

The GRO 95577 CR1 chondrite and hydration of the CR parent body

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Abstract—We carried out a petrologic and instrumental neutron activation analysis (INAA) whole chondrite compositional study of Grosvenor Mountains (GRO) 95577. GRO 95577 has many petrological similarities to the CR chondrites. Although the INAA data show patterns indicative of terrestrial weathering, some of the elemental abundances are consistent with a relationship to CR chondrites. The oxygen isotopic composition of GRO 95577 plots close to the Renazzo CR chondrite on the three-isotope diagram. However, GRO 95577 is remarkable in that the chondrules are completely hydrated, consisting almost entirely of phyllosilicates, magnetite, and sulfides. Although GRO 95577 is completely hydrated, the initial chondrule textures are perfectly preserved. The chondrules are in sharp contact with the matrix, their fine-grained rims are clearly visible, and the boundaries of the dark inclusions can be easily discerned. Many chondrules in GRO 95577 have textures suggestive of type I chondrules, but the phenocrysts have undergone perfect pseudomorphic replacement by yellow to brownish serpentine-rich phyllosilicate, with sharp original crystal outlines preserved. The chondrule mesostasis is a green aluminous chlorite-rich material, most likely a hydration product of the feldspathic mesostasis commonly found in anhydrous type I chondrules. Some chondrules contain magnetite spheres, most likely formed by oxidation of metal. We propose that GRO 95577 be classified as a CR1 chondrite, making it the first known CR1 chondrite and expanding the range of alteration conditions on the CR parent body.

INTRODUCTION

There are two intriguing characteristics of Grosvenor Mountains (GRO) 95577 that led to the initiation of this study. 1) GRO 95577 was initially described as a highly altered C2 chondrite consisting of large chondrules (up to 1.8 mm in diameter), made up almost entirely of serpentine (Mason 1997), and 2) its oxygen isotopic composition ($\delta^{18}\text{O} = 6.32$, $\delta^{17}\text{O} = 2.83$) plots close to the Renazzo CR chondrite ($\delta^{18}\text{O} = 6.25$, $\delta^{17}\text{O} = 2.29$) on the three-isotope diagram (Clayton and Mayeda 1999). Thus, it appears to be related to the CR chondrites, but is more heavily hydrated than any other CR chondrite. It therefore has potential for extending the range of alteration recorded in the CR chondrites and furthering our understanding of the alteration history of the CR chondrite parent body. Additionally, the high degree of hydration of GRO 95577, combined with a high degree of preservation of its primary chondrule-matrix texture is a striking aspect that warrants documentation and investigation.

This is a report of our petrologic and whole rock chemistry study of GRO 95577. The goals are to survey its characteristics, determine its classification and relationships to the CR chondrites, and decipher information about the degree of hydration and alteration environment of the CR parent body. We show that GRO 95577 is unique among the CR chondrites in its degree of hydration and pseudomorphic replacement textures, and therefore should provide further information on the alteration of small, asteroidal-size bodies. We explore its classification as a CR1 chondrite.

METHODS

Thin section GRO 95577,11 was documented with transmitted light photomicrographs and backscattered electron (BSE) images using the Hitachi S4700 field emission gun scanning electron microscope (FEG-SEM) equipped with a PGT EDS. Mineral analyses were carried out using a Cameca SX100 electron microprobe. Natural and synthetic standards were chosen based on the compositions of the

