



# Lunar basalt chronology, mantle differentiation and implications for determining the age of the Moon



Joshua F. Snape<sup>a,\*</sup>, Alexander A. Nemchin<sup>a,b</sup>, Jeremy J. Bellucci<sup>a</sup>, Martin J. Whitehouse<sup>a,c</sup>, Romain Tartèse<sup>d,e</sup>, Jessica J. Barnes<sup>e</sup>, Mahesh Anand<sup>e,f</sup>, Ian A. Crawford<sup>g</sup>, Katherine H. Joy<sup>h</sup>

<sup>a</sup> Department of Geosciences, Swedish Museum of Natural History, SE-104 05 Stockholm, Sweden

<sup>b</sup> Department of Applied Geology, Curtin University, Perth, WA 6845, Australia

<sup>c</sup> Department of Geological Sciences, Stockholm University, SE-106 91 Stockholm, Sweden

<sup>d</sup> Institut de Minéralogie, de Physique des Matériaux et de Cosmochimie, Muséum National d'Histoire Naturelle, Sorbonne Universités, CNRS, UPMC & IRD, 75005 Paris, France

<sup>e</sup> Planetary and Space Sciences, The Open University, Walton Hall, Milton Keynes MK7 6AA, UK

<sup>f</sup> Department of Earth Sciences, The Natural History Museum, Cromwell Road, London, SW7 5BD, UK

<sup>g</sup> Department of Earth and Planetary Sciences, Birkbeck College, University of London, Malet Street, London WC1E 7HX, UK

<sup>h</sup> School of Earth, Atmospheric and Environmental Sciences, University of Manchester, Oxford Road, Manchester M13 9PL, UK

## ARTICLE INFO

### Article history:

Received 24 March 2016

Received in revised form 11 July 2016

Accepted 15 July 2016

Available online 27 July 2016

Editor: B. Marty

### Keywords:

lunar basalts

Pb isotopes

volcanism

lunar magma ocean

lunar origin

## ABSTRACT

Despite more than 40 years of studying Apollo samples, the age and early evolution of the Moon remain contentious. Following the formation of the Moon in the aftermath of a giant impact, the resulting Lunar Magma Ocean (LMO) is predicted to have generated major geochemically distinct silicate reservoirs, including the sources of lunar basalts. Samples of these basalts, therefore, provide a unique opportunity to characterize these reservoirs. However, the precise timing and extent of geochemical fractionation is poorly constrained, not least due to the difficulty in determining accurate ages and initial Pb isotopic compositions of lunar basalts. Application of an *in situ* ion microprobe approach to Pb isotope analysis has allowed us to obtain precise crystallization ages from six lunar basalts, typically with an uncertainty of about  $\pm 10$  Ma, as well as constrain their initial Pb-isotopic compositions. This has enabled construction of a two-stage model for the Pb-isotopic evolution of lunar silicate reservoirs, which necessitates the prolonged existence of high- $\mu$  reservoirs in order to explain the very radiogenic compositions of the samples. Further, once firm constraints on U and Pb partitioning behaviour are established, this model has the potential to help distinguish between conflicting estimates for the age of the Moon. Nonetheless, we are able to constrain the timing of a lunar mantle reservoir differentiation event at  $4376 \pm 18$  Ma, which is consistent with that derived from the Sm–Nd and Lu–Hf isotopic systems, and is interpreted as an average estimate of the time at which the high- $\mu$  urKREEP reservoir was established and the Ferroan Anorthosite (FAN) suite was formed.

© 2016 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

## 1. Introduction

The lunar magma ocean (LMO) model, proposed after the first analyses of the Apollo samples, remains the canonically accepted explanation for the magmatic differentiation of the Moon (Wood et al., 1970; Elkins-Tanton et al., 2011). In its current form, the model predicts the formation of a global magma ocean as a consequence of a Moon-forming “giant impact” between the Earth and a Mars-sized body (Hartmann and Davis, 1975)  $\sim 60$  million years (Ma)

after Solar System formation at 4567 Ma (Touboul et al., 2007; Connelly et al., 2012; Avicé and Marty, 2014). Development of the major lunar rock suites then occurred as a result of cooling and differentiation of this magma ocean, followed by partial melting of the mantle reservoirs that formed during differentiation. However, the age of the LMO (and the Moon), as well as the time interval required for its crystallization, remain unclear. While W-isotope data, suggesting that the short-lived  $^{182}\text{Hf}$  was extinct by the time of lunar formation (Touboul et al., 2007), place the oldest limit for the age of the LMO at about 4500 Ma, the attempts to define the youngest limit are based on studies of the oldest identified lunar rocks, represented by the highland samples. These samples are in-

\* Corresponding author.

