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## Evolution, Lunar: From Magma Ocean to Crust Formation

Juliane Gross[1,2,3] and Katherine H. Joy[4]
[1]Department of Earth and Planetary Sciences, Rutgers University, Piscataway, NJ, USA
[2]American Museum of Natural History, New York, NY, USA
[3]Lunar and Planetary Institute, Houston, TX, USA
[4]School of Earth and Environmental Sciences, University of Manchester, Manchester, UK

### Introduction

The lunar crust provides a record of the planetary formation and early evolutionary processes and contains a wealth of information about the origin and evolution of the Earth-Moon system (e.g., Taylor 1982; NRC 2007; Canup 2008, 2012; Cuk and Stewart 2012; Young et al. 2016). Understanding these processes is crucial for the reconstruction of the early evolutionary stages of the Earth, e.g., the early geological evolution of a terrestrial planet, inner Solar System impact bombardment, and the solar and galactic environment throughout the last 4.5 billion years (Ga) (e.g., NRC 2007; Crawford et al. 2012).

Our knowledge of the lunar highland crust has advanced enormously. Studies of lunar meteorites; experimental and computational studies; remote sensing of mineralogy, chemistry, and topography of the lunar surface; new gravity data; geochronology; geochemistry, especially isotopic constraints; and the abundances and source reservoirs of lunar volatiles have brought, and continue to bring, valuable insights to understanding the Moon's geological evolution (e.g., Shearer et al. 2006; Elkins-Tanton et al. 2011; Elardo et al. 2011; Zuber et al. 2013; Wieczorek et al. 2013; Borg et al. 2015).

### The Lunar Magma Ocean Paradigm

The early history and broad-scale petrogenesis of the Moon were glimpsed from the first manned and unmanned missions to the Moon that returned ~382 kg of lunar rocks and soils from the lunar surface (Vaniman et al. 1991). These were collected by the Apollo and Luna missions from the central and eastern nearside of the Moon (Fig. 1). Based on numerous studies of these returned Apollo and Luna samples, hypotheses of the Moon's differentiation and crust formation were made. The most supported model for the formation and evolution of the Moon is that of a giant impact between proto-Earth and another large planetary body early in the Solar System history (e.g., Canup 2008, 2012; Canup et al. 2015; Cuk and Stewart 2012), chemically mixing the two bodies (e.g., Young et al. 2016). This produced a lunar magma ocean (LMO), although the global extent of this ocean and depth of melting that occurred is debated (Wood et al. 1970; Smith et al. 1970; Solomon 1986; Binder 1986;


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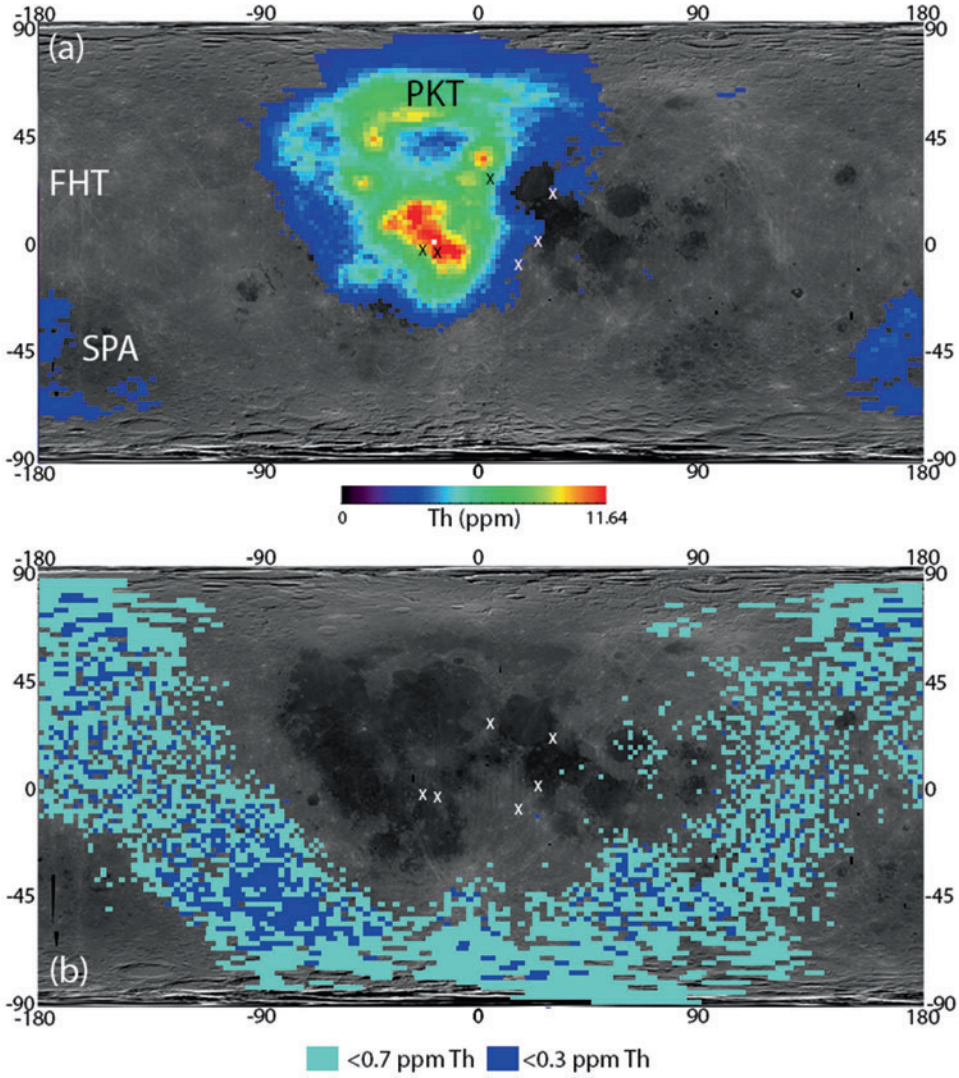
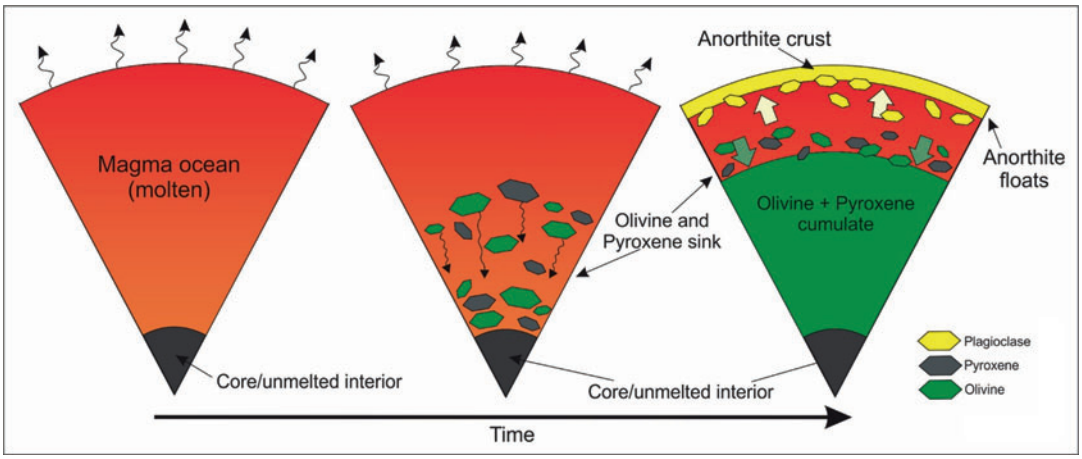



**Evolution, Lunar: From Magma Ocean to Crust Formation, Fig. 1** Clementine mission albedo map of the Moon in a cylindrical projection, overlain with locations of the Apollo sample return missions (as indicated by crosses). (**a**) Map is overlain with the distribution and concentration of regions with >2 ppm Th as mapped by the Lunar Prospector mission (2° per pixel data calibration; Prettyman et al. 2006) showing surface expression of KREEP-bearing lithologies. Major crustal terranes as mapped by Jolliff et al. (2000) are denoted as South Pole-Aitken (SPA) basin, feldspathic highland terrane (FHT) and Procellarum KREEP Terrane (PKT). (**b**) Map is overlain with the distribution and concentration of regions with <0.7 ppm Th (*cyan*-colored pixels) and <0.3 ppm Th (*dark blue*-colored pixels) (Prettyman et al. 2006). The threshold <0.7 ppm Th is taken as regolith with no or a positive Eu-anomalies (O'Hara and Nui 2015). It is important to note that the gamma-ray spectrometer data sample the upper 30 cm of the lunar regolith, and mapped regoliths will include a wide mix of igneous rocks, reworked impact melt breccias, and impact glass over a scale of 60 km per pixel, so we also highlight in Fig. 2b regoliths with <0.3 ppm Th, taken as equivalent to significant positive Eu-anomalies akin to Apollo igneous FAN rocks (<0.15 ppm Th, Taylor 2009), bearing in mind the average uncertainty of the Lunar Prospector dataset (Prettyman et al. 2006). An interesting point to note is that none of the average Apollo landing site soils have positive Eu-anomalies as they all contain soil components rich in negative Eu-anomalies-bearing KREEPy mafic impact melt breccias and/or mafic mare basalt material

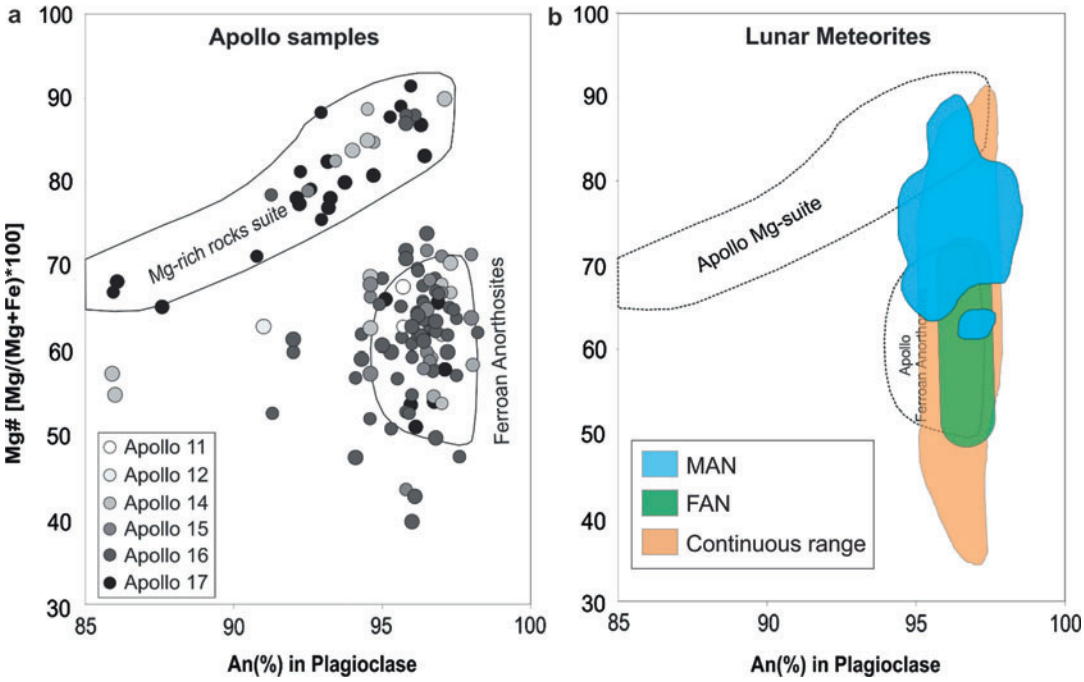



**Evolution, Lunar: From Magma Ocean to Crust Formation, Fig. 2** Schematic sketch of the (**a**) differentiation and (**b**) crystallization of the global lunar magma ocean (LMO). (**b**) The LMO crystallized mafic cumulates of olivine and pyroxene crystals. These cumulates sank into the interior to form the lunar mantle (Shearer et al. 2006 and refs. therein; Elardo et al. 2011). (**c**) After ~75 to 80 % of LMO crystallization, plagioclase began to crystallize (Snyder et al. 1992) and floated to the top of the LMO producing the global anorthositic crust, the light-colored highlands seen on the lunar surface today. The residual magma, trapped between the anorthositic crust and the underlying ultramafic mantle, continued to crystallize and late-stage melt became increasingly enriched in KREEP. For more details, see text (Modified from the classroom illustration of Jennifer Rapp (2013) from the Lunar and Planetary Institute; Center for Lunar Science and Exploration http://www.lpi.usra.edu/nlsi/training/illustrations/planetaryInteriors)

Pritchard and Stevenson 2000; Shearer et al. 2006 and refs. therein; Delano 2009).

