

Geochemistry and mineralogy of a feldspathic lunar meteorite (regolith breccia), Northwest Africa 2200

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Abstract

The lunar meteorite Northwest Africa (NWA) 2200 is a regolith breccia with a ferroan feldspathic bulk composition ($\text{Al}_2\text{O}_3 = 30.1 \text{ wt.}\%$; $\text{Mg}^\# = \text{molar } 100 \times \text{Mg}/(\text{Mg} + \text{Fe}) = 59.2$) and low Th content ($0.42 \mu\text{g/g}$). Lithologically, NWA 2200 is a diverse mixture of lithic and glassy clasts, mineral fragments, and impact glass spherules, all embedded in a dark glassy matrix. NWA 2200 contains some feldspathic brecciated rock components (ferroan anorthositic granulitic breccia, poikiloblastic granulitic breccia, and glassy melt breccia with an intersertal texture). The bulk compositions of these brecciated components indicate they are derived from ferroan troctolitic or noritic anorthosite lithologies (bulk $\text{Al}_2\text{O}_3 = 26\text{--}30 \text{ wt.}\%$; bulk $\text{FeO}/\text{MgO} > 1.0$). The bulk composition of NWA 2200 is more ferroan and feldspathic than the Apollo feldspathic regolith samples and feldspathic lunar regolith meteorites, and is also more depleted in incompatible elements (e.g., rare earth elements) than Apollo 16 feldspathic regolith samples. We conclude that NWA 2200 originated from a location different to the Apollo landing sites, and may have been sourced from the ferroan KREEP-poor highlands, “KREEP” materials are enriched in such elements as potassium (K), rare earth elements (REE), phosphorus (P).

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1. Introduction

Numerous meteorites have recently been found and collected in the North African desert. Some of these have been categorized as being meteorites that originated from the Moon. These lunar meteorites provide

information about areas of the Moon not sampled by the Apollo and Luna missions, which collected samples from a relatively small and geochemically anomalous region of the lunar surface (Warren and Kallemeyn, 1991). Therefore, lunar meteorites can be used to develop more representative geochemical datasets from which it is possible to evaluate lunar petrogenesis. In particular, it is likely that feldspathic lunar meteorites with low incompatible element

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abundances originate from the inner and outer regions of the Feldspathic Highlands Terrane (FHT). These meteorites represent a variety of lunar highlands crustal lithologies (e.g., Arai et al., 2008; Cahill et al., 2004; Joy et al., 2010; Korotev et al., 2003; Palme et al., 1991; Takeda et al., 2006; Treiman et al., 2010; Warren et al., 2005; Yamaguchi et al., 2010).

We report here the geochemistry, petrology, and mineralogy of the feldspathic lunar meteorite Northwest Africa (NWA) 2200. This stony meteorite weighing 552 g was found in Morocco (Connolly et al., 2006). Our study is the first to present a detailed examination of the bulk major and trace element composition, petrology, and mineralogy of NWA 2200, although brief descriptions of the geochemistry (Korotev et al., 2008; Nagaoka et al., 2008, 2009), and petrology and mineralogy (Kuehner et al., 2005; Nagaoka et al., 2008, 2009) have been reported elsewhere as conference abstracts. This study combines bulk chemical results obtained by neutron-induced prompt gamma ray analysis (PGA) and instrumental neutron activation analysis (INAA) with mineral descriptions and compositions determined by scanning electron microscope (SEM) and electron probe microanalyzer (EPMA), respectively. Our new geochemical and mineralogical results for NWA 2200 allow us to compare it with other feldspathic lunar meteorites and Apollo rock samples, and to infer its petrogenesis.

2. Bulk chemistry of NWA 2200

NWA 2200 is a lunar feldspathic breccia (Connolly et al., 2006). A 233 mg slice of NWA 2200 was used in this study. The sample separation procedures for NWA 2200 and analytical methods applied to each sample are presented in Fig. 1.

2.1. Neutron activation analysis

For PGA, the slice of NWA 2200 was first sealed in a thin fluorinated ethylene polyethylene film bag and irradiated for 2 h with a thermal neutron beam (flux: $1.6 \times 10^8 \text{ cm}^{-2} \text{ s}^{-1}$) from the Japan Research Reactor (JRR-3M) at the Japan Atomic Energy Agency, Ibaraki, Japan. At the same time, the prompt gamma rays emitted from the sample were measured for 2 h. Elemental concentrations in the sample were determined by comparison with the response to the JB-1 standard (a geochemical reference sample issued by the Geological Survey of Japan) treated with the same procedures (Imai et al., 1995a, b; Terashima et al., 1994).

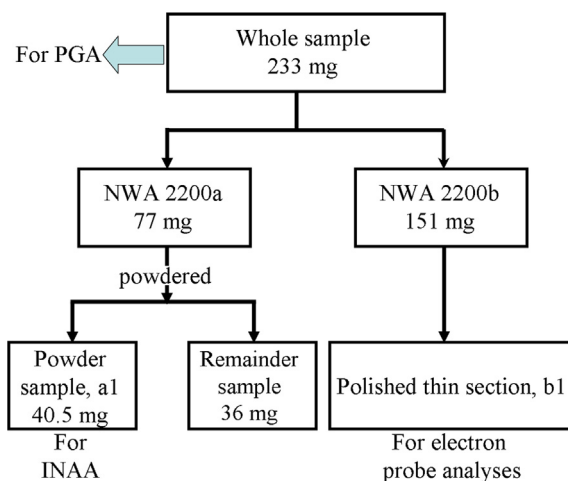


Fig. 1. Sample separation procedures for NWA 2200 and the analytical methods used for each sample.

A description of the PGA procedures can be found in Latif et al. (1999).

After a two-month cooling period, the slice of NWA 2200 was divided into two pieces for further chemical and mineralogical analyses (77 mg = NWA 2200a; 151 mg = NWA 2200b). NWA 2200a was used for chemical analysis and ground to a powder in a clean agate mortar. A 40.5 mg fraction of the powdered sample (powder sample, a1) was used for INAA, and was irradiated two times with different irradiation periods, which were adjusted in accordance with the half-lives of nuclides used for the determination of elemental concentrations. The powder sample, a1 was sealed in high-purity polyethylene bags and irradiated with thermal neutrons at the PN-3 (flux = $1.5 \times 10^{13} \text{ cm}^{-2} \text{ s}^{-1}$) in the Japan Research Reactor (JRR-3M) of the Japan Atomic Energy Agency for 10 s. After a few minutes of cooling after irradiation, gamma rays emitted from the sample were measured for 5 min. JB-1 was used as a reference standard.

After approximately 1 yr of cooling, the powder sample, a1 was re-irradiated for 10 min with thermal neutrons at HR-1 (flux = $9.6 \times 10^{13} \text{ cm}^{-2} \text{ s}^{-1}$) in the Japan Research Reactor (JRR-3M) of the Japan Atomic Energy Agency. After irradiation, gamma rays emitted from the sample were measured several times over different cooling times at the RI Research Center of Tokyo Metropolitan University, Tokyo, Japan. Both JB-1 and an Allende meteorite reference sample issued by the Smithsonian Institute (Washington DC, USA) (Jarosewich et al., 1987) were used as reference standards. Details of the INAA procedures are given in Shirai and Ebihara (2004).

Uncertainties on the analyses are due to: (1) counting statistics (1σ) on gamma ray counting for elements in NWA 2200 and the reference standards; (2) the accuracy of our JB-1 and Allende standard measurements relative to the preferred literature concentration values (JB-1: Imai et al., 1995a, b; Terashima et al., 1994; Allende: Jarosewich et al., 1987). For the PGA, NWA 2200 measurement has a total relative precision error range of between 1.1% (Al) and 28.0% (Mn) for all the analyzed elements, whereas the JB-1 standard measurement has a total relative precision error range of between 1.4% (Na) and 12.5% (Mn) for all the analyzed elements. For the INAA with irradiations of 10 s, the NWA 2200 measurement has a total relative precision error range of between 0.5% (Al) and 31.4% (V), whereas the JB-1 standard measurement has a total relative precision error range of between 0.6% (Al) and 6.0% (Mg) for all the analyzed elements. For the INAA with irradiations of 10 min, the NWA 2200 measurement has a total relative precision error range of between 0.1% (Na) and 23.0% (Au), whereas the JB-1 standard measurement has a total relative precision error range between 0.1% (Sc, Cr, and Fe) and 29.4% (Ga) and the Allende standard measurement has a total relative precision error range of between 0.3% (Ir) and 4.4% (Au) for the elements analyzed (Ni, Ir, and Au). Accuracies of the JB-1 standard measurements relative to the preferred literature values (Imai et al., 1995a, b; Terashima et al., 1994) have a percent error relative difference between 0.8% (Si) and 27.0% (Ta) for all elements. Accuracies of the Allende standard measurements relative to the preferred literature values (Jarosewich et al., 1987) have a percent error relative difference between 1.4% (Ni) and 12.2% (Ir) %. The information of uncertainties on the analyses is summarized in Appendices Ia–b.

2.2. Bulk major and trace element results

Bulk elemental concentrations of NWA 2200 were obtained by PGA and INAA (Appendix I). FeO concentrations of NWA 2200 (3.51 wt.% by PGA; 3.31 wt.% by INAA) were estimated from the total Fe⁰ and Fe²⁺ contents, as Fe⁰ and Fe²⁺ could not be measured independently by our analytical methods. Table 1 presents the bulk chemical composition of NWA 2200, and also compares our data with the preliminary bulk data for this meteorite (Korotev et al., 2008) and the average composition of feldspathic lunar meteorites (“surface of typical feldspathic lunar crust”; Korotev et al., 2003). Silicon cannot be

Table 1

Elemental compositions of NWA 2200 (this work; Korotev et al., 2008) and typical feldspathic lunar crust (Korotev et al., 2003).

