Majindeite, Mg₃Mo₃O₉₈, a new mineral from the Allende meteorite and a witness to post-crystallization oxidation of a Ca-Al-rich refractory inclusion

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ABSTRACT

Majindeite (IMA 2012-079), Mg₃Mo₃O₉₈, is a new mineral, occurring as submicrometer-sized crystals with Ni-Fe and Ru-Os-Ir alloys, ± apatite and Nb-oxide. The observed assemblages are partially or wholly enclosed by MgAl₂O₄ spinel in a Type B1 Ca-Al-rich inclusion, ACM-2, from the Allende CV3 carbonaceous chondrite. The type majindeite has an empirical formula of (Mgₓₐ₈₆;Feₓₐ₄₆)Moₓ₄₋₉₈O₉₈, and a nolanite-type P₆₃mc structure with a = 5.778 Å, c = 9.904 Å, V = 286.35 Å³, and Z = 2, leading to a calculated density of 5.54 g/cm³.

Majindeite likely formed during the subsolidus oxidation of Mo-rich precursor phase(s) included in Fe-Ni rich alloys in a system that was open to O, Mg, and Ca, which were derived externally and introduced via cracks, subgrain boundaries, and/or surfaces exposed at the exterior of the spinel. If magnetite existed in the phase assemblage, it was lost due to Fe volatilization prior to the formation of majindeite. The immediate precursor to majindeite was likely kамиokitе. Majindeite formed during an oxidation event contemporaneous with or postdating the formation of grossular-rich veins in melilite.

Kамиokitе, the Fe-rich analog of majindeite, also occurs in ACM-2 but only within phase assemblages that contain magnetite and which are entirely enclosed in melilite ± alteration products. Here, grossular-rich veins are not observed and the coexisting awaruite are more Fe-rich than those observed with majindeite. As with majindeite, the precursors for kamiokite grains were also likely to have been Mo-rich alloys, but the Mo-oxide remained magnetite-saturated throughout the alteration process and therefore remained Fe-rich.

Keywords: Majindeite, Mg₃Mo₃O₉₈, new mineral, kamiokite group, Allende meteorite, CV3 carbonaceous chondrite, EBSD, Ca-Al-rich inclusions

INTRODUCTION

The origin and evolution of Ca-Al-rich inclusions (CAIs) in meteorites is a story of the origin and early evolution of the Solar System. Although bulk compositions of these objects can aid in deciphering some of the pages (e.g., Beckett and Grossman 1988; Grossman et al. 2000), it is in the constituent minerals that most of the information on environment lies. New minerals can provide special insight because they sample special environments not encountered by most inclusions (e.g., Ma et al. 2011b) or because they represent responses to aspects of an environment that was encountered by other phases but poorly recorded (e.g., Ma et al. 2014a). In this work, we consider a new Mo-Mg oxide mineral, majindeite, Mg₃Mo₃O₉₈, which was discovered in the Allende Type B1 Ca-Al-rich inclusion (CAI) ACM-2. In addition to majindeite, this inclusion is the source of three previously described new minerals, grossmanite (Ca₄Al₂SiO₆), monipite (MoNiP), and nuwaite (Ni₃GeS₅) (Ma and Rossmann 2009b; Ma et al. 2014a; Ma and Rossman 2015a), and two first occurrences in a meteorite for the Mo-oxides tugarinovite (MoO₃) and kamiokite (Fe₃Mo₃O₈) (Ma et al. 2014a). Molybdenum is a major constituent of five different minerals in this inclusion [majindeite, kamikite, monipite, tugarinovite, and molybdenite (MoS₂)], which speaks to varying fates for Mo that depend on microenvironment and initial phase composition tied together through a common thread of thermal and metasomatic processing.

Phases of the type X₃Mo₃O₉₈, where X is a divalent cation, are readily synthesized using a wide variety of cations including Cd, Co, Cu, Fe, Mg, Mn, Ni, and Zn (e.g., McCarroll et al. 1957; Knorr and Mueller 1995; Abe et al. 2010) and they are of considerable interest in research on frustrated magnetic systems (e.g., Nakayama et al. 2011) because of the layered honeycomb structures in which Mo-O and X²⁺-O coordinated sheets alternate. However, only two of these compounds, kamiokite (Fe₃Mo₃O₈) and iseite (Mn₃Mo₃O₈), were previously known to exist in nature (e.g., Johan and Picot 1986; Nishio-Hamane et al. 2013). In this work, we describe the first occurrence in nature of the Mg-end-member of the X₃Mo₃O₉₈ class of phases. This mineral is named majindeite (Mg₃Mo₃O₉₈). We show through electron backscatter diffraction (EBSD) that majindeite has a nolanite-type P₆₃mc structure, isostructural with kamiokite and iseite. We use electron probe microanalysis (EPMA) and high-resolution scanning electron microscopy (SEM) to characterize the petrographic settings and compositions of majindeite and associated phases. We then connect these data and those for kamiokite-bearing phase assemblages, which also occur in the CAI ACM-2, to implications for precursors and the processes that led to their formation. Preliminary results of this work are given by Ma et al. (2009).