As this LMO cooled, crystals that precipitated from the melt separated due to density differences (Fig. 2). This has been modeled (e.g., Solomon and Longhi 1977; Dreibus et al. 1977; Longhi 1980, 2003; Tonks and Melosh 1990; Snyder et al. 1992; Meyer et al. 2010; Elkins-Tanton et al. 2011) and experimentally tested (Elardo et al. 2011; Rapp and Draper 2012, 2013). These models consider two end-member forms: (1) fractional crystallization from start to finish (the "one-stage model") and (2) a "two-stage model" in which early equilibrium crystallization occurred followed by fractional crystallization of the residual magma ocean. In all models, Mg-rich olivine is the liquidus phase, followed by orthopyroxene crystallization. These dense mafic (Mg-rich) minerals sank and formed the mantle, enriching the residual magma in iron and more incompatible elements (e.g., Th, Ti, K).

After ~75–80 % of the LMO had solidified, the calc-end-member of plagioclase feldspar (anorthite) began to crystallize. Recent studies suggest that initialization of plagioclase crystallization occurred at depths of >75 km in the LMO (Nakvasil et al. 2015). Upon formation, this low-density plagioclase overcame a density contrast with dense comagmatically crystallizing mafic phases by buoyantly rising and migrating toward the lunar surface, forming a thick "onion shell" anorthosite crust (Warren 1990; Elkins-Tanton et al. 2011) (Fig. 2). This crystal separation also removed the plagiophile compatible element Eu from the magma ocean melt, providing the anorthositic crust with a positive chondrite-normalized ($_{cn}$) Eu-anomalies (i.e., Eu/Eu* >1, where Eu/Eu* = ($Eu_{cn}$ /($Sm_{cn}$ + $Gd_{cn}$)^0.5)) and rocks that have low concentrations of incompatible trace elements. Analyses of Apollo returned samples show that this primary feldspathic crust is composed of anorthositic rock with plagioclase An# (molar Ca/[Ca + Na + K]) of 94–98, with mafic minerals that have a Mg# (molar Mg/[Mg + Fe]) ranging from ~40 to ~70, although varieties within that range exist (Warren et al. 1983; James et al. 1989; Jolliff and Haskin 1995; Nyquist et al. 2006) (Fig. 3a). These rocks are called the




**Evolution, Lunar: From Magma Ocean to Crust Formation, Fig. 3** Graph of An (molar Ca/[Ca + Na + K]) in plagioclase versus Mg# (molar Mg/[Mg + Fe]*100) in mafic minerals (olivine and pyroxene) in feldspathic rock fragments in lunar samples. (**a**) Apollo samples. (**b**) Anorthosite clasts in lunar feldspathic meteorites (Modified from Gross et al. (2014). Data from Warner et al. (1976), Warren and Wasson (1979), Warren (1993), and Meyer (2010) and from Gross et al. (2014) and references therein)

ferroan anorthosite suite (FAN; Fig. 3a). FANs are common at the Apollo 16 highland landing site and are also present at the mare regions visited by the other Apollo missions (Wood et al. 1970).

The development of a thick "onion shell" anorthosite crust would have likely caused a large thermal blanketing effect on the lunar interior (Shearer et al. 2006). The rate of cooling in the remaining molten lunar interior (be it the dregs of a magma ocean, more localized melt environments, or Moon-wide partial melts) would have rapidly slowed, and the melt itself would have become increasingly FeO-rich and dense (Warren 1990) and crystallized to yield abundant ilmenite ($FeTiO_3$). Very late-stage residual melt products (after 90–95 % of crystallization) would have ponded and crystallized in the intermediate regions between the "buoyantly risen" anorthosite-rich crust and the "sunken" mafic cumulate mantle. Such residual melt was enriched in incompatible and heat-producing elements like thorium (Th), potassium (K), rare earth elements (REE), and phosphorus (P) that were not incorporated into the previously formed cumulates. This residual melt is called the KREEP (K, REE, and P) geochemical component (Warren and Wasson 1979; Snyder et al. 1995; also see review by Shearer et al. 2006 and refs. therein; Taylor and McLennan 2009).

By the end of differentiation, the Moon had a small dense core, an inner mantle made of Mg- and Fe-rich silicate minerals (olivine and pyroxene), and an outer feldspathic crust, the so-called "primary" crust which makes up much of the white highland areas of the Moon (Fig. 1). Numerical models predict that upon solidification of the LMO, a density gradient existed, with denser (cooler and more Fe-rich) cumulates near the surface, under the buoyant anorthosite crust, compared to less dense cumulates (Mg-rich) at depth. This gravitational unstable stratigraphy leads to overturn via Rayleigh-Taylor instability resulting

in mixing and/or relocation of early- and late-stage LMO cumulates (Ringwood and Kesson 1976; Herbert 1980; Spera 1992; Shearer and Papike 1993, 1999; Hess and Parmentier 1995; Elkins-Tanton et al. 2002, 2011).

*Post-LMO magmatism*: After the lunar anorthositic crust was formed, partial melts from the interior of the Moon intruded into the plagioclase rich crust and formed magmatic "secondary" crustal rocks known as the high-magnesian suite (HMS – mafic rocks with a wide range of plagioclase compositions, mafic minerals with Mg# ranging from ~65 to 90, and KREEP component; Fig. 3a) and the high-alkali suite (HAS – rocks with a high bulk alkali KREEPy component). Magnesian-suite (Mg-suite) rocks (Fig. 4c) and KREEP-rich material are present in rocks collected from all Apollo sites. Trace element geochemistry has shown that the Mg-suite rocks are petrogenetically not related to the FAN crust (Shearer and Papike 2005, and refs. therein). Their typical KREEPy geochemical signatures also suggest that Mg-Suite cumulates must have been formed after the closure of KREEP formation in an LMO and, therefore, are sourced from melting events that postdate LMO closure.

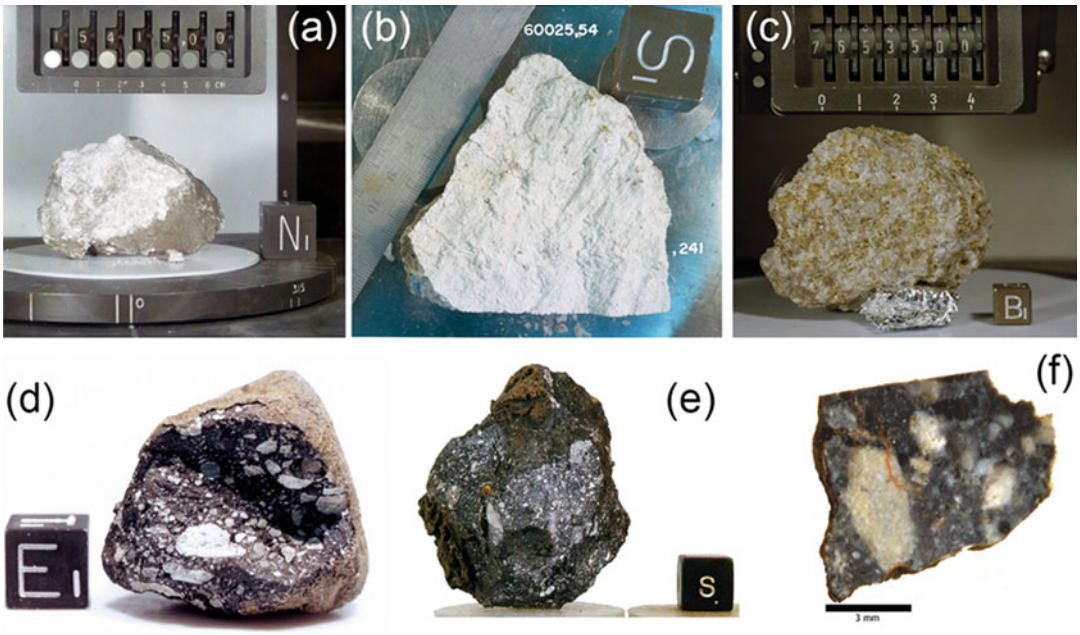
Geochemical modeling requires that this plutonic suite was generated by the melting of deep, early-crystallized, magma ocean mafic cumulates and the assimilation of KREEP during ascent (Hess 1994; Hess and Parmentier 1995, 2001; Longhi 2003). The presence of a KREEPy-ITE signature and isotopic systematics suggest that there is a petrologic link between the HMS rocks and HAS samples (Shearer and Floss 2000; Shearer et al. 2006). They are either likely to represent a continuum of crystallized products of parental magmas with compositions similar to the KREEP basalts (Snyder et al. 1995) or to represent a more complex scenario with KREEP magmas assimilating different amounts of crustal ferroan anorthosites and/or magma mixing (Shervais and McGee 1998, 1999).

*Post-LMO crustal modification*: Throughout the past 4.5 Ga, the Moon has been constantly resurfaced by impacting asteroids and comets (see review by Stöffler et al. 2006). Before ~3.8 Ga, the rates of impact bombardment were notably higher, and large impactors created the lunar basins >300 km in diameter, as well as many smaller craters on the lunar surface. However, the duration and magnitude of the duration of basin formation is debated (Hartmann 1970; Turner et al. 1973; Tera et al. 1974; Wetherill 1975; Turner 1979; Hartmann and Neukum 2001; Ryder 2003; Stöffler et al. 2006; NRC 2007; Norman 2009; Morbidelli et al. 2012; Fernandes et al. 2013; Miljkovic et al. 2013).

*Young volcanism*: After the youngest basin (Orientale) was formed at ~3.8 Ga, effusive volcanism became the dominant crust-forming process. Mare basalts, thought to be partial melts of the cumulate mantle, filled many of the older impact basins (see review by Hiesinger and Head 2006). The mare basalt surface exposure is about 15 % of the global lunar surface, and most of it is concentrated on the lunar nearside, only a few basalt outcrops exist on the lunar farside. Trace element geochemistry has shown that the source regions of the mare basalts are complementary to the plagioclase-rich crust, i.e., their source regions had plagioclase removed, resulting in rocks with negative Eu-anomalies (Eu/Eu* <1.0) (Warren 1985; Delano 2009). The observation that the majority of igneous rocks from the lunar highlands have a positive Eu-anomalies and that the lunar mare basalts have a complementary negative Eu-anomalies is generally taken as supporting evidence for the LMO model of early evolution (Warren 1985; Jolliff et al. 2000; Shearer et al. 2006; Delano 2009). However, it has been proposed that the negative Eu-anomalies born by mare basalt may be the result of low-pressure fractionation of lavas after ponding into lava lakes (e.g., O'Hara 2000; O'Hara and Niu 2015); hence, there is some debate about the interpretation of this critical geochemical indicator.

