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Evidence for impact induced pressure gradients on the Allende CV3 parent body: Consequences for fluid and volatile transport

Alastair W. Tait [a,*], Kent R. Fisher [b], Poorna Srinivasan [c], Justin I. Simon [d]

[a] School of Geosciences, Monash University, Melbourne, Vic., 3800, Australia
[b] University of Cincinnati, Cincinnati, OH, 45219, United States
[c] University of New Mexico, Department of Earth and Planetary Sciences, Albuquerque, NM, 87131, United States
[d] Center for Isotope Cosmochemistry and Geochronology, ARES, NASA Johnson Space Center, Houston, TX, 77058, United States

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ABSTRACT

Carbonaceous chondrites, such as those associated with the Vigarano (CV) parent body, exhibit a diverse range of oxidative/reduced alteration mineralogy (McSween, 1977). Although fluids are often cited as the medium by which this occurs (Rubin, 2012), a mechanism to explain how this fluid migrates, and why some meteorite subtypes from the same planetary body are more oxidized than others remains elusive. In our study we examined a slab of the well-known Allende ($CV3_{OxA}$) meteorite. Using several petrological techniques (e.g., Fry's and Flinn) and Computerized Tomography (CT) we discover it exhibits a strong penetrative planar fabric, resulting from strain partitioning among its major components: Calcium–Aluminum-rich Inclusions (CAIs) ($64.5\%_{CT}$) > matrix ($21.5\%_{Fry}$) > chondrules ($17.6\%_{CT}$). In addition to the planar fabric, we found a strong lineation defined by the alignment of the maximum elongation of flattened particles interpreted to have developed by an impact event. The existence of a lineation could either be non-coaxial deformation, or the result of a mechanically heterogeneous target material. In the later case it could have formed due to discontinuous patches of sub-surface ice and/or fabrics developed through prior impact compaction (MacPherson and Krot, 2014), which would have encouraged preferential flow within the target material immediately following the impact, compacting pore spaces. We suggest that structurally controlled movement of alteration fluids in the asteroid parent body along pressure gradients contributed to the formation of secondary minerals, which may have ultimately lead to the different oxidized subtypes.

1. Introduction

On Earth, penetrative planar petrofabrics are commonly found inside metamorphosed rocks that have undergone various degrees of stress. These diagnostic fabrics can be used to interpret the magnitude and origin of the stresses that deformed rocks, such as mylonites. Similar fabrics were first reported in meteorites in the 1960s (Dodd, 1965), but have been limited to a few studies since then (e.g., Cain et al., 1986; Gattacceca et al., 2005; Hanna et al., 2015; Watt et al., 2006).

The petrofabrics are generally found in carbonaceous chondrite types CM (Mighei-like) (Hanna et al., 2015; Rubin, 2012), CV (Vigarano-like) (Cain et al., 1986; Rubin, 2012) and some OC (Ordinary Chondrites) (Dodd, 1965; Krzesińska et al., 2015; Sneyd et al., 1988). The fabrics are defined by the alignment of oblate particles (e.g., chondrules and CAIs) implying pure shear (Cain et al., 1986; Sneyd et al., 1985, 1988). Pure shear requires differential stress, the difference between the maximum and minimum stress tensors, and results in coaxial deformation. Geological processes that create pure shear with an even confining pressure have been used to explain the origin of these petrofabrics (Passchier and Trouw, 2005). Early studies favor gravitational overburden to describe the uniaxial shortening, which is due to the apparent unrecoverable viscous textures (Cain et al., 1986; Dodd, 1965). However more recent studies cite evidence for an impact driven mechanism (Bland et al., 2014; Gattacceca et al., 2005; Rubin, 2012; Sneyd et al., 1988).

In addition to planar fabrics, penetrative lineations have also been reported in meteorites (Dodd, 1965; Hanna et al., 2015). However, these lineations have received even less attention by the planetary community than their planar counterparts; they have either been measured but not reconciled (Dodd, 1965), dismissed as being too weak as to affect the interpretation of the petrofabric forming mechanism (Sneyd et al., 1988), or not observed.

* Corresponding author.
E-mail address: alastair.tait@monash.edu (A.W. Tait).

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Table 1
CV Subtype characteristics related to shock.

Name	Subtype	Shock stage[a]	Permeability[b] (m^2)	Matrix porosity[b] (%)	Bulk porosity[b] (%)	Bulk porosity[c] (%)	Planar fabric bulk (R_f)	Lineation
Allende	OxA	S1	$(2.2–52.) \times 10^{-16}$	25	20	21.9	1.45	Yes
Axtell	OxA	S1	–	–	–	23.4	None[g]	?
Mokoia	OxA + Ox B	S1	–	30	24	27.7	–	?
Grosnaja	OxB	S3	–	–	–	–	Strong[e]	?
Bali	OxB	S3	$(2.8–16) \times 10^{-17}$	2	10	–	Well-defined[f]	?
Vigarano	Red + Ox	S1–S2	$\leq 9.4 \times 10^{-17}$	6	2–7	8.3	Moderate[e]	?
Leoville	Red	S3	$\leq 4 \times 10^{-18}$	–	2	2.1	1.82[h], 2.0[d] Strong[e]	?
Efremovka	Red	S4	$(2–3) \times 10^{-18}$	1	7	0.5	Strong[b]	?

