Earth and Planetary Science Letters 388 (2014) 318–328

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

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Lunar feldspathic meteorites: Constraints on the geology of the lunar highlands, and the origin of the lunar crust

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ARTICLE INFO

Article history:
Received 15 October 2012
Received in revised form 20 November 2013
Accepted 3 December 2013
Available online 3 January 2014
Editor: T. Elliott

Keywords:
Lunar Magma Ocean
magnesian anorthosite
ferroan anorthosite
lunar crust
lunar highlands
serial magmatism

ABSTRACT

The composition of the lunar crust provides clues about the processes that formed it and hence contains information on the origin and evolution of the Moon. Current understanding of lunar evolution is built on the Lunar Magma Ocean hypothesis that early in its history, the Moon was wholly or mostly molten. This hypothesis is based on analyses of Apollo samples of ferroan anorthosites (>90% plagioclase; molar Mg/(Mg + Fe) = Mg# < 75) and the assumption that they are globally distributed. However, new results from lunar meteorites, which are random samples of the Moon's surface, and remote sensing data, show that ferroan anorthosites are not globally distributed and that the Apollo highland samples, used as a basis for the model, are influenced by ejecta from the Imbrium basin. In this study we evaluate anorthosites from all currently available adequately described lunar highland meteorites, representing a more widespread sampling of the lunar highlands than Apollo samples alone, and find that ~80% of them are significantly more magnesian than Apollo ferroan anorthosites. Interestingly, Luna mission anorthosites, collected outside the continuous Imbrium ejecta, are also highly magnesian. If the lunar highland crust consists dominantly of magnesian anorthosites, as suggested by their abundance in samples sourced outside Imbrium ejecta, a reevaluation of the Lunar Magma Ocean model is a sensible step forward in the endeavor to understand lunar evolution. Our results demonstrate that lunar anorthosites are more similar in their chemical trends and mineral abundance to terrestrial massif anorthosites than to anorthosites predicted in a Lunar Magma Ocean. This analysis does not invalidate the idea of a Lunar Magma Ocean, which seems a necessity under the giant impact hypothesis for the origin of the moon. However, it does indicate that most rocks now seen at the Moon's surface are not primary products of a magma ocean alone, but are products of more complex crustal processes.

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1. Introduction

The Lunar Magma Ocean model: In the current Lunar Magma Ocean (LMO) hypothesis, the early Moon was wholly or mostly molten (Wood et al., 1970; Shearer et al., 2006). Mg-bearing minerals (olivine and pyroxene) crystallized first from that magma ocean and sank to form the Moon's mantle, enriching the remaining magma in iron and the incompatible elements (e.g., Al, Ti, K). After ~75–80% of the LMO had solidified, plagioclase feldspar began to crystallize, floated in the dense Fe-rich melt (Warren, 1990; Elkins-Tanton et al., 2011), and collected at the Moon's surface to form a global crust of ferroan anorthosite – rock composed of >90% calcic plagioclase (An_{95-98}, Fig. 1a; with some examples to An_{93}: McGee, 1993; Nyquist et al., 2006), the so called "primary" feldspathic crust. Mafic minerals in ferroan anorthosites include olivine, orthopyroxene, and augite in varying proportions, and nearly all have Mg# [molar Mg/(Mg + Fe)] between 40 and 70 (Fig. 1a). Within these ranges, there are many distinct varieties of ferroan anorthosite (Warren et al., 1983; James et al., 1989; McGee, 1993; Jolliff and Haskin, 1995; Nyquist et al., 2006).

The residue of the LMO, trapped between the ultramafic cumulates of the lunar mantle and the crustal anorthosites, became enriched in incompatible elements including Ti, and crystallized abundant ilmenite ($FeTiO_3$). The residual melt was highly enriched in the remaining incompatible elements including potassium (K), rare earth elements (REE), phosphorus (P), Thorium (Th) etc.; traces of that residual melt appears in lunar rocks as the geochemical KREEP (K, REE, and P) component (Warren and Wasson, 1979; review by Shearer et al., 2006 and references therein).

Numerical models predict that the ultramafic cumulate pile, the mantle, had dense ferroan cumulates above magnesian cumulates, and thus was gravitationally unstable and overturned rapidly (Elkins-Tanton et al., 2011), mixing early magnesian cumulates with late ferroan cumulates, some of which had co-crystallized with plagioclase, ilmenite-rich rocks, and/or KREEP.

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http://dx.doi.org/10.1016/j.epsl.2013.12.006

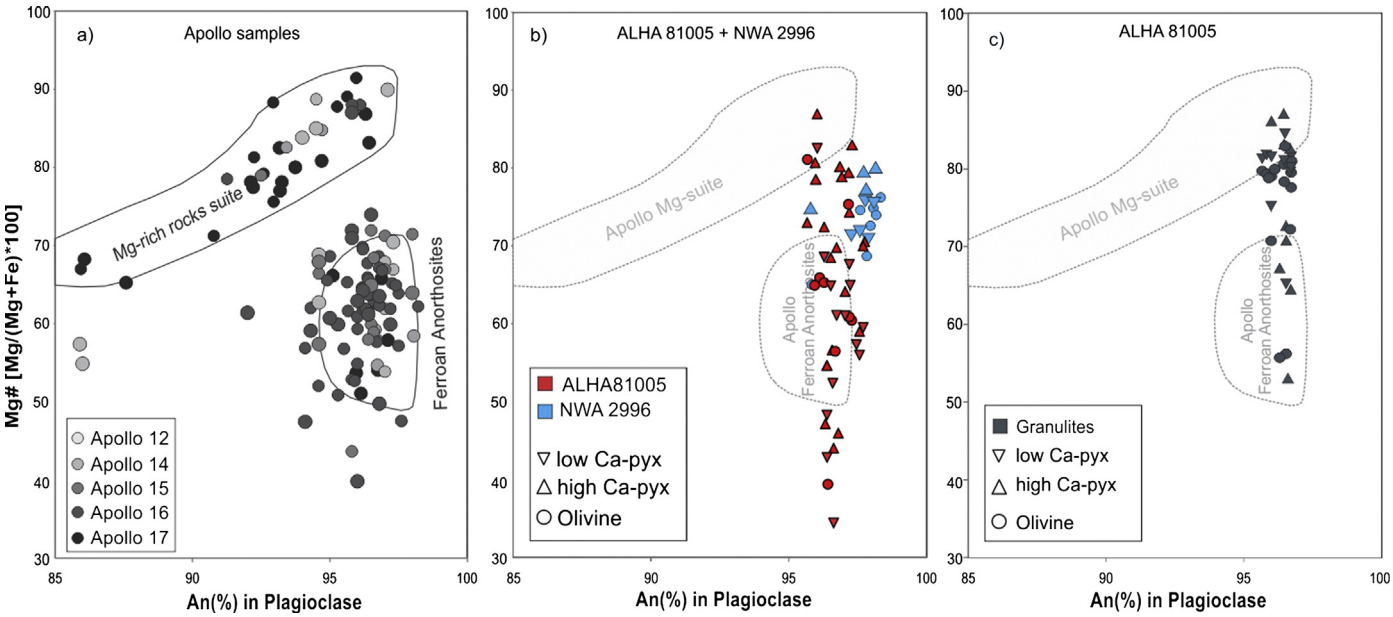


Fig. 1. Graph of anorthite component (mol%) in plagioclase versus *Mg#* (= Mg/[Mg + Fe]*100) in mafic minerals in lunar samples. a) Apollo highland samples. Data from Warner et al. (1977), Warren and Wasson (1979), Warren (1993), and Meyer (2013); fields from Goodrich et al. (1984); b) Anorthosite clasts in ALHA 81005 (red symbols) and NWA 2996 (blue symbols); c) Granulites in ALHA 81005. For all analyses see online supplemental.