## New Views of the Evolution of the Lunar Crust

We have learned a great deal about the lunar formation history from studies of Apollo samples. However, these interpretations have been made




**Evolution, Lunar: From Magma Ocean to Crust Formation, Fig. 4** Photos of lunar crust samples. (**a**) NASA curation photographs of pristine lunar anorthosite sample 15,415, which is also known as the "Genesis Rock" (NASA photo S-71-42951). (**b**) NASA curation photographs of sliced section of pristine anorthosite 60025 (NASA photo S75-32823). (**c**) NASA curation photographs of igneous intrusive sample 76535, which is a troctolite and part of the lunar Mg-suite (NASA photo S73-19458). (**d**) Antarctic feldspathic regolith breccia Allan Hills (ALHA) 81005 showing clast-rich interior and brown fusion crust (Photo: NASA). (**e**) Antarctic feldspathic regolith breccia Yamato 791197 (Photo: NIPR). (**f**) Polished slab of hot desert (Libya) feldspathic regolith breccia Dar al Gani 400 (Photo: Katherine Joy; as studied in Joy et al. 2010) (Figure adapted from those shown in Crawford et al. (2014))

from a dataset that comes from a restricted geographically region (Fig. 1). Notably remote-sensing data of K and Th abundances have subsequently shown that many of the Apollo and Luna landing sites actually sampled a geochemically unusual region, with enhanced concentrations of the KREEP component (Jolliff et al. 2000). This geochemical signature is not globally distributed (see Fig. 1a), but instead is mostly localized and closely associated with impact ejecta from the nearside Imbrium impact basin (Lawrence et al. 2003; Gillis et al. 2004). It is, therefore, now acknowledged that Apollo samples may not necessarily represent the full range of the Moon's global geological makeup, and several lines of new evidence are emerging to make us re-examine the LMO paradigm (e.g., Longhi 2003; Arai et al. 2008; Gross et al. 2014; O'Hara and Niu 2015; Borg et al. 2015; Yamamoto et al. 2016) and question the formation mechanisms responsible for the formation of the Moon's crust (see also Pernet-Fisher and Joy 2016 for a summary).

## Remote-Sensing Records: A Compositionally Variable Lunar Crust

The last 20 years have seen a renaissance in lunar orbital missions with vast amounts of data being acquired from mapping the morphology, gravity, chemistry, and mineralogy of the lunar surface and upper crust (see Crawford et al. 2014 for an overview of lunar recent exploration). These new global datasets have revealed the complex makeup of the Moon's crust, helping to test the LMO paradigm and models of crust formation.

Remote-sensing data (optical reflectance, gamma ray, and X-ray emission) have suggested that a large portion of 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; Piskorz and Stevenson 2014; Crites and Lucey 2015), supporting the model of a global plagioclase-rich flotation crust. This assumption has recently been questioned by O'Hara (2000) and O'Hara and Niu (2015) who argue that on the basis of the relationship between bulk lunar sample Eu-anomalies (Eu/Eu*) and Th concentration (Korotev and Haskin 1988; O'Hara 2000; O'Hara and Niu 2015), global Th element maps do not provide evidence that the lunar highlands have positive Eu-anomalies. We examine this further in Fig. 1b, using the threshold of <0.7 ppm Th (where Th is derived from the 2° per pixel Th dataset of Prettyman et al. 2006) to locate regolith with equivalent positive Eu-anomalies (Eu/Eu* >1), following the relationship defined by O'Hara and Niu (2015). Our results show the lunar highlands typically do have low Th concentrations representative of positive Eu-anomalies, supporting the long-standing view that the feldspathic highland terrane and outer regions (FHT-O) are the surface expression of regolith formed from plagioclase-rich underlying crust (Taylor 2009 and refs. therein).

However, other compositional evidence does indicates that the lunar feldspathic highland crust is compositionally heterogeneous (e.g., Jolliff et al. 2000; Spudis et al. 2000, 2002), with some indication that the farside highlands may be more magnesian than the ferroan central nearside highland crust sampled by the Apollo missions (Arai et al. 2008; Ohtake et al. 2012; Crites and Lucey 2015). This observation, if confirmed by future in situ geological sampling efforts (Mimoun et al. 2012) and high-resolution chemical mapping instruments, would imply that the lunar anorthositic crust may have been formed in a more complex way than suggested by the simple compositionally homogenous onion floatation model (Arai et al. 2008; Ohtake et al. 2012; Pernet-Fisher and Joy 2016).

Moreover, the central peaks of impact craters have been used to probe vertical stratigraphic variation in the lunar crustal (e.g., Tompkins and Pieters 1999). Outcrops of "pure anorthosite" (i.e., regoliths and rocks with <2 % Fe-bearing mafic minerals) have also been observed in many globally distributed uplifted crater center peaks and peak rings (Donaldson Hanna et al. 2014; Hawke et al. 2003; Ohtake et al. 2009; Yamamoto et al. 2012). These observations have been used to suggest that there was a global pure anorthosite crust ~50 km in depth (Yamamoto et al. 2012; Piskorz and Stevenson 2014), supporting the model of a globally extensive floatation crust.

Profiles of the central peaks using Clementine mission data revealed that the crust increases in mafic content with depth (anorthosite → gabbroic-noritic-troctolitic anorthosite → anorthositic norite) and that the lower crust is actually much more compositionally diverse than implied by surface mapping alone (Ryder and Wood 1977; Spudis and Davis 1985). The survey also identified craters excavating "massive" mafic lithologies (gabbros and troctolites), consistent with plutons being intruded at depth throughout the lunar crust (Pieters 1991; Pieters et al. 2001).

Recent gravity model data from the GRAIL mission estimate that the lunar crust is on average only 34–43 km thick (Wieczorek et al. 2013; Taylor et al. 2013), which is much thinner than previously inferred from the simple global plagioclase floatation magma ocean model (Taylor et al. 2013) and the calculations of crustal thickness derived from observations of pure anorthosite outcrops (Yamamoto et al. 2012).

Another observation that argues against the existence of a continuous onion shell-like LMO crustal formation model is the compositional diversity between the nearside and farside of the Moon: if KREEP was formed in the LMO as a late-stage precipitated globally extending layer, then KREEPy rock signatures would be expected to commonly appear across the whole of the Moon. However, the large Th anomaly associated with ejecta from the Imbrium basin in the nearside Procellarum KREEP Terrane is not significantly seen in the farside South Pole-Aitken (SPA) basin (Fig. 1a). As the SPA should have excavated more deeply through the lunar crust than Imbrium, this observation suggests that LMO-derived urKREEP may be asymmetrically spatially distributed, rather than forming a global uniform

layer as dictated by the simple global LMO onion skin more of crust formation (e.g., Jolliff et al. 2000; Elphic et al. 2000; Wieczorek and Phillips 2000; Haskin et al. 2000; Lawrence et al. 2003; Gillis et al. 2004).

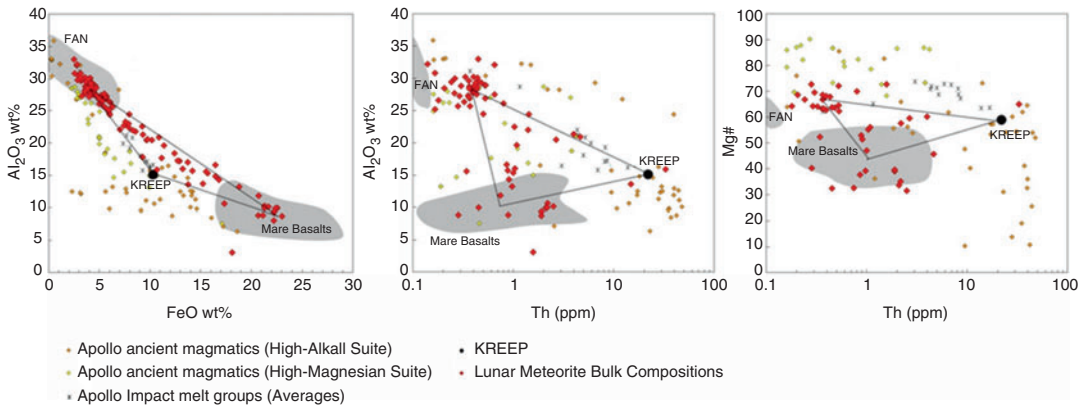
## Lunar Meteorite Record

In addition to the new remote-sensing datasets, there is also a new lunar sample resource – the lunar meteorites – that can be used to test models of lunar crust formation and provide insights to the LMO model (e.g., Palme et al. 1991; Korotev et al. 2003; Korotev 2005; Demidova et al. 2007; Arai et al. 2008; Joy and Arai 2013; Gross et al. 2014). Lunar meteorites are rock fragments that were ejected from the Moon by impact events. They provide samples of the Moon from regions not visited by Apollo or Luna mission (Korotev et al. 2003; Caldeza-Diaz et al. 2015) and are presumably representative, on average, of the compositional diversity of the lunar surface (Korotev 2005).

About 60 % of lunar meteorites collected are feldspathic (Fig. 4d–f), with low KREEP concentrations (<2 ppm Th, < ~5 ppm Sm, < 1 % $TiO_2$) and high bulk-rock Al (>20 wt% $Al_2O_3$) compositions (Fig. 5) (Wieczorek et al. 2006; Joy et al. 2010; Korotev 2005, 2012; Korotev et al. 2013). These feldspathic meteorites plausibly sample regoliths and impact breccias derived from crust from the southern nearside, polar regions, and the farside highlands (e.g., Palme et al. 1991; Korotev et al. 2003; Cahill et al. 2004; Takeda et al. 2006; Arai et al. 2008; Joy et al. 2010; Treiman et al. 2010; Calzada-Diaz et al. 2015).

Many of these feldspathic meteorites contain fragments of anorthositic material (fragments with >75 % anorthite). Gross et al. (2014) noticed that by plotting the compositions of minerals in these clasts, i.e., the anorthite component (An#) of plagioclase versus Mg# of their mafic minerals, three compositional distinct groups can be recognized (Fig. 3b):

1. Magnesian anorthosites (MAN): ~56 % of all the meteorites plotted have fragments that contain mafic minerals with a Mg# ranging from 65 to 90 (Fig. 3b).
2. Ferroan anorthosites FAN (19 %): mafic minerals within FAN fragments show a Mg# ranging from 50 to 68 (Fig. 3b), comparable to those of pristine Apollo ferroan anorthosites (Fig. 3a).
3. Continuous range (25 %): anorthositic lithologies that span a wide range of compositions from hyperferroan (~Mg# 35) to highly




**Evolution, Lunar: From Magma Ocean to Crust Formation, Fig. 5** Lunar meteorite bulk compositions (electronic database of Wieczorek et al. 2006; Joy et al. 2010; Korotev 2012) compared with Apollo samples (electronic database of Wieczorek et al. 2006 and Clive Neal's mare basalt database). Mixing lines are drawn between the bulk composition of KREEP (Warren 1989), the estimated bulk composition of the lunar feldspathic highlands (Korotev et al. 2003), and the center of the mare basalt fields

magnesian (~Mg# 90) (Fig. 3b; see Gross et al. 2014 and refs. within).

Moreover, the Luna 20 and 24 missions returned samples from outside the continuous ejecta blanket of the Imbrium basin, and their highland materials are also dominated by magnesian anorthositic rocks, not ferroan rocks (Korotev et al. 2003; Arai et al. 2008). Taken together, this suggests that the lunar crust represented by Apollo-sampled FANs is characteristic only of a small part of the lunar highlands, whereas MANs seem characteristic of many other highland areas (also see Arai et al. 2008; Takeda et al. 2006). However, it is currently hard to account for such MAN rocks with a Mg# >75 from the traditional LMO plagioclase floatation crust model since it predicts that at the time of plagioclase crystallization, the cogenetic mafic minerals – such as olivine and pyroxene – will crystallize with an average Mg# of 75 or lower (Dreibus et al. 1977; Snyder et al. 1992). In that model, MANs with Mg# >75 could only be produced if these mafic minerals became entrapped in the plagioclase floatation matrix/mush right at the moment of plagioclase crystallization (at the time of plagioclase saturation of the melt), before the LMO could evolve to more ferroan compositions (Gross et al. 2014). Thus, formation of abundant MAN is difficult to explain at this point.

