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Redistribution of chondrules in a carbonaceous chondrite parent body: A model

Kazushige Tomeoka [a,*], Ichiro Ohnishi [b]

[a] *Department of Earth and Planetary Sciences, Faculty of Science, Kobe University, Nada, Kobe 657-8501, Japan*
[b] *EM Business Unit, JEOL Ltd., 3-1-2 Musashino, Akishima, Tokyo 196-8558, Japan*

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Abstract

Carbonaceous chondrites mainly consist of chondrules and inclusions embedded in a fine-grained matrix. This texture is widely believed to have formed primarily by direct accretion of solar nebular materials, although it may have been modified to various extents by subsequent parent-body processes.

Recently, we studied all chondrules and inclusions larger than 400 μm in diameter and their rims (referred to as chondrules/rims) in the Mokoia CV3 carbonaceous chondrite using a scanning electron microscope, and found that the chondrules/rims experienced various degrees of aqueous alteration and that some also exhibit evidence of thermal metamorphism. The mineralogical and petrographic characteristics of the chondrules/rims suggest that the alteration and metamorphism occurred within the meteorite parent body. In contrast, however, the surrounding matrix does not show evidence of such alteration and metamorphism. These findings indicate that the alteration and metamorphism of the chondrules/rims did not occur in situ. Based on these results, we proposed a model that the chondrules/rims are actually clasts transported from regions in the parent body different from the location where the host meteorite was finally lithified.

If it can be assumed that the chondrules and inclusions studied are representative of all chondrules and inclusions in Mokoia, the results and interpretation pose a fundamental challenge regarding the formation of the whole Mokoia lithology; that is, it cannot be explained by either direct accretion of the solar nebula or conventional parent-body brecciation. We propose a model for the development of the Mokoia lithology through formation of chondrules/rims and fine matrix grains by fragmentation in different regions in the parent body, followed by transportation, mixing, and accumulation in a fluid state, and finally lithification of those objects. These processes may have been repeated, cyclically, within the parent body.

1. INTRODUCTION

Most carbonaceous chondrites consist mainly of millimeter-to-submillimeter-sized chondrules, Ca–Al-rich inclusions (CAIs), and amoeboid olivine inclusions (AOIs) embedded in a fine-grained matrix. Chondrules and inclusions are commonly surrounded by fine-grained rims (10 to several hundred micrometers in thickness). This carbonaceous chondrite texture is widely believed to have retained its basic state when the components were accreted into their parent bodies, although it may have been modified to various extents by subsequent parent-body processes (e.g., Wood, 1963, 1985, 1988; Metzler et al., 1992; Shu et al., 1996; Cuzzi et al., 2005).

The matrix and rims constitute 30–70 vol.% of the carbonaceous chondrites of major groups and consist mainly of fine grains (typically < 1–10 μm in diameter) of Mg–Fe silicates with a variety of minor minerals, and they are commonly very similar in texture and mineralogy to each other (e.g., Zolensky et al., 1993; Scott and Krot, 2005; Huss

* Corresponding author.
E-mail address: tomeoka@kobe-u.ac.jp (K. Tomeoka).

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et al., 2005). The rims are generally thought to have formed by accretion of dust onto the surfaces of chondrules and inclusions while floating in the solar nebula (e.g., Metzler et al., 1992; Cuzzi et al., 2005). Although some researchers suggested that the rims were formed by parent-body processes (e.g., Sears et al., 1993; Tomeoka and Tanimura, 2000; Trigo-Rodriguez et al., 2006), those views are not widely held. The matrix is also thought to be composed mainly of nebular grains mixed with fragments of chondrules and inclusions that resulted from brecciation after accretion to the parent bodies, although it has experienced various degrees of alteration and metamorphism in the parent bodies (e.g., Metzler et al., 1992; Huss et al., 2005; Bischoff et al., 2006).