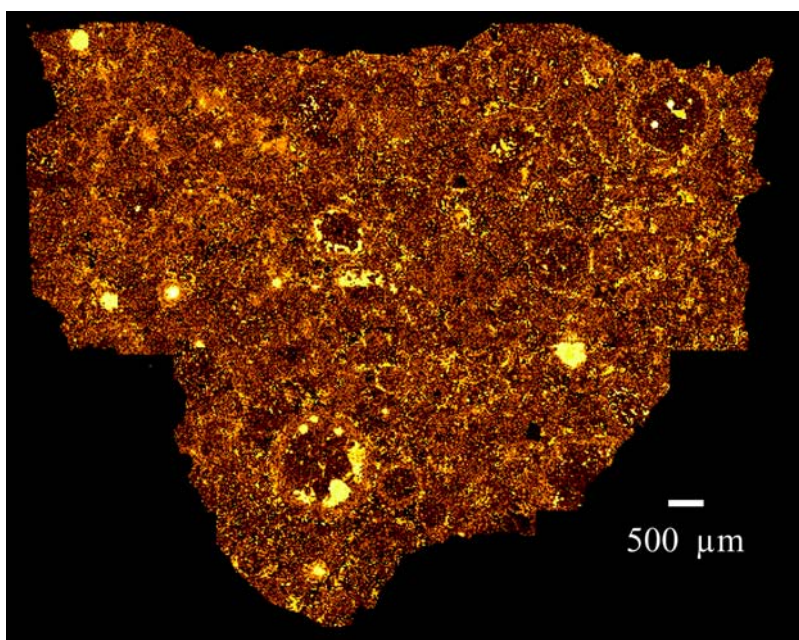


Fig. 1. Fe K α X-ray map of polished thin section GRO 95577, 11. Section shows large chondrules that range in size up to 1.8 mm. The silicates in all chondrules have been altered to phyllosilicates. Bright white areas are Fe-Ni metal, most of which has been altered to magnetite (bright yellow). The large chondrules appear to have been metal-rich, containing large round metal blebs, similar to chondrules in the CR chondrites (e.g., Weisberg et al. 1993).

minerals being analyzed. Silicate compositions were acquired using an accelerating potential of 15 keV and a sample current of 20 nA. Metal compositions were determined using operating conditions of 20 keV and 25 nA. Counting times were 20 s on peak and 10 s on background (off-peak) spectrometer positions. Based on counting statistics, relative uncertainties (2σ) for major elements (Si, Fe, Mg) are estimated to be <2%, and for Ti, Cr, Mn, and Ca they are estimated to be 10%, 10%, 9%, and 5%, respectively. Data reductions were carried out using methods described by Pouchou and Pichoir (1991). The Cameca SX100 was also used to collect K α X-ray maps of Fe (e.g., Fig. 1) as well as other elements (Si, Mg, S, Ni). Dwell time used was 50 ms.

To determine the whole chondrite composition of GRO 95577, we ran triplicate analysis of INAA, both with short (1 min) and long (3 h) irradiations. Repeated INAA analysis not only reduces the analytical uncertainties due to the sampling procedure, but also helps in distinguishing weather patterns from genuine differences in carbonaceous chondrite finds. The samples were irradiated at the TRIGA Mark I reactor of the University of California, Irvine with a neutron flux of 1.8×10^{12} neutrons $\text{cm}^{-2} \text{s}^{-1}$. Sample masses were 104 mg, 161 mg, and 288 mg respectively, and were cut into rectangular blocks 3 mm thick. Standards included the Allende meteorite (Jarosewich et al. 1987), the USGS international reference materials granite G-2 and BHVO-1 (Govindaraju 1994), and elemental solutions pipetted onto MgO (for Os, Ir, Au, and Ru). Analyses were performed at UCLA in four measurement cycles with counting times from

0.2 to 24 h. For elements with radionuclides of short half-lives, the pneumatic irradiation facility and counting hardware at UC Irvine were used to determine the abundances of Al, Mn, Mg, and others. Samples were irradiated for 60 s and counted for 200 s after a short cooling period. Standards used in the latter procedure included the USGS international reference materials BHVO-1, BIR-1 (Govindaraju 1994), and the Allende meteorite (Jarosewich et al. 1987).

RESULTS

Texture

GRO 95577 has petrologic similarities to the CR chondrites. The section we studied contains several chondrules and irregularly shaped objects that are at least 1 mm in their longest dimension; the largest is 1.8 mm, and it has numerous small objects that are generally 200 to 300 μm in size (Fig. 1). This characteristic is similar to Al Rais and other CR chondrites that contain large chondrules up to about 2 mm in diameter and numerous chondrules and aggregates in dark inclusions, many of which are about 200 μm in size (Weisberg et al. 1993; Bischoff et al. 1993). However, it is remarkable in that all of the chondrules in GRO 95577 are completely hydrated, consisting almost entirely of phyllosilicates, magnetite, and sulfides. Although GRO 95577 is completely hydrated, the initial chondrule textures and chondrule-matrix boundaries are well-preserved (Figs. 1 and 2a).