Other compositional and isotopic discrepancies exist between the Apollo and lunar meteorite anorthositic material. For example, plagioclase fragments in relict clasts in these types of feldspathic lunar meteorites (Cahill et al. 2004; Joy 2013; Russell et al. 2014) have a wider range of trace element concentrations and variably Eu-anomalies compared with plagioclase in Apollo FAN samples (Papike et al. 1997; Floss et al. 1998). Also, recent studies of neodymium isotopes in Apollo samples and lunar meteorites create complexities for FAN origin as primary crust formed from a primordial LMO. Variation in εNd values suggest that FANs originated from both super- and sub-chondritic source regions (Nyquist et al. 2006, 2010; see also the summary by Arai et al. 2008), which is not consistent with FANs originating from a LREE-depleted LMO from prior removal of early forming pyroxene (Snyder et al. 1992).

Intriguingly, KREEP-bearing Mg-suite rocks are almost completely absent in many of the feldspathic meteorites (Korotev 2005; Gross et al. 2014; Shearer et al. 2015), but lunar meteorites contain a wealth of intriguing lithologies that are not well represented in the Apollo suite. An example is the magnesian granulites, which are crystalline rocks with granulitic textures (rounded grain shapes) that formed by recrystallization during prolonged annealing (Warner et al. 1977; Lindstrom and Lindstrom 1986). These granulites are chemically distinct in having major element mineral compositions (i.e., Mg#) similar to magnesian-suite plutonic rocks, but containing no trace of KREEP component (Warner et al. 1977; Lindstrom and Lindstrom 1986; Korotev and Jolliff 2001; Treiman et al. 2010). They do not represent simple mixtures of FAN and KREEP-bearing Mg-suite rocks (Korotev et al. 2003; Treiman et al. 2010). Their protoliths are not known, but they could provide evidence for magnesian plutonic rocks other than Mg-suite, with distinctive chemistry including an absence of KREEP (Korotev and Jolliff 2001; Korotev et al. 2003, 2006, 2012; Takeda et al. 2006; Treiman et al. 2010; Zeigler et al. 2012; Shearer et al. 2015).

Taken together, the emerging compositional evidence suggests that anorthositic protoliths sampled by many feldspathic lunar meteorites are compositionally variable from pristine Apollo ferroan anorthosites. This suggests that they represent products of different parent melts, which is inconsistent with a simple global LMO anorthosite flotation crust (Gross et al. 2014; Russell et al. 2014). However, the argument is controversial because of the usually small sample size (< few mm) of rock fragments in currently available lunar meteorites compared with hand specimen-sized Apollo pristine rocks (Warren 2012). The sampling problem is caused by extensive impact bombardment and mixing in the lunar highlands, resulting in cataclastics and promoting annealing and inter- and intra-mineral element diffusion that may mask the true chemical and isotopic record of

small highland rock fragments (McCallum et al. 1997; Pernet-Fisher et al. 2016).

### Sample Ages and Isotopic Anomalies

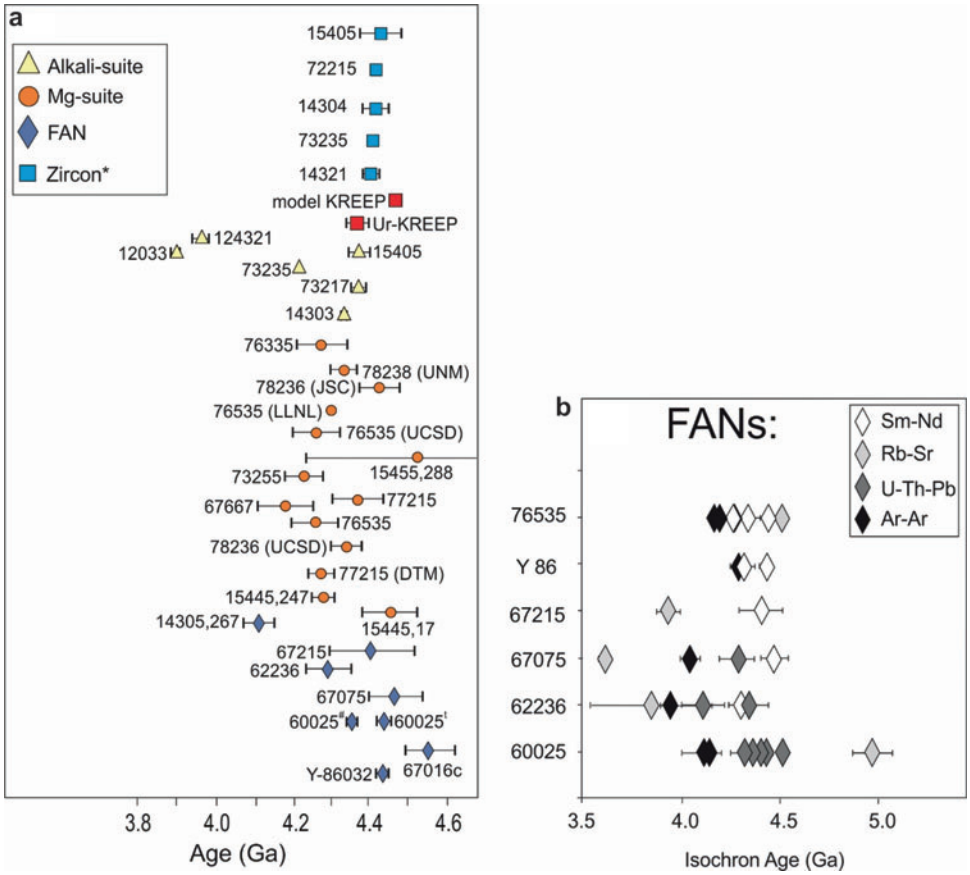
The radiometric age determination of lunar highland rocks are the primary tool that is used to place constraints on their chronological relationships, as well as to constrain the origin and evolution of their sources (e.g., Carlson and Lugmair 1981; Alibert et al. 1994; Borg et al. 1999, 2011, 2012, 2015 and ref. therein; Cohen et al. 2000, 2005; Norman et al. 2003; Nyquist et al. 2006, 2010; Boyet and Carlson 2007).

In the onion skin floatation crust LMO model, FANs represent the primary lunar crust and, therefore, are expected to yield the oldest radiometric ages of any lunar rocks. Age investigations of FANs, however, are typically very difficult because FANs are often nearly monomineralic, making isochron mineral separate isotopic analyses challenging (Fig.6a, b) Borg et al. 1999, 2015). They also often have had their isotopic systematics disturbed by the heavy bombardment of the lunar crust which could have reset their radiometric clocks and/or geochemically mixed them with younger material or fractionated elements through outgassing and volatilization from the rock (Borg et al. 1999, 2015). Experimental investigations of shocked and heated lunar samples demonstrate that Sm-Nd is least mobile during shock metamorphism and, therefore, is the most reliable recorder of igneous events (Gaffney et al. 2011; Borg et al. 2015). Application of this Sm-Nd system to lunar highland samples is hindered though, by the very low abundances of Nd in FANs (Borg et al. 2011, 2012). In contrast, Ar-Ar, Rb-Sr, and U-Pb systems are more easily disturbed (Fig. 6b). Individual isochron age measurements have mostly not been confirmed by application of additional isotopic systems (Carlson and Lugmair 1988; Hanan and Tilton 1987; Norman et al. 2003) leading to non-reproducible ages and large uncertainties (Fig. 6b) (Borg et al. 1999, 2015). These analytical challenges account for the wide range of ages reported for lunar highland feldspathic samples (Fig. 6b). When the ages of lunar samples are assessed for reliability (using a number of key indicators such as agreement between isotopic dating systems, consistency with petrogenesis of the samples, and others – see Borg et al. 2015), it appears that oldest ferroan anorthosite samples have the least reliable age and overlap in age with samples from the Mg-suite rocks (Fig. 6a) (Borg et al. 2015). This is problematic for the classic lunar magma ocean scenario, which proposes that the magmatic HMS rocks are intruded into older FAN samples (Fig. 6a). This could imply that the Moon either accreted relatively slowly after the giant impact or that it retained enough heat to delay cumulate formation or that some FANs were produced by a more recent melting event(s) rather than being a product of the magma ocean (Borg et al. 2011, 2015).

## Alternative Crust Formation Models

If evidence continues to support complexities in the simple magma ocean floatation crust onion skin model (Figs. 2 and 7a), alternative crust formation mechanisms should be considered (Longhi 2003; Arai et al. 2008; Gross et al. 2014; Pernet-Fisher and Joy 2016; Yamamoto et al. 2016). Some alternative hypotheses are summarized and discussed below and illustrated in Fig. 7. Some of these hypotheses still necessitate a lunar magma ocean model to account for an olivine- and pyroxene-rich mantle, prior to the onset of plagioclase formation, but others seek more complex non-magma ocean early lunar differentiation models:

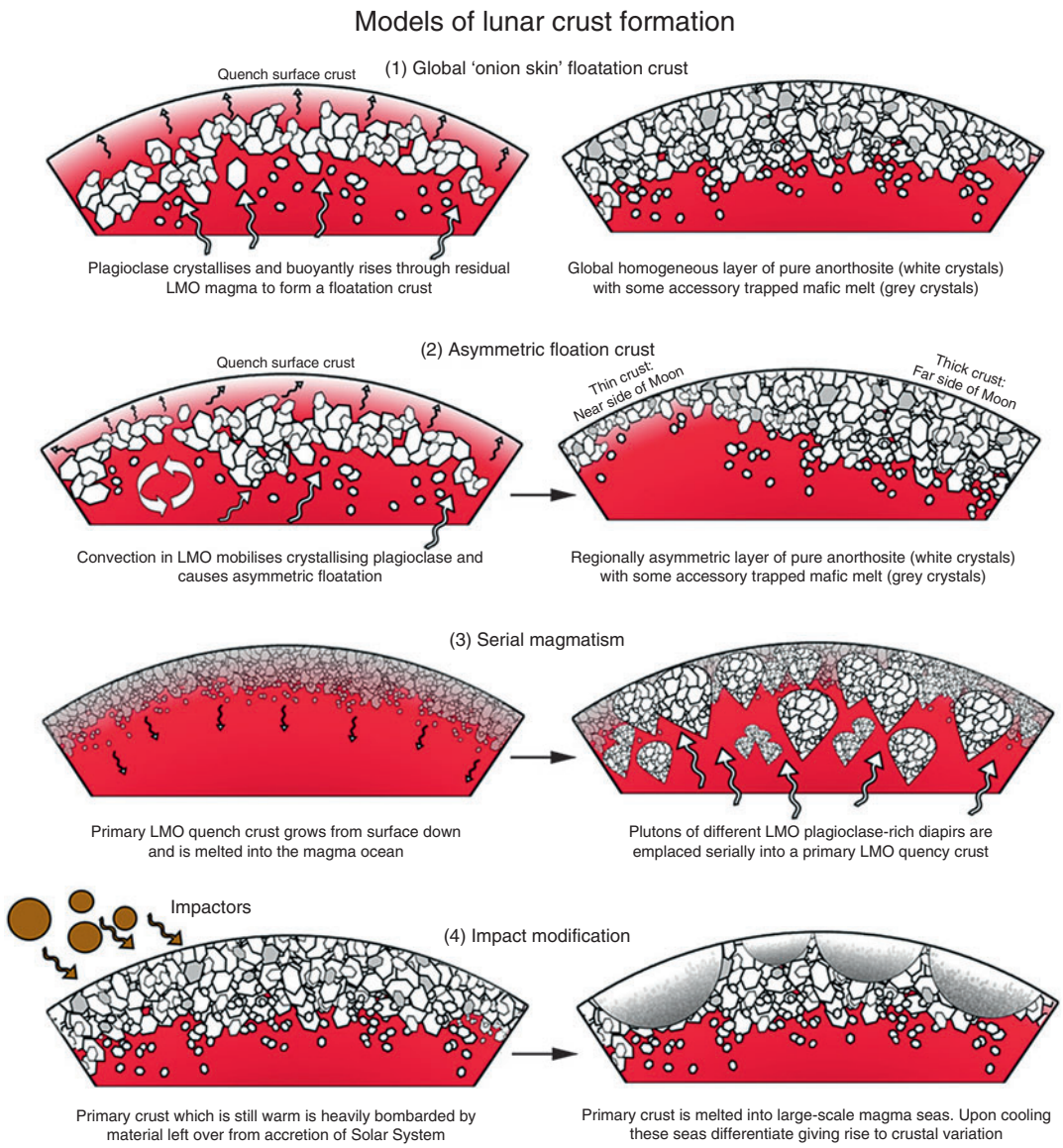
1. **Heterogeneous accretion and/or magma ocean:** It has been proposed that rigorous convection within a magma ocean may have caused asymmetrical aggregation of refractory parental melts or plagioclase floatation mushes, accounting for the crustal thickness variations and compositional variations between the farside (more magnesian, early precipitates) and nearside (more ferroan, later precipitates) crustal regions (Fig. 7b; Arai et al. 2008; Yamamoto et al. 2016). Such convection could have been driven by a range of processes including (i) tidally driven




