

Low Pressure Crystallization of a Lunar Highlands Basalt: A Means for Producing Anorthosite Locally?

N. J. DiFrancesco,¹ H. Nekvasil,¹ D. H. Lindsley¹, and G. Ustunisik.² ¹Stony Brook University, Department of Geosciences, Earth and Space Science Building, Stony Brook, NY 11794. Nicholas.Difrancesco@stonybrook.edu. ²American Museum of Natural History, Department of Earth and Planetary Sciences, New York, NY.

Introduction: Anorthosites are found in abundance in the Highlands. These rocks are believed to represent some of the earliest crust of the Moon, produced in a Lunar Magma Ocean (LMO) approximately 4.4 billion years ago [1]. While many of these anorthosites are highly calcic with plagioclase anorthite contents over 95% (>An₉₅), some anorthosite samples contain more sodic cumulus plagioclase [2, 3]. Orbital data from the Lunar Reconnaissance Orbiter also suggest sizeable deposits of less calcic anorthosite at the surface of the Moon [4, 5]. Anorthosite with compositions more albitic (such as An₇₀₋₉₀) than typically found in the Highlands would be difficult or impossible to be produced in an LMO that was also crystallizing large volumes of nearly pure anorthite at late stages.

Additional questions regarding the origin of the anorthosite come from recent age redeterminations. The current lunar paradigm states that all lithologies other than ferroan anorthosites found on the Moon formed after solidification of the LMO and crystallization of the anorthosites. However, radiometric age data have demonstrated that the ferroan anorthosite suite (FANs) crystallized over a period of several hundred million years [6], and the ages of some of the members overlap with other rocks. This incompatibility with the lunar paradigm requires evaluation of the possibility of a post-magma ocean origin for at least some anorthosite. In light of these apparent problems with current theory, it was our goal to look for a mechanism of anorthosite formation that satisfies the compositional and new temporal requirements.

Fractional crystallization is an efficient mechanism to produce a variety of rock compositions over time, and a reasonable process to have been acting on the Moon early in its history. Apollo basalt 14053 was chosen as a starting composition for our experiments due to the extensive amount of data that has been collected on it [e.g., 7], textural evidence that its composition reflects that of a liquid, its original location in the Highlands, and the fact that its composition is sufficiently aluminous that it should give rise to plagioclase early, yet has sufficient ferromagnesian components to ensure that minerals such as olivine or pyroxene will be part of the final crystalline assemblage. This sample also contains apatite, which provides evidence of F and Cl (and H₂O) in the melt, and sulfide, attesting to the presence of S [8] - giving us the opportunity to investi-

gate the role of Cl, F, and S on crystallizing magmas on the early Moon.

Methods: Two mixes of the 14053 composition were produced (see Table 1); one mix contained added Cl and F and S (VOL), and one was volatile-free (NVA). These starting compositions were synthesized from powdered oxides, (SiO₂, TiO₂, Al₂O₃, CaO, MgO, Fe₂O₃, MnO, P₂O₅), Fe⁰ metal, K- and Na-silicates, as well as CaSO₄, MgCl₂ and MgF₂ for the VOL mixes. After grinding in an automatic mortar the powder was loaded into ultra-pure Fe capsules, dried in evacuated silica glass tubes at ~800°C for 15 minutes, and after sealing of the tubes, loaded into a Pt-wound furnace. Each experiment started by raising the temperature above the experimentally-determined liquidus (1200°C for NVA experiments and 1180°C for VOL experiments) for one hour to create a homogenous melt. For each experiment the temperature was then stepped down (15-20°C/min, limited by the furnace response time) to the final crystallization temperature and held there for 24-120 hours. The pressure of crystallization was ~1bar.

	14053[7]	VOL	NVA
SiO ₂	46.08	45.94	46.67
TiO ₂	2.91	2.83	2.96
Al ₂ O ₃	12.54	12.66	13.22
FeO	16.97	17.83	16.59
MnO	0.26	0.23	0.24
MgO	8.97	7.66	7.88
CaO	11.07	10.21	10.58
Na ₂ O	0.44	0.49	0.47
K ₂ O	0.1	0.13	0.11
P ₂ O ₅	0.11	0.07	0.11
SO ₂	0.13	0.21	-
Cl	-	0.45	-
F	-	0.51	-

Table 1. Composition of Apollo Sample 14053 and starting compositions for experiments: Volatile-bearing (VOL), and No Volatile Added (NVA).

