Meteoritics & Planetary Science 38, Nr 4, 645–661 (2003)
Abstract available online at http://meteoritics.org

Chronology, geochemistry, and petrology of a ferroan noritic anorthosite clast from Descartes breccia 67215: Clues to the age, origin, structure, and impact history of the lunar crust

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(Received 15 October 2003; revision accepted 28 January 2003)

Abstract–The petrology, major and trace element geochemistry, and Nd-Ar-Sr isotopic compositions of a ferroan noritic anorthosite clast from lunar breccia 67215 have been studied in order to improve our understanding of the composition, age, structure, and impact history of the lunar crust. The clast (designated 67215c) has an unusually well preserved igneous texture. Mineral compositions are consistent with classification of 67215c as a member of the ferroan anorthositic suite of lunar highlands rocks, but the texture and mineralogy show that it cooled more rapidly and at shallower depths than did more typical ferroan anorthosites (FANs). Incompatible trace element concentrations are enriched in 67215c relative to typical FANs, but diagnostic signatures such as Ti/Sm, Sc/Sm, plagiophile element ratios, and the lack of Zr/Hf and Nb/Ta fractionation show that this cannot be due to the addition of KREEP. Alternatively, 67215c may contain a greater fraction of trapped liquid than is commonly present in lunar FANs. ^{147}Sm-^{143}Nd isotopic compositions of mineral separates from 67215c define an isochron age of 4.40 ± 0.11 Gyr with a near-chondritic initial ε^{143}_{Nd} of +0.85 ± 0.53. The ^{40}Ar-^{39}Ar composition of plagioclase from this clast records a post-crystallization thermal event at 3.93 ± 0.08 Gyr, with the greatest contribution to the uncertainty in this age deriving from a poorly constrained correction for lunar atmosphere ^{40}Ar. Rb-Sr isotopic compositions are disturbed, probably by the same event recorded by the Ar isotopic compositions. Trace element compositions of FANs are consistent with crystallization from a moderately evolved magma ocean and do not support a highly depleted source composition such as that implied by the positive initial ε^{143}_{Nd} of the ferroan noritic anorthosite 62236. Alternatively, the Nd isotopic systematics of lunar FANs may have been subject to variable degrees of modification by impact metamorphism, with the plagioclase fraction being more strongly affected than the mafic phases. ^{147}Sm-^{143}Nd isotopic compositions of mafic fractions from the 4 ferroan noritic anorthosites for which isotopic data exist (60025, 62236, 67016c, 67215c) define an age of 4.46 ± 0.04 Gyr, which may provide a robust estimate for the crystallization age of lunar ferroan anorthosites.

INTRODUCTION

Lunar ferroan anorthosites (FANs) are relicts of an ancient, primary feldspathic crust that is commonly thought to have formed by accumulation of plagioclase from a global magma ocean. Compositions and ages of ferroan anorthosites provide fundamental information about the evolution of the moon, the structure and impact history of the lunar crust, and the timescales of planetary differentiation in the inner solar system. Here, we report the results of petrologic, geochemical, and isotopic (Nd-Ar-Sr) studies of a ferroan noritic anorthosite clast from lunar breccia 67215 to improve our understanding of the chronology, structure, and origin of the lunar crust.

Lunar sample 67215 is a feldspathic fragmental breccia that was collected from the rim of North Ray Crater, Apollo 16. Although classified by Lindstrom and Lindstrom (1986) as a granulitic breccia, the presence of aphanitic, microporphyritic melt breccia clasts in 67215 (McGee 1988) demonstrates a lithologic affinity with the feldspathic fragmental breccia suite. These breccias have aluminous bulk compositions (28–30% Al_2O_3) that are poor in KREEP, low in meteoritic siderophiles, and lack solar wind carbon compared to lunar impact melts or regolith breccias (Norman 1981). They appear to represent a regionally significant unit exposed in the Descartes terrane of the lunar highlands, and their bulk compositions are broadly similar to those of large regions of anorthositic crust discovered on the far side of the moon by the Clementine and Lunar Prospector missions. The Descartes terrain may, therefore, provide a glimpse of a more representative region of the lunar crust than the near side KREEP-rich breccias that dominate the Apollo sample collection. The Descartes breccias also contain magnesian and ferroan components that may represent important lithologies of the ancient lunar crust (Lindstrom and Lindstrom 1986). The antiquity of at least some of these lithologies is demonstrated by the 4.53 ± 0.12 Gyr ^{147}Sm-^{143}Nd isochron age obtained for a ferroan noritic anorthosite clast from the Descartes breccia 67016 (Alibert et al. 1994). Breccia 67215 consists predominantly of lithic clasts and mineral fragments derived from ferroan noritic anorthosite (Lindstrom and Lindstrom 1986; McGee 1988), and one of the clasts in this breccia is the subject of this study.

We also address the recent controversy concerning the age and magmatic source composition of lunar ferroan anorthosites. Conventional magma ocean models predict crystallization of FANs and related rocks early in lunar history from a moderately evolved parental magma with near-chondritic relative abundances of LREE and Nd isotopic compositions (i.e., initial ε^{143}_{Nd} ~0). However, previous Nd isotopic studies of lunar FANs (Carlson and Lugmair 1988; Alibert et al. 1994; Borg et al. 1999) do not provide strong support for the classical view of lunar crustal genesis and, in fact, provoke significant challenges to the magma ocean paradigm. Specifically, the young Sm-Nd isochron age of 4.29 Gyr, combined with a remarkably positive initial ^{143}Nd isotopic composition ($\varepsilon^{143}_{Nd} = +3$) for ferroan noritic anorthosite 62236 (Borg et al. 1999), is difficult to accommodate within a conventional magma ocean interpretation. This has led to alternative proposals for lunar crustal petrogenesis involving remelting of mafic cumulates (Borg et al. 2002; Longhi 2002) or early depletion of the lunar magma ocean by a proto-crust enriched in LREE (Warren 2001).

Sample Preparation and Analytical Methods

During examination of breccia 67215 in the Planetary Materials Curatorial Laboratories of the NASA Johnson Space Center, a coarse-grained clast was identified and extracted from the breccia. This clast was subsequently allocated for chemistry as 67215, 46 (hereafter 67215c), and a polished thin section (67215, 55) prepared from a small chip containing a fragment of the clast and adhering host breccia. A whole rock sample of host breccia (67215, 39) was also allocated for chemistry.

Clast 67215c was prepared for analysis in a manner similar to that used in our previous study of 62236 (Borg et al. 1999). After separating the clast from adhering breccia matrix, ~280 mg of uncontaminated clast material was recovered. Grain size fractions of 100–200, 200–325, and >325 mesh were produced by gentle crushing in a boron carbide mortar. Plagioclase and mafic mineral concentrates were obtained using heavy liquids with density cuts at <2.85, 2.85–3.32, and >3.32 g/cm^3, and the mineral separates were further purified by handpicking. Prior to crushing, 2 small fragments that appeared to be representative of the clast were separated for whole rock trace element analysis; these were crushed separately with an agate mortar and pestle. A small number of grains were also taken from the density separates for petrography and mineral analysis, including a few polymineralic fragments with abundant fine-grained opaques. These "rocklets" were thought to offer the best possibility of sampling minor phases such as phosphates that might be present interstitially. Petrographic observations were obtained on the polished thin section and the grain mounts using optical microscopy and backscattered electron imaging. Mineral compositions were determined by wavelength-dispersive electron microprobe using count times of 20–40 sec for major elements and 40–60 sec for minor elements. Plagioclase was analyzed using a 10 micron diameter defocused beam; all other phases were analyzed using a focused beam at 15 keV. Backgrounds were counted on both sides of the analyte peak. Natural mineral standards were used for calibration.

Major and trace element data were obtained on the two samples of 67215 (clast and breccia) by solution ICPMS (Table 1). Rock powders were dissolved in HF + HNO_3 and brought to final volume with 2% HNO_3 (Norman et al. 1998a). For trace element analysis, the sample was diluted 1000×. For the major element analysis, an additional 100× dilution was applied to the trace element solution. Potassium abundances were measured in "cool plasma" mode using a low forward power setting (700 W), which reduces the background on ^{39}K caused by the argon plasma. For comparison, we also report major and trace element compositions on aliquots of whole rock powders and mineral separates from 62236. The major element composition of 62236 was determined by fusing 15 mg of rock powder to a glass on an Ir strip and analyzing the glass by electron microprobe. Trace element abundances were measured on whole rock samples by solution ICPMS, as described above, and by INAA (Mittlefehldt and Lindstrom 1993). Trace element abundances in splits of plagioclase and mafic silicate fractions used for the isotopic analysis were also measured by INAA.

Sm-Nd and Rb-Sr isotopic data were obtained on whole rock and mineral separates of 67215 (Table 2 and 3) following procedures similar to those used for our previous study of 62236 (Borg et al. 1999). Before isotopic analysis, Nd and Sr concentrations were measured by isotope dilution on small aliquots of each sample to enable optimum amounts of the mixed Rb-Sr and Sm-Nd spike to be added. The Sm isotopic

Table 1. Major and trace element compositions of 67215, 62236, and BHVO–2 .

