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THE COLONY METEORITE AND VARIATIONS IN CO3 CHONDRITE PROPERTIES

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The Colony meteorite is an accretionary breccia containing several millimeter- to centimeter-size chondritic clasts embedded in a chondritic host. Colony is one of the least equilibrated CO3 chondrites; it has an unrecrystallized texture and contains compositionally heterogeneous olivine and low-Ca pyroxene, kamacite with low Ni and Co and high Cr, amoeboid inclusions with low FeO and MnO, a fine-grained silicate matrix with very high FeO, and numerous small chondrules with clear pink glass. However, Colony differs from normal CO chondrites in several respects: Although Al, Sc, V, Cr, Ir, Fe, Au and Ga abundances are consistent with a CO chondrite classification, certain lithophiles (Mg and Mn), siderophiles (Ni and Co) and chalcophiles (Se and Zn) are depleted by factors of 10-40%. The shape of Colony's thermoluminescence (TL) glow curve is similar to that of Allan Hills A77307 (another unequilibrated chondrite with CO3 petrological characteristics) and different from those of normal CO chondrites. [ALHA77307 also resembles Colony in having low Mg, Mn, Ni and Co, compared to normal CO chondrites, but it possesses CO-CV levels of Se and Zn and nearly CV levels of Cd.]

Colony is badly weathered; it contains 22.7 wt.% Fe_2O_3 and 5.7 wt.% H_2O. Recalculating the analysis on an H_2O-free basis with all Fe_2O_3, NiO and CoO converted to metal, yields an inferred original metallic Fe,Ni abundance of $\sim$ 19 wt.%. This is similar to that of Kainsaz (an unweathered CO3 fall), but much higher than that of all other CO3 chondrites ($\leq$ 6.3 wt.%). Although it is possible that Colony and either ALHA77307 or Kainsaz constitute distinct CO3 chemical subgroups, the weathered nature of Colony and ALHA77307 preclude the drawing of firm conclusions. Nevertheless, it is clear that CO3 chondrites vary more in compositional and petrological properties than was previously recognized.

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INTRODUCTION

Type 3 chondrites are known from six of the nine major chondrite groups. There are two groups of type 3 carbonaceous chondrites, CO and CV, that differ in their chemical and petrological properties. Relative to CV3 chondrites, CO3 chondrites have lower abundances of refractory lithophile elements (Kallemeyn and Wasson, 1982a) and contain smaller chondrules (55 - 800 μm; King and King, 1978), slightly less abundant fine-grained opaque silicate matrix (29 - 44 vol.%; McSween, 1977a; Scott *et al.*, 1981) and more amoeboid inclusions (rimmed olivine aggregates) (4.9 - 16.0 vol.%; McSween, 1977a; H.Y. McSween, personal communication, 1984).

CO3 chondrites form a metamorphic sequence (McSween, 1977a), in many ways analogous to that of type 3 ordinary chondrites (e.g., Huss *et al.*, 1981; Sears *et al.*, 1980, 1982). Because even mild metamorphism can cause some modification of textures and compositions, it is important to study the least metamorphosed type 3 chondrites. Kainsaz and Allan Hills A77307 have previously been assigned to the least metamorphosed type of CO3 chondrite (McSween, 1977a; Scott *et al.*, 1981), but several workers have questioned whether Allan Hills A77307 is really a CO chondrite. Additional unmetamorphosed CO3 chondrites need to be studied to determine the extent to which different CO3 chondrites vary in their individual characteristics, and to evaluate the possible existence of CO3 chemical subgroups.

Around 1975, a weathered 3.9 kg stone meteorite was found by a farmer near the town of Colony, Washita County, Oklahoma after the stone was caught in the tines of a cotton cultivator (Nininger and Westcott, 1984). Our petrologic and chemical data indicate that Colony is one of the least metamorphosed CO3 chondrites.

ANALYTICAL PROCEDURES

Two slabs of Colony were examined microscopically in reflected light. One slab was loaned to UCLA by J. Westcott; the other belongs to the Smithsonian Institution (USNM 6264). Polished thin sections USNM 6264-1 and 6264-3 of Colony and an unnumbered USNM section of Kainsaz (all obtained from the Smithsonian Institution) were studied microscopically in transmitted and reflected light. Modal analyses were made microscopically using an automated point counter. Mineral compositions were determined with an electron microprobe using crystal spectrometers and following standard Bence-Albee and ZAF correction procedures. Analyses of metallic Fe,Ni were also corrected for Co interference from the low-energy tail of the K_β peak of Fe. Bulk compositions of amoeboid inclusions and matrix areas were determined with the microprobe using a broad (10 - 50 μm) electron beam. Bence-Albee corrections were applied.

About 7 g of a heavily weathered sample of Colony were made available for wet chemical analysis. The sample was analyzed using a modified analytical procedure published earlier (Jarosewich, 1966). Because the sample was so weathered, the conventional reporting of iron would yield anomalously high FeO values; thus, an attempt was made to determine the FeO content directly with the method used in standard rock analyses. The very low abundance of metallic Fe made this possible; however, the presence of FeS might have interfered with this determination, resulting in higher FeO values and an uncertainty of ~ 1 wt.% FeO.

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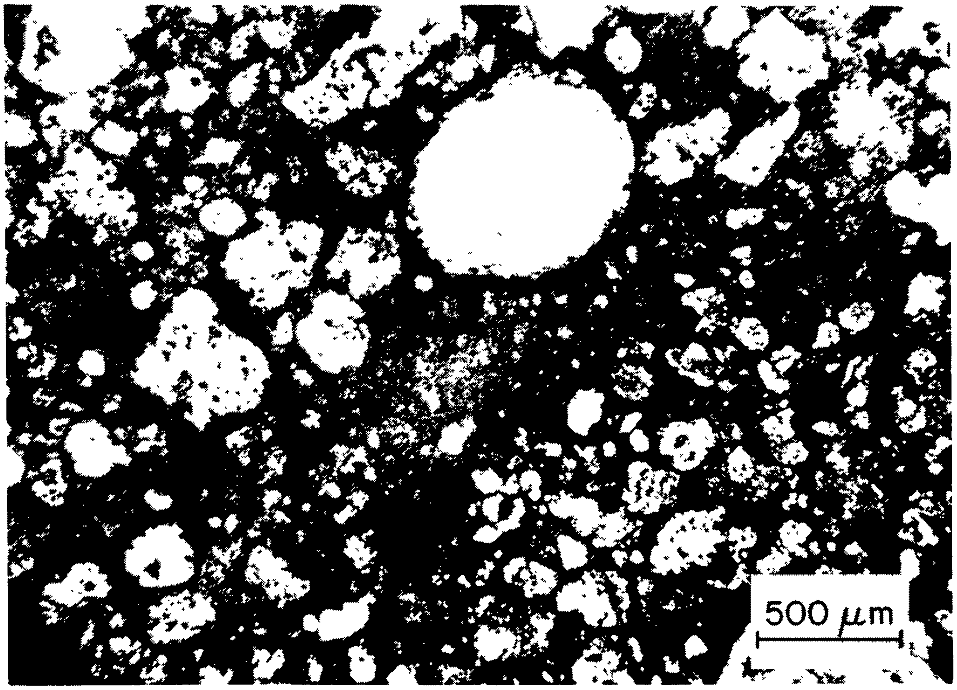