Oxide (wt.%)	NWA 2200 (This work)	NWA 2200 (Korotev et al., 2008)	Typical feldspathic lunar crust (Surface) (Korotev et al., 2003)
SiO ₂	42.9 (1.9)	n.r.	44.7 (0.3)
TiO ₂	0.17 (0.02)	n.r.	0.22 (0.04)
Al ₂ O ₃	30.1 (0.6)	n.r.	28.2 (1.0)
Cr ₂ O ₃	0.0693 (0.0102)	0.0737	0.096 (0.014)
FeO	4.26 (0.15)	3.95	4.4 (0.5)
MnO	0.0550 (0.0040)	n.r.	0.063 (0.004)
MgO	3.47 (0.55)	n.r.	5.4 (1.4)
CaO	16.6 (1.0)	n.r.	16.3 (0.9)
Na ₂ O	0.325 (0.015)	0.330	0.35 (0.03)
K ₂ O	0.0501 (0.0060)	n.r.	0.027 (0.008)
Total	98.0 (2.3)	—	—
Mg [#]	59.2	—	69
Elements (Ir and Au for ng/g, others for µg/g)			
Sc	7.28 (0.52)	6.95	8.0 (1.0)
V	14.3 (4.7)	n.r.	n.r.
Co	22.5 (3.1)	n.r.	17 (3)
Ni	290 (38)	175	185 (45)
Sr	170 (20)	n.r.	150 (12)
La	2.58 (0.36)	n.r.	2.3 (0.6)
Ce	6.89 (0.72)	n.r.	6.0 (1.6)
Sm	1.19 (0.12)	1.09	1.1 (0.3)
Eu	0.784 (0.081)	0.796	0.78 (0.05)
Gd	1.6 (0.2)	n.r.	1.3 (0.3)
Tb	0.28 (0.08)	n.r.	0.23 (0.05)
Yb	0.84 (0.13)	n.r.	0.89 (0.2)
Lu	0.11 (0.02)	n.r.	0.13 (0.03)
Hf	0.74 (0.13)	n.r.	0.8 (0.2)
Ta	0.196 (0.061)	n.r.	0.11 (0.02)
Ir	15 (2)	n.r.	7.5 (2.8)
Au	13 (3)	n.r.	2.8 (1.0)
Th	0.42 (0.05)	0.40	0.37 (0.11)

Note: Our values in parentheses indicate errors due to: (1) counting statistics (1σ) on gamma-ray counting of elements in NWA 2200 and the reference standards; (2) accuracy of the JB-1 and Allende standard measurements compared with the preferred literature values (JB-1 in Imai et al., 1995a, b; Terashima et al., 1994; Allende in Jarosewich et al., 1987). Our error on the “Total” value was derived by error propagation from the errors on each of the oxides. n.r. = not reported. In Korotev et al. (2003), values in parentheses indicate uncertainties that are the 95% confidence limits on the mean values of feldspathic lunar meteorite compositions.

determined by typical INAA methods and the INAA result for Ti was unreliable compared with the PGA result (e.g., Latif et al., 1999); as such, we utilize the PGA data for SiO₂ and TiO₂ in Table 1. All the other elemental concentration data are INAA results.

In terms of the bulk composition of NWA 2200, our results exhibit small differences as compared with those of Korotev et al. (2008) as follows: Cr₂O₃ is 6% lower; FeO is 8% higher; Na₂O is 2% lower; Sc is 5%

higher; Sm is 9% higher; Eu is 2% lower; and Th is 5% higher. However, our elemental concentrations for NWA 2200 are broadly ($<\pm 10\%$) consistent with those reported by Korotev et al. (2008), with the exception of Ni. Our Ni value (290 $\mu\text{g/g}$) is 66% higher than that of Korotev et al. (2008) (175 $\mu\text{g/g}$).

The whole-rock FeO/MnO ratio of NWA 2200 (77 ± 6) is consistent with the FeO/MnO ratios of feldspathic lunar meteorites (70 ± 5 ; Korotev, 2005) and, thus, supports a lunar origin for this meteorite. The error reported by Korotev (2005) reflects the standard deviation of the FeO/MnO variability exhibited by feldspathic lunar meteorites. The high Al_2O_3 concentration of NWA 2200 ($30.1 \pm 0.6 \text{ wt.}\%$) suggests that NWA 2200 is one of the most feldspathic lunar meteorites (e.g., 26–31 wt.% Al_2O_3 ; Korotev, 2005; Korotev et al., 2003). Mg numbers ($\text{Mg}^\#$) of bulk feldspathic lunar meteorites vary widely, and the $\text{Mg}^\#$ value (59) of NWA 2200 is amongst the lowest reported for feldspathic lunar meteorites (e.g., $\text{Mg}^\# = 60\text{--}73$, Korotev et al., 2003; $\text{Mg}^\# = 78$ for Dhofar 489, Takeda et al., 2006). The feldspathic and ferroan composition of NWA 2200 indicates that this rock was derived from a ferroan anorthositic suite of rocks (e.g., Lucey et al., 2006; Taylor et al., 1991). This is consistent with the petrological results of Kuehner et al. (2005) who showed that most clasts in NWA 2200 have ferroan anorthosite (FAN) lithologies.

Concentrations of siderophile elements in NWA 2200 (e.g., Ni = $290 \pm 38 \mu\text{g/g}$; Ir = $15 \pm 2 \text{ ng/g}$) are very similar to those in Queen Alexandra Range (QUE) 93069 (Ni = 295 $\mu\text{g/g}$; Ir = 16 ng/g; Korotev et al., 1996) and Pecora Escarpment (PCA) 02007 (Ni = 354 $\mu\text{g/g}$; Ir = 16.8 ng/g; Korotev et al., 2006), and are consistent with NWA 2200 being a regolith breccia. The bulk Th content of NWA 2200 ($0.42 \pm 0.05 \mu\text{g/g}$) is within uncertainty of that of typical feldspathic lunar crust ($0.37 \pm 0.11 \mu\text{g/g}$) (Korotev et al., 2003).

3. Mineralogy of NWA 2200

3.1. Electron probe microanalysis

A polished thin section of NWA 2200 (polished thin section, b1; $6 \times 6 \text{ mm}$ in size) was made from NWA 2200b at the National Institute of Polar Research (NIPR), Tokyo, Japan. This section was used for petrographic and mineralogical studies. Before SEM and EPMA analyses, the polished thin section was carbon-coated. Back-scattered electron (BSE) images were obtained with a JEOL JXA-8200 EPMA at NIPR

and a HITACHI S-3000N SEM at Waseda University, Tokyo, Japan. Qualitative elemental maps were made with the HITACHI S-3000N SEM. Mineral chemistry was determined with the JEOL JXA-8200 EPMA at NIPR and a JEOL JXA-8900 EPMA at the Atmosphere and Ocean Research Institute, University of Tokyo (AORI), Chiba, Japan, with reference to well-characterized oxide and silicate standards. The EPMA was operated using an accelerating voltage of 15 kV, probe current of $1.2 \times 10^{-8} \text{ A}$, and beam size $\sim 5 \mu\text{m}$ (e.g., Takeda et al., 2006). Our EPMA data presented in Tables 2 and 3 are averaged mineral compositions with totals between 97 and 103 wt.%. The errors on each mineral composition are the one standard deviation variation of the individual mineral

Table 2

Average compositions (wt.%) of breccia matrix (Bx), glass spherules, and mineral fragments in polished thin section, b1.

	Bx		Glass spherules	Mineral fragments	
	Av.	SD		Pl	Ol
	No.	3	15	4	
SiO ₂	43.70	0.39	41.30 (1.63)	43.61 (0.55)	37.55 (1.30)
TiO ₂	0.20	0.03	0.17 (0.05)	b.d.	0.07 (0.01)
Al ₂ O ₃	30.99	0.31	31.30 (0.24)	35.24 (0.38)	0.25 (0.15)
Cr ₂ O ₃	0.15	0.10	0.05 (0.00)	b.d.	b.d.
FeO	3.12	0.35	4.43 (0.71)	0.29 (0.09)	28.02 (7.47)
MnO	0.06	0.00	0.07 (0.01)	b.d.	0.31 (0.09)
MgO	2.82	0.34	4.34 (0.82)	0.14 (0.07)	32.32 (5.99)
CaO	17.90	0.47	17.35 (1.06)	19.83 (0.37)	0.27 (0.18)
Na ₂ O	0.33	0.02	0.07 (0.01)	0.36 (0.09)	b.d.
K ₂ O	0.05	0.01	b.d.	0.05 (0.02)	b.d.
Total	99.32		99.08	99.52	98.79
Mg [#]	61.6		63.6	47.3	67.3

Note: b.d. = below the detection limit. Pl = plagioclase, Ol = olivine. The average (Av.) composition of breccia matrix (Bx) was obtained by averaging three areas (Bx1, Bx2, and Bx3 given in Appendix II). Bx1 data are the average composition of 7 points $\times$ 7 points analyzed along a line at 0.04 mm intervals (Appendix IIa). A bulk composition of the Bx1 area was determined by averaging 41 data points with totals of 97–103 wt.%. Bx2 data are the average composition of 10 points $\times$ 5 points analyzed along a line at 0.04 mm intervals (Appendix IIb). The bulk composition of the Bx2 area was determined by averaging 42 data points with totals of 97–103 wt.%. Bx3 data are the average composition of 5 points $\times$ 10 points analyzed along a line at 0.04 mm intervals (Appendix IIc). The bulk composition for the Bx3 area was determined by averaging 35 data points with totals of 97–103 wt.%. Each area is assumed to be the bulk composition of breccia matrix within a 0.08 mm^2 area. These areas were chosen for analysis because small mineral or lithic fragments were volumetrically minor within these regions as compared with other parts of the matrix. The standard deviation (SD) of the Bx data is the standard deviation (1σ) of the elemental compositions of the three sub-areas (Bx1, Bx2, and Bx3), and reflects compositional heterogeneity. No. = number of analyses. Values in parentheses are the standard deviation (1σ) of the individual fragment compositions, and reflect the compositional range of each fragment in the polished thin section.

Table 3

Average compositions (wt.%) of minerals in the ferroan anorthositic granulitic breccia in NWA 2200.