	67215, 31	67215, 46	62236, 43		62236, 21		BHVO–2
	breccia	clast	WR	WR	PLAG	MAFIC	
wt%	ICPMS	ICPMS	EMP	INAA	INAA	INAA	ICPMS
SiO_2	45.42[a]	45.10[a]	43.89	–	–	–	50.57[a]
TiO_2	0.24	0.18	–	–	–	–	2.77
Al_2O_3	27.36	28.26	27.63	–	–	–	13.76
FeO	5.73	5.48	6.16	8.09	1.15	32.6	11.26
MnO	0.08	0.08	0.05	–	–	–	0.17
MgO	4.63	4.29	5.96	–	–	–	7.26
CaO	16.21	16.26	15.77	15.7	19.6	0.53	11.43
Na_2O	0.31	0.32	0.18	0.184	0.228	0.0084	2.23
K_2O	0.019	0.018	–	<0.019	<0.028	<0.005	0.56
Sum	100.00	100.00	99.64	–	–	–	100.00
ppm	ICPMS	ICPMS	ICPMS	INAA	INAA	INAA	ICPMS
Li	3.1	3.2	1.5				4.7
K	156	147	–	–	–	–	–
Sc	13.4	11.2	5.2	3.46	1.03	10.7	32.3
Ti	1470	1183	341	–	–	–	17338
V	20	16	14	–	–	–	327
Cr	–	–	–	492	153	864	na
Co	10	16	8.5	18.7	2.8	74.8	46
Ni	28	49	8.7	23	<10	<70	123
Cu	1.3	0.9	3.2	–	–	–	123
Zn	12	10	1.8	–	–	–	101
Ga	2.8	3.1	2.7	–	–	–	20.6
Rb	0.9	0.5	0.65	–	–	–	9.4
Sr	139	156	149	128	157	<80	387
Y	6.3	5.1	0.95	–	–	–	27.8
Zr	11.6	10.9	1.90	–	–	–	178
Nb	0.57	0.53	0.10	–	–	–	19.3
Mo	0.01	0.02	nd	–	–	–	4.21
Sn	0.11	0.05	0.02	–	–	–	2.1
Cs	0.099	0.049	0.114	0.087	0.092	0.12	0.10
Ba	17.0	22.4	7.30	<15	15	<30	131
La	0.88	0.95	0.188	0.139	0.162	0.017	15.3
Ce	2.32	2.31	0.464	0.37	0.42	–	36.8
Pr	0.32	0.31	0.060	–	–	–	5.16
Nd	1.60	1.43	0.286	–	–	–	24.1
Sm	0.55	0.45	0.088	0.055	0.055	0.031	6.10
Eu	0.75	0.82	0.685	0.593	0.742	<0.02	2.04
Gd	0.75	0.63	0.109	–	–	–	6.12
Tb	0.13	0.11	0.020	0.021	0.0076	<0.03	0.95
Dy	0.93	0.75	0.145	–	–	–	5.21
Ho	0.21	0.17	0.034	–	–	–	0.99
Er	0.63	0.52	0.106	–	–	–	2.53
Yb	0.64	0.54	0.117	0.077	0.037	0.18	1.94
Lu	0.096	0.078	0.018	0.012	0.0044	0.031	0.27
Hf	0.31	0.26	0.049	<0.05	<0.028	<0.1	4.28
Ta	0.033	0.029	0.006	<0.02	<0.01	<0.06	1.24
Pb	0.39	0.20	0.15	–	–	–	1.51
Th	0.070	0.068	0.011	<0.035	<0.015	<0.06	1.21
U	0.019	0.024	0.0023	<0.06	<0.04	<0.21	0.41

[a]SiO_2 by difference.

composition of a split of 67215 host breccia was measured to evaluate the effects of neutron exposure on the lunar surface. Two splits of the 67215 breccia matrix were analyzed for Rb-Sr isotopic composition (Table 2).

^{40}Ar-^{39}Ar isotopic data were obtained on a 21 mg sample of plagioclase from the 67215 clast and on a 63 mg whole rock sample from the 67215 breccia matrix. These samples and the NL-25 hornblende monitor were irradiated with fast neutrons (J-value of 0.0314) at the University of Missouri. Ar was extracted in stepwise temperature release, and its isotopic composition was measured on a mass spectrometer following the procedures of Bogard et al. (1995). The isotopic data were corrected for system blanks, radioactive decay, and reactor-produced interferences. For most extractions ^{40}Ar and ^{39}Ar blanks were 2–3% and 3–4%, respectively. Because of the large Ca/K ratio in the plagioclase, corrections for the reaction ^{42}Ca (n, α) ^{39}Ar were 15–29% for the various extractions. We used a ^{39}Ar/^{37}Ar correction factor of 7.45 ± 0.20 × 10^{-4}. This factor was obtained by irradiating several samples of pure CaF_2 at different times in the same reactor position as used for 67215, and we believe the uncertainty given for this factor is realistic. Where we report an average Ar-Ar age with an uncertainty, that uncertainty includes consideration of uncertainties in isotopic ratio measurement, blank, decay, reactor corrections, and uncertainty in irradiation constant. However, the Ar-Ar age spectra presented for stepwise temperature extractions do not contain the uncertainty in the J value.

RESULTS

Petrography and Mineral Compositions

The noritic anorthosite clast 67215c has an unbrecciated igneous texture that is easily distinguished from the fragmental host breccia (Fig. 1). Plagioclase (An_{96-98}) grains are euhedral to subhedral and range in size from ~0.1–0.7 mm long with a median length of ~0.5 mm. Interstitial pyroxene and olivine ($Fo_{49.3-54.1}$) take irregular shapes, with low-Ca pyroxene > high-Ca pyroxene >> olivine. Thin (≤5 microns wide) exsolution lamellae are abundant in both low-Ca and high-Ca pyroxene, with compositions ranging from $Wo_{1.4}En_{58.3}$ to $Wo_{44.5}En_{39.8}$ (Fig. 2). Chromite, ilmenite, FeNi metal, and troilite are present as minor phases and often occur as complex, fine-grained intergrowths interstitial to the plagioclase and pyroxene. Although the clast has not been brecciated, shock effects are apparent in the irregular extinction and micro-fracturing that are especially visible in plagioclase (Fig. 1). Modal analysis of the clast gives plagioclase 70.5 vol%, mafic silicates 28.2 vol%, ilmenite + chromite 0.7 vol%, and FeNi metal 0.7 vol% (610 points). Plagioclase and mafic silicate compositions in 67215c are similar to those of lunar ferroan anorthosites (Fig. 3). Al and Ti contents of pyroxenes in 67215c fall along a 2:1 cation trend (Fig. 4), indicating a $Ti^{VI}Al_2^{IV}$ substitution mechanism consistent with crystallization from a plagioclase-saturated magma. FeNi metal compositions have relatively high Ni (3–5 wt%) and Co (1 wt%) contents and low Ni/Co ratios, which is atypical for lunar ferroan anorthosites (cf., Ryder et al. 1980).

Major and Trace Elements

The clast and host breccia samples of 67215 and the split of 62236 analyzed for this study all have similar bulk compositions that reflect the relatively high modal abundance of pyroxene and olivine in these rocks (27–28 wt% Al_2O_3, 5–8 wt% FeO; Table 1). The fused bead prepared from 62236 was internally heterogeneous, with Al_2O_3 ranging from 25.5–31.2 wt% and other elements showing correlated variations, indicating incomplete mixing between plagioclase and mafic minerals. Nonetheless, the average composition of the glass bead probably provides a reasonable estimate of the bulk composition of 62236 considering the close agreement with CaO and Na_2O contents measured independently by INAA (Table 1). The similarity in composition between the 67215 clast and the host breccia also extends to trace element abundances, which are almost identical for many incompatible elements (Table 1; Fig. 5). The major and trace element data, therefore, support previous suggestions based on mineral chemistry that breccia 67215 is composed predominantly of a single ferroan noritic anorthosite lithology (McGee 1988).

Incompatible trace element concentrations in 67215c are elevated compared to 62236 and most other lunar ferroan anorthosites (cf., Norman and Ryder 1979; James 1980) but below those of 67016c (Fig. 6). As expected from the whole rock compositions, the plagioclase and the mafic fractions of 67215c also have high concentrations of Nd and Sm (Table 2). In this respect, 67215c is similar to 67016c (Alibert et al. 1994) and distinct from both 62236 (Borg et al. 1999) and 60025 (Carlson and Lugmair 1988), which have trace element compositions more typical of lunar FANs. Strontium concentrations in plagioclase from 67215c (176 ppm) are within the range observed for lunar ferroan anorthosites (Hubbard et al. 1971; Floss et al. 1998; Papike et al. 1997; Carlson and Lugmair 1988; Alibert et al. 1994; Borg et al. 1999). The INAA data for mineral separates taken from 62236 show that the mafic fraction of this rock is strongly depleted in LREE and enriched in HREE relative to plagioclase, with the whole rock split having a composition consistent with a mixture of ~80–85 wt% plagioclase and 15–20 wt% mafics.

The Ni and Co contents of 67215c exceed those commonly found in more plagioclase-rich samples of ferroan anorthosite, but similar values were also measured in 62236 (Table 1) and probably relate to the greater abundance of mafic phases in these noritic anorthosites. The low Ni/Co

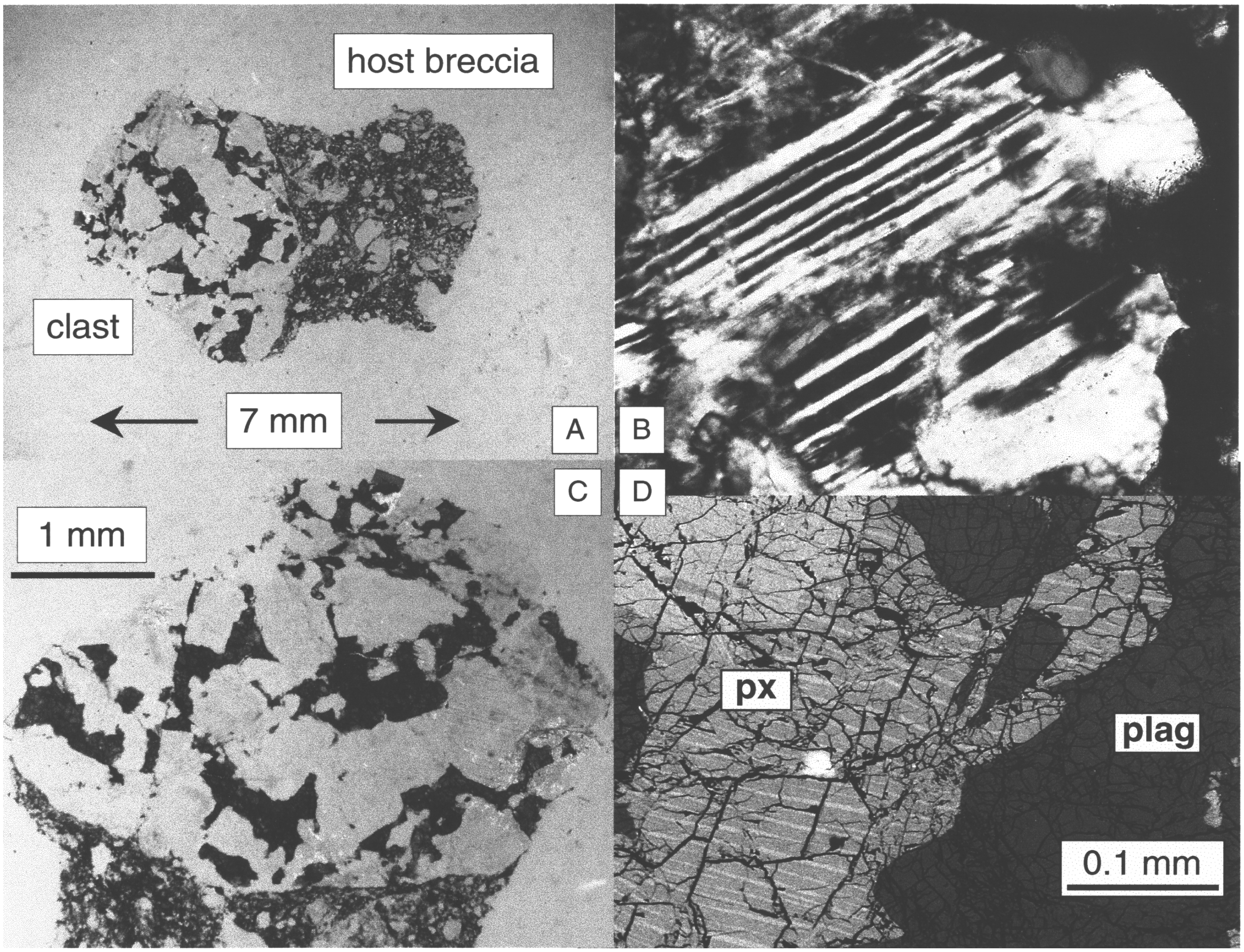

Fig. 1. Photomicrographs of the ferroan noritic anorthosite clast from breccia 67215: a) thin section 67215, 55 showing the contact between the clast analyzed for this study on the left and the host fragmental breccia on the right; b) a plagioclase grain in crossed-nichols showing the shock features and igneous twinning; c) close up view of the clast illustrating the well preserved igneous texture; d) backscatter image of a pyroxene grain showing the fine-scale exsolution lamellae indicating relatively rapid cooling and shallow depth of emplacement.