Fig. 1 **Photomicrograph of Colony thin section USNM 6264-1 (transmitted light), showing its unrecrystallized texture. The Colony host (bottom) has a darker fine-grained matrix than the clast (top).**

Two 200 mg fragments of Colony were analyzed by instrumental neutron activation analysis (INAA) in two irradiations along with samples of the Allende meteorite and two samples of USGS standard rock BCR-1. Irradiations were performed at the University of Missouri research reactor; samples were counted for various times over a period of eight weeks. The data are listed in Table 6; selected literature data on the control samples are listed in the Appendix. Our data agree well with literature data, and our accuracy, as indicated by replicate analyses, is acceptable.

The thermoluminescence (TL) measurements were made using the apparatus and techniques described in Sears and Ross (1983), although a wider aperture (4 mm instead of 2 mm) and longer irradiations (5 to 10 min instead of 2 min) were used in order to obtain a signal-to-noise ratio of more than 10. As in previous work, the TL sensitivity is expressed relative to that of the Dhajala meteorite to enable inter-laboratory comparisons.

RESULTS

1. Petrography

Colony contains numerous well-defined, unrecrystallized chondrules (Fig. 1); porphyritic olivine, porphyritic olivine-pyroxene, porphyritic pyroxene, barred olivine, cryptocrystalline, radial pyroxene and granular olivine-pyroxene types occur. The last two types are very rare. Many chondrules contain clear pink glass. Most of the Type I

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porphyritic chondrules (McSween, 1977a) are metal-rich; they contain 10 - 25 vol.% metallic Fe,Ni blebs and additional sulfide. Some porphyritic olivine-pyroxene chondrules contain "dusty" olivine phenocrysts containing submicrometer-size metal grains. Most chondrules range in size from 60 - 900 μm. However, one 32 μm radial pyroxene microchondrule and one 1200 μm porphyritic olivine chondrule were identified.

Amoeboid inclusions (rimmed olivine aggregates) are 200 - 525 μm in size; they have suffered little recrystallization and appear similar to those in Kainsaz.

Refractory inclusions include 200 - 400 μm aphanitic objects and coarser-grained 450 - 700 μm "chondrules." One such "chondrule" contains blades of gehlenite within a fine-grained mesostasis. Another consists of a spinel-rich core surrounded by a mantle of forsterite, clinoenstatite and numerous kamacite blebs; anorthite comprises the mesostasis throughout this object. A. Bischoff (personal communication, 1984) found several Al-rich "chondrules" in Colony that are extremely rich in pyroxene and poor in olivine relative to the Al-rich "chondrules" in CV3 chondrites. He also discovered several hibonite-bearing "blue spherules" that are similar to those in Murchison (CM2).

Fine-grained, opaque silicate matrix constitutes ~ 29 vol.% of Colony (Table 1) and appears unrecrystallized (Fig. 1) and similar in texture to Kainsaz matrix. Some isolated grains of metallic Fe,Ni and troilite occur in Colony's matrix. "Lithic fragments," consisting of chondrule fragments and isolated mineral grains, occur throughout the matrix.

Colony is a breccia. The slabs contain three angular 1 - 6 mm-size chondritic clasts, of which two are darker and one is lighter-colored (Fig. 2) than the host. (The weathered nature of the rock may inhibit the identification of other clasts.) The clasts contain small chondrules and amoeboid inclusions and appear similar to CO3 chondrites. Clast-host boundaries are very sharp. One centimeter-size clast is evident in thin section (Fig. 1); this was the only one analyzed. The fine-grained matrix of this clast is more transparent than that of the host and silicates in it appear to have slightly more pronounced undulose extinction.

2. Mineralogy

Random analyses of $\geq$ 5 μm grains of olivine and low-Ca pyroxene from both chondrules and matrix show these minerals to be compositionally heterogeneous (Fig. 3; Table 2), with olivine the more variable. Significant peaks in compositional distributions occur at Fa_{0-1} and Fs_{0-1} (Fig. 3). Random analyses of isolated mineral grains and fragments (33 olivines and 15 low-Ca pyroxenes) show these grains to have compositional distributions identical to those in chondrules (i.e., the remaining 50 olivines and 50 low-Ca pyroxenes from Fig. 3); this indicates that the isolated grains were derived primarily from chondrules (McSween, 1977b).

The most abundant metallic Fe,Ni mineral is kamacite (Table 3), which is most similar in composition to that of Kainsaz and Allan Hills A77307. Most grains are zoned, with less Ni at their rims than their centers. One grain of Co-rich kamacite was analyzed; such grains have not previously been observed in CO3 chondrites, but are found in the most highly oxidized LL chondrites (Sears and Axon, 1976) and in some areas of the Leoville CV3 polymict breccia (Kracher *et al.*, 1984). Taenite and Ni-rich taenite (or tetrataenite) are rare; only one grain of each was identified with the microprobe. The taenite grain is zoned, with 37.1 wt.% Ni at its edge and 32.8 wt.% Ni at its center.

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Table 1
Modal abundances of constituents in Colony, Allan Hills A77307, Kainsaz and CO3 chondrites.

