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New Evidence for 4.32 Ga Ancient Silicic Volcanism on the Moon

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Key Points:

- One rare mm-sized granitic fragment has been identified in lunar basaltic breccia meteorite Northwest Africa 10447
- This granitic fragment has a crystallization age of 4.32 Ga, which is consistent with the ages of the oldest Apollo granite samples
- Lunar granite may occur outside of the Procellarum KREEP Terrane of the Moon (i.e., the mare region with low Th and TiO_2 contents)

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract The currently available Apollo-returned granitic lithology is restricted to only the nearside of the Moon (e.g., Procellarum KREEP Terrane [PKT]). In contrast, lunar meteorites represent randomly ejected crustal material, and they extend our understanding of the lunar magmatic history through time and space. Here, we report a 4,321.5 ± 5.2 Ma (2σ) granitic fragment found in lunar basaltic breccia meteorite Northwest Africa (NWA) 10,447, which is compositionally similar to the regoliths from the Moon's Non-PKT regions. This granitic fragment has crystallization age similar to the oldest (~4.32 Ga) granites sampled during the Apollo 12 and 17 missions, and adds to the growing evidence of ancient silicic volcanism on the Moon. In addition, this newly identified granitic fragment in the Th- and TiO_2- poor breccia NWA 10447 provides evidence for that lunar granite may occur outside of the PKT of the Moon (i.e., the mare region with low Th and TiO_2 contents).

Plain Language Summary Lunar granite, that is, highly evolved lithologies, can provide valuable information about the magmatic evolution of the lunar crust. At present, only a few (~20) granites have been found in the Apollo samples (i.e., Apollo 12, 14, 15, and 17) and lunar breccia meteorites (e.g., NWA 4472), and they occur as rock fragments (e.g., 12,013) or mm-sized clasts within breccia (e.g., 14,321). In this paper, we report a mm-sized granitic fragment in lunar basaltic breccia meteorite NWA 10447, which has relatively low contents of Th (0.79 ppm) and TiO_2 (0.6 wt%). This fragment provides evidence for that lunar granite would occur outside of the PKT of the Moon, where the breccia meteorite NWA 10447 is ejected from. In addition, the granitic fragment has crystallization age (~4.32 Ga) similar to the oldest granites returned by Apollo 12 and 17 missions, providing new evidence for the existence of more ancient silicic volcanism on the Moon. This study also indicates that our understanding of lunar silicic magmatism is still insufficient. The further investigation of more silicic lithologies from other lunar meteorites (e.g., Th-poor breccias) will be helpful in filling this knowledge gap.

1. Introduction

On the Moon, the highly evolved lithologies that primarily consist of granophyric intergrowths of silica and K-feldspar are commonly called granite (Seddio et al., 2013). This type of rock represents a late-stage product of the extreme fractional crystallization of a magma and provides valuable information about the history of lunar magmatism (Bonin, 2012; Jolliff, 1991). Granite is rare on the Moon, but it is frequently found as either clastic fragments or as small, isolated clasts within both the Apollo-returned samples and some breccia meteorites (e.g., Apollo 12, 14, 15, and 17 samples; breccia meteorite Northwest Africa [NWA] 4,472; Jolliff et al., 1999; Joy et al., 2011; Seddio et al., 2013; Taylor et al., 1980; Warner et al., 1978). In addition, the global remote-sensing data has detected a series of silicic volcanisms distributed mostly on the nearside of the Moon within the Procellarum KREEP Terrane (PKT) (e.g., Hansteen Alpha, Gruithuisen domes, Helmet, and Lassell Massif on the nearside; Compton-Belkovich on the far side; Glotch et al., 2010; Jolliff et al., 2011). However, the currently available lunar samples collected during the Apollo and Luna missions only represent ~4.4% of the lunar surface (Warren et al., 2005), which limits our understanding of the granitic activity on the Moon, particularly that in the non-sampled regions. In contrast, the randomly ejected lunar meteorites are thought to be more representative of the lithologies of the lunar crust, and thus, they provide valuable material for investigating the geological history of the Moon (e.g., Gross et al., 2020, 2014; Jolliff et al., 2009; Snape et al., 2011; Zeigler et al., 2017).

Lunar Apollo-granites have been dated using a large range of isotopic methods (e.g., the ^{40}Ar-^{39}Ar, Sm-Nd, U-Pb, and Pb-Pb systems), which have yielded a range of dates from 3,880 Ma to 4,320 Ma (i.e., from Pre-Nectarian to Nectarian; Meyer et al., 1996; Nyquist and Shih, 1992; Thiessen et al., 2018; Turner, 1970). These ages indicate that the episode of granitic activity on the Moon occurred over about 450 million years (Bonin, 2012). Subsequently, with the acquisition of new data from lunar meteorites, the oldest lunar basaltic rock (∼4,370 Ma, Kalahari 009) and the oldest (i.e., ∼4,380 Ma) zircon evidence for lunar immiscible silica-rich melts have been discovered (Snape et al., 2018; Zeng, Joy, et al., 2020). These findings suggest that it is very likely that ancient magmatic processes occurred outside of the Apollo landing areas, and these magmatic events were capable of producing highly evolved granites. To address this hypothesis, identifying and studying ancient lunar granite is critical to revealing the granitic activity and magmatic processes that occurred on the Moon.