This mixed (but not homogeneous) mantle was partially melted to form basaltic magmas, early melts were parental to the magnesian-suite intrusives. The Mg-suite plutonic rock suite includes gabbros, norites, troctolites, and dunites that are characterized by magnesian mafic minerals, Mg# to 95, and a significant abundance of KREEP elements (Shearer and Papike, 2005). Later melts were parental to the younger mare basalts that erupted onto the surface as lava flows and filled many of the older impact basins (see review by Hiesinger and Head, 2006). The lunar mare basalts span a wide range of compositions from 'normal' to Ti-rich to Al-rich. Nearly all mare basalts are strongly depleted in Eu relative to other REEs, implying that their source regions had experienced significant plagioclase removal (Warren, 1985), i.e. they were complementary to ferroan anorthosites.

The global LMO hypothesis is consistent with most petrologic and geochemical data from returned samples. Ferroan anorthositic rock, magnesian-suite plutonic rocks, and KREEPy material are common at the Apollo 15 and 16 (highland) sites, and are present at the other sample return sites except Apollo 12 and Luna 24 (Wood et al., 1970; Bence and Grove, 1978; Simon and Papike, 1985). Crystallization ages of the ferroan anorthosites are ancient (Shearer et al., 2006; Lucey, 2004), consistent with formation early in the Moon's history. Orbital remote sensing of areas not sampled by Apollo missions shows that the Moon's highland crust is anorthositic (Lucey, 2004; Prettyman et al., 2006; Ohtake et al., 2009; Greenhagen et al., 2010; Narendranath et al., 2011; Yamamoto et al., 2012), which is broadly consistent with a global distribution of anorthosite suggested by the LMO model.

***Problems with the LMO model*:** However, several observations are not consistent with this simple, global model of a LMO and its implied global distribution of these rock types. The Apollo highlands samples are known not to represent the highlands of the whole Moon, as they characterize only a few sites on the nearside, all of which are affected by the continuous ejecta of the Imbrium basin (Warren, 1990; Spudis et al., 2011). In addition, Apollo 16 ferroan anorthosites formed from source regions depleted in light rare earth elements (LREE; Borg et al., 1999; Shearer et al., 2006). This is not possible within the LMO model unless the Moon originally had a significantly non-chondritic Sm/Nd ratio (Boyet and Carlson, 2007).

The ages of lunar anorthosites and magnesian suite plutonic rocks, by radiogenic isotopes, also present problems for the LMO model. Crystallization ages of Apollo ferroan anorthosites span 200 million yr (Borg et al., 1999, 2011, 2012; Shearer et al., 2006), while most models of LMO formation would have it solidified in tens of millions of years (Elkins-Tanton et al., 2011). Equally perplexing is that radiometric ages of ferroan anorthosites overlap with those of magnesian suite plutons (Shearer et al., 2006; Elkins-Tanton et al., 2011), while the LMO model would require magnesian suite plutons all crystallized after the ferroan anorthosite crust was stabilized.

Another important lunar rock type, magnesian granulite, has no obvious place in the simple LMO model. Granulites in general are polymict clastic breccias that recrystallized during prolonged annealing forming granulitic textures with equigranular and rounded grains (Warner et al., 1977; Lindstrom and Lindstrom, 1986) and contain slightly less plagioclase component (70–80%) than anorthosites. Apollo granulites divide cleanly into ferroan types (mineralogically similar to ferroan anorthosites) and magnesian types (Lindstrom and Lindstrom, 1986), which have unusual trace element abundances, notably a very high Th/Sm ratio (Korotev and Jolliff, 2001; Korotev et al., 2003). Magnesian granulites are more abundant on the farside as evident from their prevalence in farside meteorites (Treiman et al., 2010). They do not represent simple mixtures of Apollo ferroan anorthosites and magnesian-suite rocks (Korotev et al., 2003; Treiman et al., 2010). Granulites from the farside are chemically distinct from the Apollo types in having 'normal' Th/Sm ratios (Treiman et al., 2010). Many granulites are ancient, with radiometric ages as old as 4.3 Ga (James and Hammarstrom, 1977; Warner et al., 1977), indicating that this rock type formed prior to the last major basin-forming epoch, and likely originated from the early crust (see Arai et al., 2008, and refs. therein). The protoliths of magnesian granulites are not known, but could be magnesian plutonic rocks similar to the Apollo magnesian suite but lacking detectable KREEP (Korotev and Jolliff, 2001; Treiman et al., 2010). If so, that would imply that at least some basaltic plutonic rocks pre-dated formation of KREEP, which is seemingly inconsistent with the simple LMO model.

At a larger scale, one accepted product of the LMO is not globally distributed: KREEP. KREEP, recognized by chemical analyses

of returned samples, is detectable from orbit by γ-ray emissions from its high abundances of K and Th and neutron absorption by rare earths Sm and Gd (Elphic et al., 2000). These geochemical signatures of KREEP are concentrated around the nearside Imbrium impact basin, in the so-called Procellarum KREEP terrain (Jolliff et al., 2000; Lawrence et al., 2003; Gillis et al., 2004). In addition, the Moon's highlands are also inhomogeneous in abundances of other elements, similarly showing that most of the lunar farside, the 'Feldspathic Highlands Terrane' (FHT), has low abundances of Mg and Fe relative to the feldspathic terrane on the nearside (e.g., Jolliff et al., 2000; Spudis et al., 2000, 2002; Gillis et al., 2004; Lucey, 2004; Lucey and Cahill, 2006; Arai et al., 2008), and a distinctly higher Mg# (Arai et al., 2008; Lucey and Cahill, 2006; Ohtake et al., 2012).

Based on observations made from newer global datasets Ohtake et al. (2009) and Yamamoto et al. (2012) suggested that there was a global pure anorthosite crust ~50 km in depth, consistent with a simple plagioclase flotation crust. However, pure anorthosites are absent from the collection of lunar meteorites (Korotev et al., 2010) and recent modeling based on new gravity data from the GRAIL spacecraft suggest that the lunar crust is only 32–43 km thick on average (Wieczorek et al., 2006; Taylor et al., 2013), which is not consistent with the depth estimates of Yamamoto et al. (2012).

***Lunar meteorites*:** The predicted global distribution of LMO products can be tested with lunar meteorites, rock and regolith fragments ejected from the Moon by impact events. Lunar meteorites are inferred to represent samples from randomly distributed sites across the lunar surface (Korotev, 2005), because the proportion of feldspathic to basaltic meteorites is the same as the proportion of lunar highlands areas to lunar mare areas and because there is no difference in cratering rate or delivery efficiency (Gallant et al., 2009; Miljkovic et al., 2013). To date ~178 individual (named) lunar meteorites are known (Korotev, 2013) which represent ~84 distinct lunar meteoroids that have fallen to Earth (Korotev et al., 2009; Korotev, 2013). Of those, 10 are mare basalts and 49 are feldspathic (i.e., highland rocks with bulk compositions of $\geqslant$25% Al_2O_3 and $\leqslant$6% FeO), and the remainder are mixed (Righter, 2013; Korotev, 2013). The bulk compositions of individual feldspathic breccia meteorites are more magnesian than soils of the lunar nearside highlands (Korotev et al., 2012; Zeigler et al., 2012). A majority of the feldspathic meteorites (for which we have adequate descriptions) do not contain ferroan anorthosites, KREEP, or Mg-suite rocks (Korotev, 2005). This alone suggests that these hallmark products of the LMO may not be globally distributed confirming that the lunar crust is heterogeneous.

