RAGLAND, AN LL3.4 CHONDRITE FIND FROM NEW MEXICO

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The Ragland, New Mexico chondrite was found in 1978, and consists of a single stone of 12.16 kg that broke into three pieces. The stone is moderately weathered and has a pronounced chondritic texture. Bulk composition favors an LL classification, and modal analysis and oxygen isotopic composition are consistent with this. The thermoluminescence sensitivity of 0.056 ± 0.020 normalized to Dhajala, compositional variability of olivine (mean Fa 18.3, σ = 10.1) and low-Ca pyroxene (mean Fs 14.6, σ = 6.7), and Ca concentrations in olivine indicate metamorphic subtype 3.4 ± 0.1. The isotopically heavy oxygen composition, which is characteristic of subtypes 3.0-3.1, may be a primary characteristic and not a result of weathering. Low concentrations of radiogenic ^{40}Ar and planetary ^{36}Ar suggest noble gas loss.

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INTRODUCTION

The Ragland meteorite was found in 1978 about 2.5 km southeast of Forrest, Quay County, New Mexico by Freddy and Johnny Beevers during the combining of wheat on the Beevers farm, 34° 46′ 04″ N, 103° 33′ 33″ W. Because of the unusual appearance and size of this stone, which was found in what appeared to have been a stone-free field, it was saved for identification. In 1982, a small sample was sent to the American Meteorite Laboratory where it was identified as meteoritic. The stone consists of three pieces weighing a total of 12.16 kg, which fit together to form a well-oriented meteorite of 27.8 × 26.6 cm measured at right angles across its base and 16.7 cm from base to apex (Fig. 1). The anterior surface of the somewhat cone-shaped stone is covered with nearly uniform regmaglypts streaming outward from a near-central apex. Fusion crust covers 65-70% of the sculptured surface. Light-colored chondrules are visible both in the fusion crust and in areas where the fusion crust is absent. At least four fragments and other material weighing a total of 4-5 kg are missing from the periphery of the stone, possibly because of weathering.

Because there are already two Forrest meteorites, this meteorite has been named for the town next closest to the find site: Ragland, Quay County, New Mexico. Specimens weighing 57.7 g are presently in the University of New Mexico collection; the remainder is at the American Meteorite Laboratory.

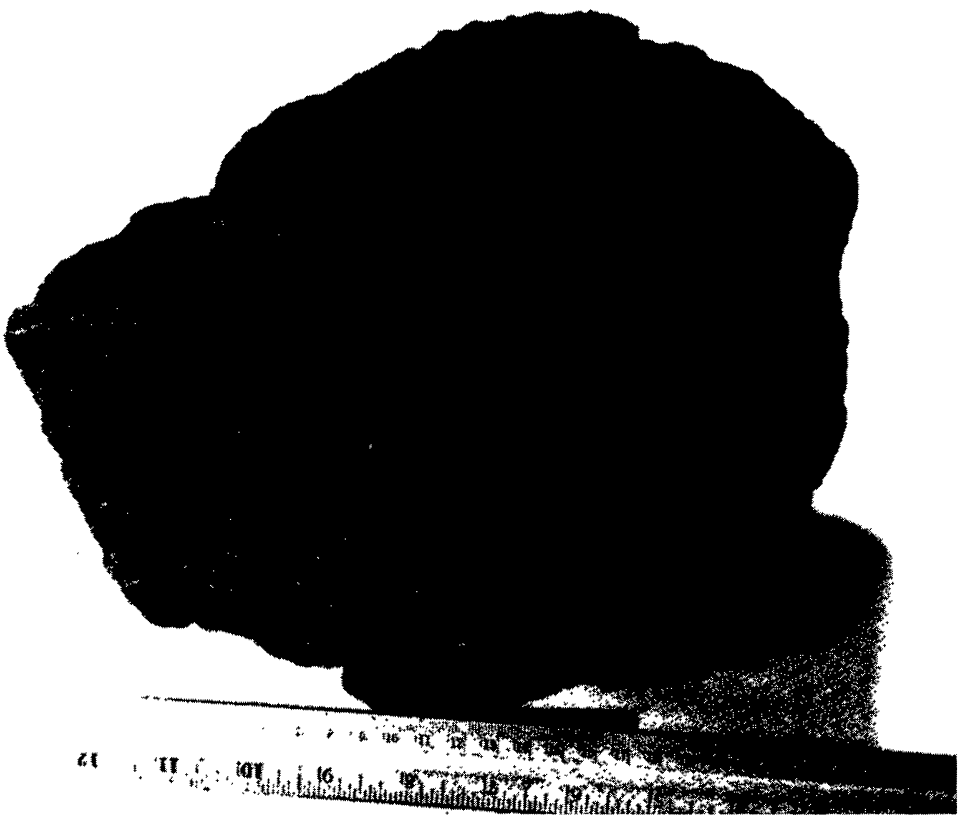

Fig. 1 Photograph of the reconstructed Ragland stone, which is composed of 3 fragments with a total weight of 12.16 kg. Prominent fusion crust and regmaglypts are visible over most of the surface of this type 3 ordinary chondrite.

