

UNUSUAL CARBONATE-SULFIDE ASSEMBLAGES IN COLD BOKKEVELD CM CHONDRITE. Stefan Farsang¹, Timothy D. Raub², Iris Buisman¹, Giulio I. Lampronti¹ and Monica M. Grady^{3,4}, ¹Department of Earth Sciences, University of Cambridge, Downing St, Cambridge, CB2 3EQ, UK (sf571@cam.ac.uk); ²School of Earth & Environmental Sciences, University of St Andrews, Irvine Building, St Andrews, KY16 9AL, UK; ³School of Physical Sciences, The Open University, Walton Hall, Milton Keynes, MK7 6AA, UK; ⁴Department of Earth Sciences, Natural History Museum, Cromwell Rd, London, SW7 5BD, UK.

Introduction: CM carbonaceous chondrite parent bodies experienced various degrees of aqueous alteration. This process altered much of their primary mineralogy and chemistry and resulted in the formation of secondary phases, including carbonate minerals.

Cold Bokkeveld is a petrologic type 2.2 CM carbonaceous chondrite [1]. A number of studies have addressed the presence of carbonates in Cold Bokkeveld and used mineral and isotopic chemistry to reconstruct aqueous alteration conditions on its parent body [1-9]. Despite such detailed work, new and enigmatic assemblages have recently been found in the meteorite, which require geologic interpretation. This study explores the petrography and chemistry of several unusual carbonate assemblages in Cold Bokkeveld, in order to determine the alteration environments prevailing on its parent body at the time of carbonate formation. The assemblages include calcite and dolomite crystals associated with the sulfide minerals pyrrhotite and pentlandite, and their alteration product, magnetite.

Methods: *SEM.* A Quanta 650F instrument at the University of Cambridge was used for secondary electron (SE), back scattered electron (BSE), and cathodoluminescence (CL) imaging of a polished section of Cold Bokkeveld (P5449 from BM.1727), for chemical analysis by using energy dispersive spectroscopy (EDS) and quantitative evaluation of minerals by scanning electron microscopy (QEMSCAN), and for phase and textural analysis by electron back scattered diffraction (EBSD).

EPMA. A Cameca SX-100 microprobe at the University of Cambridge with five wavelength-dispersive spectrometers (WDS) was used for high precision quantitative chemical analysis.

Results: *Dolomite.* Abundant dolomite has been found in a 1.1 × 0.6 mm calcite-rich clast in contact with up to 250 μm tabular monoclinic pyrrhotite crystals. The dolomite shows prominent compositional zonation (Fig. 1).

Calcite. An isolated 80 μm pyrrhotite crystal partially replaced by calcite has been found. The pyrrhotite is surrounded by a calcite rim of uniform crystallographic orientation that is overlain by pentlandite crystals (Fig. 2). Interstitial calcite has also been found in other areas of the polished section in association with pentlandite and magnetite (Fig. 3).

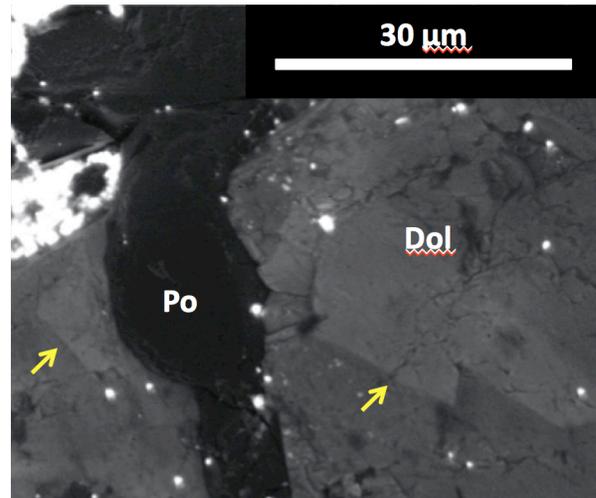


Figure 1. CL image of dolomite (Dol) in contact with pyrrhotite (Po). Dolomite shows prominent compositional zonation.

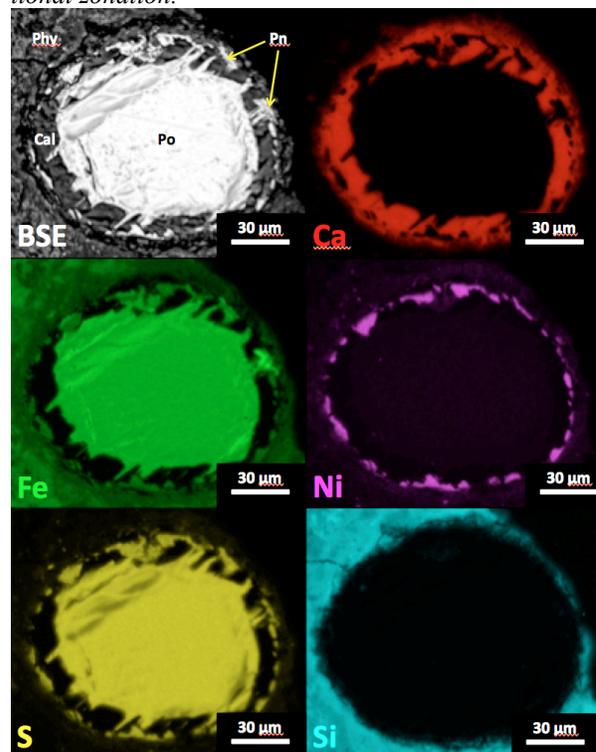


Figure 2. BSE image and EDS element maps of a pyrrhotite (Po) crystal partially replaced by calcite (Cal) with pentlandite (Pn) grains embedded in phyllosilicate (Phy) matrix.

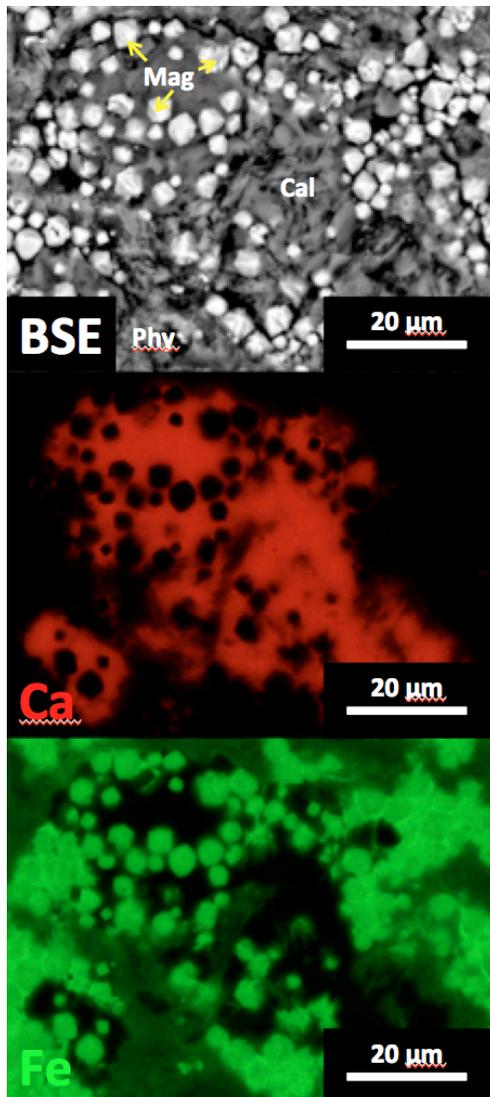


Figure 3. BSE image and EDS element maps of magnetite crystals (Mag) with interstitial calcite (Cal) embedded in phyllosilicate (Phy) matrix.

Discussion: Petrographic evidence suggests that carbonate precipitation from aqueous fluids took place in at least two distinct stages. The first stage of carbonate precipitation postdates pyrrhotite and pentlandite formation, noting that the sulfides themselves are the product of aqueous alteration, and the second stage postdates magnetite formation. As carbonate formation in Cold Bokkeveld requires reducing environments with a minimum pH value of 11.7 [10], while magnetite formation requires oxidizing environments [11], it is clear that between the two stages of carbonate formation there had to be a period dominated by oxidizing conditions. Contact relationships suggest that dolomite precipitated after the formation of phyllosilicates, unlike most of the dolomite in other CM chondrites,

which formed in the first stages of carbonate precipitation [9].

Conclusions: We suggest four major periods in CM parent body evolution relevant to the formation of carbonate-sulfide assemblages, which were accompanied by fluctuation in pH. The first one is accretion, which is followed by at least three stages of alteration. In the first phase of alteration, reducing conditions with high S activity dominate the CM parent body, during which Fe,Ni-metal grains alter to sulfides. Pentlandite crystals surrounding the pyrrhotite crystal are likely to reflect the original distribution of Ni in Fe,Ni-metal, i.e., kamacite with taenite rim. At the end of this stage, Ca activity increases, probably due to dissolution of Ca-rich silicates. The first generation of carbonates forms in contact with sulfide grains. In the second stage, possibly initiated by impact-induced heating, a significant amount of water is introduced, accompanied by a drop in pH and switch to oxidizing conditions. Some sulfides alter to magnetite. Water alters silicates to phyllosilicates. In the third stage, after an increase in pH and switch back to reducing conditions, carbonate precipitation continues. Dolomite precipitation takes place, followed by the formation of interstitial calcite between magnetite grains and single calcite grains clearly postdating the surrounding phyllosilicates, which have been observed in this study and elsewhere [2]. The coexistence of dolomite and calcite and the compositional zonation of both phases indicate significant changes in aqueous fluid composition throughout this stage.

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