Widespread magmatic activities on the angrite parent body at 4562 Ma ago

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Mn-Cr chronology of four quenched angrites showed that they formed nearly at the same time (4562 Ma) on the surface of the parent-body. Based on the chemical compositions, the cosmic ray exposure ages, and considerations on the thermal history of an achondrite parent-body, we suggest that the four angrites formed on top of a shallow magma ocean on the angrite parent body.

Key words: Age, angrites, Mn-Cr dating, SIMS.

1. Introduction

Age determination of angrites is important because the angrites LEW86010 and Angra dos Reis are used as an anchor for connecting Pb-Pb absolute ages (4557.8 ± 0.5 Ma, Lugmair and Galer, 1992) and Mn-Cr ages (^{53}Mn/^{55}Mn = $(1.25 \pm 0.07) \times 10^{-6}$, Lugmair and Shukolyukov, 1998) and because igneous activities on the angrite parent body are yet poorly understood.

Recently, several new angrites were found. Among them, D'Orbigny is the largest and best studied both petrologically (Mittlefehldt *et al.*, 2002) and chronologically (Nyquist *et al.*, 2003; Glavin *et al.*, 2004). The ^{53}Mn/^{55}Mn initial ratio for D'Orbigny reported by Glavin *et al.* (2004) is $(3.24 \pm 0.04) \times 10^{-6}$, which appears to be slightly inconsistent with that $(2.83 \pm 0.25) \times 10^{-6}$ reported by Nyquist *et al.* (2003). In any case, D'Orbigny is nearly 5 Ma older than LEW86010 and Angra dos Reis (Glavin *et al.*, 2004). The Pb-Pb age of D'Orbigny was initially reported to be 4557 ± 1 Ma: (Jagoutz *et al.*, 2003) and nearly identical with those of LEW86010 and Angra dos Reis (4557.8 Ma: Lugmair and Shukolyukov, 1998). But recent reevaluation of the Pb-Pb data of D'Orbigny has resulted in an age of 4563 ± 1 Ma (referred in Spivak-Birndorf *et al.*, 2005). Therefore, the Mn-Cr and the Pb-Pb ages of these three angrites are in excellent agreement with each other. Excess ^{26}Mg due to decay of ^{26}Al was detected in D'Orbigny (Nyquist *et al.*, 2003; Spivak-Birndorf *et al.*, 2005) confirming old ages of this angrite.

Here we report Mn-Cr ages of four angrites measured by secondary ion mass spectrometry (SIMS). Preliminary reports in abstract form of this study have been published as Sugiura (2002) and Sugiura *et al.* (2003).

2. Samples and Experimental Procedures

Four angrites (D'Orbigny, Sahara 99555, Asuka 881371 and Northwest Africa (NWA) 1670) were examined. Petrologic description of the Asuka 881371 has been reported by Yanai (1994) and by Mikouchi *et al.* (1996). Petrology and chemistry of D'Orbigny and chemistry of Sahara 99555 have been reported by Mittlefehldt *et al.* (2002). Petrology of NWA1670 has been reported by Mikouchi *et al.* (2003). Generally, these four angrites appear to have cooled more rapidly than LEW86010 and Angra dos Reis. They are called as "quenched angrites" by Mikouchi *et al.* (2003). Burial depth of less than 0.5 m was suggested for D'Orbigny and Asuka 881371 (Mikouchi *et al.*, 2001). Because of the finer grain size of NWA 1670 than that of the other angrites, its burial depth was probably much shallower than 0.5 m.

Polished sections of the four angrites were examined with a Scanning Electron Microscope (SEM) and Mn-rich, Cr-poor spots in olivine were selected for SIMS measurements. Fe-poor olivines having low Mn/Cr ratios were also measured to precisely determine the y-intercept of isochron.

