

VARIATIONS IN OXYGEN-ISOTOPE COMPOSITIONS OF THE GASEOUS RESERVOIR DURING FORMATION OF TYPE-I AND TYPE-II CHONDRULES IN CR CARBONACEOUS CHONDRITES. D. L. Schrader*, K. Nagashima, and A. N. Krot. HIGP/SOEST, University of Hawai'i at Mānoa, Honolulu, HI 96822, USA. *schrader@higp.hawaii.edu.

Introduction: The O-isotope compositions of chondrule silicates resulted from melting of isotopically diverse precursors and O-isotope exchange of chondrule melts with an ambient nebular gas [e.g., 1–6]. Neither the compositions of the chondrule precursors nor of the nebular gas are well constrained. *In situ* O-isotope measurements of chondrule phenocrysts in the CVs, COs, and Acfer 094 (ungrouped) suggest their chondrules recorded exchange with isotopically distinct gaseous reservoirs [7–9]. Schrader et al. [6] concluded that type-I and type-II porphyritic chondrules from CR chondrites experienced O-isotope exchange with a compositionally similar gaseous reservoir and the differences in $\Delta^{17}\text{O}$ between these chondrule types (Fig. 1) mainly reflect a different degree of O-isotope exchange they underwent with this reservoir [6]. Since barred olivine (BO) chondrules experienced a higher degree of melting than porphyritic chondrules [e.g., 7, 9–11], their O-isotope composition may be closer to the O-isotope composition of the nebular gas with which they exchanged [e.g., 9, 12–14]. Here, we report on the *in situ* O-isotope measurements of type-I and type-II BO chondrules from CR chondrites to estimate the O-isotope compositions of the nebular gas in the CR chondrule-forming region.

Samples and analytical procedures: The mineralogy and O-isotope compositions of olivine grains in 7 type-I and 4 type-II BO chondrules from the CR chondrites Gao-Guenie (b), GRA 95229, PCA 91082, and Shisr 033 were studied with the UH JEOL JXA 8500F field emission electron microprobe and Cameca ims-1280 ion microprobe, respectively (for details see [6]).

Results: Oxygen-isotope compositions of olivine grains in the CR type-I BO chondrules plot in the field of olivine phenocrysts from the CR type-I porphyritic chondrules; the former, however, show a smaller range of $\Delta^{17}\text{O}$ values ($\sim 2.5\text{‰}$) (Fig. 1). Compositions of olivine grains within each chondrule are homogeneous.

Oxygen-isotope compositions of most olivine grains in the CR type-II BO chondrules plot in the field of olivine phenocrysts from the CR type-II porphyritic chondrules; they are systematically ^{16}O -depleted relative to olivine grains from the type-I BO chondrules (Fig. 1). Compositions of olivine grains within each chondrule are homogeneous. The only exception are olivine grains in Ch3 from PCA 91082 that have a similar $\Delta^{17}\text{O}$ value ($\sim 0\text{‰}$) but show a wide range of $\delta^{18}\text{O}$ values ($\sim 3.0\text{‰}$).

Discussion: Olivine grains in type-I and type-II BO chondrules from CR chondrites have similar O-isotope

compositions to those of olivine phenocrysts from their porphyritic counterparts (Fig. 1a), suggesting that BO and the relict-free porphyritic chondrules experienced similar degrees of O-isotope exchange with an ambient gas. The O-isotope compositions of type-I and type-II BO chondrules, however, are distinct (Fig. 1): the $\Delta^{17}\text{O}$ values of type-I BO chondrules range from $-3.4 \pm 0.3\text{‰}$ (weighted mean ± 2 standard error (SE)) to $-1.6 \pm 0.3\text{‰}$, and of type-II BO chondrules from $-0.7 \pm 0.3\text{‰}$ to $0.6 \pm 0.3\text{‰}$. These observations may indicate that type-I and type-II BO chondrule precursors had different O-isotope compositions and/or they experienced exchange with isotopically distinct gaseous reservoirs. This interpretation is consistent with the resolvable differences in O-isotope compositions of olivine phenocrysts among isotopically uniform individual type-I and type-II chondrules (Fig. 1).