	Pl	Ol	Cpx	Opx	Cr-rich Sp
No.	10	4	2	2	2
SiO ₂	43.90 (0.21)	35.28 (0.25)	51.23 (0.02)	52.09 (0.04)	0.62 (0.26)
TiO ₂	b.d.	b.d.	0.57 (0.04)	0.36 (0.01)	13.83 (2.46)
Al ₂ O ₃	34.23 (0.14)	0.07 (0.03)	1.18 (0.01)	0.71 (0.06)	7.41 (0.48)
Cr ₂ O ₃	b.d.	b.d.	0.35 (0.01)	0.19 (0.00)	35.25 (0.46)
FeO	0.10 (0.04)	38.73 (1.12)	11.78 (0.09)	23.23 (0.71)	37.72 (2.45)
MnO	b.d.	0.41 (0.04)	0.24 (0.02)	0.38 (0.01)	0.39 (0.03)
MgO	0.04 (0.01)	26.28 (1.01)	13.96 (0.12)	20.82 (0.36)	1.94 (0.63)
CaO	19.15 (0.19)	0.13 (0.05)	19.43 (0.01)	1.66 (0.03)	0.55 (0.13)
Na ₂ O	0.35 (0.02)	b.d.	0.04 (0.00)	b.d.	b.d.
K ₂ O	0.03 (0.01)	b.d.	b.d.	b.d.	b.d.
Total	97.92	100.90	98.78	99.44	97.71
Mg [#]	41.6	54.7	67.9	61.5	8.4

Note: b.d. = below the detection limit. Pl = plagioclase, Ol = olivine, Cpx = clinopyroxene, Opx = orthopyroxene, Sp = spinel. No. = number of analyses. Values in parentheses are the standard deviations (1σ) of the individual mineral compositions, and reflect the compositional variation of each mineral in the ferroan anorthositic granulitic breccia.

compositions, and reflect compositional variation in our polished thin section or each clast, and are not representative of analytical uncertainties. However, the compositional variations may not be necessarily representative of the true heterogeneities in the parent rocks, due to the small clasts we analyzed.

3.2. Results for breccia matrix and mineral fragments

NWA 2200 is a lunar feldspathic breccia and is composed of a diverse mixture of mineral fragments, lithic clasts, glassy clasts, and impact glass spherules embedded in a brown glassy matrix (Fig. 2a–c). The most abundant discrete mineral fragments imbedded in the matrix are Ca-rich plagioclase (An_{95–98}). Olivine and pyroxene fragments are also widely present, but volumetrically minor as compared with plagioclase. The olivine fragments (Fo_{56–78}) are angular and have grain sizes from 10 to 100 μ m. The pyroxene fragments (Mg[#] = 49–79) are also angular with grain sizes from 10 to 60 μ m. The average compositions of the breccia matrix, impact glass spherules, and mineral fragments are summarized in Table 2. On the basis of the classification of lunar highland rocks reported by Stöffler et al. (1980), the brown glassy matrix and presence of impact glass spherules both suggest that NWA 2200 can be categorized as a regolith breccia.

3.3. Results for lithic and glassy clasts

Most clasts either have granulitic or fine-grained and impact melt textures. Mineral compositions and textures enable the large lithic or glassy clasts (>0.4 $\times$ 0.4 mm) to be characterized as: (a) ferroan anorthositic granulitic

breccia (Fig. 3a and b); (b) poikiloblastic granulitic breccia (Fig. 3c and d); or (c) glassy melt breccia with an intersertal texture (Fig. 2b). Descriptions of these clasts are presented in later sections.

Several impact glass spherules that are a few tens to a hundred microns in diameter are present in the matrix (Fig. 2c). The feldspathic compositions (Al₂O₃ = 31.30 wt.%; FeO + MgO = 8.77 wt.%) of the glass spherules (Table 2) are different to the mafic-rich compositions (Al₂O₃ < 10 wt.%; FeO + MgO > 30 wt.%) of Apollo volcanic glasses (Delano, 1980; Shearer and Papike, 1993) and, therefore, it is probable that the glass spherules in NWA 2200 were produced by impact events.

The following clast types were not observed in NWA 2200: (a) magnesian brecciated clasts typical of mafic impact melt breccias (Korotev, 1997) and magnesian granulitic breccias (Korotev, 1997; Lindstrom and Lindstrom, 1986) observed in Apollo 16 regolith; (b) magnesian anorthosites as present in the feldspathic lunar meteorites Dhofar 489 (Takeda et al., 2006) and Yamato 86032 (Yamaguchi et al., 2010), and magnesian troctolitic granulites of the Dhofar 489 group (Takeda et al., 2006, 2007, 2008; Treiman et al., 2010) and Allan Hills (ALHA) 81005 (Treiman et al., 2010); (c) KREEP rocks (enriched in such elements as potassium [K], rare earth elements [REE], phosphorus [P]); (d) granitic clasts; (e) Mg-suite clasts; and (f) mare basalts (e.g., Taylor et al., 1991). Our studied sample of NWA 2200 is only part of a whole-rock and it may not contain every rock type from the source region, particularly given that small amounts of mare basalt in other pieces of this meteorite have been reported (Kuehner et al., 2005).

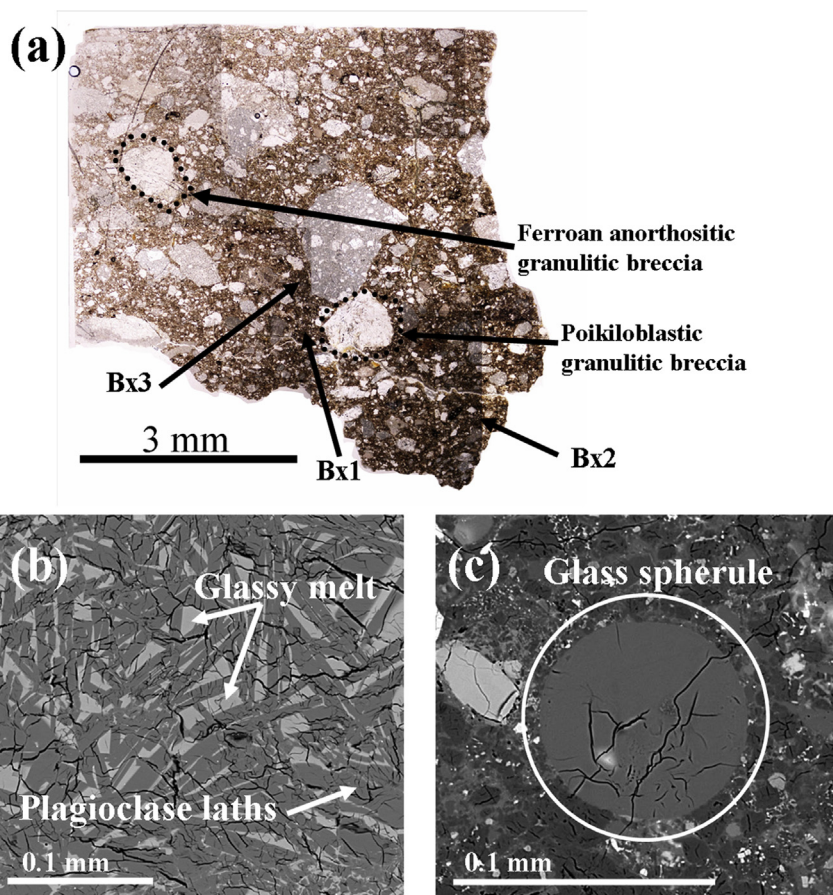


Fig. 2. (a) Photomicrograph of the polished thin section, b1 (scale bar is 3 mm). Back-scattered electron images of the breccia matrix (Bx) areas Bx1, Bx2, and Bx3 are provided in [Appendix II](#). (b) Back-scattered electron image of the glassy melt breccia with an intersertal texture (scale bar is 0.1 mm). (c) Back-scattered electron image of glass spherule embedded in Bx (scale bar is 0.1 mm).

3.3.1. Ferroan anorthositic granulitic breccia

The large anorthositic clast (0.7×0.7 mm) comprises plagioclase and olivine, with coexisting orthopyroxene and augite (Fig. 3a and b). Modal analysis of this clast shows that by area it is 78.0% plagioclase, 15.4% olivine, 4.3% orthopyroxene, 2.0% augite, and 0.3% Cr-rich spinel (chromite) (Fig. 4a). If this clast were representative of a rock, it would be classified as a troctolitic anorthosite (Prinz and Keil, 1977). The grain sizes of mafic minerals in this clast (≤ 0.1 mm) are much smaller than those in Apollo plutonic rocks (e.g., 1 mm olivine grains in 62237; Dymek et al., 1975). The clast shows differences in mafic mineral shape between its upper left and lower right regions. In the lower right area of this clast, olivine (≤ 100 μm) and pyroxene (≤ 50 μm) grains have angular shapes, whereas olivine (≤ 40 μm) and pyroxene (≤ 30 μm) grains have rounded shapes in the upper left area. These features highlight the granulitic texture of the clast.

The average mineral compositions in this clast are presented in Table 3. The chemical compositions of plagioclase (An_{96-97}) are similar throughout the clast. Fig. 4b shows the pyroxene and olivine compositions in the clast (olivine = $\text{Mg}^\#$ 53–57; orthopyroxene = $\text{Mg}^\#$ 60–63), which appear to be unzoned across the clast. The plagioclase and mafic silicate compositions are typical of the range for ferroan anorthosites (FAN) sampled by the Apollo missions (Fig. 4c) and consistent with the results of Kuehner et al. (2005). As such, we classify this clast as “ferroan anorthositic granulitic breccia”.