Here we present new data on two lunar feldspathic meteorites, ALHA 81005 and NWA 2996, in context with currently recognized, well-described (for this study) feldspathic meteorites from the literature of which there are 18 to date. These 18 meteorites represent 16 distinct meteorite falls and thus represent a random sampling of the lunar highlands. Taken together, these data demonstrate that the current LMO model for the simple formation of the lunar highland crust is problematic. The current LMO model does not explain the abundance of magnesian anorthositic rocks across the Moon's surface, and does not explain the rarity of KREEP, Mg-suite rocks and ferroan anorthosite outside the Imbrium area.

2. Sample and analytical techniques

Lunar meteorites ALHA 81005 and NWA 2996 are feldspathic, polymict, regolith breccias composed of rock and mineral fragments from the lunar highlands (Treiman and Drake, 1983; Gross and Treiman, 2010; Mercer et al., 2013; Korotev, 2013) with very little (NWA 2996) to no (ALHA 81005) KREEP component (Korotev et al., 2009; Mercer et al., 2013). Two thin sections of ALHA 81005 (,8 & ,9) and one thin section of NWA 2996 (TAL-1*) were analyzed in this study. Both meteorites contain fragments of anorthosites that range from 200 μm to 3.5 mm in diameter (Fig. 2), with >80–98 vol% plagioclase and 2–10 vol% olivine, low- and high-Ca pyroxenes, ± accessory ilmenite. Other clasts include granulites, medium-grained gabbros, anorthositic norites and troctolites, mineral fragments, shocked clasts, glass beads, and devitrified glasses set in an agglutinitic matrix. Fragments of Mg-suite rocks are rare or absent (Gross and Treiman, 2010; Gross et al., 2012; Mercer et al., 2013; Treiman and Gross, 2013).

Backscattered electron (BSE) images and quantitative mineral analyses were obtained with a JEOL 7600F field-emission scanning electron microscope (SEM) and a Cameca SX100 electron microprobe (EMP) at NASA Johnson Space Center. BSE images were used to determine the textural characteristics and the modal mineral abundance of meteorite clasts using techniques described by Maloy and Treiman (2007). EMP operating conditions were: 15 kV accelerating voltage, 10–20 nA beam current, focused electron beam (1 μm in diameter) for analyses of olivine and pyroxene, and defocused electron beam (5 μm in diameter) for analyses of plagioclase/maskelynite. Peak and background counting times were 20–40 s per element. Analytical standards were well-characterized synthetic and natural oxides and minerals including diopside (Si, Ca, Mg,), olivine (Si, Mg, Fe), oligoclase, albite, jade (Na), hematite (Fe), rutile (Ti), corundum, anorthite (Al), chromite (Cr), rhodochrosite (Mn), and orthoclase (K). Data quality was ensured by analyzing secondary standard materials as unknowns.

3. Petrography and mineral chemistry

***ALHA 81005*:** Twenty-six anorthositic clasts and eighteen granulitic clasts in two thin sections of ALHA 81005 were analyzed. The clast sizes range from 200 μm to 1.5 mm in diameter. The anorthositic clasts are primarily composed of 90–98% plagioclase. Plagioclase is highly anorthitic in composition and homogeneous within each clast but ranges from An_{96} to An_{98} among clasts (Table 1; Fig. 1b). It is typically heavily cracked and/or partially converted to melt or maskelynite. Other minerals in anorthositic clasts include one or more of the following: pyroxene (low- and high-Ca), olivine, and accessory ilmenite (Fig. 2). These mafic silicate minerals are xenomorphic to granular in shape and their compositions are uniform in each clast, but vary widely among clasts. The mafic minerals' Mg#s (molar Mg/[Mg + Fe]) range from highly magnesian (Mg# = 87), to hyper-ferroan (Mg# = 39) and are illustrated in Fig. 1b. The granulitic clasts (Fig. 1c) are primarily composed of 70–90% plagioclase. Plagioclase is highly anorthitic in composition and homogeneous within each clast and ranges from An_{96} to An_{97} among clasts. Olivine and pyroxene within the clasts are equigranular and rounded in shape. Their compositions are uniform in each clast, but vary widely among clasts. The mafic minerals' Mg#s (Fig. 1c) range from highly magnesian (Mg# = 87), to ferroan (Mg# = 57).

***NWA 2996*:** Eleven anorthositic clasts in one thin section of NWA 2996 were analyzed. Anorthosite clasts are typically large (up to 3.5 mm), equigranular in texture, and contain 80–95% plagioclase, sub-equal amounts of olivine and low-Ca pyroxene, and minor augite; ilmenite is a common accessory (Fig. 2; Mercer et al., 2013). The plagioclase grains are up to 1 mm across, subhedral to anhedral, and preserve igneous textures although they are extensively fractured and show undulatory extinction. Plagioclase compositions are highly anorthitic ($An_{96–98}$) and coexisting pyroxenes and olivine are Mg-rich, ranging from Mg# = 64–85 (Table 2; Fig. 1b). For a detailed description of NWA 2996, see Mercer et al. (2013).

***Pristine character of the anorthositic clasts*:** We compare the anorthositic clasts from this study to Apollo ferroan anorthositic