An ion probe (IMF-6f) at Univ. of Tokyo was used for the Mn-Cr measurements. An intense O-primary beam (~5 nA, ~30 μm in diameter) was used for sputtering. Secondary ions ($^{52}Cr^+$, $^{53}Cr^+$ and Mn^+) were accelerated with 10 kV. The mass resolving power was set to ~4500. Isotope anomaly of ^{53}Cr is expressed as δ^{53}Cr which is defined as permil deviation from the ^{53}Cr/^{52}Cr of terrestrial materials. Instrumental isotopic fractionation was assumed to be nearly constant for this study. This is because ^{50}Cr cannot be measured accurately due to severe ^{50}Ti interference and hence cannot be used for monitoring instrumental isotopic fractionation. According to our previous experience on Mn-Cr measurements of iron meteorites, the deviation of instrumental isotopic fractionation of δ^{53}Cr is ~1.9‰ (Sugiura and Hoshino, 2003) and is insignificant compared with large isotopic signals due to decay of ^{53}Mn, though this deviation is propagated to the reported errors. The Mn/Cr relative sensitivity (defined as $(Mn^+/Cr^+)/([Mn]/[Cr])$ where [Mn]/[Cr] represents the atomic ratio in target materials) for Fe- and Ca-rich olivine was estimated to be 1.62 ± 0.12 (2σ) from measurements of synthetic glass samples that have bulk compositions similar to the Fe- and Ca-rich olivine