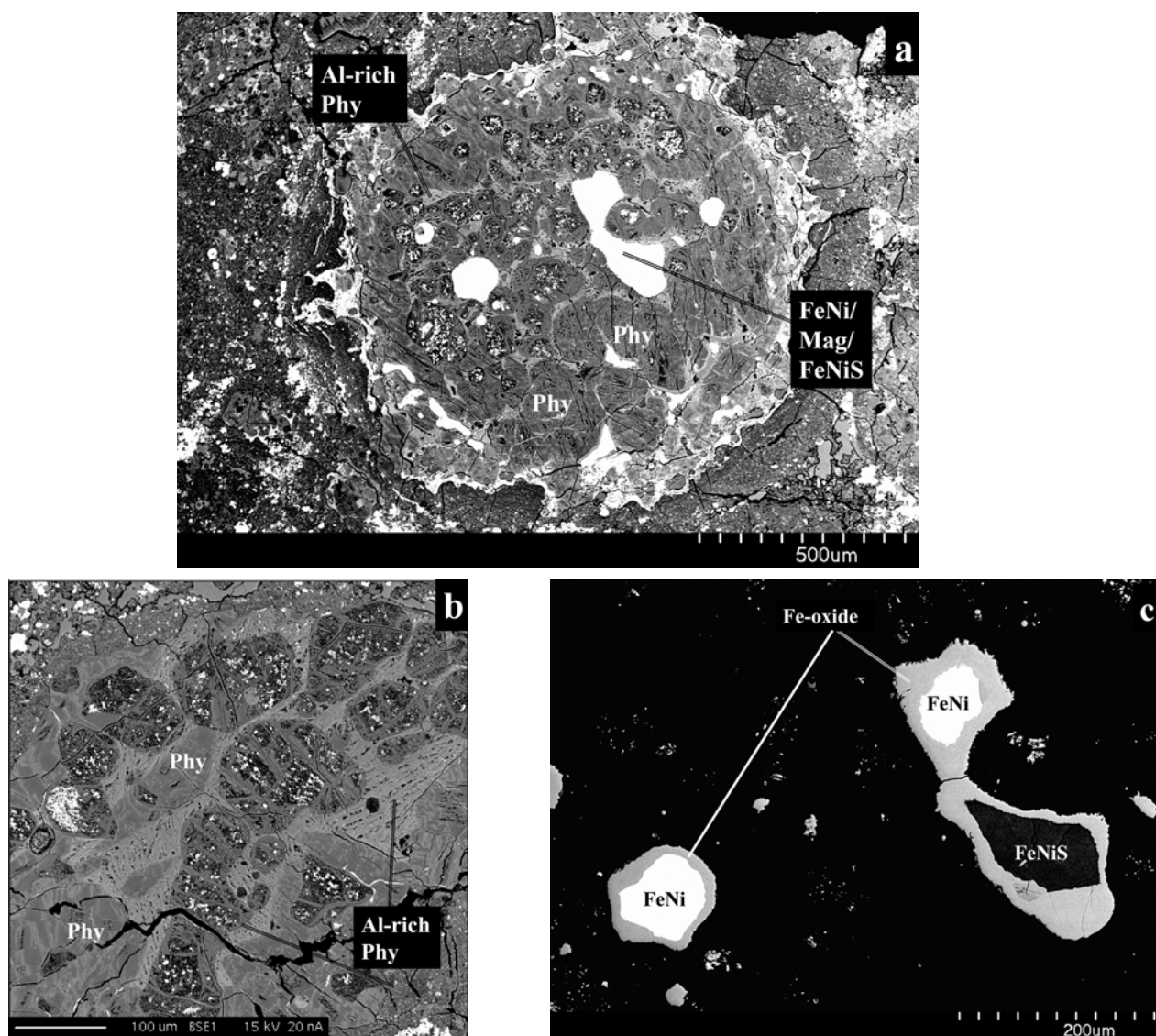


Fig. 2. BSE images of a) A chondrule from GRO 95577 that was originally a metal-rich porphyritic chondrule altered to a magnetite-phyllsilicate- (Mag-Phy) rich chondrule. Phenocrysts that were originally olivine and pyroxene have been altered to phyllosilicate. The original mesostasis has been altered to chlorite (Al-rich Phy). b) Enlargement of (a) showing the altered phenocrysts and mesostasis. c) Enlargement showing metal, oxide, and sulfide inclusions in the chondrule shown in (a).

The chondrules are in sharp contact with the matrix, their fine-grained rims are clearly visible, and the boundaries of other components such as fine-grained dark lithic inclusions (e.g., Zolensky et al. 1992; Weisberg et al. 1993; Endress et al. 1994) can be easily discerned. Many chondrules in GRO 95577 have textures suggestive of type I chondrules (Fig. 2a), which is the most common chondrule type in the CR chondrites (Weisberg et al. 1993). However, all components in GRO 95577 are completely altered. While type I chondrules in the less-altered CR2 chondrites (e.g., Elephant Moraine [EET] 87770, EET 92042, and Renazzo) have olivine and pyroxene phenocrysts, the phenocrysts in GRO 95577 chondrules have all been replaced by yellow to brownish phyllosilicates. However, sharp original crystal outlines are preserved

(Figs. 2a and 2b), showing pseudomorphic replacement. The chondrule mesostasis is a green aluminous chlorite-rich material in some chondrules, most likely a hydration product of the feldspathic mesostasis commonly found in anhydrous type I chondrules. In CR2 chondrites, some chondrules contain a feldspathic glassy to microcrystalline mesostasis, and in others the mesostasis has been altered to phyllosilicate (Weisberg et al. 1993; Ichikawa and Ikeda 1995; Noguchi 1995). Detailed observations and analyses of alteration in chondrule mesostases in CR chondrites have been recently reported by Burger and Brearley (2004, 2005), showing a wide range in degree of alteration.

