

Roosevelt County 075: A petrologic, chemical and isotopic study of the most unequilibrated known H chondrite

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Abstract—Roosevelt County (RC) 075 was recovered in 1990 as a single 258-gram stone. Classification of this meteorite is complicated by its highly unequilibrated nature and its severe terrestrial weathering, but we favor H classification. This is supported by O isotopes and estimates of the original Fe,Ni metal content. The O isotopic composition is similar to that of a number of reduced ordinary chondrites (e.g., Cerro los Calvos, Willaroy), although RC 075 exhibits no evidence of reduced mineral compositions. Chondrule diameters are consistent with classification as an L chondrite, but large uncertainties in chondrule diameters of RC 075 and poorly constrained means of H, L and LL chondrites prevent use of this parameter for reliable classification. Other parameters are compromised by severe weathering (e.g., siderophile element abundances) or unsuitable for discrimination between unequilibrated H, L and LL chondrites (e.g., Co in kamacite, $\delta^{13}\text{C}$). Petrologic subtype 3.2 \pm 0.1 is suggested by the degree of olivine heterogeneity, the compositions of chondrule olivines, the thermoluminescence sensitivity, the abundances and types of chondrules mapped on cathodoluminescence mosaics, and the amount of presolar SiC. The meteorite is very weakly shocked (S2), with some chondrules essentially unshocked and, thus, is classified as an H3.2(S2) chondrite. Weathering is evident by a LREE enrichment due to clay contamination, reduced levels of many siderophile elements, the almost total loss of Fe,Ni metal and troilite, and the reduced concentrations of noble gases. Some components of the meteorite (e.g., type IA chondrules, SiC) appear to preserve their nebular states, with little modification from thermal metamorphism. We conclude that RC 075 is the most unequilibrated H chondrite yet recovered and may provide additional insights into the origin of primitive materials in the solar nebula.

INTRODUCTION

One of the major aims of meteorite research is to unravel the conditions that existed in the solar nebula during formation of the Solar System 4.55 Ga ago. Chondritic meteorites, with their host of nebular components, have been the targets of such research, although identification of the most primitive chondrites remained problematic until about 15 years ago. This obstacle was overcome when it was recognized that the type 3 chondrites could be subdivided on the basis of increasing metamorphism (Sears *et al.*, 1980; Huss *et al.*, 1981). This allowed researchers to identify chondrites which had been subjected to the lowest degree of parent body metamorphism and, thus, most likely contain the least altered nebular components.

The petrologic subtypes (3.0–3.9; Sears *et al.*, 1980) were originally interpreted as representing increasing degrees of thermal metamorphism. Indeed, subsequent studies (McCoy *et al.*, 1991) have confirmed that many of the components (e.g., chondrules) in LL chondrites of subtypes 3.1–3.9 were once like those in type 3.0 chondrites but have been altered by metamorphism. Thus, type 3.0 represents the least thermally metamorphosed and, hence, the most unequilibrated chondritic material. Guimon *et al.* (1988) have noted that the low petrologic subtypes (<3.3) also experienced aqueous alteration not present in the higher subtypes.

The realization that these low petrologic subtype chondrites are unmetamorphosed or very weakly metamorphosed allowed a bounty of new results about processes in the solar nebula. Research on unequilibrated ordinary chondrites has contributed extensively to understanding chondrule genesis. Semarkona (LL3.0), for example, has been the subject of numerous studies (e.g., Jones and Scott, 1989; Jones, 1990). This research confirmed that mineral compositions in Semarkona chondrules formed by closed system fractional crystallization in the nebula, although the chondrules themselves likely formed by melting of pre-existing dust. Isotopic anomalies have been discovered in several unequilibrated ordinary chondrites of petrologic type <3.6 (e.g., Alaerts *et al.*, 1979; Alexander *et al.*, 1990; Huss, 1990), and studies of chondrite matrices (e.g., Scott *et al.*, 1988; Alexander *et al.*, 1989) contributed to an understanding of the effects of mild metamorphism and aqueous alteration on these primitive components.

Many of the studies which have been successful in tracing the effects of nebular and parent body processes in unequilibrated L and LL ordinary chondrites have been impossible in the case of H chondrites because of the lack of low petrologic subtypes in the world's meteorite collections: Sears and Weeks (1986) noted the total absence of H3.0–3.3 chondrites. While the recovery of two paired H3.0 chondrites from Antarctica (LEW 86102 and 86105, totalling only 28 g) has filled this void to some extent, no detailed studies of a low petrologic subtype H chondrite have been published. This paper reports detailed petrologic, chemical and isotopic studies of Roosevelt County (RC) 075, the least metamorphosed H chondrite yet recovered (H3.2(S2)).

ANALYTICAL TECHNIQUES

Polished thin section UH-82 in the collection of the Planetary Geosciences Division at the University of Hawaii-Manoa was prepared from the main mass of RC 075, which has been returned to the finder

(IEW). The section was studied by optical microscopy in transmitted and reflected light, and mineral compositions were determined with a Cameca Camebax electron microprobe. Minerals of well-known compositions were used as standards and data were corrected using a ZAF routine.

RC 075 was subjected to a number of petrologic (microprobe, thermoluminescence, cathodoluminescence), chemical (INAA, total C) and isotopic (noble gases, O, C, N, H) studies. The initial total C analyses were done using a LECO ELC12 C analyzer following techniques outlined by Moore *et al.* (1971). Total C was analyzed using a static vacuum mass spectrometer described by Carr *et al.* (1986), using the gas extraction method described by Swart *et al.* (1983) and Ash *et al.* (1990). The speciation of C-containing volatiles was provided by dynamic high temperature mass spectrometry (Muenow *et al.*, 1992). Nitrogen contents and isotopic compositions were determined mass spectrometrically (Wright *et al.*, 1988a), using the stepped combustion extraction methods described by Boyd *et al.* (1988). Hydrogen contents were determined by first heating the sample at 150 °C *in vacuo* to drive off loosely bound water, then combusting the sample at 1050 °C for 1 h to produce water, which was then reduced over Zn at 450 °C. The H isotopic compositions were then determined by mass spectrometry as described by Morse *et al.* (1993), and H contents were calculated from the calibrated beam current. A seven-step pyrolysis between room temperature and 1100 °C was carried out, with the water produced being reduced as described above. All isotopic data are given relative to the appropriate international standards.

