MAGNESIAN MEMBERS OF THE LUNAR FERROAN ANORTHOSITE SUITE: Odette B. James, 959 National Center, U.S. Geological Survey, Reston, VA, 22091

Introduction: Lunar ferroan anorthosites are generally thought to be relics of the earliest lunar crust, formed as flotation cumulates atop a differentiating, moon-wide, primordial magma ocean. Most of these rocks are nearly monomineralic (>95% plagioclase), and their original textures have been obscured by impact-induced cataclasis, making it difficult to date them isotopically and to evaluate the processes that might have been involved in their origin. The most magnesian members of the suite, however, are appreciably richer in mafic minerals, and some have relict primary igneous textures. Intensive study of these rocks holds promise for helping delineate the composition and crystallization history of their parent magma and the postcrystallization history and age of the rocks. Examples are listed below. Mineral compositions in all lithologies described are homogeneous.

Most ferroan-anorthosite hand samples that have been studied in detail have been found to consist of aggregates of granulated anorthosites, noritic anorthosites, and troctolitic anorthosites. These individual rock types commonly vary in mode and mg' (molar Mg/Mg+Fe), but all appear to be genetically related. Most workers have interpreted such samples as the products of impact-induced fragmentation and mixing of the rocks of a layered plutonic igneous complex [1-5]. Many of the rocks described below have been found in such associations, juxtaposed with less magnesian members of the suite.

Noritic anorthosite from 64435: This clast from breccia 64435 [5,6] is the most magnesian member of the suite yet found. It consists mostly of plagioclase (An_{97}), low-Ca pyroxene (En_{75}), augite ($Wo_{45}En_{46}$), and olivine (Fo_{71}); the mafic minerals make up 13% of the rock. Traces of chrome spinel and ilmenite (4.4-6.2 wt.% MgO) are present. Locally, relict igneous texture is well preserved. Inverted pigeonite and subhedral plagioclase grains are < 2 mm across. Olivine grains have thin partial rims of orthopyroxene and are < 0.5 mm across. Pigeonite and olivine grains locally include small plagioclase grains. One pigeonite grain has a core of partly resorbed olivine that has a narrow subhedral rim of orthopyroxene. Primary augite is interstitial, < 0.4 mm across, and occurs at the edges of the grains of inverted pigeonite. Cumulus phases were plagioclase and pigeonite, plus unreacted olivine with orthopyroxene rims.

"Dunite" and "pyroxenite" from 60025: These lithologies were found closely juxtaposed with more ferroan lithologies [4]. Their modes are probably not representative. The "dunite" (zone A of [4]) consists of olivine (Fo_{67}) and minor low-Ca pyroxene (En_{72}); a separate small chip of 60025 containing similar mafic minerals also contained plagioclase (An_{98}). The "pyroxenite" (zone C of [4]) consists of a 4-mm grain of inverted pigeonite (En_{69}), with minor olivine (Fo_{65}) and plagioclase (An_{98}). Relict textures are not preserved.

Troctolitic anorthosite 15437: This rock [7,8] consists of about 80% plagioclase (An_{96}) and 20% mafic minerals; olivine (Fo_{67}) is more abundant than the pyroxenes ($Wo_{40}En_{47}$ and Wo_2En_{72}). Traces of chrome spinel and mafic symplectite have been observed [8]. The rock was extensively granulated and recrystallized; no relict texture is preserved.

Troctolitic anorthosite from 62236: This lithology was found closely juxtaposed with norite and anorthosite [3]. It consists of about 80% plagioclase (An_{97}), 20% olivine (Fo_{63}), and minor orthopyroxene (En_{69}). Relict textures are well preserved. Plagioclase is < 2 mm across; olivine is 1 mm across, wraps around the plagioclase grains, and is partly replaced by a thin rim of orthopyroxene.

Anorthosite 67636: The analyzed chip of this rock [9] consists of about 92% plagioclase (An_{95}), 6% low-Ca pyroxene (En_{68}), and 2% olivine (Fo_{61}). The rock has been granulated, but plagioclase grains 2 mm across are preserved.

Troctolitic anorthosite from 62237: This lithology [10,11] has an occurrence like that of the 62236 troctolitic anorthosite. It consists of about 80% plagioclase (An_{97}) and 20% olivine (Fo_{60}), with minor orthopyroxene (En_{67}), chrome spinel and ilmenite (3.3 wt.% MgO). Some relict texture is preserved. Relict grain size is as much as 3 mm. Plagioclase and olivine were cumulus phases. Orthopyroxene fills interstices and forms thin septa along grain boundaries; this mineral formed in part by reaction of melt with olivine [10].

Discussion: The similar mineralogies of the rocks described above suggest they are cogenetic. Their pyroxenes and olivines show correlated variations in mg' (Fig. 1). Their pyroxenes appear to have similar minor-element contents (based on comparison of data for 62236, 62237, and 64435). Variations in chrome spinel and ilmenite compositions are correlated with variations in mg' of mafic minerals. The data show no correlation between An content in plagioclase and mg' of the mafic minerals for the different rocks, but the total range in An content for the entire suite is small (4%) and interlaboratory bias could obscure a correlation if one exists. Investigations of ferroan anorthosites where all analyses have been made in the same laboratory have reported slight, but consistent, positive correlations of mg' in mafic minerals with An content in plagioclase [3,4,11].

Several studies [3,4,12] have concluded that the rocks of the ferroan-anorthosite suite

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formed by strong fractional crystallization and near-perfect adcumulus growth, with virtually no trapping of interstitial liquid. In all the relatively magnesian rocks considered herein, plagioclase is clearly a cumulus mineral. The sizes of the olivine and inverted pigeonite grains, where relict textures are preserved, indicate that these minerals were cumulus phases as well. Orthopyroxene occurs only as rims on olivine grains and filling interstices; this mineral was a cumulus phase only where it was part of polymineralic cumulus grains.