MINERALOGY AND PETROLOGY

Three polished thin sections of Ragland (UNM 672, 673, and 677) were studied under reflected and transmitted light. Quantitative mineral analyses were conducted on a JEOL Model 733 Superprobe equipped with crystal spectrometers using the method of Bence and Albee (1968) for correction of differential matrix effects.

Thin section studies indicate that the meteorite is moderately weathered. Metallic iron-nickel and troilite not contained within chondrules have been largely altered to iron oxides and hydroxides, although weathering veins are absent. Modal analysis of three polished sections yields the following volume abundances: 65% chondrules and silicate grains > 15 μm in size, which are probably chondrule fragments; 18% fine-grained silicates including translucent and recrystallized matrix, and 3-15 μm silicate grains; 16% iron oxides and hydroxides; 1.4% opaque matrix; 0.1% troilite; < 0.1% metallic Fe,Ni; < 0.1% chromite. We use the terms 'recrystallized' and 'translucent' matrix as defined by Huss *et al.* (1981) and Scott *et al.* (1982). The abundance of chondrule and silicate fragments is higher than in many type 3 chondrites; Ragland closely resembles Chainpur in this respect. Much of the inter-chondrule material is weathered, making it difficult to distinguish between translucent and recrystallized matrix and other fine-grained silicate material.

Ragland contains sharply defined chondrules of all types described by Gooding and Keil (1980), with a wide range of apparent diameters, 0.2-3 mm (Fig. 2). Some porphyritic olivine chondrules contain pink or colorless, clear glass. Several chondrules rimmed with matrix material are also present. Ragland shows no evidence of pervasive shock. However, some individual mineral grains do exhibit a slight undulose extinction. One section (UNM 677) contains a 2 mm long clast or region (Fig. 3) which has a high proportion of silicate fragments 3-50 μm in size. Broad-beam analyses suggest that it is similar in composition to the rest of the chondrite.

Results of random analyses of olivine and pyroxene grains larger than 15 μm in size are shown in Figure 4. Analyses of 109 olivine grains have a mean of 18.3 mole% fayalite with a standard deviation of 10 mole% Fa, and a mean CaO concentration of 0.12 wt% (σ = 0.10). Analyses of 38 low-Ca pyroxenes have a mean of 14.6 mole% ferrosilite (σ = 6.7) and 1.5 mole% wollastonite (σ = 1.4).

Means and standard deviations of 4-10 analyses for fayalite and CaO in olivine in each of 19 chondrules are shown in Figure 5. The 19 chondrules have mean olivine compositions of Fa 2-30. Chondrules with mean olivine compositions of Fa 0-2, which are relatively common in type 3.0 chondrites like Semarkona (Scott and Taylor, 1983), were not found in Ragland. At the other extreme, chondrules with homogeneous, low-Ca olivine, which are common in type 3.6 and higher petrologic types (Scott, 1984), were also not found.

BULK CHEMICAL COMPOSITION

A sample of the freshest available material weighing 4 g was used for bulk chemical analysis following the procedures of Jarosewich (1966). All S is reported as FeS. Because of the extensive weathering of metallic Fe,Ni and troilite, estimates of the proportions of Fe^{3+} and Fe^{2+} were made in two different ways. The FeO concentration in Table 1, column 1 was obtained from an approximate chemical analysis for Fe^{2+}, and the remainder of the Fe, after allowance for FeS, was assigned to Fe_2O_3.