Noble gases were analyzed by static mass spectrometry. Details of the experimental technique and data reduction are given by Graf *et al.* (1990a) and Wieler *et al.* (1991). Oxygen isotope analyses of a whole-rock sample (with and without HCl treatment to remove weathering products) were carried out by the methods of Clayton and Mayeda (1963, 1983). Bulk composition was analyzed by INAA using the procedures currently in use at Johnson Space Center, Houston, Texas. Two samples weighing about 67 and 42 mg were packaged in pure silica tubes and irradiated for 20 hours in a flux of $5.5 \times 10^{13} \text{ n cm}^{-2} \text{ s}^{-1}$ at the Research Reactor Facility of the University of Missouri in Columbia, Missouri. The samples were counted at about 0.5, 1, 5 and 19 weeks after irradiation in order to obtain data for nuclides with differing half-lives. Details of standards used and data reduction procedures are given in Mittlefehldt and Lindstrom (1991) and Mittlefehldt *et al.* (1992).

RESULTS

Recovery

Roosevelt County 075 was recovered as a single stone of 258 g in 1990 April from Section 36, R33E, T1S of Roosevelt County, New Mexico, USA (approximately 34°11'N, 103°26'W). Unlike most of the Roosevelt County meteorites which were found in deflation surfaces, RC 075 was recovered from the surface of a concrete driveway near the town of Portales, New Mexico. It was discovered by the home owner the morning after a rock fight in front of his house, probably having been thrown there during the fight. Thus, RC 075 is neither a meteorite fall nor find, but might facetiously be called the first meteorite "throw". One of us (IEW) speculates that it was carried into the neighborhood for a rock garden and may be a fragment of a larger stone. The source of these rocks is uncertain, but they probably came from somewhere in Roosevelt County.

Petrographic Description

The outer surface of the hand sample is stained brown and shows areas of distinctly different shades, probably representing fracture surfaces of different ages. A sawn surface shows very distinct chondrules of various types set in a dark matrix, indicating a relatively low petrologic type. No Fe,Ni metal is observed in hand sample. Optical microscopy confirms the low

petrologic type; chondrules are distinct (Fig. 1), twinned low-Ca pyroxene is very abundant, and pink, isotropic glass is preserved in some chondrules. Although extreme weathering makes confident determination of the degree of matrix recrystallization difficult, much of the matrix appears opaque, indicating a low petrologic subtype.

All of the common chondrule types are present, including type IA and type II chondrules (Scott and Taylor, 1983). Compound chondrules are also observed. One large (3.8 x 2 mm) chondrule is irregular in shape and composed largely of olivine, with minor mesostasis. The average diameter of 50 chondrules measured in thin section traverses is $632 \pm 322 \mu\text{m}$, with a range from 260 μm to 1.7 mm.

Cathodoluminescence mosaics indicate that all the most primitive compositional chondrule groups described by Sears *et al.* (1992) and found in Semarkona and Krymka are also represented in RC 075. Classification of nearly 100 chondrules in RC 075 (Fig. 2) indicates that it is similar to Semarkona and Krymka in having a significant abundance of A1 chondrules and a low relative abundance of A5 chondrules, which are the dominant chondrule type in high petrologic type meteorites. Among the meteorites studied in detail (DeHart *et al.*, 1992), the chondrules of RC 075 are most like Krymka; A3 and B2 chondrules are found as opposed to the distinctive A2 and B1 chondrules of Semarkona; and A4 chondrules, found in Chainpur and other meteorites of higher petrologic type within the type 3 range, are absent or rare. Chondrules of compositional group A4 are also found in Krymka but are relatively rare. The relative abundances of chondrule types favors a classification of petrologic type 3.1 for RC 075.

We have also measured the diameters of the chondrules mapped in cathodoluminescence mosaics. The average diameter of all chondrules is $650 \mu\text{m}$ ($1\sigma = 320 \mu\text{m}$, $N = 102$), with a range from 315 μm to 2.74 mm. This average is in excellent agreement with chondrule diameters measured in thin section traverses. There is a slight tendency for B2 (avg. diameter $700 \pm 380 \mu\text{m}$, range 320–2740 μm , $N = 44$) and A5 ($740 \pm 300 \mu\text{m}$, 440–1610 μm , $N = 16$) chondrules to be larger than A1 ($610 \pm 270 \mu\text{m}$, 315–1210 μm , $N = 16$) and A3 ($540 \pm 160 \mu\text{m}$, 275–870 μm , $N = 25$) chondrules in RC 075, but there is considerable size overlap between the chondrule groups. It does, however, appear that the largest chondrules in the meteorite are either B2 or A5 chondrules. The average

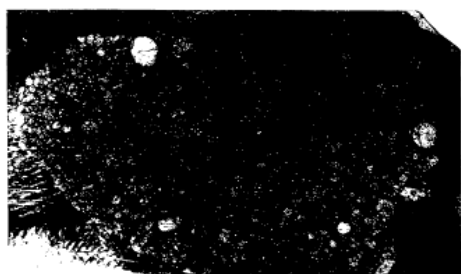


FIG. 1. Transmitted light photograph of polished thin section UH 82 of RC 075 (H3.2(S2)), displaying prominent chondrules of all types. Longest dimension = 2.5 cm.

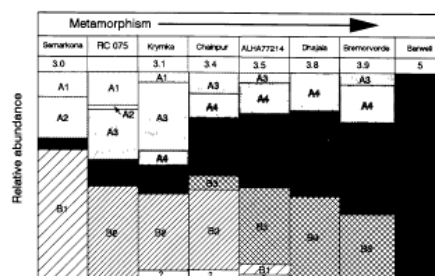


FIG. 2. Relative abundances of chondrules of various compositional groups in RC 075, compared with other type 3 ordinary chondrites and Barwell (type 5). Chondrules in RC 075 are most similar to those in Krymka. Note especially the low abundance of group A5 chondrules, which are the dominant chondrule type in equilibrated meteorites. Data for meteorites other than RC 075 from DeHart *et al.* (1992).

chondrule diameters on both thin section traverses and cathodoluminescence mosaics are within the range for L chondrites (600–800 μm ; Grossman *et al.*, 1988). However, our data on RC 075 have large standard deviations which overlap the poorly constrained means for H, L and LL chondrites. For these reasons, we place little confidence in this method for determining the chemical group of ordinary chondrites.

