Allendeite (Sc\textsubscript{4}Zr\textsubscript{3}O\textsubscript{12}) and hexamolybdenum (Mo,Ru,Fe), two new minerals from an ultrarefractory inclusion from the Allende meteorite

**CHI MA**, **JOHN R. BECKETT** AND **GEORGE R. ROSSMAN**

Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California 91125, U.S.A.

**ABSTRACT**

During a nanomineralogical investigation of the Allende meteorite with analytical scanning electron microscopy, two new minerals were discovered; both occur as micro- to nano-crystals in an ultrarefractory inclusion, ACM-1. They are allendeite, Sc\textsubscript{4}Zr\textsubscript{3}O\textsubscript{12}, a new Sc- and Zr-rich oxide; and hexamolybdenum (Mo,Ru,Fe,\textit{Ir},Os), a Mo-dominant alloy. Allendeite is trigonal, \(R\bar{3}, a = 9.396\), \(c = 8.720, V = 666.7\ \text{Å}^3\), and \(Z = 3\), with a calculated density of 4.84 g/cm\(^3\) via the previously described structure and our observed chemistry. Hexamolybdenum is hexagonal, \(P6_3/mmc, a = 2.7506, c = 4.4318\ \text{Å}, V = 29.04\ \text{Å}^3\), and \(Z = 2\), with a calculated density of 11.90 g/cm\(^3\) via the known structure and our observed chemistry. Allendeite is named after the Allende meteorite. The name hexamolybdenum refers to the symmetry (primitive hexagonal) and composition (Mo-rich). The two minerals reflect conditions during early stages of the formation of the Solar System. Allendeite may have been an important ultrarefractory carrier phase linking Zr-, Sc-oxides to the more common Sc-,Zr-enriched pyroxenes in Ca-Al-rich inclusions. Hexamolybdenum is part of a continuum of high-temperature alloys in meteorites supplying a link between Os- and/or Ru-rich and Fe-rich meteoritic alloys. It may be a derivative of the former and a precursor of the latter.

**Keywords:** Allendeite, Sc\textsubscript{4}Zr\textsubscript{3}O\textsubscript{12}, hexamolybdenum, new alloy, new mineral, EBSD, nanomineralogy, Allende meteorite, CV3 carbonaceous chondrite

**INTRODUCTION**

Processes that occurred during the first few million years of our solar system are largely inferred from the study of meteorites and their constituents (e.g., Kerridge and Matthews 1988; Lauretta and McSween 2006). Where the elements and/or isotopes in a mineral are fractionated or one phase is stabilized over another, it is often possible to constrain the nature of the environment and/or the intensity of the process(es) that led to these fractionations and changes in stability. Thus, each new phase adds a new voice and, with appropriate thermodynamic and/or kinetic data, it may also be possible to understand some of the lyrics.

The Allende meteorite, which fell near Pueblito de Allende, Chihuahua, Mexico, on February 8, 1969, is a CV3 carbonaceous chondrite. It is the largest carbonaceous chondrite ever recovered on the Earth and is often called the best-studied meteorite in history. More than four decades after it fell, this meteorite continues to be the source of new discoveries. For example, in the first decade after its fall, Allende yielded at least seven minerals not previously observed in meteorites (Fuchs 1969, 1971; Keil and Fuchs 1971; Fuchs and Blander 1977; Lovering et al. 1979) and, in the last several years, Allende has yielded another 18 minerals new to meteorites, 12 of which are also new to science (Ma 2010, 2013a, 2013b; Ma and Rossman 2008b, 2009a, 2009b, 2009c; Ma and Krot 2013; Ma et al. 2009b, 2012, 2013a, 2013b, 2013c, 2014; this work). Overall, Allende, one of nearly 40000 known meteorites, is the original source of nearly one in ten of the known minerals in meteorites (cf. Rubin 1997). In this work, we describe two of these new minerals, allendeite and hexamolybdenum, which were discovered in an Allende ultrarefractory inclusion, named ACM-1. We describe the properties and chemistry of both phases and explore their origin and evolution. Preliminary results of the work reported in this study are given by Ma et al. (2009a).

**MINERAL NAMES AND TYPE MATERIALS**

The section containing the holotype allendeite specimen was prepared from a 1 cm diameter fragment of Allende (Caltech Meteorite Collection No. Allende-12A) and deposited in the Smithsonian Institution’s National Museum of Natural History under catalog number USNM 7554. The holotype hexamolybdenum specimen described in the text, a 1.2 \(\mu\)m crystal occurring with allendeite in USNM 7554, was the crystal most amenable to detailed characterization, but the grain was lost during the attempted ion probe analysis of an adjacent grain. Additional specimens of hexamolybdenum can, however, be found in the Smithsonian Institution’s National Museum of Natural History Allende section USNM 3509HC12 and in section USNM 7590 of NWA 1934, another CV3 chondrite. Some of the refractory alloy grains from acid residues of the Murchison CM2 chondrite described by Harries et al. (2012) are also hexamolybdenum.

The name allendeite refers to the host meteorite, Allende, which has proven to be a treasure trove of new minerals, as noted above, and is the target of many important studies on the origin and evolution of the Solar System. The name hexamolybdenum refers to the symmetry (primitive hexagonal) and composition...