ratios of the 67215 clast (Ni/Co = 3.1) and host breccia (Ni/Co = 2.8) are similar to that of metal grains in the clast. The two splits of 62236 analyzed by ICPMS and INAA have disparate Ni (23 versus 8.7 ppm) and Co (18.7 versus 8.5 ppm) contents but similar Ni/Co ratios (1.0–1.2).

Sm-Nd Isotopes

The ^{147}Sm-^{143}Nd isotopic compositions of mineral separates from 67215c yield an isochron age of 4.40 ± 0.11 Gyr with an initial ε^{143}_{Nd} of +0.85 ± 0.53 (Fig. 7). Corrections for neutron exposure at the lunar surface were not necessary because Sm isotopic compositions measured on a split of the host breccia were normal. The positive initial Nd indicates a source region which experienced long-term LREE-depletion relative to chondritic reference values (CHUR; ^{147}Sm/^{144}Nd = 0.1967; ^{143}Nd/^{144}Nd = 0.511847; Wasserburg et al. 1981). 67215c is the fourth lunar ferroan noritic anorthosite to yield a Sm-Nd internal isochron age. Other previously dated samples include 60025 (4.44 ± 0.02 Gyr; Carlson and Lugmair 1988); a clast from breccia 67016 (4.53 ± 0.12 Gyr; Alibert et al. 1994), and 62236 (4.29 ± 0.06 Gyr; Borg et al. 1999). The ^{147}Sm/^{143}Nd ratios of mineral separates from 67215c are similar to those in 67016c (Alibert et al. 1994), with the mafic fractions having less extreme compositions than 62236 (Borg et al. 1999) and 60025 (Carlson and Lugmair 1988). Notable is the presence of a leachable component with highly radiogenic ^{143}Nd/^{144}Nd isotopic compositions in both the plagioclase and the pyroxene fractions of 67215c (Table 2), which was not included in the isochron calculation.

^{39}Ar-^{40}Ar Isotopes

For 67215c, the Ar-Ar ages generally increase slowly as the Ar extraction proceeds (Fig. 8a). A few of the early

Table 2. Sm-Nd isotopic compositions for lunar sample 67215,46.

Sample	Weight (mg)	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$
WR	119.99	0.3938	1.237	0.19258 ± 19	0.511767 ± 10
WR1	43.93	0.9286	2.812	0.19967 ± 20	0.511928 ± 10
WR2 (<325mesh)	9.32	1.294	3.900	0.20056 ± 20	0.511982 ± 12
Plag1	30.78	–	–	–	–
(residue)	–	0.2698	1.355	0.12042 ± 12	0.509695 ± 14
(leachate)	–	–	–	0.14532 ± 29	0.510851 ± 20
Plag2	22.66	–	–	–	–
(residue)	–	0.4295	1.748	0.14863 ± 15	0.510500 ± 17
(leachate)	–	–	–	0.15689 ± 37	0.511490 ± 11
Px + Ol	9.40	–	–	–	–
(residue)	–	1.466	3.697	0.23977 ± 24	0.513204 ± 14
(leachate)	–	–	–	0.16516 ± 55	0.515928 ± 17
Px	6.98	–	–	–	–
(residue)	–	3.886	9.152	0.25677 ± 26	0.513660 ± 13
(leachate)	–	–	–	0.20532 ± 168	0.512532 ± 10

extractions show higher apparent ages, probably due to the release of adsorbed atmospheric ^{40}Ar and ^{40}Ar released during melting of the Al foil that contained the sample. This sloped age spectrum is what would be expected if the clast had lost a small amount of its ^{40}Ar by diffusion. The clast age prior to such diffusive loss would be given by the average age of 3.93 ± 0.02 Gyr defined by the four extractions releasing ~62–100% of the ^{39}Ar. This is identical to the Ar-Ar age of 62236 (3.93 ± 0.04; Borg et al. 1999). Concentrations of K and Ca for both are essentially identical at 140 ppm K and 11.0–11.2% Ca and agree with the determinations given in Table 1.

The Ar-Ar age spectrum for the matrix sample (Fig. 8b) is more complex. While the matrix suggests older ages than the clast at high extraction temperatures, it also shows even greater diffusive loss of ^{40}Ar. The shape of the matrix age spectrum suggests that two different ^{40}Ar diffusion-loss profiles produce these sloped ages, one occurring over ~8–68% ^{39}Ar release, and another occurring over ~75–100% ^{39}Ar. These diffusion profiles correlate with 2 apparent peaks in the rate of release of Ar as a function of temperature and suggest the presence of 2 populations of K-bearing grains that differ slightly in their Ar diffusion properties. The heating event that produced ^{40}Ar diffusive loss in the matrix sample was later than 3.8 Gyr ago and possibly much later. This heating event may not have been experienced by the clast. The time of assembly of the 67215 breccia is unknown, and the greater ^{40}Ar loss shown by the matrix sample may have occurred prior to this brecciation event.

Yet another uncertainty affects the Ar-Ar ages. For both clast and matrix samples, the $^{36}Ar/^{38}Ar$ ratios for most extractions are larger than the ratio of ~0.7 expected from cosmic-ray production and indicate the presence of solar-wind ^{36}Ar and probably lunar-atmosphere ^{40}Ar. The trapped $^{40}Ar/^{36}Ar$ ratio in 67215 is unknown, and the Ar-Ar "plateau" age of 3.93 Gyr for the clast was determined by correcting for trapped $^{40}Ar/^{36}Ar$ = 5.0. Trapped $^{40}Ar/^{36}Ar$ ratios for several

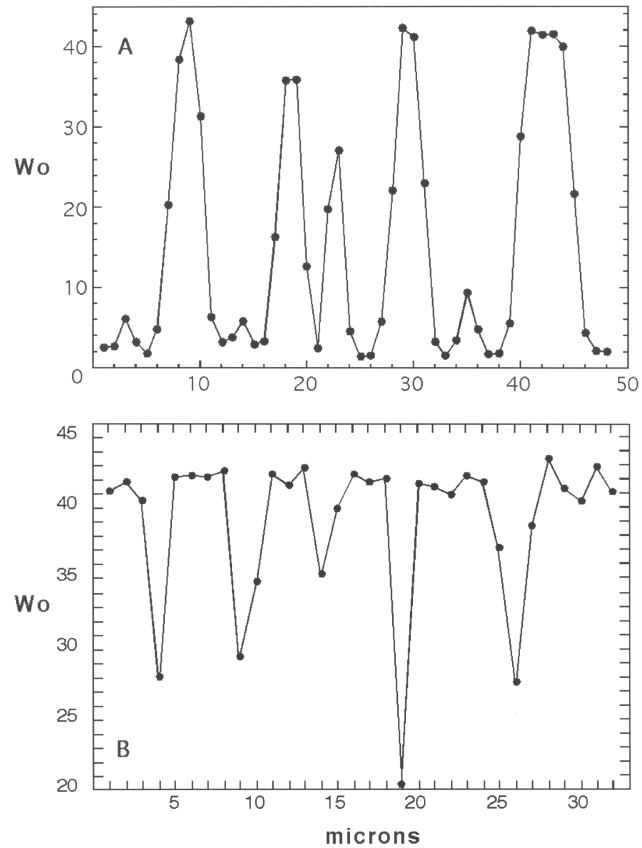

Fig. 2. Line scan electron microprobe traverses taken at 1 micron steps across two pyroxene grains in 67215c demonstrating the existence of fine (2–5 micron) exsolution lamellae in both (a) low-Ca and (b) high-Ca pyroxenes.

Apollo 16 regolith breccias lie in the range of <1 to ~12, and this ratio tends to be significantly larger for lunar samples that acquired their trapped gases early in lunar history (McKay et al. 1986). An isochron plot (R^2 = 0.994) of $^{40}Ar/^{36}Ar$ versus $^{39}Ar/^{36}Ar$ for 9 extractions of the clast releasing ~17–100% of the ^{39}Ar gives an age of 4.06 Gyr and a trapped $^{40}Ar/^{36}Ar$ intercept of –5.2 ± 2.8. This negative intercept (and the associated age) is without merit and gives no insight as to the trapped Ar composition. If we assume a trapped $^{40}Ar/^{36}Ar$ ratio of 1, the age plateau for the clast would be 3.99 Gyr. If we assume trapped $^{40}Ar/^{36}Ar$ = 10, this plateau age becomes 3.85 Gyr. Ar-Ar ages of the matrix would require similar corrections, except that the few highest temperature extractions require no correction and, thus, indicate that matrix ages of 3.9 Gyr are real.