Weathering is extensive, with only traces of Fe,Ni metal and troilite remaining. Unweathered grains up to 40 μm in size can be found, but these occur almost exclusively in chondrules or enclosed in silicates. We have not analyzed these grains, because Co contents of kamacite in unequilibrated ordinary chondrites cannot be used to distinguish between chemical groups (Rubin, 1990). Hydrated Fe oxides of terrestrial origin occur as veins, patches and pigments throughout. Red, semi-transparent areas of weathering products, pockets of which have outlines consistent with their origin from the weathering of large metal or troilite grains, comprise 24 vol% of RC 075, based on modal analysis of 2000 points covering the entire thin section ($\sim 3 \times 2.5 \text{ cm}$). Carbonates (*i.e.*, caliche), which are present on the surface of the meteorite, appear to have been removed during thin section preparation. No clays were noted in these weathering pockets, although some of the fine-grained matrix may have been altered to clay. The meteorite is classified in weathering category C in the scheme proposed for Antarctic meteorites (*e.g.*, *Antarctic Meteorite Newsletter*, 1992) and as weathering class W4 in a newly proposed scheme for microscopic weathering features (Wlotzka, 1993). We have determined the modal abundance of hydrated Fe oxides (24 vol%) in an attempt to infer the original amount of Fe,Ni metal, using the method described by Recca *et al.* (1986). All weathering products are assumed to be FeOOH. Conversion to metallic Fe and subtraction of Fe occurring in troilite in unweathered chondrites yields 14.5 wt% Fe,Ni metal for RC 075. Although large uncertainties exist in this method, the abundance of Fe,Ni metal is within the range for H chondrites (14.2–19.8 wt%; Keil, 1962), suggesting that RC 075 is an H chondrite.

The meteorite is assigned to shock stage S2 (very weakly shocked) in the classification of Stöffler *et al.* (1991), based on the presence of olivines with undulatory extinction and the lack

of planar fractures. However, some individual chondrules have olivine grains with sharp extinction and would, individually, be classified as belonging to shock stage S1. This is not surprising considering the heterogeneous nature of shock.

Silicate Compositions

Silicate compositions provide the best measure of degree of chondrite equilibration, since the large grains analyzed here have not been altered by weathering (*i.e.*, converted to iddingsite). Analyses of randomly selected grains of olivine and low-Ca pyroxene greater than 20 μm in diameter in both chondrules and the matrix yield average $\text{Fa}_{13.1}$ ($\sigma = 7.1$; $N = 49$; $\sigma/\text{avg} = 54\%$; Fig. 3) and $\text{Fs}_{11.5}$ ($\sigma = 9.6$; $N = 30$), respectively. Olivine composition suggests that RC 075 is of petrologic subtype ≤ 3.3 (Sears and Hasan, 1987). Note that during analysis, care was taken to avoid areas stained by hydrated iron oxide weathering products.

The least equilibrated H chondrite listed in the review of Sears *et al.* (1980) is Sharps (H3.4). Dodd *et al.* (1967) report a mean Fe content of olivine for Sharps of 14.0, with a percent mean deviation of 37. The mean FeO content of olivines in RC 075 is 12.2, with a percent mean deviation of 46. The significantly higher percent mean deviation of RC 075 when compared to Sharps is consistent with the interpretation that RC 075 is more unequilibrated than any previously recovered H chondrite.

We have also studied type IA and II chondrules (Scott and Taylor, 1983) in an attempt to classify the meteorite. We analyzed 4–8 points on olivine crystals in six type IA and five type II chondrules, sampling both cores and rims of crystals (Fig. 4). Type IA chondrules have mean olivine Fa contents of 0.7–7.2 mol% and mean olivine CaO contents of 0.11–0.36

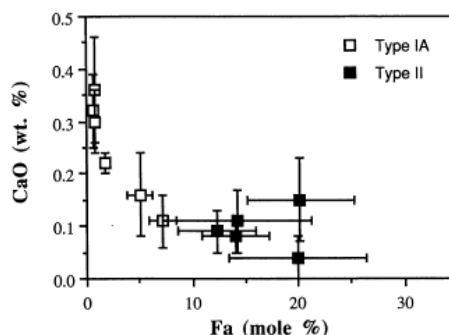


FIG. 4. Plot of CaO (wt%) vs. Fa (mol%) in olivines in type IA and type II chondrules from RC 075. For each chondrule, the mean of 4–8 analyses and bars showing $\pm 1 \sigma$ are shown. Four of six type IA chondrules have mean olivine Fa values from 0–2, typical of type IA chondrules in the unmetamorphosed Semarkona (LL3.0) chondrite. Two type IA chondrules have higher mean olivine Fa values. Type II chondrules also show a range of mean olivine Fa values.

wt%. As would be expected, CaO decreases as Fa increases. While some type IA chondrules contain glass, no relationship is observed between chondrule compositions and the presence or absence of glassy mesostases. Four of the type IA chondrules have mean olivine Fa contents of 0–2 mol%, compositions which are common in the unmetamorphosed chondrite Semarkona (LL3.0) (Jones and Scott, 1989). Type II chondrules likewise show a range of mean olivine Fa contents (12.3–20.2 mol%), indicating that RC 075 is highly unequilibrated.

Bulk Composition

Thirty elements were determined on one or both of two splits of RC 075 (67.49 mg, A; 42.16 mg, B) (Table 1). On the whole, these data illustrate the high degree of weathering of the meteorite; for example, extreme enrichments (10.6–86.5x CI) are observed for U, Ba and La. Uranium is very mobile once oxidized, and Ba and La enrichments can be attributed to addition to the meteorite of a terrestrial clay component. The rare earth element pattern (Fig. 5) is also strongly influenced by terrestrial weathering. The heavy REEs are essentially flat at about 2x CI, whereas the light REEs show more complex patterns. We interpret these patterns as an overall LREE enrichment caused by a clay contaminant, with an overprinted negative Ce anomaly caused by weathering.