**Evolution, Lunar: From Magma Ocean to Crust Formation, Fig. 6** Summary of lunar ages modified after Borg et al. (1999, 2011, 2012, 2015). (**a**) The diagram shows the ages of the oldest lunar samples and model ages of cumulate source regions. Symbols refer to ages reported on individual samples. Diamonds (*blue* and the *gray* scale) represent FANs, *orange filled circles* represent Mg-suite samples, *yellow triangles* represent Alkali-suite samples, the *red square* represents a model age for KREEP, and the *blue squares* represent zircon ages for lunar Mg-suite and Alkali-suite. Error bars are uncertainties reported for individual age determinations. *denotes maximum age measured for zircons (After Borg et al. 2015). # = age date for 60025 by Borg et al. (2011); t = age date for 60025 by Carlson and Lugmair (1988) (Data are from Borg et al. (1999, 2011, 2012, 2015) and references therein). (**b**) The diagram shows the variation of ages for FANs depending on the isotopic system that was used (Borg et al. 2012)

convection (Garrick-Bethell et al. 2010), (ii) asymmetric primordial accretion or thermally driven lunar magma ocean convection as a result of one face of the Moon being tidally locked facing the hot early Earth (Loper and Werner 2002; Laneuville et al. 2013; Roy et al. 2014), and (iii) potential regional differences in impact rates between the Moon's leading and trailing hemispheres causing different regions of melting and crustal thinning (Wood 1970; Wood et al. 1970; Wasson and Warren 1980; Morota and Furumoto 2003; Le Feuvre and Wieczorek 2011; Miljkovic et al. 2013). However, it is still not understood if the Moon has always been locked in the same orbital configuration or has been at different orientations in the past (Wieczorek and Le Feuvre 2009), making it challenging to access the cause(s) of these proposed LMO convection mechanisms.

2. **Serial magmatism:** The long-standing alternative to the floatation crust model is that of




**Evolution, Lunar: From Magma Ocean to Crust Formation, Fig. 7** Schematic diagram of the differentiation of the Moon and different lunar magma ocean models. Subsequent models of crust formation are debated and alternative models are illustrated here (see text for details): (*1*) the traditional global floatation crust model, (*2*) heterogeneous magma ocean crust formation model involving asymmetric floatation crust, (*3*) serial magmatism model of crust formation, (*4*) modification of the primary lunar crust by widespread early impact bombardment, creating a series of magma seas that differentiate to form regionally variable crustal terranes (Adapted from Crawford and Joy (2014) and Pernet-Fisher and Joy (2016))

serial magmatism in which the variation in anorthosite chemistry can be explained as products of repeated intrusions of pods of basaltic magma into a preexisting crust or when discrete "rockberg" plagioclase crystal mushes floated as self-driven diapirs by upward thermal convection (Fig. 7c) (Walker 1983; Longhi and Boudreau 1979; Longhi and Ashwall 1985; Ashwall 1993; Jolliff and Haskin 1995; Longhi et al. 1999; Longhi

2003, 2006; Vander Auwera et al. 2006; Gross et al. 2014).

The controversy for these models arises as to whether the parent magmas of such diapirs/rockbergs were precipitated from a magma ocean of the same parent melt composition (i.e., a global magma ocean with a simple onion skin flotation crust) or from discrete pockets (i.e., individual magma seas) all with different parent melt compositions or if the diapirs are the result of melting of a previously existing stratified lunar interior which had overturned (Longhi 2003).

In the serial magmatism model, each diapir could potentially have differentiated during and after emplacement and would be generally similar to large layered basic intrusion on Earth, like the Stillwater complex (Raedeke and McCallum 1980; Salpas et al. 1983), and terrestrial massif anorthosites like the Nain complex (Ashwal 1993). To account for the wide range of Mg# in olivine and pyroxene (Gross et al. 2014) and variable range of REE (Russell et al. 2014) with essentially constant plagioclase compositions observed in the anorthosite suites (Nekvasil et al. 2015), each cooling plagioclase crystal mush zone may have had fractionation of interstitial melt during emplacement (Jolliff and Haskin 1995) or undergone further partial melting from interacting with the residual hot magma ocean (Longhi and Boudreau 1979). Deformation of the diapirs could squeeze out the intercumulus melts producing fairly pure anorthosite bodies (Korotev et al. 2010) as observed spectroscopically on the lunar surface as the "PAN" deposits (Donaldson Hanna et al. 2014; Ohtake et al. 2012; Yamamoto et al. 2012). If this emplacement and differentiation style continued throughout a long LMO closure period (i.e., ~200 Ma), this could account for the different ages (Borg et al. 2015), compositions (Gross et al. 2014), and isotopic chemistries (Longhi 2003; Borg et al. 2009, 2011; Nyquist et al. 2010) of highland anorthositic samples (see Gross et al. 2014 for a more detailed discussion).

In this crust formation model, the sources of mare basalts can form as mixtures of primitive mantle with the complementary dense sinking diapirs of mafic material (Longhi and Ashwall 1985; Gross et al. 2014). Such a model can account for the hybridized nature of the lunar mantle (Elkins-Tanton et al. 2002; 2011), for example, each complementary mafic diapir could have unique degree of Eu depletion, Ti enrichment, and KREEP enrichment, accounting for the observed wide range of mare basalt Ti contents and Eu-anomalies (Gross et al. 2014).

3. **Impact bombardment:** Models involving the modification of the Moon by impacting bodies have been evoked to explain near- and farside discrepancies in thickness and composition. For example, one end-member model proposes to the early addition (i.e., within tens of millions of years of the Moon's formation) of a compositionally similar smaller "companion moon," impacting at very low velocity to the lunar farside, generating a thickened crust (Jutzi and Asphaug 2011).

Alternatively, it is plausible that ferroan anorthosites (and maybe even KREEP: Haskin et al. 1981, 1998), that dominate the Apollo sample collection, are actually just localized products of the Procellarum KREEP Terrane. The lunar meteorites support this idea: of the 24 feldspathic highland meteorites with adequate data, approximately about a quarter contain ferroan anorthosite similar to Apollo ferroan anorthosite (Gross et al. 2014); this proportion is comparable to the proportion of the lunar highlands that is affected by the continuous Imbrium ejecta. It may be that FANs sampled by the Apollo missions are the product(s) of a large regional melting event (i.e., a magma sea), and it is interesting to ask the question if this was caused by the postulated giant Procellarum basin, which may have formed very early in the Moon's history on the central nearside of the Moon (Wilhelms 1987; Nakamura et al. 2012). The presence of the Procellarum basin is controversial (Spudis 1993; Schulz 2007) and has not been clearly identified in recent gravity datasets (Zuber et al. 2013). However, it

may be that such an event occurred when the lunar crust was still warm and ductile and could not support a typical basin structure (Soloman et al. 1982; Miljkovic et al. 2013). Further, it may be that such large basin-scale events would form regional magma seas (Fig. 7d) that could internally differentiate (Wetherill 1976; Vaughan et al. 2013; Hurwitz and Kring 2014) to form localized serial magmatism or plagioclase floatation crust (i.e., mini LMO) building episodes (Fig. 7d) (Yamamoto et al. 2016).

## Implications

The chemical evolution of large planetary bodies has been thought to begin with the differentiation through the solidification of magma oceans many hundreds of kilometers in depth (Wood et al. 1970; Smith et al. 1970; Lapen et al. 2010). The Earth's Moon is the classic example of this type of differentiation.

Evidence for a lunar crust formation comes mainly largely from the ferroan anorthosite (FAN) suite of Apollo sample, their compositional and mineralogical characteristics, and ancient ages. The FANs are considered to represent flotation cumulates, crystallized from the LMO, that formed the primary lunar crust (Wood et al. 1970; Smith et al. 1970; Shearer et al. 2006 and refs. therein). However, newly integrated results from lunar meteorite studies; global chemical, mineralogical, and gravitational maps; experimental and computational modeling; and age isotopic anomalies have revealed that the simple LMO model has inconsistencies with the diverse crustal composition, stratigraphy (including thickness), and age of the lunar highland crust. All these new and integrated results show that the geologic history of our Moon is complex and that there is a great need to study more lunar geological history in great detail. Based on these new observations, several new models have been proposed that could explain the observed anomalies, ranging from a heterogeneous magma ocean to serial magmatism or an impact modified crust (Fig. 7). All of these models need further investigations through future sample return from targeted geological field locations, in situ geophysical measurements, and high spatial resolution remote-sensing mapping efforts coupled with computational models and laboratory experiments. Ultimately, there is still much to do to investigate the early geological evolution of our nearest planetary neighbor (NRC 2007), and the next phase of lunar exploration and science will help us to better understand the Earth-Moon system through space and time.

