MILDLY SHOCKED OLIVINE IN THE KOLANG CM CHONDRITE – EVIDENCE AGAINST PETROFABRIC FORMATION IN A SINGLE IMPACT. L. E. Jenkins[1], M. R. Lee[1], L. Daly[1,2,3], and A. J. King[4]. [1]School of Geographical and Earth Sciences, University of Glasgow, Glasgow, Scotland (l.jenkins.1@research.gla.ac.uk), [2]Australian Centre for Microscopy and Microanalysis, The University of Sydney, NSW, 2006, Australia, [3]Department of Materials, University of Oxford, Oxford, OX1 3PH, UK, [4]Planetary Materials Group, Natural History Museum, London, England.

Introduction: Petrofabrics (a preferred alignment of objects such as chondrules) are sometimes observed in carbonaceous chondrites and are typically thought to have been caused by impacts [1]. Despite experimental impact studies confirming petrofabric formation by shock [2,3], many carbonaceous chondrites that display petrofabrics have no mineral shock effects [1,4]. There are five explanations for these contradictory observations: i) erasure of mineral shock effects by alteration [5], ii) experimental impacts not accurately recreating natural impact conditions [1], iii) multiple low-intensity impacts [4], iv) burial compaction [6], and v) freeze-thaw cycles [5]. However, to date, none of these explanations have been definitively proven.

Kolang fell in 2020 and is a ‘Mighei-like’ carbonaceous (CM) chondrite that has a petrologic subtype of 2.2 on Rubin’s scale [7,8]. It is a breccia whose clasts share a pronounced petrofabric, despite differing in their alteration histories, with some containing unaltered tochilinite and others having dehydrated remnants of it [9]. As these clasts have a common petrofabric, the event responsible must have postdated the juxtaposition of the clasts and was one of the last processes that Kolang experienced. If this petrofabric was caused by an impact, its mineral shock effects should have been preserved as there was no subsequent aqueous alteration or post-hydration heating to erase them [9]. Herein, we evaluate an impact event as the cause of its petrofabric by studying two thin sections of Kolang for signs of shock metamorphism with electron backscattered diffraction (EBSD) and optical petrography, with focus on the mineral olivine.

Methods: Both thin sections studied, Kolang_01 and Kolang_02, are ~1.3 cm^2 in area, each. EBSD data were collected for eight chondrules in Kolang_01 with a Carl Zeiss Sigma variable pressure analytical scanning electron microscope (SEM) in the Geoanalytical Electron Microscopy lab at the University of Glasgow. Kolang_02 was studied using optical petrography.

Results: Seven pyroxene and 18 olivine grains were studied optically. Four pyroxene and eight olivine grains showed undulatory extinction. Three pyroxene and 10 olivine grains had straight extinction. No planar fractures were observed, nor were there any melt veins or significant fracturing in the matrix. Thus, Kolang belongs to the C-S2 shock stage of Stöffler [10].

Seven out of eight chondrules targeted with EBSD contain olivine. Grain reference orientation deviation (GROD) maps for the chondrules in Kolang_01 show a small, but consistent amount of deformation in olivine (Fig. 1). This finding is supported by the Mean Grain Orientation Spread (MeGOS) and Maximum Grain Orientation Spread (MaGOS) (Table 1), whose means for each area are 0.8-1.1° and 3.0-4.0°, respectively.

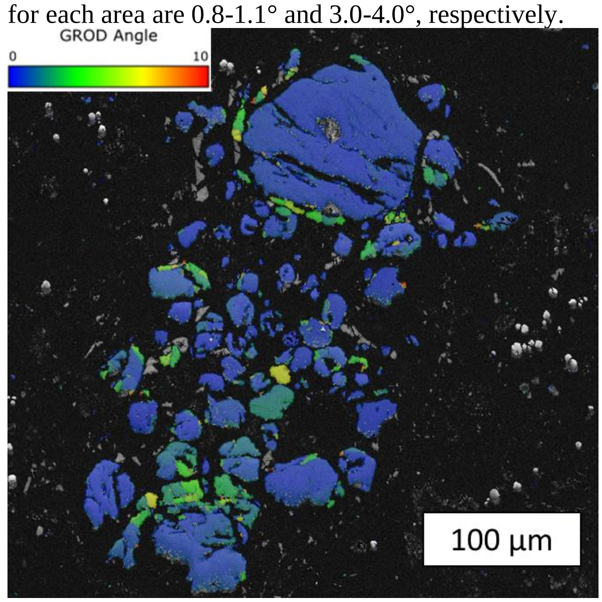

Fig 1. EBSD GROD map for olivine in Kolang_01 chondrule 2 showing mild deformation.