All run products were analyzed using the Cameca SX100 electron microprobe at the American Museum of Natural History, NY. Two operating conditions were used, a 15kV accelerating voltage, 2nA beam current, and a defocused beam was employed for Na, K and F

analyses to mitigate loss of these elements. A 20 nA beam current and a focused electron beam was used for all other element analyses.

Results: Crystallization experiments conducted on the two compositions of sample 14053 show plagioclase and pyroxene are dominant in the mineral assemblage. The plagioclase crystallized over the temperature range investigated has the range An_{89-91} for VOL experiments and An_{85-87} for the NVA composition, suggesting that more anorthitic plagioclase is stabilized in the presence of halogens. That halogens can be retained during crystallization at low pressure is shown in Fig. 1 where both F and Cl contents in the residual melt rises to over 2 wt.%. These volatiles also induce Fe concentration in the melt at low fO_2 , perhaps through the formation of Fe-chloride and sulfide melt complexes.

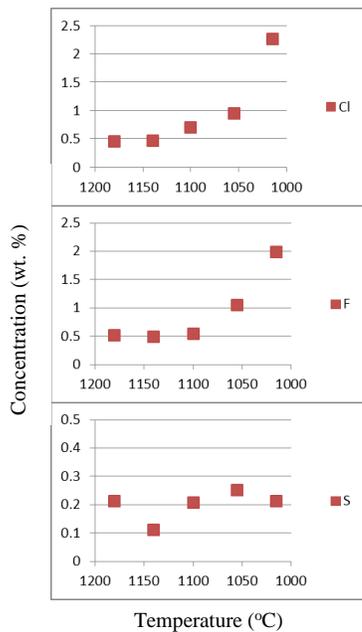


Figure 1. Abundance of dissolved volatiles in the VOL residual liquids at each temperature (compositions are normalized to 100%).

Both sets of experiments produce a dense residual liquid. Calculations of liquid density were done using the expressions of [9] and assuming that all volatiles were water. This should underestimate the density of F-, and Cl- bearing liquid allowing for a “lower limit” of liquid density. The accepted densities of anorthite and pigeonite [10] were compared to that of the residual liquid (fig. 2). Anorthite was used as an upper limit for liquid density. As shown in Figure 2, even using the lowest density liquid values and highest density plagioclase, the liquid densities along both the

VOL and NVA crystallization paths permit plagioclase floatation and pyroxene settling.

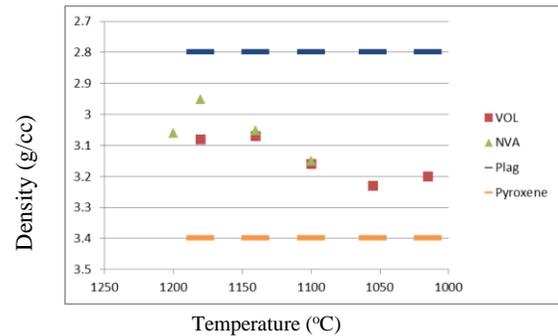


Figure 2. Computed density of residual liquids from VOL and NVA experiments with density of plagioclase (anorthite) and pyroxene (pigeonite) produced in experiments.

The liquid densities coupled with the early crystallization of plagioclase and the relatively large amount of remaining liquid at moderate temperatures, strongly suggest the possibility that plagioclase floatation or liquid draining could have produced localized anorthosites with bytownitic plagioclase compositions at any point of lunar evolution that produced basaltic magma with terrestrial-like alumina contents. Halogens may have played a role in keeping the magma molten over longer periods of time through suppression of the solidus temperature and induced Fe-enrichment of residual liquid, which enhanced plagioclase floatation and liquid draining.

References: [1] Wood, J. A. (1975) *Proc. of the 6th Lunar Sci. Conf.* pp 1087-1102 [2] Lindstrom, M. M. et al. (1984) *J. of Geophys. Research*, 89, pp C41-C49. [3] Shervais, J. W. et al. (1984) *J. of Geophys. Research*, 89, pp C25- C40. [4] Greenhagen, B. T., et al. (2010) *Science*, 329, 5998, pp 1507-1509. [5] Glotch T. D. et al. (2010) *Science* 329, pp 1510-1513 [6] Elkins-Tanton, L. T. (2011) *EPSL* 304, 3, pp 326-336. [7] Papike J. J., et al. (1976) *Rev. Geophys. Space Phys.* 14, 475-540. [8] McCubbin F. M. et al. (2010) *PNAS*, 107, pp 11223-11228. [9] Lange R.A. and Carmichael, I. S. E. (1987) *Geochim. et Cos. Acta*, 51, 11, pp 2931-2946. [10] Klein, C. (2002) *Mineral Science* 22nd Ed.

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