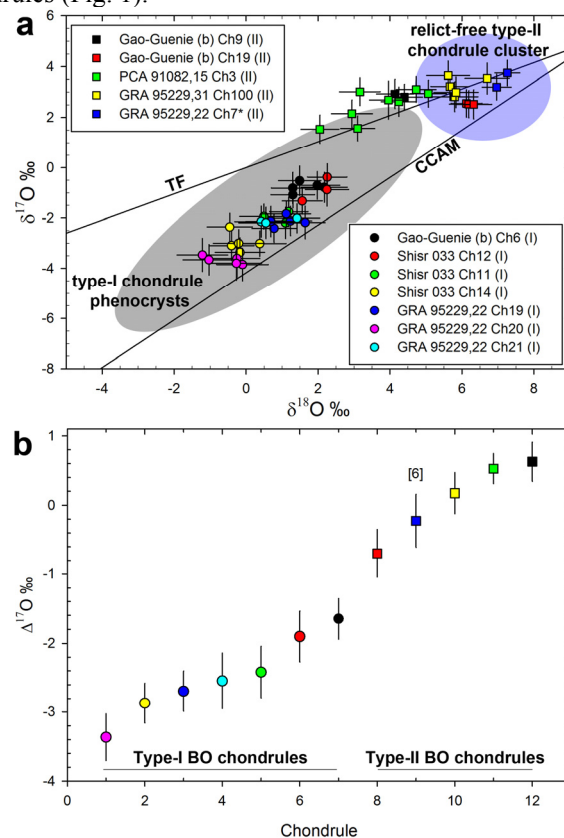


Fig. 1. Three-isotope oxygen diagram (a) and weighted mean of $\Delta^{17}\text{O}$ values (b) of olivine phenocrysts from the CR type-I and type-II BO chondrules. Ranges of O-isotope compositions of olivine phenocrysts from type-I and type-II porphyritic chondrules, and *, are from [6]. Errors are 2SD in (a) and 2SE in (b).

Extrapolation of experimental work to conditions relevant to chondrule formation suggests that a degree of O-isotope exchange between the chondrule melts and the surrounding nebular gas could have been ~50% [15]. Theoretical modeling of O-isotope exchange between the chondrule melts and the nebular gas indicates the degree of O-isotope exchange depends on the amount of O in the gas relative to that in silicate dust in the chondrule-forming region [16]. The O-isotope compositions and fayalite contents of chondrule olivine appear to be related, suggesting both could have been controlled by the $\text{H}_2\text{O}/\text{H}_2$ ratio in the surrounding nebular gas [5, 6].

To estimate the O-isotope composition of the nebular gas in the formation region of the CR type-I porphyritic and BO chondrules having an average $\Delta^{17}\text{O}$ value of -3‰ (this study, [6]), we assume an average $\Delta^{17}\text{O}$ value of their precursors to be ~-6‰ [5, 6, 17] and two values of an exchange degree with the gas, 50% and 75%. This results in an estimated $\Delta^{17}\text{O}$ value of the nebular gas between -2‰ to 0‰.

The observations that relict magnesian olivine grains in CR type-II chondrules have O-isotope compositions similar to olivine phenocrysts in the CR type-I chondrules [3, 6], and the existence of type-II-like ferroan igneous rims around some type-I porphyritic chondrules in CR chondrites [17] indicate that type-II chondrule precursors may have consisted of a mixture of type-I chondrules or chondrule fragments and finer-grained materials of unknown O-isotope composition. We assume that an average $\Delta^{17}\text{O}$ value of the CR type-II chondrule precursors is similar to an average $\Delta^{17}\text{O}$ value of the CR type-I chondrules (-3‰; this study, [6]). The final O-isotope composition of type-II chondrules is assumed to be ~0‰, which represents an average value of the relict-free CR type-II chondrules [6] and type-II BO chondrules (this study). As for type-I chondrules, two values of an exchange degree with the gas are considered, 50% and 75%. We estimate $\Delta^{17}\text{O}$ value of the nebular gas during formation of the CR type-II chondrules to be ~+1‰ to +3‰.