3.3.2. Poikiloblastic granulitic breccia

This large white clast (0.9×0.7 mm) is dominated by feldspathic glassy breccia, with one olivine grain and a few grains of Fe–Ni metal (10 μm) (Fig. 3c and d). The olivine grain (100 μm) has a rounded shape, which suggests that this grain is granulitic olivine that

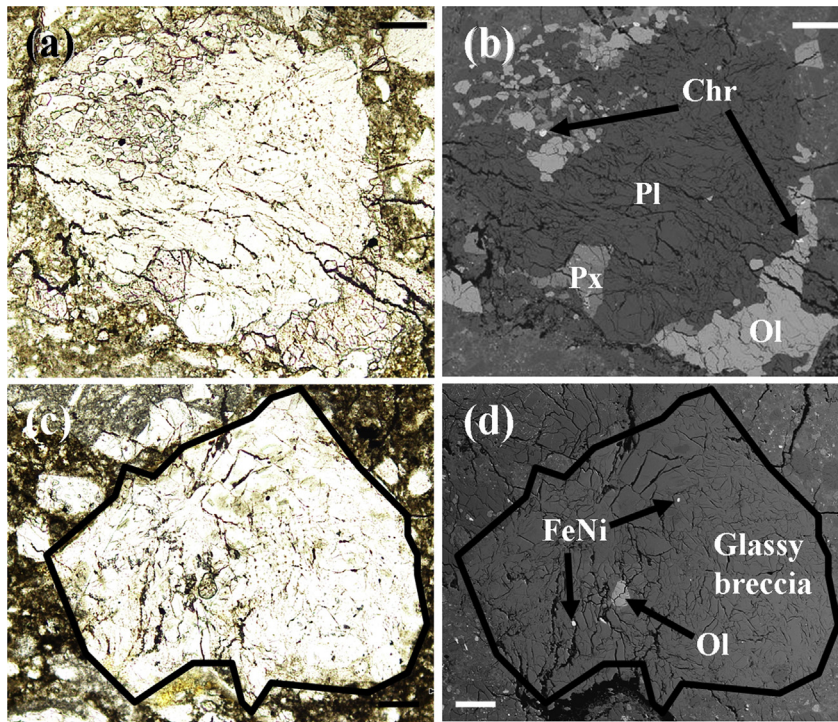


Fig. 3. Images of the analyzed clasts. (a, b) photomicrograph and back-scattered electron image of the ferroan anorthositic granulitic breccia. (c, d) Photomicrograph and back-scattered electron image of the poikiloblastic granulitic breccia. Scale bar is 0.1 mm. Pl = plagioclase, Px = pyroxene, Ol = olivine, Chr = chromite, FeNi = Fe–Ni metal.

has recrystallized in response to thermal metamorphism. This clast could not be a pristine lithology before the remelting, and may have been a granulite with a poikiloblastic texture (e.g., Taylor et al., 1991) that was partly remelted by an impact melting event.

The chemical composition of the white part of the clast was analyzed by multipoint EPMA measurements ($n = 61$ points), and averaged with errors based on the standard deviation (1σ) of the measured data. The averaged chemical composition of the clast ($\text{SiO}_2 = 44.43 \pm 0.49$ wt.%, $\text{Al}_2\text{O}_3 = 29.24 \pm 0.53$ wt.%, $\text{CaO} = 17.64 \pm 0.53$ wt.%, $\text{FeO} = 3.71 \pm 0.41$ wt.%, and $\text{MgO} = 3.38 \pm 0.38$ wt.%) is mafic-rich as compared with common plagioclase mineral fragments. The white part of this clast might be glassy breccia. The granulitic olivine grain has a composition of Fo₅₇.

3.3.3. Glassy melt breccia with an intersertal texture

The glassy melt breccia clast (0.5×0.4 mm) comprises 60% plagioclase laths and 40% glassy melt (Fig. 2b). This clast is texturally classified as a glassy melt breccia with an intersertal texture (e.g., Taylor et al., 1991).

An approximate bulk composition of this clast was determined by averaging EPMA compositions

according to their modal proportions ($n = 6$ for plagioclase; $n = 16$ for glassy melt), yielding 44 wt.% SiO_2 , 26 wt.% Al_2O_3 , 16 wt.% CaO , 6.1 wt.% FeO , 5.7 wt.% MgO , 0.35 wt.% Na_2O , 0.24 wt.% TiO_2 , 0.11 wt.% Cr_2O_3 , 0.09 wt.% MnO , and 0.06 wt.% K_2O .

4. Discussion

4.1. Petrogenesis of the individual rock components in NWA 2200

4.1.1. Comparison of the ferroan anorthositic granulitic breccia in NWA 2200 with other troctolitic anorthosites in lunar samples

Although pyroxene is typically more abundant than olivine in the ferroan anorthosite (FAN) rocks returned from the Apollo landing sites, a small number of ferroan troctolitic anorthosites were sampled there (e.g., Wiczorek et al., 2006). If the ferroan anorthositic granulitic breccia in NWA 2200 represents the composition of a rock, it would be classified as a troctolitic anorthosite (Prinz and Keil, 1977). The bulk chemical composition of the ferroan anorthositic granulitic breccia in NWA 2200 is given in Appendix III, and compared with selected compositions of

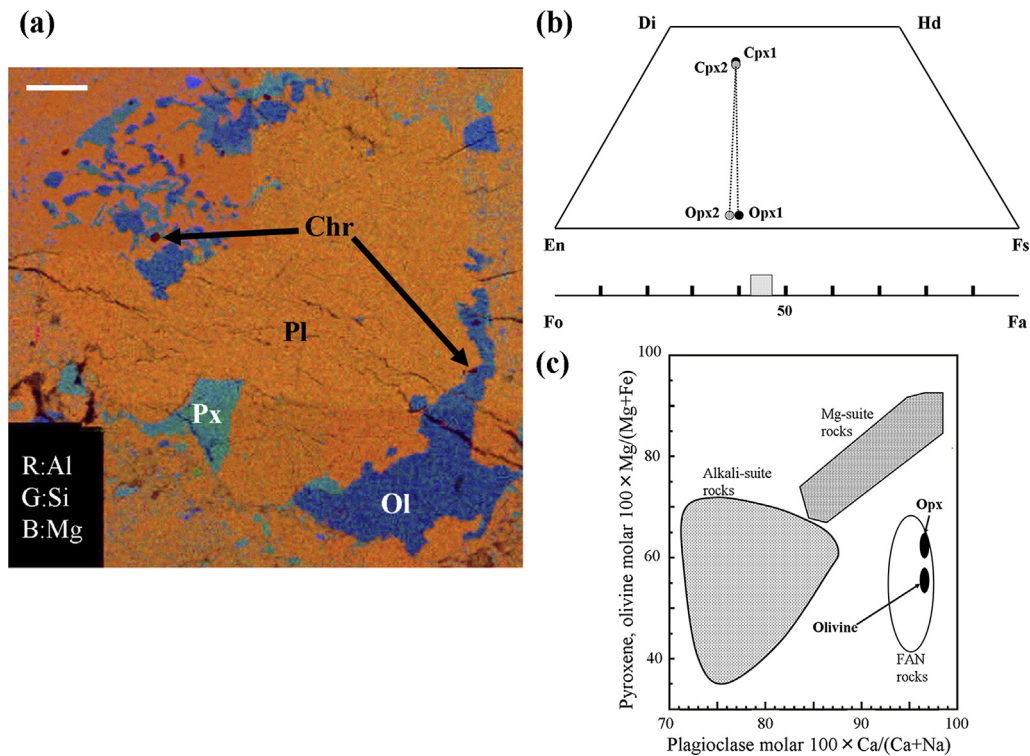


Fig. 4. (a) Combined X-ray elemental map (scale bar is 0.1 mm) of the ferroan anorthositic granulitic breccia (red = Al; green = Si; blue = Mg). Pl = plagioclase, Px = pyroxene, Ol = olivine, Chr = chromite. (b) Clinopyroxene (Cpx), orthopyroxene (Opx), and olivine compositions in the ferroan anorthositic granulitic breccia. Cpx1 co-exists with Opx1, and Cpx2 co-exists with Opx2. (c) Mineral chemistry of phases in the ferroan anorthositic granulitic breccia plotted as plagioclase An values versus the Mg numbers of coexisting mafic minerals in Apollo samples (e.g., Warner et al., 1976; Warren and Wasson, 1977). The fields were taken from Arai et al. (2008).

ferroan anorthosite samples, including the ferroan troctolitic anorthosite in the Apollo samples 15437 (Warren and Wasson, 1978), 62237 (Dymek et al., 1975), and 64435 (James et al., 1989). These samples contain 10%–20% olivine, whereas “typical” ferroan anorthosites contain <5% mafic minerals. The mineral compositions in the ferroan anorthositic granulitic breccia from NWA 2200 are compared with those in the Apollo ferroan troctolitic anorthosites (15437, 62237, and 64435) in Appendices IV and V. The composition of plagioclase in the ferroan anorthositic granulitic breccia (An_{96-97}) in NWA 2200 is almost the same as those in the Apollo ferroan troctolitic anorthosites (An_{95-99}). The bulk $Mg^\#$ (56) and mineral compositions of the ferroan anorthositic granulitic breccia in NWA 2200 are most similar to sample 62237 (bulk $Mg^\# = 60$; Dymek et al., 1975) in the Apollo ferroan troctolitic anorthosites, although the chemical compositions of olivines in the ferroan anorthositic granulitic breccia (Fo_{53-57}) in NWA 2200 are almost the same as or more ferroan than those in 62237 (Fo_{59-61} ; Dymek et al., 1975). Orthopyroxenes in the

ferroan anorthositic granulitic breccia ($Mg^\# = 60-63$) in NWA 2200 are also more ferroan than those in 62237 ($Mg^\# = 68$; Dymek et al., 1975).

The presence of coarse olivine and plagioclase (>1 mm) in the Apollo ferroan troctolitic anorthosites (Dymek et al., 1975; James et al., 1989; Warren and Wasson, 1978) indicates that the original minerals had coarse grain sizes of igneous origin. Large fractured grains of plagioclase and olivine are suggestive of an igneous cumulate origin. A similar troctolitic anorthosite clast was also observed in 62236 (Nord and Wandless, 1983). Samples 62236 and 62237 were probably both originally plagioclase, pyroxene, and olivine cumulates (Warren and Wasson, 1978). Norman et al. (2003) suggested that the petrological and geochemical features (mineral and trace element chemistry) of sample 62236 (anorthosite) represent primary magmatic features and that the petrogenesis of these rocks is closely linked with more plagioclase-rich varieties of lunar ferroan anorthosites.