E-mail address: [joshua.snape@nrm.se](mailto:joshua.snape@nrm.se) (J.F. Snape).

terpreted as remnants of either the primary anorthositic crust (Ferroan Anorthosites; FAN) that formed as part of the LMO differentiation sequence, or early plutonic magmatic rocks (Magnesian- and Alkali-Suite rocks; Elkins-Tanton et al., 2011; Carlson et al., 2014; Borg et al., 2015; Pernet-Fisher and Joy, 2016). Crystallization age estimates for FANs range from 4290–4570 Ma, while the Magnesian-suite rocks have crystallization ages of 4110–4570 Ma, but analytical uncertainties for a significant number of these dates are often close to 100 million years or more (Borg et al., 2015). Such large uncertainties, and the wide range of overlapping ages for FAN and Magnesian-suite rocks, have led to the traditional LMO model for lunar differentiation being challenged in recent studies (Borg et al., 2011; Carlson et al., 2014; McLeod et al., 2014; Gaffney and Borg, 2014). In particular, some of these studies suggested that the age of the Moon and the LMO may be more than 100 million years younger (i.e. ~4400 Ma) than indicated by other isotopic constraints (e.g. Avice and Marty, 2014). The younger age of the Moon, however, conflicts with dates as old as  $4417 \pm 6$  Ma determined in zircon grains identified in lunar breccias, which have been interpreted as placing a lower time limit on the final stages of LMO crystallization (Nemchin et al., 2009).

The Apollo mare basalts have younger crystallization ages, typically between 3800–3000 Ma (e.g. Albee et al., 1970; Turner, 1970; Papanastassiou et al., 1970; Davis et al., 1971; Murthy et al., 1971; Papanastassiou and Wasserburg, 1971; Compston et al., 1971, 1972; Nyquist et al., 1975, 1979, 1981; Guggisberg et al., 1979; Tartèse et al., 2013). Nevertheless, the melts from which these rocks crystallized are thought to have been sourced from silicate reservoirs in the lunar mantle generated during the LMO crystallization, therefore providing a link to this initial phase of the Moon's evolution. As such, four mare basalt and two KREEP-rich (material enriched in K, REE and P; Warren and Wasson, 1979) basalt samples have been investigated using high spatial resolution Secondary Ion Mass Spectrometry (SIMS) to obtain a new set of Pb isotope data and help constrain early lunar magmatic evolution.

Previous attempts to apply Pb isotope systematics to fundamental questions related to the early history of the Moon have utilized Thermal Ionization Mass Spectrometry (TIMS) analyses of chemically separated Pb fractions. While this approach has been successfully applied to the investigation of differentiation processes on the Earth (e.g. Zartman and Doe, 1981; Kramers and Tolstikhin, 1997), the inherently low Pb concentrations in lunar samples (relative to those from the Earth) renders the data particularly susceptible to the influence of laboratory contamination. The low Pb content in lunar samples is thought to be a consequence of extensive loss of volatile Pb early in the history of the Moon (e.g. Tatsumoto, 1970), most likely resulting from the giant Moon-forming impact. This concept is consistent with previous attempts to measure Pb isotopes in lunar samples (Tatsumoto, 1970; Tera and Wasserburg, 1972; Tatsumoto et al., 1987; Gaffney et al., 2007a; Nemchin et al., 2011), which indicate that the ratio of  $^{238}\text{U}/^{204}\text{Pb}$  ( $\mu$ ) in many lunar rocks is significantly higher (~100–600) than  $\mu$ -values inferred for the Earth's mantle (typically ~8–10; Zartman and Doe, 1981; Kramers and Tolstikhin, 1997). These high  $\mu$ -values of lunar rocks also result in very radiogenic Pb isotope compositions, making it difficult to distinguish between analyses representing Pb accumulated in the samples by *in situ* radioactive decay of U (radiogenic Pb) and those reflecting the initial Pb composition inherited during crystallization, or various mixtures of the two. The high spatial resolution SIMS approach undertaken here makes it possible to limit contamination, focus on the individual phases in which Pb is concentrated, and overcome the issues associated with the multi component Pb mixtures present in lunar samples, helping to determine both the crystallization ages of these samples and their initial Pb compositions.

