. [10] Russell et al., (2014) *Phil. Trans. R. Soc*. A372, 20130241. [11] Papike et al. (1996) *GCA*, 60, 3967-3978. [12] Cherniak (2003) *Chem. Geol*. 193, 25-41. [13] Joy (2013) *LPSC* #1033.

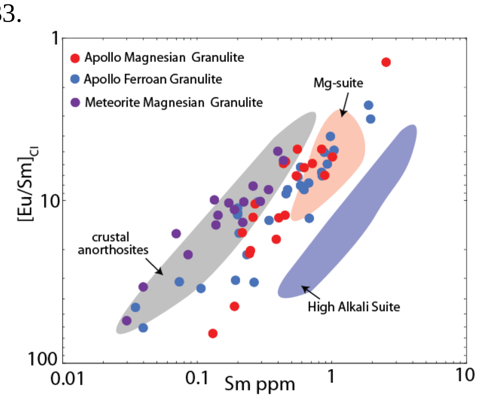


**Figure 2:** Plagioclase $[Eu/Sm]_{CI}$ vs. Sm ppm. Pristine highland rock suites form sub-parallel arrays [8, 9]. Apollo ferroan granulites (blue) and magnesian granulite (red). Lunar meteorite magnesian granulite data (purple) from [5,6].