Chondrules in CR chondrites, e.g., Renazzo, generally contain abundant spheres of Fe-Ni metal. In GRO 95577, the

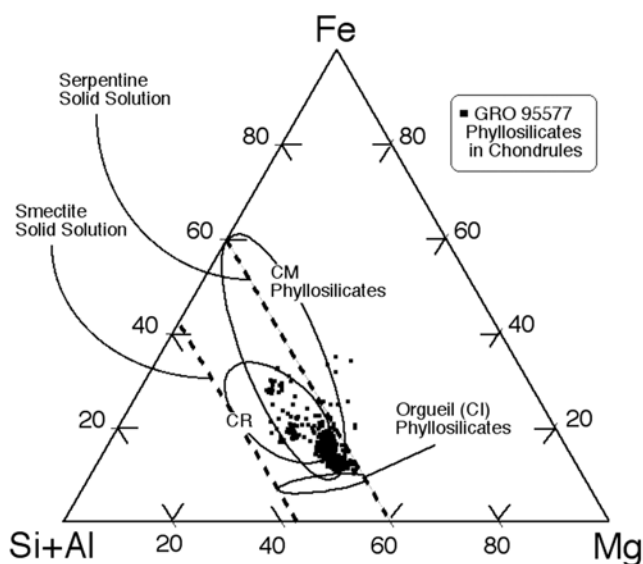


Fig. 3. Mg-Fe-Si + Al ternary diagram showing the compositions of phyllosilicates in chondrules from GRO 95577. Also shown are the areas in which phyllosilicates from CR, CM, and CI chondrites plot and tie lines indicating serpentine and smectite solid solution. Data for GRO 95577 chondrules overlap with those from CR and CM chondrite, plotting at the Mg-rich end close to CI chondrites. CR data are from Weisberg et al. (1993). CM and CI data are from Bunch and Chang (1980) and Tomeoka and Buseck (1988).

chondrules contain magnetite spheres, most likely formed by alteration of chondrule metal. Some of these spheres contain relic Fe-Ni in their interiors (Fig. 2c). Additionally, large (mm-sized) metallic chondrules are present in the CR chondrites. GRO 95577 contains similar chondrules, but they have been completely or partially replaced by magnetite having relic metal in the interior.

As in other CR chondrites, matrix in GRO 95577 makes up more than 30 vol% of the chondrite (estimated from thin section) and dark inclusions are common. The GRO 95577 matrix and dark inclusions are fine-grained mixtures of phyllosilicates, magnetite, and sulfides. Calcium-rich carbonates, up to 40 μm in size are also present. Some dark inclusions contain small (200 μm in size) chondrules. Another notable feature of the meteorite is that no veins were observed. In contrast, some hydrated chondrites, including CI and CM chondrites, contain veins filled with carbonate, phyllosilicate, or Fe oxyhydride (e.g., Tomeoka 1990; Lee 1993; Hanowski and Brearley 2000).

Mineral Chemistry

No anhydrous silicates were found in the section that was studied. Chondrule silicates are exclusively phyllosilicate. They range in composition and are most likely mixtures of saponite and serpentine minerals. Totals for the electron probe data range from about 85 to 90 wt%, suggesting about 10 to 15 wt% H_2O in the phyllosilicates. The average and range of

compositions are given in Table 1; compositions are plotted on an Mg-Fe-Si + Al ternary diagram with the fields for the range of phyllosilicate compositions in CR, CM, and CI chondrites (Fig. 3). GRO 95577 phyllosilicates appear to be mostly serpentine and overlap in composition with phyllosilicates from CR and CM chondrites, close to the field for CI chondrites. Both CR and CM chondrites show a wide range of compositions whereas the phyllosilicates in CI chondrites seems to be more homogeneous. Al-rich phyllosilicate interpreted to be chlorite is also present as chondrule mesostasis and has some compositional similarity to Al-rich phyllosilicate in CR chondrite chondrules (Table 1).

