Earth and Planetary Science Letters 319-320 (2012) 277–286

Contents lists available at SciVerse ScienceDirect

Earth and Planetary Science Letters

journal homepage: www.elsevier.com/locate/epsl

Comparative zircon U–Pb geochronology of impact melt breccias from Apollo 12 and lunar meteorite SaU 169, and implications for the age of the Imbrium impact

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A R T I C L E I N F O

Article history:
Received 29 July 2011
Received in revised form 8 December 2011
Accepted 9 December 2011
Available online 25 January 2012

Editor: R.W. Carlson

Keywords:
SHRIMP U–Pb analysis
impact-melt breccia
Apollo 12
SaU 169
Imbrium
Moon

A B S T R A C T

The ages of zircons from high-Th impact-melt breccias (IMBs) from meteorite Sayh al Uhaymir (SaU) 169 and from rock fragments in soil samples from Apollo 12 have been determined using the SHRIMP-II ion microprobe. The IMBs are very similar to each other in chemistry, mineralogy and texture, and the zircons from the KREEP-rich (high-Th) crystalline impact melt have similar U and Th contents and identical ages, within uncertainties, of 3920 ± 13 (2σ) Ma (SaU 169) and 3914 ± 7 (2σ) Ma (Apollo 12). The age results support the idea that the high-Th IMBs (Apollo 12 and SaU 169) formed in the same impact event. The similarity of composition and age suggest that SaU 169 and the high-Th IMB fragments of Apollo 12 originated from the same area of the Procellarum KREEP Terrane. We interpret the age of zircon grains in the Apollo 12 high-Th IMB as a precise and direct determination of the age of the Imbrium impact. This age is significantly older than the commonly cited age of 3.85 Ga but is similar to recent determinations from SIMS U–Pb dating of Apollo 14 apatite grains and with anticipated revision of ages by ^{40}Ar–^{39}Ar and ^{87}Rb–^{86}Sr. The present zircon ^{207}Pb–^{206}Pb age is the first direct zircon age determination of the Imbrium impact event from an Apollo sample. Previous measurements of zircon ages of Apollo IMBs have recorded events pre-dating the Imbrium basin-forming event.

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1. Introduction

Rock and mineral fragments and impact-melts contained in lunar impact breccias carry a textural and isotopic record of the complex history of shock and heating events involved in their formation. The Apollo 12 landing site was in the Imbrium–Procellarum region (known as the Procellarum KREEP Terrane or PKT), which is distinctive because of the high content of KREEP (K, rare earth elements, P, as well as other incompatible elements such as Zr, Th, U, etc.) of the nonmare materials at the surface, as shown in Apollo and Lunar Prospector gamma-ray spectrometer data (Elphic et al., 2000; Feldman et al., 1999; Lawrence et al., 1998, 2000; Reedy, 1978). Thus KREEP-rich impact-melt breccias (IMBs) record important information about the internal and thermal evolution of the Moon.

The U–Pb isotopic system in zircon grains is likely the geochronological system most resistant to shock metamorphism and we have applied this technique to investigate the age of formation and the correlation of Th- and U-rich IMBs in lunar meteorite SaU (Sayh al Uhaymir) 169 and similar small rock fragments discovered in soils from the Apollo 12 landing site (Fig. 1; Korotev et al., 2011). Our results have implications for the correlation and formation of Th-rich IMBs, the origin of the impact melt, the age of the Imbrium impact event, and of events that predate and post-date the period of impact-basin formation as recorded on the Moon.

2. Samples and analytical methods

Apollo 12 high-Th IMB rock fragments were mounted on two separate polished microprobe thick-section mounts. In one section, we mounted seven chips from five different Apollo 12 high-Th IMB fragments: 12032,366-2; 12032,366-10a; 12032,366-10b; 12033,624-24; 12033,634-29; 12033,638-1a1; and 12033,638-1a2. Each of the rock fragments in this section was irradiated for instrumental neutron activation analysis (INAA) as described in Korotev et al. (2011). In the second section, we mounted a large, unirradiated chip of sample 12033,638-1c (from the same rock fragment as 12033,638-1a1 and ,638-1a2). Photos showing the Apollo 12 rock fragment sample mounts are in an on-line supplemental file (Fig. S-1). We also investigated zircons in several IMB chips from the SaU 169 lunar meteorite. Four chips about 4 mm across of SaU 169 were included on one polished microprobe thick-section mount (Fig. S-2).

