



# Mn–Cr ages and formation conditions of fayalite in CV3 carbonaceous chondrites: Constraints on the accretion ages of chondritic asteroids

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## Abstract

Chondritic planetesimals are among the first planetary bodies that accreted inside and outside water snow line in the protoplanetary disk. CV3 carbonaceous chondrite parent body accreted relatively small amount of water ice, probably near the snow line, and experienced water-assisted metasomatic alteration that resulted in formation of diverse secondary minerals, including fayalite (Fa<sub>80–100</sub>). Chemical compositions of the CV3 fayalite and its Mn–Cr isotope systematics indicate that it formed at different temperature (10–300 °C) and fluid pressure (3–300 bars) but within a relatively short period of time. Thermal modeling of the CV3 parent body suggests that it accreted ~3.2–3.3 Ma after CV3 CAIs formation and had a radius of >110–150 km. The inferred formation age of the CV3 parent body is similar to that of the CM2 chondrite parent body that probably accreted beyond the snow line, but appears to have postdated accretion of the CO and ordinary chondrite parent bodies that most likely formed inside the snow line. The inferred differences in the accretion ages of chondrite parent bodies that formed inside and outside snow line are consistent with planetesimal formation by gravitational/streaming instability. © 2016 Elsevier Ltd. All rights reserved.

**Keywords:** Aqueous alteration; Fayalite; CV3 carbonaceous chondrites; Mn–Cr method; Age determination; Equilibrium thermodynamics; Thermal modeling

## 1. INTRODUCTION

About 4.6 billion years ago, the Solar System began as a solar nebula consisting mainly of hydrogen gas and minor amounts of dust. At or beyond the water ice evaporation front known as the water snow line (hereafter snow line)

(Hayashi, 1981; Stevenson and Lunine, 1988; Cyr et al., 1998; Cuzzi and Zahnle, 2004; Ciesla and Cuzzi, 2006), water existed as vapor, ice and hydrates. Accretion of dust, vapor, ice and hydrates formed primitive bodies (planetesimals), which further aggregated into larger planetary embryos and planets. Small terrestrial planets formed inside the water snow line and are volatile depleted, while the gas-giant planets formed outside the snow line. This suggests that planet formation processes inside and outside the snow

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line could have been different. Understanding the earliest histories of planetesimals formed near the snow line can reveal unique insights into this critical transition zone between the inner and outer early Solar System.

Chondritic meteorites (chondrites) are fragments of planetesimals that preserve records of their origins and evolutionary histories. Isotopic and petrological studies of minerals in chondrites constrain both the timescales and physical–chemical conditions of their formation. Chondrites are currently classified into fifteen groups based on their bulk chemical and isotopic compositions and petrographic characteristics. Each group may represent a different parent body, formed in a distinct nebular region and/or at a particular time (e.g., Zolensky and McSween, 1988; Wood, 2005; Brearley, 2006; Krot et al., 2006; Rubin, 2010, 2011). The differences in bulk elemental abundances and volatile contents among chondrite groups are thought to reflect radial variations in the temperature and composition of the nebular gas and the abundances of dust, chondrules, and Ca–Al-rich inclusions (CAIs). The relative heliocentric distances of the formation regions of different chondrite groups have been inferred from their petrographic properties, chemical and isotope compositions, and volatile contents (e.g., Rubin and Wasson, 1995; Wood, 2005; Rubin, 2010, 2011). Rubin (2010, 2011) proposed that the forming regions of chondrite groups could be ordered as EH–EL, OC, R, CR, CV–CK, CM–CO, and CI with increasing heliocentric distance. More recently, van Kooten et al. (2016) proposed that CR chondrite parent body formed further from the Sun than other chondrite parent bodies because of its high abundances of presolar grains and primordial  $\delta^{54}\text{Cr}$  and  $\delta^{26}\text{Mg}$  isotopic signatures. The small amount of secondary minerals and volatile components in CV chondrites may suggest their parent body accreted just beyond the snow-line (e.g., Wood, 2005).