	Colony			ALHA77307	Kainsaz				CO3 chondrites
	1	2	3	4	1	1	5	6	7
	vol.%	vol.%	vol.%	vol.%	vol.%	wt.%	vol.%	wt.%	vol.%
Chondrules*									
Type I	5	12.1	13.5	6.6					7.8(5.2-13.2)
Type I (metal-rich)	38	18.3	18.7	22.1					26.9(12.4-36.0)
Type II	2	0.5	0.8	1.3					1.9(0.9-2.7)
Type III	0.4	1.2	0.8	0.5					0.8(0.5-1.6)
Inclusions									
Amoeboid	6	10.1	5.6	4.9					10.3(7.4-16.0)
Refractory	1	3.0	3.6	1.2					1.9(0.9-3.5)
Lithic fragments	9	22.3	24.5	18.7					10.0(6.8-18.3)
Matrix	35	28.9	29.7	43.1			47.32	39.90	34.6(28.7-44.2)
Opaque phases		3.6	2.8						
Metallic Fe,Ni	2			0.3	6.6	14.6	10.74	22.64	2.9(1.3-5.9)
Sulfide	1			0.9	4.0	5.3	0.93	1.21	2.9(1.1-4.6)
Silicates					89.4	80.2			
Olivine							11.62	10.50	
Pyroxene							29.39	25.75	
Total	99.4	100.0	100.0	99.6	100.0	100.1	100.00	100.00	100.0
Points counted	1533	1000	1000	2250	2519	2519	8 slices		

1 = This study; 2 = USNM 6264-1 and 3 = USNM 6264-3 (H.Y. McSween, personal communication, 1984); 4 = H.Y. McSween (personal communication, 1984); 5,6 = Chirvinsky and Ushakova (1946); 7 = McSween (1977a) and H.Y. McSween (personal communication, 1984). This average includes Allan Hills A77003, A77029, Felix, Isna, Kainsaz, Lancé, Ornans and Warrenton.

*Type I = MgO-rich porphyritic olivine; Type II = FeO-rich porphyritic olivine; Type III = radial pyroxene.

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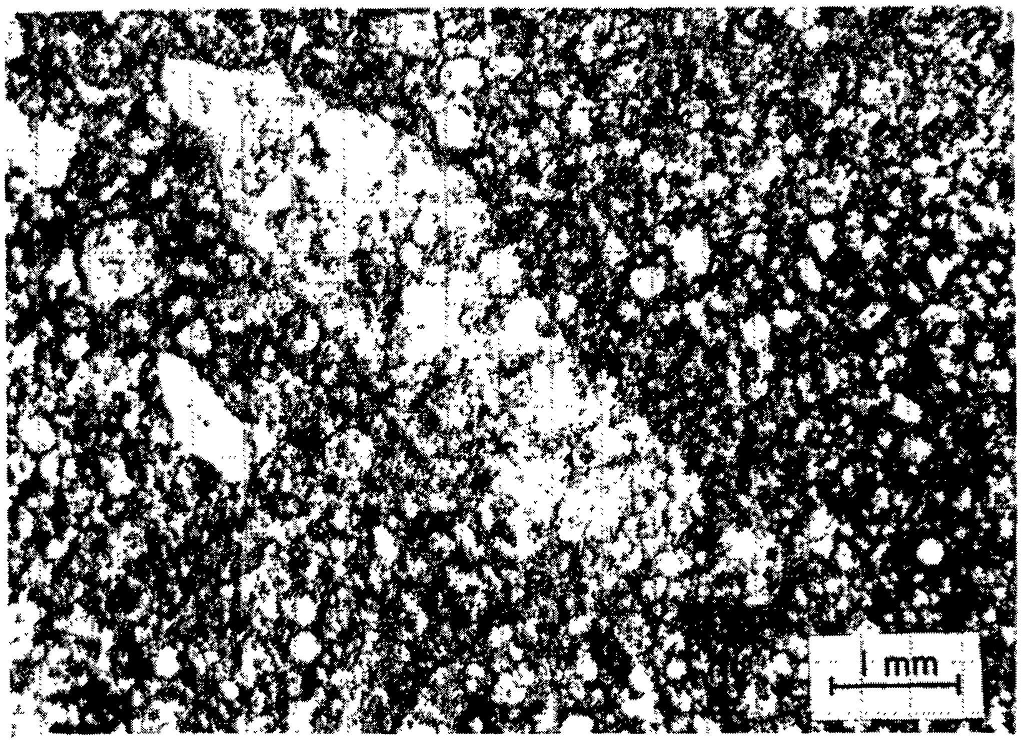

Fig. 2 Light-colored chondritic clast embedded in Colony host in the slab loaned to UCLA by J. Westcott.

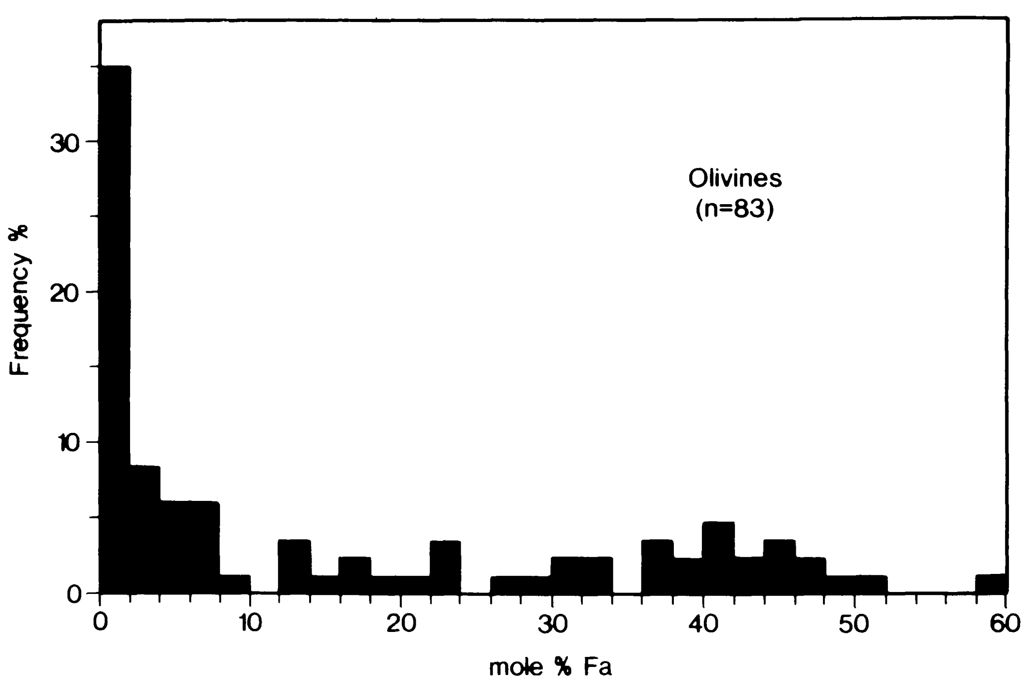

Fig. 3a Compositional distribution of random ≥ 5 μm-size olivine grains in Colony chondrules and matrix.