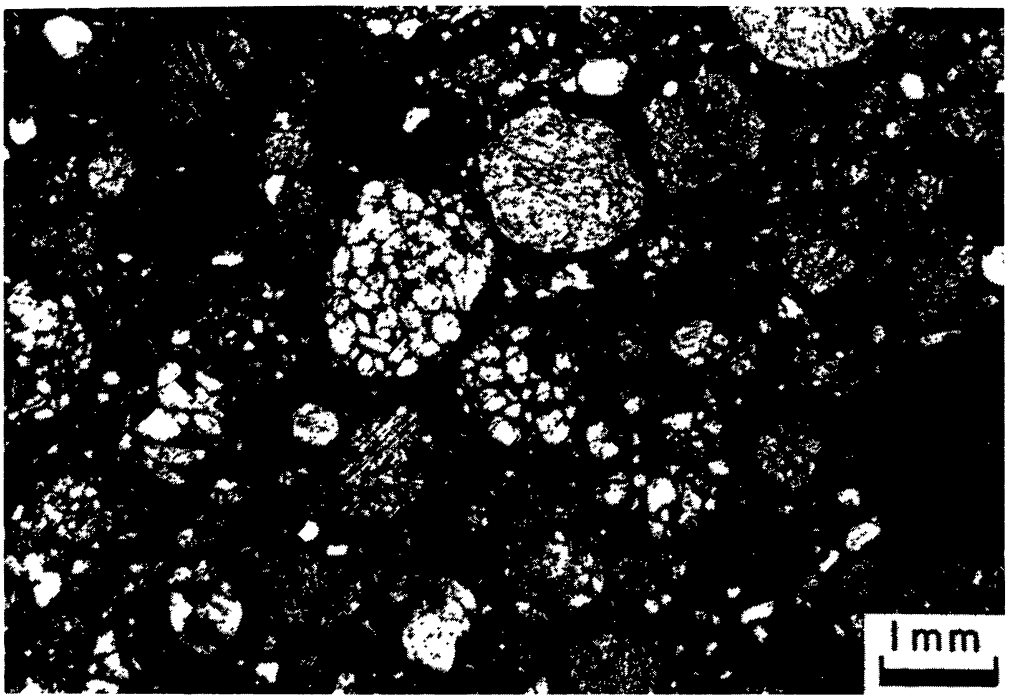

Fig. 2 Transmitted-light photograph of a polished thin section of Ragland (LL3.4), showing prominent chondrules of diverse types separated by chondrule and silicate fragments and translucent matrix.

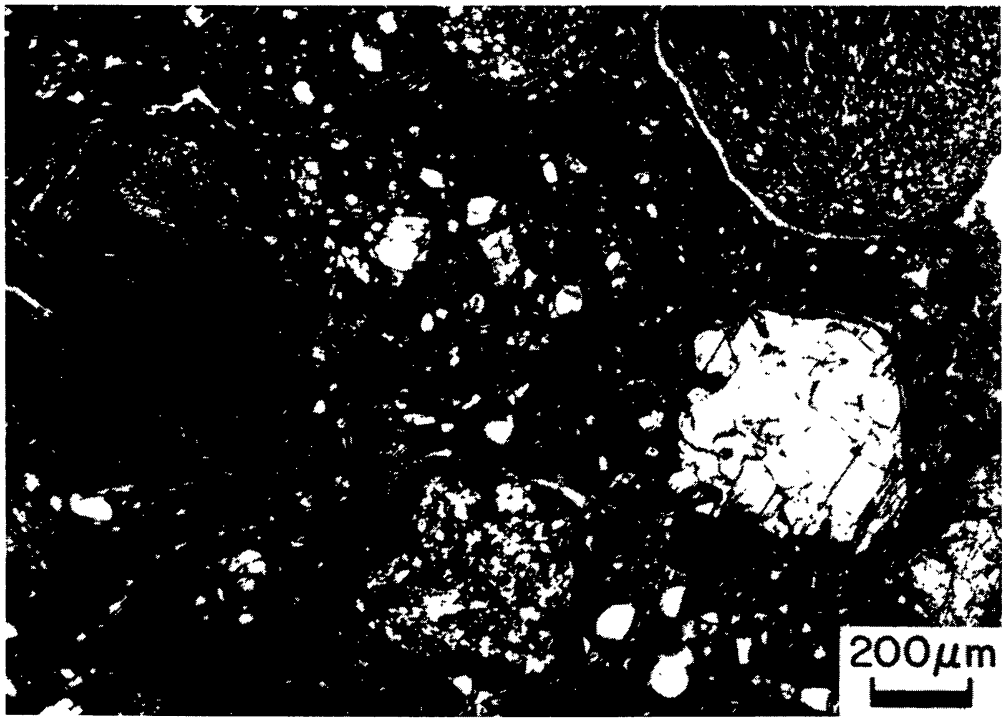

Fig. 3 Transmitted, plane polarized light photomicrograph of a region (possibly an ill defined clast) in Ragland containing abundant silicate fragments (5-50 μm in size) and translucent matrix between chondrules. Elsewhere, silicate fragments are less abundant but are still a characteristic feature of this chondrite. Ragland closely resembles Chainpur in this respect.

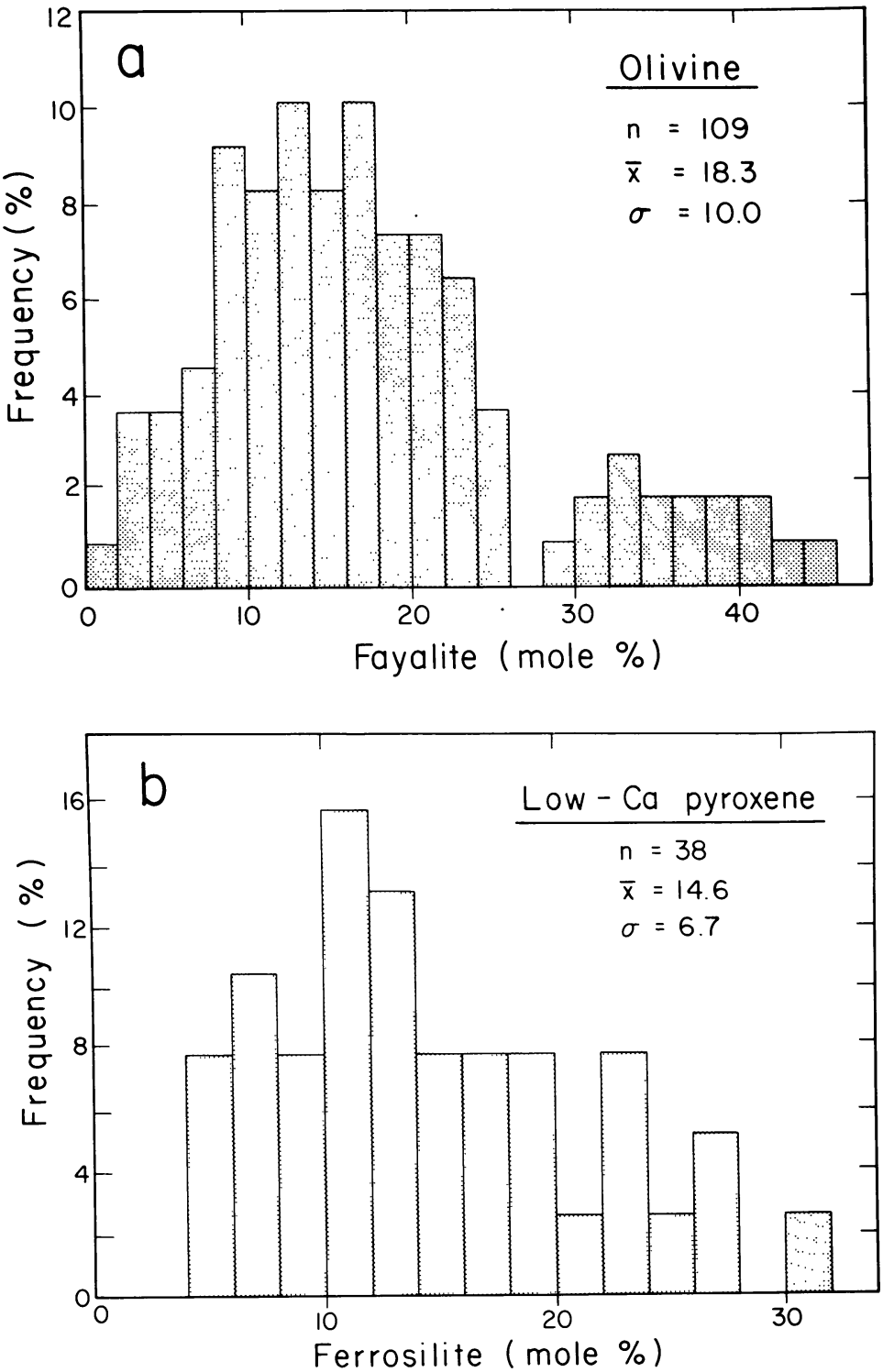

Fig. 4 **Histograms of electron probe analyses of randomly chosen (a) olivine and (b) low-Ca pyroxenes in Ragland; $\bar{x}$ is the mean, σ is the standard deviation of the analyses, and n the number of analyses. The heterogeneity of silicates indicates a petrologic subtype of 3.1-3.4.**

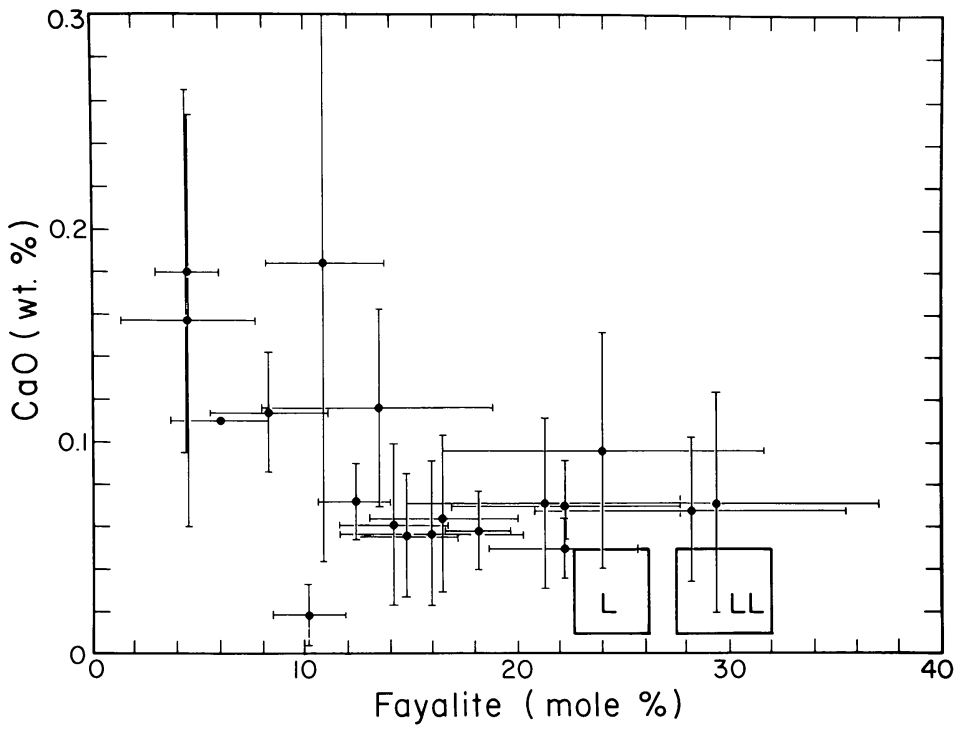

Fig. 5 **Plot of CaO in olivine against fayalite concentration for 19 chondrules in Ragland. The mean of 4-10 analyses and ±1σ of these analyses are shown for each chondrule. Ragland lacks chondrules with mean olivine compositions of Fa 0-2, which are present in type 3.0 chondrites, and chondrules with mean olivine compositions inside the ranges of mean olivine compositions in equilibrated L and LL chondrites (represented by the two boxes), which are common in type 3.6-4 chondrites. This is consistent with the thermoluminescence sensitivity of Ragland, which indicates a subtype of 3.4.**

Errors in the FeO analysis are largely due to the uncertainties in the behavior of FeS and metallic Fe, but because FeS and metallic Fe concentrations are low, the relative error in FeO is probably less than 8% relative. An alternative method of estimating the bulk FeO from the mean olivine and low-Ca pyroxene compositions determined from electron probe analysis, which was used by Keil *et al.* (1978) for Inman (L3), gives a lower FeO concentration of 7.1 wt%. However, the approximate chemical analysis of 13.0% FeO is preferred because of the heterogeneous silicate compositions (Fig. 4) and our bias during probe analysis against small silicate grains (< 10 μm in size), which are commonly richer in FeO than large grains (Huss *et al.*, 1981). The recalculated analysis in column 2 of Table 1 is discussed in a later section.

We note that weathering has caused a very large loss of S. The FeS concentration of 0.77 wt% is about 15% of the value for ordinary chondrites. Similarly, the Na_2O concentration of 0.4% is only 40% of the expected level, and the measured Ni concentration is much lower than normal L and LL levels.

Twenty-one elements were determined in a 203 mg sample of Ragland by instrumental neutron activation. The methods used are described in Sears and Weeks (manuscript in preparation, 1985), except that since only a single sample of Ragland was

Table 1
Bulk chemical analysis of the Ragland chondrite (wt%)

Component	1	2
SiO_2	39.60	42.84
TiO_2	0.11	0.12
Al_2O_3	2.38	2.58
Cr_2O_3	0.55	0.60
Fe_2O_3	11.82*	—
FeO	13.0*	14.04
MnO	0.33	0.36
MgO	23.00	24.89
CaO	1.85	2.00
Na_2O	0.36	0.40
K_2O	0.06	0.06
P_2O_5	0.20	0.22
$H_2O(+)$	2.45	—
$H_2O(-)$	0.63	—
Fe	0.64	9.64
Ni	0.68	0.74
Co	0.03	0.03
FeS	0.77	0.83
C	0.61	0.66
Total	99.07	100.01
Total Fe	19.58	21.18

Column 1, as analyzed; Column 2 recalculated on an H_2O-free basis with Fe_2O_3 converted to Fe.

*Approximate FeO analysis; Fe_2O_3 calculated by difference from total Fe.

analyzed, the uncertainties are a factor of 1.4 greater. Nine of the elements were determined by both INAA and wet-chemical methods and, except for Ni and Co, the agreement between the two sets of data is well within experimental uncertainty. For these two elements, which can be determined with high precision by INAA, the INAA values are about 20% higher.

The INAA data are listed in Table 2 and plotted in Figure 6. Lithophile concentrations are generally very close to mean ordinary chondrite values, and concentrations of elements which are important for classification purposes, Ir, Ni, Co, Fe, Au, As, and Ga, are close to those of LL chondrites. Sodium and K are low, as is commonly observed in weathered finds, presumably due to leaching during weathering. Selenium, like S discussed above, is depleted with respect to the mean LL value by about 20-30% and this could also be related to weathering. Zinc is close to the LL group mean, but the scatter in the literature data for Zn is large and this could be fortuitous. Siderophile elements in type 3 ordinary chondrites of all classes are depleted 5-15% compared with their equilibrated counterparts and we see some suggestion of this in the Ragland data (Weeks and Sears, 1985).

Table 2
Results of instrumental neutron activation analysis of Ragland

Na	Mg	Al	K	Sc	V	Cr	Mn
mg/g	mg/g	mg/g	μg/g	μg/g	μg/g	mg/g	mg/g
2.87	133	12.4	472	7.96	85.7	3.84	2.19
Fe	Co	Ni	Zn	Ga	As	Se	
mg/g	mg/g	mg/g	μg/g	μg/g	μg/g	μg/g	
200	359	8.7	43	4.3	1.1	5.70	
La	Sm	Eu	Yb	Ir	Au		
ng/g	ng/g	ng/g	ng/g	ng/g	ng/g		
363	242	84	194	377	135		

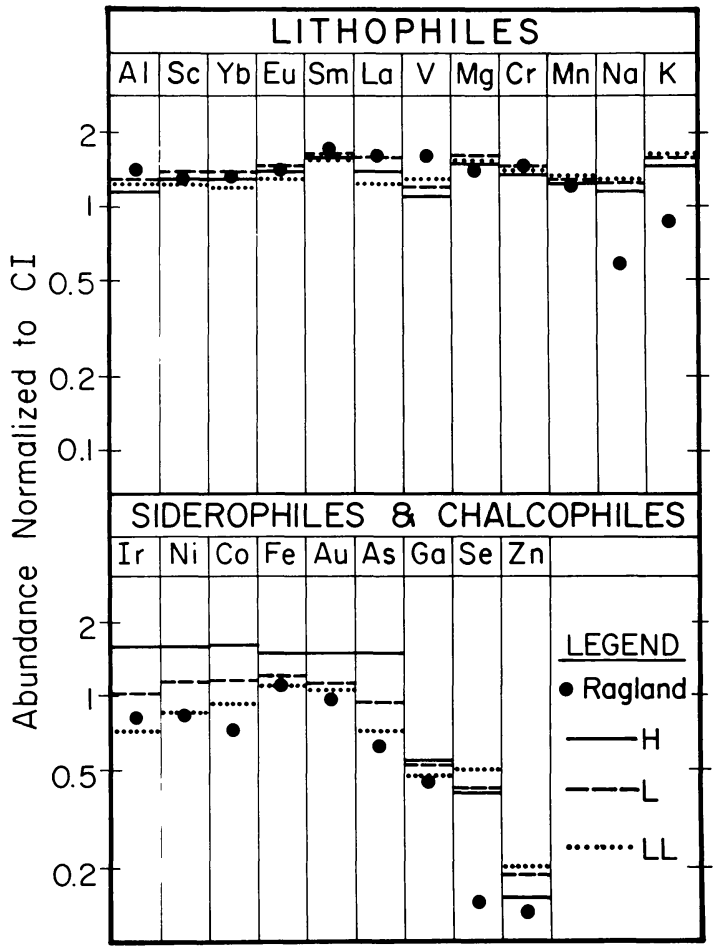

Fig. 6 **Composition of the Ragland meteorite (Table 2) expressed as elemental abundances normalized to CI chondrites, compared with mean H, L, and LL abundances (data from sources given in Weeks and Sears, manuscript in preparation, 1985). On the basis of bulk composition, Ragland is an LL chondrite with low Na, K, and Se, probably due to weathering.**

THERMOLUMINESCENCE SENSITIVITY

Measurements of the thermoluminescence sensitivity of two samples of Ragland using the procedures of Sears *et al.* (1982) gave a mean value of 0.056 ± 0.020, normalized to Dhajala. The maximum induced TL was measured at 126 ± 10°C and the width of the TL peak at half its maximum intensity is 78 ± 12°C. Weathering of the Ragland sample may have caused a two or three-fold reduction in TL sensitivity (Sears *et al.*, 1982).

OXYGEN ISOTOPIC COMPOSITION

The isotopic composition of a non-magnetic separate yielded $\delta^{18}O$ of 6.33‰ and $\delta^{17}O$ of 4.15‰ relative to standard mean ocean water, using standard techniques (Clayton *et al.*, 1976). Figure 7 shows that Ragland has the heaviest oxygen isotopic composition of any analyzed ordinary chondrite. It is unlikely that this is due to weathering, as Ragland plots close to an extension of the L-LL fractionation trend. However, modest additions of terrestrial oxygen cannot be excluded. Meteorites with isotopic compositions closest to that of Ragland are Semarkona (LL3.0), Bishunpur (LL3.1), and Yamato 790964, a shock-melted LL chondrite.

NOBLE GASES

Helium, Ne, and Ar in two adjacent samples of Ragland were determined by the procedures described by Signer *et al.* (1977). Table 3 shows that both analyses are in good agreement except for radiogenic ^{40}Ar, which must be attributed to inhomogeneous K concentrations in samples < 200 mg (cf. Schultz and Signer, 1976). Besides the measured values, trapped and cosmogenic components are also given in Table 3. The trapped noble gas component is of the planetary type. The cosmic ray exposure age is 30 Ma, using the ^{21}Ne production rate and shielding correction given by Nishiizumi *et al.* (1980). The $^{3}He/^{21}Ne$ and $^{22}Ne/^{21}Ne$ ratios indicate relatively low shielding of the sample.

Using the K concentration in Table 1, nominal K-Ar ages of 2.8 and 2.2 Ga are calculated for the two samples in Table 2. Nominal U-Th-He ages should not be higher than K-Ar ages, because of the lower retentivity of He. To accumulate the observed ^{4}He amounts in 2.5 Ga, a U concentration of about 22.5 ppb would be required (Th/U = 4). This is at the very high end of observed U concentrations in L/LL chondrites, which indicates that part of the ^{4}He is probably primordial.

Table 3
He, Ne, and Ar concentrations ($10^{-8}cm^3$ STP/g) and isotopic ratios in 2 samples of Ragland

	weight (mg)	^{3}He	^{4}He	^{21}Ne	20/22	22/21	^{36}Ar	^{38}Ar	^{40}Ar	^{20}Ne (tr)	22/21 (cos)	^{36}Ar (tr)	^{38}Ar (cos)	T_{21} (Ma)
1	152.0	38.3	1505	7.75	1.06	1.17	9.32	2.45	1250	1.47	1.15	8.82	0.80	29
2	50.5	41.1	1625	8.28	1.06	1.16	9.78	2.52	850	1.54	1.15	9.29	0.79	30

Errors are 4% for gas concentrations and 1% for isotopic ratios.

Cosmogenic and trapped Ne and Ar values are calculated by assuming: $^{20}Ne/^{22}Ne_{tr} = 8.4$, $^{22}Ne/^{21}Ne_{tr} = 32$, $^{20}Ne/^{21}Ne_{cos} = 0.91$, $^{36}Ar/^{38}Ar_{tr} = 5.35$, $^{36}Ar/^{38}Ar_{cos} = 0.63$.

DISCUSSION

Chemical Group

The classification of type 3 ordinary chondrites is difficult because of heterogeneities in mineral and oxygen isotopic compositions and, in the case of L and LL chondrites, the lack of a well-defined hiatus in bulk composition. The classification of Ragland has also been obscured by terrestrial weathering, which has altered metallic Fe,Ni and troilite to iron oxides and hydroxides. Modal analyses yield 8 ± 2 wt% metallic Fe,Ni when all oxidized Fe is assumed to be FeOOH, converted to metallic Fe and corrected for the troilite content of unweathered chondrites. This value is indicative of an L chondrite (Keil, 1962) but is too uncertain to exclude LL classification. Olivine and pyroxene mean compositions are too heterogeneous to indicate Ragland's chemical group.

Terrestrial weathering has altered Ragland to such an extent that we cannot be certain of its original concentrations of reduced and oxidized Fe. If we assume the iron oxides and hydroxides to be due solely to closed-system weathering of metallic Fe,Ni, then recalculation of the analysis on a water-free basis and conversion of Fe_2O_3 to metallic iron should yield a composition close to that of the unweathered meteorite (Table 1, column 2). The weight ratio of metallic Fe to total Fe calculated in this manner is 0.46, which is too high even for an L chondrite, whereas the ratio of total Fe to Mg, 1.41, is indicative of L classification (Jarosewich and Dodd, 1981). However, the abundances of siderophiles (Fig. 6) provide reasonably good evidence for classifying Ragland as an LL chondrite.

The oxygen isotopic composition of Ragland (Fig. 7) may have been marginally affected by weathering, but clearly favors an LL classification, as no L chondrites have been found with such ^{16}O-poor oxygen. The absence of such L chondrites may, however, be due to poor sampling because of a lack of L3.0-3.5 chondrites.

Petrologic type

All our studies show that Ragland is a type 3 ordinary chondrite. Its thermoluminescence sensitivity, peak width, and peak temperature indicate a petrologic subtype of 3.4 ± 0.1, using criteria of Sears *et al.* (1980) and Guimon *et al.* (1985). The olivine heterogeneity indicates a similar subtype: σ/(mean Fa) and the mean deviation of Fe are 55 and 39%, respectively, suggesting a subtype of 3.0-3.4 (Sears *et al.*, 1982). Calcium concentrations in olivine (Scott, 1984) are characteristic of subtypes 3.1-3.5, and bulk carbon (0.61%, Table 1), which has probably increased during weathering (Swart *et al.*, 1983), is typical of type 3.0 chondrites. As discussed above, the olivine compositions of chondrules (Fig. 5) also suggest that Ragland is a type 3.1-3.6 chondrite.

The major discordant parameter is the concentration of planetary ^{36}Ar, which is appropriate to subtype 3.7 in the Sears *et al.* (1980) scheme, and 3.9 according to the classification based on volatile content that was proposed by Anders and Zadnik (1985). This may be due to Ar loss or it may be a primary feature of Ragland. The low apparent K-Ar age shows that radiogenic Ar was lost. Concerning a possible loss of radiogenic ^4He, no conclusion is possible, because of the unknown U concentration and the possible presence of primordial He. However, incomplete retention of radiogenic Ar

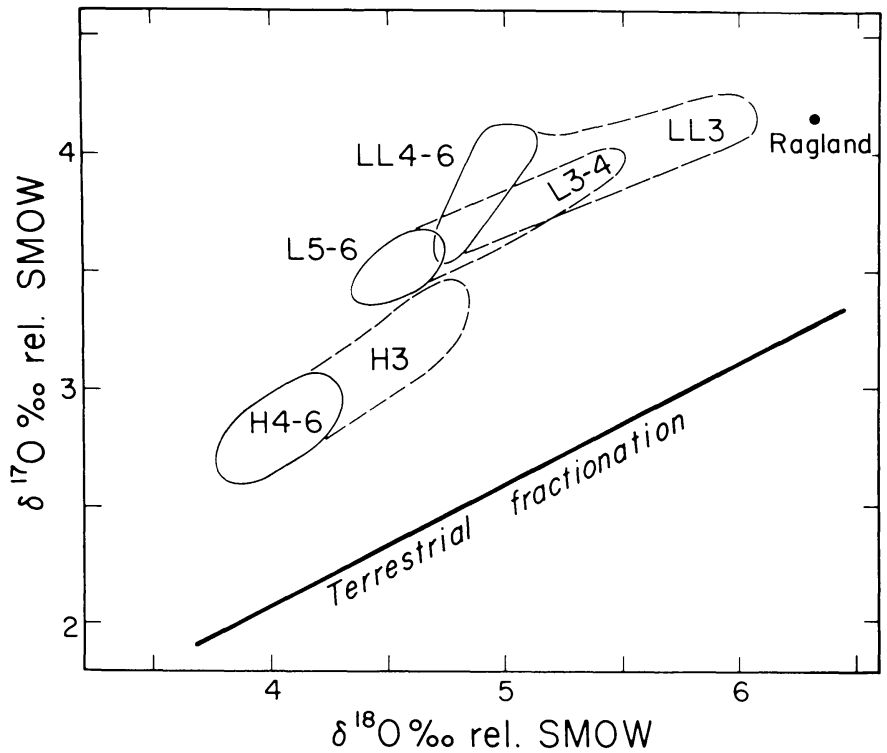

Fig. 7 **Bulk oxygen isotopic composition of Ragland and fields for other ordinary chondrites. Ragland lies at the ^{16}O-poor end of the ordinary chondrite field, suggesting that it is a very unequilibrated LL3 chondrite. However, minor displacement due to terrestrial weathering cannot be excluded.**

suggests a partial loss of the planetary Ar also. Therefore, on the basis of ^{36}Ar alone, it cannot be decided whether Ragland is more depleted in volatiles than its metamorphic subtype indicates, as Anders and Zadnik (1985) found for Allan Hills A77278 and Parnallee.

Weathering and an admixture of 3-15 μm silicate fragments prevent the use of matrix composition, abundance and degree of recrystallization (Huss *et al.*, 1981) for subtype determination.

CONCLUSIONS

Ragland is a moderately weathered LL chondrite of metamorphic subtype 3.4 ± 0.1, which has an unusually heavy oxygen isotopic composition and a low planetary ^{36}Ar concentration. The abundance and brecciated nature of the interchondrule material and the lack of type 3.7-4 chondrules suggest that brecciation occurred during accretion, rather than after metamorphism.

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