Regolith breccia NWA 10447 is a lunar basaltic meteorite that has not been well characterized. It is Th-poor (i.e., Th = 0.79 ppm; Korotev and Irving, 2021) and is distinctly different from the Apollo-returned samples from the PKT regions (i.e., Th > 2–3 ppm; Korotev, 2005; Lucey et al., 2006). Recently, one granitic fragment was found in the matrix of this breccia meteorite (Figure 1), providing us with an opportunity to investigate the ancient granitic activity on the Moon. Here, we report the petrology, mineralogy, and chronology of this lunar granitic fragment with the aims of (1) characterizing the petrological features of granitic fragment occurred in the Th-poor lunar basaltic breccia; and (2) discussing the provenance and implications of this granitic fragment from NWA 10447.

2. Sample and Analytical Methods

The breccia meteorite NWA 10447 was provided by Fabien Kuntz, who holds the main mass of this sample (Bouvier et al., 2017). In this study, the polished thick sections of NWA 10447, ∼1.5 × 2.5 cm in size, was prepared at the Institute of Geochemistry, Chinese Academy of Sciences (e.g., Figure S1). Then, the studied granitic fragment (i.e., Clast-GF; Figure 1) in this section of NWA 10447 was characterized using a wide range of in situ analytical techniques.

Back-scattered electron (BSE) images of Clast-GF were taken using the FEI Scios dual-beam focused ion beam/scanning electron microscope (FIB/SEM) at the Institute of Geochemistry, Chinese Academy of Sciences. The conditions were as follows: a 15 kV accelerating voltage, a 3.2 nA beam current, and a 7–8 mm working distance. X-ray elemental mapping of Clast-GF was performed using the energy-dispersive spectrometer attached to the FEI Scios FIB/SEM, with the same current and voltage setting noted above. Based on the BSE and X-ray mapping images, the modal mineralogy (vol%) of Clast-GF was estimated. The pixels of each mineral phases in this clast were counted using Photoshop. In addition, the quantitative mineral composition of Clast-GF were determined using the JXA 8230 electron microprobe analyzer (EMPA) at the Institute of Geochemistry, Chinese Academy of Sciences (Table S1). The operating conditions were as follows: a 15 kV accelerating voltage, a 20 nA beam current, and a 1 μm focused beam. Natural minerals and synthetic minerals were used as standards. The typical detection limits for most of the elements were 0.02–0.03 wt%.

Micro-Raman spectroscopy was performed using the Renishaw (RM 2000 and inVia Plus) micro-Raman spectrometer at the Institute of Geochemistry, Chinese Academy of Sciences. The laser (532 nm) energy was 50 mW. Silicon (520.7 cm^{-1} Raman shift) was used as the standard to calibrate this instrument. The Raman spectra for the silica phases in Clast-GF were collected under the following conditions: (1) the ×50 objective was used to focus the excitation beam on a ∼1 μm spot; (2) the acquired spectral range was 100–1,200 cm^{-1}; (3) the exposure time for each spectrum was 15–50 s (1 times); and (4) the power of the laser energy (i.e., 0.5–5 mW) was 1%–10%.

The in-situ U-Pb isotopic system of the zircon in Clast-GF was measured using the CAMECA IMS 1280-HR secondary ion mass spectrometer (SIMS) at the Guangzhou Institute of Geochemistry, Chinese Academy