Table 1. Mean MeGOS and MaGOS values for olivine chondrules in Kolang_01 with standard deviation.

Chondrule	Average MeGOS (°)	Average MaGOS (°)
1	0.9±0.6	4.0±3.1
2	1.1±0.9	3.9±3.1
3	1.1±0.7	3.0±1.8
4	0.8±0.4	3.5±2.3
6	1.0±2.7	3.3±2.7
7	0.9±0.5	3.5±2.1
8	1.0±0.7	3.5±3.4

Discussion: Kolang contains mineral shock effects, however, its shock level is mild. Many olivine grains still show straight extinction and there are no signs of deformation beyond undulatory extinction, indicating that Kolang cannot have experienced peak shock pressures beyond 10 GPa [2,10]. Additionally, the MeGOS and MaGOS values from Kolang are only a little greater than those for S1 meteorites [11]. Taken together, this evidence is consistent with its C-S2 classification.

Kolang displays a pronounced petrofabric, with many of its chondrules being aligned [9]. Experimental studies have produced such petrofabrics in samples that have experienced more than 10 GPa of peak shock pressure [2,3]. Thus, Kolang's shock level (<10 GPa) is inconsistent with the amount of shock required to produce its petrofabric in a single impact (>10 GPa). There are a few possible explanations for this finding, such as experimental impact studies not being comparable to natural impact events with respect to petrofabric generation, or Kolang's petrofabric being caused by a means other than a single impact (e.g., burial compaction, multiple impacts, freeze-thaw cycles).

Experimental impacts are limited in size and cannot recreate all aspects of a natural impact. Experimental impacts tend to occur over shorter timescales and have lower post-shock temperatures than natural impacts [12,13]. Because not all parts of Kolang experienced post-hydration heating [9], the effect of post-shock temperature on annealing and thus the observed strain is minimal. Regarding duration, static high-pressure studies have shown similar strain levels and effects to those generated by experimental impacts [13]. Impact duration would not have affected the level of strain observed in Kolang's olivine and likely did not have an effect on the observed petrofabric. Even with the limitations of experimental impacts, they are good analogues for shock deformation in CM chondrites.

Freeze-thaw cycles have been proposed by Zolensky et al. [5] as a potential cause for chondrule alignment in CMs. The scenario described requires multiple cycles of aqueous alteration to occur however, with grains being altered and aligned over an extended period of time, akin to processes in terrestrial soils. This process would result in the disaggregation and relithification of chondrules into a single rock within Kolang, which is not observed; Kolang's petrofabric spans multiple clasts with varying geological histories, from aqueous alteration to post-hydration heating [9]. Freeze-thaw cycles are therefore not a plausible explanation for the petrofabric formation in Kolang.

Burial compaction can flatten and align objects. However, for it to be a plausible explanation, the minimum diameter of the CM parent body would have to be 750 km to achieve the pressures required to deform olivine at temperatures low enough not to dehydrate tochilinite [14,15]. Given that most parent bodies for carbonaceous chondrites are estimated to have had diameters of only a few tens of kilometres [16], this is an extremely unlikely scenario. Despite its low probability, it is worth mentioning that burial compaction has yet to be extensively explored by any study and its plausibility as the cause of petrofabric formation or lack thereof cannot be definitively established.

Other studies have shown that various shocked CM chondrites contain evidence for multiple impact events, with veins opened up by shock being infilled with carbonates during aqueous alteration, which were then shocked in one or more additional impacts [1,4,17]. Kolang does not have any veins or significant fractures to display this evidence; these would require shock pressures greater than 10 GPa [2,10], which Kolang also has not experienced. It is therefore plausible for multiple impact events to be the cause of Kolang's pronounced petrofabric as long as every impact event generated peak shock pressures lower than 10 GPa. This is a reasonable explanation and was the most probable cause of Kolang's petrofabrics.

Conclusions: Kolang displays mineral shock effects consistent with it having a shock stage of C-S2 and cannot have experienced shock pressures greater than 10 GPa. This evidence is in contrast to its pronounced petrofabric, which would have required peak shock pressures greater than 10 GPa to have formed by a single impact event. The most plausible explanation for this incongruency is petrofabric formation by multiple impact events whose peak pressures were all under 10 GPa.

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