Based on 39 carbonate analyses, the carbonate in GRO 95577 is CaCO_3 with up to 0.6 wt% FeO (average = 0.4 wt%), up to 0.3 wt% MgO (average = 0.09 wt%), and up to 0.4 wt% MnO (average = 0.13 wt%). Metal grains large enough for electron probe analysis ($>3 \mu\text{m}$) are rare in GRO 95577, but the grains that were measured are within the compositional range of metal in other CR chondrites and they show the positive Ni-Co relationship that is also characteristic of the CR chondrites (Fig. 4) (Weisberg et al. 1993).

INAA Whole Chondrite Chemistry

Whole chondrite lithophile element abundances (Mg-normalized, relative to CI) have similarities to those of CR, CM, and CO chondrites, but with some unusual characteristics possibly due to modification by terrestrial weathering (Fig. 5a). The abundance of Al is enriched relative to those of mean CR and CI chondrites, but are close to Al abundances in the Al Rais (anomalous) CR chondrite. Scandium, on the other hand, is even more enriched and more like that in mean CM chondrite. Ca abundances show a marked spike compared to any chondrite group and is most likely the result of Ca mobilization. La, Sm, Eu, and Yb abundances in two splits are close to abundances in mean CR, Al Rais, and CI chondrite. In the third split La is close to CM chondrite abundances and Sm, Eu, and Yb are highly enriched, more than any other chondrite and like Ca, may be due to weathering. Lu in two splits of GRO 95577 is close to Lu abundances in mean CM and CO chondrites and slightly enriched relative to mean CR. Moderately volatile lithophile elements are highly depleted, which is similar to carbonaceous chondrites with Mn plotting closest to but slightly above CM, and Na and K are highly depleted similar to CR. However, Na and K may have both been modified (partially lost or remobilized) during parent body alteration.

Siderophile and chalcophile element abundances display a two-fold result. In Fig. 5b, the siderophile elements patterns show the enrichments and depletions that are characteristic of mean CR and CM chondrite, whereas the chalcophile

Table 1. Average (and range) of phyllosilicate compositions in GRO 95577 chondrules and representative analyses of Al-rich phyllosilicates in chondrules from GRO 95577 and CR chondrites.

wt%	GRO 95577 Serpentine average	GRO 95577 Al-rich Phy average	GRO 95577 Al-rich Phy	CR chondrite chlorite	CR chondrite chlorite
SiO ₂	39.2 (32.0–42.4)	30.8 (26.4–33.6)	29.3	30.4	27.9
TiO ₂	0.08 (b.d.–0.24)	0.15 (b.d.–0.34)	0.31	0.21	0.07
Al ₂ O ₃	1.89 (0.83–3.0)	12.8 (11.0–16.7)	15.8	15.1	15.5
Cr ₂ O ₃	0.90 (0.07–2.1)	0.41 (0.11–0.87)	0.14	0.15	b.d.
FeO	16.1 (12.4–24.9)	22.4 (18.9–30.2)	19.1	20.9	25.9
MnO	0.24 (0.08–0.45)	0.35 (0.23–0.64)	0.41	0.41	0.14
MgO	27.2 (21.7–31.2)	19.3 (14.2–21.7)	19.8	21.1	18.3
CaO	b.d.	b.d.	0.04	1.07	0.22
Na ₂ O	0.44 (0.08–1.8)	0.19 (0.11–0.29)	0.14	0.23	0.15
Total	86.05	86.40	85.04	89.57	88.18
H ₂ O by difference	13.95	13.6	14.96	10.43	11.82
Number of analyses chondrules	349 12	42 7	1		

CR = Chondrite data from Weisberg et al. (1993).

b.d. = below detection (<0.03).

elements tend to plot completely differently from the values for mean chondrite groups. They have CI-like distribution but abundances in the range of $0.6 \times$ CI. They do not display the volatility-controlled depletions that are characteristics of mean CM, CO, or CR. They are most similar to abundances in the heavily hydrated Al Rais (anomalous) CR chondrite. Within the siderophile elements, Os, Ni, and Fe are slightly enriched and Co slightly depleted for the mean sample compared to mean CR and Al Rais.

