



Fayalite in the Vigarano CV3 carbonaceous chondrite: Occurrences, formation age and conditions

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ABSTRACT

We have performed petrographic characterization, ⁵³Mn–⁵³Cr age determination and thermodynamic stability evaluations of fayalite in Vigarano meteorite that belongs to the reduced subgroup of CV3 chondrites. Vigarano is a breccia consisting of clasts which are separate chondrules surrounded by olivine-rich fine-grained materials. Four out of twenty three explored clasts contain fayalites that represent materials of the Bali-like oxidized subgroup of CV3 chondrites. The fayalites (Fa_{>80}) with grain sizes typically <20 μm occurs in veins that extend from chondrules into the fine-grained materials. The fayalite commonly coexists with troilite and/or magnetite. The fayalite-bearing veins terminate at the boundaries of clasts. No evidence of strong impact enough to make melt veins is found in materials adjacent to the veins. These observations suggest that the fayalite-bearing veins in the Bali-like clasts formed through aqueous alteration in an asteroid prior to fragmentation and re-accretion to the Vigarano parent body. In saponite-rich fine-grained materials, we also found troilite–magnetite veins, which are similar to the fayalite-bearing veins in morphology. Morphological evidences and thermochemical equilibrium calculations suggest that fayalite replaced magnetite, and that replacement occurred at temperatures <200 °C and low water/rock mass ratios from 0.07 to 0.18, which represent aqueous to metamorphic transition. Fayalite grains typically show iron–magnesium zoning (fayalite content decreases towards the grain edges). Based on equilibrium models, this zoning may have occurred at increasing temperature. The observed initial ratio of (⁵³Mn/⁵⁵Mn)₀ = (2.3 ± 0.5) × 10^{−6} suggests that fayalite formed ~5 Ma before the timing when the Mn–Cr system was closed in angrite NWA 4801 and has an absolute age of ~4563 ± 1 Ma. The age of fayalite is identical within errors to that in Mokoia and Kaba CV3 chondrites, which belong to the Bali-like oxidized subgroup. The identical age implies that aqueous alteration occurred at the same time in parent asteroids of Bali-like subgroup materials. These fayalite-bearing materials may have been derived from a single CV3 asteroid or from separate CV3 asteroids where aqueous alteration simultaneously occurred.

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1. Introduction

CV3 carbonaceous chondrites are subdivided into the reduced (CV3_{Red}) and two oxidized subgroups, Allende-like (CV3_{OxA}) and Bali-like (CV3_{OxB}) (McSween, 1977; Weisberg et al., 1997). These subgroups are considered to be affected by different degrees of aqueous alteration and subsequent metamorphism, which resulted in different secondary mineralization (Lee et al., 1996; Krot et al., 1995, 1998a, 1998b, 2004). For example, olivine in the CV3_{Red} and CV3_{OxA} chondrites is Fa_{30–60}, but that of CV3_{OxB} chondrite is Fa_{10–100} (Weisberg et al., 1997; Krot et al., 2004). Generally, only CV3_{OxB} chondrites contain near-pure fayalite (Fa_{>90}) (Hua and Buseck, 1995; Krot et al., 1995, 1998a, 1998b,

2000, 2004; Weisberg et al., 1997; Hutcheon et al., 1998; Choi et al., 2000; Hua et al., 2005).

The near-pure fayalite in the CV3_{OxB} chondrites occurs as discrete grains (up to 600 μm in size) or as a component of veins. The fayalite commonly associates with troilite and/or magnetite, and exists in chondrules and in matrix. Several formation models of the CV3_{OxB} fayalite have been proposed (Nagahara et al., 1988, 1994; Hua and Buseck, 1995; Krot et al., 1998a, 1998b, 2000, 2004; Choi et al., 2000; Ohnishi and Tomeoka, 2002; Krot et al., 2004; Hua et al., 2005; Zolotov et al., 2006; Jogo et al., 2008). According to the asteroidal models, fayalite may have formed through aqueous alteration (e.g., Krot et al., 1998a, 1998b, 2000, 2004; Choi et al., 2000; Jogo et al., 2008), or dehydration of Fe-rich phyllosilicates (e.g., Krot et al., 1995; Ohnishi and Tomeoka, 2002). According to the nebular model, fayalite may have formed by condensation of a gas (e.g., Nagahara et al., 1988, 1994), or by reaction of SiO gas and magnetite (e.g., Hua and Buseck,

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1995). The asteroidal origin of fayalite is consistent with the oxygen isotopic data for fayalite and magnetite (Choi et al., 2000; Hua et al., 2005; Jogo et al., 2008). Thermodynamic analysis of fayalite stability is also consistent with asteroidal formation at temperatures below 300–350 °C (Krot et al., 1998a,b; Zolotov et al., 2006).