James et al. (1989) identified two types of troctolitic anorthosites in sample 64435. The first is a monomict,

coarse-grained, troctolitic anorthosite with abundant (10%–20%) mafic minerals (maximum grain sizes: plagioclase = 3.9 mm; inverted pigeonite = 2 mm; olivine = 1 mm; primary augite = 0.4 mm). The second is a fine-grained, troctolitic anorthosite with a granulitic to brecciated texture, which has angular grains and most olivine grains that are 10–180 μm in size. These textures indicate that the mafic mineral grains were derived by granulation and subsequent recrystallization of original larger grains (James et al., 1989).

Angular olivine grains (up to 100 μm) in the ferroan anorthositic granulitic breccia in NWA 2200 (Fig. 3a, b, and Fig. 4a) are much smaller than those of coarse olivine (>1 mm) in the Apollo ferroan troctolitic anorthosites, apart from the fine-grained troctolitic anorthosite in sample 64435 (James et al., 1989). However, the similarity in the textures of fine-grained, angular, mafic minerals in the ferroan anorthositic granulitic breccia in NWA 2200 and the fine-grained troctolitic anorthosite in sample 64435 suggests that the fine-grained, angular, mafic minerals in the lower right area of the ferroan anorthositic granulitic breccia (Fig. 3a, b, and Fig. 4a) were also derived by granulation and subsequent recrystallization of original larger grains. Smaller mafic grains with rounded shapes were observed in the upper left area of the ferroan anorthositic granulitic breccia (Fig. 3a, b, and Fig. 4a). The formation history of this breccia clast may have been highly complex. We speculate that the ferroan anorthositic granulitic breccia in NWA 2200 experienced a two-stage thermal metamorphic history. The first event converted original coarse-grained mafic minerals (>1 mm; not observed) into the angular, fine-grained, minerals (lower right of clast; Fig. 3a, b, and Fig. 4a) as explained for the fine-grained troctolitic anorthosite in 64435 (James et al., 1989). The second event converted smaller, angular, fine-grained minerals into the mafic minerals with rounded shapes (upper left of clast; Fig. 3a, b, and Fig. 4a). This may be due to the smaller mafic mineral grains having been more affected by thermal metamorphism relative to larger grains.

Other ferroan troctolitic anorthosites have been identified in lunar feldspathic meteorites. A ferroan troctolitic anorthosite clast in the lunar meteorite NWA 482 (Daubar et al., 2002) contains Fo_{67} olivine, which is slightly more magnesian as compared with olivine Fo_{53-57} in the ferroan anorthositic granulitic breccia of NWA 2200. The lunar meteorite MacAlpine Hills (MAC) 88104/05 contains ferroan troctolitic anorthosite “W2” (An_{97} plagioclase, Fo_{55} olivine,

$\text{Wo}_4\text{En}_{60}\text{Fs}_{36}$ orthopyroxene, and $\text{Wo}_{39}\text{En}_{43}\text{Fs}_{18}$ augite; Jolliff et al., 1991), which has very similar mineral compositions to those of the ferroan anorthositic granulitic breccia in NWA 2200. These troctolitic anorthosites also fall in the ferroan anorthosite grouping of rocks.

Fragments of troctolitic granulite showing generally similar modal abundances as the ferroan anorthositic granulitic breccia in NWA 2200 and the Apollo ferroan troctolitic anorthosites are found in some feldspathic lunar meteorites. Takeda et al. (2006) reported the presence of magnesian spinel troctolite with a granulitic texture (ST; 72% plagioclase, 25% olivine, 2.2% orthopyroxene, 0.5% augite, and 0.3% spinel) in Dhofar 489, although the grain sizes of olivine are much coarser (0.15×0.08 mm to 0.69×0.23 mm) than those in the ferroan anorthositic granulitic breccia in NWA 2200 (Fig. 3a, b, and Fig. 4a). Clasts with similar modal abundances are observed in Dhofar 307 and 309 (Takeda et al., 2006, 2007, 2008). Treiman et al. (2010) also reported the presence of magnesian troctolitic granulite in ALHA 81005 and Dhofar 309 with modes and mineral compositions similar to those of ST. The mafic minerals in these granulitic clasts ($\text{Mg}^\# > 80$) are considerably more magnesian than those in the ferroan anorthositic granulitic breccia in NWA 2200. Fig. 5 compares spinel compositions from

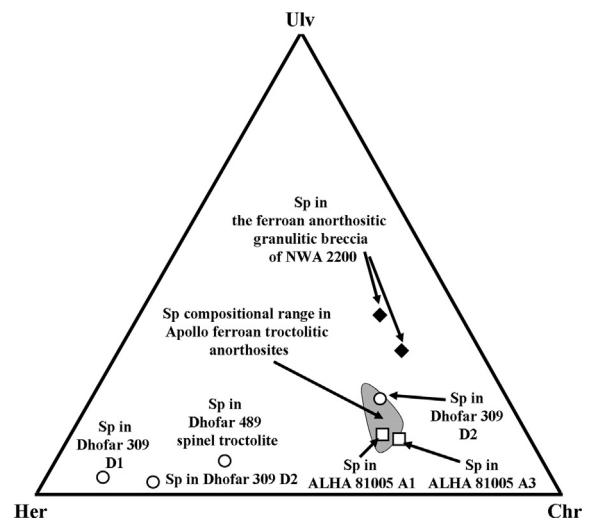


Fig. 5. Spinel (Sp) compositional variations (e.g., Arai et al., 1998) in the ferroan anorthositic granulitic breccia of NWA 2200, Apollo ferroan troctolitic anorthosites (Dymek et al., 1975; James et al., 1989; Nord and Wandless, 1983; Warren and Wasson, 1978), and magnesian troctolitic granulite clasts (Dhofar 489 spinel troctolite; Dhofar 309 D1 and D2; ALHA 81005 A1 and A3) (Takeda et al., 2006; Treiman et al., 2010). Chr is chromite (Cr), Ulv is ulvospinel (Ti), and Her is hercynite (Al).

the ferroan anorthositic granulitic breccia in NWA 2200, Apollo ferroan troctolitic anorthosites, and magnesian troctolitic granulites. Spinel in the ferroan anorthositic granulitic breccia in NWA 2200 and the Apollo ferroan troctolitic anorthosites exhibit a Cr-rich trend, which could be inferred to be chromite. The spinels in the magnesian troctolitic granulites have a Mg–Al-rich trend. Mineral chemistry indicates that the ferroan anorthositic granulitic breccia in NWA 2200 has a different origin to the magnesian troctolitic granulites.

4.1.2. Poikiloblastic granulitic breccia

The poikiloblastic granulitic breccia contains granulitic olivine (Fig. 3c and d), and the white part of this clast may be glassy breccia rather than plagioclase, given its high FeO (3.71 wt.%) and MgO (3.38 wt.%) contents. On the basis of the bulk Al_2O_3 content (29.24 wt.%) in the glassy breccia, the plagioclase mass component is <90%. The high mafic element contents may be due to remelting of pyroxene and olivine. Fe–Ni metal grains in this clast have high P contents ($P = \sim 5$ wt.%; $\text{Ni} = \sim 5$ wt.%). Schreibersite ($[\text{Fe}, \text{Ni}]_3\text{P}$) associated with Fe–Ni metal blebs has been described in the Apollo 16 samples, where the Fe–Ni metal blebs (20–200 μm) typically have a schreibersite rim that is 3–20 μm wide (Brown et al., 1973). Therefore, our EPMA data for the Fe–Ni metals could partly include schreibersite rims, given the small grain size of the Fe–Ni metals (~ 10 μm) and width of the electron beam. Poikiloblastic granulitic breccia in NWA 2200 was partly remelted by an impact melting event, which may have formed the glassy breccia phase.

4.1.3. Glassy melt breccia with an intersertal texture

The glassy melt breccia (Fig. 2b) consists of plagioclase laths and interstitial glassy melt. The lath-shaped crystals of plagioclase imply that this clast crystallized from non-plutonic melts and is of impact melt origin. Amongst the feldspathic impact melt clasts in feldspathic lunar meteorites, Al_2O_3 , FeO, and MgO contents (26 wt.% Al_2O_3 , 6.1 wt.% FeO, 5.7 wt.% MgO, and $\text{FeO}/\text{MgO} = 1.1$) of the glassy melt breccia in NWA 2200 are similar to those of MAC High-ITE type 4 (27 wt.% Al_2O_3 , 6.6 wt.% FeO, 6.0 wt.% MgO, and $\text{FeO}/\text{MgO} = 1.1$) in MAC 88104/05 (Joy et al., 2010) and to QUE G (25.9 wt.% Al_2O_3 , 6.17 wt.% FeO, 5.54 wt.% MgO, and $\text{FeO}/\text{MgO} = 1.11$) in QUE 93069 (Cohen et al., 2005). However, Ti contents in MAC High-ITE type 4 (1.15 wt.% TiO_2) in MAC 88104/05 (Joy et al., 2010)

are much higher than those in the glassy melt breccia (0.26 wt.% TiO_2) in NWA 2200. The glassy melt breccia with an intersertal texture in NWA 2200 may have been derived from melting of different lithologies as compared with MAC High-ITE type 4.

4.2. Comparison of the bulk composition of NWA 2200 with Apollo 16 regolith samples and feldspathic lunar regolith breccia meteorites

4.2.1. Siderophile element abundances in NWA 2200 and lunar regolith breccias

Lunar regolith samples have been vertically and laterally mixed by many micrometeorite impacts and some crater-forming meteorites, resulting in the siderophile elements (e.g., Ni and Ir) in brecciated lunar meteorites being almost entirely derived from extra-lunar meteoritic materials (Korotev, 2005; Korotev et al., 2006).

