FERROAN ANORTHOSITE: A WIDESPREAD AND DISTINCTIVE, HIGH-OLIVINE/PYROXENE, LUNAR ROCK TYPE

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The title of this work is an homage to Dowty et al. [1]. Between that seminal work and [2], the distinctiveness of ferroan anorthosite (FA) was noted in terms of it being (a) a compositionally "pristine" lunar rock type, (b) uniquely plagioclase-rich (potentially *buoyant*) among decently sampled pristine rocks, with (c) low *mg* (≡ molar MgO/[MgO+FeO]) despite (c1) low-sodium plagioclase, (c2) low REE (etc.), and (c3) distinctive ratios of plagiophile element pairs such as Eu/Al and Ga/Al. Another noteworthy but complex, hard-to-constrain [3] trait is (d) uncommonly ancient crystallization ages. If any lunar rock type formed as flotation crust over a primordial magma ocean, FA is surely the leading candidate. Another important and distinctive FA trait (c4), high olivine/pyroxene ratio despite low *mg*, has until now, with added constraint from some new meteorites, gone rather underappreciated.

In low-pressure, moderate-*mg* basaltic crystallization, olivine tends to precede pyroxene [4]. Olivine commonly becomes mantled by orthopyroxene, as happened at a late (probably post-flotation) stage in the crystallization of FA 62237 (Fig. 1). In a different way, the few "large" samples of the Mg-suite (i.e., essentially all of the lunar highland cumulate rocks *other than* FA) also show a systematic olvn-px relationship. Of the 10 with estimated mass >10 grams, 3 have vastly more olivine than px combined with bulk (literature-average) *mg* in the range 86-87.2, the other 7 have px as their only mafic silicate and bulk *mg* in the range 67-82 [5]. This step function distribution is consistent with early, magnesian olivine giving way to late, relatively ferroan pyroxene. If we hazard to extend the database with four samples with mass between 3 and 10 g, this picture does not change much; olivine-dominated samples have *mg* no lower than 83.2, with one exception at 73.3 mol%: the "feldspathic lherzolite" 67667 – a breccia with no Eu anomaly that possibly is a limited "ortho"-cumulate.

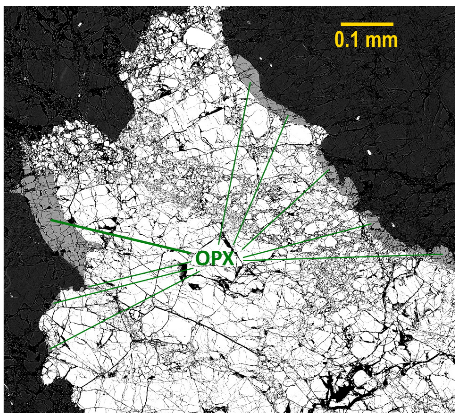

Fig. 1: Backscattered-electron image of opx mantling olivine in ferroan an'site 62237,23.

The picture changes radically if FA are added. Despite bulk *mg* in the range 50-63.3, of the four FA samples that are both large (57-1800 g) and relatively mafic-rich, 60025, 62275, 62237 and 62236, three contain more olivine than px. Even the exception, 62236, contains significant (4 vol%) olivine. If we hazard to extend the database with the next most massive of the relatively mafic-rich FA (64435c, ~6 g [6]) the story changes only in detail. In short, the FA (at least those FA relatively rich in mafic silicates) contain far more olivine than px, despite having *mg* much lower than the ratio at which among Mg-suite cumulates the mafic silicates transition from olivine to px.

Recently, a few anorthosites have turned up among lunar meteorites: Gadamis 004, Ghadduwah 001, Northwest Africa (NWA) 12965 and NWA 13907, all described in the *Met. Bull.* by Carl Agee. Although (despite the fact that) they are unlikely to all be pristine, all four are thoroughly FA in their mineral chemistry, with low-Na plagioclase and implied bulk *mg* in the range ~ 61-64 mol%. All are also said to contain olivine, mentioned first (before px) in all four cases. Even assuming these rocks are not pristine, we can still evaluate as unlikely a hypothetical scenario of origin by mixing between an olivine-free FA and olivine-bearing Mg-suite material. If the starting pristine FA is assumed to have had *mg* not vastly lower than known FA, then unless the admixed olivine had *mg* far lower than the observed range (83-87 mol%) among olivine-rich Mg-suite cumulates, given the observed (61-64 mol%) *mg*, the final olivine/px ratio should not be nearly as high as 1 (space does not permit detailed discussion here of the mass balance).

Implications: These olivine/pyroxene-*mg* relationships strengthen the evidence for FA being "distinctive" [1]. The moderate-high olivine/px ratios of the FA are also hard to explain except by formation of FA as a series of cumulates that buoyantly accumulated toward the top of a magma so immense that it spanned a significant range in pressure. In a magma with convection working toward an adiabatic *T*-depth gradient, crystallization occurs both shallow (at low *T*) and deep (at high pressure *P*). The phase equilibria [e.g., 4] imply that a few kbar of *P* displaces the olivine/px stability boundary such that the same magma that forms px deep may form olivine shallow. The FA may be blends of floated cumulus plagioclase, originally (pre-accumulation) deep-formed cumulus px, and shallow-formed cumulus olivine, along with additions (Fig. 1) from trapped liquid and (shallow) "adcumulus growth".

References: [1] Dowty E. (1974) *EPSL 24*, 15-25. [2] Warren P. H. and Kallemeyn G. W. (1984) *Proc. LPSC 15*, C16-C24. [3] Borg L. E. et al. (2015) *MaPS 50*, 715-732. [4] Morse S. A. (1980) *Basalts and Phase Diagrams*. [5] Warren P. H. (1993) *Amer. Mineral. 78*, 360-376. [6] James O. B. et al. (1991) *Proc. LPSC 21*, 365-393.