Fe, Ni metal and troilite are heavily weathered, and this is clearly reflected in the low abundances of siderophile and chalcophile elements. Siderophile element abundances (*e.g.*, Sears and Weeks, 1986; Wasson and Kallemeyn, 1988) in unweathered ordinary chondrites show a decrease in the sequence from H to L to LL chondrites, consistent with the decreasing metal content. In RC 075, however, abundances of Co and Ni are well below those observed in any unweathered ordinary chondrite, reflecting the high degree of weathering. The abundance of Au is comparable only to the LL3 chondrite ALH A77176, whereas Ir and As are similar to L chondrites. It is somewhat surprising that Ir and As are similar to L chondrites

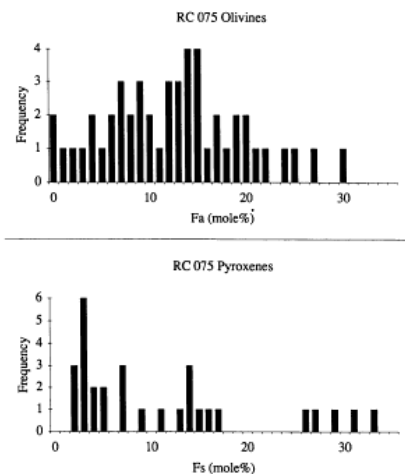


FIG. 3. Histograms of analyses of randomly chosen olivine (Fa content) and low-Ca pyroxene (Fs content) grains from RC 075. The large heterogeneity indicates classification of the meteorite as a petrologic type ≤ 3.3 .

TABLE 1. Bulk composition data for two splits of Roosevelt County 075 as determined by instrumental neutron activation analysis.

Unit	Split A	Split B	Ave.	Ave/CI
Na wt%	0.1426±0.0023	0.1732±0.0029	0.1579	0.32
K wt%	0.046±0.004	0.056±0.005	0.051	0.92
Ca wt%	0.92±0.10	0.82±0.13	0.87	0.94
Sc ppm	10.44±0.11	9.11±0.10	9.78	1.7
Cr ppm	4510±50	4390±50	4450	1.7
Fe wt%	18.75±0.25	19.97±0.25	19.36	1.0
Co ppm	198.6±2.1	227.9±2.4	213.2	0.42
Ni ppm	4390±80	4840±70	4615	0.42
As ppm	1.88±0.06	1.77±0.09	1.82	0.99
Se ppm	3.65±0.21	4.08±0.19	3.87	0.21
Br ppm	0.90±0.08	0.86±0.11	0.88	0.25
Rb ppm	15±4	--	15*	6.5
Sb ppm	0.061±0.009	0.068±0.010	0.064	0.46
Cs ppm	0.059±0.013	0.064±0.016	0.062	0.33
Ba ppm	177±11	228±11	203	86.5
La ppm	3.13±0.04	1.86±0.03	2.50	10.6
Ce ppm	2.45±0.24	1.87±0.30	2.16	3.6
Nd ppm	<16	<7	--	--
Sm ppm	0.522±0.008	0.339±0.007	0.431	2.9
Eu ppm	0.126±0.003	0.105±0.003	0.116	2.1
Tb ppm	0.091±0.009	0.065±0.007	0.078	2.1
Yb ppm	0.342±0.022	0.265±0.027	0.304	1.9
Lu ppm	0.053±0.004	0.040±0.006	0.047	1.9
Hf ppm	0.230±0.025	0.177±0.022	0.204	2.0
Ta ppm	0.033±0.011	0.031±0.012	0.032	2.3
W ppm	0.19±0.05	<0.37	0.19*	2.1
Ir ppb	335±8	449±9	392	0.81
Au ppb	60.5±1.3	98.5±2.0	79.5	0.57
Th ppm	<0.09	0.036±0.016	0.036*	1.2
U ppm	0.10±0.04	<0.24	0.10*	12.3

* Averages for these elements are taken as the one significant analysis.

while Ni and Co are so depleted, especially considering that all four elements are probably largely incorporated in Fe,Ni metal. We conclude that bulk compositional data cannot be used to classify RC 075 into either H, L, or LL groups, due to severe terrestrial weathering.

Oxygen Isotopes

The isotopic composition of an untreated whole rock sample of RC 075 is $\delta^{18}\text{O} = +6.28\text{‰}$, $\delta^{17}\text{O} = +3.90\text{‰}$, yielding a $\Delta^{17}\text{O}$ value of $+0.64\text{‰}$. An acid-washed sample yields $\delta^{18}\text{O} = 4.29\text{‰}$, $\delta^{17}\text{O} = 2.63\text{‰}$ and a $\Delta^{17}\text{O}$ value $+0.40\text{‰}$. The mean of 22 H-chondrite falls is $\delta^{18}\text{O} = 4.08 \pm 0.22$ and $\delta^{17}\text{O} = 2.86 \pm 0.15$. Finds weathered in arid non-Antarctic environments usually have higher δ values. The $\Delta^{17}\text{O}$ value of the acid-washed sample is significantly below the averages for H3 finds (0.66 ± 0.11) and falls (0.68 ± 0.04) (Clayton *et al.*, 1991). These values are closer to the terrestrial mass fractionation line than those of L3 finds ($\Delta^{17}\text{O} = 0.92 \pm 0.14$) and LL3 finds ($\Delta^{17}\text{O} = 1.04 \pm 0.19$).

The O isotopic composition of RC 075 is similar to a number of chondritic meteorites, most of which are more reduced in their FeO contents than H chondrites (Wasson *et al.*, 1993). These meteorites are clearly unrelated to the acapulcoites and lodranites, although they have similar Fa contents (Clayton *et al.*, 1992). Unlike some of the meteorites described by Wasson

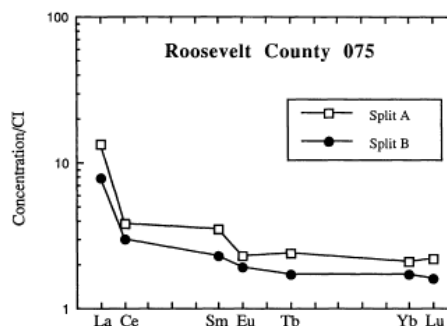


FIG. 5. Rare earth element plot of two splits from RC 075, both showing similar patterns. The heavy REEs are flat at around 2x CI, while the LREEs are enriched. We interpret the LREE pattern to overall enrichment caused by a clay contaminant, with an overprinted Ce anomaly caused by weathering.

et al. (1993), RC 075 shows no evidence for reduced mineral compositions, possibly because of its highly unequilibrated nature. The relationship between these reduced chondritic meteorites and H chondrites is uncertain. Too few samples exist to confidently assert the existence of a more reduced ordinary chondrite parent body (HH). Additionally, the full range of O isotopic compositions in highly unequilibrated H chondrites is not fully known, due to a lack of such meteorites. For these reasons, we suggest classification of RC 075 as an H chondrite, but recognize that its O isotopic composition lies beyond the range previously found for H chondrites.