Most chondrites that belong to the CV group, which is one of the representative chemical groups of carbonaceous chondrites, consist primarily of anhydrous minerals, and thus are thought to have escaped significant aqueous alteration. However, many dark clasts (also called "dark inclusions") that appear to have undergone parent-body aqueous alteration and thermal metamorphism have been reported from CV3 chondrites (e.g., Kojima et al., 1993; Kojima and Tomeoka, 1996; Buchanan et al., 1997; Krot et al., 1997). Mokoia is a CV3 chondrite, but it differs from most others in that it contains minor amounts of hydrous phyllosilicates (Cohen et al., 1983; Tomeoka and Buseck, 1990; Kimura and Ikeda, 1998; Krot et al., 1998). Abundant dark clasts were also reported from Mokoia (Ohnishi and Tomeoka, 2002). They have characteristics of aqueous alteration, incomplete dehydration due to thermal metamorphism, and even intense shock metamorphism of a precursor equivalent to the host meteorite. In addition, one clast in which the matrix has been almost completely altered to phyllosilicates by intense aqueous alteration (Tomeoka and Ohnishi, 2011) and clasts that underwent strong thermal metamorphism (Jogo et al., 2013) have been reported. These results, taken together, suggest that the Mokoia parent body consisted of many regions that differed in degrees of aqueous alteration, thermal metamorphism, and shock metamorphism, and that brecciation and material transport occurred actively within the parent body.

We recently studied all chondrules, CAIs, and AOIs that are >400 μm in diameter in six thin sections of the Mokoia meteorite and found that they can be divided into three categories: those surrounded by phyllosilicate-rich rims, those surrounded by olivine-rich rims, and those without rims (Tomeoka and Ohnishi, 2010, 2014). We showed that those chondrules, inclusions, and their rims (generically referred to as chondrules/rims) have experienced various degrees of hydrothermal alteration, but their surrounding matrix shows no evidence of such alteration. The mineralogical and textural characteristics of the chondrules/rims indicate that the alteration occurred within the parent body. From these results, we proposed a model that the chondrules/rims are actually clasts transported from regions in the parent body that were different from the region where Mokoia was finally lithified. This means that the rims are remnants of a former matrix adhering to the chondrules.

We initiated these studies to elucidate the formation of the fine-grained rims in Mokoia. However, the results obtained through our studies lead us to recognize that there is a more fundamental problem regarding the formation of the whole Mokoia lithology, beyond that of rim formation. The problem inevitably arose from our conclusion that all of the chondrules/rims studied were clasts derived from regions in the parent body different from the region where the host meteorite was finally lithified. In this paper, we summarize the results of our previous studies of Mokoia, discuss various problems brought up by the results, and address a model that explains the formation of the whole Mokoia lithology. Our conclusion casts doubt upon the long-standing consensus among meteorite scientists that "the texture of carbonaceous chondrites retains the basic state when their components were accreted from the solar nebula into their parent bodies."

2. PREVIOUS STUDIES

In this section, we briefly summarize the results of our recent electron microscopic studies of Mokoia and our model of rim formation (Tomeoka and Ohnishi, 2010, 2014). Most images and micro-beam chemical data are indicated only by the numbers of figures and tables in the two papers, which will be abbreviated as TO-2010 and TO-2014, respectively.

2.1. Petrography and mineralogy

2.1.1. General features

Mokoia consists of chondrules, CAIs, and AOIs embedded in a fine-grained matrix (Fig. 1). The six thin sections we studied (272 mm^2 total area) contain 112 chondrules, 10 CAIs, and 7AOIs with diameters larger than 400 μm. For each of these three types of components, the numbers of those with phyllosilicate-rich rims, with olivine-rich rims, and without rims are listed in Table 1.

All of the chondrules contain various amounts of hydrous phyllosilicates, Fe-rich saponite and minor

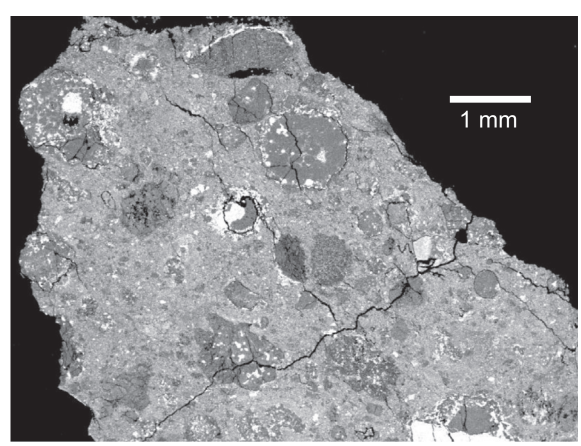

Fig. 1. Back-scattered electron image of a portion of one of the Mokoia thin sections, exhibiting a typical CV3 chondrite texture consisting of chondrules and inclusions embedded in a fine-grained, olivine-rich matrix. Methods for electron microscopy are described in Tomeoka and Ohnishi (2010).