A XENOLITH-BEARING XENOLITH IN THE COLD BOKKEVELD CM CARBONACEOUS CHONDRITE: A WINDOW INTO THREE GENERATIONS OF PRIMITIVE ASTEROIDS. M. R. Lee[1], C. J. Floyd[1] and S. Griffin[1], [1]School of Geographical and Earth Sciences, University of Glasgow, Glasgow G12 8QQ, U.K. (Martin.Lee@Glasgow.ac.uk).

Introduction: Many CM carbonaceous chondrites are breccias [1, 2]. The most abundant types of clasts in these fragmental rocks are 'cognate clasts', which are CM lithologies that are most likely to be from the same parent body (i.e., they have been locally redistributed by processes such as regolith gardening). These clasts can be distinguished from their host meteorite by properties such as their petrofabric [3]. The OSIRIS-REx spacecraft may have observed cognate clasts in the process of being redistributed around the B-type asteroid Bennu ('pebble transport' [4]).

Clasts of non-CM lithologies (i.e., xenoliths) have rarely been described within CM meteorites (e.g., [5–7]), but may be more abundant than assumed, especially those of a C1 lithology [8]. Xenoliths can provide unique insights into the early Solar System because they may sample primitive bodies that are otherwise unrepresented in the meteorite record [8]. Most xenoliths were incorporated into their host meteorite's parent body after it had been aqueously altered [7]. However, [9] described a C2 xenolith in LaPaz Icefield (LAP) 02239 (CM2) that had been accreted before the LAP 02239 parent body had been aqueously altered. One key line of evidence supporting this interpretation is that the xenolith has a fine-grained rim that is petrographically and chemically comparable to rims on chondrules and other objects in LAP 02239. The xenolith therefore interacted with the same region of rim-forming dust as the chondrules whilst free-floating in the protoplanetary disk.

Here we describe another rimmed xenolith from Cold Bokkeveld. In addition to providing insights into the geological evolution of its own parent body, including evidence for fracture-mediated fluid flow, the xenolith itself contains a xenolith that samples an even earlier body. Thus, a millimeter size area of Cold Bokkeveld contains material from three generations of primitive parent bodies.

Materials and methods: Cold Bokkeveld is clast-rich CM2 carbonaceous chondrite [10]. BSE images and X-ray maps were obtained using a Zeiss Sigma SEM in the University of Glasgow from a polished block (BM13989 P19255) on loan from the Natural History Museum, London.

Results: The xenolith that is the focus of this study is oval in shape, 0.66 mm on its long axis, and is enclosed by a ~70 μm thick fine-grained rim (Fig. 1).

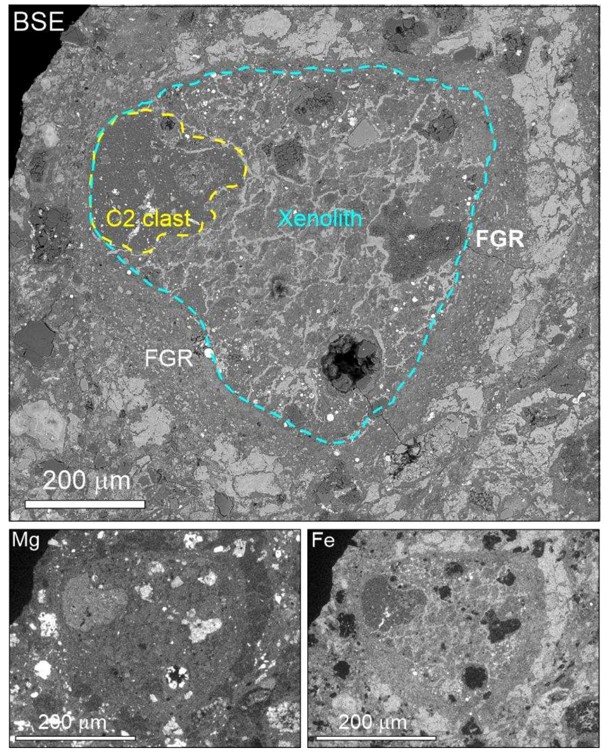

Figure 1. BSE image, and corresponding Mg and Fe X-ray maps of the xenolith. Its outer edge is delineated by a dashed blue line, and its enclosing fine-grained rim is labelled (FGR). The outer edge of a C2 clast within the xenolith is delineated by a dashed yellow line.

The xenolith contains fragments of type-I chondrules (~50–150 μm on their long axis), grains of anhydrous silicates a few tens of micrometers in size, and a lithic clast (described below), all in a fine-grained matrix. The chondrule fragment and some of the mineral grains have fine-grained rims. The matrix is dissected by numerous ~5 μm wide veins of Fe-rich phyllosilicate (Fig. 2) and contains abundant spherical grains of Ca-phosphate a few micrometers in diameter.