All of these Ar-Ar ages are younger than the Sm-Nd isochron age because of the impact heating history of 67215. We conclude that the 67215 clast was last completely degassed 3.93 ± 0.08 Gyr ago, where the greatest contribution to the uncertainty in this age derives from a correction for lunar atmosphere ^{40}Ar. The Ar-Ar age spectra for the matrix and the clast suggest that subsequent, milder heating events also

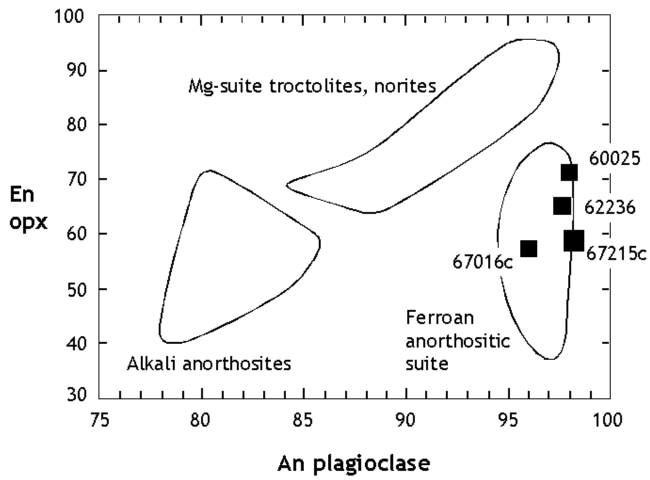

Fig. 3. Compositions of plagioclase (An) and low-Ca pyroxene (En) in the principal suites of lunar highlands igneous rocks. All four of the ferroan noritic anorthosites for which Sm-Nd isochrons have been obtained have mineral compositions consistent with a classification of these rocks as members of the ferroan anorthositic suite.

occurred. This Ar-Ar age of the clast could be consistent with the formation of one of several large lunar basins. For example, preferred (but not uncontested) lunar basin ages are ~3.92 Gyr for Nectaris, ~3.85–3.89 Gyr for Serenitatis and Crisium, and ~3.85 Gyr for Imbrium (Stöffler and Ryder 2001).

Rb-Sr Isotopes

Rb-Sr isotopes in 67215c have been disturbed and the data do not form an isochron. The whole rock (WR) + plagioclase compositions are consistent with an event at 3.93 ± 0.06 Gyr and an initial $^{87}Sr/^{86}Sr$ of 0.699104 ± 10 in the rock at that time (Fig. 9). Rb-Sr systematics of the mafic fractions in 67215c fall to the left of the 3.93 Gyr reference line, indicating unsupported radiogenic Sr possibly due to loss of volatile Rb during impact metamorphism (Borg et al. 1999). The $^{87}Sr/^{86}Sr$ ratios measured in the mafic fractions of 67215c are similar to those of 67016c (Alibert et al. 1994) and lower than the values measured for mafic fractions in 62236 (Borg et al. 1999), suggesting that the extent of Rb mobility in 67215c was less than that proposed for 62236 (Borg et al. 1999). $^{87}Rb/^{86}Sr$ ratios of plagioclase separates from 67215c are similar to those of 62236 and 67016c and less than those of 60025. In addition to having highly radiogenic $^{143}Nd/^{144}Nd$ compositions, the leachable component in 67215c also has radiogenic $^{87}Sr/^{86}Sr$ (Table 3).

Table 3. Rb-Sr isotopic compositions for splits of lunar sample 67215.

Sample	Weight (mg)	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
67215,46 (clast)					
WR	7.13	0.758	130.8	0.01676 ± 8	0.700066 ± 14
WR1	2.58	0.396	129.2	0.00887 ± 4	0.699718 ± 16
WR2 (<325 mesh)	9.32	0.385	132.4	0.00841 ± 4	0.699677 ± 11
Plag1	1.75	0.183	176.0	0.00301 ± 2	0.699273 ± 12
Plag1 (leachate)	–	–	–	0.03048 ± 15	0.703522 ± 11
Plag2	1.29	0.165	175.6	0.00272 ± 1	0.699260 ± 11
Plag2 (leachate)	–	–	–	0.03507 ± 18	0.703933 ± 14
Px + Ol	9.40	–	–	–	–
(residue)	–	0.0689	48.39	0.00412 ± 3	0.699514 ± 16
(leachate)	–	–	–	0.07946 ± 40	0.704495 ± 29
Px	6.98	–	–	–	–
(residue)	–	0.0238	10.78	0.00638 ± 11	0.700231 ± 17
(leachate)	–	–	–	0.04158 ± 60	0.709544 ± 42
67215,39 (host breccia)					
Mag	96.02	0.7404	113.4	0.01890 ± 9	0.700170 ± 12
Non-Mag	104.48	0.7275	154.9	0.01359 ± 7	0.699873 ± 12

DISCUSSION

Petrological and Geochemical Affinity of 67215c with the Ferroan Anorthosite Suite

To extract information about the magmatic and thermal history of the lunar crust, understanding the petrological and geochemical context of the ferroan noritic anorthosites is necessary. 60025 and 62236 have long been recognized as mafic members of the ferroan anorthositic suite of lunar highlands rocks and are, therefore, presumed to be linked genetically to the more common plagioclase-enriched members of the suite such as 15415 and 60015 (Dixon and Papike 1975; Dymek et al. 1975; Warren and Wasson 1977). Major element compositions of plagioclase and pyroxene also classify 67215c and 67016c as members of the ferroan anorthositic suite of lunar highlands rocks (Fig. 3 and 4). Whole rock trace element compositions of the ferroan noritic anorthosites have Ti/Sm and Sc/Sm ratios that fall within the range defined by other lunar ferroan anorthosites and which are distinct from the compositions of KREEP and Mg-suite norites and troctolites (Fig. 10). Plagiophile element compositions (e.g., Al/Eu, Sr/Ga, Sr/Eu) of the ferroan noritic anorthosites are also more like those of ferroan anorthosites than either Mg-suite norites and troctolites or KREEP (Fig. 11). This is consistent with our previous conclusion that the elevated abundances of incompatible trace elements in 67215c and 67016c cannot result from an admixed KREEP component (Fig. 6).

The possibility that the ferroan noritic anorthosites are mixed rocks is further mitigated by the unusually low Ni/Co ratios of the metal and the bulk rocks compositions, which are distinct from those of most meteorite-contaminated lunar impact melts (Hewins and Goldstein 1975; Ryder et al. 1980). This appears to be a primary magmatic feature of the ferroan noritic anorthosites. Nickel contents comparable to those of the ferroan noritic anorthosites (10–50 ppm) are not uncommon in monomict lunar rocks (Haskin and Warren 1991), and similar values for indigenous lunar crustal abundances have been inferred based on mixing relations of

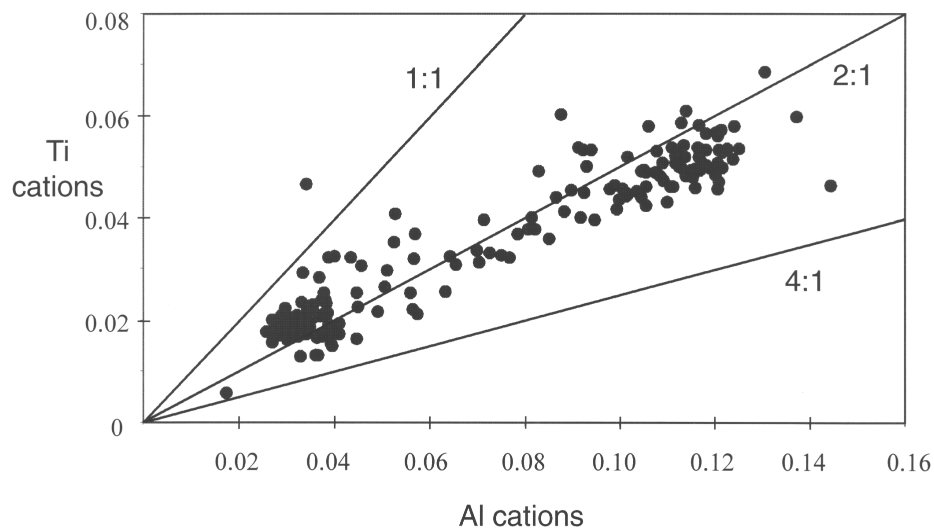

Fig. 4. Cation proportions of Al and Ti in pyroxenes (per 6 oxygens) in 67215c fall along a 2:1 correlation line, indicating crystallization of the pyroxenes from a magma saturated in plagioclase.

polymict highlands breccias (Palme 1980; Korotev 1987). From the combination of mineral compositions and diagnostic trace element signatures, we conclude that the petrological and geochemical features of 67215c and the other ferroan noritic anorthosites represent primary magmatic characteristics and that the petrogenesis of these rocks is closely linked with more plagioclase-rich varieties of lunar ferroan anorthosites.

Compared to other ferroan anorthositic suite rocks, 67215c and 67016c are unusual in having more abundant augite, ilmenite, and chromite, raising the possibility that 67215c and 67016c are part of a common magmatic system preserved in the Descartes breccias. Jolliff and Haskin (1995) showed that a set of soil particles collected from the rim of North Ray Crater belong to a coherent, ferroan magmatic suite that produced bulk compositions ranging from anorthosite to noritic anorthosite. Although most of these particles are fragmental or impact-melt breccias, the monomict varieties include noritic anorthosites with exsolved pyroxenes and trace quantities of both Cr-spinel and ilmenite, and 67016c and 67215c are both possibly related to this magmatic system. In contrast to 67016c, however, the subhedral granular texture of 67215c shows that this clast was not brecciated or metamorphosed significantly after it crystallized from a melt. The $Ti^{VI}Al_2^{IV}$ substitution inferred for pyroxenes in 67215c (Fig. 4) shows that this magma was already saturated in plagioclase, and the presence of exsolution lamellae in both high-Ca and low-Ca pyroxene in 67215c suggests that both pigeonite and augite (plus minor olivine) were magmatic phases.

Thermal modeling of pyroxene compositions in 67215c indicates emplacement of the magma at very shallow (≤0.5 km) depths in the lunar crust (McCallum et al. 2002). This is much more shallow than previously inferred depths of other ferroan anorthositic suite rocks such as 67075 and 60025, which have pyroxene compositions consistent with cooling at 14–20 km depth (McCallum and O'Brien 1996). Lithologies related to the ferroan anorthositic suite of lunar highlands rocks appear to be distributed through the middle and upper crust of the moon.

The primary magmatic lunar crust appears to have been grossly stratified, with a relatively mafic upper crust containing both ferroan and more magnesian lithologies underlain by relatively pure ferroan anorthosite at depth. This generalized view of the lunar crust is supported by remote sensing observations demonstrating regionally extensive layers of relatively pure anorthosite at mid-crustal depth (Hawke et al. 1993, 2002), the compositions of lunar meteorites (Korotev 2000), and recent studies of crustal stratigraphy based on lithologic units exposed in lunar craters (Wieczorek and Zuber 2001). In this context, 67215c and 67016c may represent samples of relatively shallow noritic anorthosite crust enriched in trapped liquid, while other ferroan anorthositic rocks such as 60025 and 62236 may represent adcumulates derived from greater depths and containing very little trapped liquid. If all of these samples crystallized from a common magmatic system as suggested by their coherent mineralogical and trace element characteristics, it must have been at least 20 km deep, and probably >45–60 km deep to account for the lack of complementary mafic and ultramafic cumulates in the lunar crust.