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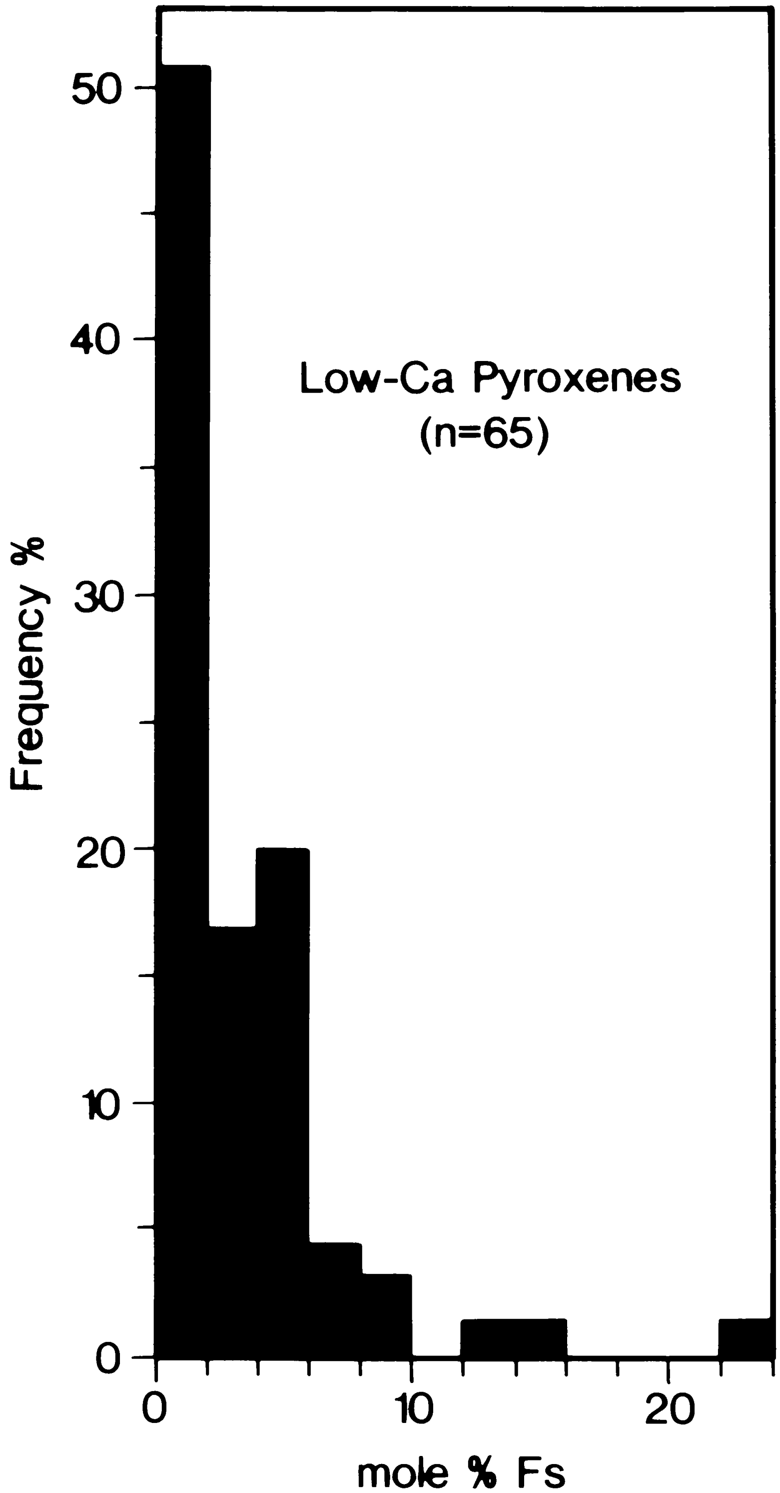

Fig. 3b Compositional distribution of random ≥5 μm-size low-Ca pyroxene grains in Colony chondrules and matrix.

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Table 2
Average compositions of olivine and low-Ca pyroxene in Colony chondrules and matrix (wt.%).

	Olivine	Low-Ca Pyroxene
No. of grains	83	65
SiO_2	40.3 (34.6-44.5)	59.3 (55.4-61.4)
Al_2O_3	<0.04(<0.04-0.15)	1.1 (0.13-3.0)
FeO	13.5 (0.21-45.4)	2.3 (0.40-15.8)
MgO	44.5 (18.2-56.2)	36.5 (26.8-39.0)
CaO	0.30(0.06-1.02)	0.87(0.12-2.6)
MnO	0.20(<0.04-0.57)	0.13(<0.04-0.44)
TiO_2	<0.08(<0.08-0.16)	0.15(<0.08-0.34)
Cr_2O_3	0.33(<0.05-0.68)	0.64(0.29-1.2)
Total	99.13	100.99
Endmember	$Fa_{14.6}(Fa_{0.2-58})$	$Fs_{3.4}Wo_{1.6}(Fs_{0.6-24})$
σ	17.5	3.8
%MD	94.4	72.8

Table 3
Average composition of metallic Fe,Ni in Colony matrix (wt.%).

	Kamacite	Co-rich Kamacite	Taenite	Ni-rich Taenite
Number of grains	24	1	1	1
Si	<0.04	<0.04	<0.04	<0.04
P	0.08	<0.04	<0.04	<0.04
Co	0.42	4.7	0.46	1.3
Ni	4.6	3.3	32.8	54.9
Fe	94.5	91.8	65.8	43.6
Cr	0.48	<0.09	0.73	0.09
Total	100.08	99.80	99.79	99.89

Troilite (essentially pure FeS) is the only sulfide we found. Despite a search, no pentlandite, magnetite or carbides were found.

The bulk composition of opaque matrix in the Colony host (Table 4) differs from those in other chondrites in several respects: FeO and MgO are, respectively, the highest and lowest concentrations reported for matrix in any carbonaceous chondrite (McSween and Richardson, 1977; Scott *et al.*, 1981), and K_2O and Na_2O are higher and lower, respectively, than in CO3 matrices. Other oxides have concentrations within the CO3 matrix range. Opaque matrix material in the analyzed clast is richer in MgO and Cr_2O_3 and poorer in Na_2O, K_2O, CaO and SO_3 than matrix material in the host. Nevertheless, the clast's matrix material is similar to that of the host in being extremely rich in FeO and poor in MgO relative to the matrices of other CO3 chondrites.

Several amoeboid inclusions were also analyzed. McSween (1977a) found that the more metamorphosed CO3 chondrites have amoeboid inclusions with higher FeO and

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Table 4
Composition of opaque matrix in Colony and average CO3 chondrites (wt.%).