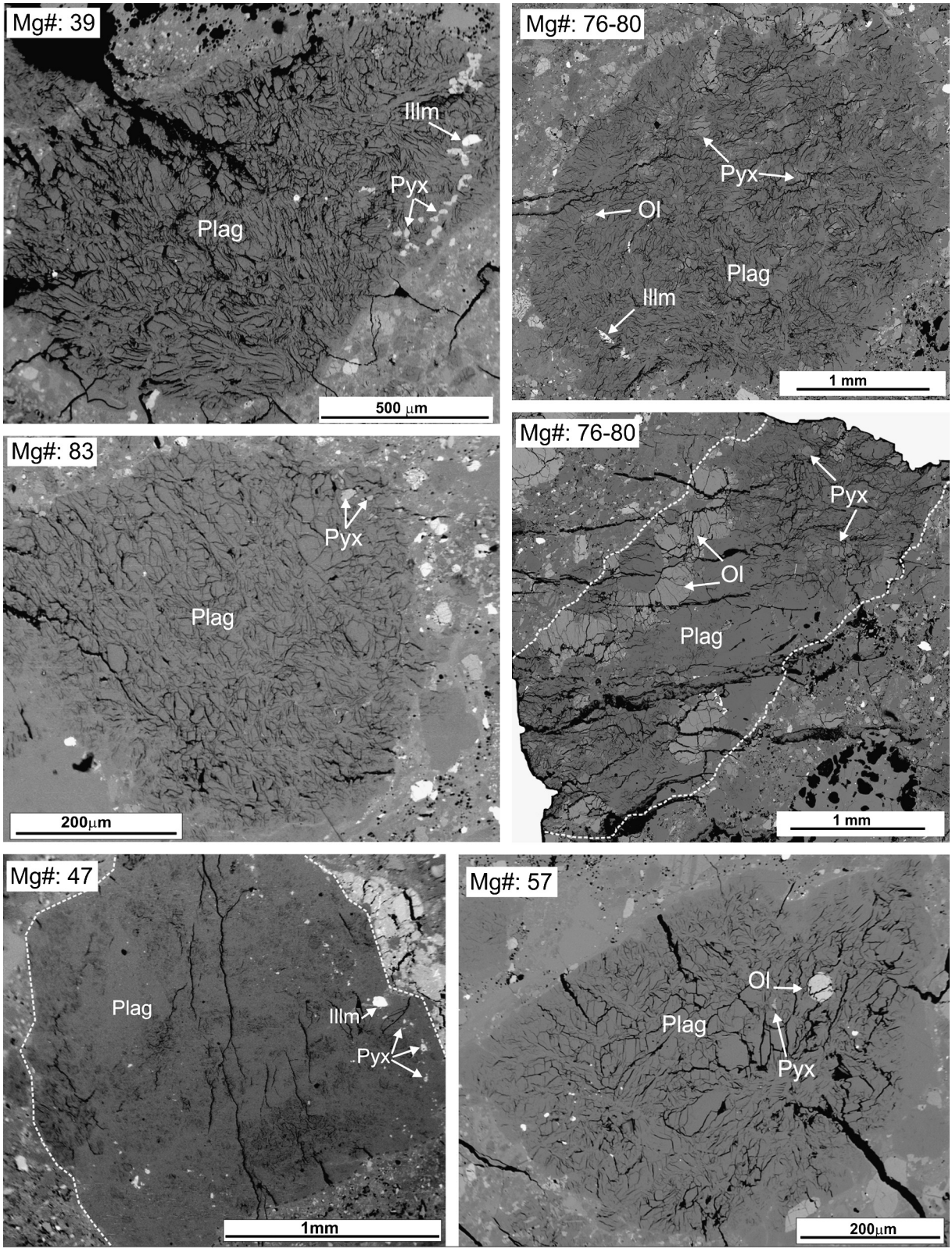


Fig. 2. Back scattered electron images of four typical anorthositic clasts in ALHA 81005 (left side, and lower right image) and two typical anorthositic clasts in NWA 2996 (upper right side, 2 images). Clast boundary in bottom right marked by dotted line. Plag = plagioclase; Pyx = pyroxene; Ol = olivine; Ilm = Ilmenite; Mg# = [molar Mg/(Mg + Fe)]. For images on all clasts see online supplemental.

clasts (Fig. 1) using the classic diagram whereby the anorthite content of plagioclase is plotted against the Mg# of the mafic minerals in those clasts (e.g., Raedeke and McCallum, 1980). This diagram was originally developed for pristine Apollo samples (Fig. 1a) and in general, for any credible petrogenetic interpretation to be made regarding lunar evolution, the pristine character of the samples must be established (Warren, 2012). Warren and Wasson (1977) presented criteria for recognizing the pristine nature of nonmare

Table 1
Representative EMP analyses of plagioclase, olivine, and pyroxene from anorthositic clasts in ALHA 81005.

ALHA 81005											
Plagioclase				Olivine				Pyroxene				
Clast name oxides (wt%)	C 23-8	C 26	C 19-8		C 3	C 46	C 78n		Low Ca		High Ca	
									C 1	C 76n	C 1	C 76n
SiO_2	43.55	44.44	43.66	SiO_2	33.33	36.73	38.13	SiO_2	49.07	55.26	49.27	52.92
TiO_2	bdl	bdl	0.03	TiO_2	0.03	0.03	0.05	TiO_2	0.30	0.58	0.53	0.95
Al_2O_3	35.20	35.63	35.43	Al_2O_3	0.03	0.24	0.10	Al_2O_3	0.29	0.91	0.78	1.30
Cr_2O_3	0.02	bdl	0.02	Cr_2O_3	0.03	0.01	0.16	Cr_2O_3	0.09	0.23	0.27	0.30
CaO	18.97	19.30	19.41	CaO	0.14	0.22	0.28	CaO	2.43	1.34	14.70	21.41
MgO	0.02	0.02	0.01	MgO	16.88	32.45	40.94	MgO	10.65	30.06	9.51	17.58
MnO	bdl	bdl	0.01	MnO	0.55	0.34	0.23	MnO	0.77	0.16	0.47	0.10
FeO	0.15	0.10	0.14	FeO	49.66	30.03	19.01	FeO	36.07	11.30	23.25	4.75
NiO	bdl	bdl	0.02	NiO	0.01	0.04	0.01	NiO	0.01	0.02	0.03	0.01
Na_2O	0.39	0.49	0.26	Na_2O	0.02	bdl	bdl	Na_2O	bdl	bdl	0.03	0.08
K_2O	0.01	0.02	0.00	K_2O	bdl	bdl	bdl	K_2O	bdl	bdl	0.01	0.01
Total	98.32	100.01	98.97	Total	100.68	100.10	98.92	Total	99.68	99.86	98.84	99.62
An	0.963	0.955	0.977	Mg#	37.733	65.830	79.334	Mg#	34.480	82.591	42.164	86.826
Ab	0.036	0.044	0.023									
Or	0.001	0.001	0.000									

bdl = below detection limit.

Table 2
Representative EMP analyses of plagioclase, olivine, and pyroxene from anorthositic clasts in NWA 2996.

NWA 2996											
Plagioclase				Olivine			Pyroxene				
Clast name oxides (wt%)	C 2	C 45	C 60A		C 2	C 60A		Low Ca		High Ca	
								C 2	C 45	C 2	C 60A
SiO_2	44.11	42.88	45.25	SiO_2	38.20	36.78	SiO_2				
TiO_2	0.04	0.04	0.05	TiO_2	0.05	0.04	TiO_2	0.81	0.27	1.31	1.00
Al_2O_3	35.59	35.98	34.37	Al_2O_3	0.11	0.05	Al_2O_3	0.99	1.39	1.97	1.98
Cr_2O_3	bdl	bdl	bdl	Cr_2O_3	0.06	0.06	Cr_2O_3	0.46	0.53	0.73	0.67
CaO	19.14	19.33	18.37	CaO	0.11	0.24	CaO	3.18	1.86	16.88	18.43
MgO	0.08	0.10	0.20	MgO	38.03	32.01	MgO	26.06	30.96	18.13	15.90
MnO	bdl	bdl	bdl	MnO	0.28	0.33	MnO	0.30	0.19	0.20	0.21
FeO	0.13	0.23	0.33	FeO	23.80	30.60	FeO	14.54	9.59	8.24	9.68
NiO	bdl	bdl	bdl	NiO	bdl	0.06	NiO	bdl	bdl	0.06	bdl
Na_2O	0.14	0.43	0.90	Na_2O	bdl	bdl	Na_2O	0.03	bdl	0.08	0.07
K_2O	0.03	0.10	0.06	K_2O	bdl	bdl	K_2O	bdl	bdl	bdl	0.03
Total	99.51	98.99	99.52	Total	100.64	100.12	Total	100.35	100.27	99.83	99.36
An	98.04	98.00	95.59	Mg#	74.02	65.10	Mg#	76.17	85.20	79.76	74.56
Ab	1.89	1.98	4.22								
Or	0.06	0.02	0.19								

bdl = below detection limit.

