Available online at www.sciencedirect.com

ScienceDirect

Geochimica et Cosmochimica Acta 177 (2016) 254–274

Geochimica et Cosmochimica Acta

www.elsevier.com/locate/gca

Chemical evidence for differentiation, evaporation and recondensation from silicate clasts in Gujba

Jonathan Oulton[a], Munir Humayun[a,*], Alexei Fedkin[b], Lawrence Grossman[b,c]

[a] National High Magnetic Field Laboratory & Department of Earth, Ocean and Atmospheric Science, Florida State University, Tallahassee, FL 32310, USA
[b] Department of the Geophysical Sciences, The University of Chicago, Chicago, IL 60637, USA
[c] Enrico Fermi Institute, The University of Chicago, Chicago, IL 60637, USA

Received 21 June 2015; accepted in revised form 14 January 2016; available online 23 January 2016

Abstract

The silicate and metal clasts in CB chondrites have been inferred to form as condensates from an impact-generated vapor plume between a metal-rich body and a silicate body. A detailed study of the condensation of impact-generated vapor plumes showed that the range of CB silicate clast compositions could not be successfully explained without invoking a chemically differentiated target. Here, we report the most comprehensive elemental study yet performed on CB silicates with 32 silicate clasts from nine slices of Gujba analyzed by laser ablation inductively coupled plasma mass spectrometry for 53 elements. Like in other studies of CBs, the silicate clasts are either barred olivine (BO) or cryptocrystalline (CC) in texture. In major elements, the Gujba silicate clasts ranged from chondritic to refractory enriched. Refractory element abundances ranged from 2 to 10 × CI, with notable anomalies in Ba, Ce, Eu, and U abundances. The two most refractory-enriched BO clasts exhibited negative Ce anomalies and were depleted in U relative to Th, characteristic of volatilization residues, while other BO clasts and the CC clasts exhibited positive Ce anomalies with excess U (1–3 × CI), and Ba (1–6 × CI) anomalies indicating recondensation of ultra-refractory element depleted vapor. The Rare Earth Elements (REE) also exhibit light REE (LREE) enrichment or depletion in several clasts with a range of $(La/Sm)_{CI}$ of 0.9–1.8. This variation in the LREE is essentially impossible to accomplish by processes involving vapor–liquid or vapor–solid exchange of REE, and appears to have been inherited from a differentiated target. The most distinctive evidence for inherited chemical differentiation is observed in highly refractory element (Sc, Zr, Nb, Hf, Ta, Th) systematics. The Gujba clasts exhibit fractionations in Nb/Ta that correlate positively with Zr/Hf and span the range known from lunar and Martian basalts, and exceed the range in Zr/Hf variation known from eucrites. Variations of highly incompatible refractory elements (e.g., Th) against less incompatible elements (e.g., Zr, Sr, Sc) are not chondritic, but exhibit distinctly higher Th abundances requiring a differentiated crust to be admixed with depleted mantle in ratios that are biased to higher crust/mantle ratios than in a chondritic body. The possibility that these variations are due to admixture of refractory inclusion-debris into normal chondritic matter is raised but cannot be definitively tested because existing “bulk” analyses of CAIs carry artifacts of unrepresentative sampling. The inferences drawn from the compositions of Gujba silicate clasts, here, complement what has been inferred from the compositions of metallic clasts, but provide surprisingly detailed insight into the structure of the target. Evidence that metal and silicate in CB chondrites both formed from impact-generated vapor plumes, taken together with recent work on metallic nodules in E chondrites, and on ordinary chondrites, indicates that chondrule formation occurs by this mechanism quite widely. However, the nature of

---

* Corresponding author.
E-mail addresses: jjo11d@my.fsu.edu (J. Oulton), humayun@magnet.fsu.edu (M. Humayun), avf@uchicago.edu (A. Fedkin), yosi@uchicago.edu (L. Grossman).

http://dx.doi.org/10.1016/j.gca.2016.01.008

the impact on the CB body is quite different than the popular conceptions of impact of partially or wholly molten chondritic bodies and the younger (5 Ma) age of CB chondrules is consistent with origin in a disk with more evolved targets and impactors gravitationally perturbed by nascent planets.

