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Multistage formation processes in the acapulcoite-lodranite parent body: Mineralogical study of anomalous lodranite, Yamato 983119

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ABSTRACT

Y 983119 is a coarse-grained rock consisting mainly of orthopyroxene (44–71 vol%, $Wo_3En_{94}Fs_4$), olivine (4–30 vol%, Fo_{97}), Fe, Ni metal (4–14 vol%) and interstitial plagioclase (9–14 vol%, $Or_2Ab_{67}An_{29}$) and augite (2–5 vol%, $Wo_{46}En_{53}Fs_2$). The modal abundance of orthopyroxene is higher than known acapulcoites and lodranites. Olivine grains show chemical zoning with higher Fe/Mn values along rims and cracks. Orthopyroxene and olivine contain melt inclusions that mainly consist of augite, feldspar and glass. Hornblende, biotite, rutile and baddeleyite were also found in melt inclusions. Based on the compositions of melt inclusions, the parent melt is felsic, and contains a significant amount of Na, K, Ti, Zr, F and OH. The major mineral and oxygen isotopic compositions indicate that Y 983119 is a lodranite. However, the high abundance of orthopyroxene and the presence of melt inclusions indicate that Y 983119 is not a residue in contrast to other lodranites. We suggest that Y 983119 formed by more complex formation processes than the other lodranites.

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1. Introduction

Primitive achondrites are a group of meteorites that have both chondritic and achondritic features. It is generally accepted that primitive achondrites are derived from planetesimals that suffered recrystallization and partial melting of chondritic precursors (Weisberg et al., 2006). The information from primitive achondrites provides better understanding of the earliest stages of metamorphism and magmatism in differentiated planetesimals.

The acapulcoite-lodranite clan is the second largest clan of the primitive achondrites next to ureilites (N = 148, Meteoritical Bulletin Database, May, 2017). Acapulcoites and lodranites are primarily distinguished based on the grain sizes of mafic silicates and mineralogies (McCoy et al., 1996, 1997a). Acapulcoites have finer-grained textures (150–230 μ m), chondritic modal abundances and chondritic bulk chemical compositions. A few acapulcoites contain relict chondrules (e.g., Yanai and Kojima, 1991). In contrast, lodranites have coarser-grained textures (~0.5–0.7 mm), modal abundances more depleted in troilite and/or plagioclase and more fractionated bulk chemical compositions from chondritic

compositions than acapulcoites. Several workers proposed a transitional type based on trace and bulk chemical compositions (e.g., Floss, 2000; Patzer et al., 2004). The similar oxygen isotopic compositions indicate that acapulcoites and lodranites formed in the same parent body or very similar separate bodies that experienced variable degrees of heating (Clayton and Mayeda, 1996; McCoy et al., 1997a). It is generally accepted that acapulcoites and lodranites are residues formed after partial melting (e.g., McCoy et al., 1997a, 1997b; Nagahara, 1992; Yugami et al., 1998). Mineral modal abundance studies indicate that acapulcoites and lodranites suffered <20% melting of a chondritic precursor (McCoy et al., 1997a).

Since acapulcoites and lodranites record a transitional stage of planetesimal evolution, they are the most suitable meteorites for better understanding of evolution from chondritic to achondritic planetesimals. Here we report petrology and mineralogy of Yamato (Y) 983119 for better understanding of its formation process and petrologic relationship with other acapulcoites and lodranites. Preliminary study indicates that Y 983119 is an anomalous lodranite (Yasutake and Yamaguchi, 2017). Y 983119 reveals another snapshot of igneous and metamorphic processes of the acapulcoite-lodranite parent body.

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2. Sample and analytical techniques

Lodranite Y 983119 is a small meteorite (original main mass = 52.6 g) collected in a bare ice field near the Yamato Mountains, Antarctica by the 39th Japanese Antarctic research expedition (Yamaguchi et al., 2012). This meteorite is partly covered with fusion crust (Fig. 1). We prepared three polished thick/thin sections (PTS), Y 983119,35, Y 983119,51 and Y 983119,51-2 from two opposite sides of the main mass (~4 cm away). Sizes of the thin sections are 12 × 18 mm for PTS,35, 7 × 9 mm for PTS, 51 and 6 × 11 mm for PTS,51-2.

These sections were examined using an optical microscope and a field emission scanning electron microscope (FE-SEM) (JEOL JSM-7100F) equipped with an energy dispersive spectrometer (EDS) and an electron backscatter diffraction (EBSD) detector (AZtec, Oxford Instruments) at the National Institute of Polar Research, Tokyo (NIPR). The major and minor elements of constituent minerals were measured by using of an electron probe micro analyzer (EPMA) (JEOL JXA-8200) at NIPR. All mineral phases were analyzed with 15 kV electron accelerating voltage. Olivine, pyroxene and chromite were analyzed with 10 nA beam current. Plagioclase, alkali-feldspar, hornblende, biotite, phosphate and glass were analyzed with 6 nA beam current. Fe, Ni metal, troilite and phosphide were analyzed with 30 nA beam current. Counting times range from 10 to 100 s on peaks for each mineral. Correction procedures are based on the ZAF method. Natural and synthetic silicates, oxides, and metals with well-known chemical compositions were used as standards. For quantifying of F, we used F-apatite standard for phosphates, and F-phlogopite standard for hornblende and biotite. Modal abundances were estimated from the X-ray elemental maps obtained by the SEM-EDS system. The X-ray elemental maps were obtained at 15 kV accelerating voltage, 10 nA probe current and with about 2.5 μm step size. Electron backscatter diffraction (EBSD) analyses were performed to obtain lattice-preferred orientation (LPO) and to identify mineral phases. The EBSD analysis was conducted at 15 kV accelerating voltage, 10 nA beam current and 25 mm working distance. Specimens were inclined at 70° to incident beam during analyses. We also identified mineral phases by using of Raman spectroscopy (Renishaw In via Raman).