	Colony				CO3 chondrites*
	Host	σ	**Clast**	σ	
Number of analyses	25		10		
Na_2O	0.13	0.13	0.07	0.03	0.31(0.19-0.45)
MgO	11.6	2.7	14.0	2.8	19.8 (17.6-24.3)
Al_2O_3	2.5	0.78	2.1	0.97	3.01(2.09-3.59)
SiO_2	25.6	2.4	24.9	2.8	27.6 (24.8-30.6)
SO_3	0.87	0.72	0.35	0.72	0.62(0.22-1.11)
K_2O	0.14	0.07	0.07	0.02	0.04(0.02-0.10)
CaO	0.79	0.37	0.44	0.10	1.00(0.39-2.01)
TiO_2	0.11	0.05	nd	—	0.08(0.07-0.11)
Cr_2O_3	0.38	0.08	0.48	0.33	0.43(0.35-0.65)
MnO	0.32	0.08	0.24	0.03	0.22(0.14-0.33)
FeO	46.0	5.1	46.6	2.6	30.8 (25.4-33.9)
NiO	2.0	0.42	1.7	0.80	0.82(0.59-1.25)
P_2O_5	0.41	0.12	0.37	0.13	nd
Total	90.85		91.32		84.73

*(McSween and Richardson, 1977; excluding Karoonda)
nd = not determined

MnO (Fig. 4). Those in Colony have low FeO and MnO and are most similar in composition to those of Kainsaz (McSween, 1977a).

3. Bulk Composition

The bulk composition of Colony, determined by wet chemical analysis, is listed in Table 5. The analyzed sample was heavily weathered; it contains 5.7 wt.% H_2O and 22.7 wt.% Fe_2O_3. We recalculated the analysis on an H_2O-free basis after converting Fe_2O_3, NiO and CoO to metal (Table 5, column 2). Relative to CO3 chondrites, the recalculated analysis is low in MgO, CaO and Ni, very low in FeO, FeS and Na_2O, high in C, and extremely high in metallic Fe. [These data agree well with the INAA results (reported below).] The severe weathering of Colony is probably responsible for the low FeS and Na_2O values. Enhanced C probably resulted from terrestrial contamination. The recalculated analysis of Colony (Table 5) implies an original metallic Fe,Ni abundance of ~ 19 wt.% (~ 9 vol.%). Thus, Colony is similar to Kainsaz (an unweathered fall) in having low FeO and very high metallic Fe. Modal abundances of metallic Fe,Ni in Kainsaz are consistent with the wet chemical data for this meteorite (Table 1.).

Our INAA data are presented in Table 6 and are plotted in Fig. 5. For most elements, our data are in excellent agreement with those obtained by G.W. Kallemeyn (personal communication, 1984). The ratio of Colony over mean CI is plotted in order of assumed decreasing nebular volatility for lithophile elements and for siderophile and chalcophile elements. Most lithophile elements in Colony are in proportions consistent with a CO chondrite classification: Al, Sc, Eu and Cr are within experimental limits of the mean CO values. Sodium and K have previously been observed to be low in carbonaceous meteorite finds and this has been accredited to leaching during the

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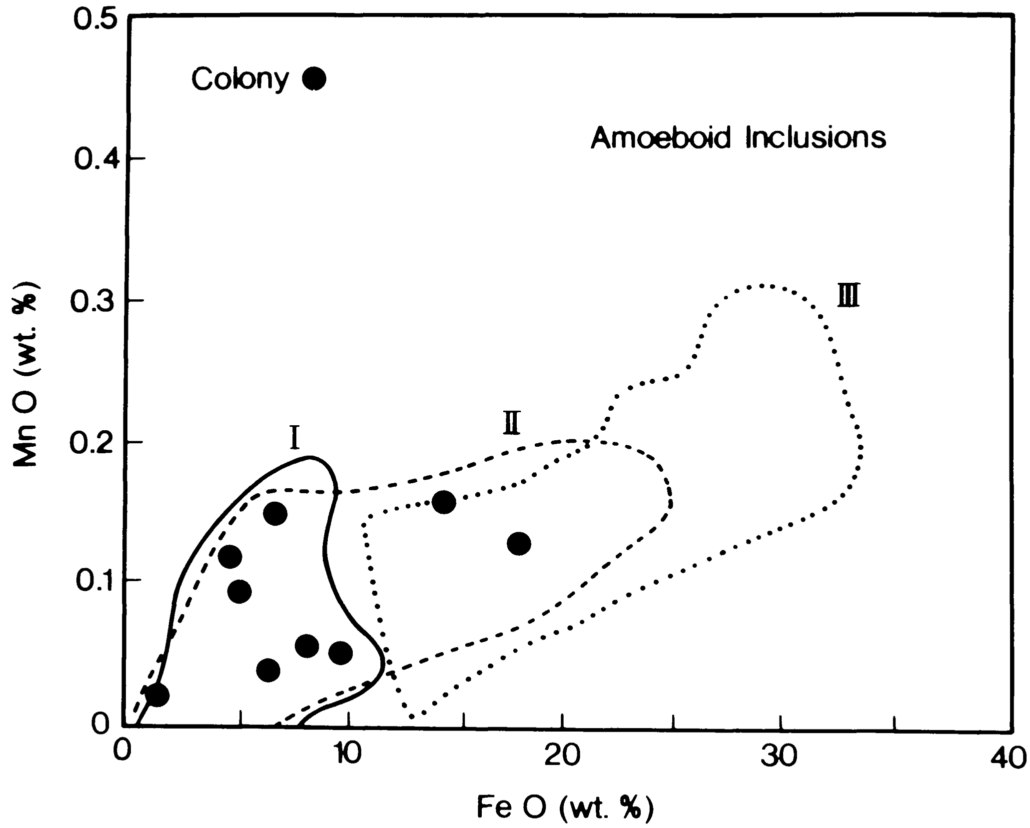

Fig. 4 **Compositions of amoeboid inclusions in Colony and other CO3 chondrites. I, II and III refer to the CO3 subgroups in order of increasing metamorphic grade (McSween, 1977a). Four outlying points of subgroup II are not included in the illustration.**

weathering process. Our K value is higher than the CO range and intermediate between CO and ordinary chondrites; G.W. Kallemeyn (personal communication, 1984) has observed high K (and low Ca) in weathered CV3 chondrites. The chalcophile elements, Se and Zn, are about 20% below CO and CM values, consistent with the low FeS in the wet chemical analysis. Depletions in chalcophiles are probably due to weathering. The low Mg and Mn and the high, fractionated La and Sm values are more problematic. It is possible that these abundances are also due to weathering, but it is plausible that they are primary features; a few ordinary chondrite falls (e.g., Guidder, LL5 and, to a lesser extent, Albereto, L4) have similar rare earth element patterns (G.W. Kallemeyn, personal communication, 1984). The pattern of siderophile elements in Colony is striking: Ni and Co are depleted by 35 - 40% relative to CO, whereas Ir, Fe, Au and Ga are much closer to CO and CM proportions.