Thermoluminescence Sensitivity

Measurement of the induced TL level of an untreated bulk sample of RC 075 yields a value of 0.0036 ± 0.0007 , relative to the standard Dhajala. This would indicate a petrologic subtype of 3.0, equivalent to Semarkona (LL3.0) (Sears and Hasan, 1987). However, weathering can have a marked effect on the TL sensitivity of an ordinary chondrite, reducing the TL level. For this reason, the sample was acid-washed to remove weathering products. The acid-washed bulk sample gave a TL level of 0.022 ± 0.004 , on the boundary between petrologic subtypes 3.2 and 3.3. However, induced TL peak temperatures and widths (~ 160 and 140 °C, respectively) favor petrologic type 3.2.

Noble Gases

A whole rock sample of RC 075 was analyzed for noble gases (Table 2), after having been preheated in the extraction line for 24 h at 100 °C. The ratios $(^{22}\text{Ne}/^{21}\text{Ne})_{\text{cos}}$ and $(^3\text{He}/^{21}\text{Ne})_{\text{cos}}$ indicate "average" shielding. The shielding corrected ^{21}Ne exposure age (Graf *et al.*, 1990b) is about 24 Ma, assuming H chondrite composition and a pre-atmospheric size <30 cm. The concentration of ^4He is normal, indicating no reheating event. Argon-40 is exceptionally low, however, less than 10% of the typical values. We suggest that this is due to weathering. A somewhat preferential weathering of K-rich phases is indicated

TABLE 2. Noble Gases in Roosevelt County 075.

^3He	^4He	^{20}Ne	20/22	22/21	^{36}Ar	36/38	^{40}Ar	^{84}Kr	^{132}Xe	Cosmogenic Fraction			
										^{21}Ne	^{38}Ar	22/21	3/21
35.0	1600	8.95	1.012	1.129	18.6	4.57	390	0.105	0.0903 ¹	7.83	1.654	1.103	4.46
1.4	60	0.35	0.010	0.007	0.7	0.04	20	0.006	0.0006	0.30	0.040	0.007	0.22

Concentrations in $10^{-8} \text{ cm}^{-3} \text{ STP/g.}$

The second number in each column is the analytical uncertainty.

Sample Mass - 224 mg.

¹ Roughly 30% atmospheric contamination.

by the relatively low K concentration (0.92x CI) compared to unweathered ordinary chondrites ($\sim 1.4x$ CI). Roughly 30% of the ^{132}Xe is of atmospheric origin, despite the preheating, as is indicated by the Xe isotopic composition (not given). Weathered meteorites are often contaminated by atmospheric noble gases, indicated by elevated $^{84}\text{Kr}/^{132}\text{Xe}$ ratios (Loeken *et al.*, 1992). The $^{84}\text{Kr}/^{132}\text{Xe}_{\text{pl}}$ ratio of RC 075 lies to the right of the correlation line defined by these authors from data on H3 and H4 chondrite falls. This suggests that roughly half of the ^{84}Kr in RC 075 is also atmospheric. On the other hand, less than 7% of the ^{36}Ar can be air contamination, since the measured $^{40}\text{Ar}/^{36}\text{Ar}$ ratio is only ~ 21 .

The concentrations of planetary ^{36}Ar and ^{132}Xe correspond to petrologic type 3.9 in the scheme of Anders and Zadnik (1985). At face value, the noble gases thus indicate that RC 075 is considerably more equilibrated than all other criteria discussed here would suggest. However, since radiogenic ^{40}Ar has been lost, presumably by weathering, we may ask whether planetary gases in RC 075 and other heavily weathered meteorites are a useful indicator of petrologic type. A substantial fraction of the planetary gases survives etching of a

chondrite by HF/HCl (Lewis *et al.*, 1975). One would certainly not expect these gases to be lost by weathering. However, ordinary chondrites lose ~ 25 –90% of their trapped ^{36}Ar and ~ 30 –70% of their Xe during HF/HCl dissolution (Schelhaas *et al.*, 1990). We do not know how tightly bound this fraction of the planetary gas is, but it seems possible that part of it may not survive thousands of years of weathering.

It is noteworthy that the $^{36}\text{Ar}/^{132}\text{Xe}$ ratio in RC 075 is very high. The spallation corrected value is 201 and that of the planetary component is some 30% higher, because part of the Xe is atmospheric. One notes a rough trend between the petrologic subtype of unequilibrated ordinary chondrites and their $^{36}\text{Ar}/^{132}\text{Xe}$ ratio. Values around 200 or higher are found only in subtypes ≤ 3.5 (Anders and Zadnik, 1985). This trend extends to higher petrologic types. H4-6 chondrite falls without solar noble gases have $^{36}\text{Ar}/^{132}\text{Xe}$ ratios between 30 and 60 (L. Schultz, pers. comm., 1993). The data for RC 075 thus suggest that a high $^{36}\text{Ar}/^{132}\text{Xe}$ ratio may hint at a low petrologic type, but only in cases where a contribution of solar ^{36}Ar can be excluded.

Carbon Abundance and Isotopes by Combustion

Because of its low petrologic subtype classification, C abundances and isotopes were measured in RC 075. Initial combustion experiments on a bulk sample carried out at Arizona State University gave 1.3 wt% C. Combustion experiments at the Open University yielded a value of 1.5 wt% C. This value is extraordinarily high (Fig. 6) when compared to the range for other ordinary chondrites, which have C contents up to 0.95 wt% (ALHA77214; Grady *et al.*, 1982a, 1982b), and prompted us to conduct more detailed studies. Although earlier comparisons of finds and falls show no systematic differences in C content (Moore and Lewis, 1967; Grady *et al.*, 1982a), the effect of the unique conditions encountered in the weathering regime of Roosevelt County (*i.e.*, exhumation after a soil residence measured in thousands of years) are unknown. A stepped combustion technique was therefore employed in an attempt to distinguish the contaminant from indigenous carbon by combustion temperature and isotopic composition.