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## References

Alibert C, Norman MD, McCulloch MT (1994) An ancient age for a ferroan anorthosite clast from lunar breccia 67016. Geochim Cosmochim Acta 58:2921–2926

Arai T, Takeda H, Yamaguchi A, Ohtake M (2008) A new model of lunar crust: asymmetry in crustal composition and evolution. Earth Planets Space 60:433–444

Ashwal LD (1993) Anorthosites. Springer, Berlin, 422

Binder AB (1986) The initial thermal state of the Moon. In: Hartmann WK, Phillips RJ, Taylor GJ (eds) Origin of the Moon. Edwards Bros, Houston, pp 425–434

Borg LE, Norman M, Nyquist L, Bogard D, Snyder G, Taylor L, Lindstrom M (1999) Isotopic studies of ferroan anorthosite 62236: a young lunar crustal rock from a light rare-earth-element-depleted source. Geochim Cosmochim Acta 63:2679–2691

Borg LE, Amy MG, Charles KS, Donald JP, Ian DH, Thomas LO, Erick R, Greg B (2009) Mechanisms for incompatible-element enrichment on the Moon deduced from the lunar basaltic meteorite Northwest Africa 032. Geochimica et Cosmochimica Acta 73, no. 13, pp 3963–3980

Borg LE, Connelly J, Boyet M, Carlson R (2011) Chronological evidence that the Moon is either young or did not have a lunar magma ocean. Nature 477:70–72

Borg LE, Gaffney AM, Shearer CK (2012) Chronologic confusion in the lunar highlands. Second conference on the lunar highland crust, Bozeman, #9008

Borg LE, Gaffney AM, Shearer CK (2015) A review of lunar chronology revealing a preponderance of 4.34–4.37 Ga ages. Meteorit Planet Sci 50:715–732

Boyet M, Carlson RW (2007) A highly depleted moon or a non-magma ocean origin for the lunar crust? Earth Planet Sci Lett 262:505–516

Cahill JT, Floss C, Anand M, Taylor LA, Nazarov MA, Cohen BA (2004) Petrogenesis of lunar highlands

meteorites: Dhofar 025, Dhofar 081, Dar al Gani 262, and Dar al Gani 400. Meteorit Planet Sci 39:503–529

Calzada-Diaz A, Joy KH, Crawford IA, Nordheim TA (2015) Constraining the source regions of lunar meteorites using orbital geochemical data. Meteorit Planet Sci 50:214–228. doi:10.1111/maps.12412

Canup RM (2008) Lunar-forming collisions with pre-impact rotation. Icarus 196:518–538

Canup RM (2012) Forming a moon with an earth-like composition via a giant impact. Science 338:1052–1055

Canup RM, Visscher C, Salmon J, Fegley B Jr (2015) Lunar volatile depletion due to incomplete accretion within an impact-generated disk. Nat Geosci 8:918–921

Carlson RW, Lugmair GW (1981) Time and duration of lunar crust formation. Earth Planet Sci Lett 56:1–8

Carlson RW, Lugmair GW (1988) The age of ferroan anorthosite 60025: oldest crust on the Moon? Earth Planet Sci Lett 90:119–130

Cohen BA, Swindle TD, Kring DA (2000) Support for the lunar cataclysm hypothesis from lunar meteorite impact melt ages. Science 290:1754–1756

Cohen BA, Swindle TD, Kring DA (2005) Geochemistry of 40Ar-39Ar geochronology of impact-melt clasts in feldspathic lunar meteorites: implications for lunar bombardment history. Meteorit Planet Sci 40:755–777

Crawford IA, Joy KH (2014) Lunar exploration: opening a window into the history and evolution of the Earth-Moon system. Phil Trans R Soc A (Origin of the Moon) 372:20130315. doi:10.1098/rsta.2013.0315

Crawford IA, Anand M, Cockell CS, Falcke H, Green DA, Jaumann R, Wieczorek MA (2012) Back to the Moon: the scientific rationale for resuming lunar surface exploration. Planet Space Sci 74:3–14

Crawford IA, Joy KH, Anand M (2014) Lunar exploration. In: Spohn T, Johnson TV, Breuer D (eds) Encyclopedia of the solar system 3rd addition. Elsevir, Part V - Earth and Moon as Planets; sub-chapter 25

Crites ST, Lucey PG (2015) Revised mineral and Mg# maps of the moon from integrating results from the lunar prospector neutron and gamma-ray spectrometers with clementine spectroscopy. Am Mineral 100:973–982

Cuk M, Stewart ST (2012) Making the moon from a fast-spinning earth: a giant impact followed by resonant despinning. Science 338:1047–1052

Donaldson Hanna KL, Cheek LC, Pieters CM, Mustard JF, Greenhagen BT, Thomas IR, Bowles NE (2014) Global assessment of pure crystalline plagioclase across the Moon and implications for the evolution of the primary crust. J Geophys Res Planets 119:1516–1545

Delano JW (2009) Scientific exploration of the moon. Elements 5(1):11–16

Demidova SI, Nazarov MA, Lorenz CA, Kurat G, Brandstaetter F, Ntaflos T (2007) Chemical composition of lunar meteorites and the lunar crust. Petrology 15:386–407

Dreibus G, Kruse H, Spettel B, Waenke H (1977) The bulk composition of the Moon and the eucrite parent body. In: Proceedings of the 8th lunar science conference, Houston, pp 211–227

Elardo SM, Draper DS, Shearer CK Jr (2011) Lunar magma ocean crystallization 423 revisited: bulk composition, early cumulate mineralogy, and the source regions of the 424 highlands Mg-suite. Geochim Cosmochim Acta 75:3024–3045

Elkins Tanton LT, Burgess S, Yin Q-Z (2011) The lunar magma ocean: reconciling the solidification process with lunar petrology and geochronology. Earth Planet Sci Lett 304:326–336

Elkins-Tanton LT, Van Orman JA, Bradford HH, Grove TL (2002) Re-examination of the lunar magma ocean cumulate overturn hypothesis: melting or mixing required. Earth Planet Sci Lett 196:239–249

Elphic RC, Lawrence DJ, Feldman WC, Barraclough BL, Maurice S, Binder AB, Lucey PG (2000) Lunar rare earth element distribution and ramifications for FeO and $TiO_2$: lunar prospector neutron spectrometer observations. J Geophys Res 105:20333–20345

Fernandes VA, Fritz J, Weiss BP, Garrick-Bethell I, Shuster DL (2013) The bombardment history of the Moon as recorded by 40Ar-39Ar chronology. Meteorit Planet Sci 48:241–269

Floss C, James OB, McGee JJ, Crozaz G (1998) Lunar ferroan anorthosite petrogenesis: clues from trace element distributions in FAN subgroups. Geochim Cosmochim Acta 62:1255–1283

Gaffney AM, Borg LE, Asmerom Y, Shearer CK, Burger PV (2011) Disturbance of isotope systematics during experimental shock and thermal metamorphism of a lunar basalt with implications for martian meteorite chronology. Meteorit Planet Sci 46:35–52

Garrick-Bethell I, Nimmo F, Wieczorek MA (2010) Structure and formation of the lunar farside highlands. Science 330:949–951

Gillis JJ, Jolliff BJ, Korotev RL (2004) Lunar surface geochemistry: Global concentrations of Th, K, and FeO as derived from lunar prospector and clementine data. Geochim Cosmochim Acta 68:3791–3805

Greenhagen BT, Lucey PG, Wyatt MB, Glotch TD, Allen CC, Arnold JA, Bandfield JL, Bowles NE, Donaldson Hanna KL, Hayne PO, Song E, Thomas IR, Paige DA (2010) Global silicate mineralogy of the Moon from the diviner lunar radiometer. Science 329:1507–1509

Gross J, Treiman AH, Mercer CN (2014) Lunar feldspathic meteorites: constraints on the geology of the lunar highlands, and the origin of the lunar crust. Earth Planet Sci Lett 388:318–328

Hanan BB, Tilton GR (1987) 60025: relict of primitive lunar crust? Earth Planet Sci Lett 84:15–21

Hartmann WK (1970) Lunar cratering chronology. Icarus 2:299–301

Hartmann WK, Neukum G (2001) Cratering chronology and the evolution of mars. Space Sci Rev 96:165–194

Haskin LA, Lindstrom MM, Salpas PA, Lindstrom DJ (1981) On compositional variations among lunar anorthosites. Proc Lunar Planet Sci Conf 12(B):41–66

Haskin LA, Korotev RL, Rockow KM, Jolliff BL (1998) The case for an Imbrium origin of the Apollo thorium-rich impact-melt breccias. Meteorit Planet Sci 33:959–975

Haskin LA, Gillis JJ, Korotev RL, Jolliff BL (2000) The materials of the lunar procellarum KREEP terrane: a synthesis of data from geomorphological mapping, remote sensing, and sample analyses. J Geophys Res 105:20403–20415

Hawke BR, Peterson CA, Blewett DT, Bussey DBJ, Lucey PG, Taylor GJ, Spudis PD (2003) Distribution and modes of occurrence of lunar anorthosite. J Geophys Res 108:5050. doi:10.1029/2002JE001890, E6

Herbert F (1980) Time-dependent lunar density models. Proc Lunar Planet Sci Conf 11th: 2015–2030

Hess PC (1994) Petrogenesis of lunar troctolites. J Geophys Res 99(E9):19083–19093

Hess PC, Parmentier EM (1995) A model for the thermal and chemical evolution of the Moon's interior: implications for the onset of mare volcanism. Earth Planet Sci Lett 134:501–514

Hess PC, Parmentier EM (2001) Thermal evolution of a thicker KREEP liquid layer. J Geophys Res: Planets 106(E11):28023–28032

Hiesinger H, Head JWIII (2006) New views of lunar geoscience: an introduction and overview. Reviews in mineralogy and geochemistry. In new views on the moon. Rev Mineral 60:1–81

Hurwitz DM, Kring DA (2014) Differentiation of the South Pole-Aitken basin impact melt sheet: implications for lunar exploration. J Geophys Res: Planets 119:1110–1133

James OB, Lindstrom MM, Flohr MK (1989) Ferroan anorthosite from lunar breccia 64435: implications for the origin and history of lunar ferroan anorthosites. In: Proceedings of the 19th lunar and planetary science conference, Houston, pp 219–243

Jolliff BL, Haskin LA (1995) Cogenetic rock fragments from a lunar soil: evidence of a ferroan noritic-anorthosite pluton on the Moon. Geochim Cosmochim Acta 59:2345–2374

Jolliff BL, Gillis JJ, Haskin LA, Korotev RL, Wieczorek MA (2000) Major lunar crustal terranes: surface expressions and crust-mantle origins. J Geophys Res 105:4197–4416

Joy KH (2007) Ph. D. thesis: 'topics in lunar evolution using sample analysis and remotely sensed information'. University of London, July 2007

Joy KH (2013) Trace elements in lunar plagioclase as indicators of source lithology. 44th lunar and planetary science conference, Houston, #1033

Joy KH, Arai T (2013) Lunar meteorites: new insights into the geological history of the Moon. Astron Geophys 54:4.28–4.32

Joy KH, Crawford IA, Russell SS, Kearsley AT (2010) Lunar meteorite regolith breccias: an in situ study of impact melt composition using LA-ICP-MS and implications for the composition of the lunar crust. Meteorit Planet Sci 45:917–946

Jutzi M, Asphaug E (2011) Forming the lunar farside highlands by accretion of a companion moon. Nature 476(7358):69–72

Korotev RL (2005) Lunar geochemistry as told by lunar meteorites. Chem Erde 65:297–346

Korotev RL (2012) Lunar meteorites from Oman. Meteorit Planet Sci 47:1365–1402

Korotev RL (2013) The lunar meteorite list http://meteorites.wustl.edu/lunar/moon_meteorites_list_alumina.htm#DHO303

Korotev RL, Haskin LA (1988) Europium mass balance in polymict samples and implications for plutonic rocks of the lunar crust. Geochim Cosmochim Acta 52:1795–1813. doi:10.1016/0016-7037(88)90004-X

Korotev RL, Jolliff BL (2001) The curious case of the lunar magnesian granulitic breccias. In: Lunar and planetary science conference, Houston, vol 32, p 1455

Korotev RL, Jolliff BL, Zeigler RA, Gillis JJ, Haskin LA (2003) Feldspathic lunar meteorites and their implications for compositional remote sensing of the lunar surface and the composition of the lunar crust. Geochim Cosmochim Acta 67:4895–4923

Korotev RL, Zeigler RA, Jolliff BL (2006) Feldspathic lunar meteorites Pecora Escarpment 02007 and Dhofar 489: contamination of the surface of the lunar highlands by post-basin impacts. Geochim Cosmochim Acta 70:5935–5957

Korotev RL, Jolliff BL, Zeigler RA (2010) On the origin of the moon's feldspathic highlands, pure anorthosite, and the feldspathic lunar meteorites. 41st lunar and planetary science conference, Houston, # 1533