Mn–Cr dating were performed on the large fayalite grains (100 to 600 μm in size) in the CV3_{oxB} Mokoia and Kaba meteorites. The fayalite grains in both meteorites show excesses of ⁵³Cr corresponding to the initial (⁵³Mn/⁵⁵Mn)₀ ratios of $(2.32 \pm 0.18) \times 10^{-6}$ (Mokoia, Hutcheon et al., 1998) and of $(2.07 \pm 0.17) \times 10^{-6}$ (Kaba, Hua et al., 2005). These ratios indicate that both of the Mokoia and Kaba fayalite have formed at the same time of 4562–4563 Ma, which is calculated using the angrite NWA 4801 as a time marker; Pb–Pb age of this angrite is 4558.0 ± 0.13 Ma (Amelin and Irving, 2007) and the corresponding (⁵³Mn/⁵⁵Mn) ratio is $(0.96 \pm 0.04) \times 10^{-6}$ (Shukolyukov et al., 2009).

Although Vigarano meteorite is classified to the CV3_{Red} subgroup, it also contains fayalite (Fa₈₀) (Krot and Todd, 1998; Meibom and Krot, 1998; Tomeoka and Tanimura, 2000; Krot et al., 2000; Noguchi et al., 2003). The fayalite has similar occurrence to the CV3_{oxB} fayalite. It coexists with troilite and/or magnetite, and occurs as discrete grains (up to 50 μm in size) or as a component of veins. The Vigarano fayalite exists in chondrules, and in fine-grained materials in “clasts” (not in the host Vigarano). The clasts are considered to have formed at a CV3 asteroid(s) prior to formation of Vigarano breccia (Tomeoka and Tanimura, 2000; Krot et al., 2000). Noguchi (1997) reported magnetite–troilite veins in Vigarano with similar morphology to the fayalite-bearing veins. This may suggest that fayalite-bearing veins replaced the magnetite–troilite veins (Noguchi, 1998, 1999; Noguchi and Nakamura, 2000; Noguchi et al., 2003).

In this study, we describe new fayalite-bearing veins in Vigarano CV3_{Red} chondrite. We determined the age of fayalite grains in a vein using the ⁵³Mn–⁵³Cr dating method. This is the first report of the age of CV3_{Red} fayalite formation that is important to constrain the time of formation of the Vigarano breccia. We also proposed a formation mechanism of the fayalite-bearing veins based on detailed mineralogical observations and thermochemical equilibrium calculations in a water-rock system.

2. Methods

2.1. Mineralogical characterization

We examined two polished thin sections of CV3_{Red} Vigarano with areas of ~2 cm² and ~3 cm² using an optical microscope, a scanning electron microscope (SEM), a field emission scanning electron microscope (FE-SEM) and an electron probe micro analyzer (EPMA). Carbon thin film (25 nm) was applied on the surface prior to SEM, FE-SEM and EPMA analyses in order to eliminate the electrostatic charge. The SEMs (JEOL-5300 at Tokyo Institute of Technology, JEOL-5600LV at Ibaraki University, and JEOL-5800LV at Kyushu University) equipped with a backscattered electron (BSE) imaging system and an energy-dispersive X-ray spectrometer. X-ray spectra were used at 15 keV accelerating voltage and 0.5 nA beam current to identify minerals. To observe micro-texture of fayalite and other secondary minerals, we used the FE-SEMs (JEOL JSM-6700F at JEOL Co. Ltd and JSM-7000F at University of Tokyo), operated at 15 keV accelerating voltage and 0.3 nA beam current. Chemical composition of fayalites and other silicates and opaque minerals were obtained using the EPMA (JEOL-JCXA733 at Kyushu University) equipped with a wavelength-dispersive X-ray spectrometer. Quantitative chemical analyses were performed at 15 kV accelerating voltage and 10 nA beam current. The following natural minerals were used for standard materials for silicates: diopside for SiO₂ and CaO, rutile for TiO₂, almandine for Al₂O₃ and FeO, rhodonite for MnO, olivine for MgO and NiO, jadeite for Na₂O, sanidine for K₂O, chromite for Cr₂O₃, apatite for P₂O₅, and barite for SO₃; for opaques: MnS for Mn, cobaltite for Ni and Co, apatite for P,

marcasite for Fe and S and Cr-metal for Cr. Quantitative chemical compositions were obtained via the atomic number (Z), absorption (A), and fluorescence (F) (ZAF) correction method and the detection limits are 0.05 wt.% for elements analyzed, and the reproducibility is less than 5% of concentrations of each element on the basis of the repeated analysis of the standard minerals. The composition of representative fayalite in Vigarano, as determined by spot analyses by EPMA, are given in Table 1.