The majority of C in ordinary chondrites is present in one of two forms, organic material and graphite. The latter includes the poorly graphitized C described by Scott *et al.* (1987). There is evidence for the presence of organic material in many low petrologic type ordinary chondrites (*e.g.*, Semarkona, Bishunpur, Chainpur). However, organics are generally rare or absent in

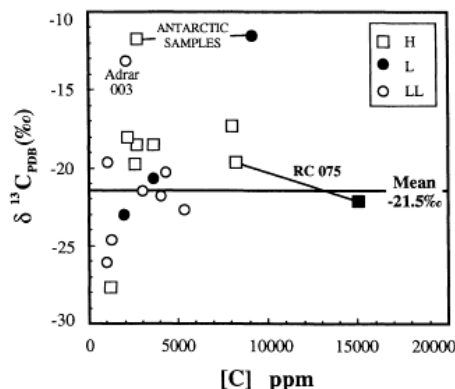


FIG. 6. Carbon content and isotopic composition of type 3 ordinary chondrites. Filled RC 075 square is uncorrected for terrestrial contamination, open square after contamination correction. (Some data from Grady *et al.*, 1982a).

petrologic subtypes greater than 3.6, where graphite is the predominant form of the carbonaceous material. There are also graphite-rich nodules present in some unequilibrated ordinary chondrites (e.g., Sharps (L3.4), ALHA77214 (L3.4)), which can account for a substantial proportion of the C budget (Scott *et al.*, 1987; Grady *et al.*, 1982b).

The C stepped combustion profile for RC 075 for temperatures up to 1200 °C is shown in Fig. 7. The total C content measured during stepped combustion is 1.5 wt%. The majority of the C is released over a broad temperature range, up to 550 °C. An expanded portion of the C combustion profile for temperatures from 200–500 °C is shown in Fig. 8. Two yield peaks are observed for the components which nearly co-combust, but which show distinct isotopic compositions. The low combustion temperature suggests that they may both be due to the presence of organic material with different isotopic compositions. The lower temperature component combusts between 200° and ~400 °C with a $\delta^{13}\text{C}$ of -26‰ ($\pm 1.1\text{‰}$). Although the 250° to 300 °C step is somewhat isotopically heavier than this (-20.8‰), the larger analytical error for this step means that it could, in fact, be close to this range. The second organic peak is associated with C with a higher $\delta^{13}\text{C}$ of -20‰ , with six consecutive steps between 375° and 525 °C having a $\delta^{13}\text{C}$ within 1.1‰ of this value. This we attribute to combustion of an indigenous C component, as the isotopic composition of this C is significantly heavier than typical terrestrial organic material, in keeping with the organic material found in other ordinary chondrite falls. If the terrestrial material is mathematically stripped from the profile by assuming a mix of two components, with compositions of -26‰ and -20.8‰ , then a C content of 0.82% is calculated for the indigenous organic component of this meteorite.

There is a further, small C release over the 600° to 700 °C temperature range with a $\delta^{13}\text{C}$ of -17.5‰ , the same isotopic composition and combustion temperature as the C from the graphite-magnetite rich nodules from Sharps (-17.3‰) and the same combustion temperature as this component in ALHA77214 (Grady *et al.*, 1982b). However, it is present in RC 075 as a minor component, representing less than 500 ppm of the total C, whereas in both Sharps and ALH A77214, it is the major C phase.

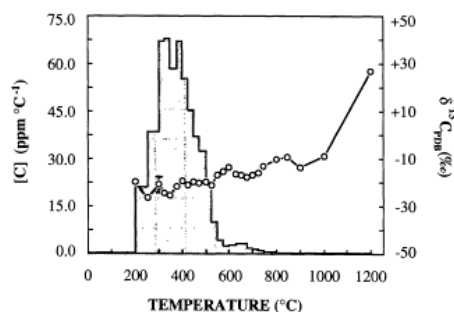


FIG. 7. Carbon stepped combustion of RC 075. The histogram shows the amount of C released at each temperature step, while the points give the isotopic composition for each step. Most of the C is released in a broad temperature range up to 550 °C.

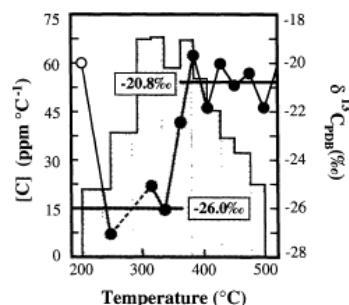


FIG. 8. Expanded view of C stepped combustion of RC 075 over the 200° to 500 °C temperature range. Histogram and points are the same as in Fig. 7. Two components can be resolved. The first at $\delta^{13}\text{C}$ of -26‰ combusts at 200° to 400 °C, while the second at -20.8‰ combusts from 375° to 525 °C. We interpret the -20.8‰ component as indigenous, whereas the -26‰ component appears to be a contaminant.

By 800 °C, most of the C has burned and, since the amount of crystalline graphite is small, the isotopic signature of the presolar SiC can be seen in the 1000° to 1200 °C temperature steps. Thus, from the high resolution stepped combustion of whole rock low grade unequilibrated ordinary chondrites, the approximate presolar SiC abundance may be calculated, by assuming the $\delta^{13}\text{C}$ of SiC is $+1400\text{‰}$ (Wright *et al.*, 1988b; Russell *et al.*, 1991), and that this mixes with C of "normal" isotopic composition. From this, the SiC abundance of RC 075 appears to be ~330 ppb. As can be seen in Fig. 9, this is close to the number determined by Huss (1990) for Krymka (3.2) and Inman (3.3), hence suggests petrologic subtype of 3.3 ± 0.1 for RC 075.