## 2. Analytical methods

### 2.1. Data acquisition

Four of the samples (10044,645; 12039,44; 14072,61 and 15386,46) were thin sections prepared at NASA Johnson Space Center and cleaned with isopropyl alcohol before being carbon coated for Scanning Electron Microscope (SEM) analysis. The 12038,263 and 12063,330 samples were chips mounted in EPOTEK epoxy resin blocks at Birkbeck College, University of London. Initial Back Scattered Electron (BSE) and elemental mapping of the four thin sections was performed at the Open University with a Quanta 3D Focused Ion Beam (FIB) Scanning Electron Microscope (SEM), while 12038,263 and 12063,330 were mapped at Birkbeck College using a JEOL JXA-8100 electron microprobe (Fig. A.1). Both instruments were fitted with Oxford Instruments INCA energy dispersive X-ray (EDS) detectors. Acquisition of additional BSE and elemental maps was performed with a Quanta 650 Field Emission Gun (FEG) SEM and accompanying Oxford Instruments EDS detector at Stockholm University. For all three SEM setups, the mapping and analysis of the samples was conducted with an electron beam accelerating voltage of 15–20 kV at a working distance of 10–15 mm. The BSE and element maps were then used to identify phases for SIMS analyses; these included plagioclase and pyroxene grains, as well as accessory phases (such as K-feldspar and K-rich glass; Fig. A.2), which were identified based on regions of high-K and high-Si.

Following SEM documentation of the samples and prior to the SIMS analyses, the samples were cleaned with isopropyl alcohol before applying a 30 nm thick gold coat. The Pb isotopic compositions of various phases (Table B.1) were determined over three analytical sessions using a CAMECA IMS 1280 ion microprobe at the NordSIMS facility in the Swedish Museum of Natural History, Stockholm, using a methodology similar to that outlined in previous studies (Whitehouse et al., 2005; Nemchin et al., 2011; Bellucci et al., 2015). Apertures in the primary column were used to generate a slightly elliptical  $\text{O}_2^-$  sample probe with dimensions appropriate to the target. The smaller accessory phases (including K-feldspar and K-rich glass) were analysed using a ~10  $\mu\text{m}$  spot (beam current ca. 2–3 nA), while larger accessory phases and plagioclase grains were analysed with either a ~20  $\mu\text{m}$  spot (beam current ca. 10–12 nA), or a ~30  $\mu\text{m}$  spot (ca. 19–20 nA) (Fig. A.2). Prior to each measurement, an area of 20–35  $\mu\text{m}$  around the spot location was rastered for 60 s in order to remove the gold coating and minimise possible surface contamination. The instrument was operated in high-transmission mode, corresponding to a transfer magnification of 160 $\times$ . In this mode, the field aperture size was chosen to limit the field of view on the sample surface (i.e. the area from which ions will be admitted to the mass spectrometer) to be bigger than the unrastered spot but smaller than the rastered area, further minimising the possibility of surface contamination. The mass spectrometer was operated at a nominal mass resolution of 4860 ( $M/\Delta M$ ), sufficient to resolve Pb from known molecular interferences. An NMR field sensor regulated the stability of the magnetic field. Pb-isotopes were measured simultaneously in multi-collector mode using four low-noise (<0.01 counts per second) ion counting electron multipliers (Hamamatsu 416) with electronically gated deadtimes of 60 ns. Background counts for each channel were measured at regular intervals during each session. The average background counts for each session were used to correct the sample analyses and are presented in Table B.2.

Analyses of the USGS basaltic glass reference material, BCR-2G, were used to correct for mass fractionation and detector gain calibration. The BCR-2G analyses were all within  $\pm 5\%$  of the values presented by Woodhead and Hergt (2000), and these deviations were used to generate correction factors for the data. The reproducibility of the BCR-2G analyses for all three sessions were

Download English Version:

<https://daneshyari.com/en/article/6427259>

Download Persian Version:

<https://daneshyari.com/article/6427259>

[Daneshyari.com](https://daneshyari.com)