Modified table from MacPherson and Krot (2014).
[a] Scott et al. (1992).
[b] Corrigan et al. (1997); relative errors for permeability not given; relative errors for porosity estimated to be ±15% of value shown.
[c] Macke et al. (2011a, 2011b); Errors on individual porosity measurements 1–4% for small samples (mass <90 g) and approximately 1–2% for mass >90 g.
[d] Cain et al. (1986).
[e] Martin et al. (1975).
[f] Keller et al. (1994).
[g] Simon et al. (1995).
[h] Almeida et al. (2015).

Piazolo and Passchier (2002) define lineations into two board categories: 1) "Object Lineations", which are distinct elongate parts of the rock with a measurable volume (e.g., grain lineation, aggregate lineations). 2) "Trace Lineations", which are material lines of zero volume (e.g., intersection lineations, crenulation lineations, shatter cone orientations). Lineations produced by deformation on Earth are of the utmost importance to structural geologists as they are used to show a heterogeneity in all three stress fields, which results in preferred shape orientation along one axis (e.g., Passchier and Trouw, 2005).

An important consequence of lineations on Earth is their control on fluid transport within rocks (Carter et al., 1990; Weinberg et al., 2013). Potential consequences of lineations for chondrite parent bodies include both implied pressure gradients due to compaction, as well as, preferential pathways for fluid transport. In other words, a bolide impact would create a seismic event increasing stress in the rock that exceeds the strength of the rock. Dilation due to rock failure would draw in fluids providing a mechanism for fluid transport (Carter et al., 1990). This could control the transport of magmatic and volatile fluids and/or ductal migration of metal phases. Recently, evidence for such a mechanism was found in the CM2 Murchison chondrite, with cross cutting alteration veins found to be parallel to the foliation (Hanna et al., 2015). In addition, the same study found micrometer scale evidence of volatile transport and alteration in chondrules. The study revealed that the chondrules were deformed internally from an impact, allowing for fluids to infiltrate micrometer scale "pull apart" structures and form serpentines, resulting in an overall flattened appearance of the chondrules. Understanding fluid transport is more difficult in the absence of preserved microstructures. Such observations may be hard to find in higher petrological type specimens. For instance, alteration textures from the CV's or OC's may have been destroyed by high degrees of thermal processing.

In an effort to more universally understand fluid transport on such bodies, our study compared petrofabrics we observed in the CV3 Allende meteorite to microstructures seen in Murchison (Hanna et al., 2015). One consistent observation in CV subtypes is that reduced subtypes have increased shock (S3–S4), $CV3_{OxB}$ types have light to moderate shock S1–S3, and $CV3_{OxA}$ types have low shock (S1) (Scott et al., 1992). Interestingly, there is also a decrease in permeability and porosity with increased shock grade in the reduced subtype (Corrigan et al., 1997; Macke et al., 2011a, 2011b; MacPherson and Krot, 2014; Rubin, 2012) (see Table 1). Some debate exists as to whether the compaction and reduced porosity in $CV3_{red}$ subtypes restricted later alteration (Rubin, 2012), or if the compaction from the impact expelled the fluids out of the pore spaces (MacPherson and Krot, 2014). Evidence for the latter are "dish structures", which indicates that fluid moved through dark inclusions (Tomeoka and Kojima, 1998), but the timing of this fluid migration is still an ongoing debate. One final observation is that the porosity in $CV3_{OxB}$ is lower than $CV3_{OxA}$ despite their higher shock and increased chemical alteration (Rubin, 2012). It should be noted that the vast majority of these observations are qualitative (Keller et al., 1994; Martin et al., 1975; Scott et al., 1992; Simon et al., 1995), using colloquial terms (see Table 1). Among the CV3 meteorites only Leoville and Allende (Almeida et al., 2015; Cain et al., 1986) have had their strain quantitatively measured. Our study aims to add to the quantitative data in the literature.

In this study, we will show that Allende, the archetypical $CV3_{OxA}$ meteorite, does contain a planar, as well as a linear petrofabric. We interpret this to be evidence of mechanical heterogeneity surrounding the point of impact on the parent body, resulting in preferred deformation and a stress field gradient by which fluids could be preferentially mobilized. Additionally, we discuss recently proposed non-coaxial deformational models (Krzesińska et al., 2015). Such a formation history might help explain the distinct alteration histories among the CV3 subtypes, although it is complicated by radiogenic heating (Doyle et al., 2015; Wasson et al., 2013). This conclusion is reached through detailed study of a slab of Allende (∼27 cm × ∼20 cm × 5 mm), using conventional 2D strain analysis techniques, in conjunction with X-ray Computerized Tomography (CT). These novel observations are discussed in terms of how the lineation fits into current petrofabric formation ideas and ultimately what these observations may mean for fluid and volatile transport on chondrite parent bodies.

2. Methods

For this study a ∼25 cm^2 slab of the Allende CV3 meteorite was chosen due to its uniquely large size (Fig. 1). Most geological discrimination of textures and mineralogy is done using thin sections. If not carefully integrated with outcrop scale observations, such studies can introduce a sizing bias by emphasizing local thin section scale mineralogical/textural heterogeneities to the overall system (Palin et al., 2015). Meteorite analysis is no different, and observation on thin sections could make observers miss larger trends and extrapolate smaller heterogeneities to the whole parent body. This slab provides a unique opportunity in meteoritics to minimize this bias by allowing for an order of magnitude larger petrographic discrimination. It is worth noting that the parent mass of the sample used was cut into slabs for meteorite collectors long before this study. As such we had no control of where the