Constraints on the composition and evolution of the lunar crust from meteorite NWA 3163

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The lunar meteorite NWA 3163 (paired with NWA 4881, 4483) is a ferroan, feldspathic granulitic breccia characterized by pigeonite, augite, olivine, maskelynite and accessory Ti-chromite, ilmenite and troilite. Bulk rock geochemical signatures indicate the lack of a KREEP-derived component (Eu/Eu* = 3.47), consistent with previously studied lunar granulites and anorthosites. Bulk rock chondrite-normalized signatures are however distinct from the anorthosites and granulites sampled by Apollo missions and are relatively REE-depleted.

In-situ analyses of maskelynite reveal little variation in anorthite content (average An% is 96.9 ± 1.6, 2σ). Olivine is relatively ferroan and exhibits very little variation in forsterite content with mean Fo% of 57.7 ± 2.0 (2σ). The majority of pyroxene is low-Ca pigeonite ($En_{57}Fs_{33}Wo_{10}$). Augite ($En_{46}Fs_{21}Wo_{33}$) is less common, comprising approximately 10% of analyzed pyroxene. Two pyroxene thermometry on co-existing orthopyroxene and augite yield an equilibrium temperature of 1070°C which is in reasonable agreement with temperatures of 1096ºC estimated from pigeonite compositions.

Rb-Sr isotopic systematics of separated fractions yield an average measured $^{87}Sr/^{86}Sr$ of 0.699282±0.000007 (2σ). Sr model ages are calculated using a modern day $^{87}Sr/^{86}Sr$ BABI value of 0.70475, from an initial BABI value $^{87}Sr/^{86}Sr$ of 0.69891 and a corresponding $^{87}Rb/^{86}Sr$ of 0.08716. The Sr model T_{MA} age, which represents the time of separation of a melt from a source reservoir having chondritic evolution, is 4.56±0.1 Ga. A Sr model T_{RD} age, which is a Rb depletion age and assumes no contribution from Rb in the sample in the calculation, yields 4.34±0.1 Ga (i.e. a minimum age). The Ar-Ar dating of paired meteorite NWA 4881 reveals an age of *c*. 2 Ga, likely representing the last thermal event this meteorite experienced. An older ^{40}Ar-^{39}Ar age of *c*. 3.5 Ga may record the thermal event which produced the granulitic texture. Additional chronological constraints will be provided by Sm-Nd systematics.

Ferroan Anorthosites like NWA 3163 have been interpreted to represent direct lunar magma ocean (LMO) crystallization products. If this is the case, trace element concentrations in NWA 3163 primary mineral phases should be in equilibrium with residual LMO liquids present during crystallization of those phases. Results from petrogenetic modeling suggest that the NWA 3163 protolith did not form from crystallization of an initially LREE depleted LMO but rather require an initially chondritic LMO with early garnet crystallization. Furthermore, a two-stage crystallization model where plagioclase crystalized prior to pyroxene (93% vs. 99.5% of LMO crystallization) is implied.