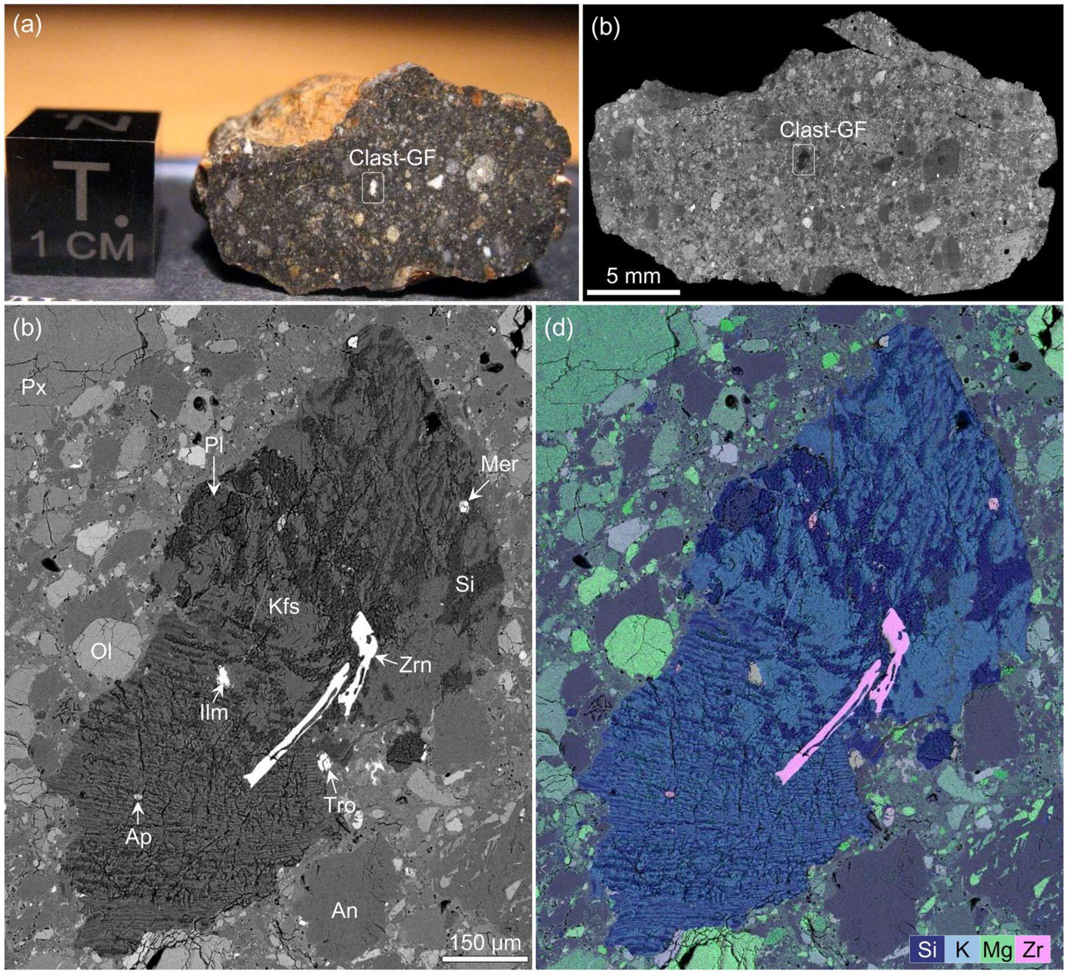

Figure 1. Occurrence, texture, and mineralogy of lunar granite fragment Clast-GF in breccia meteorite Northwest Africa (NWA) 10447. (a–b) Hand sample (Courtesy of F. Kuntz) and Back-scattered electron (BSE) images of lunar breccia meteorite NWA 10447. The studied granite fragment (Clast-GF) was marked in these images. (c) BSE image of Clast-GF. (d) X-ray element distribution maps (i.e., Si, K, Mg, and Zr) overlay on the BSE image of Clast-FG. Mineral phases in Clast-GF were labeled: Kfs = K-feldspar, Si = silica, Pl = plagioclase, Px = pyroxene, Ol = olivine, An = anorthosite, Zrn = zircon, Ilm = ilmentite, Tro = troilite, Ap = apatite, and Mer = merrillite.

of Sciences. The detailed analytical procedures were same as those described by Li et al. (2009) and Xu et al. (2020). The O^{2-} primary ion beam was used, with a spot size of 20 × 30 μm and a beam intensity of ~10 nA. Zircon standard Plesovice was used to calibrate this instrument (Sláma et al., 2008). Another standard zircon (SA 01; Huang et al., 2020) was also analyzed as an unknown sample to monitor the reliability of the entire procedure. The measured ^{204}Pb was used for the common Pb correction, which was assumed to be surface contamination from the sample preparation, and the composition of the sample was calculated according to the two-stage evolution model (Stacey and Kramers, 1975). The U-Pb dating results are presented in Table S2.

3. Results

3.1. Occurrence, Petrology, and Mineralogy

NWA 10447 is a basaltic regolith breccia, which is mainly composed of basaltic clasts, impact melt breccia clasts, volcanic glass fragments, impact glass fragments, and mineral phrases (Figures S1 and S2). Geochemically, this breccia meteorite has a bulk FeO content of 15.15 wt% and relatively low incompatible trace element contents (e.g., Th = 0.79 ppm, Sm = 2.59 ppm, and TiO_2 = 0.6 wt%), which are chemically

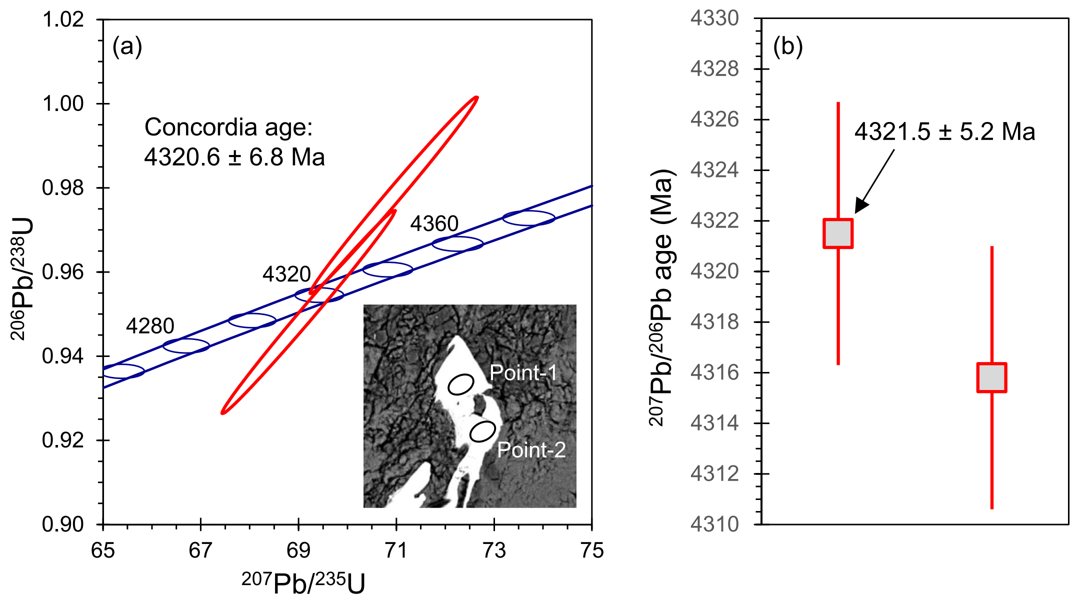

Figure 2. (a) U-Pb data for the zircon in lunar granite Clast-GF in Northwest Africa 10447. Back-scattered electron image was provided showing the two analyzed points. (b) Concordant $^{207}Pb/^{206}Pb$ ages of the analyzed zircon. Error bars for $^{207}Pb/^{206}Pb$ ages are 2σ.