Allan Hills A77307 was classified as a CO3 chondrite by Scott *et al.* (1981) on the basis of its major petrological features. However, it possesses a number of unique characteristics which have caused several authors to suggest that it is not a normal CO chondrite. These characteristics include the presence of haxonite ($Fe_{23}C_6$) and cohenite (Fe_3C), abundant magnetite, opaque matrix with high SO_3, high bulk Se and Zn, very high bulk Cd (215 ± 35 ng/g) and an unusual TL glow curve (Scott *et al.*, 1981; Kallemeyn and Wasson, 1982a; Biswas *et al.*, 1981; Sears and Ross, 1983). The

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Table 5
Bulk compositions (wt.%) of Colony, Kainsaz and CO3 chondrites determined by wet chemical methods.

	Colony		Kainsaz	CO3 chondrites
	1	2	3	4
SiO_2	32.11	37.03	34.68	33.88(33.23-34.82)
TiO_2	0.13	0.15	0.22	0.13(0.10-0.15)
Al_2O_3	2.73	3.15	3.72	2.72(2.18-2.93)
Cr_2O_3	0.50	0.58	0.72	0.50(0.44-0.58)
Fe_2O_3	22.68			
FeO	10.21	11.77	7.37	23.82(21.78-25.32)
MnO	0.21	0.24	0.30	0.22(0.18-0.31)
MgO	19.94	22.99	24.72	23.63(23.53-23.87)
CaO	1.39	1.60	2.50	2.23(1.99-2.64)
Na_2O	0.09	0.10	2.46	0.62(0.55-0.74)
K_2O	0.05	0.06	0.20	0.11(0.05-0.23)
P_2O_5	0.24	0.28	0.18	0.27(0.20-0.35)
$H_2O(+)$	4.33			0.72(0.10-1.40)
$H_2O(-)$	1.37			0.33(0.00-0.88)
Fe	<0.1	18.29	18.36	3.07(0.72-4.72)
Ni		1.13	1.65	1.43(1.36-1.51)
Co		0.07		0.07(0.07-0.09)
NiO	1.25			
CoO	0.08			
FeS	1.67	1.93	4.15	5.48(4.52-6.49)
C	0.55	0.63		0.31(0.19-0.46)
Total	99.53	100.00	101.23	99.54
Total Fe	24.86	28.67	26.73	25.41(24.51-26.19)

1 = As received; 2 = Recalculated on H_2O-free basis; 3 = Dyakonova (1964); 4 = Wiik (1956), Methot *et al.* (1975) and Marvin and Mason (1980). This average includes Allan Hills A77003, Felix, Isna, Lancé, Ornans and Warrenton.

kamacite composition (Scott *et al.*, 1981) and the olivine and low-Ca pyroxene compositional distributions (E.R.D. Scott, personal communication, 1984) of Allan Hills A77307 are very similar to those of Colony.

In Figure 5, we have plotted the analysis of Allan Hills A77307 by Kallemeyn and Wasson (1982a). In many respects, it resembles our analysis of Colony. For most lithophile elements, Allan Hills A77307 plots close to CO values but between the CO and CM values; Ca depletions are similar to those of Colony and may be due to weathering. Sodium and, to a lesser extent, K, are depleted in Allan Hills A77307, also presumably due to weathering. The siderophile and chalcophile elements are largely in CO rather than CV abundances, although Cd is in the CV range. Like Colony, Allan Hills A77307 shows a significant Ni depletion, but, unlike Colony, only a minor Co depletion. In contrast, the Antarctic CO3 chondrites Allan Hills A77003 and A77029 are not depleted in Ni, Co or Se relative to average CO chondrites (Kallemeyn and Wasson, 1982b).

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Table 6

INAA data on duplicate samples of the Colony meteorite, and Allende and BCR-1 control samples.

	Irrad	Mass (mg)	Na (mg/g)	Mg (mg/g)	Al (mg/g)	K (mg/g)	Ca (mg/g)	Sc (μg/g)	V (μg/g)	Cr (mg/g)	Mn (mg/g)	Fe (mg/g)	Co (μg/g)	Ni (mg/g)	Zn (μg/g)	Ga (μg/g)	Se (μg/g)	La (μg/g)	Sm (μg/g)	Eu (μg/g)	Ir (μg/g)	Au (μg/g)
Colony	JU 83	152.0	0.60	113	15.5	0.61	—	9.6	96	3.4	1.5	265	399	7.87	76	—	5.5	.710	.280		.610	.140
Colony	FE 84	206.0	0.64	109	14.1	0.54	11.8	10.9	89	3.3	1.3	302	450	9.19	93	7.5	5.8	.610	.290	.107	.700	.165
Allende *1	JU 83	122.5	3.8	140	24.1	0.265	19.1	13.4	102	3.5	1.4	236	662	13.8	112	—	8.3	.519	.312	.198	.1017	.122
Allende *2	JU 83	152.6	3.7	135	17.5	0.270	15.6	10.5	102	3.4	1.5	230	652	13.1	86	—	6.4	.463	.264	.146	.664	
Allende 2	FE 84	157.6	4.1	149	17.2	0.305	18.9	12.1	96	3.6	1.5	263	721	15.5	114	5.9	9.2	.493	.301	.120	.779	.150
Allende lit.†			3.41	148	17.3	0.272	19.1	10.9	115	3.68	1.47	233	629	14.0	116	6.27	7.95	.475	.276	.116	.791	.163
std. dev.			±.13		±.26		±.60	±.89		±.12	±.08	±8.4	±27	±.79	±4.2	±.33	±.79	±.026	±.036	±.027	±.077	±.040
BCR-1	JU 83	150.7	26.7		76.9	15.1	—	34.1	422		1.40	94.5	39.0		126			28.2	6.59	1.96		
	FE 84	140.7	26.4		73.5	18.7	40.7	35.2	428		1.32	99.1	39.9		146			26.0	6.94	1.73		
BCR-1 lit.‡			24.3	20.8	72.0	14.1	49.5	33.0	399	17.6	1.4	93.7	38.0	15.8	120	20		26.0	6.6	1.94		.095

*1, Smithsonian Institution, split 3, position 18; 2, Smithsonian Institution 3636.
†See appendix for references. No standard deviations are quoted for elements with less than 4 determinations.
‡Flanagan [29].