Whole Rock Oxygen Isotopes

The whole rock oxygen isotope composition of GRO 95577 has been previously reported (Clayton and Mayeda 1999) and is reviewed here because it is an important aspect of meteorite classification and group relationship. On the oxygen three-isotope diagram, the CR chondrites define a mixing line of slope ~ 0.7 (Fig. 6) (Weisberg et al. 1993). This line differs from the carbonaceous chondrite anhydrous mineral (CCAM) line, on which CV, CO, and CK chondrites plot, and it differs from the line defined by CM chondrites (e.g., Clayton and Mayeda 1999). GRO 95577 plots between the CR chondrite mixing line and the terrestrial mass fraction line on the oxygen-isotope diagram, just above the Renazzo CR chondrite (Fig. 6). It should be noted that its composition plots further from the line defined by the CR chondrites than many other CRs. However, other weathered CR chondrites, e.g., Acfer 324, plot even further off the CR line (Sipiera and

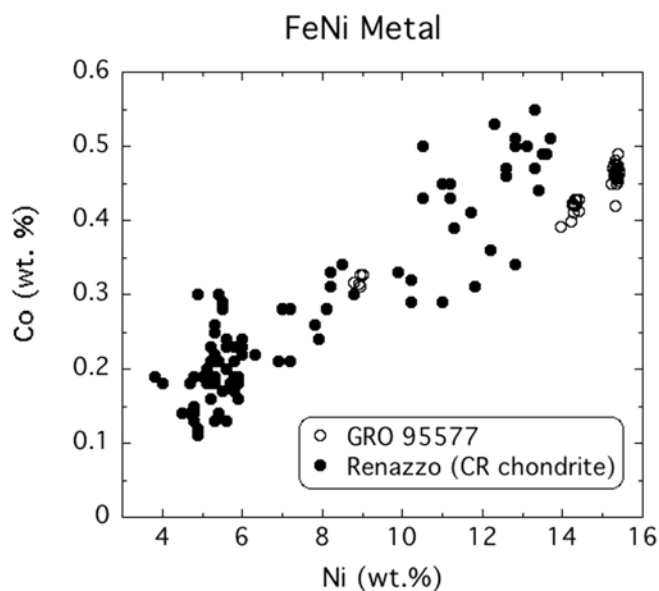


Fig. 4. Fe-Ni metal in GRO 95577 plotted on a Ni versus Co (wt%) diagram with data from Renazzo (Weisberg et al. 1993) show for comparison. The limited metal data from GRO 95577 overlaps in composition with metal from Renazzo and shows a similar positive Co-Ni relationship.

Cole 2004). Additionally, the oxygen isotope composition of GRO 95577 is closer to the CR chondrites, specifically Renazzo, than to any other chondrite group.