Our bulk concentrations of Fe and Ni in NWA 2200 (3.31 ± 0.12 wt.% Fe; 290 ± 38 $\mu\text{g/g}$ Ni) are higher than those reported by Korotev et al. (2008) (3.07 wt.% Fe; 175 $\mu\text{g/g}$ Ni). Our Ni concentration is 65.7% higher than the Ni value reported by Korotev et al. (2008). This difference in Ni contents might imply that our sample is slightly more contaminated with extra-lunar materials as compared with the sample studied by Korotev et al. (2008). The Ni concentration obtained for NWA 2200 in this study is equivalent to the addition of 2.6% of CI chondrite material (data of Anders and Grevesse, 1989), whereas that of Korotev et al. (2008) is equivalent to the addition of 1.6% CI chondrite material. If the difference between the concentration of Ni in this study and that of Korotev et al. (2008) reflects a difference in the degree of contamination by chondrite material, then the Fe concentration (2.88 ± 0.18 wt.%) obtained by our study can be corrected for by removing a CI chondrite component equivalent to the degree of contamination. This corrected FeO value is consistent with the FeO concentration reported by Korotev et al. (2008) (2.81 wt.%), which was corrected in the same fashion. Therefore, the different Ni concentrations of this work and that of Korotev et al. (2008) can be explained by slight differences in the degree of contamination with extra-lunar materials.

4.2.2. Rare earth element abundances in lunar feldspathic regolith samples

Given that NWA 2200 is a feldspathic regolith breccia, the bulk rare earth element (REE) composition of this rock can be compared with those of other

feldspathic regolith samples. In general, REE are incompatible elements. Fig. 6 presents CI-chondrite-normalized REE abundance patterns for NWA 2200, typical feldspathic lunar crust based on the mean values of feldspathic lunar meteorite compositions (surface; Korotev et al., 2003), and the average of Apollo 16 typical mature regolith and soil samples (Lucey et al., 2006). REE abundances of NWA 2200 are much lower than those in average Apollo 16 typical mature regolith and soil samples. Most regolith samples from the Apollo 16 landing site were contaminated with KREEP materials from the Procellarum KREEP Terrane (PKT) region (e.g., Korotev, 1997; Lucey et al., 2006). The REE abundance pattern of NWA 2200 is similar to that of typical feldspathic lunar crust (Korotev et al., 2003). REE abundances of NWA 2200 suggest that this meteorite originated from a region of the KREEP-poor highlands.

4.2.3. Major element abundances and trace element ratios of lunar feldspathic regolith samples

Fig. 7a plots bulk data for NWA 2200 on a FeO/MgO ratio versus Al_2O_3 content diagram, along with Apollo feldspathic regolith and soil samples,

feldspathic lunar meteorite regolith samples, and Apollo FAN samples with troctolitic or noritic compositions ($\text{Al}_2\text{O}_3 = 26\text{--}30$ wt.%). These elemental ratios and abundances vary widely amongst lunar feldspathic regolith samples. The range for feldspathic lunar meteorites that represent regolith breccias is almost the same as that of the Apollo 16 regolith breccias and soils, whereas NWA 2200 is more ferroan and Al-rich than the Apollo feldspathic regolith and lunar meteorite regolith samples.

The bulk compositions of the individual rock components in NWA 2200 are plotted in Fig. 7b, along with feldspathic impact melt breccias and mafic impact melt breccias from the Apollo 16 samples (Korotev, 1994, 1997), feldspathic impact melt clasts in feldspathic lunar meteorites (e.g., Cohen et al., 2005; Joy et al., 2010; Snape et al., 2011), and magnesian troctolitic granulites in ALHA 81005 and Dhofar 489 (Treiman et al., 2010). The ferroan feldspathic compositions of the individual rock components in NWA 2200 (bulk $\text{Al}_2\text{O}_3 = 26\text{--}30$ wt.%; bulk $\text{FeO}/\text{MgO} > 1.0$) suggest they are derived from ferroan troctolitic or noritic anorthosite compositions.

Al, Eu, and Sr are “plagiophile elements” that are generally incompatible in most igneous minerals, apart

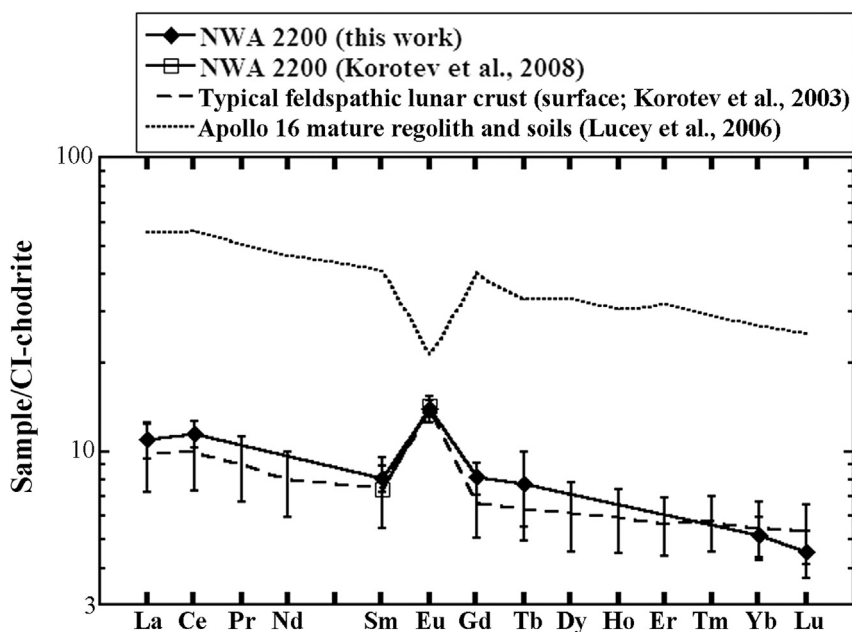


Fig. 6. Chondrite-normalized rare earth element patterns of NWA 2200, typical feldspathic lunar crust (surface) based on the mean value of feldspathic lunar meteorites (Korotev et al., 2003), and average typical Apollo 16 mature regolith and soil samples (Lucey et al., 2006). Chondrite normalizing values were taken from Anders and Grevesse (1989). The Sm and Eu data of NWA 2200 reported by Korotev et al. (2008) are also plotted in this figure.

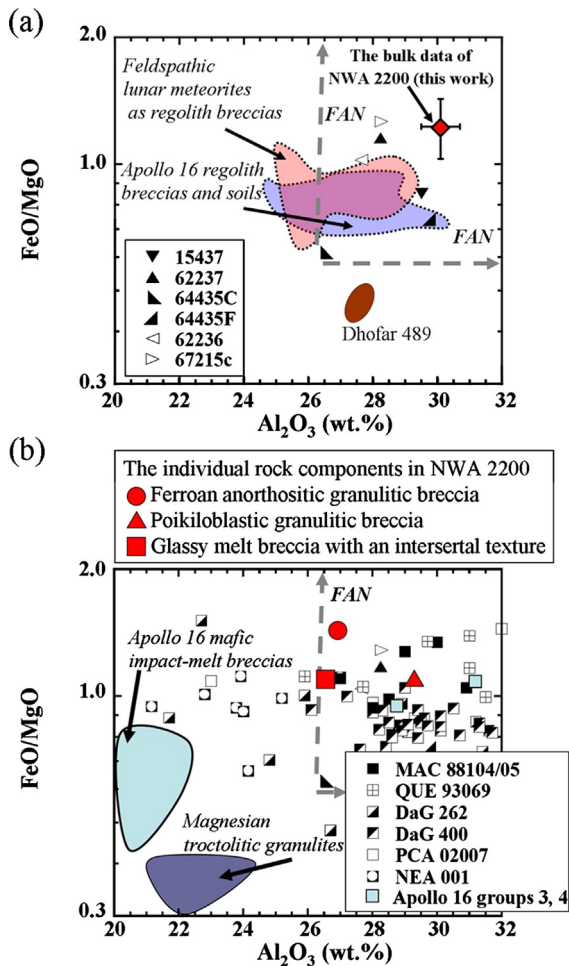


Fig. 7. (a) Variation in Al₂O₃ contents with FeO/MgO ratios for the bulk compositions of NWA 2200, feldspathic lunar meteorites that are regolith breccias (e.g., Bischoff et al., 1998; Cahill et al., 2004; Korotev et al., 1996, 2006; Palme et al., 1991; Warren and Kallemeyn, 1991; Warren et al., 2005), Apollo 16 regolith and soil samples (Korotev, 1997; McKay et al., 1986), Apollo 16 ferroan troctolitic anorthosites (15437 from Warren and Wasson (1978); 62237 from Dymek et al. (1975); 64435 Coarse (C) and Fine (F) clasts from James et al. (1989), ferroan noritic anorthosite (62236 and 67215c from Norman et al., 2003), and Dhofar 489, with the most magnesian compositions of feldspathic lunar meteorites (Korotev et al., 2006; Takeda et al., 2006). The ferroan anorthosite (FAN) compositional range is shown by gray arrowed lines (e.g., Dymek et al., 1975; James et al., 1989; Norman et al., 1995, 2003; Warren and Wasson, 1978). (b) Variation in Al₂O₃ contents with FeO/MgO ratios for the bulk compositions of the individual rock components in NWA 2200 (ferroan anorthositic granulitic breccia, poikiloblastic granulitic breccia, and glassy melt breccia with an intersertal texture), feldspathic impact melt breccias in the Apollo 16 samples (Apollo 16 groups 3 and 4; Korotev, 1994), mafic impact melt breccias in the Apollo 16 samples (Korotev, 1994, 1997), and feldspathic impact melt clasts in feldspathic lunar meteorites (Mac-Alpine Hills (MAC) 88104/05, Queen Alexandra Range (QUE) 93069, Dar al Gani (DaG) 262, DaG 400, Pecora Escarpment (PCA 02007) (Cohen et al., 2005; Joy et al., 2010), feldspathic impact melt

from plagioclase (Warren and Kallemeyn, 1984). It has been suggested that whole-rock Al/Eu and Sr/Eu ratios indicate that FAN rocks are genetically distinct from other lunar rock samples (troctolites, norites, and KREEP basalts), because of their distinct geochemical behavior (Fig. 8) (Norman et al., 1995; Warren and Kallemeyn, 1984). Bulk Al/Eu and Sr/Eu ratios of NWA 2200 are mostly within the range of those of FAN including ferroan troctolitic or noritic anorthosites, and distinct from Apollo 16 regolith breccias and soils. This could support that the individual rock components in NWA 2200 are derived from ferroan troctolitic or noritic anorthosite lithologies. We infer that this meteorite originated from the ferroan KREEP-poor highlands region, and not near the Apollo landing sites.