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doi:10.1016/j.epsl.2011.12.014

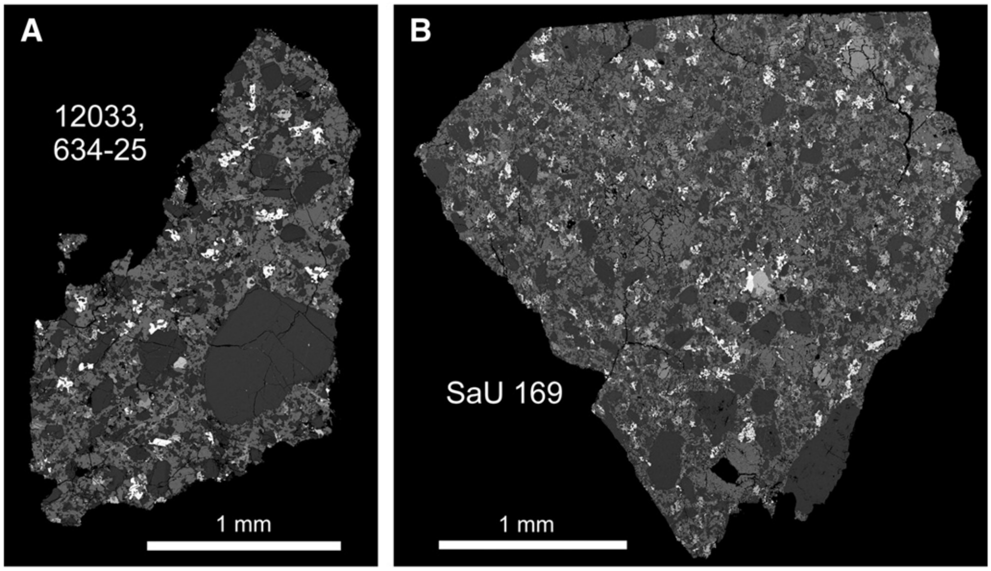

Fig. 1. Backscattered-electron images of (A) Apollo 12 high-Th IMB 12033,634-25 and (B) the IMB lithology in lunar meteorite SaU 169. Both rocks contain calcic plagioclase clasts (dark gray; An_{95}) in a matrix dominated by more sodic plagioclase ($An_{55–80}$) and pyroxene (medium gray; $En_{61–68}Wo_{<7}$), and abundant accessory phases (typically light gray to white): K-feldspar, apatite, RE-merrillite, ilmenite, zircon, baddeleyite, and troilite. SaU 169 contains a small amount of olivine (e.g., large grain, upper right), which is slightly brighter than pyroxene.

For petrographic characterization of samples, we used the JEOL 8200 electron microprobe at Washington University. Mineral compositions were determined by wavelength-dispersive X-ray analysis. Zircons were located using a combination of backscattered-electron (BSE) images and X-ray images obtained through a combination of wavelength and energy dispersive spectrometers.

Major and trace-element compositions were determined by a combination of INAA (Korotev, 1991; Korotev et al., 2011) and fused bead analysis by EPMA (electron probe microanalysis) as described in Zeigler et al. (2005) and Korotev et al. (2011). Average compositions from these analyses are shown in Table 1.

Sample mounts for SHRIMP analysis were coated with gold and U–Pb measurements done on the SHRIMP II at the Beijing SHRIMP Center following established operating procedures described by Williams (1998). The standard Ceylon zircon BR266 (Stern, 2001) was analyzed on a separate mount, and standard analyses were made preceding and alternately during analyses of the unknowns. The analytical spot size was 12 μm for SaU 169, fragment 12033,638-1c and a few other analyses (634-25-1.1; 366-10a-3.1, 7.1, 9.1, 9.2, 10.1); the spot size was 8 μm for all other analyses. The primary current was 1 nA. Each spot was rastered for 8–10 min prior to analysis and five scans were made for each age determination. The common Pb correction used was from the model of Stacey and Kramers (1975) assuming that the major contribution of common Pb was derived from sample processing. This assumption follows the experience of Nemchin et al. (2008). The SQUID and ISOPLOT programs were used to process the SHRIMP-II data. The uncertainties for individual analyses in Tables 2 and 3 are given at the 1-sigma level, whereas the uncertainties on weighted mean $^{207}Pb/^{206}Pb$ values in the text are given at the 2-sigma level.