Ba-Sr in Plagioclase: Evidence Against a Depleted Parent Magma for Lunar Ferroan Anorthosites

One of the more provocative conclusions to come from previous Sm-Nd isotopic studies of lunar ferroan anorthositic suite rocks is that their parental magmas were derived from

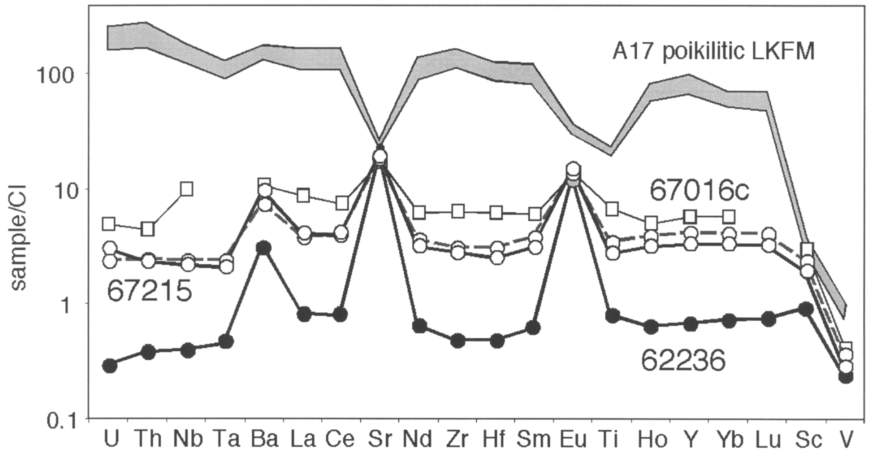

Fig. 5. Trace element compositions of 67215c (open circles, solid line), the 67215 host breccia (open circle, dashed line), 62236 (filled circles), and 67016c (open squares; Norman and Taylor 1992) normalized to chondritic abundances (Anders and Grevesse 1989) and compared with the compositions of Apollo 17 KREEP (data from Norman et al. 2002).

source regions that experienced long term depletions of LREE (i.e., high Sm/Nd), as indicated by their highly positive initial ε^{143}_{Nd} compositions (Borg et al. 1999). 62236 has the most extreme initial ε^{143}_{Nd} composition (ε^{143}_{Nd} = +3.1 at 4.29 Gyr), but all of the ferroan noritic anorthosites for which Sm-Nd isochrons are available show at least a modestly positive initial ε^{143}_{Nd} that is resolvably higher than the nominal chondritic reference values (Carlson and Lugmair 1988; Alibert et al. 1994; Borg et al. 1999; Fig. 7). The initial ^{143}Nd of 62236 implies a source region with a ^{147}Sm/^{144}Nd of 0.287 (Borg et al. 1999), similar to that of the high-Ti mare basalt cumulate source regions (Snyder et al. 1994; Nyquist et al. 1995). The conclusion that lunar ferroan anorthosites were derived from a fractionated and highly depleted source region would, if confirmed, provide a serious challenge to the magma ocean paradigm for lunar evolution.

In contrast to the highly depleted source composition implied by the apparent initial ^{143}Nd composition of 62236, whole rock trace element compositions of 62236 and 67215c provide little evidence for fractionated parental magma compositions or severe depletions of the highly incompatible elements (Fig. 5 and 6). In addition, REE compositions of parental liquids inferred from plagioclase and pyroxene compositions in lunar ferroan anorthosites typically show flat to slightly LREE-enriched, chondrite-normalized patterns (Hubbard et al. 1971; Phinney 1991; Papike et al. 1997; Floss et al. 1998; James et al. 2002) rather than the LREE-depletion implied by the positive initial ε^{143}_{Nd} compositions.

To investigate the composition of ferroan noritic anorthosite parental magmas in greater detail, we examined the Sr and Ba contents of plagioclase in lunar ferroan anorthosites. During the generation and evolution of basaltic magmas, Ba behaves as a highly incompatible element (similar to La), while Sr is somewhat more compatible (similar to Nd), so that a LREE-depleted source would be expected to also have a subchondritic Ba/Sr ratio, while crystallization of a lunar magma ocean would be expected to produce residual melts with a near-chondritic or slightly super-chondritic Ba/Sr ratio. Barium and Sr are both more compatible in plagioclase than the REE, and mineral-melt distributions are relatively well known (Blundy and Wood 1991; Bindeman et al. 1998), so this approach may provide a more robust indication of parental magma compositions than those based on highly incompatible elements.

Barium and Sr concentrations of plagioclase from lunar ferroan anorthosites were compiled, and melt compositions in equilibrium with the plagioclase were estimated using mineral-melt distribution coefficients (D) calculated from the regressions of Blundy and Wood (1991), assuming T = 1500 K and a plagioclase composition of An_{96}. The resulting values are D_{Sr} = 1.098 and D_{Ba} = 0.120. Plagioclase compositions were obtained primarily from published ion microprobe studies (Papike et al. 1997; Floss et al. 1998). Both of these studies include data for 60025. Floss et al. (1998) report ion microprobe data for five lithic clasts from breccia 67215, but did not include the specific clast described here. However, breccia 67215 is dominated by a specific ferroan noritic anorthosite lithology (McGee 1988), and the material analyzed by Floss et al. (1998) appears to be similar petrologically and geochemically to the clast that we studied. For 62236, laser ablation ICP-MS data were used (Norman et al. 1998b and unpublished data). For 67016c, plagioclase compositions were estimated from whole rock Sr and Ba data (Norman and Taylor 1992) assuming 70% plagioclase (Norman et al. 1995) and that all of the Sr and Ba in these rocks are contained in the feldspar. Neutron activation data were not used because Ba in many lunar FANs is near the detection limit for this technique (~10 ppm; Warren and Kallemeyn 1984; Palme et al. 1984) and, therefore, subject to large uncertainties.

For comparison, a simple crystallization model was calculated to illustrate the compositional evolution of a

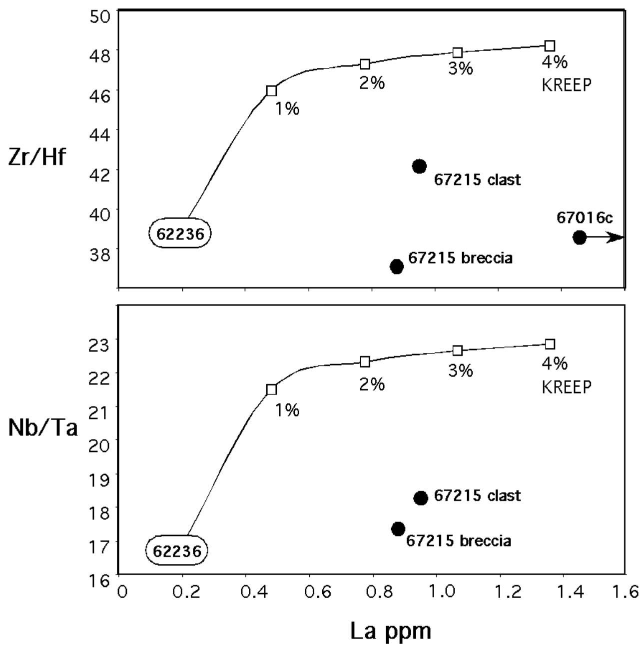

Fig. 6. A comparison of Zr/Hf and Nb/Ta ratios versus La concentrations predicted for mixtures of a ferroan anorthosite with low incompatible element concentrations (62236) and KREEP with those measured in the 67215 clast and host breccia, and 67016c (Norman and Taylor 1992). The relatively unfractionated Zr/Hf and Nb/Ta ratios in 67215 and 67016c show that the elevated concentrations of incompatible elements in these samples cannot be due to admixture of a KREEP component. The KREEP composition is the average of 11 Apollo 17 poikilitic impact melt rocks given by Norman et al. (2002). The compositions of 62236 and 67215 are from this study.

chondritic magma ocean. A magma ocean with initial concentrations 3× the CI-chondritic values of Anders and Grevesse (1989) was assumed (23.4 ppm Sr; 7.02 ppm Ba; Sr/Ba = 3.33), and residual melt compositions were calculated for 1% fractional crystallization increments, assuming bulk distribution coefficients of $D_{Sr} = 0.01$ and $D_{Ba} = 0.001$. This approximates the formation of mafic cumulates in the lunar mantle. Melt compositions in equilibrium with plagioclase from lunar FANs intersect the trend for residual liquids predicted by this model at about 75% crystallization (100 ppm Sr, 30.5 ppm Ba) and extend to higher Ba contents and higher Ba/Sr ratios (Fig. 12). Melts with high Ba contents and high Ba/Sr ratios can be produced by continued evolution of the magma during which plagioclase enters the crystallization sequence with ~25% residual liquid remaining and forms 50% of the crystallizing assemblage. This is consistent with the crystallization sequence and relative phase proportions calculated by Snyder et al. (1992) for a lunar magma ocean.

Plagioclase compositions in most lunar FANs are consistent with crystallization from a lunar magma ocean (Fig. 12). Melt compositions inferred from the plagioclase in 60025 and 62236 fall along the trend predicted for equilibrium crystallization after plagioclase has joined the crystallization sequence (Fig. 12). In contrast, melts in equilibrium with plagioclase in the 67215 clasts and 67016c apparently had much higher Ba contents and very high Ba/Sr ratios, unlike those of the other FANs. Floss et al. (1998) also recognized that the clasts in 67215 are not related in any simple way to the other lunar FANs. If all of the plagioclase in 67215c and 67016c is a cumulus phase, the melts from which these rocks crystallized would have been highly evolved, with some characteristics of KREEP (Fig. 12), although a simple mixture of FAN with KREEP can be ruled out by the bulk rock and mineral compositions (Floss et al. 1998; Fig. 6). Alternatively, plagioclase in 67215c and 67016c may not be completely cumulus in origin but may contain a greater fraction of trapped liquid than most other lunar FANs. Unfortunately, in this case, distribution coefficients cannot be used to infer trace element concentrations in the parental liquid without an independent estimate of the amount of trapped melt. Regardless of their exact origin, the superchondritic Ba/Sr of 67215c and 67016c shows that they cannot have been derived from a subchondritic or depleted source.