Relict textures in the 64435 noritic anorthosite and the 62236 and 62237 troctolitic anorthosites indicate the crystallization sequence of their parent magma [3,5,10]. Olivine and plagioclase initially coprecipitated. Olivine reacted with the melt to form orthopyroxene. Orthopyroxene was quickly superceded by pigeonite, which coprecipitated with plagioclase. Augite was the last mafic silicate to begin to crystallize, and it precipitated along with pigeonite and plagioclase. Minor amounts of oxide minerals also crystallized, chrome spinels throughout the sequence and ilmenite simultaneously with the pigeonite and augite.

The crystallization sequence indicated by the textures is the same as in Mg-suite rocks and different from that suggested by some of the trace-element data. The REE [4,12] and Sc [12] data have been interpreted as indicating that the parent liquid had not yet crystallized plagioclase, but it had crystallized pyroxene. These conflicting observations might be reconciled if, as suggested by Warren and Wasson [13], pressure effects were important in crystallization of the primordial magma ocean. The parent magma might have previously fractionated at depth in the Moon, where olivine and low-Ca pyroxene were liquidus phases, and then ascended and crystallized near the surface, where olivine and plagioclase but not pyroxene were liquidus phases.

Comparisons with other members of the ferroan anorthosite suite: Preliminary synthesis of the data for lunar ferroan anorthosites suggests that, on the basis of modes and mineralogy, most of these rocks fall into three groups (Fig. 1): 1) the relatively magnesian, relatively mafic group discussed herein; 2) a highly anorthositic, ferroan group; and 3) a relatively mafic, ferroan group. Most members of the suite fall into the second group. They contain more than 95% plagioclase, their dominant mafic mineral is low-Ca pyroxene less magnesian than En_{66}, and olivine is absent. Samples that fall into the third group have been found at North Ray Crater, Apollo 16, and include clasts from breccias 67915, 67455, 67075, and 67215 [2,14,15, and Flohr, unpublished]. These rocks contain more than 8% mafic minerals, olivine is present in most, and the mafic minerals are highly ferroan (olivine is Fo_{37-55}, low-Ca pyroxene is En_{37-63}). Because olivine is in reaction relation with the melt in the magnesian rocks discussed herein, the presence of olivine in these ferroan rocks is paradoxical if all crystallized from the same parent magma. A possible explanation of the paradox is as follows. The parent magma was crystallizing and evolving at depth in the Moon, at a level where olivine and pyroxene were precipitating stably together (>100 km?); magma composition was perhaps at the olivine-pyroxene-plagioclase cotectic. Periodically batches of this magma ascended to near the lunar surface, where it was saturated only with olivine and(or) plagioclase and not with pyroxene. Near-surface crystallization of each batch of magma first produced troctolitic rocks, then noritic rocks. The batches of magma had progressively lower mg's, as did the rocks that crystallized from them.

References: [1] A. Peckett and G.M. Brown, 1973, Nature 242, 252. [2] I.S. McCallum et al., 1975, EPSL 26, 36. [3] G.L. Nord and M.-V. Wandless, 1983, PLPSC 13, A645. [4] G. Ryder, 1982, GCA 46, 1591. [5] O.B. James and M.K. Flohr, 1985, LPS XVI, 396. [6] M.M. Lindstrom, 1984, LPS XV, 483. [7] P.H. Warren and J.T. Wasson, 1978, PLPSC 9, 185. [8] G. Ryder, 1985, Catalog of Apollo 15 Rocks, JSC 20787, 681. [9] P.H. Warren and J.T. Wasson, 1980, PLPSC 11, 431. [10] R.F. Dymek et al., 1975, PLSC 6, 301. [11] M.J. Kempa and O.B. James, 1982, LPS XIII, 377. [12] H. Palme et al., 1984, PLPSC 15, C3. [13] P.H. Warren and J.T. Wasson, 1979, PLPSC 10, 2051. [14] E. Roedder and P.W. Weiblen, 1974, PLSC 5, 303. [15] M.M. Lindstrom and D.J. Lindstrom, 1986, PLPSC 16, D263. [16] J.R. Dixon and J.J. Papike, 1975, PLSC 6, 263. [17] G. Ryder and M. Norman, 1979, Catalog of Pristine Non-mare Materials, Pt. 2, JSC 14603.

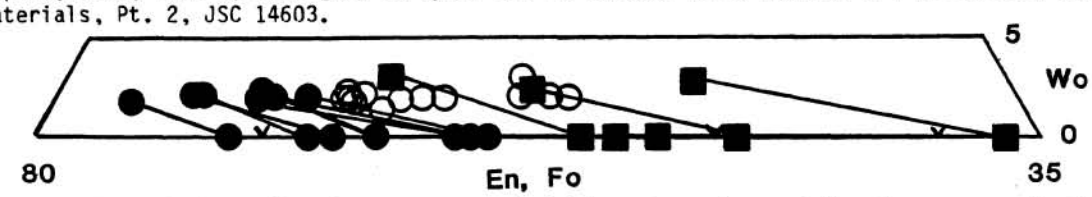

Fig. 1. Compositions of orthopyroxenes and olivines in members of the ferroan-anorthosite suite; tie lines connect compositions of minerals found in the same lithology. Filled circles: relatively magnesian, relatively mafic rocks. Open circles: anorthositic, ferroan rocks. Filled squares: relatively mafic, ferroan rocks. Data sources for the relatively mafic rocks are those cited in the text, for the anorthositic rocks are [9,17,7,17].