Carbon Abundance and Speciation by Vacuum Pyrolysis

The high C content of RC 075 determined by stepped combustion prompted us to conduct vacuum pyrolysis experiments (Muenow *et al.*, 1992) to determine both the abundance and speciation of volatiles in RC 075. Results from vacuum pyrolysis/dynamic mass spectrometry, however, are not directly comparable to those by combustion. During combustion, O is introduced into the system, changing both the volatile release temperatures and speciation. It does, however, allow for the removal of all C, including graphitic C. In contrast, vacuum pyrolysis releases volatiles in a manner more closely simulating the natural changes the meteorite would experience upon heating in an asteroid. Pyrolysis at the temperatures used in this study (≤ 1300 °C) cannot extract graphitic C. An advantage of dynamic mass spectrometry is the ability to simultaneously analyze a variety of volatile species, including many not capable of being detected (e.g., F) and some which are converted to CO_2 during stepped combustion/static collection mass spectrometry.

As expected from such a highly weathered sample, the major volatile release at low temperatures is water from both physically adsorbed sites and decomposition of "rust" minerals such as goethite (FeOOH). This water comprises ~5 wt% of

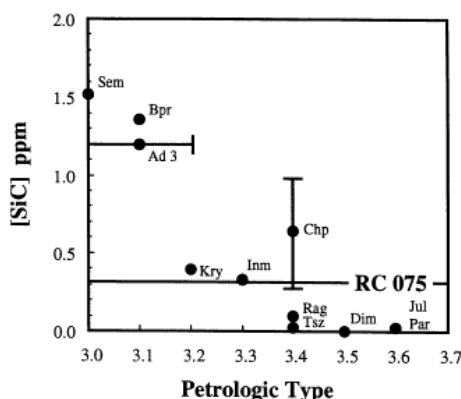


FIG. 9. The variation of presolar SiC concentration with petrologic type, with the calculated value for RC 075 shown as a line at 330 ppb. Meteorite abbreviations are Adrar 003 (Ad 3), Bishunpur (Bpr), Chainpur (Chp), Dimmitt (Dim), Inman (Inm), Julesburg (Jul), Krymka (Kry), Parnallee (Par), Ragland (Rag), Semarkona (Sem) and Tieschitz (Tsz). Data from Huss (1990) and Russell *et al.* (1992). Error bars in SiC for Chainpur are analytical uncertainty (Huss, 1990), while error bars in petrologic type in Adrar 003 reflect uncertainty in classification. The abundance of SiC in RC 075 indicates petrologic type 3.3 ± 0.1 .

the meteorite and is released at temperatures between 150° and 650 °C. The release maximum occurs at approximately 350 °C.

Carbon-containing species are released over a wide range of temperatures (Fig. 10). At temperatures <600 °C, a total of 0.23 wt% C is released. This C occurs principally as low molecular weight C_1 – C_4 hydrocarbons. At temperatures above 600 °C, a total C abundance of 0.64 wt% is measured. This C is released primarily as CO and CO_2 , with minor amounts of CH_4 . The release of these C-containing volatiles at temperatures above 600 °C occurs in three distinct peaks. An intense, well-defined peak is centered at 750 °C. We interpret this peak as release of CO_2 from carbonates. Approximately 0.21 wt% CO_2

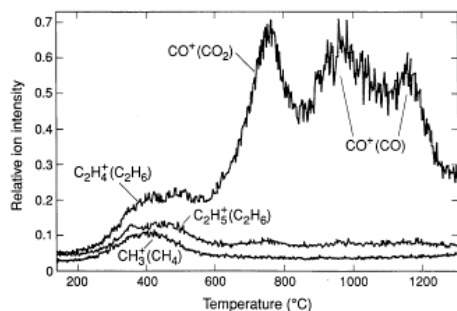


FIG. 10. Mass pyrogram for C-bearing species in RC 075, showing release profile from 150–1300 °C (background uncorrected). Ionic species are those detected; species in parentheses are their neutral molecular precursors (see Muenow *et al.*, 1992 for details).

is released which, if produced by the decomposition of $CaCO_3$, would require ~0.48 wt% carbonate to be present in the sample we analyzed, an amount not unusual for a highly weathered meteorite from Roosevelt County. Between 900° and 1100 °C, a broad peak occurs, and a final, smaller peak is observed at 1150–1200 °C. These peaks are due to CO. Methane is released at these same temperatures but in very small amounts. No hydrocarbons other than CH_4 are observed above 600 °C. Vacuum pyrolysis releases a total of 0.87 wt% C, although this value must be considered a minimum value for total C.

We have also detected the release of Cl, S_2 , Na and F beginning at 1100 °C. Intensities of Cl, S_2 and Na are still increasing at 1300 °C (the upper temperature operating limit), so no estimate of their total abundance is possible. The source of F is probably from the decomposition of a terrestrial fluoride.

We have examined a polished thin section (UH 205) of the residue from the vacuum pyrolysis experiment. It differs dramatically from the unheated RC 075 described earlier. It contains no visible terrestrial weathering products. Vesicles comprise 23.4 vol% of the residue and occur as ovoid, elongate and irregular voids up to 3 mm in length. The residue contains abundant metal (9.5 wt%), in strong contrast to the unheated RC 075, where metal is exceedingly rare. Metal in the heated residue occurs as round blebs and stringers up to 100 μm in length, dominantly in the fine-grained matrix and lining the vesicles. Qualitative analyses of numerous grains and quantitative analyses of a small number of grains reveals that they contain variable amounts of Ni (~10–20 wt%) and Co (~0.4–0.5 wt%). We suggest that these metal particles formed from the terrestrial weathering products upon heating. This process involves both dehydration at temperatures from 150–650 °C and then reduction of Fe, Ni and Co oxides by both indigenous and contaminant graphitic and organic C. This process released water at low temperatures (150–650 °C) and CO at higher temperatures (900–1200 °C). Some reduction of FeO-rich silicates may also have contributed to the formation of metal and CO.