3. Sample descriptions

3.1. Sayh al Uhaymir 169 lunar meteorite

Lunar meteorite SaU 169, found in the Sultanate of Oman (Russell et al., 2003), is an unusual dilithologic meteorite, consisting of a fine-grained polymict IMB partially rimmed by shock-lithified regolith. The IMB lithology in SaU 169 has been described by Gnos et al. (2004) as a holocrystalline, fine-grained polymict breccia consisting of shocked igneous rocks and mineral clasts in fine-grained

Table 1
Compositions of impact-melt breccias and KREEP.

Column notes	KREEP IMB					Avg mafic	KREEP
	A12 Typical	A12 High-Th	SaU 169	A 14 Typical	A14 Th>24	IMB	Av High-K
	1	2	3	4	5	6	7
SiO_2	49.2	47.5	45.5	48.8		47.17	50.3
TiO_2	1.62	2.33	2.3	1.7		1.39	2.0
Al_2O_3	16.9	15.3	15.2	16.6		18.1	15.1
Cr_2O_3	0.19	0.13	0.13	0.18	0.16	0.21	0.2
FeO	10.0	10.8	11.4	10.3	10.3	9.24	10.3
MnO	0.14	0.13	0.15	0.13		0.12	0.13
MgO	8.9	10.3	10.8	10.1		11.34	8.29
CaO	10.2	9.66	11.1	9.90	10.2	11.0	9.79
Na_2O	0.95	1.07	0.87	0.82	0.88	0.68	0.94
K_2O	0.73	0.52	0.41	0.72		0.41	0.96
P_2O_5	0.73	1.14	1.32	*0.5*		0.43	0.80
Sum	99.6	98.9	99.2	99.2		100.1	98.8
Mg/(Mg + Fe)	0.61	0.63	0.63	0.64		0.69	0.59
Sc	21.6	23.5	25.8	20.9	24.2	17.7	23
Co	25.9	22.5	30.2	33.6	27.7	34.1	25
Ni	192	166	252	335	247	369	–
Sr	204	221	310	184		178	200
Zr	1240	2240	2260	1300	2108	780	1400
Cs	0.72	0.70	0.52	0.84	1.19	0.46	1.0
Ba	993	1430	1285	970	1366	575	1300
La	90.2	166	172	87.4	139	57.5	110
Ce	230	417	436	224		149	280
Nd	135	242	258	135		88	178
Sm	39.3	70.5	74.8	38.5	60.9	25.8	48
Eu	3.14	4.01	3.95	2.71	2.75	2.16	3.3
Tb	7.94	14.3	15.2	7.63	12.3	5.21	10
Yb	28.6	52.6	54.8	27.9	43.7	18.0	36
Lu	3.92	7.15	7.5	3.82	5.97	2.48	5
Hf	30.4	53.1	52.4	30.4	50	19.7	38
Ta	3.7	6.7	6.5	3.7	5.9	2.35	5
Th	16.4	30.4	30	17	28	9.95	22
U	4.6	8.0	7.9	4.6	7.5	2.73	6.1

Notes:
Oxide concentrations are in weight percent; others are in ppm. Mg/(Mg + Fe) is molar.
Columns 1–3 are from Korotev et al., 2011; Column 4 is from Jolliff, 1998.
Column 5, Th > 24 ppm, is from data reported by Jolliff et al., 1991; average is for 5 samples, all INAA.
Column 6 is average of compositions in Table 1, Jolliff, 1998, plus the two Ap 12 compositions in this table.
Column 7 is from Warren, 1989.

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