CV3 chondrites are divided into three subgroups, the oxidized Allende-like (CV3<sub>OxA</sub>), the oxidized Bali-like (CV3<sub>OxB</sub>) and the reduced (CV3<sub>Red</sub>) type, based on their mineralogy, petrology and bulk chemical and isotopic compositions (McSween, 1977; Weisberg et al., 1997). The CV3<sub>OxB</sub> chondrites experienced aqueous alteration that resulted in formation of secondary fayalite, ferroan olivine, phyllosilicate, magnetite, Fe,Ni–sulfide, Fe,Ni–carbide, salite-hedenbergite pyroxenes, and andradite (Krot et al., 2004). The CV3<sub>OxA</sub> chondrites experienced relatively high-temperature Fe-alkali-halogen metasomatic alteration (Brearley, 1997, 1999; Bonal et al., 2006) that resulted in formation of secondary ferroan olivine, nepheline, sodalite, andradite, grossular, wollastonite, kirschsteinite, and salite-hedenbergite pyroxenes (Kimura and Ikeda, 1995; Ikeda and Kimura, 1995; Krot et al., 1995, 1998, 2004). The CV3<sub>Red</sub> chondrites experienced similar metasomatic alteration to that of the CV3<sub>OxA</sub> chondrites, but to a smaller degree (Krot et al., 1995, 1998, 2004).

Secondary fayalite can be used to constrain the timescales and hydrothermal evolutionary processes of the CV3 parent body. In particular, the chemical compositions of fayalite reflect the physical–chemical conditions within the parent body during aqueous alteration (Hua and Buseck, 1995; Krot et al., 1998; Choi et al., 2000; Hua

et al., 2005; Zolotov et al., 2006; Jogo et al., 2009). Near-pure fayalite ( $\text{Fa}_{>90}$ ,  $\text{Fa} = \text{Fe}/(\text{Fe} + \text{Mg}) \times 100 \text{ mol}\%$ ) occurs only in the CV3<sub>OxB</sub> chondrites and CV3<sub>OxB</sub> clasts in CV3<sub>Red</sub> chondrites (Krot et al., 2000; Tomeoka and Tanimura, 2000; Jogo et al., 2009). In addition, fayalite is suitable for  $^{53}\text{Mn}$ – $^{53}\text{Cr}$  dating ( $^{53}\text{Mn}$  decays to  $^{53}\text{Cr}$  with a half-life of 3.7 million years) due to its high Mn/Cr ratios (Hutcheon et al., 1998; Hua et al., 2005; Jogo et al., 2009).

The formation timescales and aqueous alteration conditions inferred from the analyses of secondary fayalite can yield further constraints on the accretion timing of CV3 chondrites. Such inferences are made by constructing thermal evolutionary models that successfully account for the timing and the conditions of aqueous alteration constrained by fayalite. The thermal history of a parent body is a function of the  $^{26}\text{Al}$  abundance, water ice/rock ratio and parent body size. In thermal models for the CV3 parent body, different values for parameters such as peak temperature,  $^{26}\text{Al}$  content, and water/rock ratios have been used. As a result, various evolutionary processes of CV3 bodies were proposed (Travis and Schubert, 2005; Palguta et al., 2010; Elkins-Tanton et al., 2011; Fu and Elkins-Tanton, 2014). Details are discussed in the Section 4.2.

Here we present results of chemical and Mn–Cr isotopic analyses of fayalite in CV chondrites and derive constraints on the thermal and physical evolution of the CV chondrite parent body. We performed detailed mineralogical and chemical investigations of fayalite in four CV3 chondrites; CV3<sub>OxB</sub> clasts in CV3<sub>Red</sub> Asuka 881317 (A881317), CV3<sub>OxB</sub> Yamato 86009 (Y86009), CV3<sub>OxB</sub> Meteorite Hills 00430 (MET00430) and CV3<sub>OxB</sub> MET01074, and estimated temperature and fluid pressure conditions of its formation. We determined formation ages of fayalite in these chondrites based on *in-situ* Mn–Cr isotopic measurements using ion microprobes and modeled the thermal evolution of the CV3<sub>OxB</sub> chondrite parent body. A comparison of formation conditions and ages of fayalite with evolutionary models allowed us to constrain the accretion time, size and early history of the CV3 parent body.

## 2. MATERIAL AND METHODS

### 2.1. Sample description

Chemical compositions, mineralogical and petrological characterization of fayalite in A881317, Y86009, MET00430 and MET01074 chondrites, were obtained by scanning electron microscopy (SEM), field emission scanning electron microscopy (FE-SEM) and electron microprobe (EPMA). A 25 nm-thick carbon film was applied to the sample surfaces prior to SEM, FE-SEM and EPMA analyses in order to eliminate the electrostatic charge. The SEM (JEOL-5800LV at Kyushu University and JSM-6610 at Korea Polar Research Institute) was equipped with a backscattered electron (BSE) imaging system and an energy dispersive X-ray spectrometer. X-ray spectra were obtained at 15 keV accelerating voltage and 0.5 nA beam current to identify minerals. To observe micro-textures in fayalite and other secondary minerals associated with fayalite, we used the FE-SEM (JSM-7000F at University of

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