consistent with other lunar basaltic samples (FeO = 16–22 wt%) and are distinctly different from the composition of KREEP-rich (Th > ~2–3 ppm and Sm > ~7 ppm) Procellarum KREEP Terrane (PKT) materials (Figures S3 and S4). The studied lunar granite fragment in NWA 10447 (i.e., Clast-GF) was to be located in the matrix of this meteorite, and the clast is ~1.2 × 0.5 mm in size (Figures 1a and 1b). Texturally, Clast-GF is characterized by micrographic intergrowths of K-feldspar ($An_{3.9-5.7}Ab1_{6.4-23.2}Or_{71.0-78.7}$; ~60 vol%) and silica (~30 vol%) (Figures 1c and 1d). A few plagioclase grains ($An_{33.7-36.4}Ab_{53.0-54.4}Or_{10.6-11.9}$) are present in minor quantities (i.e., <2 vol%) and are associated with the feldspar-quartz intergrowths. Notably, Clast-GF contains two strip-shaped zircons that are ~20 × 300 μm and ~35 × 200 μm in size. In addition, a few (<2 vol%) accessory mineral phrases were also observed in Clast-GF as micron-sized (<15 micron) grains, including ilmentite, troilite, apatite, and merrillite (Figures 1c and 1d).

3.2. Characteristics of Silica Phase

The silica phases in Clast-GF were characterized using the micro-Raman and EPMA techniques. The Raman spectra for these silica phases show that they have Raman peaks at 127 cm^{-1}, 202 cm^{-1}, 353 cm^{-1}, and 464 cm^{-1}, which are consistent with the Raman spectra of quartz (Figure S5). Texturally, the quartz grains in Clast-GF are fractured in a hackled pattern (Figure S6), which are similar to the micro-morphology of the quartz particles in the Apollo 12 samples (e.g., 12023,147–10, 12001,909–14, and 12033,634–30; Jolliff et al., 1999; Seddio et al., 2015). The minor-oxide (e.g., FeO and TiO_2) contents of the quartz grains in Clast-GF were determined. The FeO and TiO_2 contents of the quartz grains are 0.04–0.14 wt% and 0.1–0.18 wt%, respectively (Figure S7 and Table S1).

3.3. U-Pb Isotopic Compositions and Age of Zircon

Two U-Pb analyses were performed on a relatively large zircon grain (~35 μm in width) in Clast-GF (Figure 2). This zircon has U and Th contents of 141–241 ppm and 79–149 ppm, respectively (Table S2). The SIMS results show that the two U-Pb analyses are concordant, yielding a concordia age of 4,320.6 ± 6.8 Ma (2σ uncertainty; Figure 2a). The measured $^{207}Pb/^{206}Pb$ ages are 4,321.5 ± 5.2 Ma (2σ uncertainty) and 4,315.8 ± 5.2 Ma (2σ uncertainty), which are identical within the uncertainties (Figure 2b). Since the U-Pb system of the zircon within Clast-GF could have been disturbed by impact or thermal events, which are

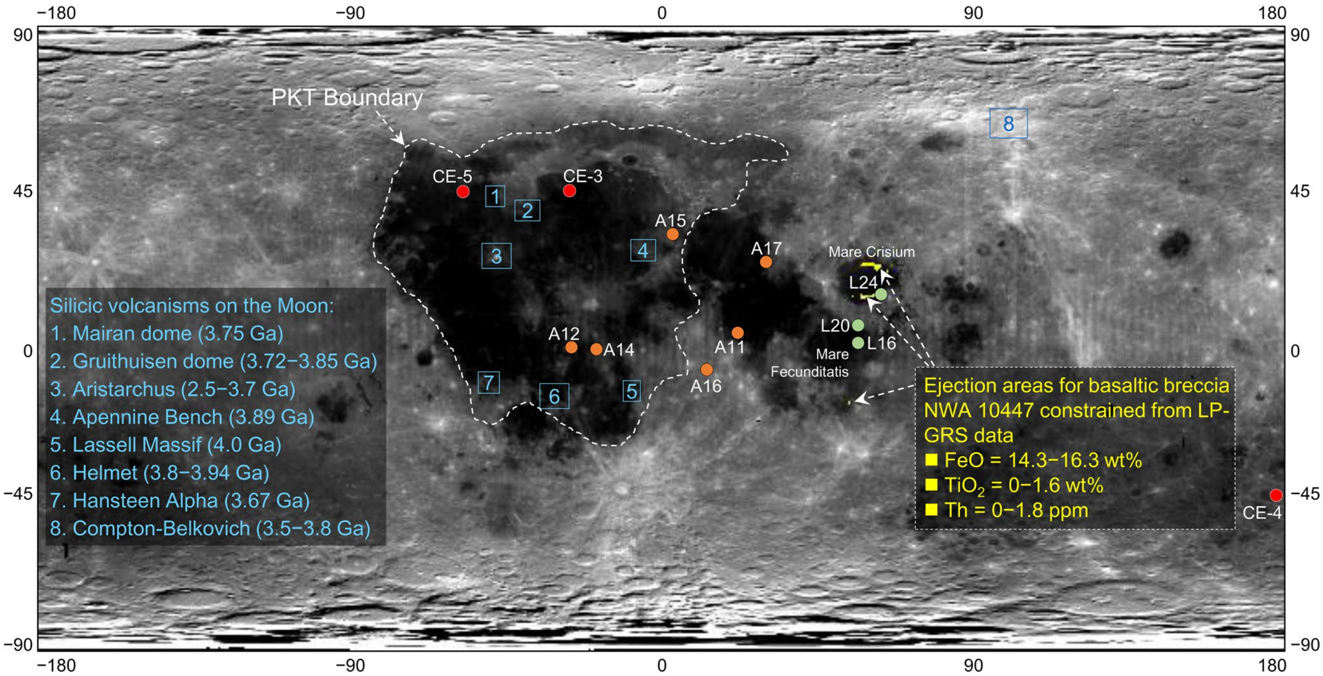

Figure 3. Possible ejection areas for lunar breccia meteorite Northwest Africa 10447 based on its bulk composition (i.e., FeO = 15.15 ± 1 wt%, TiO_2 = 0.6 ± 1 wt%, and Th = 0.79 ± 1 ppm). Locations and the ages of silicic volcanisms identified on the Moon have also been shown in this image (see Table S4 for details).

pervasive on the Moon, we took the oldest concordant $^{207}Pb/^{206}Pb$ age (i.e., 4,321 ± 5.2 Ma; 2σ uncertainty) as the minimum crystallization age of Clast-GF.

4. Discussion

4.1. Non-PKT Origin of Lunar Breccia NWA 10447

NWA 10447 is a regolith breccia meteorite consolidated from the surface materials on the Moon. By comparing this meteorite's composition with the global gamma ray spectroscopy geochemical data, the possible ejection regions of the lunar meteorite have been constrained (e.g., Calzada- Diaz et al, 2015; Gross & Joy, 2016; Joy et al., 2010; Zeng et al., 2018; Zeng, Li, et al., 2020). In this study, we used this geochemical data (i.e., FeO = 15.15 ± 1 wt%, TiO_2 = ± 1 wt%, and Th = 0.79 ± 1 ppm; Korotev and Irving, 2021; Table S3) as input parameters to locate regolith samples that are compositionally similar to NWA 10447 (see Text S1 for details). The resulting map shows that lunar breccia meteorite NWA 10447 is compositionally similar to the regoliths from the south of Mare Fecunditatis and the Mare Crisium outside of the Non-PKT regions (Figure 3). This implies that Clast-GF within NWA 10447 is most likely a lithic clast from the lunar Non-PKT region where this meteorite was consolidated from. This assumption is further supported by the commonly occurrence of granitic clasts in NWA 10,447: other six granitic clasts (see Figure S2) were observed in this breccia meteorite, indicating that the granitic Clast-GF is more likely local origin rather than the lithology that was ejected from the PKT region by impact events.

4.2. Petrogenesis of Clast-GF

The identification of a silica polymorph would give clues to the petrogenesis of the lunar granite samples (e.g., Seddio et al., 2015). Quartz grains with a hackle fracture pattern have been commonly observed in lunar granites, indicating that they were inverted from a high-temperature, low-pressure polymorph (either tridymite or cristobalite; Seddio et al., 2015). The silica phases in Clast-GF were identified as quartz grains with a hackled pattern (Figure S6), which is consistent with an orderly transformation from tridymite or cristobalite (indicative of rapid cooling) at a later time. Thus, it is reasonable to suggest that Clast-GF represents an extrusive lunar lithology (i.e., extrusive silicic volcanism).

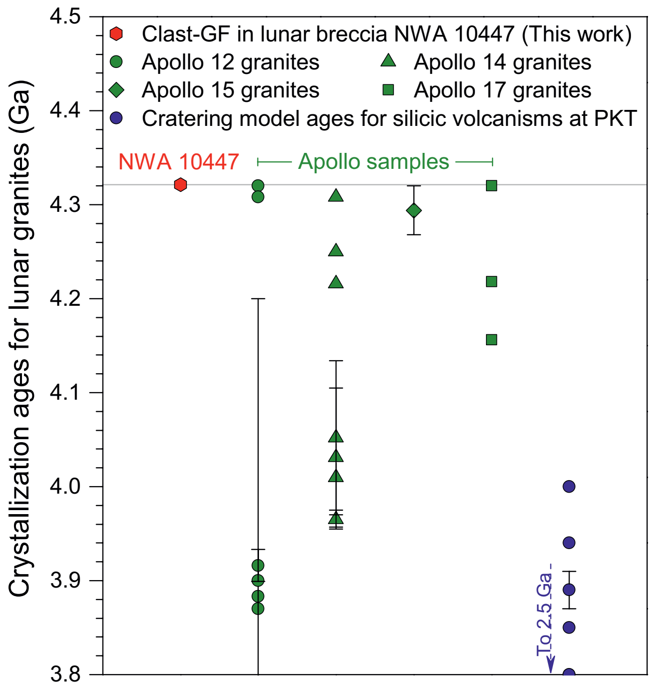

Figure 4. Comparison of the crystallization age (4.32 ± 0.0052 Ma; 2σ) of Clast-GF in Northwest Africa 10447 and the crystallization ages of the Apollo granitic samples and the cratering model ages of lunar silicic volcanism identified by remote sensing data (see Table S4 for details). Most error bars in this image are smaller than the symbols.