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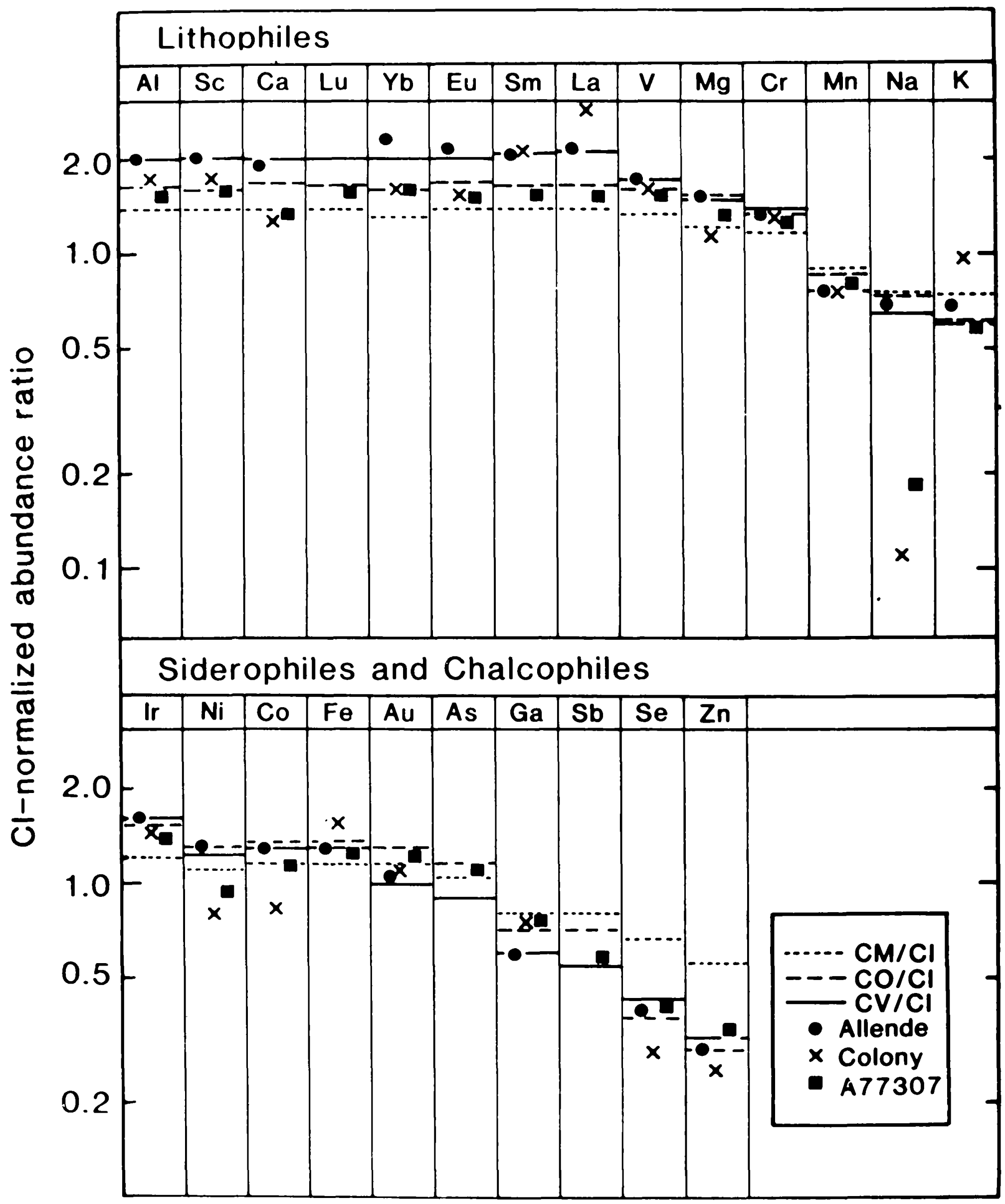

Fig. 5 **CI-normalized abundance data for elements in the Colony meteorite (this work), Allan Hills A77307 (Kallemeyn and Wasson, 1982a) and average CM, CO and CV chondrites (Kallemeyn and Wasson, 1981).**

4. Thermoluminescence

The most significant aspect of the TL data is the similarity in shape of Colony's glow curve (TL emission as a function of temperature) to that of Allan Hills A77307. The glow curves of these two meteorites (Fig. 6) differ from those of normal CO chondrites such as Ornans and Isna. Colony has a single broad band of emission which peaks at 180°C with an inflection suggesting a second peak at ~ 250°C and perhaps a third at ~ 100°C. The curve is very noisy, reflecting a very low TL sensitivity, but the general features are quite similar to those of Allan Hills A77307 (which has a peak at 170°C and inflections at 100°C and 250°C). We estimate that the uncertainties of these peak temperatures are

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~ 10% at the 1 sigma level. In contrast, the six CO chondrites examined by Sears and Ross (1983) have discrete peaks at 91 ± 7°C and 203 ± 11°C and an inflection suggesting another peak at ~ 270°C. (The uncertainties represent 1 sigma of the mean values of the six CO3 chondrites.)

The TL sensitivity of Colony is much lower than that of Allan Hills A77307 and any of the CO chondrites. The Dhajala-normalized mean TL sensitivity for two fragments (200 and 150 mg), measured 3 to 5 times on separate occasions, is 0.024 ± 0.005. This is an order of magnitude lower than that of the lowest CO chondrite and is comparable to the TL sensitivities of type 3.3 ordinary chondrites.

DISCUSSION

1. Classification

Colony's petrologic characteristics and lithophile element abundances indicate that Colony is a carbonaceous chondrite. As described above, its chemical composition is similar to that of Allan Hills A77307 and its inferred original metallic Fe,Ni abundance is similar to that of Kainsaz. All three meteorites have petrological properties consistent with a CO3 classification, including small chondrule sizes, high proportion of metal-rich chondrules, appropriate modal matrix abundance, abundance and composition of amoeboid inclusions, composition of kamacite, and compositional distributions of olivine and low-Ca pyroxene. Nevertheless, all three have anomalous properties: (1) Kainsaz has (and Colony is inferred to have had) extremely abundant metallic Fe,Ni and unusually low FeO, and (2) Colony and Allan Hills A77307 both have low bulk Ni, Co, Mg and Mn and unusual TL glow curves. We offer three possible interpretations of these data: (1) Colony and Allan Hills A77307 are normal CO chondrites whose properties were modified by weathering, (2) none of the three is a CO chondrite, but all are anomalous carbonaceous meteorites occupying a hiatus between CV-CO-CM chondrites, and (3) all are normal CO chondrites, but the group is so poorly sampled that the full extent of its compositional and petrological variations has not previously been appreciated.

We doubt that the first possibility is the full explanation, although certain compositional characteristics are probably related to weathering (e.g., low Na, high K, and, possibly, low Ca). Our petrologic observations indicate that Mg and Mn are located primarily in the mafic silicates, which are not normally considered to be highly susceptible to weathering. Nickel and Co are located primarily in the metal and analyses of weathered ordinary chondrites have not shown that weathering preferentially lowers both of these elements. However, if the inferred original metallic Fe,Ni abundance in Colony is correct, then Colony has lost so much metal due to weathering that the significance of its bulk siderophile element abundances must be evaluated with caution.

