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Long-lived magnetism on chondrite parent bodies

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ABSTRACT

We present evidence for both early- and late-stage magnetic activity on the CV and L/LL parent bodies respectively from chondrules in Vigarano and Bjurböle. Using micro-CT scans to re-orientate chondrules to their *in-situ* positions, we present a new micron-scale protocol for the paleomagnetic conglomerate test. The paleomagnetic conglomerate test determines at 95% confidence, whether clasts within a conglomerate were magnetized before or after agglomeration, i.e., for a chondritic meteorite whether the chondrules carry a pre- or post-accretionary remanent magnetization. We found both meteorites passed the conglomerate test, i.e., the chondrules had randomly orientated magnetizations. Vigarano's heterogeneous magnetization is likely of shock origin, due to the 10 to 20 GPa impacts that brecciated its precursor material on the parent body and transported it to re-accrete as the Vigarano breccia. The magnetization was likely acquired during the break-up of the original body, indicating a CV parent body dynamo was active ∼9 Ma after Solar System formation. Bjurböle's magnetization is due to tetrataenite, which transformed from taenite as the parent body cooled to below 320 °C, when an ambient magnetic field imparted a remanence. We argue either the high intrinsic anisotropy of tetrataenite or brecciation on the parent body manifests as a randomly orientated distribution, and a L/LL parent body dynamo must have been active at least 80 to 140 Ma after peak metamorphism. Primitive chondrites did not originate from entirely primitive, never molten and/or differentiated parent bodies. Primitive chondrite parent bodies consisted of a differentiated interior sustaining a long-lived magnetic dynamo, encrusted by a layer of incrementally accreted primitive meteoritic material. The different ages of carbonaceous and ordinary chondrite parent bodies might indicate a general difference between carbonaceous and ordinary chondrite parent bodies, and/or formation location in the protoplanetary disk.

1. Introduction

Chondrites formed mainly by accreting up to millimeter-sized chondrules, micrometer-sized fine-grained dust, millimeter-sized calcium-aluminum rich inclusions (CAIs) and opaque phases approximately 4.6 Ga ago (e.g. Scott, 2007; Connelly et al., 2012). Chondrules are thought to have formed in the presence of magnetic fields before accretion of the parent asteroid, and have the potential to record pre-accretionary magnetic remanences that can be used to estimate the role of magnetic fields in early Solar System momentum transport and chondrule formation (Desch et al., 2012; Fu et al., 2014a). However, many primitive and unequilibrated chondritic meteorites show some evidence of secondary alteration on their parent bodies (Butler, 1972; Krot et al., 1995; Gattacceca et al., 2016). Such alteration could have affected the magnetic carriers, thereby resetting or contaminating pre-accretionary magnetizations. It is, therefore, highly important to unequivocally determine whether the chondrules carry a pre- or post-accretionary magnetic remanence, and to determine the origin of remanence in the case of the latter.

The so called 'conglomerate test' (Graham, 1949) is a paleomagnetic test to determine the timing of magnetization for an accreted body, and has been used before in several meteoritic studies, e.g., Allende (CV3) (Butler, 1972; Sugiura et al., 1979; Carporzen et al., 2011; Fu et al., 2014b), Bjurböle (L/LL4) (Strangway and Sugiura, 1982; Wasilewski et al., 2002), and Vigarano (CV3) (Weiss et al., 2010). These studies have found both random and aligned paleomagnetic directions amongst sub-samples, suggesting, in the former, a pre-accretionary remanence, and in the latter, complex parent-body processing. However, there are some inconsistencies:

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for some meteorites both types of magnetization have been reported, e.g., Butler (1972) found a homogeneous magnetization amongst sub-samples of Allende, then Sugiura et al. (1979) found inhomogeneous magnetization and finally Carporzen et al. (2011) again found homogeneous magnetizations. Some of these inconsistencies could lie in the difficulty of performing conglomerate tests on the sub-millimeter scale: sampling, orienting and measuring smaller than standard samples ($\sim$11 cm^3 in terrestrial studies) leads to greater angular-dispersion errors as well as sampling both chondrule and matrix material together into individual samples (Butler, 1972; Strangway and Sugiura, 1982; Böhnel et al., 2009; Böhnel and Schnepp, 2014). Chondrules are particularly small, with volumes of $\sim$0.0005 cm^3. Physical disaggregation and reorientation of individual chondrules from a chondrite by hand is likely to introduce errors that are difficult to quantify and, due to scarcity of material, cannot be reduced by simply measuring more samples as is the case for most terrestrial studies. Gattacceca et al. (2016) were not able to mutually orient their sub-samples of Kaba. Accurate reorientations ($<5°$ error) of chondrule samples have been achieved by working with cut-sections of material (Carporzen et al., 2011; Fu et al., 2014a, 2014b), however these studies worked with sample sections, and not with whole chondrule samples.

Experimental methods that are non-destructive and minimize human error are particularly important when studying the paleomagnetism of meteorites and their constituents. X-ray micro-computed tomography (micro-CT) has been a successful technique for the 3D volumetric non-destructive characterization of meteorites, and is widely being incorporated into the curation procedure for meteorites (e.g., Hezel et al., 2013a; Smith et al., 2013; Zeigler et al., 2015). In this paper we report a new sub-millimeter-scale method for the paleomagnetic conglomerate test that uses x-ray micro-computed tomography (micro-CT) images with the aid of computer software to rotate the *ex-situ* chondrules to their *in-situ* positions, allowing their paleodirections to be determined at an accuracy equal to that of routine terrestrial paleomagnetic measurements. We have developed and applied this technique on chondrules from two meteorites: Bjurböle (L/LL4) and Vigarano (CV3). For these two meteorites we have determined the relative orientation of the remanent magnetization of their constituent chondrules.

