LUNAR ANORTHOSITES AS TARGETS FOR EXPLORATION. M. D. Norman[1,2], [1]Lunar and Planetary Institute, Houston TX 77058 USA, [2]Research School of Earth Sciences, Australian National University, Canberra ACT 0200 Australia (Marc.Norman@anu.edu.au).

Introduction: The discovery of anorthosite was arguably the second major surprise to come from the first sample return mission to the Moon, the first being the extraordinarily high TiO_2 contents of Apollo 11 mare basalts. The juxtaposition of these two extreme lithologies formed the cornerstone of our current understanding of the Moon as a highly differentiated body composed predominantly of igneous cumulates.

In the context of a global exploration program, it will be useful to distinguish two fundamental classes of anorthositic lithologies on the Moon: (1) igneous anorthosites and (2) polymict breccias with anorthositic mineralogy and bulk compositions. The occurrence and distribution of these two types lithologies can be used to address distinct processes and a variety of science questions.

Igneous anorthosites. Despite the mineralogical simplicity of igneous lunar anorthosites (most are >99% plagioclase+pyroxene), their geochemistry is surprisingly complex in major and trace element compositions. A simplified generic classification of igneous lunar anorthosites might recognize (1) ferroan anorthosites, and (2) anorthosites associated with the Mg-suite of highlands cumulates and related lithologies.

Ferroan anorthosites are the quintessential highlands crustal cumulate. Type examples, collected mainly at the Apollo 15 and 16 sites, are composed of ≥98% plagioclase with a narrow range of anorthite contents (An_{95-98}). Mafic phases are predominantly opx although some examples have olivine > pyroxene. In contrast to the plagioclase compositions, mafic phases have a relatively broad range of major element compositions with Mg# ~50-75.

In addition to the highly anorthositic type examples, the 'ferroan anorthositic suite' also includes a variety of related, generally more mafic lithologies. James [1] recognized two varieties of troctolitic anorthosite, one with 10-20% mafics having Mg# at the upper end of the range for ferroan anorthosite (66-75), and a second, somewhat less-mafic variety with lower Mg# (50-63). A troctolitic anorthosite clast in the Dhofar 489 lunar meteorite with Fo_{79} olivine [2] may represent an extension of James' high-Mg# group. Noritic anorthosites with px > olivine and relatively abundant cpx have also been recognized and linked to the ferroan anorthositic suite using major and trace element compositions [3, 4, 5]. James [1] also recognized a slightly sodic variety of ferroan anorthosite based on their slightly lower An contents of the plagioclase (An_{94-95}).

Ferroan anorthosites are the best candidates for a primitive flotation crust from a lunar magma ocean [6, 7], but we do not yet have a detailed petrogenetic model that explains the petrologic and geochemical diversity of the ferroan anorthositic suite. Trace elements that are concentrated in plagioclase (Sr, Eu, Ba, Ga), and therefore likely to be robust against subsequent disturbance, are broadly consistent with crystallization from an evolving magma ocean having initially chondritic relative abundances of refractory lithophile elements [5, 8, 9]. The REE compositions of 'typical' or 'main group' ferroan anorthosites are also consistent with accumulation from a moderately evolved magma ocean [7], despite potential complications from disturbance by shock and/or metamorphic re-equilibration during slow cooling.

The petrogenesis of other subgroups of the ferroan anorthositic suite appears to be more complex. The more mafic varieties tend to have anomalously high contents of REE and other incompatible elements [5,7], possibly indicating a greater proportion of trapped melt or contamination with more evolved melts. Cooling rates estimated from pyroxene exsolution lamellae also indicate a range of emplacement conditions within the lunar crust. At least some of the ferroan anorthosites likely formed depths of 10-20 km [10] whereas others cooled much more rapidly [5], possibly in localized, near-surface plutons [4].

Crystallization ages of ferroan anorthosites are not well established. Their Sr isotopic compositions are consistent with early crystallization from a primitive magma but redistribution of Rb by impact metamorphism has obscured this record [11]. ^{147}Sm-^{143}Nd mineral isochrons are restricted to examples with atypically high abundances of mafic minerals, and have yielded a range of apparent ages extending from 4.29-4.54 Ga [5]. The petrologic or geochronological significance of this range is also not well understood. If the isochron ages are real they may reflect a complex petrogenesis of ferroan anorthositic suite rocks that includes post-magma ocean magmatism [11] or compositional modification during tectonic emplacement and/or re-crystallization [12]. Alternatively, the apparent range of Sm-Nd isochron ages may be an artifact of impact metamorphism. A preferred age of 4.46 $\pm$ 0.04 Ga can be calculated based on Sm-Nd systematics of mafic phases, on the assumption these are more resistant to disturbance than the coexisting plagioclase [5]. However, this analysis assumes that the four samples for which Sm-Nd mineral data exists are related to a common magmatic system. A peculiar characteristic of some ferroan anorthosites is the apparent disequilibrium between REE abundances in plagioclase and co-existing pyroxene [7]. The reason for this decoupling is not understood, but it may have significant implications for attempts to obtain Sm-Nd crystallization ages of ferroan anorthosite, using mineral isochrons.