1. INTRODUCTION

The heat source for the origin of chondrules has proven elusive (Zanda, 2004), but might include nebular shocks (Desch and Connolly, 2002; Morris and Desch, 2010) or protoplanetary impacts of partially differentiated bodies (Zook, 1981; Sanders, 1996; Chen et al., 1998; Lugmair and Shukolyukov, 2001; Krot et al., 2005; Hevey and Sanders, 2006; Asphaug et al., 2011), or even a hybrid model (Ruzicka, 2012). An impact origin of chondrules is receiving increasing attention (Asphaug et al., 2011; Sanders and Scott, 2012). Chronologic constraints indicate that chondrules may have formed ~2 Ma after CAIs (e.g., Amelin et al., 2002), contemporaneously with or later than the earliest differentiated bodies (Kleine et al., 2009). Paleomagnetic observations on chondrites (Carpozen et al., 2011) have led to models of partially differentiated chondrite parent bodies (Elkins-Tanton et al., 2011) that, on impact disruption, could lead to the release of abundant molten droplets (Asphaug et al., 2011). Meteoritic constraints implying an impact origin for chondrules include the Fa-content of ordinary chondrite chondrules (Fedkin et al., 2012), sodium retention during chondrule melting (Fedkin and Grossman, 2013) and differentiated siderophile element patterns in metal-sulfide-silicate assemblages in enstatite chondrites (van Niekirk et al., 2009; Horstmann et al., 2014). Among the carbonaceous chondrites, the CB chondrites have attracted the most attention as potential products of protoplanetary impacts (Kallemeyn et al., 1978; Wasson and Kallemeyn, 1990; Krot et al., 2001b, 2005; Campbell et al., 2002, 2005; Rubin et al., 2003; Fedkin et al., 2015).

CB chondrites are a group of metal-rich carbonaceous chondrites (Krot et al., 2002) that are characterized petrographically by rounded barred olivine (BO) and cryptocrystalline (CC) silicate clasts, abundant Fe–Ni metal spheroids, and a dark silicate matrix containing both brecciated clast material and veins of shock-impact melt (Weisberg and Kimura, 2010). Elemental studies have shown that CBs are severely depleted in volatile elements and enriched in refractory elements (Kallemeyn et al., 1978; Krot et al., 2001a; Campbell et al., 2002; Rubin et al., 2003). CBs contain isotopically heavy nitrogen (Prombo and Clayton, 1985; Franchi et al., 1986; Sugiura et al., 2000), which together with oxygen isotopic studies have revealed a potential genetic link between CBs and CR/CH chondrites (Weisberg et al., 1990; Krot et al., 2002). The CB chondrites are further classified into two subgroups (Weisberg et al., 2001). Meteorites of the CB_a subgroup include Bencubbin, Gujba, Weatherford, etc., which contain ~40 vol% silicate clasts, ~50 vol% metal, and ~10 vol% matrix, and clast size ranges from millimeters to centimeters. Silicate clasts are FeO-poor, metals contain 5–8 wt% Ni, and the bulk chondrites exhibit $\delta^{15}N$ up to +1000 ‰. Meteorites of the CB_b subgroup include QUE94411, Hammadah al Hamra (HaH) 237, etc., which contain ~30 vol% silicate clasts, ~70 vol% metal, and <5 vol% matrix, and clast sizes are constrained to millimeter-scale. Metals contain 4–15 wt% Ni, and bulk $\delta^{15}N$ is up to +200 ‰ (Weisberg et al., 2001). Additionally, CB_b metal grains containing >7–8 wt% Ni are chemically zoned in Ni, Co and refractory PGEs (decreasing core-rim), and Cr (increasing core-rim) (Meibom et al., 2000; Campbell et al., 2001, 2002, 2005).

Siderophile element studies of the large metal clasts in Gujba and other CB_a's showed that Pd behaved more like a refractory element (e.g., Ir) than like Fe, which occurs only at high temperatures and at pressures well above canonical nebular conditions requiring condensation of the metal from an impact-induced vapor plume (Campbell et al., 2002; Fedkin et al., 2015). Other evidence, including the chondritic Ni-Co systematics of the metal, has been cited that supports that CBs or some of their components originated by condensation from the solar nebula (Newsom and Drake, 1979; Weisberg et al., 1990, 2001). The relationship between the metal and silicate clasts is unclear since the silicate clasts have virtually no metal and there are no isotopic clues that have been able to link the two types of clasts in CBs. Krot et al. (2001a) described the major element and rare earth element (REE) abundances in silicate clasts from CB_b chondrites. They reported two types of chondrules: those with barred olivine (BO) texture were enriched in Ca, Al and REE, and those with cryptocrystalline (CC) texture were chondritic to depleted in Ca, Al and REE. These distinct chemical and textural relations were interpreted to originate by fractional condensation from an impact plume (Krot et al., 2001b, 2005).

Fedkin et al. (2015) developed a model for condensation from an impact plume following Campbell et al. (2002) and Krot et al. (2001b, 2005) that explained the available constraints on metal and on silicate clasts in CBs. Their study found that the composition of the silicate clasts reported by Krot et al. (2001a) could not be explained by fractional condensation. To successfully model the observed compositions of CB chondrules, Fedkin et al. (2015) required condensation from an impact on a target differentiated into crust and mantle. Such an inherited crustal differentiation should leave distinct chemical effects in the compositions of CB silicate clasts or chondrules. The present study tests the viability of the premises of Fedkin et al. (2015) by analyzing chemical abundances in silicate clasts from the Gujba CB_a chondrite. With the exception of the study by Krot et al. (2001a) that reported major elements and REE for CB_b clasts, we are aware of only one chemical analysis of