4.3. Implications for the diversity of lunar feldspathic crustal lithologies

Lunar meteorites originate from craters that are randomly distributed on the lunar surface and provide information about areas of the Moon not sampled by the Apollo and Luna missions (e.g., Warren and Kallemeyn, 1991). This makes lunar meteorites useful in the ground truthing of remote sensing measurements of the lunar surface, which are a powerful tool to understand lunar crustal genesis (e.g., Arai et al., 2008; Korotev et al., 2003; Warren, 2005). Global mapping of element and mineral distributions by remote sensing can reveal the variety of lunar crust lithologies (e.g., Gillis et al., 2004; Jolliff et al., 2000; Lucey et al., 1995, 1998; Prettyman et al., 2006). Moreover, a gamma ray spectrometer carried on Japan's first large-scale lunar explorer *Kaguya* (Kaguya Gamma Ray Spectrometer, KGRS) had an energy resolution (0.4% at 662 keV) that was an order of magnitude greater than the spectrometers used by previous missions (Hasebe et al., 2008, 2009). KGRS constructed absolute abundance maps of three radioactive elements (K, Th, and U) on the lunar surface (Kobayashi et al., 2010; Yamashita et al., 2010), and confirmed the enrichment of these elements in the PKT region. KGRS observed two low-Th regions in the central farside FHT and found that the Th distribution corresponds with crustal thickness variations, with an inverse correlation being evident between the Th

and impact melt breccia clasts in Northeast Africa (NEA) 001 (Snape et al., 2011), and the magnesian troctolitic granulites in ALHA 81005 and Dhofar 309 (Treiman et al., 2010).

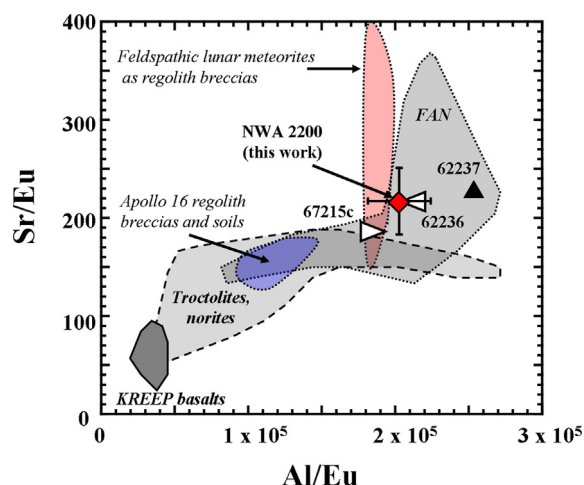


Fig. 8. Variation between Al/Eu with Sr/Eu for the bulk compositions of NWA 2200, feldspathic lunar meteorites representing regolith breccias (e.g., Bischoff et al., 1998; Cahill et al., 2004; Korotev et al., 1996, 2006; Palme et al., 1991; Warren and Kallemeyn, 1991; Warren et al., 2005), Apollo 16 regolith and soil samples (Korotev, 1997; McKay et al., 1986), as compared with representative compositions of plutonic rocks and KREEP basalts (Norman et al., 1995). The ferroan troctolitic anorthosite (62237) data were taken from Haskin et al. (1981). The ferroan noritic anorthosite (62236 and 67215c) data were taken from Norman et al. (2003).

abundance and crustal thickness (Kobayashi et al., 2012). Ohtake et al. (2012) reported a global Mg number distribution map using data from Spectral Profiler (SP) onboard *Kaguya*. This map also identified a dichotomic distribution, with magnesian highlands regolith ($Mg^{\#} > 70$) widely distributed on the central farside FHT region. The presence of magnesian anorthositic lithologies had been proposed on the basis of studies of feldspathic lunar meteorites (e.g., Arai et al., 2008; Korotev et al., 2003; Takeda et al., 2006).

Incompatible element (e.g., REE and Th) abundances in NWA 2200 are consistent with mean values for feldspathic lunar meteorites (Table 1), and lower than those in average Apollo 16 mature regolith samples (Fig. 6). The ferroan feldspathic and KREEP-poor bulk composition of NWA 2200 implies that this meteorite could possibly have originated from the ferroan KREEP-poor highlands, but not from the central farside FHT where magnesian regolith is widely distributed.

5. Summary

The lunar meteorite NWA 2200 is a feldspathic regolith breccia with a bulk ferroan composition ($Al_2O_3 = 30$ wt.%; $Mg^{\#} = 59$) and a low Th content

($0.42 \mu g/g$), which is composed of a diverse mixture of lithic clasts, glassy clasts, mineral fragments, and impact glass spherules embedded in a dark glassy matrix. Feldspathic brecciated clasts in NWA 2200 are ferroan anorthositic granulitic breccia, poikiloblastic granulitic breccia, and glassy melt breccia with an intersertal texture.

The ferroan anorthositic granulitic breccia comprises 78% plagioclase, 15% olivine, and 6% pyroxene. The texture of this clast bears evidence of a complex formation history. The poikiloblastic granulitic breccia was remelted by a meteoritic impact to partly feldspathic glassy breccia. The glassy melt breccia with an intersertal texture consists of plagioclase laths and glassy melt that crystallized from non-plutonic melts, and is of impact melt origin. These brecciated rock components with bulk $Al_2O_3 = 26$ – 30 wt.% and $FeO/MgO > 1.0$ were derived from ferroan troctolitic or noritic anorthosite lithologies.

The bulk composition of NWA 2200 is more ferroan and Al-rich than Apollo mission samples of feldspathic regolith and lunar meteorite regolith samples, as evidenced by the absence of mafic impact melt breccias as observed in the Apollo 16 regolith samples (e.g., Korotev, 1994, 1997) and magnesian troctolitic granulites (e.g., Takeda et al., 2006; Treiman et al., 2010). Incompatible element (e.g., REE and Th) abundances in NWA 2200 are consistent with mean values of feldspathic lunar meteorites, and lower than average typical Apollo 16 mature regolith samples. Most regolith samples from the Apollo 16 landing site were contaminated with KREEP materials from the PKT region (e.g., Korotev, 1997; Lucey et al., 2006). NWA 2200 may have originated from the ferroan KREEP-poor highlands.

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Appendix I.

Appendix Ia.

Summary of relative precision errors (%) of counting statistics (1σ) on gamma-ray counting of elements in NWA 2200 and the reference standards (JB-1 and Allende).

Element	PGA		INAA “Short period”		INAA “Long period”		Allende
	NWA 2200	JB-1	NWA 2200	JB-1	NWA 2200	JB-1	
Na	5.1	1.4	11.6	1.5	0.1	0.2	n.u.
Mg	b.d.		14.3	6.0	n.m.		
Al	1.1	1.7	0.5	0.6	n.m.		
Si	3.1	3.0	n.m.		n.m.		
K	b.d.		n.m.		8.7	6.5	n.u.
Ca	1.4	2.2	3.2	4.4	3.8	6.8	n.u.
Sc	n.m.		n.m.		0.2	0.1	n.u.
Ti	5.6	1.5	20.4	5.2	n.m.		
V	n.m.		31.4	2.1	n.m.		
Cr	n.m.		n.m.		0.2	0.1	n.u.
Mn	28.0	12.5	2.8	1.3	n.m.		
Fe	6.5	4.7	n.m.		0.3	0.1	n.u.
Co	14.6	9.7	n.m.		0.4	0.2	n.u.
Ni	b.d.		n.m.		13.0	n.u.	0.6
Zn	n.m.		n.m.		3.5	0.8	n.u.
Ga	n.m.		n.m.		15.1	29.4	n.u.
Sr	n.m.		n.m.		8.9	3.7	n.u.
La	n.m.		n.m.		8.5	1.2	n.u.
Ce	n.m.		n.m.		2.8	0.3	n.u.
Sm	8.4	2.7	n.m.		2.2	0.8	n.u.
Eu	n.m.		n.m.		2.0	0.9	n.u.
Gd	n.m.		n.m.		11.0	3.9	n.u.
Tb	n.m.		n.m.		15.3	5.2	n.u.
Yb	n.m.		n.m.		8.5	4.8	n.u.
Lu	n.m.		n.m.		10.6	5.5	n.u.
Hf	n.m.		n.m.		4.3	1.0	n.u.
Ta	n.m.		n.m.		15.3	1.6	n.u.
Ir	n.m.		n.m.		7.2	n.u.	0.3
Au	n.m.		n.m.		23.0	n.u.	4.4
Th	n.m.		n.m.		9.6	0.4	n.u.

Note: b.d. = below the detection limits. n.m. = element not measured. n.u. = elemental data not used for determining the concentration in NWA 2200. JB-1 is a reference standard in Imai et al. (1995a, b) and Terashima et al. (1994). Allende is a reference standard in Jarosewich et al. (1987). INAA “Short period” points the data for the sample irradiated for 10 s. INAA “Long period” points the data for the sample irradiated for 10 min.

Appendix Ib.

Summary of accuracies (%) of the JB-1 and Allende standard measurements relative to the preferred literature values (JB-1 in Imai et al., 1995a, b; Terashima et al., 1994; Allende in Jarosewich et al., 1987).

Element	JB-1	Allende
Na	4.3	n.u.
Mg	2.1	n.u.
Al	1.4	n.u.
Si	0.8	n.u.
K	4.9	n.u.
Ca	1.3	n.u.
Sc	7.1	n.u.
Ti	4.5	n.u.
V	9.5	n.u.
Cr	14.8	n.u.
Mn	7.2	n.u.
Fe	3.4	n.u.
Co	13.6	n.u.
Ni	n.u.	1.4
Zn	11.6	n.u.
Ga	16.2	n.u.
Sr	6.5	n.u.
La	11.1	n.u.
Ce	10.0	n.u.
Sm	9.7	n.u.
Eu	10.1	n.u.
Gd	9.6	n.u.
Tb	23.2	n.u.
Yb	12.2	n.u.
Lu	9.4	n.u.
Hf	16.9	n.u.
Ta	27.0	n.u.
Ir	n.u.	12.2
Au	n.u.	6.7
Th	7.6	n.u.