(i.e., highland) endogenous igneous rocks of ancient lunar crust. The criteria rely on the grain size, texture, and chemical composition (Warren, 2012), and include: [1] low siderophile element concentrations ($<3 \times 10^{-4} \times$ chondrites); [2] low incompatible element abundances ($<5 \times 10^{-3} \times$ KREEP); [3] coarse grain sizes (>3 mm); [4] antiquity (>4.2 Ga); [5] homogeneity of mineral compositions; [6] low initial $^{87}Sr/^{86}Sr$ ratio (<0.6992); and [7] "cumulate" character. By these criteria, ALHA 81005 and NWA 2996 are not pristine, nor is any clast in feldspathic lunar meteorites. Lunar highland meteorites are fine-grained regolith breccias and impactites with highly siderophile elements (HSE) in high abundances and meteoritic proportions. The clast sizes within these meteorites are generally too small to have mineral grains >3 mm, or to analyze for HSE. However, one anorthositic clast in ALHA 81005 has HSE $<1.6 \times 10^{-3} \times$ CI (Boynton and Hill, 1983) which is not quite low enough to fulfill the pristinity criteria of Warren and Wasson (1977) but is significantly lower than the bulk HSE abundances of feldspathic lunar meteorites.

Although anorthositic clasts in lunar feldspathic meteorites are not pristine by the Warren and Wasson (1977) criteria, until more lunar samples are available, it seems overly restrictive to exclude lunar meteorites from consideration because they are small, lack age and isotopic data, and might contain more than 0.01% chondritic contamination. Therefore, we characterize these samples, and speculate on what they may imply about the evolution of the lunar highland crust.

4. Comparison of Apollo lithologies and feldspathic meteorite clast lithologies

Of the 49 identified feldspathic lunar meteorites (grouping paired meteorites together: Korotev et al., 2009; Korotev, 2013), data on 18 (16 documented from previous studies and two, ALHA 81005 and NWA 2996, from this study) are adequate to evaluate the composition of their anorthositic lithologies (Korotev, 2013; Righter, 2013). Those 18 meteorites represent 16 distinct meteorite falls. By plotting the chemical compositions of minerals in the anorthositic clasts, i.e., anorthite component of plagioclase versus Mg# of their mafic minerals, three compositional distinct groups can be recognized: 1) nine of those 16 meteorite falls (~56%, including NWA 2996; also see Fig. 1b) contain anorthositic clasts with only highly magnesian mafic silicates (Fig. 3a); 2) three of those 16 meteorites (~19%) contain anorthositic clasts with only ferroan mafic silicates that are comparable to those of Apollo

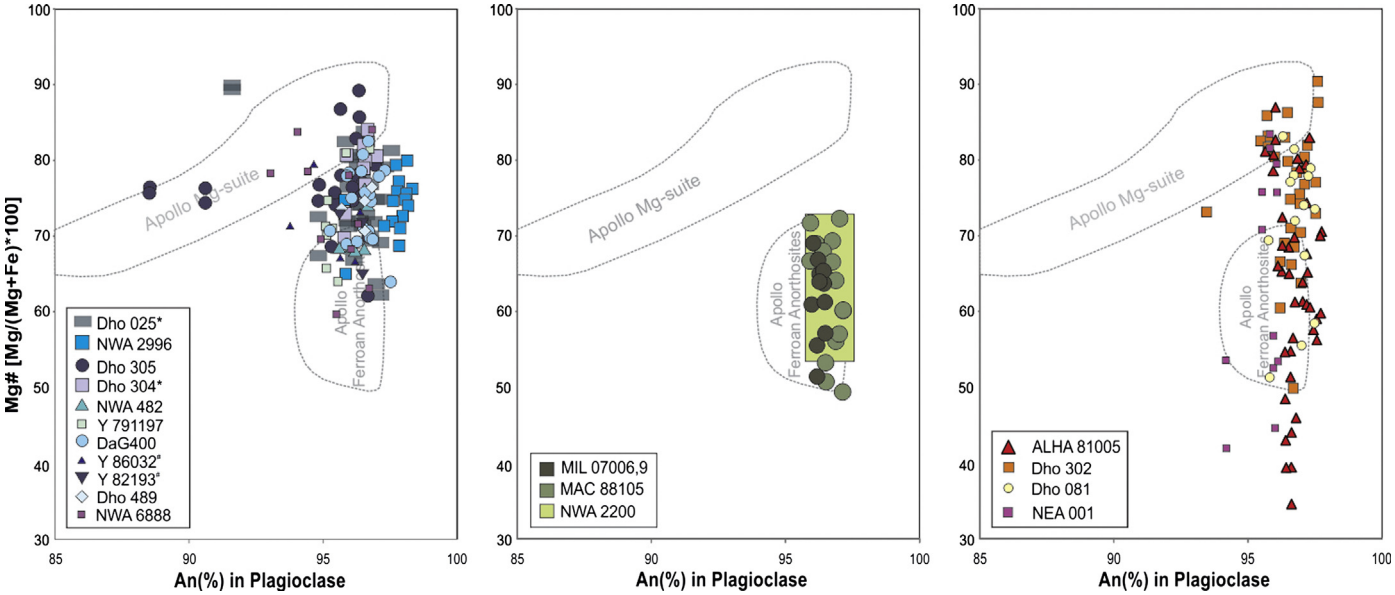


Fig. 3. Graph of anorthite (mol%) in plagioclase versus Mg# [= Mg/(Mg + Fe)*100] in mafic minerals in lunar feldspathic highland samples. ∗, # denotes paired stones. a) nine out of 16 meteorite falls contain anorthositic clasts that are highly magnesian; b) three out of 16 meteorite falls contain anorthositic clasts comparable in composition to Apollo ferroan anorthosites; c) four out of 16 meteorite falls contain anorthositic clasts that have a composition that ranges continuously from highly magnesian to hyper ferroan. Data from Righter (2013) and Korotev (2013) and references therein.

ferroan anorthosites (Fig. 3b); and 3) four of those 16 meteorites (25%; including ALHA 81005; also see Fig. 1b) contain anorthositic lithologies which span a wide range of Mg# from highly magnesian to hyperferroan (Fig. 3c). Therefore, if the lunar feldspathic meteorites come from random sites in the highlands, then the lunar crust represented by Apollo ferroan anorthosites is characteristic only of a minor part of the lunar highlands (i.e., Imbrium basin ejecta), whereas magnesian anorthosites seem characteristic of a major part of the lunar highlands. The third group of meteorites (25%), those with anorthosites of a wide range in Mg#, could represent mixtures from the first two groups. Interestingly, ALHA 81005 contains anorthosites that are hyperferroan, which are not known in the Apollo sample collection, and have only been reported from this meteorite (Goodrich et al., 1984). The precursor rock to hyperferroan anorthosite is unknown.

Mg-suite rocks (comparable to Apollo Mg-suite) are almost completely absent from all of these meteorites, including NWA 2996 and ALHA 81005 (Treiman and Gross, 2013), and they contain only trace proportions of the other characteristic LMO products like KREEPy material. Thus, 13 out of 16 the lunar feldspathic meteorites evaluated here contain material distinct from the highlands sampled by the Apollo missions, and show a variety of unique compositional ranges, inconsistent with a simple, homogeneous, global LMO.