Alkali and Mg-suite anorthosites. Other types of igneous lunar anorthosite have mineral and chemical characteristics indicating crystallization from KREEP-rich or Mg-suite magmas. These include the highly evolved alkali anorthosites [13] and small samples of anorthosite that have petrologic and geochemical affinities with Mg-suite troctolites [14]. These types of anorthosite are most abundant in the Apollo 12 and 14 collections, consistent with a close petrogenetic association with KREEP.

Alkali suite anorthosites are distinguished from ferroan anorthosites by their more sodic plagioclase (An_{76-86}), compositional zoning in the plagioclase (normal and reverse), and igneous textures indicating predominantly near-surface crystallization [12,14]. Mafic phases are sparse and have relatively low Mg# (50-70). The Mg-suite anorthosites have mineral compositions similar to those of Mg-suite troctolites (An_{94-97}, Fo_{84-90}) [14]. These small fragments may represent fine-scale layering within an Mg-suite pluton rather than bodies of anorthosite [14].

Parental magmas for the alkali anorthosites and the Mg-suite anorthosites have evolved trace element characteristics (high Eu/Al, low Sc/Sm, high REE abundances) but the alkali and Mg-suites cannot be related by simple closed-system crystallization of a common parental magma [7,8,14]. Their petrological and geochemical characteristics apparently require a diverse set of igneous processes including assimilation and magma mixing. By analogy with cooling rates inferred from Mg-suite gabbronorite, sodic ferrogabbro, and quartz monzodiorite, the alkali anorthosites were probably emplaced at relatively shallow depths in the uppermost lunar crust (0.2-0.5 km) [10].

Another variant of sodic anorthosite that also has relatively ferroan mafic phases but plagioclase compositions intermediate between those of ferroan and alkali anorthosites (An_{91-94}) was described by Norman et al. [15]. These sodic anorthosites also have unusually high Sr and Eu contents, and mineral compositions suggesting affinities with Mg-suite gabbronorites, but their petrogenesis has not been clearly elucidated.

Polymict anorthositic breccias with feldspathic bulk compositions close to that of anorthosite (~30 wt% Al_2O_3) were collected at the Apollo 16 site and have been found as lunar meteorites (e.g. Dhofar 081 and 489). These feldspathic polymict breccias generally have low contents of incompatible trace elements and may be difficult to distinguish from igneous anorthosite based on remote sensing data alone. Metamorphosed polymict breccias with granoblastic textures also have mineralogy and bulk compositions similar to some igneous anorthosites.

Such lithologies may be relatively common at the lunar surface. Large regions of the farside, north of the South Pole-Aitken basin, have bulk compositions very close to that of anorthosite (<2% FeO) [16]. The lithologic affinity of these regions is unclear, but they may represent either SPA ejecta, or a veneer of SPA ejecta over primary anorthositic upper crust [16]. The Apollo 16 feldspathic fragmental breccias may represent ejecta from either the Imbrium or Nectaris basins.

Targets and Questions. The anorthosite massifs observed in the rings of several lunar basins [16] are obvious targets for closer inspection by LRO. High-value targets might include the Inner Rook ring of Orientale, described as a "mountain range of anorthosite" [16], the eastern rings of Grimaldi near the contact with Oceanus Procellarum, and the northwestern region of Nectaris near Theophilus and the Kant Plateau. These large bodies of anorthosite apparently occurred at pre-excavation depths similar to those obtained form the cooling rate calculations on ferroan anorthosites [10], sandwiched between layers of more mafic material [16]. Questions that might be addressed by closer observation of these regions include: (1) The nature of the contacts between mid-crustal anorthosite and the more mafic layers above and below the anorthosite. Are the contacts igneous or depositional? Is there evidence for diapiric emplacement of the anorthosite? (2) Can highly feldspathic breccia despoits be recognized and if so, can they be linked with confidence to basin ejecta? What is the fraction of locally reworked vs. transported ejecta in these deposits?

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