Korotev RL, Jolliff BL, Zeigler RA (2012) What lunar meteorites tell us about the lunar highlands crust. Second conference on the lunar highland crust, Bozeman, # 9003

Laneuville M, Wieczorek MA, Breuer D, Tosi N (2013) Asymmetric thermal evolution of the moon. J Geophys Res 118:1435–1452

Lapen TJ, Righter M, Brandon AD, Debaille V, Beard BL, Shafer JT, Peslier AH (2010) A younger age for ALH84001 and its geochemical link to shergottite sources in Mars. Science 328:347–351

Lawrence DJ, Elphic RC, Feldman WC, Prettyman TH (2003) Small-area thorium features on the lunar surface. J Geophys Res 108:5102

Le Feuvre M, Wieczorek MA (2011) Nonuniform cratering of the moon and a revised crater chronology of the inner solar system. Icarus 214:1–20

Lindstrom MM, Lindstrom DJ (1986) Lunar granulites and their precursor anorthositic norites of the early lunar crust. Proceedings of the sixteenth lunar and planetary science conference, Part 2. J Geophys Res 91: D263–D276

Longhi J (1980) A model of early lunar differentiation. In: Proceedings of the 11th lunar and planetary science conference, Houston, pp 289–315

Longhi J (2003) A new view of lunar ferroan anorthosites: postmagma ocean petrogenesis. J Geophys Res 108:2–1

Longhi J (2006) Petrogenesis of picritic mare magmas: constraints on the extent of early lunar differentiation. Geochim Cosmochim Acta 70:5919–5934

Longhi J, Ashwal L (1985) Two-stage models for lunar and terrestrial anorthosites: petrogenesis without a magma ocean. J Geophys Res Sold Earth 90:C571–C584

Longhi J, Boudreau AE (1979) Complex igneous processes and the formation of the primitive lunar crustal rocks. Proc Lunar Planet Sci Conf 10th: 2085–2105

Longhi J, Vander Auwera J, Fram MS, Duchesne JC (1999) Some phase equilibrium constraints on the origin of Proterozoic (massif) anorthosites and related rocks. J Petrol 40:339–362

Loper DE, Werner CL (2002) On lunar asymmetries 1. Tilted convection and crustal asymmetry. J Geophys Res 107(E6):5046

Lucey PG (2004) Mineral maps of the moon. Geophys Res Lett 31:L08701

McCallum IS, Schwartz JM, O'Brien HE (1997) Minor elements in plagioclase in evolved lunar crustal rocks. Lunar Planet Sci XXVIII:897–898, abstract 1594

Meyer J, Elkins-Tanton L, Wisdom J (2010) Coupled thermal-orbital evolution of the early Moon. Icarus 208:1–10

Miljkovic K, Wieczorek MA, Gareth SC, Laneuville M, Neumann GA, Melosh HJ, Solomon SC, Phillips RJ, Smith DE, Zuber MT (2013) Asymmetric distribution of lunar impact basins caused by variations in target properties. Science 342:724–726

Mimoun D, Wieczorek MA, Alkalai L, Banerdt WB, Baratoux D, Bougeret J-L, Bouley S, Cecconi B, Falcke H, Flohrer J, Garcia RF, Grimm R, Grott M, Gurvits L, Jaumann R, Johnson CL, Knapmeyer M, Kobayashi N, Konovalenko A, Lawrence D, Le Feuvre M, Lognonné P, Neal C, Oberst J, Olsen N, Röttgering H, Spohn T, Vennerstrom S, Woan G, Zarka P (2012) Farside explorer: unique science from a mission to the farside of the Moon. Exp Astron 33:529–585. doi:10.1007/s10686-011-9252-3

Morbidelli A, Marchi S, Bottke WF, Kring DA (2012) A - sawtooth-like timeline for the first billion years of lunar bombardment. Earth Planet Sci Lett 355:144–151. doi:10.1016/j.epsl.2012.07.037

Morota T, Furumoto M (2003) Asymmetrical distribution of rayed craters of the Moon. Earth Planet Sci Lett 206:315–323

Nakamura R, Yamamoto S, Matsunaga T, Ishihara Y, Morota T, Hiroi T, Takeda H, Ogawa Y, Yokota Y, Hirata N, Ohtake M, Saiki K (2012) Compositional evidence for an impact origin of the Moon's procellarum basin. Nat Geosci 5:775–778. doi:10.1038/NGEO1614

Narendranath S, Athiray PS, Sreekumar P, Kellett BJ, Alha L, Howe CJ, Joy KH, Grande M, Huovelin J, Crawford IA, Unnikrishnan U, Lalita S, Subramaniam S, Weider SZ, Nittler LR, Gasnault O, Rothery D, Fernandes VA, Bhandari N, Goswami JN, Wiezoreck MA, C1XS team (2011) Lunar X-ray fluorescence observations by the Chandrayaan-1 X-ray spectrometer (C1XS): results from a lunar highland region. Icarus 214:53–66. doi:10.1016/j.icarus.2011.04.010

National Research Council (2007) The scientific context for exploration of the Moon. The National Academies Press, Washington, DC

Neal CR, Taylor LA (1992) Petrogenesis of mare basalts: a record of lunar volcanism. Geochim Cosmochim Acta 56:2177–2211

Nekvasil H, Lindsley DH, DiFrancesco N, Catalano T, Coraor AE, Charlier B (2015) Uncommon behavior of plagioclase and the ancient lunar crust. Geophys Res Lett 42(24):10573–10579

Norman MD (2009) The lunar cataclysm: reality or "myth conception"? Elements 5:23–28. doi:10.2113/gselements.5.1.23

Norman MD, Borg LE, Nyquist LE, Bogard DD (2003) Chronology, geochemistry, and petrology of a ferroan noritic anorthosite clast from Descartes breccia 67215: clues to the age, origin, structure, and impact history of the lunar crust. Meteorit Planet Sci 38:645–661

Nyquist L, Bogard D, Yamaguchi A, Shih C-Y, Karouji Y, Ebihara M, Reese Y, Garrison D, McKay G, Takeda H (2006) Feldspathic clasts in Yamato-86032: remnants of the lunar crust with implications for its formation and impact history. Geochim Cosmochim Acta 70:5990–6015

Nyquist L, Shih C-Y, Reese D, Park J, Bogard DD, Garrison DH, Yamaguchi A (2010) Lunar crustal history recorded in lunar anorthosites. 41st lunar and planetary science conference, Houston, #1383

O'Hara MJ (2000) Flood basalts, basalt floods or topless Bushvelds? Lunar petrogenesis revisited. J Petrol 41(11):1545–1651

O'Hara MJ, Niu YL (2015) Obvious problems in lunar petrogenesis and new perspectives. In: Foulger GR, Lustrino M, King SD (ed) The interdisciplinary earth: a volume in honor of Don L. Anderson. Geological Society of America Special Paper 514 and American Geophysical Union Special Publication 71. pp 339–366. doi:10.1130/2015.2514

Ohtake M, Matsunaga T, Haruyama J, Yokota Y, Morota T, Honda C, Ogawa Y, Torii M, Miyamoto H, Arai T, Hirata N, Iwasaki A, Nakamura R, Hiroi T, Sugihara T, Takeda H, Otake H, Pieters CM, Saiki K, Kitazato K, Abe M, Asada N, Demura H, Yamaguchi Y, Sasaki S, Kodama S, Terazono J, Shirao M, Yamaji A, Minami S, Akiyama H, Josset J-L (2009) The global distribution of pure anorthosites on the moon. Nature 461:236–240. doi:10.1038/nature08317

Ohtake M, Takeda H, Matsunaga T, Yokota Y, Haruyama J, Morota T, Yamamoto S, Ogawa Y, Hiroi T, Karouji Y, Saiki K, Lucey PG (2012) Asymmetric crustal growth on the Moon indicated by primitive farside highland

materials. Nat Geosci 5:384–388. doi:10.1038/ngeo1458

Palme H, Spettel B, Jochum KH, Dreibus G, Weber H, Weckwerth G, Wänke H, Birschoff A, Stöffler D (1991) Lunar highland meteorites and the composition of the lunar crust. Geochim Cosmochim Acta 55:3105–3122

Papike JJ, Fowler GW, Shearer CK (1997) Evolution of the lunar crust: SIMS study of plagioclase from ferroan anorthosites. Geochim Cosmochim Acta 61:2343–2350

Pernet-Fisher JR, Joy KH (2016) The lunar highlands: old crust, new ideas. Astron Geophys 57(1):1.26–1.30. doi:10.1093/astrogeo/atw039

Pernet-Fisher JR, Joy KH, Martin DJP (2016) Plagioclase in Regolith Breccias: critical tool for deciphering the shock history of the lunar highlands. 47th lunar and planetary science conference, Houston [abstract #1499]

Pieters CM (1991) Bullialdus: strengthening the case for lunar plutons. Geophys Res Lett 18:2129–2132

Pieters CM, Head JWIII, Gaddis L, Jolliff B, Duke M (2001) Rock types of South Pole-Aitken basin and extent of basaltic volcanism. J Geophys Res 106:28001–28022

Piskorz D, Stevenson DJ (2014) The formation of pure anorthosite on the Moon. Icarus 239:238–243

Prettyman TH, Hagerty JJ, Elphic RC, Feldman WC, Lawrence DJ, McKinney GW, Vaniman DT (2006) Elemental composition of the lunar surface: analysis of gamma ray spectroscopy data from lunar prospector. J Geophys Res 111:E12007. doi:10.1029/2005JE002656

Pritchard ME, Stevenson DJ (2000) Thermal implication of lunar origin by giant impact. In: Canup RM, Righter K (eds) Origin of the Earth and Moon. The University of Arizona Press, Tucson, pp 179–196

Raedeke LD, McCallum IS (1980) A comparison of fractionation trends in the lunar crust and the stillwater complex. In: Papike JJ, MerrilL RB (eds) Proceedings of the conference on the highlands lunar crust. Lunar and Planetary Institute, Houston, pp 133–153

Rapp JF (2013) Lunar magma ocean differentiation. Center for lunar science and exploration classroom illustrations. http://www.lpi.usra.edu/nlsi/training/illustrations/planetaryInteriors

Rapp JF, Draper DS (2012) Experimental fractional crystallization of the lunar magma ocean. 43rd lunar and planetary science conference, Houston, #1659

Rapp JF, Draper DS (2013) Can fractional crystallization of a lunar magma ocean produce the lunar crust? 44th lunar and planetary science conference, Houston, #2732

Ringwood AE, Kesson SE (1976) A dynamic model for mare basalt petrogenesis. In: Lunar and planetary science conference proceedings, Houston, vol 7, pp 1697–1722

Roy A, Wright JT, Sigurðsson S (2014) Earthshine on a young moon: explaining the lunar farside highlands. Astrophys J Lett 788:2

Russell SS, Joy KH, Jeffries TE, Consolmagno GJSJ, Kearsley AT (2014) Heterogeneity in lunar anorthosite meteorites: implications for the lunar magma ocean model. Phil Trans R Soc A (Origin of the Moon) A 372:20130241. doi:10.1098/rsta.2013.0241

Ryder G (2003) Bombardment of the Hadean Earth: wholesome or deleterious? Astrobiology 3:3–6

Ryder G, Wood JA (1977) Serenitatis and Imbrium impact melts-implications for large-scale layering in the lunar crust. 8th lunar and planetary science conference proceedings, Houston, pp 655–668

Salpas PA, Haskin LA, McCallum IS (1983) Stillwater anorthosites: a lunar analog? Proceedings of the 14th lunar and planetary science conference. J Geophys Res 88(Suppl):B27–B39

Schultz PH (2007) A possible link between Procellarum and the South-Pole- Aitken basin. Lunar Planet Sci XXXVIII:1839–1840