5. Are magnesian anorthosites (and granulites) mixtures of other known lithologies?

The magnesian nature of the anorthositic (and granulitic) clasts in a large proportion of the lunar highland meteorites studied here leads to the question of whether the magnesian anorthosites (and magnesian granulites) simply represent mixtures of Apollo ferroan anorthosites and Mg-suite rocks formed through processes such as impact gardening (e.g., Cahill et al., 2004). Magnesian anorthosite is present, though rare, in the Apollo sample set (Lindstrom et al., 1984). However, most Mg-suite rocks contain relatively sodic plagioclase (Figs. 2, 3), and thus mixtures between them and ferroan anorthosite should also have relatively sodic plagioclase. Such a trend is not observed in anorthositic clasts from lunar meteorites in this study (Figs. 2, 3). On the other hand Mg-suite fragments can contain plagioclase as calcic as An_{95}, and thus the absence of a sodic plagioclase does not disprove the mixture model (Cahill et al., 2004). However, fragments of Mg-suite rocks are nearly unknown in lunar meteorites (Korotev et al., 2003; Treiman and Gross, 2013), and thus it is not clear that such materials were available for mixing. Magnesian anorthosites, therefore, seem likely to be a rock type not represented within the Apollo sample collection.

Magnesian granulites, similar in mineral composition to the magnesian anorthosites, have been described in meteorites and Apollo samples throughout the literature (e.g., Korotev et al., 2003; Arai et al., 2008; Treiman et al., 2010; Gross and Treiman 2010; 2011; Gross et al., 2012). In major element composition the magnesian granulites are similar to Mg-suite rocks. However, Treiman et al. (2010) and Korotev et al. (2003) demonstrated that the trace element characteristics (i.e. Ti/Sm) of the Mg-suite rocks are inconsistent with those of the magnesian granulites and thus, magnesian granulites cannot represent mixtures of those with ferroan anorthosites. These granulites must instead represent or include chemical components or processes that are not evident among known pristine monomict samples (Korotev et al., 1983a, 1983b, 2003; Korotev and Jolliff, 2001; Treiman et al., 2010) and thus, Mg-rich feldspathic lithologies other than the known Mg-suite rocks could exist (Arai et al., 2008). Magnesian anorthosite could represent a missing Mg-rich, feldspathic, chemical component to form magnesian granulites.

6. Lunar highland crust formation

A wealth of data on the lunar highlands is not consistent with a global LMO, including anorthosite compositions and the Mg# of their mafic components (complied in this study), the localized distribution of KREEP, the ages and isotopic characters of anorthosites and Mg-suite rocks, and the rarity of Mg-suite plutonic material in meteorites from the lunar surface. These data do not invalidate the idea of a LMO, which seems necessary under the giant impact hypothesis for the origin of the moon (Shearer et al., 2006). However, it does indicate that most rocks now seen at the Moon's surface are not primary products of a magma ocean alone, but are

Table 3
Composition of the LMO after 80% crystallization and composition of the olivine that co-crystallizes at this point.

Author/Study	Mg# magma ocean	Mg# olivine
Ringwood (1976)	38.7	67.2
Ringwood and Kesson (1977)	37.9–37.3	66.7–66.2
Dreibus et al. (1977)	33.8–33.5	62.3–62.6
Longhi (1978)	52.7	80.2
Morgan et al. (1978)	46.8–45.2	74–74.5
Taylor and Bence (1975)	47.6	74.8
Taylor (1976)	47.3–47.2	74.9–75.2
Snyder et al. (1992)	∼58	∼82
Elardo et al. (2011)	81.5–74.3*	–
Elkins-Tanton et al. (2011)	<57	<80
Davenport and Neal (2012)	∼50	∼77
Rapp and Draper (2012)	∼50	∼75

* Mg# of LMO after 50% crystallization.

products of more complex crustal processes that produced a larger variety of anorthosite compositions.

The lunar feldspathic meteorites data compiled in this study show that only ∼19% contain anorthosite clasts that are only ferroan. Interestingly, this is comparable to the proportion of the lunar highlands surface that is affected by the continuous Imbrium ejecta (Spudis et al., 2011). This suggests that ferroan anorthosites may not be globally distributed but instead represent only a small part of the lunar highland crust. Magnesian anorthosites and granulites on the other hand, are an abundant component of the other lunar feldspathic meteorites studied here, and thus could be the more representative material of the lunar highland crust. These lunar meteorites are not particularly unusual in containing magnesian anorthositic rocks rather than ferroan anorthosites; in fact, the Luna 20 and 24 missions returned samples from outside the continuous ejecta of Imbrium (Spudis et al., 2011), and their feldspathic highlands materials contain magnesian anorthositic rocks, not ferroan anorthosites (Taylor et al., 1973; Bence and Grove, 1978; Korotev et al., 2003; Arai et al., 2008).

Further, it is problematic to produce magnesian anorthositic rock as a primary flotation cumulate from a simple LMO. Models, computational simulations and experimental studies of LMO crystallization (Table 3) show that plagioclase appears only after ∼80% or more of the LMO has crystallized (Taylor and Bence, 1975; Taylor, 1976; Ringwood, 1976; Ringwood and Kesson, 1977; Dreibus et al., 1977; Longhi, 1978; Snyder et al., 1992; Elardo et al., 2011; Elkins-Tanton et al., 2011; Davenport and Neal, 2012; Rapp and Draper, 2012, 2013). At this point in the LMO evolution, olivine that co-crystallizes with plagioclase has a Mg# that ranges from ∼62 to 82 (Dreibus et al., 1977; Snyder et al., 1992), depending on the model, with an average of 75 (Table 3). In this scenario, formation of abundant ferroan anorthosites (and mafic minerals with Mg# <75) seems reasonable. However, these LMO scenarios imply formation of little magnesian anorthositic rock (with mafic minerals of Mg# >75). Anorthosites with such high Mg# can be formed only when olivine (or pyroxene) crystals of Mg# >75 become trapped in the matrix (or mush) of plagioclase crystals before the LMO evolves to more ferroan compositions. In addition, these magnesian anorthosites could not contain significant interstitial trapped melt, because the melt would have lower Mg# than the igneous olivine, and reduce the average Mg# of the rock (i.e., the average mineral Mg# after sub-solidus equilibration and metamorphism). This scenario seems unlikely – formation of abundant global anorthosites just at the moment of plagioclase saturation and without significant trapped melt.

6.1. An alternative to the LMO model

The long-standing alternative to the LMO hypothesis is serial magmatism – that the observed lunar crust is the product of multiple intrusions of basaltic magma, each differentiating during and after emplacement so that the (unknown) primordial lunar crust is obscured (Longhi and Ashwal, 1985; Longhi, 2003). In the serial magmatism model, basaltic magmas were generated by partial melting of the lunar mantle and emplaced into pre-existing lunar crust. These magmas were magnesian to ferroan (controlled by the Mg# of the source mantle) and near saturation with plagioclase (controlled by the plagioclase or spinel components of the source mantle). Upon emplacement, these intrusions differentiated to form anorthositic and mafic–ultramafic layers, akin to layered basic intrusions on Earth. The anorthositic and mafic–ultramafic portions separated because of their different densities – the former possibly moving upwards as diapirs (depending on the density of the pre-existing crust), and the latter sinking to the mantle. Repeated intrusion and diapirism would have obscured and heavily modified the original lunar crust.