We doubt that the unusual TL properties of Colony and Allan Hills A77307 result from weathering effects; Allan Hills A77003 is a normal CO3 chondrite from Antarctica with normal TL (Sears and Ross, 1983; Fig. 6) that is of the same weathering category as Allan Hills A77307 (category A; i.e., least weathered). However, these weathering categories are based on the amount of surface rust on the Antarctic samples and are not quantitative parameters.

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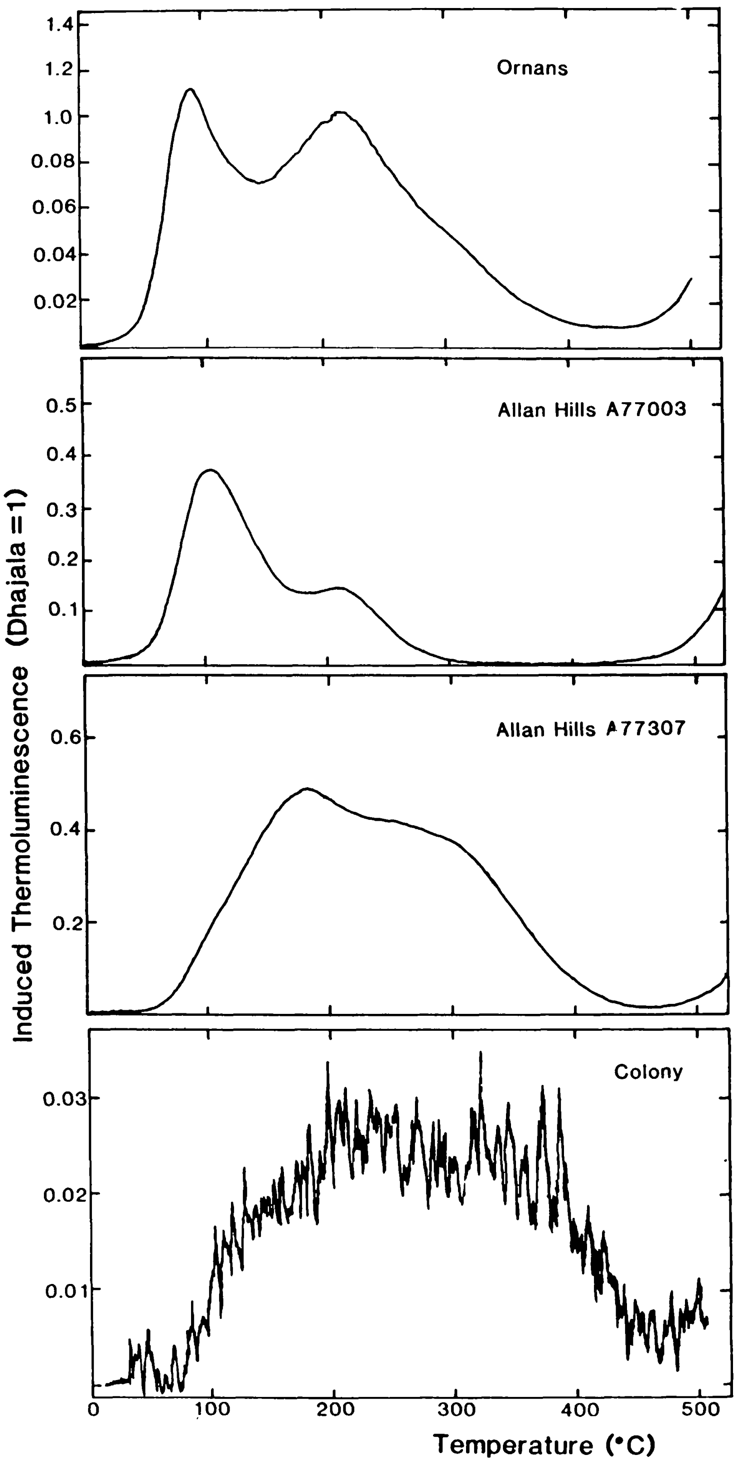

Fig. 6 Thermoluminescence glow curves for Colony and Allan Hills A77307 compared with the CO chondrites Ornans and Allan Hills A77003.

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Kallemeyn and Wasson (1982a) suggested that Allan Hills A77307 is intermediate between the CO and CM groups largely on the basis of its lithophile element abundances. The similarities in bulk composition and TL between Allan Hills A77307 and Colony indicate that these two meteorites are related. Because both share most of the petrological characteristics of normal CO3 chondrites and because Colony appears to have had the same high abundance of metallic Fe,Ni as Kainsaz (which is otherwise a normal CO3 chondrite), we think it unlikely that any of these meteorites is an anomalous or ungrouped carbonaceous chondrite.

We believe that Colony, Kainsaz and Allan Hills A77307 are normal CO chondrites that exhibit compositional variations not previously recognized among members of the CO3 group. Primary variations among different type 3 ordinary chondrites are well known (e.g., Huss *et al.*, 1981). These include abundant graphite-magnetite aggregates in Allan Hills A77011 (L3) (McKinley *et al.*, 1981), abundant feldspathic "white matrix" material in Tieschitz (H3) (Christophe Michel-Lévy, 1976), abundant "translucent matrix" material in Allan Hills A79003 (LL3) (Scott *et al.*, 1982) and high concentrations of alkalies in Manych (LL3) (Dodd *et al.*, 1967). CV chondrites also vary in their primary properties. McSween (1977c) showed that CV chondrites comprise an oxidized and a reduced subgroup. These two subgroups differ in their abundances of metallic Fe,Ni and magnetite, sulfide Ni content and bulk Cd content (McSween, 1977c; Kallemeyn and Wasson, 1982a).

It is possible that Colony and Allan Hills A77307 constitute a distinct chemical subgroup of CO3 chondrites characterized by low Mg, Mn, Ni and Co and unusual TL properties. Allan Hills A77307 also contains very high Cd, but Cd has not yet been measured in Colony. The differences in siderophile abundances between Colony (and Allan Hills A77307) and (other) CO3 chondrites (Fig. 6) are somewhat similar to the differences between LL and H or between EL and EH chondrites. However, the inferred high initial metallic Fe,Ni abundance in Colony makes the analogy inexact. It is also possible that Colony and Kainsaz constitute a reduced CO subgroup characterized by high metallic Fe,Ni and low FeO. However, the weathered nature of Colony and Allan Hills A77307 prevents us from drawing firm conclusions about the possible existence of any CO3 subgroups.

2. