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^{39}Ar-^{40}Ar chronology of R chondrites

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Abstract–This study presents the first determinations of ^{39}Ar-^{40}Ar ages of R chondrites for the purpose of understanding the thermal history of the R chondrite parent body. The ^{39}Ar-^{40}Ar ages were determined on whole-rock samples of four R chondrites: Carlisle Lakes, Rumuruti, Acfer 217, and Pecora Escarpment #91002 (PCA 91002). All samples are breccias except for Carlisle Lakes. The age spectra are complicated by recoil and diffusive loss to various extents. The peak ^{39}Ar-^{40}Ar ages of the four chondrites are ≥4.35, ~4.47 ± 0.02, 4.30 ± 0.07 Ga, and ≥4.37 Ga, respectively. These ages are similar to Ar-Ar ages of relatively unshocked ordinary chondrites (4.52–4.38 Ga) and are older than Ar-Ar ages of most shocked ordinary chondrites (<<4.2 Ga).

Because the meteorites with the oldest (Rumuruti, ~4.47 Ga) and the youngest (Acfer 217, ~4.30 Ga) ages are both breccias, these ages probably do not record slow cooling within an undisrupted asteroidal parent body. Instead, the process of breccia formation may have differentially reset the ages of the constituent material, or the differences in their age spectra may arise from mixtures of material that had different ages. Two end-member type situations may be envisioned to explain the age range observed in the R chondrites. The first is if the impact(s) that reset the ages of Acfer 217 and Rumuruti was very early. In this case, the ~170 Ma maximum age difference between these meteorites may have been produced by much deeper burial of Acfer 217 than Rumuruti within an impact-induced thick regolith layer, or within a rubble pile type parent body following parent body re-assembly. The second, preferred scenario is if the impact that reset the age of Acfer 217 was much later than that which reset Rumuruti, then Acfer 217 may have cooled more rapidly within a much thinner regolith layer. In either scenario, the oldest age obtained here, from Rumuruti, provides evidence for relatively early (~4.47 Ga) impact events and breccia formation on the R chondrite parent body.

INTRODUCTION

Though most undifferentiated meteorites are breccias, they rarely contain clasts or fragments of other meteorite groups, implying little lateral mixing within the asteroid belt during meteorite formation (Taylor 1992). R chondrites are a group of non-carbonaceous chondrites that are distinct from other chondrite groups (H, L, LL, and E) in that they define a ½ slope trend in the oxygen 3-isotope plot that has delta^{17}O values higher than that of any other chondrite group (Bischoff et al. 1994; Weisberg et al. 1991). The R chondrites also have a high oxidation state and high matrix/chondrule modal abundance ratios. These factors may suggest R chondrites formed at a greater heliocentric distance compared with other chondrites (Kallemeyn, Rubin, and Wasson 1996), or possibly from relatively primitive solar system material (Wiens, Huss, and Burnett 1999). Despite the potentially greater heliocentric distance of the R chondrite parent body, the transit time of R chondrites and ordinary chondrites to Earth is similar, as suggested by the similar exposure age range of R chondrites to that in ordinary chondrites (Schultz and Weber 2001). (The shortest exposure age among R chondrites is 0.2 ± 0.1 Ma for NWA 053, whereas a significantly longer exposure age of 35.6 ± 7.1 Ma was determined for PCA 91002.) The thermal history of R chondrites is of interest to understand the possible differences in solar system history of the R chondrite parent body compared with those of ordinary chondrites.

To address this thermal history, we measured ^{39}Ar-^{40}Ar ages on whole rock samples of four R chondrites. The impact and thermal metamorphic history of the R chondrite and ordinary chondrite parent bodies will be compared using the ^{39}Ar-^{40}Ar ages of shocked and unshocked chondrites. The various chondrite parent bodies probably formed ~4.56 Ga ago (Göpel, Manhes, and Allegre 1994). Several lines of evidence suggest that ordinary chondrites (H, L, and LL) experienced a period of extended internal metamorphism following formation of their parent bodies. This evidence includes ^{39}Ar-^{40}Ar ages of 4.52–4.38 Ga (Turner, Enright, and Cadogan 1978), Pb-Pb ages of whole rock and phosphate samples of ~4.41–4.56 Ga, Pu fission track ages down to ~4.4 Ga (Pellas and Fieni 1988), and Ni metallographic cooling rates as low as a few °C/Myr (Scott and Rajan 1981). In contrast, Ar-Ar ages of shocked ordinary chondrites are generally <4.2 Ga, though a few ages (such as Shaw) that lie between 4.3 and 4.54 Ga may have been produced by early impacts (Bogard 1995; Bogard and Hirsch 1980; Taylor et al. 1979; Turner 1969). In addition, Ni metallographic cooling rates of some strongly shocked chondrites are much faster (1°C/100 yr to 100°C/d), indicating post-shock cooling at relatively shallow depths of less than 1 km (Smith and Goldstein 1977). Prior to the present study, possible similarities or differences between the thermal histories of the R chondrite parent body and the parent bodies of other chondrites were unknown because there are only limited chronologic (classical K-Ar) data available for R chondrites (Bischoff et al. 1994; Nagao et al. 1999). ^{39}Ar-^{40}Ar dating is capable of producing more accurate ages than classical K-Ar dating.

MINERALOGY, PETROLOGY, AND EXPOSURE AGES

The R chondrite samples studied in this investigation are: Rumuruti, Carlisle Lakes, PCA 91002–41, PCA 91002–42 (two pieces from the same meteorite, not paired meteorites), and Acfer 217. Sample EET 96026 was originally included in this study, but has since been determined to belong to the class of carbonaceous chondrites rather than R chondrites (E. Tonui, personal communication; Schultz and Weber 2001).

In general, the R chondrites are characterized by moderate metamorphic recrystallization and significant brecciation and/or moderate impact melting (Rubin and Kallemeyn 1994). Ten out of 18 previously studied R chondrites are regolith breccias (Schultz and Weber 2001). The brecciated R chondrites are comprised of clasts containing relict chondrules of olivine and pyroxene in a finer-grained matrix comprised of olivine, pyroxene, plagioclase, and minor sulfides (pyrrhotite and pentlandite) (Bischoff et al. 1998; Kallemeyn, Rubin, and Wasson 1996; Rubin and Kallemeyn 1989; Rubin and Kallemeyn 1994; Schulze et al. 1994). The olivine in R chondrites has a higher Fa content than any other chondrite group, $Fa_{37–40}$, and a broad total range (e.g., $Fa_{0.4}$ to $Fa_{45.2}$ in ALH 85151) (Kallemeyn, Rubin, and Wasson 1996). This range is likely to represent the minimum range in compositions prior to partial equilibration. There are two pyroxene phases: Ca-pyroxene, and low-Ca-pyroxene, with Ca-pyroxene being the more abundant phase, ~5.8 ± 2.0 wt%, similar to the abundance in ordinary chondrites (~4–5 wt%) (Kallemeyn, Rubin, and Wasson 1996). Calcic pyroxene is classified as subcalcic augite to diopside with compositions ranging from Fs_9 to Fs_{16} (in ALH 85151 and PCA 91002, respectively). Plagioclase in R chondrites is commonly sodic, with average compositions of $Ab_{87}Or_4An_9$ in PCA 91002, $Ab_{82}Or_4An_{14}$ in Carlisle Lakes, $Ab_{85–91}Or_{2–4}An_{5–13}$ in Acfer 217, and $Ab_{86}Or_4An_{10}$ in Rumuruti (Bischoff et al. 1994; Rubin and Kallemeyn 1989; Rubin and Kallemeyn 1994; Schulze et al. 1994). Most of the radiogenic ^{40}Ar is expected to reside in plagioclase, but a minor amount may reside in the Ca-pyroxene.

Petrographic Type

The petrographic type of chondrites provides an indication of the degree of recrystallization resulting from thermal metamorphism at depth within the parent body or from shock-induced heating, both of which influence the ^{39}Ar-^{40}Ar chronometer. In brecciated samples (e.g., most of the R chondrites), the petrographic type of groundmass, clasts, and the overall petrographic type may differ. The descriptions of petrographic types below are divided into unbrecciated and brecciated samples.

Unbrecciated Sample

Though Carlisle Lakes is not classified as a breccia, the petrographic type of the groundmass and olivine phenocrysts differ. Carlisle Lakes is moderately recrystallized, with an overall petrographic type 3.8 ± 0.2, but the homogeneous olivine phenocrysts are indicative of types 4–6 (Kallemeyn, Rubin, and Wasson 1996). The matrix of Carlisle Lakes contains a relatively large proportion of translucent recrystallized material and a smaller amount of isolated silicate grains and polycrystalline fragments. The modal abundance ratio of chondrules to matrix is highest in Carlisle Lakes and much lower in the R chondrite breccias described below (Kallemeyn, Rubin, and Wasson 1996).

Brecciated Samples

Clast Lithologies: The R chondrite breccias contain clasts that have a range of petrographic types (Table 1). PCA 91002 and Acfer 217 both contain type R5–R6 clasts (Bischoff et al. 1994; Rubin and Kallemeyn 1994); Rumuruti contains types R3, -5 and -6 clasts (Schulze et al. 1994). In general, the matrices of the large light colored R5–R6 clasts are highly recrystallized. Rumuruti and Acfer 217 contain rare complete chondrules and more common chondrule fragments. The modal abundance of clasts varies in different meteorites. For example, the R5 and R6 clasts are heterogeneously distributed, are of variable size (2–20 mm), and range from 10–50 vol% of the R chondrite breccias (Kallemeyn, Rubin, and Wasson 1996).

Matrix Lithologies: The overall petrographic type of brecciated Rumuruti chondrites is based primarily on the olivine and pyroxene compositions in the groundmass

Table 1. Petrographic, shock and weathering grades, and cosmogenic exposure ages of R chondrites.

	Petrographic type	Shock[a]	Weathering	Exposure age (Ma)[b]	Breccia?
Rumuruti[c]	R3.8–6	(S2)-S3/6	W0/1	16.7 ± 0.7	Yes
PCA 91002	R3.8–6	(S2)-S5/6	W2/3	35.6 ± 7.1	Yes
Carlisle Lakes	R3.8 ± 0.2	(S3)	W2/3	6.3 ± 0.7	No
Acfer 217	R3.6–5	(S2)-S3	W5/6	34.1 ± 1.0	Yes

[a]Value in parentheses incidates overall shock grade for the meteorite. Other values give observed shock grades in clasts.
[b]Data from Schultz and Weber (2001).
[c]Rumuruti is a fall.

(Bischoff et al. 1994) and gives an indication of the overall degree of thermal metamorphism. Lack of compositional equilibration between clasts and host matrix in regolith breccias indicates that there has not been significant reheating following brecciation or during lithification (Bischoff 2000). The whole-rock matrix in becciated R chondrites is a clastic but recrystallized, impact-produced matrix that surrounds the large clastic/chondrule fragments and is distinct from pre-existing, fine-grained, interchondrule matrix within the lithic fragments (Bischoff et al. 1994). Most of the matrix that surrounds the clasts is translucent and nonporous, showing minor degrees of metamorphism with petrographic types similar to that in the matrices of type 3.7–3.9 ordinary chondrites (Huss, Keil, and Taylor 1981; Rubin and Kallemeyn 1994). This matrix consists of major olivine and minor pyroxene grains 2–3 microns in diameter (Kallemeyn, Rubin, and Wasson 1996; Rubin and Kallemeyn 1994). The overall petrographic types of the R chondrites from this study are: Acfer 217 = R3.6 ± 0.1, PCA 91002 = R3.8, Carlisle Lakes = R3.8 ± 0.2, Rumuruti = 3.8 (Kallemeyn, Rubin, and Wasson 1996). Several Yamato R chondrites studied so far also have similar overall petrographic types near 3.8 (Kallemeyn, Rubin, and Wasson 1996).

The different petrographic types of the groundmass and the clasts of the R chondrites breccias in this study may influence their ^{39}Ar-^{40}Ar ages. As has been shown for lunar breccias, the age of the clasts may be older than the age of breccia formation (Staudacher et al. 1979) because the clasts and matrix have not equilibrated in terms of their ^{39}Ar-^{40}Ar ages. Thermal metamorphism of ordinary chondrites is estimated to occur over the following ranges for different petrographic types: type 3 = 400–600ºC, type 4 = 600–700ºC, type 5 = 700–750ºC, and type 6 = 750-950ºC (Keil 2000). Most brecciated samples in this study are comprised of R3 to R6 clasts within an R3 matrix. Thus, the low petrographic type R3 matrices may have formed at temperatures 100 to 550ºC lower than those attained by the R5–R6 clasts. Because these breccias were formed at relatively low temperatures that are close to the closure temperature for argon (100–360ºC) (Turner, Enright, and Cadogan 1978), if they cooled relatively quickly, ^{39}Ar-^{40}Ar ages of the coarse-grained minerals that have relatively high closure temperatures (e.g., the highest temperature domains in feldspar) may retain a memory of their original (pre-breccia) ages. Consequently, the ^{39}Ar-^{40}Ar age derived from degassing of a given mineral may represent a mixture of ages from minerals in different clasts. The ^{39}Ar-^{40}Ar age at a given temperature could potentially be biased towards the ages of the minerals from clasts of the dominant petrographic type or towards the age of the matrix, depending on their relative modal abundances in the meteorite sample.

Weathering and Shock Effects

Weathering

The degrees of weathering and shock metamorphism of the R chondrites have been described previously but are briefly summarized here because extensive weathering and heating within the thermal environment produced by impacts can influence the ^{39}Ar-^{40}Ar age. Because Rumuruti is a fall, it is essentially unweathered (W0/1, Table 1). Carlisle Lakes and PCA 91002 are moderately weathered (W2/3), with extensively altered matrices but only minor alteration of silicate grains. Acfer 217 is severely weathered (W5/6), with staining of silicate grains, veins of iron oxides, and aqueous alteration of olivine grains (Kallemeyn, Rubin, and Wasson 1996).

Shock

The effects of shock-related heating may be important to Ar-Ar dating because some previous studies have shown that the degree of shock metamorphism of ordinary chondrites is positively correlated with the amount of noble gas loss (Anders 1964; Bogard and Hirsch 1980; Dodd and Jarosewich 1979; Heyman 1967; Stoffler, Keil, and Scott 1991). Heterogeneous shock grades in a breccia may also result from incorporation of clasts that preserve shock-features that predate breccia formation. The typical range in shock grades is S1–S6 (Stoffler, Keil, and Scott 1991). Three out of the four R chondrites in this study have low overall shock grades of S2 (Kallemeyn, Rubin, and Wasson 1996). However, individual clasts within the meteorites preserve higher shock grades. For example, the matrix and bulk of Rumuruti and Acfer 217 have shock grades of S2, but some fragments have olivine with planar fractures typical of shock stage S3 (Schulze et al. 1994; Bischoff et al. 1994). The majority of PCA 91002 is of shock stages S3–S4, but a range of shock grades, from S2–S5 (S5 = maskelynite), is preserved in its coarse-grained olivine grains (Rubin and Kallemeyn 1994). Plagioclase grains with sulfide and olivine inclusions in PCA 91002 and Rumuruti were interpreted to be impact melts (Rubin and Kallemeyn 1994). Plagioclase grains of the size observed in these samples should be produced in type 6 chondrites (Van Schmus and Wood 1967). In comparison, Carlisle Lakes, an unbrecciated sample, has experienced shock grade S3 (Table 1) (Rubin and Kallemeyn 1989).

Near complete loss of radiogenic ^{4}He and ^{40}Ar occurs at high shock pressures equivalent to S5 and S6 , whereas lower shock pressures of 10 GPa (equivalent to S1 and S2) do not cause noble gas loss (Stoffler, Keil, and Scott 1991). Although there is some suggestion that higher shock grades are associated with high petrographic types in shocked H, L, and LL chondrites, there is no strict correlation between them (Stoffler, Keil, and Scott 1991). This is probably because the response of material to shock also depends on the mineralogy, porosity, and ambient temperature prior to shock compression. The overall shock stage of a regolith breccia or fragmental breccia reflects the peak shock pressure experienced by the whole rock following lithification (Stoffler, Keil, and Scott 1991). In contrast, previously shocked, porous material, such as a poorly lithified breccia, responds heterogeneously to additional shock pressure on a microscale within the sample, so that individual grains vary spatially from unshocked to shock melted (Schaal and Horz 1980; Kieffer and Simonds 1980; Ashworth and Barber 1976; Bischoff et al. 1983; Stoffler, Keil, and Scott 1991). The available data suggest that the shock grade provides a very qualitative indication of the relative amount of shock metamorphism experienced by a brecciated meteorite.

Heterogeneous shock grades observed in the brecciated R chondrites may arise in part from a heterogeneous response of the breccia to shock. The differences in shock grades in various clasts within R chondrite breccias may alternatively suggest that they preserve a shock history that pre-dates breccia formation. The high shock grades in some regions of PCA 91002 and Rumuruti may suggest that local shock heating and loss of radiogenic argon occurred near the time of impact. In the other R chondrites from this study, the shock grades are generally low, which suggests that only minor shock-induced heating occurred.

Exposure Ages and Solar Gases

Cosmogenic noble gases are produced by reactions of energetic particles on target nuclides within near-surface regions of a body exposed to space. These cosmogenic gases yield space exposure ages, which provide an estimate of the time of exposure on the parent body and/or transit from the parent body to Earth. Solar noble gases are implanted by solar wind into the outer 1 micrometer of a target surface, and the presence of solar gases in a meteorite, including some R chondrites, is interpreted to indicate that its individual grains once resided at the surface of the parent body. These ages can be used, in conjunction with the Ar-Ar ages, to understand the history of a meteorite.

Space exposure ages calculated from cosmogenic nuclides in R chondrites (Schultz and Weber 2001) range from 0.2 to 50 Ma, with most having ages of >7 Ma. The exposure ages of Acfer 217 and PCA 91002 are similar to each other (34.1 ± 1.0 and 35.6 ± 7.1 Ma, respectively, Table 1) and would permit ejection in a single event from the parent body. These exposure ages are distinctly older than that of Rumuruti (16.7 ± 0.7 Ma) (Schultz and Weber 2001). In contrast, Carlisle Lakes (not brecciated) has a relatively young exposure age (6.3 ± 0.7 Ma). Carlisle Lakes does not contain solar gases and was probably well shielded from the solar particle flux, whereas solar gases are present in Acfer 217, PCA 91002, and Rumuruti (Schultz and Weber 2001).

METHODS

The experimental methods and data reduction procedure used in this study are similar to those described by Bogard and Hirsch (1980) and Bogard, Garrison, and McCoy (2000), with the exception of the acid treatments described below. The R chondrite samples were rock fragments obtained from at least 1 cm from the outer fusion crust of the meteorite to avoid sampling the portions of the meteorite that were heated during atmospheric entry. These fragments were coarsely crushed in a mortar and pestle. Rumuruti-a and PCA 91002–41a were only rinsed in acetone and deionized water and received no acid treatment. Previous studies (e.g., Turner and Cadogan 1974) have shown that disturbed argon spectra are common in chondrites with fine-grained matrices (for reasons that will be explained in a later section). The fine-grained nature of the R chondrites in this study precluded mineral separation as a means to eliminate this problem. Thus, acid treatment to dissolve much of the fine-grained matrix was used as an alternative approach to alleviate the problem. Acid treatment to remove the interclastic matrix also provides a means to evaluate whether there are age differences between the clasts and matrix. For all samples except Rumuruti-a and PCA 91002–41a, small chips weighing a total of 115–161 mg were ultrasonically washed in 1 N nitric acid for 5 min. PCA 91002–41b was also treated with 2 N HCl for 13 mins. Samples were then washed in DI H_2O for 2 min, in 3 N nitric acid for 10 min, DI H_2O for 2 min, dried for 1–4 hr on a hot-plate at 60ºC, then packed in aluminum foil. Though most interclastic matrix minerals were dissolved during the acid treatments of PCA 91002–41b, a small amount remained. However, for Rumuruti-b, only large white clasts remained following acid dissolution of the matrix. These white clasts were very friable and could be easily disaggregated. Several NL-25 hornblende flux monitors, also packaged in foil, were interspersed with the samples in sealed quartz tubes and were irradiated for 120 hr at the University of Missouri Nuclear Reactor with a neutron fluence of 1.3×10^{19} cm^2/sec^2. PCA 91002–41a was irradiated separately from the other meteorites. The NL-25

Table 2. Sample treatment, sample mass analyzed, and J values.

Sample	Sample mass, pre-acid treatment (g)	Sample mass, post-acid treatment (g)	% Sample dissolved	Sample mass analyzed (g)	J value
Rumuruti-a	0.0346	Not applicable	Not applicable	0.0346	0.02088 ± 0.00017
Rumuruti-b	0.135	0.093	31	0.0361	0.02030 ± 0.00017
PCA 91002–41a	0.0395	Not applicable	Not applicable	0.0395	0.02835 ± 0.00003
PCA 91002–41b	0.118	0.060	49	0.0348	0.02100 ± 0.00007
PCA 91002–42	0.161	0.114	29	0.0364	0.02100 ± 0.00007
Carlisle Lakes	0.115	0.108	6	0.0353	0.02100 ± 0.00007
Acfer 217	0.136	0.132	3	0.0342	0.02100 ± 0.00007

hornblende has an age of 2.65 Ga and uncertainty of <0.5% (Bogard et al. 1995).

The neutron irradiation constants, J, were determined from interpolation among measurements of the NL-25 hornblende monitors (Table 2). A correction for atmospheric argon was applied to the hornblende monitors. This correction was based on the assumption that all of the ^{36}Ar was atmospheric in origin and amounted to ~1% of the total ^{40}Ar. Uncertainties in J are not included in plots of the various Ar-Ar age spectra presented below, as all temperature extractions of a given sample have the same value of J. The age uncertainties in these plots were derived from all uncertainties in the ^{40}Ar/^{39}Ar ratio, including uncertainties in ratio measurement and corrections for system blanks and reactor-produced interferences. In contrast, reported Ar-Ar ages for a given sample (Table 3) were obtained by taking a mean age (weighed according to the amount of ^{39}Ar released) among individual temperature extractions possessing similar ages (Bogard, Garrison, and McCoy 2000). Uncertainties in the reported ^{39}Ar-^{40}Ar ages are derived both from the uncertainty in this mean age and the error in the J-value (Bogard, Garrison, and McCoy 2000).

RESULTS

In Figs. 1a–h, the calculated ^{39}Ar-^{40}Ar ages and K/Ca ratios are plotted against the cumulative fraction of ^{39}Ar released for individual temperature extractions of 4 R chondrites (and replicates to test the effects of acid treatment). Some of these R chondrite analyses show evidence of recent diffusive loss of loosely trapped ^{40}Ar from low temperature extractions, and some show evidence of significant recoil redistribution of ^{39}Ar during neutron irradiation. Because recoiled ^{39}Ar complicates interpretation of these age spectra, before discussing the ages from individual R chondrite analysis, we first present a brief summary of the anticipated effects of ^{39}Ar recoil on Ar-Ar age spectra.

Because ^{39}Ar recoils ~0.1 μm when it forms in the reactor via the ^{39}K(n, p)^{39}Ar reaction, a net transfer of ^{39}Ar can occur from surfaces of K-bearing grains to surfaces of K-poor grains (Huenke and Smith 1976; Turner and Cadogan 1974). This recoil redistribution is more pronounced for small grains with larger surface to volume ratios. Loss of recoiled ^{39}Ar can produce an artificially old age in some portions of the age spectrum and a gain of ^{39}Ar can produce an artificially young age in other parts of the age spectrum. In most meteorites, the K-rich, Ca-poor phase with high K/Ca ratios—commonly feldspar—degasses its Ar at lower extraction temperatures compared with K-poor phases with lower K/Ca ratios, such as Ca-pyroxene. Further, ^{39}Ar recoil effects are expected and observed during the earlier stages of degassing of a particular mineral phase, when grain surfaces release their Ar. Consequently, the initial stages of degassing of Ca-pyroxene at relatively high temperatures should cause decreases in the ^{39}Ar-^{40}Ar age, decreases in the K/Ca ratio, and concurrent increases in the fractional amounts of ^{37}Ar released (owing to the reaction ^{40}Ca[n, α]^{37}Ar). At later stages of Ca-pyroxene degassing, most of the recoiled ^{39}Ar will have been lost from

Table 3. R chondrite compositions (K, Ca) and ^{39}Ar-^{40}Ar ages.

	K (ppm)	Ca%	K/Ca	^{40}Ar cc/g (× 10^{-5})	Total gas age (Ga)[a]	Estimated age (Ga)[b]
Rumuruti-a	1055	1.30	0.081	6.06	4.29	~4.47 ± 0.02 peak 4.45 ± 0.03 plat
Rumuruti-b	1130	1.51	0.075	6.79	4.35	~4.45 ± 0.01 peak 4.40 ± 0.04 plat
PCA 91002–41a	775	1.13	0.069	2.07	3.84	>4.37 ± 0.01 peak
PCA 91002–41b	341	0.99	0.035	2.07	3.42	>4.05 ± 0.02 peak
PCA 91002–42	469	0.86	0.055	3.28	3.72	>3.35 (minima)
Carlisle Lakes	954	1.24	0.077	4.01	3.78	>4.35 ± 0.01 peak
Acfer 217	1233	1.48	0.083	4.13	3.50	4.30 ± 0.07 (4.18 ± 0.06)[c]

[a]Total gas age represents a minimum estimate of the true age because of diffusive ^{40}Ar loss from the samples.
[b]'Peak' inidcates maximum observed age from high-temperature gas extractions. 'Plat' indicates pseudo-plateau age.
[c]Secondary age plateau.

the surfaces of pyroxene grains. Consequently, at the very highest temperatures, the ^{39}Ar-^{40}Ar ages commonly increase because Ar from the highest temperature domains of feldspar dominates the total Ar released in each extraction. In some cases, the amount of recoil-induced ^{39}Ar lost from low temperature releases may be equal to the amount that is added to the high temperature releases. However, if some of the recoiled ^{39}Ar is not implanted into grain surfaces of K-poor phases, but is instead lost from the system, the ^{39}Ar recoil effect at a lower temperature may be more pronounced than the effect at a higher temperature.

Interpretation of the effects of ^{39}Ar recoil on the age spectrum can be further complicated by diffusive loss of ^{40}Ar or deposition of K on grain surfaces during terrestrial weathering. In some cases, these difficulties can be overcome by careful evaluation of the different parts of the age spectrum. As mentioned above, loss of recoiled ^{39}Ar elevates the ^{39}Ar-^{40}Ar ages of low temperature phases (fine-grained matrix phases), but loss of ^{39}Ar is unlikely to occur from phases that degas at higher temperatures. Instead, the ages of high temperature phases are more likely to be decreased by the addition of ^{39}Ar and/or diffusive loss of ^{40}Ar. Argon that degasses from the interior of grains is probably not affected by ^{39}Ar recoil redistribution, meaning that the intermediate portion of the age spectrum, and the highest temperature extractions, may be unaffected by recoil, as will be discussed in further detail in a later section.

Total Gas ^{39}Ar-^{40}Ar Ages

The total gas ^{39}Ar-^{40}Ar age is obtained from the total argon released from the sample by summing the individual gas extractions and can be compared with the best estimate of the Ar-Ar age from individual gas extractions (Table 3). In most meteorite samples from this study, low-temperature diffusive loss of ^{40}Ar appears to have lowered the total gas ages with respect to the best estimate for the Ar-Ar age from individual gas extractions. (The exception is PCA 91002–42, which has a highly disturbed release profile and so does not yield a good age estimate.) The total gas ages are lower than the best estimate for the peak Ar-Ar age by 0.1 Ga (Rumuruti-b) to 0.8 Ga (Acfer 217).

^{39}Ar-^{40}Ar Age Spectra

Peak Ages Versus Plateau Ages

The following evaluation will focus on ^{39}Ar-^{40}Ar ages from individual gas extractions, which preserve age information in addition to that determined from the total gas age. As explained above, all recoiled ^{39}Ar gained by high-temperature sites should be balanced by an equal amount of ^{39}Ar recoil loss at other sites, unless some recoiled ^{39}Ar has been lost from the sample. In order to evaluate whether ^{39}Ar has been lost, the age spectra are "corrected" by redistributing the recoiled ^{39}Ar from the high temperature sites to the low-temperature sites where it originated, using the maximum observed ^{39}Ar-^{40}Ar age as the best estimate for the true age. This correction has no effect on the total gas age because the total amount of ^{39}Ar is not changed. There are three general possible cases. First, if the ^{39}Ar subtracted from the highest temperature sites and added to the lowest temperature sites decreases the ages of the low temperature extractions to values that are younger than the maximum ages in intermediate temperature extractions, then the maximum observed ages from the intermediate temperature extractions are unlikely to have been substantially elevated by the loss of recoiled ^{39}Ar from the system. Second, if the ages of low temperature extractions are older than those from the highest temperature extractions despite redistribution of recoiled ^{39}Ar, then ^{39}Ar has clearly been lost from the sample. Third, if the ^{39}Ar subtracted from the highest temperature sites and added to the lowest temperature sites gives low temperature ages that are younger than the intermediate plateau ages, then diffusive loss of ^{40}Ar probably occurred from the sample. Note that it is sometimes difficult to determine whether the intermediate (age plateau) extractions have been affected by the ^{39}Ar transfer. Although the recoil is somewhat subjective, the corrected argon spectra provide a very general means by which to evaluate whether ^{39}Ar loss occurred from the sample and the validity of the maximum observed ^{39}Ar-^{40}Ar age from high temperature extractions.

Rumuruti: The ^{39}Ar-^{40}Ar age spectrum of Rumuruti (a fall) was analyzed on two different splits, untreated (Rumuruti-a) and acid treated (Rumuruti-b) (Table 2), and results are presented in Figures 1a and 1b. The two age spectra are similar, and both suggest age plateaus of about 4.45 Ga across ~20–80% of the ^{39}Ar release. The drop in age at ~85% ^{39}Ar release (labeled "B" in Figs. 1a, b) is correlated with a decrease in K/Ca produced by the onset of Ar degassing from a more mafic phase, probably pyroxene. This decrease in age is attributed to release of recoiled ^{39}Ar implanted into pyroxene grain surfaces and is followed by a partial recovery (increase) in age at >90% ^{39}Ar release, as the recoiled excess ^{39}Ar becomes degassed. The evidence for slightly increased ages at low extraction temperatures is attributed to a recoil loss of ^{39}Ar (e.g., at ~5–10% ^{39}Ar release) (region labeled "A" in Figs. 1a, b). However, this slight increase in age appears to represent an insufficient amount of recoiled ^{39}Ar to account for the gain of ^{39}Ar that would be required to produce the low ages at >80% ^{39}Ar released, unless the ages at low temperatures were initially lowered by diffusive loss of ^{40}Ar.

We subtracted the "excess" ^{39}Ar indicated in the highest temperature extractions, where the excess is defined relative to an age of 4.45 Ga, and added it to the low temperature extractions to obtain the "corrected" Ar-Ar age spectrum for Rumuruti-b shown in Fig. 1c. Figure 1c thus represents a reconstituted age spectrum in the absence of ^{39}Ar recoil effects and suggests that this sample experienced only modest amounts of prior ^{40}Ar diffusion loss from low temperature sites. The amount of recoiled ^{39}Ar in Rumuruti-b (6×10^{-9} ccSTP/g or 4.14% of the total ^{39}Ar released) is less than in Rumuruti-a (1×10^{-8} ccSTP/g or 8.78% of the total ^{39}Ar released), as is suggested by the lower minimum age at high temperatures in Rumuruti-a. From this we conclude that the acid treatment to dissolve 30% of Rumuruti-b decreased the amount of recoil-induced ^{39}Ar, presumably by removing the smallest meteorite grains without affecting the ^{39}Ar-^{40}Ar age in the higher temperature release fractions.

It seems likely that some recent diffusive loss of ^{40}Ar has occurred from Rumuruti, which acts to mask a portion of the recoil ^{39}Ar lost in these low temperature sites. Sites with obvious ^{39}Ar loss occur only in the first ~15% of the ^{39}Ar released (Figs. 1a, b), implying that the apparent Ar-Ar age plateaus across ~20–80% of the ^{39}Ar release probably are unaffected by ^{39}Ar recoil, as might be expected for Ar degassing from interiors of feldspar grains. Rumuruti-a gives an Ar-Ar plateau age of 4.45 ± 0.03 Ga for 5 extractions releasing 15–70% of the ^{39}Ar (55% ^{39}Ar). Acid treated Rumuruti-b gives a plateau age of 4.40 ± 0.04 Ga for 8 extractions releasing 24–78% of the ^{39}Ar (54% ^{39}Ar). However, the age spectra for both samples exhibit a slight upward slope across these plateaus. This slope conceivably could have been produced by different K-Ar closure times caused by slow cooling in the parent body. More likely, however, the slope suggests that some prior diffusive loss of ^{40}Ar has occurred for these releases and that these plateau ages are lower limits to the last Ar degassing event. A preferred Ar-Ar age for each sample is better defined by the maximum age within each age plateau. Two extractions releasing 59–70% of the ^{39}Ar for Rumuruti-a gives an age of 4.47 ± 0.02 Ga, and two extractions releasing 59–72% of the treated Rumuruti-b give an age of 4.45 ± 0.01 Ga.

Acfer 217: The age spectrum of Acfer 217 (Fig. 1d) indicates diffusive loss of ^{40}Ar at relatively low temperatures, over ~0–30% of the ^{39}Ar release, and a gain of recoiled ^{39}Ar at ~80–90% ^{39}Ar release, where a decrease in K/Ca ratio indicates initial degassing from grain surfaces of a more mafic phase. This age spectrum has several extractions showing the same age within uncertainty. Interestingly, Acfer 217 displays two apparent ^{39}Ar-^{40}Ar age plateaus in the intermediate temperature steps releasing ~30–80% of the ^{39}Ar. Six extractions releasing ~30–50% of the ^{39}Ar define an Ar-Ar age of 4.18 ± 0.06 Ga, and 9 extractions releasing ~50–80% of the ^{39}Ar define an age of 4.30 ± 0.07 Ga. Both plateau ages are younger than those of other meteorites obtained in this study (with the exception of PCA 91002–42, the age of which is not well constrained).

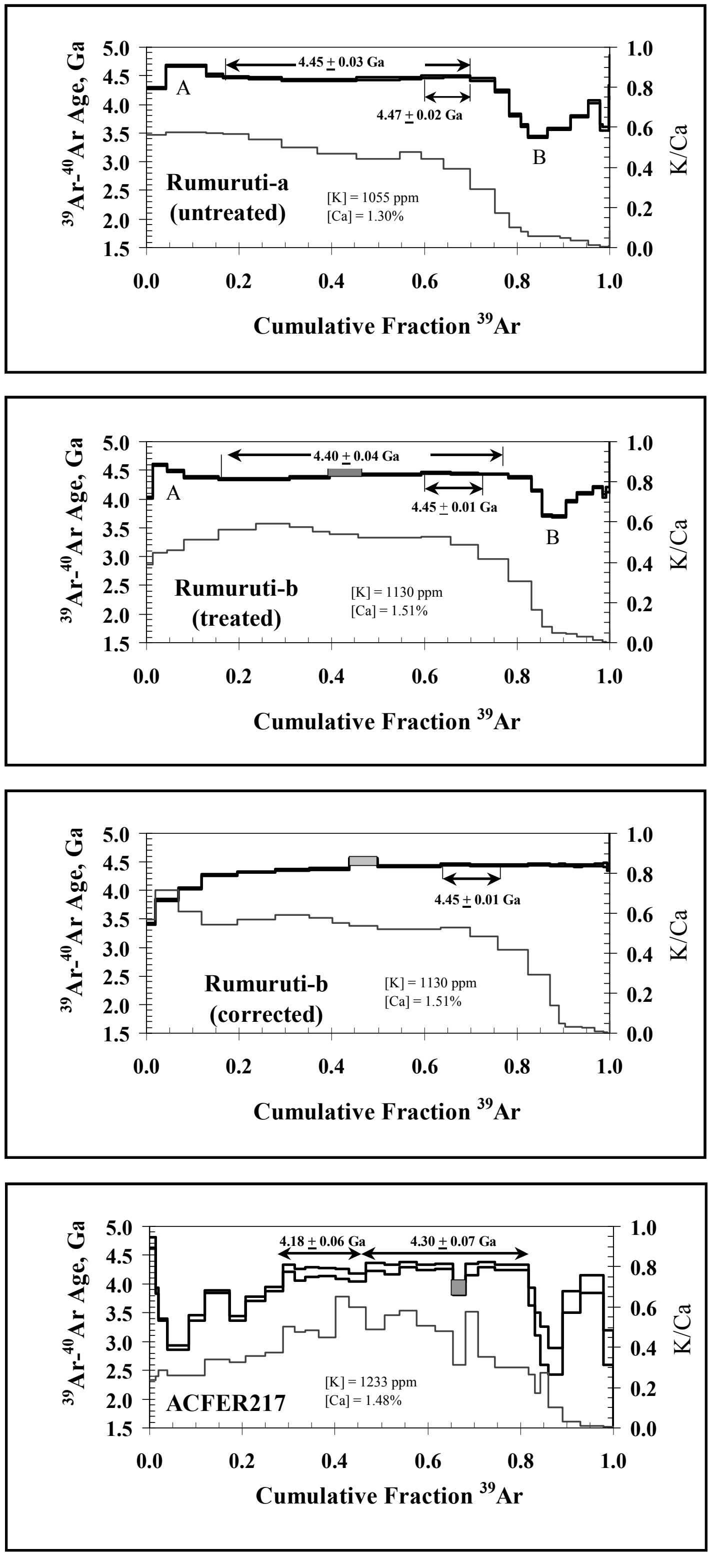
The explanation for the two apparent plateaus in the ^{39}Ar-^{40}Ar age spectra of Acfer 217 could be related to different degrees of resetting of the ^{39}Ar-^{40}Ar chronometer in different grain-size fractions (e.g., matrix versus phenocrysts). Unfortunately, owing to the lack of very accurate temperature control during small (25ºC) incremental degassing steps used for this sample, the differential release curve of argon as a function of temperature is irregular and does not permit identification of different fractions. Likewise, the K/Ca ratios are also irregular and do not provide information on the possible number of phases present.

PCA 91002: PCA 91002–41a (unetched) shows a maximum measured age of 4.37 Ga (Fig. 1e). The age spectrum indicates diffusive loss of ^{40}Ar at lower temperatures. Gain of recoiled ^{39}Ar is evident in the sharp decrease in ages down to <2.5 Ga observed in the high temperature steps (~80–100% of the ^{39}Ar release), and these same extractions also give the lowest values of K/Ca. As described above for Rumuruti, the absence of expected old ages due to ^{39}Ar recoil in the very early stages of gas release is attributed to greater effects of diffusive loss of ^{40}Ar, which would act to decrease the ages.

Acid treatment of PCA 91002–41b (Fig. 1f) dissolved 49 wt% of the sample, including much of its fine-grained matrix (Table 2). Previous studies determined that acid (HF) etching of feldspar reduced the physical grain size, which caused a decrease in the sample's total ^{40}Ar content, and a relative increase in the percentage of K in the sample residue owing to dissolution of material with relatively low K content (Zeitler and Fitz Gerald 1986). Compared with the unetched sample, PCA 91002–41b has a lower ^{40}Ar concentration (by a factor of 2.3), lower K (56% lower) and Ca contents (12.4% lower), and a 50% lower K/Ca ratio. This indicates that both K and Ca-bearing phases were dissolved in PCA 91002–41b.

In spite of the removal of significant amounts of fine-grained material by acid etching, a large recoil effect still exists in PCA 91002–41b (Fig. 1f). Furthermore, although the argon release spectra are generally similar for etched and unetched samples, the oldest age from PCA 91002–41b (4.05 ± 0.02 Ga) is ~320 Ma younger than that from PCA 91002–41a (4.37 ± 0.01 Ga) (Figs. 1f and 1e, respectively). These oldest ages are obtained from gas released between 700–825ºC in both samples.

Using the same technique described above for Rumuruti, the amount of recoil-induced ^{39}Ar, expressed as a percentage of the total ^{39}Ar released, is lower in PCA 91002–41a (11.7%) than in PCA 91002–41b (14.8%). The most likely explanations for the increase in recoiled ^{39}Ar in the etched meteorite are that first, unlike in Rumuruti, significant amounts of fine-grained intraclastic and interclastic matrix still remained in PCA 91002–41b even following acid etching. Second, acid etching probably decreased the grain-size of the feldspar phenocrysts, causing a relative increase in the amount of fine-grained K-rich material that is the source of recoiled ^{39}Ar. The slightly younger maximum observed age of PCA 91002–41b relative to PCA 91002–41a at 75–80% of the ^{39}Ar released was probably caused by concurrent


4.45 ± 0.03 Ga
4.47 ± 0.02 Ga
A
B
Rumuruti-a
(untreated)
[K] = 1055 ppm
[Ca] = 1.30%
4.40 ± 0.04 Ga
4.45 ± 0.01 Ga
Rumuruti-b
(treated)
[K] = 1130 ppm
[Ca] = 1.51%
4.45 ± 0.01 Ga
Rumuruti-b
(corrected)
[K] = 1130 ppm
[Ca] = 1.51%
4.18 ± 0.06 Ga
4.30 ± 0.07 Ga
ACFER217
[K] = 1233 ppm
[Ca] = 1.48%
39Ar-40Ar Age, Ga
K/Ca
Cumulative Fraction 39Ar

a

b

c

d

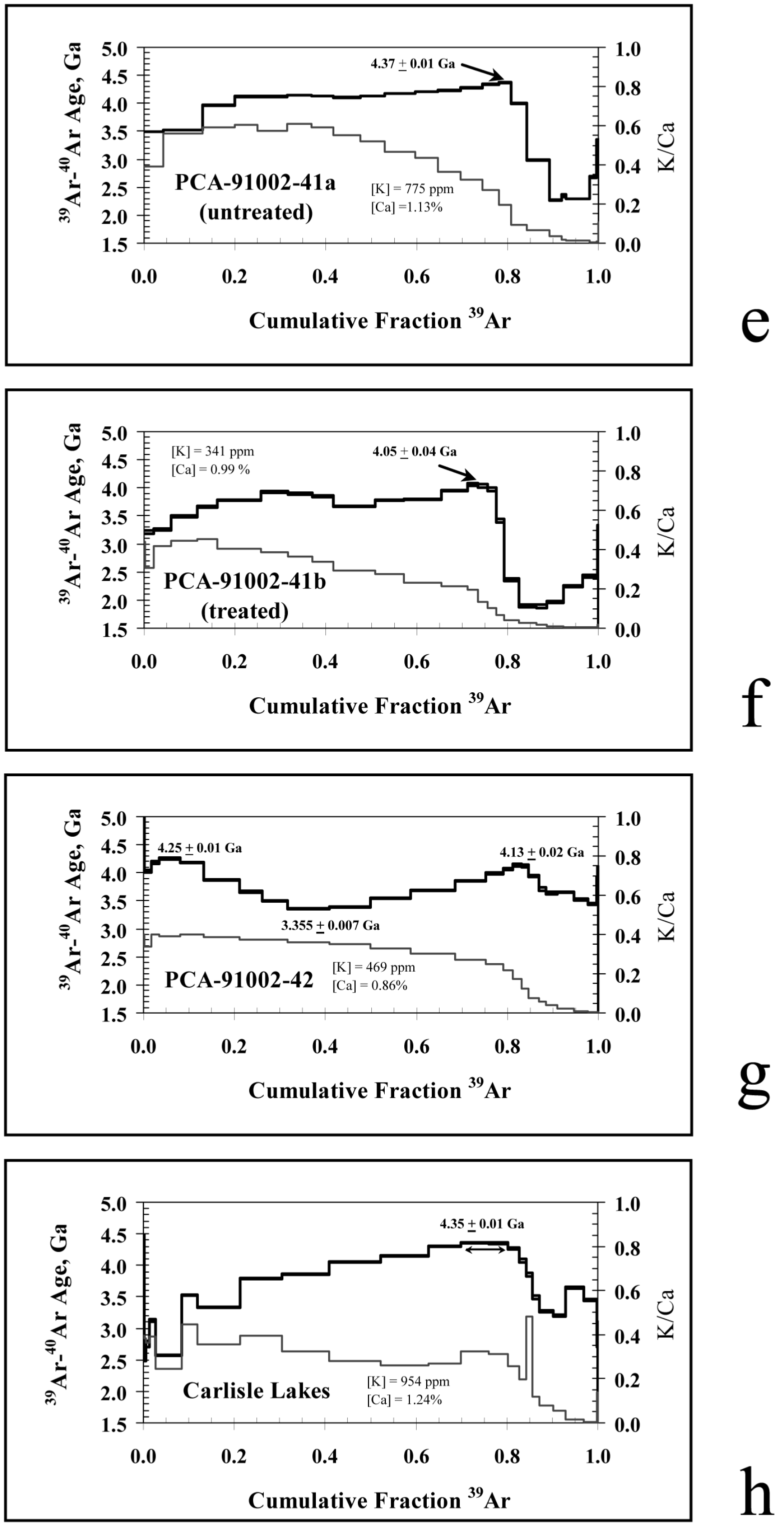


Fig. 1. ^{39}Ar-^{40}Ar age in Ga (black rectangles on primary y axis) and K/Ca ratio (light gray stepped line on secondary y axis) versus the cumulative fraction of ^{39}Ar released for eight R chondrite samples: a) Rumuruti-a (not acid-treated), see text for explanation of portions of spectrum labeled "A" and "B"; b) Rumuruti-b (acid-treated), note that the analysis shaded with a gray box is likely to be an analytical error; c) Rumuruti-b (corrected) is the corrected argon spectrum for Rumuruti-b; d) Acfer217; e) PCA 91002–41a, not acid treated; f) PCA 91002–41b is an acid-treated fraction of PCA 91002–41; g) PCA 91002–42 is a different piece of the same meteorite as those shown in e and f; h) Carlisle Lakes.

degassing of feldspar with pyroxene that had a somewhat higher proportion of ^{39}Ar. This means that the age of PCA 91002–41b (4.05 ± 0.02 Ga) is a minimum estimate. Although sample -41a was not acid-treated, the pronounced diffusion profile in its corrected age spectrum suggests that its maximum observed age of 4.37 ± 0.01 Ga is also likely to be a minimum estimate of its true ^{39}Ar-^{40}Ar age.

PCA 91002–42 was derived from a separate piece of the same meteorite than PCA 91002–41a and PCA 91002–41b and was comprised predominantly of a light colored clast. Sample PCA 91002–42, which was acid-treated, has a higher K content (469 ppm), lower Ca (0.86 wt%), and a higher K/Ca ratio (0.055) than PCA 91002–41b. The total Ar-Ar age of PCA 91002–42 (~3.72 Ga) is older in than PCA 91002–41b (~3.42 Ga) but younger than PCA 91002–41a (~3.84 Ga). A different type of ^{39}Ar-^{40}Ar age spectrum is observed in PCA 91002–42 (Fig. 1g) than in PCA 91002–41a and PCA 91002–41b. The spectrum appears "saddle-shaped," with peak ages of ~4.25 and ~4.13 Ga in the low and high temperature release fractions, respectively, and a minimum age of ~3.35 Ga in the intermediate temperature release fractions (Fig. 1g). The maximum and minimum ages are approximately correlated with variations in the differential release curves (not shown), suggesting that they are produced in part by degassing of different mineral phases and/or grain size fractions. Overall, the ^{39}Ar-^{40}Ar age of PCA 91002–42 is ambiguous. The total gas age of ~3.72 Ga is chosen as the best minimum estimate of the ^{39}Ar-^{40}Ar age, as clearly, it is much younger than the best age estimates of PCA 91002–41a and PCA 91002–41b. In summary, the differences in the age spectra of PCA 91002–41a, PCA 91002–41b and PCA 91002–42 are likely to be produced by different relative proportions of K-rich to K-poor phases, as well as to different proportions of fine-grained matrix to larger clasts.

Carlisle Lakes: Like the meteorite samples discussed above, the Ar-Ar age spectrum for Carlisle Lakes (Fig. 1h), the only unbrecciated sample from this study, shows evidence for diffusive loss of ^{40}Ar at low and intermediate temperatures and recoil gain of ^{39}Ar for those extractions where a decrease in K/Ca ratio indicates degassing of a more mafic phase (i.e., ~85–95% ^{39}Ar release). The amount of ^{40}Ar lost by diffusion is more significant in this sample than in the other samples. Substantial ^{40}Ar loss commonly occurs when samples are highly weathered. Although this sample is less weathered than Acfer 217 (Table 1), it appears to have experienced more ^{40}Ar diffusive loss, making it difficult to attribute ^{40}Ar loss in this sample solely to weathering effects. The corrected profile to redistribute recoiled ^{39}Ar does not suggest that significant amounts of recoiled ^{39}Ar have been lost from the sample, though the significant amount of diffusive ^{40}Ar loss may potentially obscure evidence of such loss. The maximum observed age of 4.35 ± 0.01 Ga is considered to be a minimum estimate of the ^{39}Ar-^{40}Ar age, in light of the significant amount of diffusive loss of ^{40}Ar compared with the apparently relatively minor recoil-induced decrease in the age at high temperatures (Fig. 1h).

DISCUSSION

Comparison of R Chondrite Ages with Ordinary Chondrite Ages

Using peak ages as the preferred measure of the closure time of the K-Ar chronometer, the R chondrites investigated in this study show a range in ages from 4.30 to >4.47 Ga, an age difference of approximately 0.17 Ga (between Rumuruti and Acfer 217). This range in ages is compared with that in ordinary chondrites in Fig. 2, a histogram of ^{39}Ar-^{40}Ar ages from the ordinary and R chondrites. The age data for the ordinary chondrites are derived mainly from Bogard (1995 and references therein) and Turner, Enright, and Cadogan (1978). It is important to bear in mind that in some studies, (e.g., Turner, Enright, and Cadogan 1978), samples with relatively low shock grades were deliberately selected, while the review by Bogard (1995) focuses on impact-reset ages. Several ordinary chondrites, mainly surface breccias, show Ar-Ar ages of ~3.5–3.9 Ga. The impacts that produced these reset Ar-Ar ages may be related to those that reset lunar highland rocks and eucrite meteorites (Bogard 1995). Many ordinary chondrites, especially shocked L-chondrites, show impact resetting of Ar-Ar ages at <1 Ga, and it has been suggested that the L-chondrite parent body may have been disrupted ~0.5 Ga ago (McConville, Kelley, and Turner 1988). We see no evidence in our Ar-Ar data for R chondrites to suggest significant impact degassing events that occurred later than ~4.0 Ga ago. Thus, these R chondrites apparently did not experience the parent object collisions of <1 Ga ago that are observed in many ordinary chondrites. Futher, these R chondrites do not show any evidence of Ar-Ar resetting during a cataclysmic bombardment ~3.5–4 Ga ago. Yet, the brecciated nature of most R chondrites, combined with evidence of a surface history on their parent body, suggests that thermal signatures of late impact events might be expected. Of course, having analyzed only four R chondrites, we cannot exclude the possibility that other R chondrites experienced significant heating from late impacts.

The range in ages of the R chondrite breccias is similar to that of relatively unshocked LL and L chondrites, which also have Ar-Ar ages from ~4.2 to ~4.5 Ga (Turner, Enright, and Cadogan 1978). We wish to resolve whether the range in ages of the R chondrites was produced by: 1) relatively early impact resetting on the R chondrite parent body; 2) relatively slow cooling within the parent body; or 3) terrestrial weathering effects. We will first address the possible effects of terrestrial weathering, which are unlikely to produce the range in observed ^{39}Ar-^{40}Ar ages in the R chondrites, and then assess the possible parent body process.

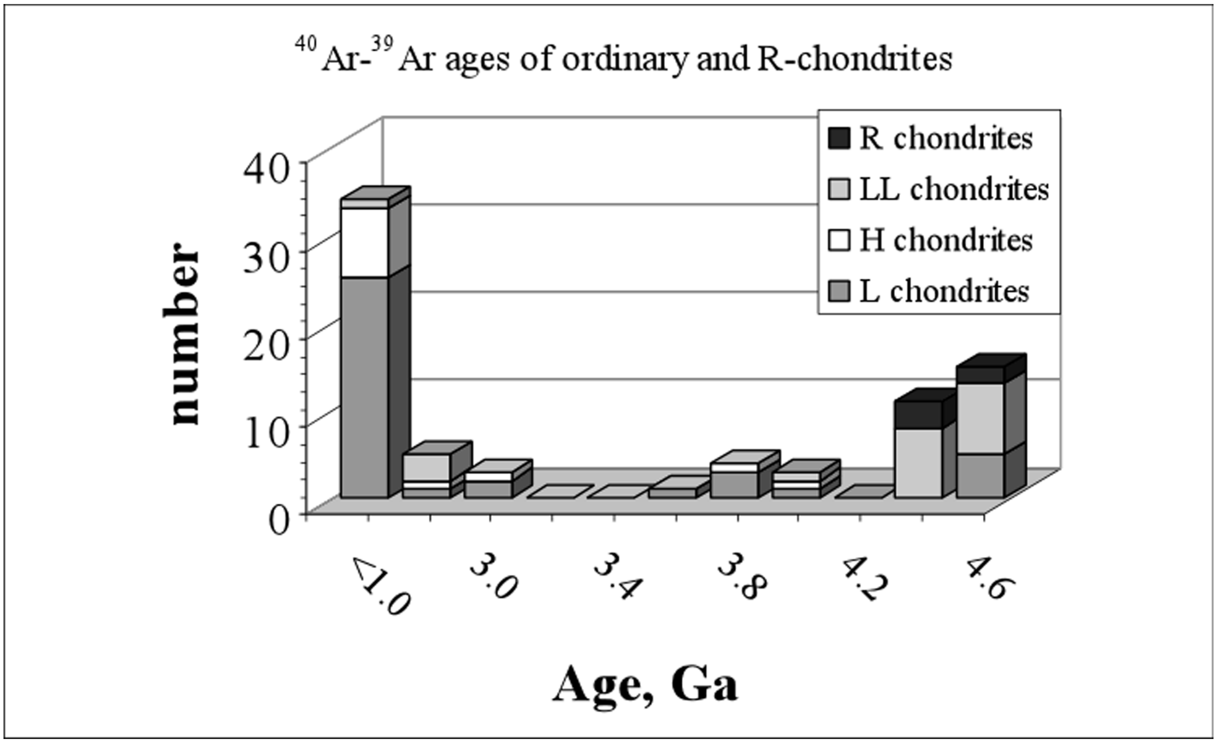


Fig. 2. Histogram of the ^{39}Ar-^{40}Ar ages of the R chondrites and the ordinary (LL, H, and L) chondrites. Note the change in the x-axis scale at 3.0 Ga. The R chondrites have relatively old ages that overlap those of the oldest L and LL ordinary chondrites. There is a secondary peak in ages of ordinary chondrites centered about 3.6–3.8 Ga not seen in any of the R chondrites from this study. Data sources: Bogard 1995 and references therein; Kaneoka 1980; Kaneoka 1981; Trieloff et al. 1994a; Trieloff, Jessberger, and Oehm 1989; Trieloff, Kunz, and Jessberger 1994b; Turner, Enrights, and Cadogan 1978.

Weathering

Acfer 217 is the most highly weathered sample (W5/6) studied here (Table 1). Nevertheless, it is unlikely that loss of ^{40}Ar due to weathering produces the younger ^{39}Ar-^{40}Ar age in this sample (4.30 Ga), relative to that of Rumuruti (~4.47 Ga, W0/1), for two reasons. First, pervasive weathering would be expected to produce a release profile in the argon age spectrum indicating pervasive diffusive loss of ^{40}Ar. However, the argon age spectrum for Acfer 217 (Fig. 1d) shows a diffusive loss profile only in the first 30% of the total ^{39}Ar released. Secondly, the relative abundances of ^{36}Ar, ^{37} Ar, and ^{38}Ar as a function of stepwise temperature release can be used to recognize terrestrial atmospheric ^{36}Ar, ^{37}Ar, and ^{38}Ar associated with weathering products degassing at lower temperatures, as explained by Garrison, Hamlin, and Bogard (2000). The Acfer 217 Ar release spectrum indicates the release of some terrestrial Ar at low temperatures but only up to 500–600°C or ~20% of the total ^{39}Ar release. These observations suggest that the maximum ^{39}Ar-^{40}Ar age, defined by the plateau between 45 and 80% of the ^{39}Ar released, is unlikely to have been affected by ^{40}Ar loss due to weathering. We conclude that the younger ^{39}Ar-^{40}Ar age for Acfer 217 is real and likely dates a different thermal event compared to that recorded in the Ar-Ar age for Rumuruti.

Parent Body Processes

We now turn to parent body processes that may have produced the range in R chondrite Ar-Ar ages. The first question is whether we can distinguish between impact-induced resetting and resetting caused by prolonged thermal metamorphism in a simple onion-shell type parent body. In unbrecciated ordinary chondrites, distinguishing between old ages produced by these means is not always easy. However, we can rule out the simple onion shell model as the sole mechanism responsible producing the age range in the R chondrites because the samples with the youngest and oldest ages from this study are breccias. The R chondrite breccias were clearly produced by impacts following metamorphism (Scott, Lusby, and Keil 1985), either at the surface by impact cratering and burial beneath regolith, or by larger scale disruption of the parent body followed by reassembly into a rubble pile structure (e.g., Grimm 1985; Keil, Haack, and Scott 1994; Taylor et al. 1987). Consequently, the observed range in Ar-Ar ages in the breccias could be produced by variable degrees of resetting of the Ar-Ar chronometer by slow cooling following burial within an impact-induced ejecta blanket or within the parent body following reassembly.

Distinguishing between shallow and deep burial as the means to produce the reset Ar-Ar ages is subject, in part, to our understanding of the size of the asteroidal parent body relative to the thickness of the regolith layer. Previous investigations of ordinary chondrites have proposed that their parent bodies were <200 km in diameter based on radiometric age determinations, ^{244}Pu thermochronometry, and metallographic cooling rates (Lipschutz, Gaffey, and Pellas 1989). It has also been suggested that these data could be reconciled with cooling at relatively shallow depths within larger asteroidal parent bodies (Pellas and Storzer 1981). However, models by Miyamoto, Fuji, and Takeda (1981) and Bennett and McSween (1996) have shown that the radii of the H and L parent bodies are likely to be on the order of 100 to 200 km in diameter, based on the Pb-Pb ages of phosphates and reasonable values of both the ^{26}Al/^{27}Al ratio and thermal diffusivities in compacted and uncompacted bodies. These models assume that the ordinary (H and L) chondrite parent bodies initially had onion shell type structures, with concentric shells of progressively higher metamorphic grades towards the centers of the asteroids (e.g., Pellas and Storzer 1981). Type 6 material is estimated to have comprised 70 vol% of the interior of the asteroids, with the remaining volume comprised of relatively thin layers of types 5–3 material progressively nearer the surface (Bennett and McSween 1996). Such model calculations have not yet been performed to determine the size of the R chondrite body, owing in part to a lack of age determinations on unbrecciated samples over a range of petrographic types. However, the presence of R3–R6 clasts in the breccias imply a similar range of metamorphic conditions existed in the R chondrite parent body prior to its disruption as existed in the H and L parent bodies. If we assume that the R chondrite parent body initially had an onion shell structure with exterior layers of type R3–5 material roughly similar in thickness to those on the exteriors of L and H chondrite bodies estimated by Bennett and McSween (1996), the minimum crater depth needed to produce an R3–6 breccia is ~5 km.

We will now qualitatively evaluate two possible explanations for the range in ages of the R chondrites: 1) a relatively early impact followed by slow cooling within a thick impact ejecta blanket or within a rubble pile type parent body; and 2) a relatively late impact followed by cooling within a relatively thin impact ejecta blanket. These models are designed to illustrate two end-member type situations, but other combinations of situations are possible. The discussion will focus on the ages of Rumuruti and Acfer 217 because these samples provide the best age estimates from this study and also have the oldest and youngest ages, respectively.

In the first scenario, impact event(s) that produced the reset 4.30 Ga Ar-Ar age of Acfer 217 occurred at ~4.47 Ga, a time similar to that which produced the Ar-Ar age of Rumuruti. The younger age of Acfer 217 than Rumuruti could then result from prolonged burial and slow cooling of Acfer 217 deeper within a regolith blanket or a rubble pile following impact. The maximum temperature of around 500ºC achieved by the breccias during cooling can be inferred from the R3 metamorphic grade of the breccia matrix. Thus, to produce its 4.30 Ga age, Acfer 217 may have cooled from ~500ºC to the closure temperature of the Ar-Ar system of 250 ± 100ºC over 170 Ma (the age difference between Rumuruti and Acfer 217). Such slow cooling would require that the regolith layer be on the order of tens to 100 km thick, depending on the thermal diffusivity of the regolith layer. This range of estimated regolith thickness is large relative to the radii of L and H chondrite parent bodies, but the R chondrite parent body may have been larger (or smaller) than those of the ordinary chondrites. Nevertheless, the size of impact required to bury Acfer 217 to such a great depth may have been sufficient to disaggregate the parent body, as has been discussed previously for the ordinary chondrite parent bodies (Grimm 1985; Keil, Haack, and Scott 1994; Taylor et al. 1987). A rubble pile structure for the R chondrite parent body may be needed to explain the young age of Acfer 217 if it was indeed produced by such slow cooling.

In the second scenario, a later impact event is proposed to have reset Acfer 217 to a younger age than Rumuruti. In this case, the breccias could have been produced by burial beneath relatively thin regolith layers to permit relatively rapid cooling. A relatively early impact at 4.47 Ga could have produced the Rumuruti breccia, whereas a later impact that occurred shortly before 4.30 Ga produced the Acfer 217 breccia, as is evaluated further below.

Petrographic Considerations

To distinguish between the two end-member processes above, we need additional information on the relative cooling rates of Acfer 217 and Rumuruti. Comparison of petrographic differences between Acfer 217 and Rumuruti may provide some indication. Relatively slow cooling of Acfer 217 within a thick regolith layer or at depth within a rubble pile type body might be expected to permit somewhat greater degrees of matrix recrystallization than in Rumuruti, possibly producing a more equilibrated, coarser-grained matrix in Acfer 217. Although the matrix grain size of Acfer 217 (<200 microns) is coarser than that of Rumuruti (1 to 10 microns), the matrix of Acfer 217 has a slightly lower petrographic type (R3.6 ± 0.1) than Rumuruti (R3.8). This indicates a lesser degree of re-equilibration of the constituent minerals in Acfer 217 than in Rumuruti (Bischoff et al. 1994; Schulze et al. 1994). These petrographic observations do not provide compelling evidence regarding the relative cooling rates of Acfer 217 and Rumuruti, but do provide some support for the second model that proposes a relatively late impact and more rapid cooling to produce the younger age of Acfer 217.

Determination of whether or not both breccias formed relatively early, prior to 4.30 Ga, may also help differentiate between the models. However, we need to evaluate whether or not the ages record the timing of breccia formation, as the age of the breccia may be biased towards the age of relatively old clasts that were not reset during the breccia forming event. Rumuruti is comprised of R3–R6 clasts and has a relatively old peak ^{39}Ar-^{40}Ar age (Table 3) that could result, in part, from preservation of relatively old ages in minerals from R3 clasts. In contrast, Acfer 217 (comprised of R5–R6 clasts) lacks R3 clasts so that its younger age could be dominated by the ages of minerals in R5 and R6 clasts.

We can evaluate the degree of Ar-Ar age equilibration for Rumuruti by comparing the age spectrum of the whole rock in Rumuruti-a (untreated), (comprised of interclastic matrix, plus clasts containing phenocrysts in an intraclastic matrix), with the age spectrum of the clasts in Rumuruti-b. First, the peak ages of the clasts and the whole rock are similar (4.45 ± 0.01 to 4.47 ± 0.02 Ga, respectively) (Table 3). In addition, as described previously, the ages from ~55% of the ^{39}Ar released (a = 15–70% and b = 24–78%) in both samples are also the same within uncertainty (a = 4.45 ± 0.03, b = 4.40 ± 0.04 Ga). These ages are lower than the peak ages owing to diffusion of ^{40}Ar. In Rumuruti-a, the low temperature part of the age spectrum should represent degassing of both the interclastic and intraclastic matrices, while in Rumuruti-b, only the intraclastic matrix is represented. The intraclastic matrix in Rumuruti-b should either predate the interclastic matrix if it has not been completely reset, or be the same age if it is reset. The similar ages obtained between 20–70% of the ^{39}Ar released in Rumuruti-a and Rumuruti-b suggests that the intraclastic and interclastic matrices were probably equilibrated in terms of their Ar-Ar ages. Thus, the Ar-Ar age of Rumuruti (~4.47 Ga) is likely to date the time that the breccia formed.

Unlike Rumuruti, the ^{39}Ar-^{40}Ar age spectrum of Acfer 217 has two plateaus, with the older plateau giving an age of ~4.30 Ga, and the younger an age of ~4.18 Ga, an age difference of 120 Ma. There are at least two possible explanations: 1) the breccia experienced two impact events and the latter event only affected Ar-Ar ages of the minerals that degas at relatively low temperatures; 2) there were at least two populations of clasts that were reset during different impact events and these clasts were subsequently formed into a breccia. In both of these cases, the Ar-Ar ages of the meteorite are not in equilibrium. It is, therefore, possible that the impact event(s) that produced the breccia occurred much later than ~4.18 Ga, and that both plateaus represent partially reset argon ages in the clasts and matrix. In other words, the age of breccia formation could be significantly younger than the two Ar-Ar plateau ages of Acfer 217. In summary, the age of Rumuruti appears to date the time of breccia formation and suggests that there were very early impacts at ~4.47 Ga on the R chondrite parent body. Acfer 217 preserves a more complex history, and supports somewhat later (~4.30 Ga) impacts. The time of breccia formation in Acfer 217 appears to post-date that of Rumuruti, supporting the model for separate impact events and a thin ejecta blanket.

Solar, Cosmogenic, and Radiogenic Gases

The history of the breccias can be further evaluated using solar gases. Solar argon is lost more readily than radiogenic Ar from feldspars during heating. Large impact events that produce a thermal environment sufficiently hot to cause resetting of the ^{39}Ar-^{40}Ar ages should also cause pervasive loss of solar gases. Thus, in breccias that have reset Ar-Ar ages and solar gases, the solar gases must reside in the matrix grains that were not heated to high temperatures during breccia formation (Bogard, Garrison, and Masarik 2001). In contrast, breccias with reset Ar-Ar ages but little or no solar gases could be inferred either to have experienced prolonged burial and heating to relatively high temperatures at depth, or to contain grains that never resided at the regolith surface. The R chondrite breccias contain solar gases, and have a range of Ar-Ar ages. One reasonable explanation is that the material that now comprises the breccia clasts in the R chondrites was first metamorphosed at a variety of depths to produce the range of petrographic types. Upon impact of the parent body, the breccia clast material was exhumed and then mixed with grains containing solar gases that had resided in the regolith, and was then consolidated at relatively low temperatures and over a relatively short time period.

The above interpretations are consistent with the ~17 Ma to 36 Ma cosmogenic exposure ages of the R chondrite breccias (Table 1). Cosmic rays penetrate to depths equivalent to 40 g/cm^2 (Eugster 1988). Bischoff et al. (1994) suggested that the cosmogenic nuclide ratios for Acfer 217 and Carlisle Lakes are consistent with exposure in relatively small (15–65 cm or 25 cm, respectively) radius bodies that experienced only a single-stage exposure history. These rocks were apparently well shielded from cosmic rays until they were ejected from the R chondrite parent body. The observations from solar gases, ^{39}Ar-^{40}Ar ages, and cosmogenic exposure ages are consistent with several early impacts, long-term residence of the brecciated material within the regolith at relatively shallow depths below 40 g/cm^2, followed by ejection from the R chondrite parent body.

CONCLUSIONS

Determination of the ^{39}Ar-^{40}Ar ages of most R chondrites is complicated by their brecciated nature and significant ^{39}Ar recoil effects produced in their fine-grained matrices. Our best estimates of the ^{39}Ar-^{40}Ar ages of four R chondrites (~4.47–4.30 Ga) are equal to or younger than those of relatively unshocked ordinary chondrites. The R chondrite samples in this study apparently did not experience the parent object collisions at <1 Ga that are observed in many ordinary chondrites nor do they show any evidence of Ar-Ar resetting during a cataclysmic bombardment at ~3.5–4 Ga. It is possible, however, that with additional analyses of the R chondrites, younger Ar-Ar ages will be found. The brecciated chondrite Rumuruti appears to provide evidence for relatively early (~4.47 Ga) impacts on the R chondrite parent body and possibly an early, ~4.4 Ga, age of breccia formation.

The large, ~170 Ma, age difference between the oldest and youngest samples from this study, Rumuruti and Acfer 217, may be explained in at least one of two end-member type scenarios. One is that the impacts that reset the ages in these meteorites occurred at similar times, but Acfer 217 experienced prolonged burial and slower cooling than Rumuruti. A very thick regolith layer or rubble pile type asteroidal parent body may be needed to permit such slow cooling. The second, preferred interpretation is that later impact events than that which produced the Rumuruti breccia occurred and reset the age of Acfer 217. Relatively rapid cooling, resulting in incomplete resetting and equilibration of the Ar-Ar age of the Acfer 217 breccia, may explain why it preserves more than one age plateau. Similar explanations to those described above for Rumuruti and Acfer 217 may apply to produce the intermediate ages of PCA 91002 and Carlisle Lakes.

Additional ^{39}Ar-^{40}Ar dating of unshocked, unbrecciated R chondrite samples would be useful to further evaluate whether the R chondrite parent body had a rubble pile type structure, probably with a thin outer regolith, or whether early impacts produced a regolith layer over an onion shell type internal structure.

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REFERENCES

Anders E. 1964. Origin, age, and composition of meteorites. *Space Science Reviews* 3:583–714.

Ashworth J. R. and Barber D. J. 1976. Lithification of gas-rich meteorites. *Earth and Planetary Science Letters* 30:222–233.

Bennett M. III and McSween H. Jr. 1996. Revised model calculations for the thermal histories of ordinary chondrites. *Meteoritics & Planetary Science* 31:783–792.

Bischoff A. 2000. Mineralogical characterization of primitive, type 3 lithologies in Rumuruti chondrites. *Meteoritics & Planetary Science* 35:699–706.

Bischoff A., Rubin A. E., Keil K., and Stoffler D. 1983. Lithification of gas-rich chondrite regolith breccias by grain boundary and localized shock melting. *Earth and Planetary Science Letters* 66: 1–10.

Bischoff A., Geiger T., Palme H., Spettel B., Schultz L., Scherer P., Loeken T., Bland P., Clayton R., Mayeda T. K., Herpers U., Meltzow B., Michel R., and Dittrich-Hannen B. 1994. Acfer 217: A new member of the Rumuruti chondrite group (R). *Meteoritics* 29:264–274.

Bischoff A., Weber D., Bartoschewitz R., Clayton R. N., Mayeda T. K., Schultz L., Spettel B., and Weber H. W. 1998. Characterization of the Rumuruti chondrite regolith breccia Hughes 030 (R3–6) and implications for the occurrence of unequilibrated lithologies on the R chondrite parent body (abstract). *Meteoritics* 33:A15.

Bogard D. D. 1995. Impact ages of meteorites: A synthesis. *Meteoritics* 30:244–268.

Bogard D. D. and Hirsch W. C. 1980. ^{40}Ar/^{39}Ar dating, Ar diffusion properties, and cooling rate determinations of severely shocked chondrites. *Geochimica et Cosmochimica Acta* 44:1667–1682.

Bogard D. D., Garrison D. H., Norman M., Scott E. R. D., and Keil K. 1995. ^{39}Ar-^{40}Ar age and petrology of Chico: Large-scale impact melting on the L chondrite parent body. *Geochimica et Cosmochimica Acta* 59:1383–1400.

Bogard D. D., Garrison D. H., and McCoy T. J. 2000. Chronology and petrology of silicates from IIE iron meteorites: Evidence of a complex parent body evolution. *Geochimica et Cosmochimica Acta* 64:2133–2154.

Bogard D. D., Garrison D. H., and Masarik J. 2001. The Monahans chondrite and halite: Argon-39/Argon-40 age, solar gases, cosmic ray exposure ages, and parent body regolith neutron flux and thickness. *Meteoritics & Planetary Science* 36:107–122.

Dodd R. T. and Jarosewich E. 1979. Incipient melting in and shock classification of L-group chondrites. *Earth and Planetary Science Letters* 44:335–340.

Eugster O. 1988. Cosmic-ray production rates for ^{3}He, ^{21}Ne, ^{38}Ar, ^{83}Kr, and ^{126}Xe in chondrites based on ^{81}Kr-Kr exposure ages. *Geochimica et Cosmochimica Acta* 52:1649–1662.

Garrison D. H., Hamlin S., and Bogard D. 2000. Chlorine abundances in meteorites. *Meteoritics & Planetary Science* 35: 419–429.

Göpel C., Manhes G., and Allegre C. J. 1994. U-Pb systematics of phosphates from equilibrated ordinary chondrites. *Earth and Planetary Science Letters* 121:153–171.

Grimm R. E. 1985. Penecontemporaneous metamorphism, fragmentation, and reassembly of ordinary chondrite parent bodies. *Journal of Geophysical Research* 90:2022–2028.

Heyman D. 1967. On the origin of hypersthene chondrites: Ages and shock effects of black chondrites. *Icarus* 6:189–221.

Huenke J. C. and Smith S. P. 1976. ^{39}Ar recoil out of small grains and implications for ^{40}Ar-^{39}Ar dating. Proceedings, 7th Lunar and Planetary Science Conference. pp. 1978–2008.

Huss G. R., Keil K., and Taylor G. J. 1981. The matrices of unequilibrated ordinary chondrites: Implications for the origin and history of chondrites. *Geochimica et Cosmochimica Acta* 45: 33–51.

Kallemeyn G. W., Rubin A. E., and Wasson J. T. 1996. The compositional classification of chondrites: VII. The R chondrite group. *Geochimica et Cosmochimica Acta* 60:2243–2256.

Kaneoka I. 1980. ^{40}Ar-^{39}Ar ages of L and LL chondrites from Allan Hills, Antarctica: ALHA 77015, 77214, and 77304. Proceedings, 6th NIPR Symposium on Antarctic Meteorites. pp. 177–188.

Kaneoka I. 1981. ^{40}Ar-^{39}Ar ages of Antarctic meteorites: Y-74191, Y-75258, Y-7308, Y-74450, and ALH 765. Proceedings, 5th NIPR Symposium on Antarctic Meteorites. pp. 250–263.

Keil K. 2000. Thermal alteration of asteroids: Evidence from meteorites. *Planetary and Space Science* 48:887–903.

Keil K., Haack H., and Scott E. R. D. 1994. Catstrophic fragmentation of asteroids: Evidence from meteorites. *Planetary and Space Science* 42:1109–1122.

Kieffer S. W. and Simonds C. H. 1980. The role of volatiles and lithology in the impact cratering process. *Reviews of Geophysics and Space Physics* 18:143–181.

Lipschutz M. E., Gaffey M. J., and Pellas P. 1989. Meteoritic parent bodies: Nature, number, size, and relation to present-day asteroids. In *Asteroids II*, edited by Binzel R. P., Gehrels T., and Matthews M. S. Tucson: University of Arizona Press. pp. 740–777.

McConville P., Kelley S., and Turner G. 1988. Laser probe ^{40}Ar-^{39}Ar studies of the Peace River shocked L6 chondrite. *Geochimica et Cosmochimica Acta* 52:2487–2499.

Miyamoto M., Fuji N., and Takeda H. 1981. Ordinary chondrite parent body: An internal heating model. Proceedings, 12th Lunar and Planetary Science Conference. pp. 1145–1152.

Nagao K., Okazaki R., Sawada S., and Nakamura N. 1999. Noble gases and K-Ar ages of five Rumuruti chondrites: Yamato Y-75302, Y-79182, Y-793575, Y-82002, and Asuka-881988 (abstract). *Antarctic Meteorite Research* 23:81.

Pellas P. and Fieni C. 1988. Thermal histories of ordinary chondrite parent asteroids (abstract). 19th Lunar and Planetary Science Conference. pp. 915–916.

Pellas P. and Storzer D. 1981. ^{244}Pu fission track thermometry and its application to stony meteorites. *Proceedings of the Royal Society of London* 374:253–270.

Rubin A. E. and Kallemeyn G. W. 1989. Carlisle Lakes and Allan Hills 85151: Members of a new chondrite grouplet. *Geochimica et Cosmochimica Acta* 53:3035–3044.

Rubin A. E. and Kallemeyn G. W. 1994. Pecora Escarpment 91002: A member of the new Rumuruti (R) chondrite group. *Meteoritics* 29:255–264.

Schaal R. B. and Horz F. 1980. Experimental shock metamorphism of lunar soil. Proceedings, 2nd Lunar and Planetary Science Conference. pp. 1679–1695.

Schultz L. and Weber H. W. 2001. The irradiation history of Rumuruti-Chondrites (abstract). 26th Symposium on Antarctic Meteorites. p. 128.

Schulze H., Bischoff A., Palme H., Spettel B., Dreibus G., and Otto J. 1994. Mineralogy and chemistry of Rumuruti: The first meteorite fall of the new R chondrite group. *Meteoritics* 29:275–286.

Scott E. R. D. and Rajan R. S. 1981. Metallic minerals, thermal histories, and parent bodies of some xenolithic, ordinary chondrites. *Geochimica et Cosmochimica Acta* 45:53–67.

Scott E. R., Lusby D., and Keil K. 1985. Ubiquitous brecciation after metamorphism in equilibrated ordinary chondrites. *Journal of Geophysical Research* 90:D137–D148.

Smith B. A. and Goldstein J. I. 1977. The metallic microstructures and thermal histories of severely reheated chondrites. *Geochimica et Cosmochimica Acta* 41:1061–1072.

Staudacher T., Jessberger E. K., Flohs I., and Kirsten T. 1979. ^{40}Ar-^{39}Ar age systematics of consortium breccia 73255. Proceedings, 10th Lunar and Planetary Science Conference. pp. 745–762.

Stoffler D., Keil K., and Scott E. R. D. 1991. Shock metamorphism of ordinary chondrites. *Geochimica et Cosmochimica Acta* 55: 3845–3867.

Taylor S. R. 1992. *Solar system evolution: A new perspective*. New York: Cambridge University Press. p. 307.

Taylor G. J., Keil K., Berkley J. L., and Lange D. E. 1979. The Shaw meteorite: History of a chondrite consisting of impact-melted and metamorphic lithologies. *Geochimica et Cosmochimica Acta* 43: 323–337.

Taylor G. J., Maggiore P., Scott E. R. D., Rubin A. E., and Keil K. 1987. Original structures, and fragmentation and reassembly histories of asteroids: Evidence from meteorites. *Icarus* 69:1–13.

Trieloff M., Jessberger E. K., and Oehm J. 1989. Ar-Ar ages of LL chondrites (abstract). *Meteoritics* 24:332.

Trieloff M., Deutsch A., Kunz J., and Jessberger E. K. 1994a. Redistribution of potassium and radiogenic argon by moderate shock pressures in experimentally shocked gabbro (abstract). *Meteoritics* 29:541.

Trieloff M., Kunz J., and Jessberger E. K. 1994b. High-resolution ^{40}Ar-^{39}Ar dating of K-rich chondritic inclusions (abstract). *Meteoritics* 29:541.

Turner G. 1969. Thermal histories of meteorites by the ^{39}Ar-^{40}Ar method. In *Meteorite research*, edited by Millman P. New York: Springer Verlag. pp. 407–417.

Turner G. and Cadogan P. H. 1974. Possible effects of ^{39}Ar recoil in ^{40}Ar-^{39}Ar dating. Proceedings, 5th Lunar and Planetary Science Conference. pp. 1601–1615.

Turner G., Enright M. C., and Cadogan P. H. 1978. The early history of chondrite parent bodies inferred from ^{40}Ar-^{39}Ar ages. Proceedings, 9th Lunar and Planetary Science Conference. pp. 989–1025.

Van Schmus W. R. and Wood J. A. 1967. A chemical-petrologic classification for the chondritic meteorites. *Geochimica et Cosmochimica Acta* 31:747–765.

Weisburg M. K., Prinz M., Kojima H., Yanai K., Clayton R. N., and Mayeda T. K. 1991. The Carlisle Lakes-type chondrites: A new grouplet with high delta^{17}O and evidence for nebular oxidation. *Geochimica et Cosmochimica Acta* 55:2657–2669.

Wiens R. C., Huss G. R., and Burnett D. S. 1999. The solar oxygen-isotopic composition: Predictions and implications for solar nebula processes. *Meteoritics & Planetary Science* 34:99–107.

Zeitler P. K. and Fitz Gerald J. D. 1986. Saddle-shaped ^{40}Ar-^{39}Ar age spectra from young, microstructurally complex potassium feldspars. *Geochimica et Cosmochimica Acta* 50:1185–1199.