4.3. Implications for the Silicic Volcanism on the Moon

Compared with the granites collected during the Apollo missions, the newly discovered granitic fragment (i.e., Clast-GF) in NWA 10447 exhibits similar textural and mineralogical characteristics to some Apollo granites. Specifically, Clast-GF is an unbrecciated lithology with an igneous texture (i.e., micrographic intergrowths of K-feldspar and silica). This feature is consistent with texture of Apollo granites 12,032,366–19 and 12,032,147–10 (Seddio et al., 2014, 2013). In addition, Clast-GF mainly consists of ~60 vol% K-feldspar and ~30 vol% silica, with less amounts of accessory mineral phases (i.e., plagioclase, zircon, ilmentite, troilite, and phosphate). Such mineral assemblage is similar to the mineralogy of Apollo granite 12,033, 507 (i.e., ~49 vol% K-feldspar, ~33 vol%, and a few amounts of troilite, ilmentite, plagioclase and phosphates; Warren et al., 1987).

Previous studies have shown that lunar magmatic processes that are capable of producing highly evolved granites or silicic volcanism occurred over an extended period of time. Specifically, the Apollo-returned granite (or felsite) samples have yielded isotopic dates ranging from 4,320 ± 3 Ma (Pre-Nectarian) to 3,884 ± 3 Ma (Nectarian) (e.g., Meyer et al., 1996; Thiessen et al., 2018; Zhang et al., 2012). Furthermore, the ages of the silicic volcanism on the Moon (~2,500 Ma to 4,000 Ma) (Figure 3) have also been estimated using the crater-counting method. Compared with these results, the studied granitic fragment (Clast-GF in NWA 10447) has a crystallization age similar to the oldest granites sampled by the Apollo 12 and 17 missions (i.e., ~4.32 Ga; Figure 4). The existence of ancient lunar granite Clast-GF provides new evidence for the existence of more ancient (i.e., ~4.32 Ga) silicic volcanism on the Moon, which produced highly evolved lithologies such as Clast-GF.

The occurrence of lunar silicic volcanism has been observed to be mainly distributed in the PKT region on the nearside of the Moon and in Compton-Belkovich on the far side of the Moon (Figure 3). Similarly, all of the Apollo granites were sampled in/near the PKT regions during the Apollo 12, 14, 15, and 17 missions. Few lunar granite samples have been found in the Non-PKT area of the Moon. Clast-GF in breccia meteorite NWA 10447 may represent a rare lunar granitic fragment from the Non-PKT region of the Moon (i.e., the mare region with low Th and TiO_2).

5. Conclusions

1. In lunar basaltic breccia meteorite NWA 10447, a mm-sized granitic fragment (Clast-GF) was recognized. Clast-GF have similar petrological and mineralogical feature similar to some granites (e.g., 12032,366–19) returned by Apollo missions. This granitic fragment has a crystallization age of 4,321.5 ± 5.2 Ma (2σ), which is consistent with the age of the oldest granite sampled during the Apollo 12 and 17 missions.
2. Unlike the regoliths from Apollo landing sites within PKT, the basaltic breccia NWA 10447 has relatively low contents of Th and TiO_2 and is compositionally similar to the regoliths from the Moon's Non-PKT regions (e.g., Mare Crisium). The identification of granitic Clast-GF (and other granitic clasts) in this meteorite provides evidence for that lunar granite most likely occurs outside of the PKT of the Moon (i.e., the mare region with low Th and TiO_2)
3. The granitic Clast-GF adds to the growing evidence of oldest (~4.32 Ga) silicic volcanism on the Moon. This may provide further constraints on lunar ancient silicic magmatism that was not recognized by the Apollo missions and remote-sensing observations
4. This work implies that much is unknown about lunar granite and the silicic magmatic activity in the Non-PKT region of the Moon. In the future, investigation of more granitic lithologies from other lunar

meteorites (e.g., the Th-poor breccias) will be helpful in extending our understanding of the silicic volcanism across the Moon

Data Availability Statement

Lunar Prospector data used for the provenance of NWA 10447 is accessible at the NASA Planetary Data System (https://pds-geosciences.wustl.edu). The petrological, geochemical, and chronological data used in this manuscript are available online (https://doi.org/10.6084/m9.figshare.13571423).

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References

Bonin, B. (2012). Extra-terrestrial igneous granites and related rocks: A review of their occurrence and petrogenesis. *Lithos*, *153*, 3–24. https://doi.org/10.1016/j.lithos.2012.04.007

Bouvier, A., Gattacceca, J., Agee, C., Grossman, J., & Metzler, K. (2017). The meteoritical bulletin, no. 104. *Meteoritics & Planetary Sciences*, *52*(10), 2284. https://doi.org/10.1111/maps.12930

Calzada-Diaz, A., Joy, K. H., Crawford, I. A., & Nordheim, T. A. (2015). Constraining the source regions of lunar meteorites using orbital geochemical data. *Meteoritics & Planetary Sciences*, *50*(2), 214–228.