Therefore, type-I and type-II chondrules in CR chondrites may have experienced exchange with isotopically slightly distinct gaseous reservoirs. This is consistent with the inferred higher $\text{H}_2\text{O}/\text{H}_2$ ratio in the formation region of type-II chondrules compared to the formation region of type-I chondrules [6, 18] and the apparently ^{16}O -depleted compositions of the nebular water compared to the silicate dust [e.g., 19 and references therein].

It is generally accepted that accretion of chondrite parent asteroids occurred rapidly after chondrule formation [e.g., 20] and that aqueously altered chondrites ac-

creted water ices together with anhydrous chondrules and matrices. The CR chondrites are known to have experienced aqueous alteration on their parent asteroid [e.g., 21]. Therefore, O-isotope compositions of the CR secondary minerals that precipitated from an aqueous solution (e.g., carbonates and magnetite) can be used to constrain $\Delta^{17}\text{O}$ value of water ice that accreted into the CR chondrite parent asteroid, if O-isotope exchange between the solutions and the anhydrous silicates was insignificant. The inferred near terrestrial $\Delta^{17}\text{O}$ value of the nebular gas in the CR chondrule-forming region is generally consistent with $\Delta^{17}\text{O}$ values of the CR carbonates (~0‰) [22].

Mass-dependent fractionation of O-isotopes in chondrules has been explained by evaporation and recondensation [4, 14]. A high abundance of O in the gas relative to that in silicate dust may suppress mass-dependent fraction by efficient exchange with the ambient gas [16]. This is consistent with mass-dependent fractionation being observed in type-I chondrules (i.e., forming under reducing conditions/relatively low $\text{H}_2\text{O}/\text{H}_2$ ratios) [4, 14]. The mass-dependent fractionation observed in Ch3 from PCA 91082 is intriguing (Fig. 1a), since it is FeO-rich and likely formed under similar $\text{H}_2\text{O}/\text{H}_2$ ratios as other type-II chondrules in the CR chondrites (i.e., ~ (230–740)×solar vs. ~ (10–100)×solar for type-I chondrules; [6]). It is also the most unequilibrated (i.e., $\text{Fa}_{36.3-73.6}$) type-II BO chondrule observed here. These observations may suggest Ch3 cooled too rapidly to efficiently exchange with the nebular gas [e.g., 11, 16].

References: [1] Krot et al. 2006. *GCA* 70:767. [2] Libourel et al. 2006. *EPSL* 251:232. [3] Connolly and Huss 2010. *GCA* 74:2473. [4] Kita et al. 2010. *GCA* 74:6610. [5] Tenner et al. 2012. *LPSC XLIII*, #2127. [6] Schrader et al. 2013. *GCA* 101:302. [7] Rudraswami et al. 2011. *GCA* 75:7596. [8] Ushikubo et al. 2012. *GCA* 90:242. [9] Tenner et al. 2013. *GCA* in press. [10] McSween. 1985. *Meteoritics* 20:523. [11] Hewins et al. 2005. In *Chondrules and Protoplanetary Disk*, 286. [12] Clayton et al. 1983. In *Chondrules and their Origins*, 37. [13] Chaussidon et al. 2008. *GCA* 72:1924. [14] Weisberg et al. 2011. *GCA* 75:6556. [15] Yu et al. 1995. *GCA* 59:2095. [16] Nagahara and Ozawa 2012. *MAPS* 47:1209. [17] Nagashima et al. 2013. *LPSC XLIV*, this volume. [18] Fedkin et al. 2012. *GCA* 87:81. [19] Zolensky et al. 2008. In *Oxygen in the Solar System, Rev. Mineral. Geochem.* 68:429. [20] Alexander et al. 2008. *Science* 320:1617. [21] Brearley. 2006. *MESS II*:584. [22] Tyra et al. 2011. *LPSC XLII*, #1639.

Acknowledgements: The authors thank the JSC and the MWG for samples. We would also E. Hellebrand and J. Davidson for analytical assistance and helpful discussions. This research was funded by NASA Grant NNX10AH76G (ANK, PI).