2.2. ⁵³Mn–⁵³Cr dating using ion probe

The ⁵³Mn–⁵³Cr isotopic measurements were carried out using a secondary ion mass spectroscopy (SIMS: CAMECA ims-6f at Kyushu University). We analyzed only large fayalites, which have high Mn/Cr ratios and are bigger than SIMS beam size. A polished thin sections containing the fayalites was coated with gold of 30 nm thickness to eliminate the electrostatic charging on the sample surface. The Mn–Cr analyses were performed using a focused ¹⁶O[−] beam ~10 μm in diameter and with the current of 0.2–0.9 nA. The primary ¹⁶O[−] ions were accelerated with +12 keV to sputter the sample surface. Positive secondary ions were accelerated with −4.5 keV and sampled with a 100 eV energy window. The mass resolving power (M/ΔM) is ~3000, that was sufficient to resolve ²⁴Mg²⁸Si⁺ to ⁵²Cr⁺, ²⁵Mg²⁸Si⁺ and ²⁶Mg²⁷Al⁺ to ⁵³Cr⁺, and ²⁸Si²⁷Al⁺ to ⁵⁵Mn⁺, but was not sufficient to resolve ⁵²CrH⁺ from ⁵³Cr⁺ and ⁵⁴FeH⁺ from ⁵⁵Mn⁺. Hutcheon et al. (1998) and Hua et al. (2005) showed that the contributions of the hydride to ⁵³Cr⁺ was confirmed to be <1% and the hydrides of ⁵⁵Mn totaled less than 1%, and consequently hydrides could be neglected. Secondary ion

Table 1
Electron microprobe analysis of fayalite.

Fayalite	Clast 1		Clast 2	Clast 4	
	Fig. 2b (A) ^a	Fig. 2d ^b	Fig. 2b (B) ^c	Fig. 4 edge ^d	Fig. 4 near ch ^e
<i>Chemical composition (wt.%)</i>					
SiO ₂	30.3	20.4	30.5	30.2	32.7
TiO ₂	B.D.	B.D.	B.D.	B.D.	B.D.
Al ₂ O ₃	B.D.	0.1	B.D.	0.1	B.D.
FeO	68.2	72.0	69.6	66.0	55.1
MnO	1.3	0.3	0.8	0.8	0.7
MgO	1.6	8.7	0.4	2.0	12.5
CaO	0.1	0.1	0.2	0.4	0.1
Na ₂ O	B.D.	B.D.	0.1	B.D.	B.D.
K ₂ O	B.D.	B.D.	B.D.	B.D.	B.D.
Cr ₂ O ₃	0.1	0.1	0.1	B.D.	0.1
NiO	B.D.	B.D.	B.D.	0.2	B.D.
P ₂ O ₅	B.D.	0.1	0.1	B.D.	B.D.
S	B.D.	0.1	B.D.	B.D.	B.D.
Total	101.8	102.0	101.8	99.7	101.2
<i>Cation formula based on 4 oxygens</i>					
Si	1.00	0.71	1.01	1.01	1.00
Ti	0.00	0.00	0.00	0.00	0.00
Al	0.00	0.00	0.00	0.00	0.00
Fe	1.88	2.09	1.92	1.84	1.41
Mn	0.04	0.01	0.02	0.02	0.02
Mg	0.08	0.45	0.02	0.10	0.57
Ca	0.00	0.00	0.01	0.01	0.00
Na	0.00	0.00	0.00	0.00	0.00
K	0.00	0.00	0.00	0.00	0.00
Cr	0.00	0.00	0.00	0.00	0.00
Ni	0.00	0.00	0.00	0.01	0.00
P	0.00	0.00	0.00	0.00	0.00
S	0.00	0.00	0.00	0.00	0.00
Total	3.00	3.28	2.99	2.99	3.00
<i>Cation ratio 100 × Fe/(Fe + Mg)</i>					
Fa#	96	82	99	95	71

^a Subhedral fayalite grain (A) in the clast 1 in Fig. 2b.

^b Small fayalite grain in the clast 1 in Fig. 2d.

^c Subhedral fayalite grain (B) in the clast 2 in Fig. 2b.

^d Large fayalite grain at the edge of the vein in the clast 3 in Fig. 4.

^e Fayalite near chondrule in the clast 3 in Fig. 4.

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