This model of serial magmatism is based on understanding of large layered basic intrusions and of massif anorthosites on Earth like, respectively, the Stillwater and Nain complexes. The Stillwater complex (Montana, USA) has been used as an analog for the petrogenesis of the lunar crust (Raedeke and McCallum, 1980; Salpas et al., 1983). Rocks of the Stillwater complex show two distinct trends of plagioclase and mafic mineral compositions, analogous to those of lunar highland samples (Fig. 4). Stillwater's ultramafic rocks and gabbros show a 'normal' trend of igneous fractionation in An and Mg#, like the trend of the lunar Mg-suite plutonic rocks (Fig. 4a). Stillwater's anorthosites show a trend of relatively constant An with a range of Mg# (arising by circulation of mafic interstitial melt among the plagioclase crystals; Raedeke and McCallum, 1980; Salpas et al., 1983); this trend is like that of lunar anorthosites (Fig. 4b). This trend is consistent with the mineral compositional trend in lunar anorthosites and anorthositic clasts in lunar feldspathic meteorites, but does not predict the rarity of ultramafic cumulates and gabbroic rocks in the lunar crust (outside the Procellarum KREEP terrain).

Thus, once anorthosite rock has formed in layered mafic intrusions, an additional process is needed to physically separate the anorthosites from the surrounding mafic and ultramafic rocks to form the Moon's anorthositic crust. The driving force for this separation is density difference, as has been invoked for formation of massif anorthosites on Earth (Fig. 4b). Massif anorthosites are inferred to form initially as plagioclase cumulates in layered mafic intrusions deep in the crust or at the crust–mantle boundary (Longhi et al., 1999; Morse, 2006). These anorthositic cumulates (with trapped mafic silicates and interstitial melt) are less dense than the surrounding crust and rise through it as diapirs of crystal-rich mush, leaving their cogenetic mafic cumulates at depth (e.g., Ashwal, 1993; Longhi et al., 1999; Vander Auwera et al., 2006); the cumulates, being denser than typical crust, presumable sink toward the mantle as diapirs. The anorthosite diapirs retain, in general, their original geochemistry, i.e. plagioclase with a limited range of An, and mafic minerals with a significant range of Mg#. The largest massif anorthosite, the Nain Complex (Labrador, Canada), >90% plagioclase and ∼17 000 km^2 in area (Ashwal, 1993) is far smaller than the lunar crust; consistent with the idea that the lunar anorthositic crust could consist of many 'massif-like' anorthosite bodies.

Longhi and Ashwal (1985) proposed a lunar version of this model, starting from an early crust of overlapping layered mafic intrusions (Fig. 5). Density contrast (enabled by heat from the Moon's interior; e.g. though mantle overturn; Longhi et al., 2010; Elkins-Tanton et al., 2011) allowed the plagioclase-rich cumulates from the intrusions to rise as diapirs (Longhi and Ashwal, 1985; Ashwal, 1993; Longhi et al., 1999), and the mafic and ultramafic material to sink (Fig. 5b; Longhi and Ashwal, 1985) in the same way that has been proposed for terrestrial massif anorthosites

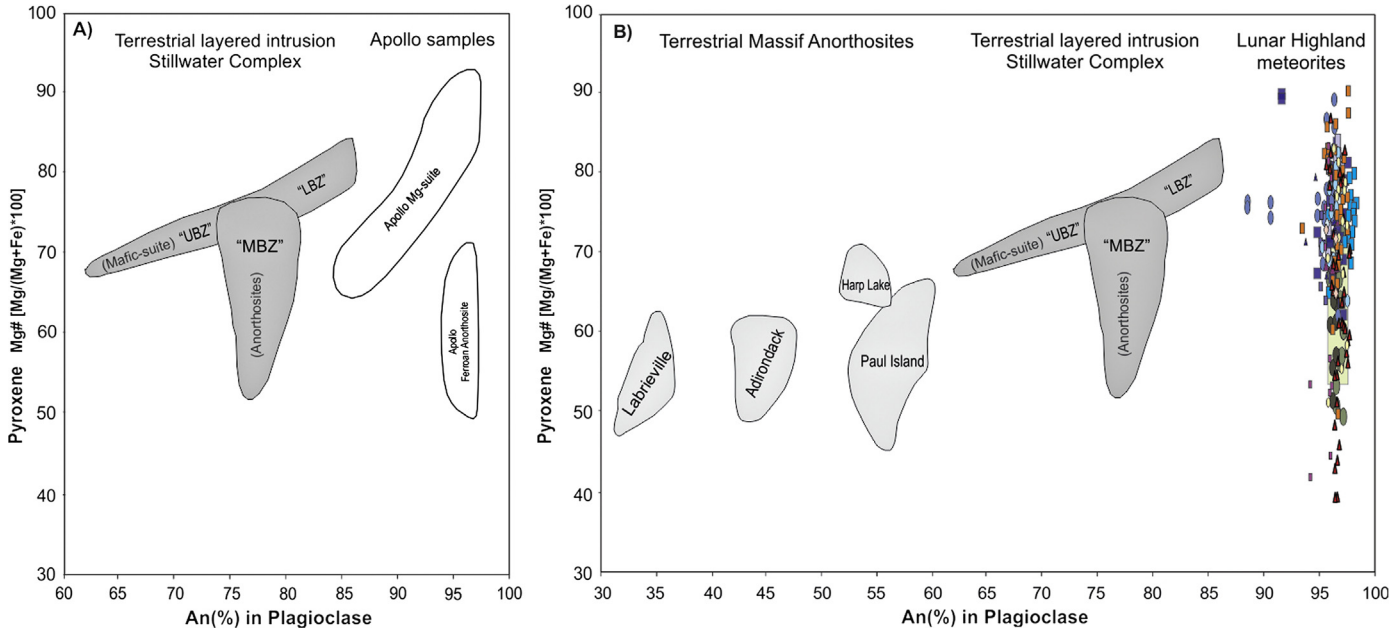


Fig. 4. Compositions of plagioclase and mafic minerals in anorthosites from Apollo ferroan anorthosites (A) and feldspathic highland meteorites (B) compared to those of a layered mafic intrusion anorthosites (dark gray = Stillwater complex; Raedeke and McCallum, 1980) and massif-type anorthosites (light gray; Ashwal, 1993). MBZ = middle banded zone; UBZ = upper banded zone; LBZ = lower banded zone (Raedeke and McCallum, 1980).

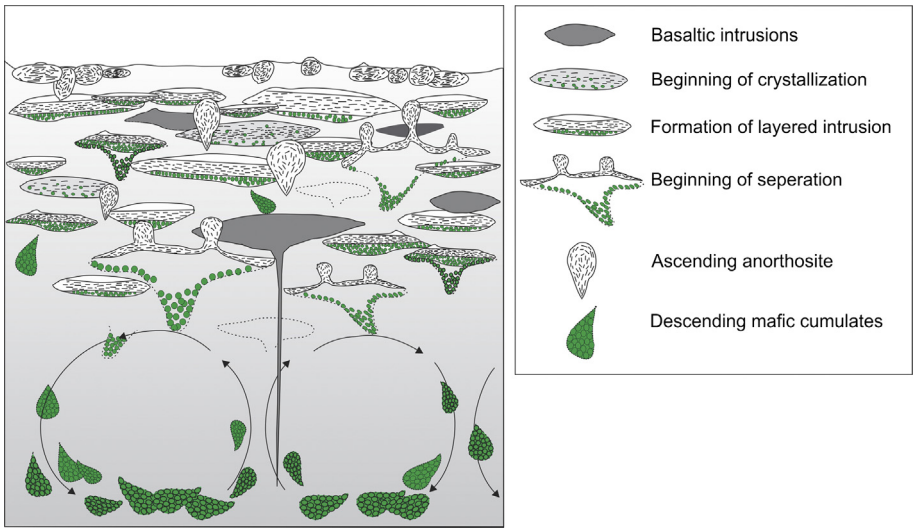


Fig. 5. Exaggerated cartoon illustration of the origin of the lunar serial magmatism/diapirism, model (modified after Longhi and Ashwal, 1985; see Walker, 1983). In the serial magmatism model the lunar crust consists of overlapping and crosscutting intrusions of basaltic magmas, emplaced into pre-existing lunar crust (light gray) continuously over time. The magmas were generated by partial melting of the lunar mantle by heat of accretion, radioactivity, and mantle overturn (Longhi et al., 2010; Elkins-Tanton et al., 2011). The intrusions crystallize and differentiate to form anorthositic cumulates, which then separate as diapirs, upwelling and down-going respectively (Longhi and Ashwal, 1985). These processes overlap in time and space, yielding a complex crust with only remnants of original crustal material (light gray) preserved.