Lithic clast within the xenolith. The lithic clast is probably itself a xenolith (i.e., it is petrographically distinct to its host lithology, the xenolith) but hereafter is referred to as the 'C2 clast' for brevity. The C2 clast contains a single chondrule fragment 90 μm in size within a fine-grained matrix. The chondrule fragment lacks a fine-grained rim, and its mesostasis has been aqueously altered. The clast's matrix is enriched in Mg and depleted in Fe relative to the host xenolith (Fig. 1).

It contains grains of magnetite, and is partly cross-cut by a couple of the Fe-rich phyllosilicate veins that are abundant in the xenolith (Fig. 2).

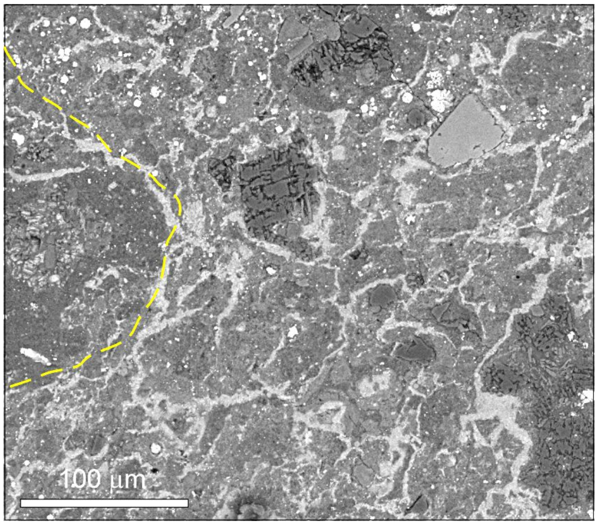

Figure 2. BSE image of the xenolith, with part of the C2 clast on the left-hand side (delineated by a dashed yellow line). The xenolith contains several coarse mineral grains, and a fragment of a chondrule (lower right). Its matrix is dissected by Fe-rich phyllosilicate veins, a couple of which also cut the C2 clast.

Discussion: Here we describe the history of the sample studied, from accretion of the C2 clast's parent body to evolution of Cold Bokkeveld's parent body.

The parent body of the C2 clast was formed by the accretion of chondrules and finer grained material that forms the matrix. It's one chondrule fragment lacks a fine-grained rim, which could be because: (i) it never formed or was detached during fragmentation or accretion; (ii) rim-forming dust was absent from the area of the protoplanetary disk between where the chondrules formed and C2 clast's parent body accreted. It cannot be determined whether the C2 clast was aqueously altered prior to being ejected from its parent body, but must have been lithified somehow to retain its integrity. After some time in the protoplanetary disk, the clast was incorporated into the xenolith's parent body along with chondrules, silicate mineral grains and fine-grained matrix material. The absence of a fine-grained rim on the C2 clast shows that it did not interact with dust whilst free-floating in the protoplanetary disk. However, some of the xenolith's other constituents did develop fine-grained rims suggesting that it accreted near a dust-rich region of the protoplanetary disk.

Following accretion of the xenolith's parent body, it was lithified by compaction and/or aqueous alteration. The matrix was then fractured by an impact, and the fractures were cemented by Fe-rich phyllosilicates to make the veins. The high density and interconnectivity of the fractures suggests that they could have supported fluid flow.

After aqueous alteration, the xenolith was ejected from its parent body and acquired a fine-grained rim as it passed through a dust-rich region of the protoplanetary disk. The rimmed xenolith was accreted into Cold Bokkeveld's parent body along with rimmed chondrules. The body then underwent aqueous alteration, which will have affected the xenolith's fine-grained rim, and may have overprinted alteration products in the xenolith and its C2 clast. The petrofabrics of other clasts/xenoliths in Cold Bokkeveld show that its parent body underwent compaction after they had been incorporated [10], but it is unclear whether this compaction occurred before or after aqueous alteration.

Conclusions: Three generations of chondritic parent bodies formed and evolved in the following sequence: (i) the C2 clast's parent body accreted, was lithified (possibly by aqueous alteration), and then a piece was ejected and transferred through the protoplanetary disk to be accreted into the xenolith's parent body; (ii) the xenolith's parent both underwent aqueous alteration including cementation of fractures, then a piece was ejected and moved through the protoplanetary disk where it acquired a fine-grained rim prior to being accreted into Cold Bokkeveld's parent body; (iii) Cold Bokkeveld's parent body underwent aqueous alteration and compaction.

The absolute timescales of these three events cannot be determined. However, if aqueous alteration was driven by ^{26}Al, then the parent bodies of the C2 clast and the xenolith must have accreted and undergone geological processing sufficiently quickly such that enough ^{26}Al remained to heat Cold Bokkeveld's parent body.

Acknowledgments: We thank the Natural History Museum, London, for loan of the Cold Bokkeveld sample, and UK STFC for funding.

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