CARBONATES IN COLD BOKKEVELD CM CHONDRITE: A PRE-ACCRETIONARY ORIGIN?

S. Farsang[1], X. Zhao[2], I. A. Franchi[2], S. A. T. Redfern[1], T. D. Raub[3] and M. M. Grady[2,4], [1]Department of Earth Sciences, University of Cambridge, Downing St, Cambridge, CB2 3EQ, UK (*sf571@cam.ac.uk), [2]School of Physical Sciences, The Open University, Walton Hall, Milton Keynes, MK7 6AA, UK, [3]School of Earth & Environmental Sciences, University of St Andrews, Irvine Building, St Andrews, KY16 9AL, UK, [4]Department of Earth Sciences, Natural History Museum, Cromwell Rd, London, SW7 5BD, UK.

Introduction: CM carbonaceous chondrite meteorites represent some of the most primitive materials formed in the early solar system. Carbonate minerals are minor phases in CM chondrites and include aragonite and calcite ($CaCO_3$), dolomite ($CaMg(CO_3)_2$), and breunnerite ($(Mg,Fe)CO_3$) [1]. Several formation mechanisms of carbonates in carbonaceous chondrites have been suggested over the last decades. Initially, carbonates were suggested to form exogenously, by nebular processes [2]. This possibility is supported by spectroscopic evidence for the existence of calcite in protostars [3,4] and calcite and dolomite in the dust shells around evolved stars [5]. Experiments indicate that carbonates may form by non-equilibrium condensation in protostellar outflows or in evolved stellar winds [6]. An alternative exogenous formation mechanism invoking pre-accretionary aqueous alteration has also been suggested [7]. More recent studies imply that carbonates in carbonaceous chondrites formed endogenously, either contemporaneously to accretion [8] or in an accreted parent body [9-11]. Cold Bokkeveld is a petrologic type 2.2 CM chondrite regolith breccia. Here we present a combined petrographic, chemical, spectroscopic, and isotopic study of carbonate assemblages in Cold Bokkeveld in order to reconstruct their formation conditions.

Methods: Scanning electron microscopy. A Quanta 650F instrument was used for secondary electron, backscattered electron, and cathodoluminescence imaging of a polished section of Cold Bokkeveld. Electron probe microanalysis. Quantitative chemical analysis was conducted by a Cameca SX 100 electron microprobe with five wavelength-dispersive spectrometers. Raman spectroscopy. Spectra were collected in the 100–1800 cm^{-1} spectral range using a Horiba Jobin Yvon LabRAM 300 Raman spectrometer. Nano secondary ion mass spectroscopy. Oxygen isotopic composition was measured by a Cameca NanoSIMS 50L instrument.

Results and discussion: The majority of carbonate grains in Cold Bokkeveld have petrographic features characteristic to type 1 and type 2 calcite precipitated on the CM parent body and described by [1]. In addition to these, we found calcite crystals occupying interstitial space between magnetite framboids, for which we suggest a new, 1c type. In one assemblage, type 1 calcite and dolomite showing prominent compositional zonation were found in contact with each other, suggesting that these phases precipitated from a fluid that changed its composition. Oxygen isotope data for this dolomite are in good agreement with data of other CM chondritic dolomites. In a different assemblage, aragonite coexists with type 2 calcite, suggesting that at least some of the calcite precipitated from previously dissolved aragonite. Three of the studied carbonate assemblages exhibit unique petrographic, chemical and spectral features, which do not resemble type 1 or type 2 carbonates. The first is a globular ~25×30 µm object, in which pentlandite clasts occur with interstitial carbonate. The central part of the carbonate is calcite, while the rim is dominantly dolomite. The second represents an irregular ~300×450 µm object, in which hundreds of P- and Cr-rich pentlandite clasts occur in interstitial calcite. The third is an isolated ~80 µm pyrrhotite crystal that has been partially replaced by calcite. The pyrrhotite is surrounded by a calcite rim that is in turn overlain by a rim of pentlandite crystals. The Raman-active modes of this calcite occur at significantly lower frequencies compared to all other Cold Bokkeveld and terrestrial reference calcites. For instance, features corresponding to external modes are located at ~142 and ~259 cm^{-1}, while in other CM chondritic calcites these lie at ~157 and ~284 cm^{-1} [12]. Our data and the large span of suggested carbonate formation temperatures, ranging from ~26 to ~225 °C based on clumped isotope thermometry [13] and oxygen isotopic compositions [14], indicate that the CM parent body experienced multiple carbonate precipitation events. For calcites exhibiting distinct features pre-accretionary formation scenarios are explored.

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