Although it is apparent that formation of lunar ferroan anorthosites and related rocks was a complex process, we conclude that: 1) there is no compelling evidence in the trace element compositions of these rocks for a source that was highly depleted in incompatible trace elements; and 2) the Ba-Sr relations in plagioclase from lunar ferroan anorthosites and related rocks are largely consistent with crystallization of a near-chondritic magma ocean. The fact that Ba and Sr contents of melts parental to FANs cluster between the equilibrium and fractional crystallization trajectories (Fig. 12) may indicate complexities in magma ocean evolution that could be traced through additional petrological and geochemical studies (Raedeke and McCallum 1979; Longhi 2002).

Disturbance in the Plagioclase Fraction: Effects on Sm-Nd Isochrons

Accepting the nominal Sm-Nd isochron ages for the ferroan noritic anorthosites at face value would imply an extended formation interval for ferroan anorthosites that spans the first 250 million years of lunar history (4.54–4.29 Gyr). Thermal models of lunar evolution do not rule out this possibility but do suggest that this is near the limit expected for crystallization of a magma ocean, even when the insulating effects of a megaregolith on the primordial crust are considered (Warren et al. 1991; Longhi 2002). This range of ages would imply that crystallization of ferroan anorthosites continued until the time of Nd isotopic closure of the lunar interior, as indicated by the isotopic compositions of lunar mare basalts (~4.32 Gyr; Nyquist et al. 1995) and KREEP model ages (~4.36 Gyr; Carlson and Lugmair 1979).

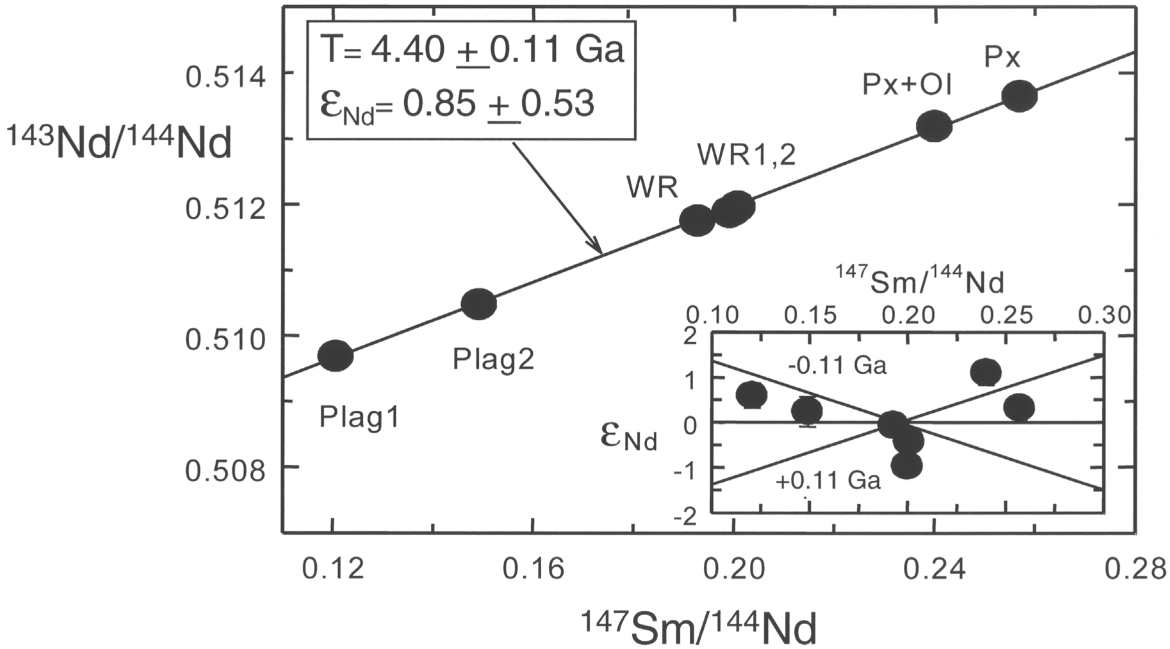

Fig. 7. Mineral separates from the 67215 ferroan noritic anorthosite clast form a ^{147}Sm-^{143}Nd isochron indicating an igneous crystallization age of 4.40 + 0.11 Gyr and an initial ε^{143}_{Nd} isotopic composition of +0.85 ± 0.53.

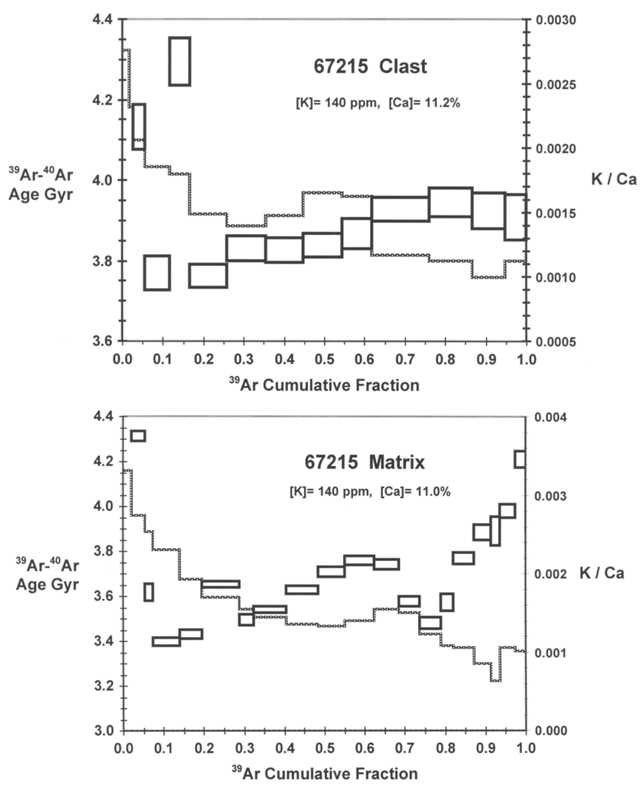

Fig. 8. ^{39}Ar-^{40}Ar ages (rectangles) and K/Ca ratios (stepped line) plotted against cumulative release of ^{39}Ar from stepwise temperature extractions of samples of (a) the 67215 clast and (b) a matrix sample from the 67215 fragmental host breccia. The release profile from the 67215 clast is consistent with an impact heating event at 3.93 ± 0.08 Gyr, with the greatest contribution to the quoted error arising from uncertainty over the composition of trapped lunar argon.

The range of ages and the LREE-depleted nature of the ferroan anorthosite source region that is implicit in the positive initial ^{143}Nd of these rocks clearly would require a new view of magmatism and crustal evolution on the moon. This interpretation has not been universally accepted. For example, Shearer et al. (2002) explored various alternatives and suggested that the young age and elevated initial ^{143}Nd of 62236 could be "totally meaningless" due to re-equilibration, mixing, or disturbance during large impact or thermal metamorphic events.

Borg et al. (1999) considered it unlikely that disturbance or re-equilibration of the Sm-Nd isotopic systematics in 62236 would produce either an isochron or an elevated initial ε^{143}_{Nd}. However, examples of unrealistically positive initial ε^{143}_{Nd} isotopic compositions indicated by ^{147}Sm-^{143}Nd mineral isochrons have also been found in primitive meteorites (Prinzhofer et al. 1992; Yamaguchi et al. 2001). In the study by Prinzhofer et al. (1992), well-behaved Sm-Nd isochrons gave initial ^{143}Nd values of +1.6 at 4.46 Gyr, and +2.1 at 4.47 Gyr for the eucrite Ibitira and silicate phases from the mesosiderite Morristown, respectively. These initial ^{143}Nd values would imply source compositions even more fractionated and LREE-depleted than that inferred for 62236, despite the relatively unfractionated Sm/Nd ratio and REE pattern of the eucrite and relatively modest LREE depletion in Morristown. Prinzhofer et al. (1992) concluded that the ^{147}Sm-^{143}Nd mineral isochrons of Ibitera and Morristown were disturbed, and they present a model in which plagioclase partially equilibrated with cogenetic phosphate at a younger time, while pyroxenes retained their primary isotopic compositions. This mechanism is capable of producing partially rotated isochrons that yield

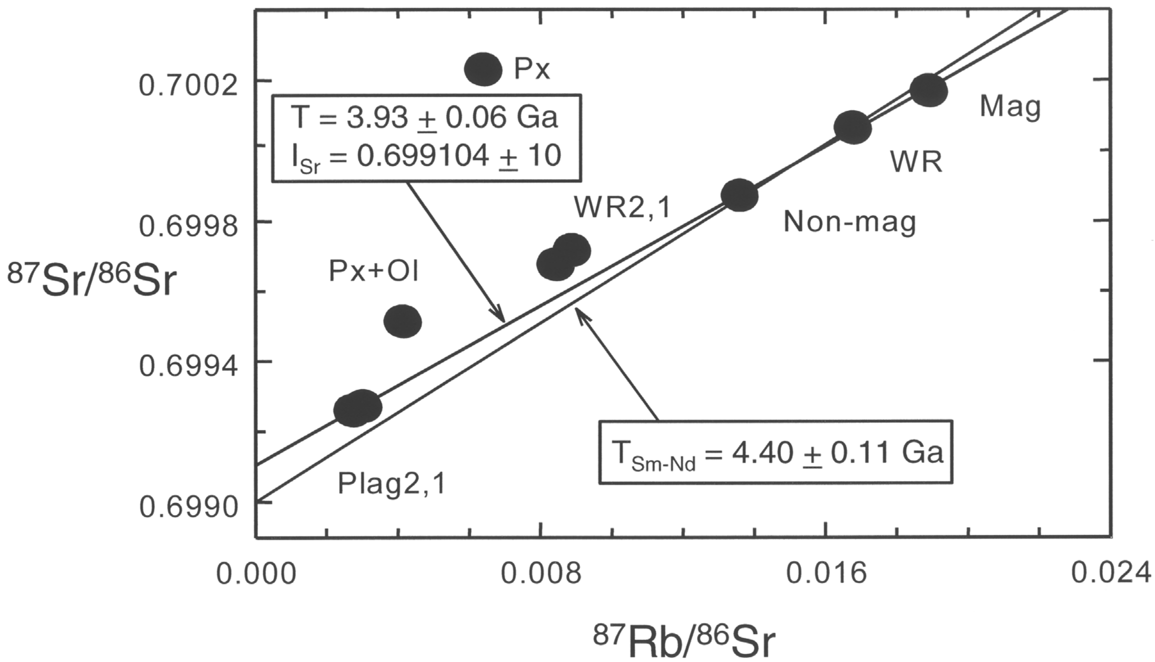

Fig. 9. Rb-Sr isotopic compositions of mineral separates in the 67215 ferroan noritic anorthosite have been disturbed and do not form an isochron. A plagioclase-whole rock tie line indicates an event at 3.93 ± 0.06 Gyr, consistent with the Ar-Ar age.

shallower slopes and, therefore, artificially younger ages with positive apparent initial ^{143}Nd values. Evidence for this process in Ibitira and Morristown include a wide scatter of ^{147}Sm-^{143}Nd model ages in the plagioclase fractions (4.18–4.63 Gyr) compared to the pyroxene fractions (4.56–4.59 Gyr; Prinzhofer et al. 1992). Yamaguchi et al. (2001) also concluded that the positive initial ^{143}Nd for eucrite EET 90020 (+1 ± 0.5) reflects transfer of radiogenic ^{143}Nd into the plagioclase during a subsequent heating event.