Glotch, T. D., Lucey, P. G., Bandfield, J. L., Greenhagen, B. T., Thomas, I. R., Elphic, R. C., et al. (2010). Highly silicic compositions on the Moon. *Science*, *329*(5998), 1510–1513. https://doi.org/10.1126/science.1192148

Gross, J., Hilton, A., Prissel, T. C., Setera, J. B., Korotev, R. L., & Calzada-Diaz, A. (2020). Geochemistry and petrogenesis of Northwest Africa 10401: A new type of the Mg-Suite rocks. *Journal of Geophysical Research: Planets*, *125*(5), e2019JE006225. https://doi.org/10.1029/2019je006225

Gross, J., Isaacson, P. J., Treiman, A. H., Le, L., & Gorman, J. K. (2014). Spinel-rich lithologies in the lunar highland crust: Linking lunar samples with crystallization experiments and remote sensing. *American Mineralogist*, *99*(10), 1849–1859. https://doi.org/10.2138/am-2014-4780

Gross, J., & Joy, K. H. (2016). Evolution, lunar: From magma ocean to crust formation. In B. Cudnik (Ed.), *Encyclopedia of lunar science* (pp. 1–20). Springer International Publishing. https://doi.org/10.1007/978-3-319-05546-6_39-1

Huang, C., Wang, H., Yang, J. H., Ramezani, J., Yang, C., Zhang, S. B., et al. (2020). SA01–A proposed zircon reference material for microbeam U-Pb age and Hf-O isotopic determination. *Geostandards and Geoanalytical Research*, *44*(1), 103–123. https://doi.org/10.1111/ggr.12307

Jolliff, B. L. (1991). Fragments of quartz monzodiorite and felsite in Apollo 14 soil particles. *Proceedings of the Lunar and Planetary Science Conference*, *21*, (pp. 101–118).

Jolliff, B. L., Floss, C., McCallum, I. S., & Schwartz, J. M. (1999). Geochemistry, petrology, and cooling history of 14161, 7373: A plutonic lunar sample with textural evidence of granitic-fraction separation by silicate-liquid immiscibility. *American Mineralogist*, *84*(5-6), 821–837. https://doi.org/10.2138/am-1999-5-616

Jolliff, B. L., Korotev, R. L., Zeigler, R. A., & Prettyman, T. H. (2009). Connecting lunar meteorite Dhofar 961 to the South Pole-Aitken Basin through Lunar Prospector gamma-ray data. *Proceedings of the Lunar and Planetary Science Conference*.

Jolliff, B. L., Wiseman, S. A., Lawrence, S. J., Tran, T. N., Robinson, M. S., Sato, H., et al. (2011). Non-mare silicic volcanism on the lunar farside at Compton–Belkovich. *Nature Geoscience*, *4*(8), 566–571. https://doi.org/10.1038/ngeo1212

Joy, K. H., Burgess, R., Hinton, R., Fernandes, V. A., Crawford, I. A., Kearsley, A. T., & Irving, A. J. (2011). Petrogenesis and chronology of lunar meteorite Northwest Africa 4472: A KREEPy regolith breccia from the Moon. *Geochimica et Cosmochimica Acta*, *75*(9), 2420–2452. https://doi.org/10.1016/j.gca.2011.02.018

Joy, K. H., Crawford, I. A., Russell, S. S., & Kearsley, A. T. (2010). Lunar meteorite regolith breccias: An in situ study of impact melt composition using LA-ICP-MS with implications for the composition of the lunar crust. *Meteoritics & Planetary Sciences*, *45*(6), 917–946. https://doi.org/10.1111/j.1945-5100.2010.01067.x

Korotev, R. L. (2005). Lunar geochemistry as told by lunar meteorites. *Geochemistry*, *65*(4), 297–346. https://doi.org/10.1016/j.chemer.2005.07.001

Korotev, R. L., & Irving, A. J. (2021). Lunar meteorites from northern Africa. *Meteoritics & Planetary Sciences*, *56*, 206–240. https://doi.org/10.1111/maps.13617

Li, X. H., Liu, Y., Li, Q. L., Guo, C. H., & Chamberlain, K. R. (2009). Precise determination of Phanerozoic zircon Pb/Pb age by multicollector SIMS without external standardization. *Geochemistry, Geophysics, Geosystems*, *10*(4). https://doi.org/10.1029/2009gc002400

Lucey, P., Korotev, R. L., Gillis, J. J., Taylor, L. A., Lawrence, D., Campbell, B. A., et al. (2006). Understanding the lunar surface and space-Moon interactions. *Reviews in Mineralogy and Geochemistry*, *60*(1), 83–219. https://doi.org/10.2138/rmg.2006.60.2

Meyer, C., Williams, I. S., & Compston, W. (1996). Uranium-lead ages for lunar zircons: Evidence for a prolonged period of granophyre formation from 4.32 to 3.88 Ga. *Meteoritics & Planetary Sciences*, *31*(3), 370–387. https://doi.org/10.1111/j.1945-5100.1996.tb02075.x

Nyquist, L. E., & Shih, C. Y. (1992). The isotopic record of lunar volcanism. *Geochimica et Cosmochimica Acta*, *56*(6), 2213–2234. https://doi.org/10.1016/0016-7037(92)90185-l

Seddio, S. M., Jolliff, B. L., Korotev, R. L., & Carpenter, P. K. (2014). Thorite in an Apollo 12 granite fragment and age determination using the electron microprobe. *Geochimica et Cosmochimica Acta*, *135*, 307–320. https://doi.org/10.1016/j.gca.2014.03.020

Seddio, S. M., Jolliff, B. L., Korotev, R. L., & Zeigler, R. A. (2013). Petrology and geochemistry of lunar granite 12032, 366-19 and implications for lunar granite petrogenesis. *American Mineralogist*, *98*(10), 1697–1713. https://doi.org/10.2138/am.2013.4330