Shearer CK, Floss C (2000) Evolution of the moon's mantle and crust as reflected in trace-element microbeam studies of lunar magmatism. Orig Earth Moon 1:339–359

Shearer CK, Papike JJ (1993) Basaltic magmatism on the Moon: a perspective from volcanic picritic glass beads. Geochim Cosmochim Acta 57:4785–4812

Shearer CK, Papike JJ (1999) Magmatic evolution of the Moon. Am Mineral 84:1469–1494

Shearer CK, Papike JJ (2005) Early crustal building processes on the moon: models for the petrogenesis of the magnesian suite. Geochim Cosmochim Acta 69:3445–3461

Shearer CK, Hess PC, Wieczorek MA, Pritchard ME, Parmentier EM, Borg LE, Longhi J, Elkins-Tanton LT, Neal CR, Antonenko I, Canup RM, Halliday AN, Grove TL, Hager BH, Lee D-C, Wiechert U (2006) Thermal and magmatic evolution of the Moon. Rev Mineral Geochem 60:365–518

Shearer CK, Elardo SM, Petro NE, Borg LE, McCubbin FM (2015) Origin of the lunar highlands Mg-suite: an integrated petrology, geochemistry, chronology, and remote sensing perspective. Am Mineral 100(1):294–325

Shervais JW, McGee JJ (1998) Ion and electron microprobe study of troctolites, norite, and anorthosites from Apollo 14: evidence for urKREEP assimilation during petrogenesis of Apollo 14 Mg-suite rocks. Geochim Cosmochim Acta 62(17):3009–3023

Shervais JW, McGee JJ (1999) KREEP cumulates in the western lunar highlands: ion and electron microprobe study of alkali-suite anorthosites and norites from Apollo 12 and 14. Am Mineral 84(5–6):806–820

Smith J, Anderson A, Newton R, Olsen E, Wyllie P, Crewe A, Isaacson M, Johnson D (1970) Petrologic history of the moon inferred from petrography, mineralogy, and petrogenesis of Apollo 11 rocks. Geochim Cosmochim Acta 1:897–925

Snyder GA, Taylor LA, Neal CR (1992) A chemical model for generating the sources of mare basalts- combined equilibrium and fractional crystallization of the lunar

magmasphere. Geochim Cosmochim Acta 56:3809–3823
Snyder GA, Taylor LA, Halliday AN (1995) Chronology and petrogenesis of the lunar highlands suite: cumulates from KREEP basalt crystallization. Geochim Cosmochim Acta 59:1185–1203
Solomon SC (1986) On the early thermal state of the Moon. In: Hartmann WK, Phillips RJ, Taylor GJ (eds) Origin of the Moon. Edwards Bros, Houston, pp 435–452
Solomon SC, Longhi J (1977) Magma oceanography. I – Thermal evolution. 8th lunar science conference, Houston, Proceedings, pp 583–599
Solomon SC, Comer RP, Head JW (1982) The evolution of impact basins: viscous relaxation of topographic relief. J Geophys Res 87:3975–3992
Spera FJ (1992) Lunar magma transport phenomena. Geochim Cosmochim Acta 56(6):2253–2265
Spudis PD (1993) The geology of multi-ring impact basins, vol 8, Cambridge planetary science series. Cambridge University Press, New York, 263 pp
Spudis PD, Davis PA (1985) How much anorthosite in the lunar crust? Implications for lunar crustal origin. 16th lunar and planetary science conference, Houston, pp 807–808
Spudis PD, Bussey BJ, Gillis J (2000) Petrologic mapping of the Moon from clementine and lunar prospector data: incorporation of new thorium data. 31st lunar and planetary science conference, Houston, #1414
Spudis PD, Zellner N, Delano J, Whittet DCB, Fessler B (2002) Petrologic mapping of the Moon: a new approach. 33rd lunar and planetary science conference, Houston, #1104
Stöffler D, Ryder G, Ivanov BA, Artemieva NA, Cintala MJ, Grieve RAF (2006) Cratering history and lunar chronology. Rev Mineral Geochem 60:519–596
Takeda H, Yamaguchi A, Bogard DD, Karouji Y, Ebihara M, Ohtake M, Saiki K, Arai T (2006) Magnesian anorthosites and a deep crustal rock from the farside crust of the moon. Earth Planet Sci Lett 247:171–184
Taylor SR (1982) Planetary Sciences: a lunar perspective. Lunar and Planetary Institute, Houston
Taylor GJ (2009) Ancient lunar crust: origin, composition, and implications. Elements 5(1):17–22
Taylor SR, McLennan S (2009) Planetary crusts: their composition, origin and evolution, vol 10. Cambridge University Press, New York
Taylor GJ, Wieczorek MA, Neumann GA, Nimmo F, Kiefer WS, Melosh HJ, Phillips RJ, Solomon SC, Andrews-Hanna JC, Asmar SW, Konopliv AS, Lemoine FG, Smith DE, Watkins MM, Williams JG, Zuber MT (2013) Revised thickness of the lunar crust from GRAIL data: implications for lunar bulk composition. 44th lunar and planetary science conference, Houston, #1783
Tera F, Papanastassiou DA, Wasserburg GJ (1974) Isotopic evidence for a terminal lunar cataclysm. Earth Planet Sci Lett 22:1–21
Tompkins S, Pieters CM (1999) Mineralogy of the lunar crust: results from clementine. Meteorit Planet Sci 34(1):25–41
Tonks WB, Melosh HJ (1990) The physics of crystal settling and suspension in a turbulent magma ocean. Orig Earth 1:151–174
Treiman AH, Maloy AK, Shearer CK Jr, Gross J (2010) Magnesian anorthositic granulites in lunar meteorites in lunar meteorites Allan Hills 81005 and Dhofar 309: geochemistry and global significance. Meteorit Planet Sci 45:163–180
Turner G (1979) A Monte Carlo fragmentation model for the production of meteorites – implications for gas retention ages Lunar and Planetary Science Conference, 10th, Houston, March 19–23, 1979, Proceedings, vol 2. Pergamon Press, New York, pp 1917–1941. (A80-23617 08-91)
Turner G, Cadogan PH, Yonge CJ (1973) Argon selenochronology. In: Proceedings, 4th lunar science conference, Houston, pp 1889–1914
Vander Auwera J, Weis D, Duchesne JC (2006) Marginal mafic intrusions as indicators of downslope draining of dense residual melts in anorthositic diapirs? Lithos 89:326–352
Vaniman D, Dietrich J, Taylor GJ, Heiken G (1991) Exploration, samples, and recent concepts of the Moon. In: Heiken GH, Vaniman D, French BM (eds) The lunar sourcebook: a user's guide to the Moon. Cambridge University Press, New York, pp 5–26
Vaughan WM, Head JW, Wilson L, Hess PC (2013) Geology and petrology of enormous volumes of impact melt on the Moon: a case study of the orientale basin impact melt sea. Icarus 223:749–765
Walker D (1983) Lunar and terrestrial crust formation. Proceedings of the 14th lunar and planetary science conference, Part 1. J Geophys Res 88(Suppl): B17–B25
Warner JL, Simonds CH, Phinney WC (1976) Genetic distinction between anorthosites and Mg-rich plutonic rocks: new data from 76255. Lunar and Planetary Science Conference. Vol. 7
Warner JL, Phinney WC, Bickel CE, Simond CH (1977) Feldspathic granulitic impactites and pre-final bombardment lunar evolution. In: Proceedings of the 8th lunar science conference, Houston, pp 2051–2066
Warren PH (1985) The magma ocean concept and lunar evolution. Annu Rev Earth Planet Sci 13:201–240
Warren PH (1989) KREEP: major-element diversity, trace-element uniformity (Almost). In: Taylor GJ, Warren PH (eds) Workshop on Moon in transition: Apollo 14, KREEP, and evolved lunar rocks. LPI technical report 89-03. Lunar and Planetary Institute, pp 149
Warren PH (1990) Lunar anorthosites and the magma-ocean plagioclase floatation hypothesis: importance of FeO enrichment in the parent magma. Am Mineral 75:46–58
Warren PH (1993) A concise compilation of petrologic information on possibly pristine nonmare Moon rocks. Am Mineral 78:360–376

Warren PH (2012) Let's get real: not every lunar rock sample is big enough to be representative for every purpose. Second conference on the lunar highlands crust, Bozeman, # 9034

Warren PH, Wasson JT (1979) Origin of KREEP. Rev Geophys 17:73–88

Wasson JT, Warren PH (1980) Contribution of the mantle to the lunar asymmetry. Icarus 44:752–771

Wetherill GW (1975) Late heavy bombardment of the moon and terrestrial planets. In: Lunar science conference, 6th, Houston, March 17–21, 1975, Proceedings, vol 2. Pergamon Press, New York, pp 1539–1561. (A78-46668 21-91)

Wetherill GW (1976) The role of large bodies in the formation of the Earth and Moon. In: Lunar and planetary science conference proceedings 7th, Houston, pp 3245–3257

Wieczorek MA, Le Feuvre M (2009) Did a large impact reorient the Moon? Icarus 200:358–366

Wieczorek MA, Phillips RJ (2000) The "Procellarum KREEP Terrane": implications for mare volcanism and lunar evolution. J Geophys Res 105:20417–20430

Wieczorek MA, Jolliff BL, Khan A, Pritchard ME, Weiss BP, Williams JG, Hood LL, Righter K, Neal CR, Shearer CK, McCallum IS, Tompkins S, Hawke BR, Peterson C, Gillis JJ, Bussey B (2006) The constitution and structure of the lunar interior. In new views of the Moon. Rev Mineral Geochem 60:221–364

Wieczorek MA, Neumann GA, Nimmo F, Kiefer WS, Taylor GJ, Melosh HJ, Phillips RJ, Solomon SC, Andrews-Hanna JC, Asmar SW, Konopliv AS, Lemoine FG, Smith DE, Watkins MM, Williams JG, Zuber MT (2013) The crust of the Moon as seen by GRAIL. Science 6120:671–675. doi:10.1126/science.1231530

Wilhelms DE (1987) The geologic history of the Moon. U.S. Geological Survery Prof Pap, 1348, 302 pp

Wood JA (1970) Petrology of the lunar soil and geophysical implications. J Geophys Res 75(32):6497–6513

Wood JA, Dickey JS Jr, Marvin UB, Powell BN (1970) Lunar anorthosites. Science 167:602

Yamamoto S, Nakamura R, Matsunaga T, Ogawa Y, Ishihara Y, Morota T, Hirata N, Ohtake M, Hiroi T, Yokota Y, Haruyama J (2012) Massive layer of pure anorthosite on the Moon. Geophys Res Lett 39: L13201. doi:10.1029/2012GL052098

Yamamoto K, Haruyama J, Kobayashi S, Ohtake M, Iwata T, Ishihara Y, Hasebe N (2016) Two-stage development of the lunar farside highlands crustal formation. Planet Space Sci 120:43–47

Young ED, Kohl IE, Warren PH, Rubie DC, Jacobson SA, Morbidelli A (2016) Oxygen isotopic evidence for vigorous mixing during the Moon-forming giant impact. Science 29:493–496

Zeigler RA, Korotev RL, Jolliff BL (2012) Feldspathic lunar meteorite graves nunatakes 06157, a magnesian piece of the lunar highlands crust. Second conference on the lunar highlands crust, Bozeman, #9033

Zuber MT, Smith DE, Watkins MM, Asmar SW, Konopliv AS, Lemoine FG, Melosh HJ, Neumann GA, Phillips RJ, Solomon SC, Wieczorek MA, Williams JG, Goossens SJ, Kruizinga G, Mazarico E, Park RS, Yuan D-N (2013) Gravity field of the Moon from the Gravity Recovery and Interior Laboratory (GRAIL) mission. Science 339:668–671