Nitrogen

Nitrogen analyses of whole rock ordinary chondrites are rare, and all data given here are for low petrologic types (3.7 and below) analyzed at the Open University. With some notable exceptions (e.g., Yamato 74191; Sugiura and Hashizume, 1992), the bulk $\delta^{15}N$ of ordinary chondrites is generally close to 0‰, the same as the most probable terrestrial contaminant species (air and organic material) and a value for RC 075 of –5.6‰ is within the range of most other ordinary chondrites. The N content of RC 075 is high compared to other unequilibrated ordinary chondrites, in keeping with a low petrologic subtype, but N appears to have been less affected by weathering than C. The raw combustion profile is similar to that for C after the mathematical removal of the terrestrial contaminant organic C, suggesting that the contaminant is a low N organic. Nitrogen vs. C values (Fig. 11) (unpublished data, R. D. Ash and C. M. O'D. Alexander, 1993) for whole rock ordinary chondrites fall close to a straight line, indicating a constant C/N ratio which implies that the major carrier for both is the same. The raw data for RC 075 lie to the right of this line, indicating that a more C-rich material is present; but once the terrestrial organic contaminant is subtracted, the data for RC 075 plot close to this line, strengthening the assertion that the lowest temperature C is

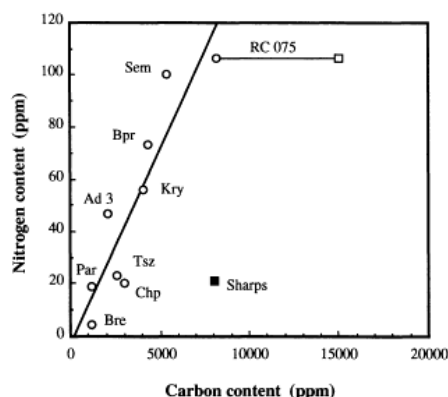


FIG. 11. Carbon and N contents of unequilibrated ordinary chondrites. RC 075: open square is the measured value, open circle is value after mathematical removal of contaminant C. Sharps contains graphite-rich nodules poor in N and, thus, appears overabundant in C. Abbreviations as in Fig. 9, with the addition of Bremervörde (Bre). Unpublished data from C. Alexander and R. D. Ash. The high abundances of C and N in RC 075 are consistent with classification as a low petrologic type.

alien to the sample. Sharps also lies off this line but, as has already been discussed, it contains numerous graphitic clasts which may be N poor, thereby accounting for the apparent overabundance of C compared with N. As can be seen in Fig. 11, there is a tendency for the lower petrologic type meteorites to be high in C and N. The high abundances of both C and N in RC 075 is further evidence for a low petrologic type.

Hydrogen

The most primitive of ordinary chondrites, with the possible exception of Krymka, show a deuterium enrichment in their H composition (Robert *et al.*, 1979; McNaughton *et al.*, 1981, 1982). It was hoped that the high organic C content of RC 075 might help to clarify the arguments as to whether the deuterium enrichment is in the organic material or bound in clay minerals. The two-step extraction yields 6.1 wt% water for the 150–1050 °C step. This large amount of terrestrial water makes it impossible to distinguish between indigenous and contaminant H. Stepped pyrolysis of RC 075 is also unable to find any water which is not of terrestrial composition, despite being carried out at higher resolution than the combustion, with seven temperature steps up to 1200 °C. The water total from the pyrolysis is only 3.9 wt%, possibly due to a lack of a suitable oxidizing agent, resulting in the breakdown of the organics and loss of the H-rich organic gases (methane, ethane, *etc.*). Figure 12 shows a comparison of the results obtained for RC 075 with those for Semarkona. It can be seen that the water content of RC 075 is some 10x that of Semarkona (a fall) and shows no signs of a deuterium enrichment.

CLASSIFICATION

Classification of unequilibrated, petrologic type 3 ordinary chondrites into H, L and LL compositional groups is

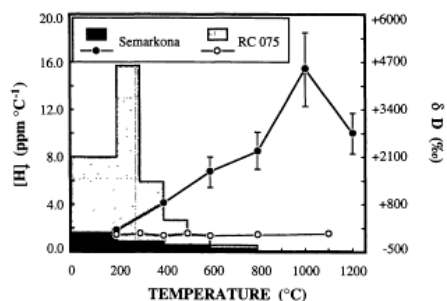


FIG. 12. Hydrogen release during stepped pyrolysis of RC 075, compared with a similar extraction of Semarkona (LL3.0). The highly weathered RC 075 contains 10x more water than Semarkona. No evidence of a deuterium enrichment is observed.

complicated and difficult, due to the general lack of clear, unambiguous classification parameters. In the case of RC 075, extensive weathering further complicates classification. The O isotopic composition of RC 075 is the most convincing parameter for classifying it as an H chondrite, although we recognize that the O isotopic composition is unusual for H chondrites. This assignment is also supported by the estimated original metallic Fe,Ni content, based on the abundances of weathering products. Mean chondrule diameters suggest classification as an L chondrite, but large uncertainties exist and the ranges of chondrule sizes in H, L and LL chondrites have not been well documented. Other parameters are not useful for chemical group classification. Siderophile element abundances have been lowered by weathering, while Co concentrations in kamacite and $\delta^{13}\text{C}$ values do not distinguish unequilibrated H, L and LL chondrites. We favor classification of RC 075 as an H chondrite but recognize the inherent difficulty in this assignment.

Classification of RC 075 as a low petrologic type is convincing, with every measurement indicating that it is an unequilibrated petrologic type 3 chondrite. Olivine heterogeneity indicates subtype ≤ 3.3 , and this is supported by the compositions of olivines in type IA and type II chondrules, some of which appear unaffected by metamorphic equilibration. Cathodoluminescence mosaics of RC 075 show that chondrules similar to those found in unequilibrated meteorites are abundant and, in terms of the type and relative abundances of chondrule groups, the meteorite is most similar to Krymka (type 3.1) and is clearly unlike Semarkona (type 3.0) and Chainpur (type 3.4). Thermoluminescence sensitivity of an acid-washed sample indicates type 3.2. Noble gas abundances indicate petrologic type 3.9, but it is conceivable that some of the less tightly bound planetary gas was lost by weathering. Finally, classification as a low petrologic subtype is reinforced by the inferred presence of presolar SiC, a mineral absent from ordinary chondrites of petrologic grade above 3.6. The abundance of presolar SiC (~ 330 ppb) is in the range of petrologic subtype 3.3 ± 0.1 . The relatively high abundance of indigenous organic matter is in keeping with such a conclusion. We, therefore, assign RC 075 to petrologic subtype 3.2 ± 0.1 and note the presence of apparently unaltered nebular components (*e.g.*, chondrules, SiC).

We have classified RC 075 as shock stage S2 (very weakly shocked), although some chondrules appear to be essentially unshocked. RC 075 is therefore classified as H3.2(S2)—the most unequilibrated H chondrite available for study.

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