Seddio, S. M., Korotev, R. L., Jolliff, B. L., & Wang, A. (2015). Silica polymorphs in lunar granite: Implications for granite petrogenesis on the Moon. *American Mineralogist*, *100*(7), 1533–1543. https://doi.org/10.2138/am-2015-5058

Sláma, J., Košler, J., Condon, D. J., Crowley, J. L., Gerdes, A., Hanchar, J. M., et al. (2008). Plešovice zircon—A new natural reference material for U–Pb and Hf isotopic microanalysis. *Chemical Geology*, *249*(1–2), 1–35. https://doi.org/10.1016/j.chemgeo.2007.11.005

Snape, J. F., Curran, N. M., Whitehouse, M. J., Nemchin, A. A., Joy, K. H., Hopkinson, T., et al. (2018). Ancient volcanism on the Moon: Insights from Pb isotopes in the MIL 13317 and Kalahari 009 lunar meteorites. *Earth and Planetary Science Letters*, *502*, 84–95. https://doi.org/10.1016/j.epsl.2018.08.035

Snape, J. F., Joy, K. H., & Crawford, I. A. (2011). Characterization of multiple lithologies within the lunar feldspathic regolith breccia meteorite Northeast Africa 001. *Meteoritics & Planetary Sciences*, *46*(9), 1288–1312. https://doi.org/10.1111/j.1945-5100.2011.01230.x

Stacey, J. S., & Kramers, J. D. (1975). Approximation of terrestrial lead isotope evolution by a two-stage model. *Earth and Planetary Science Letters*, *26*(2), 207–221. https://doi.org/10.1016/0012-821x(75)90088-6

Taylor, G. J., Warner, R. D., Keil, K., Ma, M. S., & Schmitt, R. A. (1980). Silicate liquid immiscibility, evolved lunar rocks and the formation of KREEP. In *Lunar highlands crust* (pp. 339–352).

Thiessen, F., Nemchin, A. A., Snape, J. F., Bellucci, J. J., & Whitehouse, M. J. (2018). Apollo 12 breccia 12013: Impact-induced partial Pb loss in zircon and its implications for lunar geochronology. *Geochimica et Cosmochimica Acta*, *230*, 94–111. https://doi.org/10.1016/j.gca.2018.03.023

Turner, G. (1970). ^{40}Ar-^{39}Ar age determination of lunar rock 12013. *Earth and Planetary Science Letters*, *9*(2), 177–180. https://doi.org/10.1016/0012-821x(70)90049-x

Warner, R. D., Taylor, G. J., Mansker, W. L., & Keil, K. L. A. U. S. (1978). Clast assemblages of possible deep-seated/77517/and immiscible-melt/77538/origins in Apollo 17 breccias. *Proceedings of the Lunar and Planetary Science Conference*, (Vol. 9, pp. 941–958).

Warren, P. H., Jerde, E. A., & Kallemeyn, G. W. (1987). Pristine Moon rocks: A "large" felsite and a metal-rich ferroan anorthosite. *Journal of Geophysical Research*, *92*(B4), E303–E313. https://doi.org/10.1029/jb092ib04p0e303

Warren, P. H., Ulff-Møller, F., & Kallemeyn, G. W. (2005). "New" lunar meteorites: Impact melt and regolith breccias and large-scale heterogeneities of the upper lunar crust. *Meteoritics & Planetary Sciences*, *40*(7), 989–1014. https://doi.org/10.1111/j.1945-5100.2005.tb00169.x

Xu, J., Xia, X. P., Cai, K., Lai, C. K., Liu, X. J., Yang, Q., et al. (2020). Remnants of a middle triassic island arc on western margin of south China block: Evidence for bipolar subduction of the paleotethyan Ailaoshan ocean. *Lithos*, *360–361*, 105447. https://doi.org/10.1016/j.lithos.2020.105447

Zeigler, R. A., Joy, K. H., Arai, T., Gross, J., Korotev, R. L., & McCubbin, F. M. (2017). *Lunar meteorites: A global geochemical dataset*.

Zeng, X., Joy, K. H., Li, S., Lin, Y., Wang, N., Li, X., et al. (2020). Oldest immiscible silica-rich melt on the Moon recorded in a ∼ 4.38 Ga zircon. *Geophysical Research Letters*, *47*(4), e2019GL085997. https://doi.org/10.1029/2019gl085997

Zeng, X., Joy, K. H., Li, S., Pernet-Fisher, J. F., Li, X., Martin, D. J., et al. (2018). Multiple lithic clasts in lunar breccia Northwest Africa 7948 and implication for the lithologic components of lunar crust. *Meteoritics & Planetary Sciences*, *53*(5), 1030–1050. https://doi.org/10.1111/maps.13049

Zeng, X., Li, S., Joy, K. H., Li, X., Liu, J., Li, Y., et al. (2020). Occurrence and implications of secondary olivine veinlets in lunar highland breccia Northwest Africa 11273. *Meteoritics & Planetary Sciences*, *55*(1), 36–55. https://doi.org/10.1111/maps.13421

Zhang, A. C., Taylor, L. A., Wang, R. C., Li, Q. L., Li, X. H., Patchen, A. D., & Liu, Y. (2012). Thermal history of Apollo 12 granite and KREEP-rich rock: Clues from Pb/Pb ages of zircon in lunar breccia 12013. *Geochimica et Cosmochimica Acta*, *95*, 1–14. https://doi.org/10.1016/j.gca.2012.07.023