Note: n.u. = elemental data not used for determining the concentration in NWA 2200.

Appendix Ic.

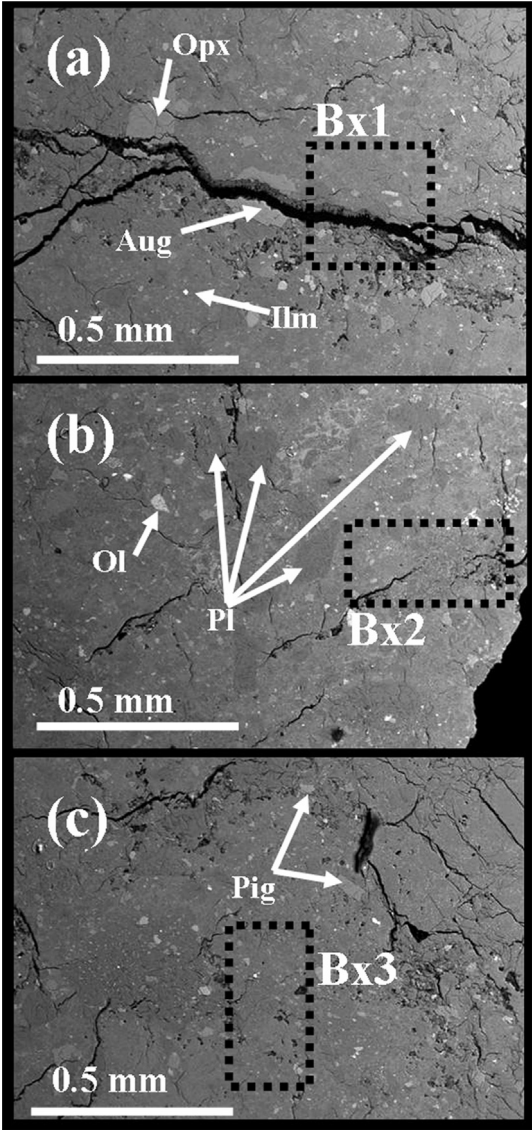
Summary of elemental abundances of NWA 2200 by PGA and INAA.

Element	PGA		INAA “Short period”		INAA “Long period”	
	Abundance	Error	Abundance	Error	Abundance	Error
Na (wt.%)	0.236	0.016	0.258	0.032	0.241	0.011
Mg (wt.%)	b.d.		2.09	0.33	n.m.	
Al (wt.%)	15.2	0.6	15.9	0.3	n.m.	
Si (wt.%)	20.03	0.88	n.m.		n.m.	
K (wt.%)	b.d.		n.m.		0.0416	0.0050
Ca (wt.%)	11.5	0.3	11.9	0.7	12.2	1.0
Sc (μg/g)	n.m.		n.m.		7.28	0.52
Ti (wt.%)	0.10	0.01	0.09	0.02	n.m.	
V (μg/g)	n.m.		14.3	4.7	n.m.	
Cr (wt.%)	n.m.		n.m.		0.0474	0.0070
Mn (wt.%)	0.0401	0.0126	0.0426	0.0031	n.m.	
Fe (wt.%)	3.51	0.31	n.m.		3.31	0.12
Co (μg/g)	22.8	5.1	n.m.		22.5	3.1
Ni (μg/g)	b.d.		n.m.		290	38
Zn (μg/g)	n.m.		n.m.		18.1	2.2
Ga (μg/g)	n.m.		n.m.		2.25	0.83
Sr (μg/g)	n.m.		n.m.		170	20
La (μg/g)	n.m.		n.m.		2.58	0.36
Ce (μg/g)	n.m.		n.m.		6.89	0.72
Sm (μg/g)	1.14	0.15	n.m.		1.19	0.12
Eu (μg/g)	n.m.		n.m.		0.784	0.081
Gd (μg/g)	n.m.		n.m.		1.6	0.2
Tb (μg/g)	n.m.		n.m.		0.28	0.08
Yb (μg/g)	n.m.		n.m.		0.84	0.13
Lu (μg/g)	n.m.		n.m.		0.11	0.02
Hf (μg/g)	n.m.		n.m.		0.74	0.13
Ta (μg/g)	n.m.		n.m.		0.196	0.061
Ir (μg/g)	n.m.		n.m.		0.015	0.002
Au (μg/g)	n.m.		n.m.		0.013	0.003
Th (μg/g)	n.m.		n.m.		0.42	0.05

Note: b.d. = below the detection limits. n.m. = element not measured. In this work, errors are due to (1) counting statistics (1σ) on gamma-ray counting of elements in NWA 2200 and the reference standard measurements (Appendix Ia); (2) accuracy of the JB-1 and Allende standard measurements compared with the preferred literature values (JB-1 in Imai et al., 1995a, b; Terashima et al., 1994; Allende in Jarosewich et al., 1987; given in Appendix Ib). INAA “Short period” points the data for the sample irradiated for 10 s. INAA “Long period” points the data for the sample irradiated for 10 min.

Appendix II.

Back-scattered electron images of breccia matrix (Bx) textures. (a) Bx1 range; (b) Bx2 range; (c) Bx3 range; scale bar is 0.5 mm. Pl = plagioclase, Opx = orthopyroxene, Pig = pigeonite, Aug = augite, Ol = olivine, Ilm = ilmenite.



Appendix III.

The bulk chemical composition (wt.%) of the ferroan anorthositic granulitic breccia in NWA 2200 (this work) compared with literature values of the ferroan troctolitic anorthosite in the Apollo sample (15437 (Warren and Wasson, 1978), 62237 (Dymek et al., 1975), 64435 (James et al., 1989)).

	NWA 2200	15437	62237	64435	
				Coarse [#]	Fine [#]
Ferroan anorthositic granulitic breccia					
	*	**	***	****	****
SiO ₂	42.94	43.4	41.94	n.r.	n.r.
TiO ₂	0.07	n.r.	0.02	n.r.	n.r.
Al ₂ O ₃	26.79	29.5	28.23	26.5	29.8
Cr ₂ O ₃	0.12	0.041	0.16	0.07	0.05
FeO	7.39	4.2	7.4	5.17	3.44
MnO	0.09	0.0589	0.09	0.06	0.05
MgO	5.26	4.88	6.34	8.3	4.6
CaO	15.42	16.9	15.74	15.2	16.8
Na ₂ O	0.27	0.226	0.2	0.274	0.275
K ₂ O	0.02	0.0067	0.01	0.02	0.02
Total	98.37	99.2	100.13	—	—
Mg [#]	55.9	67.2	60.4	74.1	70.4

Note: Coarse[#] points the coarse-grained troctolitic anorthosite clast, Fine[#] points fine-grained troctolitic anorthosite clast. *Bulk composition calculated on chemical compositions and modal abundances of each mineral by EPMA, **chemical composition by several methods (INAA and RNAA, fused bead probing), ***bulk composition calculated on an electron microprobe point count of PTS (2807 points), ****chemical composition by INAA. n.r. = not reported.

Appendix IV.

Comparison of mineral compositions (olivine (Ol) and plagioclase (Pl)) in the ferroan anorthositic granulitic breccia in NWA 2200 with those in the Apollo ferroan troctolitic anorthosites.

NWA 2200		15437		62237		64435			
Ferroan anorthositic granulitic breccia		15437,5		62237,10		Coarse [#]		Fine [#]	
Ol	Pl	Ol	Pl	Ol	Pl	Ol	Pl	Ol	Pl
Fo	53–57	66–68		59–61		71–72		63–72	
An	96–97	95–97		95–99		96–98		98	

Note: 15437; Warren and Wasson (1978). 62237; Dymek et al. (1975). 64435; James et al. (1989).

Appendix V.

Comparison of mineral compositions (orthopyroxene (opx), clinopyroxene (cpx)) in the ferroan anorthositic granulitic breccia in NWA 2200 with those in the Apollo ferroan troctolitic anorthosites.

NWA 2200		15437		62237	
Ferroan anorthositic granulitic breccia		15437,5		62237,10	
Opx	Cpx	Cpx	Opx	Cpx	
Max.	Min.	Max.	Min.	Max.	Min.
Wo	3.5 3.4	41.7 41.2	40	1.1	40.5
En	60.8 58.6	40.4 40.2	47	66.2	36.3
Fs	38.0 35.7	18.3 18.2	13	30.6	19.3
Al ₂ O ₃ (wt.%)	0.78 0.65	1.19 1.17	n.r.	0.72	1.50
TiO ₂ (wt.%)	0.37 0.35	0.60 0.53	n.r.	0.35	0.61
Cr ₂ O ₃ (wt.%)	0.19 0.19	0.36 0.34	n.r.	0.33	0.37

64435		Coarse [#]		Fine [#]	
Opx	Cpx	Opx	Cpx	Opx	Cpx
Max.	Min.	Max.	Min.	Max.	Min.
Wo	2.0 1.0	46.2 44.0	2.1	1.0	46.2 42.3
En	76.0 73.2	46.4 44.9	75.6	70.9	47.6 44.3
Fs	25.0 22.9	10.1 8.1	27.0	23.2	10.5 8.2
Al ₂ O ₃ (wt.%)	0.93 0.68	2.35 0.94	1.06	0.54	2.07 0.89
TiO ₂ (wt.%)	0.44 0.21	1.07 0.54	0.49	0.21	1.06 0.38
Cr ₂ O ₃ (wt.%)	0.33 0.15	0.67 0.29	0.35	0.13	0.53 0.26

Note: 15437; Warren and Wasson (1978), 62237; Dymek et al. (1975), 64435; James et al. (1989). Max. = maximum, Min. = minimum, n.r. = not reported.

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