3. Results

3.1. Textures

Y 983119 displays a coarse-grained texture (<4.0 mm) mainly composed of orthopyroxene (average size = 0.49 mm, 44–73 vol%), olivine (average size = 0.54 mm, 4–30 vol%) and Fe, Ni metal (kamacite and taenite, 4–14 vol%) grains with interstitial

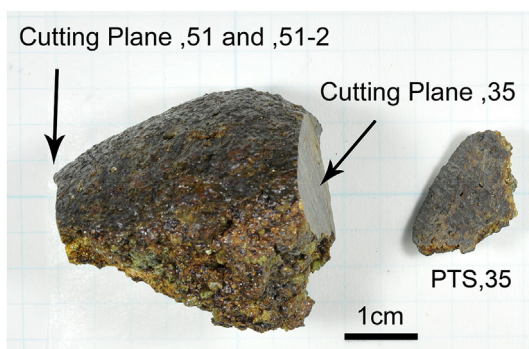


Fig. 1. Picture of the main mass of Y 983119. Upper part of the main mass is covered by fusion crust. Arrows show cutting planes of subsamples (, 35, 51 and, 51-2).

plagioclase (9–14 vol%) (Figs. 2 and 3) (Table 1). Minor minerals include augite (1.6–5.4 vol%), troilite (0.4–2.2 vol%), schreibersite, chromite, phosphate and carbon-phase (<1 vol%).

Orthopyroxene contains thin augite lamellae parallel to ⟨001⟩ direction of the host crystal, and numerous blebby augite inclusions occur with similar orientation to the host crystal (Fig. 3). Orthopyroxene grains contain elongated domains of low-Ca pyroxene (~10 μm thick) in the cores subparallel to augite lamellae. Orthopyroxene has zoning with increasing of MgO and decreasing of FeO and CaO toward the rims (Fig. 4). Several orthopyroxene contain olivine inclusions. In many cases, olivine inclusions have the same orientations in each orthopyroxene grain. Some olivine inclusions have the same orientation to adjacent olivine grains. Most orthopyroxene grains contain μm-sized troilite and metal. Crystallographic orientations of orthopyroxene are randomly oriented.

Most olivine grains have sub-rounded grain shape with or without embayment. There are few triple junctions at 120° among grains of olivine and other phases (Fig. 3). In some cases, olivine grains are intersected by plagioclase, augite and/or troilite. Olivine grains in PTS, 35 have zoning along rims and cracks (see below) (Fig. 5). Several olivine grains contain fine grains (<10 μm in size) of troilite and metal. A few olivine grains contain symplectic intergrowths along the rims. The intergrowths consist of chromite, orthopyroxene and augite. Crystallographic orientations of olivine are randomly oriented.

Plagioclase crystals have polysynthetic twins. In some cases, plagioclase partly or entirely encloses orthopyroxene and olivine grains. Plagioclase crystals in the wide area (~2 × 4 mm) have the same crystallographic orientation indicating these plagioclase grains are interconnected and single large crystals.

Augite occurs interstitially or as grains. Most interstitial augite crystals coexist with kamacite grains, and partly or completely cover kamacite grains. Several augite crystals contain thin lamellae of orthopyroxene. Several augite crystals in contact with phosphates contain domains with intergrowth consisting orthopyroxene and phosphate along the boundaries (~5 μm thick). Most augite crystals contain olivine inclusions (<20 μm). In some cases, olivine inclusions have the same crystallographic orientation to adjacent olivine grains. Intergrowths of orthopyroxene, augite, and Fe-oxide were found around the olivine inclusions. Minor minerals include phosphates, Ti-rich and Cr-rich phases.

Kamacite occurs as amoeboid grains. Few polycrystalline kamacites were found. Taenite, troilite and schreibersite coexist with kamacite or occur as isolated grains. Chromite occurs as nodules in troilite, or partly covers the troilite grains. Merrillite was found in the two PTSs, whereas Mg-rich phosphate was found in only PTS,35. In many cases, merrillite and Mg-rich phosphate coexist with kamacite and/or augite. One F-apatite grain was found in PTS,51. The carbon-phase in kamacite has a feathery texture composed of few-tens of μm wide laths. The occurrence of carbon-phase in kamacite is similar to feathery graphite in Acapulco (El Goresy et al., 2005). Carbon-phases were also found in orthopyroxene as minute inclusions (<10 μm). We could not identify the phase by EBSD and Raman spectroscopy.

Olivine, pyroxene and plagioclase in PTS,51-2 show no or weak undulatory extinction corresponding to S1-2 in the criteria of shock metamorphism (Stöffler et al., 1991). Cracks are found in all PTSs. In particular, PTS, 35 has randomly located brecciated areas. All three sections contain weathering products along cracks. Kamacite, taenite and troilite are partially replaced by the weathering products.

3.2. Melt inclusions

We found melt inclusions in orthopyroxene (N = 24) and olivine

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