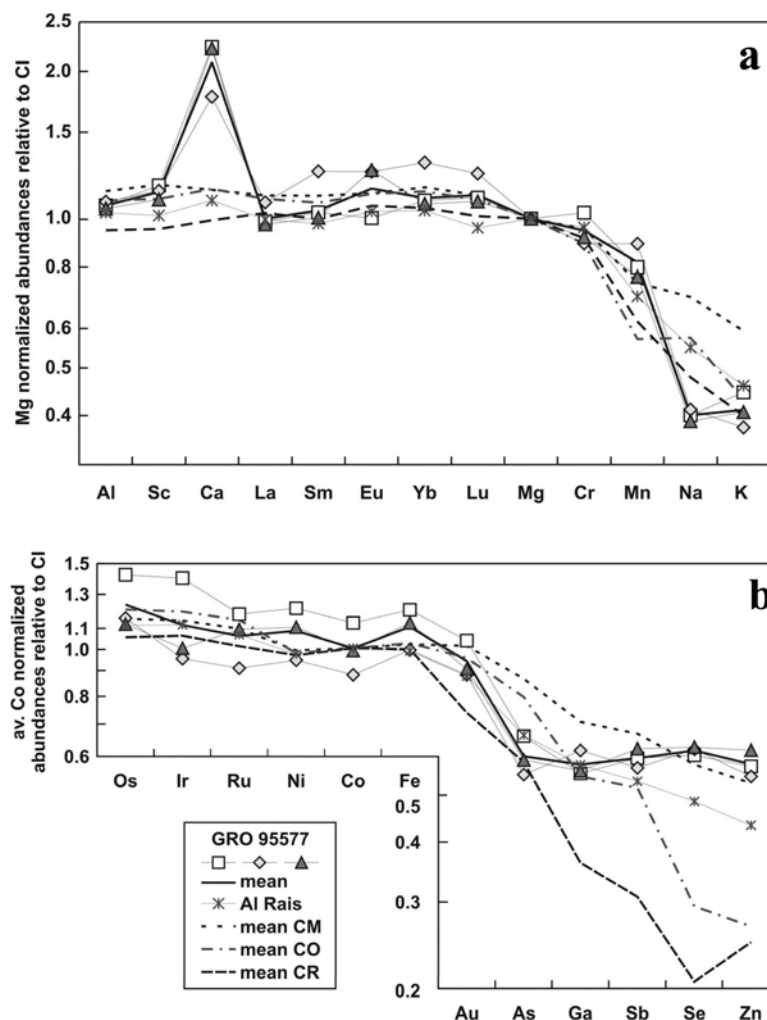


Fig. 5. Whole chondrite (INAA) bulk elemental abundances. a) Mg-normalized lithophile elemental abundances normalized to CI chondrite and (b) mean-Co-normalized siderophile and chalcophile element abundances normalized to CI for the triplicate GRO 95577 analyses and mean GRO 95577, compared to mean CM, CO, CR, and the Al Rais CR chondrite. Siderophile and chalcophile elements in the three individual GRO 95577 samples were normalized to the mean Co of the three analyses. This method was used to reduce differences in the chalcophile elements due to the normalization when Co values of each individual sample are used. As a result, the Co abundances of the three individual GRO samples are not $1 \times$ CI. CM, CO, CR, and Al Rais data are from Kallemeyn and Wasson (1981) and Kallemeyn et al. (1994).

DISCUSSION

Classification of GRO 95577

GRO 95577 is petrologically similar to the CR chondrites, albeit more altered than any other known CR. Its chondrules are similar in size to those in CR and CV chondrites. The high abundance of magnetite and low amount of Fe-Ni metal in the chondrules is unlike that of CR chondrites. However, magnetite occurs as large blebs in chondrule interiors and rims, a textural setting that mimics that of Fe-Ni metal in CR chondrites (Weisberg et al. 1993). Interiors of magnetite grains contain areas of Fe-Ni, suggesting that the magnetite formed by oxidation of metal; the Fe-Ni interiors of the magnetite are interpreted to be

relicts of the alteration event. Therefore it is concluded that GRO 95577 once contained large, metal-rich chondrules, similar to the CR chondrites. The high abundance of matrix containing small (200–300 μm in size) chondrules coupled with the low abundance of objects that can be identified as refractory inclusions is consistent with classification as a CR chondrite. CR chondrites contain relatively low abundances of refractory inclusions and the matrix and dark inclusions in CR chondrites generally contain a population of chondrules that are smaller than the characteristic large (mm size) CR chondrules (Weisberg et al. 1993). The occurrence of regions in GRO 95577 identified as dark inclusions is another characteristic of CR chondrites. Although not exclusive to CR chondrites, dark inclusions are fairly common in some CRs such as Renazzo, Al Rais, EET 92042, and the Acfer 059/El

Djouf 001 paired CR chondrites (Weisberg et al. 1993; Endress et al. 1994; Abreu and Brealey 2005).

The oxygen isotopic composition of GRO 95577 is slightly displaced (0.2 per mil) from the CR mixing line, but it is remarkably close to the Renazzo CR chondrite, supporting a relationship to CR chondrites (Clayton and Mayeda 1999; Weisberg et al. 1993). The displacement toward the terrestrial fractionation line could be due, at least in part, to terrestrial weathering, since GRO 95577 is an Antarctic find. Thus the oxygen isotope data can also be interpreted to be consistent with classification as CR.

The whole chondrite INAA data show considerable variability, some of which we attribute to terrestrial weathering. This is especially apparent in the case of Ca abundances. The chips used for INAA may have contained an unrepresentative abundance of extraterrestrial carbonate and/or, more likely, carbonate or sulfate formed during terrestrial weathering. The interior of the meteorite was described as weathered and white evaporite deposits were observed on a weathered surface of the fusion crust by C. E. Satterwhite (Mason 1997). The deposits are most likely Ca-sulfate or Ca-carbonate. However, some of the bulk chemical data are consistent with classification of GRO 95577 as a CR chondrite. For example, La, Sm, Eu, and Yb abundances in two of the splits analyzed are close to abundances in mean CR and Al Rais. Moderately volatile elements Na and K are highly depleted, like in CR chondrites. However, these elements are also highly susceptible to remobilization during weathering. The unusual chalcophile element abundances are closely matched by those in the Al Rais (anomalous) CR chondrite, and by those in NWA 1616 (Huber 2006, unpublished data). It should be noted that Al Rais is a fall and therefore its elemental abundances are most likely the result of its extraterrestrial history and not extensive terrestrial weathering.

The lack of anhydrous minerals in GRO 95577 suggests that it should be classified as petrologic type I according to criteria of Van Schmus and Wood (1967). The classic definition of petrologic type I includes a lack of visible chondrules (Van Schmus and Wood 1967). However, the original definition was based on the variety of chondrites available at the time and CI chondrites were the only completely altered (type I) group known at the time. It is unclear if the CI chondrites ever had chondrules. We therefore propose that GRO 95577 be classified as a CR1 chondrite, making it the first known CR1 chondrite and expanding the range of alteration conditions on the CR parent body.