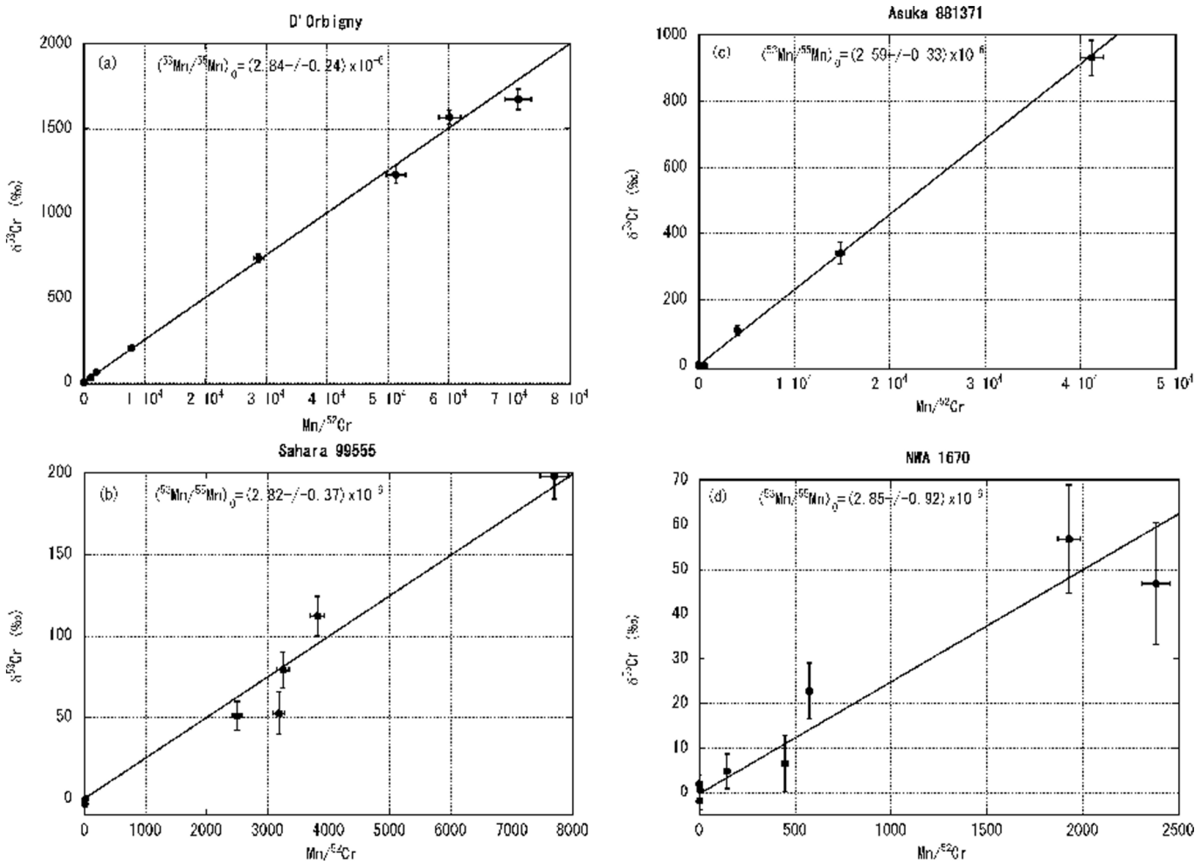

Fig. 1. Isochron diagrams for (a) D'Orbigny, (b) Sahara 99555, (c) Asuka 881371 and (d) NWA 1670. The error bars are 1σ. The errors attached to the initial Mn ratios are 2σ error including uncertainty of the relative sensitivity factor.

Table 1. Initial Mn ratios, ages before LEW 86010 and cosmic ray exposure ages (CREA) for four angrites.

	$^{53}Mn/^{55}Mn$	2σ error-1	2σ error-2	Age before LEW 86010*	CREA
D'Orbigny	2.84×10^{-6}	0.12×10^{-6}	0.24×10^{-6}	4.4±0.5 Ma	11 Ma**
Sahara 99555	2.82×10^{-6}	0.30×10^{-6}	0.37×10^{-6}	4.4±0.7 Ma	6.1 Ma**
Asuka 881371	2.59×10^{-6}	0.26×10^{-6}	0.33×10^{-6}	3.9±0.7 Ma	5.3 Ma**
NWA 1670	2.85×10^{-6}	0.89×10^{-6}	0.92×10^{-6}	4.4±1.8 Ma	~15 Ma***

2σ error-1 includes only the statistical deviation around the isochron.
2σ error-2 includes the statistical deviation and the uncertainty of the relative sensitivity factor.
*Initial ratio for LEW 86010 is 1.25×10^{-6} from Lugmair and Shukolyukov (1998). The errors correspond to the 2σ error-2 of the $^{53}Mn/^{55}Mn$ initial ratios. The absolute age of the LEW 86010 is 4557.8±0.5 Ma (Lugmair and Galer, 1992).
**Kurat *et al.* (2004) and references therein.
***Miura *et al.* (2004).

in the angrites. The synthetic sample contains ~0.34 wt% Cr_2O_3 and ~0.92 wt% MnO which were determined by EPMA (JEOL JXA-8800).

3. Results

The δ^{53}Cr vs. Mn/^{52}Cr diagrams for the four angrites are shown in Fig. 1. (The results are summarized in the supplementary table.) The ^{53}Cr isotope anomalies are well correlated with the Mn/Cr ratios, suggesting that they are due to in situ decay of ^{53}Mn. The inferred initial $^{53}Mn/^{55}Mn$ ratios are given in Table 1. The ^{53}Cr isotope anomalies are large and hence a slight change in the instrumental isotope fractionation is insignificant. The highest Mn/^{52}Cr ratio for an angrite ranges from 2400 for NWA 1670 to 7×10^4 for D'Orbigny. The relatively small ratio for NWA 1670 is probably due to the extremely fast cooling rate of this angrite that presumably caused a smaller degree of Cr fractionation during the solidification. The high Mn/^{52}Cr ratio for D'Orbigny is partly due to a low bulk Cr concentration in D'Orbigny (Mittlefehldt *et al.*, 2002). But the extremely high Mn/^{52}Cr ratio may suggest that the cooling rate of this angrite was slower than those of the other angrites. These Mn/^{52}Cr ratios obtained by SIMS are more than two orders of magnitude larger than those obtained by mineral separation (Nyquist *et al.*, 2003). For angrites with large Mn/^{52}Cr ratios and large excesses in ^{53}Cr, the initial Mn isotope ratios were determined precisely. Two kinds of errors are reported in Table 1. Error-1 is calculated from the scatter of data points around the isochron. Error-2 includes the uncertainty of the estimated relative sensitivity factor in addition to the error-1. For comparison of the initial Mn isotope ratios within the present data-set, error-1 should be used, whereas for comparison of the present data with those reported by other workers, error-2 should be used. The initial ratios for the four angrites (Table 1) are identical within the 2σ errors.

We note that the inferred $^{53}Mn/^{55}Mn$ initial ratio for D'Orbigny agrees quite well with that $(2.83 \pm 0.25) \times 10^{-6}$ reported by Nyquist *et al.* (2003). The initial ratio reported by Glavin *et al.* (2004) is $(3.24 \pm 0.04) \times 10^{-6}$ and is apparently inconsistent with the present result. However, the error given by Glavin *et al.* (2004) appears not to include 5% uncertainty of the concentration measurements. If this uncertainty is propagated to the error of their initial ratio, then the result of Glavin *et al.* (2004) is also consistent with the present result. Nyquist *et al.* (2003) reported that data for Sahara 99555 are in agreement with the D'Orbigny isochron. The present data for Sahara 99555 are also consistent with their report.

4. Discussion

It is obvious that four angrites have essentially the same initial $^{53}Mn/^{55}Mn$ ratios, and they are about 4 Ma older than LEW 86010 and Angra dos Reis. A common petrologic feature of these four angrite is the fast cooling rate compared with LEW 86010 and Angra dos Reis. In particular, the NWA 1670 seems to have cooled very rapidly at the very surface of the parent-body. Therefore, the identical Mn-Cr ages for the four angrites probably reflect the age of the initial cooling from the magmatic temperature.

Cosmic ray exposure ages of the four angrites are known (Table 1). Asuka 881371 and Sahara 99555 may have been ejected from the parent body by the same event, because the difference in the exposure ages is small. But it is clear that the four quenched angrites studied here were ejected by at least 3 different events. In addition, LEW 87051, another quenched angrite that was not studied here, has a very short cosmic ray exposure age ($\sim$0.2 Ma, Eugster and Weigel, 1995) and hence must have been ejected by an event unrelated to the ejection of the four angrites studied here. This suggests that quenched angrites are a major population on the angrite parent body.

According to the bulk chemical compositions reported by Mittlefehldt *et al.* (2002), D'Orbigny and Sahara 99555 are similar and they are slightly different from Asuka 881371. In particular, the Mg/(Mg+Fe) ratios and bulk Cr concentrations in D'Orbigny and Sahara 99555 seem to be significantly different from those in Asuka 881371. (No bulk chemical data are available for NWA 1670, yet.) Therefore, combining the cosmic ray exposure age data, the bulk chemical data and the Mn-Cr age data, it appears that the four quenched angrites were derived from four different lava flows that solidified nearly at the same time, near the surface of the angrite parent body. Absence of quenched angrites of other ages means that magmatic activities on the surface of angrite parent body occurred only briefly at 4562 Ma ago but it was wide spread on the parent body. Angra dos Reis and LEW 86010 cooled slowly somewhere in the deeper part of the parent-body, recording the Pb-Pb age of $\sim$4558 Ma.

