
Introduction: The Renazzo-like carbonaceous (CR) chondrites cover a wide range of aqueous alteration, from minimal (QUE 99177) to extensive (GRO 95577) [e.g., 1–4]. Due to its higher surface area to volume ratio, fine-grained anhydrous matrix aequously alters to secondary minerals (e.g., phyllosilicates, oxides, sulfates, and carbonates) more readily than larger components such as chondrule phenocrysts [e.g., 1,5,6]. Since matrix is generally the second most abundant component in the CR chondrites, after type I chondrules [e.g., 1,4], its composition significantly influences the whole-rock O-isotope composition of a sample. While the CR chondrites record a wide range of aqueous alteration [e.g., 1–4], the matrix O-isotope composition of only four CR chondrites has been determined [7]. We aim to determine the O-isotope composition of CR chondrite matrix across the whole range of aqueous alteration to determine: (1) the anhydrous composition of the matrix that accreted with the CR chondrite parent asteroid, and (2) the influence of aqueous alteration on matrix O-isotope compositions.

Samples and analytical procedures: The O-isotope compositions of 14 CR chondrite matrix separates (Dhofar 1432, EET 87770, Gao-Guenie (b), GRO 06100, GRO 03116, LAP 02342, LAP 04720, MET 00426, MIL 07525, MIL 090292, MIL 090657, NWA 6957, QUE 99177, and Y-793495) and four CR chondrite whole-rock samples (MIL 07525, MIL 090292, MIL 090657, and NWA 6957) were determined at the Open University using an infrared laser fluorination system [8]. Whole-rock sample chips (50–175 mg) were crushed/homogenized and ~2 mg aliquots were used for analysis. Due to the difficulty of obtaining clean matrix separates the amount of material available was limited (generally >10 mg per meteorite). Some of the matrix samples were not homogenized and instead two replicates of ~2 mg per sample were run using untreated material; the mean is reported here (Figs. 1,2). System precision for samples containing low temperature mineral assemblages such as aequously altered carbonaceous chondrites are typically ±0.2‰ for δ¹⁸O; ±0.4‰ for δ¹⁷O; ±0.1‰ for Δ¹⁸O (2σ).

Results: The O-isotope compositions of CR chondrite matrix plot near the CR-mixing line (Fig. 1) [1,4,7]. A linear least squares fit for the CR matrix data of this study (14 samples) on a three-isotope plot yields δ¹⁷O = (0.80±0.08) x δ¹⁸O – 2.74±0.22 with R² = 0.977 (errors given are 2σ, R = correlation coefficient). In comparison, a linear least squares fit for the CR whole rock data (20 samples; [4], this study) gives δ¹⁷O = (0.69±0.04) x δ¹⁸O – 2.32±0.09 with R² = 0.982. The O-isotope composition of CR chondrite matrix measured here ranges from −5.2‰ to 6.1‰ in δ¹⁸O, and −7.3‰ to 1.6‰ in δ¹⁷O (Fig. 1). The matrix separates, relative to their corresponding whole-rock values [4, this study], are ¹⁶O-enriched for Dhofar 1432, Gao-Guenie (b), MET 00426, MIL 090292, MIL 090657, and QUE 99177, and ¹⁶O-depleted for EET 87770, GRO 06100, GRO 03116, LAP 02342, LAP 04720, MIL 07525, NWA 6957, and Y-793495 (Fig. 2).

Discussion: The O-isotope compositions of CR chondrite matrix range in δ¹⁸O by ~11‰ and δ¹⁷O by ~9‰ in this study. The O-isotope composition of CR matrix is not always ¹⁶O-depleted relative to the whole-rock value, in contrast to previous work [7]. This is likely due to multiple factors: (1) whole-rock O-isotope compositions are likely dominated by highly abundant type I chondrules [1,4], and may not adequately reflect aqueous alteration; (2) as many CR chondrites are minimally aequously altered [3,4] the matrix is mostly anhydrous and records its initial O-isotope composition (i.e., ¹⁶O-enriched); and (3) as the CR chondrites are brecciated [e.g., 9] matrix likely contains minor amounts of ¹⁶O-depleted rock fragments such as type II chondrules [10,11] and dark inclusions [e.g., 1], and ¹⁶O-enriched rock fragments such as type I chondrules [e.g., 11–13] and refractory inclusions [14]. Although, if matrix samples were dominated by refractory inclusions or chondrule fragments, they would plot along the CCAM or a slope 1 [11,13] line, respectively; which they do not (Figs.

Figure 1. O-isotope composition of CR whole-rock and matrix separates [4, this study]; phenocrysts [10–13].
1,2). Therefore these fragments are likely a minor component, and as they also occur normally in chondritic matrix (i.e., due to collisions during chondrule formation, accretion, and on the parent asteroid) their contribution is not considered a contaminant. Therefore, the O-isotope composition of the matrix is considered an average value of isotopically diverse components.

![Figure 2](image)

**Figure 2.** O-isotope compositions of CR whole-rock and matrix separate pairs [4, this study].

The whole-rock and matrix O-isotope compositions of QUE 99177 are the most 18O-enriched among CR chondrites (Fig. 2) [1,4,7]. QUE 99177 matrix is more 16O-enriched than type I chondrule phenocrysts (Fig. 1), indicating a distinct component. Therefore, despite showing some evidence for aqueous alteration [e.g., 3,6], the matrix O-isotope composition of QUE 99177 (δ18O = −5.2‰, δ16O = −7.3‰) is the best approximation of the primary anhydrous composition of matrix that accreted with the CR chondrite parent asteroid.

A key requirement of the hydration model of [7] is that the matrix O-isotope composition of an aqueously altered carbonaceous chondrite is more 16O-depleted than that of its whole-rock value due to hydration by 16O-depleted water [4,7,11]. This is the case for samples studied by [7] and some samples studied here. However, the matrix compositions of six CR chondrites studied here are 16O-enriched relative to their measured whole-rock compositions (Fig. 2). The hydration model of [7] predicts that these samples are not aqueously altered. However, that is not the case as even QUE 99177 shows evidence for aqueous alteration [e.g., 3,6]. Therefore, more work is needed to determine the implications of this data on the hydration model of [7].

Regardless, assuming that the O-isotope composition of QUE 99177 matrix is a reasonable approximation of the anhydrous component of all CR chondrite matrix, we propose that the degree of matrix aqueous alteration can be approximated by the degree of 16O-depletion relative to the ‘anhydrous’ matrix.

**Conclusions:** The O-isotope composition of anhydrous CR matrix is now constrained, with QUE 99177 providing the most accurate estimate. As a result of its fine-grained nature, matrix is particularly susceptible to aqueous alteration and is therefore a more sensitive indicator of aqueous alteration than whole-rock O-isotope analyses. The wide range of aqueous alteration experienced by the CR chondrites [1–7] provides intriguing insight into the range of fluid conditions present on a single asteroid.


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