INVESTIGATING THE THERMAL HISTORY OF A COMPOUND-CHONDRULE-CAI WITHIN THE CM2 BRECCIA AGUAS ZARCAS. P. M. C. Martin1, L. Daly1,2,3, and M. R. Lee1, 1School of Geographical and Earth Sciences, University of Glasgow, Glasgow, UK. 2Australian Centre for Microscopy and Microanalysis, The University of Sydney, Sydney, NSW, Australia. 3Department of Materials, University of Oxford, Oxford, UK. (p.martin.2@research.gla.ac.uk).

Introduction: Recent studies such as [1] suggest that some Al-rich chondrules could have formed from the melting of Ameboid Olivine Aggregates (AOA) and types B and C Calcium-Aluminium-rich Inclusion (CAI) precursors. Al-rich chondrules have intermediate compositions between ferromagnesian chondrules and plagioclase-rich CAIs. [2]. It is within Al-rich chondrules that relict CAI have been found within CR, CH, and CV carbonaceous chondrite (CC) groups [3, 4] which strengthens the argument that CAIs have played a role in the formation of chondrules.

Compound-chondrule CAIs (CCCAIs) are defined as an assemblage of a CAI and a chondrule. They are scarce among the CO [5], CV [6], and CH [7] CC groups. They are even rarer within CMs; two have been reported in Paris (CM2.7) [8], and two in the brecciated CM2 lithology of Aguas Zarcas [9, 10]. These rare objects have been described as CAIs enclosing chondrules [8, 11] or as chondrules enclosing CAIs [12, 13].

The existence of CCCCAIs suggests that chondrules and CAIs interacted within high particle density environments in the protoplanetary disk, potentially in the vicinity of an early formed Jupiter. Given that CAIs are more refractory than chondrules, some CAIs or mineral components may survive chondrule formation and can thus provide insights into the temperatures associated with the process. Studying CCCCAIs could provide a new way to understand the chondrule forming environment.

Here we investigate the mineralogy and infer the thermal history of ‘the Cockerel’, a CCCAI within Aguas Zarcas that is composed of a CAI enclosed within a chondrule. The aim of this work is to elucidate the potential role of CAIs in the formation and evolution of chondrules.

Materials and Methods: The CCCAI was identified using large area Energy Dispersive X-ray Spectroscopy (EDS) maps alongside Backscattered Electron (BSE) images of two polished blocks and three thin sections of the Aguas Zarcas meteorite. These maps were produced using a Zeiss Sigma Variable Pressure Scanning Electron Microscope (SEM; accelerating voltage of 20 keV; carbon coating ~10 nm thickness) at the University of Glasgow.

The CCCAI was polished using colloidal silica and coated with 7 nm of carbon for characterization by Electron Backscatter Diffraction (EBSD). EBSD data were acquired using a NordlysMax2 EBSD detector with a step size of 0.3 μm and a 70° sample tilt. All data were collected using the AZtec v5.1 software and processed using AZtec Crystal v2.1 from Oxford Instruments.

Results: The chondrule part of the CCCAI is characteristic of a Type I Porphyritic Olivine-Pyroxene chondrule (POP-chondrule; Fig. 1), composed mainly of forsterite and diopside, with lamellar enstatite crystals (~50 μm in size with orthorhombic symmetry). EBSD data reveal up to 10° of internal misorientation and crystal plastic deformation within the chondrule’s diopside grains as evidenced by green-red colours in Grain Relative Orientation Distribution (GROD) angle maps, while forsterite grains are relatively undeformed (blue colouration in GROD-angle maps; Fig. 2).

Fig. 1. EBSD phase map of the CCCAI showing a type I chondrule enclosing an altered CAI. This assemblage is named ‘the Cockerel’ after the characteristic shape of the core of the CAI. Note that spinel is indexed as chromite in the map.

The core of the CAI within ‘the Cockerel’ is composed of multiple spinel grains (indexed as chromite by EBSD; < 5 μm in size). These grains are randomly orientated but boundaries between grains have 120° triple-junctions. The spinel cluster is enveloped by calcite (most of which was largely lost during polishing; Fig. 1). If we were to describe the refractory component of the CCCAI in the framework...
for CAIs within CC groups in general, it might have originally been similar to a type B or type C CAI.

Fig. 2. Grain Relative Orientation Distribution (GROD) angle map. The deviation of internal grain orientation from the mean grain orientation is indicated by the heat map. Blue represents low misorientation angles (undeformed areas) with increasingly deformed areas coloured from green-yellow-red.

Discussion: CCCAIs could form by either the incorporation of a CAI within a ferromagnesian melt, or the CAI could have served as an accretion nucleus for the formation of a chondrule.

Within the chondrule forming region of the protoplanetary disk, a typical type C CAI, composed of spinel, diopside, and anorthite, (like the Cockerel’s original CAI) would have likely been partially melted during chondrule formation [14, 15]. The Ca-Al-rich refractory mineralogical assemblage within this chondrule is consistent with a relic CAI.

Spinel would have remained solid within the CAI melt, having the highest melting point of any phase present (it can remain solid and stable up to ~1820 K [14]). The CAI melt would then have crystallised with the rest of the chondrule to produce anorthite at ~1320 K (Pressure = 10^4 bars, [16]). The anorthite from the CAI liquid would have crystallised at the same time as diopside (crystallisation temperature of ~1380 K), followed by the other chondrule minerals, forsterite and enstatite forming at ~1300 K (P = 10^4 bars, [16]). Subsequent aqueous alteration events within the CM chondrite body (or bodies) would then have replaced the anorthitic mantle with calcite.

In summary, our petrographic investigations suggest that during chondrule formation, the chondrule precursor material that includes this CAI was partially melted producing a chondrule silicate, a CAI liquid and residual small solid spinel crystals which clumped together and partially annealed. Subsequent aqueous alteration of anorthite to calcite on the CM parent body produced the final mineralogy of the ‘Cockerel’.

Conclusion: Studying the petrology of CCAs can provide invaluable insight on the thermal evolution of chondrule formation events. Through the characterisation of residual mineral assemblages of CAIs in CCAs it is possible to calibrate a coarse thermometer for chondrule formation. ‘The Cockerel’ defines a temperature range from 1300 K (crystallisation of olivine and enstatite) up to 1820 K (destabilisation and melting of spinel) during the melting, cooling and formation of the CCCAI prior to its incorporation within the carbonaceous parent-body.

Further studies will include Secondary-Ion Mass Spectrometry analyses to determine the origin and the role of the CAIs of the CCAs within the formation of the Solar System.

Acknowledgments: We wish to thank Dr S. Griffin for their help and guidance, C.J. Floyd, and L. Jenkins for their support, input, and help in collecting data, as well as M. Ouzillou for providing samples of Aguas Zarcas.