Simulations of thermal histories of achondrite parent bodies with a ^{26}Al heat source have been made (e.g. Ghosh and McSween, 1998). According to these studies, a small asteroidal body (radius $\sim$10 km) could be molten if they accreted within $\sim$2 Ma after the formation of CAIs and reaches a peak temperature at $\sim$4 Ma after CAIs. If the partial melt migrates to the surface, then a magma ocean is formed on the parent body. Al-Mg dating of D'Orbigny and Sahara 99555 by Nyquist *et al.* (2003) and by Spivak-Birndorf *et al.* (2005) showed that the quenched angrites formed $\sim$5 Ma after the CAI formation. Therefore, the quenched angrites may have formed by eruption on top of the cooling magma ocean. As discussed by Ghosh and McSween (1998), a partial melt in such a parent body is enriched in Al relative to the bulk asteroidal composition and temperatures can reach 1600 K or higher. Volatile elements like K and Na may have escaped from the shallow magma ocean by evaporation, resulting in the extreme depletion of these elements in the angrites (Mittlefehldt *et al.*, 2002).

Because of the very fast cooling rates of quenched angrites, some workers (Jurewicz *et al.*, 1993; Mikouchi *et al.*, 1996) suggested that they formed as impact melts. However, it is rather unlikely that four samples are derived from a single impact melt and only two samples are derived from the rest of the parent body. It seems more likely that the quenched angrites were derived from a magma ocean that covered the entire surface of the parent body. It is possible to consider that many quenched angrites were produced by different impact events. But this scenario does not explain why impact melting has to happen only during a restricted period of time, as we know that heavy bombardment continued for several hundreds of million years in the inner solar system.

One may prefer to consider that ordinary volcanic activities produced angrites rather than proposing a magma ocean. However, REE abundance patterns of quenched angrites are very similar (Floss *et al.*, 2003) suggesting that they crystallized from very similar magmas. Each volcano is supposed to have a separate magma chamber that is produced by partial melting and in which fractional crystallization may occur. Therefore, we think that volcanic rocks derived from different volcanoes may show wider scatter in the REE abundance patterns. Also, as discussed recently by Greenwood *et al.* (2005), oxygen isotopic compositions of angrites are completely homogenized, suggesting complete melting and hence formation of a magma ocean on the angrite parent body. Altogether, we think that formation of quenched angrites on top of a magma ocean is quite probable and more likely than other mechanism of angrite formation.

5. Conclusions

Mn-Cr chronology of four quenched angrites showed that they formed nearly at the same time (4562 Ma) on the surface of the parent-body. Based on the chemical compositions, the cosmic ray exposure ages, and considerations on the thermal history of an achondrite parent-body, we suggest that the four angrites formed on top of a shallow magma ocean on the angrite parent body.

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Appendix.

Supplementary Table. Mn-Cr systematics in four angrites.

	$Mn/^{52}Cr$	$\delta^{53}Cr$ (‰)	$\delta^{53}Cr$ error (‰)
D'Orbigny			
	2.04E+03	61.4	7.5
	9.50E+00	−1.8	2.1
	7.85E+03	201.5	11.1
	6.02E+04	1565	43
	5.14E+04	1227	53
	7.15E+04	1671	60
	1.12E+03	26.0	5.2
	2.88E+04	734.1	26.0
Sahara 99555			
	3.19E+03	52.5	12.8
	2.50E+03	50.8	8.7
	1.00E+01	−3.0	1.1
	1.01E+01	−0.8	1.1
	1.92E+01	−0.2	1.2
	3.26E+03	79.1	10.9
	3.82E+03	112.2	12.1
	7.70E+03	198.2	13.9
Asuka 881371			
	7.68E+02	0.3	6.0
	8.60E+00	2.1	1.2
	5.55E+04	932.0	53.2
	5.45E+03	107.0	15.2
	5.20E+00	−1.8	1.0
	2.00E+04	340.0	31.6
	7.30E+00	−0.1	1.2
NWA 1670			
	8.00E-01	2.0	0.7
	2.00E+00	−1.8	0.7
	1.95E+02	4.8	3.4
	7.72E+02	22.8	6.0
	2.60E+03	56.7	12.0
	6.03E+02	6.5	5.9
	3.80E+00	0.6	0.5
	3.21E+03	46.8	13.4

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