We suggest that a similar process may have affected the ^{147}Sm-^{143}Nd systematics of at least some of the ferroan noritic lunar anorthosites, and that the young age and highly positive initial ^{143}Nd of 62236 in particular may reflect open system behavior of plagioclase subsequent to its crystallization. Evidence for this is provided by a comparison of ^{147}Sm-^{143}Nd model ages in coexisting plagioclase and pyroxene. For this comparison, we normalized the Sm-Nd isotopic data for 67215c (this study), 62236 (Borg et al. 1999), 67016c (Alibert et al. 1994), and 60025 (Carlson and Lugmair 1988) to a common basis and calculated model ages for the plagioclase and pyroxene fractions relative to the Murchison carbonaceous chondrite analyzed by Alibert et al. (1994). Model ages for plagioclase in the noritic anorthosites span a greater range (3.94–4.83 Gyr) than the pyroxenes (4.41–4.60 Gyr) (Fig. 13), but the average model age is similar for both the plagioclase (4.42 Gyr) and pyroxene (4.47 Gyr) fractions of these rocks. 62236 and 67016c show relatively large differences in model ages for plagioclase compared to the mafic fractions of these rocks, with plagioclase model ages displaced to younger and older values, respectively (Fig. 13). In contrast, model ages for plagioclase from 67215c and 60025 agree reasonably well with those of the pyroxenes from these samples.

One possibility is that the wide range of model ages in the plagioclase fraction of these rocks reflects multi-stage evolution of the ferroan noritic anorthosites and derivation from sources that ranged from strongly LREE-depleted (62236) to relatively chondritic (67215c, 60025) to LREE-enriched (67016c). However, there is no compelling evidence for such a diversity of source compositions in the mineralogy or trace element compositions of lunar FANs. Alternatively, the ^{147}Sm-^{143}Nd systematics of plagioclase in 67016c and 62236 may have been disturbed, producing isochron ages which are too old and too young, respectively. The presence of disturbed components in plagioclase from 67016c was recognized by Alibert et al. (1994), who showed that, if they were included in the isochron age calculation, some plagioclase fractions from this clast have anomalously low ^{143}Nd/^{144}Nd compositions, producing an unrealistically old age and a negative initial ε^{143}_{Nd} isotopic composition (ε^{143}_{Nd} = –1.3 at 4.66 Gyr), while the pyroxenes were only marginally affected by this disturbance.

However, the comparison between primitive meteorites and the lunar noritic anorthosites may be flawed because the meteorites contain REE-enriched phosphates that provide considerable leverage for partial re-equilibration with the plagioclase (Prinzhofer et al. 1992; Yamaguchi et al. 2001). In contrast, no phosphate has ever been found in any lunar ferroan anorthosite, including 67215c, despite a specific and detailed search for such phases in the interstitial regions of

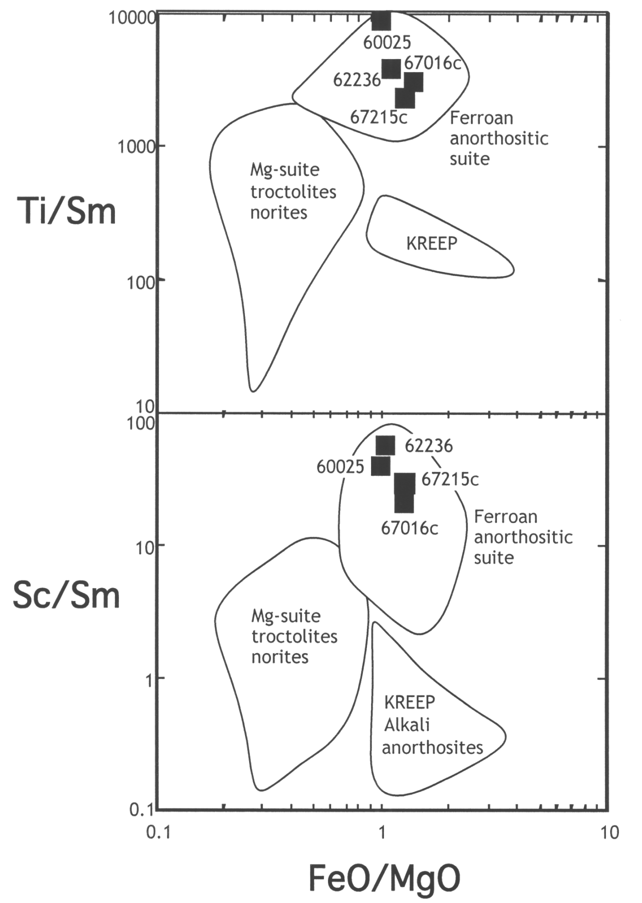

Fig. 10. A comparison of the diagnostic trace element rations Ti/Sm and Sc/Sm versus FeO/MgO in 67215c, 60025, 62236, and 67016c with the compositions of the principal suites of lunar highlands igneous rocks. The trace element ratios are consistent with a classification of these rocks as relatively mafic members of the ferroan anorthositic suite. The trace element compositions of the ferroan noritic anorthosites demonstrate a lack of KREEP component or affinity with the Mg-suite of lunar highlands cumulates.

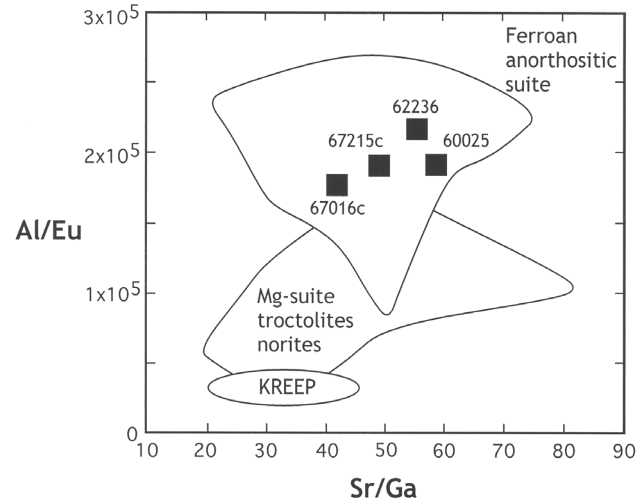

Fig. 11. Plagiophile trace element ratios such as Al/Eu, Sr/Eu, and Sr/Ga are consistent with a geochemical affinity of 67215c, 60025, 62236, and 67016c with the ferroan anorthositic suite of lunar highlands rocks.

this clast using backscatter imaging and electron microprobe analysis. In addition, Prinzhofer et al. (1992) assumed that Ibitira had been shock heated at a time much later than the true crystallization age (i.e., <4 Gyr ago), while this meteorite actually shows an Ar-Ar age of 4.49 Gyr (Bogard and Garrison 1995). An extended discussion of the origin of the Nd isotopic disturbance in the primitive meteorites is beyond the scope of the current study, but evidence exists for the presence of cryptic trace element-enriched phases or components in at least some of the lunar noritic anorthosites, which might provide the necessary leverage to account for a Nd isotopic disturbance of the plagioclase in these rocks. Although the brecciated nature of 62236 makes a detailed search for such phases difficult, laser ablation ICPMS studies of mineral separates from this sample show that clinopyroxenes in this rock are highly enriched in REE and other incompatible elements compared to plagioclase (Norman et al. 1998b). These trace element-enriched pyroxenes cannot represent cumulus phases that cocrystallized with the plagioclase in this rock. Alternatively, they may reflect late-stage crystallization of more evolved melt or exsolution from original pigeonite rather than primary cumulate phases (James et al. 2002). If these pyroxenes have highly radiogenic $^{143}Nd/^{144}Nd$, as predicted from their REE patterns, partial equilibration might account for the disturbed Nd isotopic compositions of plagioclase in 62236. The texture of 67106c also indicates a complex history involving brecciation and recrystallization (Norman et al. 1991, 1995), and a cryptic phase with elevated Sm-Nd concentrations was invoked by Alibert et al. (1994) to explain the disturbed plagioclase compositions in 67016c.

There may also be evidence of a suitable cryptic component in the Nd isotopic data from 67215c. All plagioclase and mafic fractions from this clast contain a leachable component that is more LREE-enriched than the whole rock, with the leachate from the Px + Ol fraction having a highly radiogenic $^{143}Nd/^{144}Nd$ (Table 2). The origin of this leachable component and possible relations to other phases in this rock are unclear, but isotopic exchange or physical transfer of a small amount of such material into the plagioclase during an impact or thermal metamorphic event might be sufficient to produce a rotated isochron with an elevated apparent initial ^{143}Nd isotopic composition such as that observed in 62236. Unfortunately, the lack of concentration data for this component in 67215 makes it difficult to model such a process quantitatively.