2. Samples

The bulk samples from which chondrules were extracted were 686 mg of Bjuböle and 405 mg of Vigarano. To avoid contamination of the magnetization during atmospheric entry of the meteorite, both samples were taken from their interiors, with no fusion crust present. Bjurböle is an ordinary chondrite (L/LL4) that fell in Bjurbdle Borga, Nyland, Finland in 1899, with a 330 kg approximate recovered weight (Grady, 2000). Bjurböle was selected for this study due to its friability, which allows chondrules to be easily disaggregated. Chondrule abundance in Bjurböle is about 66 vol.% and their median diameter is 0.688 $\pm$ 0.003 mm (Hughes, 1978). Vigarano is a carbonaceous chondrite (CV3) that fell in the Emilia-Romagna region of Italy in 1910 with a total recovered mass of 15 kg (Grady, 2000).

2.1. Magnetic carriers of the Bjurböle chondrules

The dominant magnetic mineral in Bjurböle chondrules has been reported as tetrataenite, a magnetically hard mineral, with a high coercivity of up to 600 mT (Wasilewski, 1988). Coercivity can be directly related to paleomagnetic stability; therefore, Bjurböle's tetrataenite phase is unlikely to have acquired a magnetic overprint since its formation. Tetrataenite transformed from taenite during cooling to below 320 °C on the parent body, so any remanent magnetization it carries will have originated from cooling to below 320 °C (Gattacceca et al., 2014). Transmission electron microscope (TEM) observations of equilibrated ordinary chondrites found the tetrataenite occurring in plessite grains consisting of $>$1 μm tetrataenite in a kamacite matrix and a high-coercivity cloudy zone of 25–250 nm tetrataenite in zoned taenite, with a rim of 1–14 μm tetrataenite grains (Uehara et al., 2011). The disordering of tetrataenite to taenite upon heating above 320 °C has been thoroughly investigated experimentally by Dos Santos et al. (2015); our sample was not thermally demagnetized to prevent this. The presence of tetrataenite also indicates the meteorite did not undergo heating to greater than 320 °C after peak metamorphism (Collinson, 1989).

Uehara et al. (2011) reported tetrataenite in the cloudy zone of individual taenite grains have homogeneous crystallographic orientations; the crystallographic orientation of tetrataenite is significant, as tetrataenite has such a strong magnetocrystalline anisotropy that can result in remanence directions that can diverge by up to 90° from the paleofield direction (Collinson, 1989). In a general conglomerate test, divergence of greater than 90° from a paleofield direction would usually suggest post-metamorphic brecciation of Bjurböle. It is expected that tetrataenite would carry no remanent magnetization if the transformation occurred under zero-field conditions (Uehara et al., 2011). If the transformation occurred in the presence of a magnetic field, the tetrataenite may carry a phase transformation remanent magnetization (PhTRM) due to the bias field (Bryson et al., 2014). The dynamics and length-scales of PhTRM acquisition in tetrataenite are uncertain, however, and alignment of the remanence to the crystallographic axes may result in scatter of the recorded paleodirections (Gattacceca et al., 2014; Bryson et al., 2014).

2.2. Magnetic carriers of the Vigarano chondrules

The magnetic mineralogy of the chondrules in Vigarano is largely Fe–Ni metal in the form of kamacite, and the matrix is magnetically dominated by magnetite (Brecher and Arrhenius, 1974). Vigarano is believed to be a regolith breccia of the CV chondrite parent body (Kojima et al., 1993; Bischoff et al., 2006) having originated from an aqueously altered precursor chondrite that was subject to impacts of 10 to 20 GPa and transported to re-accrete as Vigarano (Jogo et al., 2009). Vigarano likely underwent its secondary accretion in an anhydrous environment, so a second phase of aqueous alteration is ruled out (Krot et al., 2000; Tomeoka and Tanimura, 2000). The aqueous alteration product fayalite has been $^{53}Mn/^{53}Cr$ dated by Jogo et al. (2009) and recalibrated by Doyle et al. (2016) to date the alteration as 4563 Ma ago and brecciation of the precursor chondrite approximately 5 Ma later. There is petrographic evidence for peak metamorphic temperatures of 400–500 °C (Lee et al., 1996), which could have resulted in a partial thermoremanent magnetization (pTRM) in the presence of a bias field. These secondary alterations occurred prior to the final accretion of the Vigarano breccia (Jogo et al., 2009), so would not be evident in a conglomerate test as a homogeneous magnetization. As Vigarano underwent at least two accretions on the parent body 4565 and 4558 Ma ago (see Fig. 7 of Jogo et al., 2009), both, parent body alteration prior to final accretion and a retained Solar Nebula remanence would be manifested as a random distribution. A shock remanent magnetization (SRM) is most likely the origin of remanence in Vigarano, considering its 10 to 20 GPa impact history during brecciation. SRM can be identified by stable and efficient AF (alternating field) demagnetization (Funaki and Syono, 2010; Gattacceca et al., 2010; Tikoo et al., 2015), and if induced during brecciation of the precursor chondrite, it would likely be observed as a random distribution by the conglomerate test due to the