DEVELOPMENTS IN OUR UNDERSTANDING OF LUNAR CRUSTAL FORMATION AND EVOLUTION.

J. F. Pernet-Fisher[1] and K. H. Joy[1]; [1]SEAES, University of Manchester, UK. (john.pernet-fisher@manchester.ac.uk).

Overview. Limited sampling of primary crustal units, such as highland ferroan anorthosites (FAN), by the Apollo missions have made refining crustal formation models challenging. However, our recent understanding of lunar crustal formation and evolution has developed through the combination of analytical advances, wider observations of global lunar structure, and the increased availability of anorthositic material sampled as clasts within meteorite regolith breccias.

Highland sampling issues. Through studying lunar meteorites, we are able to sample the global diversity of the lunar highlands; many containing components of anorthositic material from the feldspathic highland terrane [1]. In most cases, these anorthositic clasts are very small (< 5 mm). This has resulted in problems interpreting their petrology, particularly for applying the criteria set out by Warren [2] for identifying 'pristine' igneous rocks sourced from the primary FAN, and secondary magmatic Mg-Suite and high-alkali suite highlands groups. Furthermore, the small sizes of these clasts make it easy to misinterpret 'secondary' impact-melt textures with 'primary' igneous textures [3], and make difficult it to conduct 'bulk rock' analyses to identify the chemical signatures associated with impact-melts.

Technique Advances. New sampling approaches and analytical techniques over the last decade has enabled more geological information to be extracted from these small highland samples. In particular, *in situ* LA-ICP-MS and SIMS mineral incompatible trace-element (ITE) analyses have now become routine tools for investigating the petrogenesis of rocks [4,5], helping to unravel the problem of igneous vs impact rock. The ITEs are particularly helpful as they are generally robust to significant post-crystallisation-modification. In particular, trace-element analyses of FAN plagioclase, in combination with advances in isotope geochronology e.g., [6] and the wealth of new remote sensing missions e.g., [7] has enable a number of important observations that are helping to refine crustal formation models [8].

Highland chemical variations. Recent studies have highlighted compositional differences within anorthosite samples sourced from the primary highlands crust. For instance, an important sub-set of clasts identified within some regolith breccias are the magnesian anorthosites ($Mg\#_{plag} > 65$ [9], cf. FAN $Mg\#_{plag} < 65$ [2]). The identification of these lithologies are consistent with remote sensing data that suggests there is a general chemical dichotomy between magnesian farside anorthosites relative to ferroan nearside anorthosites [10]. In addition to these broad major-element differences, recent ITE studies have shown that plots of plagioclase Eu-anomaly vs. ITE for suites of anorthosite clasts from individual meteorites can lie on distinct compositional trends indicating that anorthosite suites may be more petrologically heterogeneous than previously thought [4,11]. The results of these geochemical studies clearly point to a model of lunar anorthosite formation that is more complex that a single global plagioclase flotation formational event [8].

Implications of crustal formation models: The observations outlined above have resulted in a number of possible variations to the traditional global floatation crustal formation models [8]:

1) A long-standing model that has gained some favour to account for the chemical variations in anorthosite chemistry is serial magmatism model [8]. This hypothesis suggests that multiple large plagioclase-rich diapers, sourced from geochemically different mantle regions, accreted to form the lunar crust [8, 9, 12].

2) To account for the differences in anorthosite Mg# content, studies have proposed an asymmetrical plagioclase flotation model, whereby the nearside remains hotter than the farside, causing earlier farside plagioclase crystallisation from a more primitive parental magma relative to the nearside [8, 10].

3) Large impacts could also account for anorthosite chemical variably [13]. Crystallisation and subsequent plagioclase flotation of large impact melt sheets may give the appearance of 'pristine' primary rocks [14], their true origin having been 'blended in' with the surrounding lithologies during impact gardening.

Summary. There is still much to be learnt about the suite of lunar highlands from the material available to us in the Apollo and lunar meteorite collections. In particular, with micro analytical tools now readily available, the study of small rocklets or individual mineral has been demonstrated to be an effective diagnostic tools for classifying and understanding lunar samples with little or no petrographic context.

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