Formation Age of Lunar Ferroan Anorthosites: A Mafic Array

The narrow range of model ages for pyroxenes in the noritic anorthosites raises the possibility that all of these

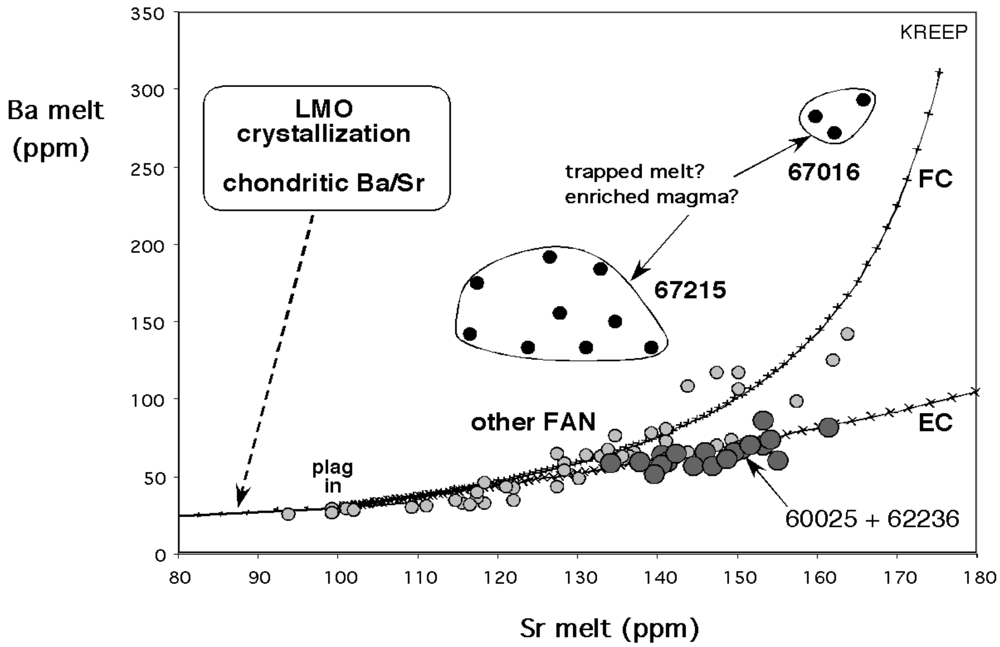

Fig. 12. A comparison of the Sr and Ba compositions of melts in equilibrium with plagioclase in ferroan anorthositic suite rocks with compositional trends predicted by crystallization models of a chondritic lunar magma ocean. Most ferroan anorthositic suite rocks, including 60025 and 62236 (dark circles), have compositions consistent with fractional (FC) or equilibrium (EC) crystallization of an evolved lunar magma ocean and show no evidence of a fractionated or highly depleted source with low Ba and Sr contents and low Ba/Sr ratios such as that implied by the measured initial $\varepsilon^{143}{}_{Nd}$ isotopic composition of 62236 (Borg et al. 1999). The compositions of melts inferred to be in equilibrium with plagioclase in 67215c and 67016c fall off the crystallization trends, possibly due to a greater component of trapped liquid in these samples compared to other ferroan anorthositic suite rocks.

samples may be related to a common crystallization event. A ^{147}Sm-^{143}Nd "isochron" based only on the mafic fractions of the four ferroan noritic anorthosites gives an apparent age of 4.46 ± 0.04 Gyr (Fig. 14). This approach is valid provided that all of these rocks crystallized from a coherent magmatic system with a common initial isotopic composition. Although the MSWD for this array is larger than would be accepted for a true isochron (MSWD = 6.5), we propose that this result provides a reasonable estimate for the crystallization age of the ferroan noritic anorthosites and the best estimate currently available of the time at which the ferroan anorthositic crust formed on the moon. The Sm-Nd mineral isochron ages of 60025 (4.44 ± 0.02 Gyr), 67215c (4.40 ± 0.11 Gyr), and 67016c (4.54 ± 0.12 Gyr) are all consistent with this age within the error limits, while the nominal isochron age of 62236 is resolvably younger (4.29 ± 0.06 Gyr). The relatively large variation of Sm/Nd in the mafic fractions from these rocks would not be unusual for a cogenetic suite of igneous cumulates, as shown by the diverse LREE patterns observed in clinopyroxene separates from anorthosites in the Stillwater igneous complex (Salpas et al. 1983) and may reflect variable proportions of cumulus phases and trapped liquid. The higher Mg# and more fractionated Sm/Nd in pyroxenes from 60025 and 62236 compared to 67215c and 67016c may be consistent with a greater proportion of cumulus pyroxene in the former.

The initial $\varepsilon^{143}{}_{Nd}$ indicated by the mafics-only isochron is indistinguishable from the chondritic value, albeit with a large uncertainty due to lack of control at low Sm/Nd ratios ($\varepsilon^{143}{}_{Nd}$ = +0.8 ± 1.4; Fig. 14). Using a similar approach, Nyquist et al. (2002) showed that including recent data from an anorthositic clast in lunar meteorite Yamato-86032 (clast GC) in the array yielded a similar age (4.49 ± 0.09 Gyr) and an initial $\varepsilon^{143}{}_{Nd}$ identical to the chondritic value with a reduced uncertainty ($\varepsilon^{143}{}_{Nd}$ = 0.0 ± 0.8). The initial $\varepsilon^{143}{}_{Nd}$ values indicated by these arrays are consistent with those expected for crystallization of a chondritic magma ocean and suggest that positive $\varepsilon^{143}{}_{Nd}$ values were not a universal feature of the early anorthositic lunar crust. The $\varepsilon^{143}{}_{Nd}$ values of 60025 (+0.9 ± 0.5; Carlson and Lugmair 1988) and 67215c (+0.8 ± 0.5; this study) are within error of the initial ^{143}Nd isotopic compositions indicated by the mafic-only arrays.

CONCLUSIONS

The petrology, geochemistry, and isotope geochronology of ferroan noritic anorthosite clast from lunar breccia 67215 provides crucial clues to the age, origin, structure, and impact history of the lunar highlands crust. The mineralogy and trace element composition of this clast (67215c) demonstrate a clear petrologic and geochemical affinity with the ferroan anorthositic suite of lunar highlands rocks. However, the clast is unusual in preserving evidence for a relatively shallow origin and greater amounts of trapped melt than is commonly

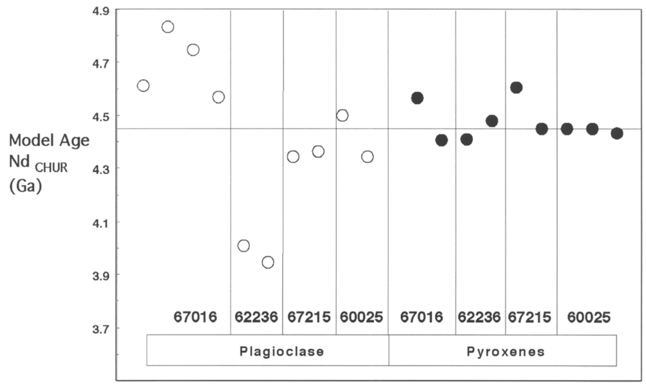

Fig. 13. A comparison of Nd model ages relative to chondrites for plagioclase and mafic mineral fractions of the noritic ferroan anorthosites 67215c, 60025, 62236, and 67016c. Plagioclase and pyroxene fractions from 67215c and 60025 give similar model ages of ~4.45 Gyr, while 62236 and 67016c show large discrepancies between the plagioclase and pyroxene fractions. Plagioclase in 62236 and 67016c may have been disturbed, possibly by impact metamorphism, while the mafic fraction in all of these rocks remained relatively resistant to this disturbance.

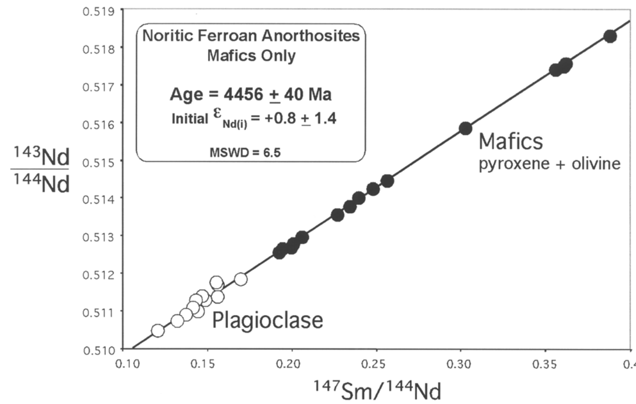

Fig. 14. The Sm-Nd isotopic compositions of mafic fractions from the ferroan noritic anorthosites 67215c, 62236, 60025, and 67016c form an array indicating an age of 4.46 ± 0.04 Gyr and an initial $\varepsilon^{143}{}_{Nd}$ value indistinguishable from chondritic. This may represent a relatively robust estimate for the crystallization age of the ferroan anorthositic lunar crust. The isochron was calculated using the ISOPLOT program (Ludwig 1999).

found in ferroan anorthosites. A ^{147}Sm-^{143}Nd internal isochron obtained from 67215c indicates a primary crystallization age of 4.40 ± 0.11 Gyr and an initial $\varepsilon^{143}{}_{Nd}$ of +0.85 ± 0.53. Crystallization ages of ≥4.4 Gyr have now been determined for two ferroan noritic anorthosites from the feldspathic fragmental breccias that were collected around North Ray crater (Alibert et al. 1994; this study). These Descartes breccias appear to carry very old and relatively little modified crustal components that were derived from a region of the moon distinct from the KREEPy near side terrains and may be more representative of the overall composition of the lunar crust than would be indicated by the majority of highlands breccias from other landing sites. ^{40}Ar-^{39}Ar and Rb-Sr isotopic compositions of plagioclase from 67215c and the host breccia indicate a significant thermal event at ~3.93 Gyr, although uncertainties in corrections for lunar atmospheric argon preclude assignment of this age to a specific basin.

Of the 4 ferroan noritic anorthosites that have now been dated by Sm-Nd isochrons, 67215c (this study) and 60025 (Carlson and Lugmair 1988) appear to best retain their primary age characteristics, while 67016c (Alibert et al. 1994) and 62236 (Borg et al. 1999) show evidence for isotopic disturbance. The effects of this disturbance are primarily in the plagioclase fraction, and we propose that the young age (4.29 ± 0.06 Gyr) and elevated initial $\varepsilon^{143}{}_{Nd}$ of 62236 (+3.1 ± 0.9; Borg et al. 1999) is due to this disturbance. The exact mechanism by which this disturbance occurs is unclear, but it may be related to redistribution of highly radiogenic components such as that found in 67215c during impact metamorphism of the lunar crust. Pyroxenes in the ferroan noritic anorthosites seem to have been more resistant to this disturbance, and yield an ^{147}Sm-^{143}Nd array indicating an age of 4.46 ± 0.04 Gyr. This may provide a robust estimate for the primary crystallization age of ferroan anorthosites and solidification of the early lunar crust. The initial $\varepsilon^{143}{}_{Nd}$ indicated by the "mafics-only" array is indistinguishable from the chondritic value, with a large uncertainty ($\varepsilon^{143}{}_{Nd}$ = 0.8 ± 1.4). Trace element systematics of plagioclase from ferroan anorthosites are also consistent with crystallization from an evolved magma ocean having near-chondritic relative abundances of refractory lithophile elements, rather than a fractionated and highly depleted source.

Acknowledgments–This work was supported by the NASA Cosmochemistry Program, the Lunar and Planetary Institute, and the Australian Research Council. Enlightening discussions with John Longhi, Randy Korotev, Stu McCallum, Paul Warren, and Marilyn Lindstrom are appreciated, as are journal reviews by Christine Floss and Jeff Taylor. Craig Schwandt, Henry Wiesmann, Chi-yu Shih, Dan Garrison, and David Mittlefehldt provided expert laboratory support and advice.

Editorial Handling—Dr. Randy Korotev

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