(Longhi et al., 1999, 2010). Diapirism like this could also affect anorthosites from a LMO (Jolliff and Haskin, 1995; Longhi, 2003; Korotev et al., 2010). During emplacement of an anorthosite dispir with interstitial melt, igneous fractionation can continue, during which the plagioclase compositions remain relatively constant (buffered by abundant plagioclase), while the Mg# of their interstitial melts and mafic minerals can evolve. Deformation in the rising diapirs will tend to squeeze out the residual melts, yielding anorthosite bodies with little interstitial melt and thus little mafic silicates (Korotev et al., 2010). Such pure anorthosites are observed on the Moon (Ohtake et al., 2012; Yamamoto et al., 2012). These last residual melt fractions would be heavily fractionated and highly enriched in incompatible elements like lunar KREEP.

In the serial magmatism/diapirism model each diapir is expected to have a unique age and chemistry (e.g., Mg# range, plagioclase composition, relative abundance of KREEP elements, isotopic initial ratios) because each parental basaltic intrusion arises from a unique parcel of mantle (i.e. formed by inhomogeneous mixing during mantle overturn), at a different time, with unique ascent history, degree of fractionation (i.e. KREEP abundance), and chemical interactions with the pre-existing lunar crust (Fig. 5). This predicted variety is, in fact, observed (Fig. 3).

So we find that much data on lunar anorthosites this study and in the literature appears to be inconsistent with the global LMO model, but is consistent with a version of the serial magmatism/diapirism model of the lunar crust, in which layered mafic intrusions would have been generated continuously over time, and

their anorthosites and mafic portions would have been separated (by density) and been emplaced continuously over time (Fig. 5).

6.2. Other tests of the serial magmatism model

Lunar mare basalts post-date the episodes of anorthosite formation and serial magmatism/diapirism. The geochemistry of mare basalts reflect those of their source regions, which could reasonably include a wide range of materials, including the incompletely mixed lunar mantle (following mantle overturn; see Elkins-Tanton et al., 2011, especially her Fig. 6), mafic (and ultramafic) cumulates from large layered mafic intrusion, which descended as diapirs back towards the mantle. Thus, each potential source area for mare basalt could have a unique mixture of materials and thus a unique geochemistry, including degrees of Eu-depletion, Ti-enrichment, and KREEP-enrichment. This variety of source areas implies a range of mare basalt compositions, as observed especially for Ti abundance. The serial magmatism model is important here as it provides a mechanism for the source areas of mare basalt magmas to become variably depleted in Eu and enriched in KREEP, as is observed; Eu-anomalies range from strongly negative to positive (Shearer et al., 2006; Joy et al., 2008; Haloda et al., 2009; Snape et al., 2011).

The observed extended age range and age overlap of lunar anorthosites and magnesian suite plutonic rocks (Borg et al., 1999, 2011, 2012; Shearer et al., 2006) is an expected outcome from serial magmatism, in which basaltic magmas intrude the crust and differentiate to form anorthosite diapirs over a long period of time. The heat required to generate magnesian suite magmas and mare basalt magmas derives from overturn of the lunar mantle and from radioactive decay.

Initial radiogenic isotope ratios are obtained as by-products of radiogenic isotope age dating and these initial ratios, notably in the ^{147}Sm–^{144}Nd system, also are difficult to reconcile with the LMO model (see Arai et al., 2008). Ferroan anorthosites that formed from a magma ocean (a melted planet) with chondritic Sm/Nd should have initial Nd isotope ratios near chondritic, $\varepsilon Nd_i = 0$, to slightly negative εNd_i representing the small LREE enrichment caused by fractional crystallization of pyroxenes in the LMO (Arai et al., 2008). However, Apollo ferroan anorthosites have a wide range of εNd_i values, ranging distinctly positive to negative (Longhi, 2003; Borg et al., 1999, 2011; Nyquist et al., 2006, 2010; see summary in Arai et al., 2008). This range of εNd_i implies that the Apollo ferroan anorthosites formed from a variety of magmas, not a single LMO, and that these parental magmas had a range of Sm/Nd ratios, both LREE-enriched and LREE-depleted (Nyquist et al., 2010). Elkins-Tanton et al. (2011) suggested that the radiometric ages of many ferroan anorthosites have been reset by metamorphism, and this would also have reset their εNd_i. This scenario, though attractive in some respects, cannot explain the full range in εNd_i; ferroan anorthosites are LREE-enriched (subchondritic Sm/Nd), metamorphic equilibration should give young ages and negative εNd_i. However, some ferroan anorthosites have distinctly positive εNd_i (summarized in Arai et al., 2008), which must indicate derivation from a LREE-depleted source.

7. Conclusions

Anorthositic clasts from this study and the bulk composition (e.g., Korotev et al., 2012) of lunar meteorites indicates that magnesian anorthositic rock is more abundant than the Apollo ferroan anorthositic rock (common at most Apollo sites), and suggests ferroan anorthosite is characteristic only of a small part of the lunar highlands (also see Arai et al., 2008). Anorthosite compositions, the Mg# of their mafic components, the localized abundance of KREEP, and the rarity of Mg-suite plutonic material in 16 feldspathic lunar meteorites suggest that the putative products of the LMO and the concomitant lunar petrogenetic history reflect processes that cannot be extrapolated to the whole Moon or to a global homogeneous LMO. Anorthositic clasts from this study and the bulk composition (e.g., Korotev et al., 2012) of lunar meteorites show that ferroan anorthosites are not globally distributed but instead represent one of many components of the lunar highland crust. Magnesian anorthositic rocks, on the other hand, seem to be more representative of the whole lunar highland crust (also see Arai et al., 2008). However, the current simple models of the LMO composition and evolution are not consistent with formation of abundant magnesian anorthosite. It is reasonable to infer that the present-day lunar crust was produced (at least in part) by many 'massif-like' anorthosite bodies. This model does not invalidate the idea of a Lunar Magma Ocean which seems a necessity under the giant impact hypothesis for the origin of the moon (Shearer et al., 2006), but it does indicate that a portion of rocks now seen at the Moon's surface are not the products of a magma ocean alone but are a product of more complex crustal processes.

Acknowledgements

We are grateful to A. Peslier for assistance with the EMP analyses, and to C. Goodrich, W. Kiefer, and P. Spudis for advice and helpful discussions. We thank T. Elliot and two anonymous reviewers, for very helpful reviews of this manuscript as well as T. Elliot for handling this manuscript and comments. Supported by NASA Cosmochemistry grant NNX13AF54G to JG and NASA Cosmochemistry grants NNX08AH78G and NNX12AH64G to AHT; LPI contribution #1736.

Appendix A. Supplementary material

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.epsl.2013.12.006.

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