Alteration of GRO 95577 and the CR Chondrites

The alteration of GRO 95577 was a remarkable replacement process that preserved the textural integrity of the initial chondrite. It was previously reported that the CR2

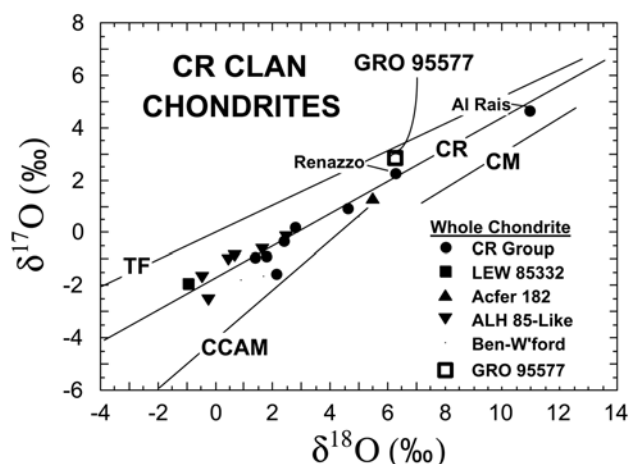


Fig. 6. Oxygen three-isotope diagram showing the whole rock oxygen isotopic composition of GRO 95577 (from Clayton and Mayeda 1999) compared with the whole rock oxygen isotopic compositions of CR, CH, and CB chondrites (Weisberg et al. 1993, 1995, 2001). Also shown on the diagram are the CR mixing line (CR), the CM line (CM), the terrestrial mass fractionation line (TF), and the carbonaceous chondrite anhydrous mixing line (CCAM). GRO 95577 plots between the CR line and the TF line, just above Renazzo. It is clearly closest to the CR chondrites and its displacement toward the TF line may be due to terrestrial weathering.

chondrites show a wide range in degree of hydrous alteration (Weisberg et al. 1993). For example, Al Rais appears to be considerably more altered than the Renazzo CR chondrite and El Djouf 001, EET 87770, and MacAlpine Hills (MAC) 87320 appear to be less altered than Renazzo. The degree of alteration in the CR2 chondrites is based on the number of chondrules that show evidence of alteration in their interiors (Weisberg et al. 1993). Other studies have also shown a range in the degree of alteration in chondrule mesostasis (e.g., Ichikawa and Ikeda 1995; Noguchi 1995). Additionally, dark inclusions in some CR chondrites are generally more hydrated than their host chondrites and appear to represent materials from the CR parent body that were altered to greater degrees than the host chondrite (Zolensky et al. 1992). The discovery of GRO 95577 indicates an even wider range of alteration conditions on the CR parent body.

Although most CR chondrites are not as heavily altered as typical CM chondrites, the range in the degree of alteration recorded in the CR chondrites may be similar to that in the CMs (e.g., Brearley 2006). GRO 95577 extends the range considerably, from CR chondrites that contain unaltered glassy mesostasis in chondrules interiors (e.g., Weisberg et al. 1993; Ichikawa and Ikeda 1995; Noguchi 1995) and in some cases unaltered olivine (Zolensky et al. 1993) and amorphous material (Abreu and Brearley 2005) in the matrix to heavily altered CR chondrites like Al Rais to GRO 95577, in which no anhydrous silicates have survived alteration. Additionally, the number of known CM chondrites is far greater than the number of CR chondrites and therefore, we may not yet have

sampled the complete range of alteration from the CR parent body or bodies. In addition, a number of meteorites (e.g., Acfer 324) have been shown to be CR3 chondrites (Sipiera and Cole 2004) or at least some CR chondrites show only minimal degrees of alteration (Abreu and Brearley 2006). If the reports of CR3 chondrites are correct, the CR chondrites are the only chondrite group in which we have the complete sequence of alteration ranging from types 3 through 1.

Alteration temperatures for the CR chondrites have been estimated to be greater than 250 °C, based on carbonate compositions (Weisberg et al. 1994), and about 300 °C based on oxygen isotope fractionation between phyllosilicate and magnetite (Clayton and Mayeda 1977). Additionally, temperatures up to 450 °C were proposed for possible CR-related dark inclusions in the Kaidun chondrite, based on the presence of hydrothermal pentlandite veins (Zolensky et al. 1996). Hydrothermal fluids of these temperatures may have been sustained in the interior of an internally heated, degassing CR parent body. As these fluids migrated through the asteroid they may have produced a wide range of alteration environments resulting in the wide range in degree of alteration observed in the CR chondrites.

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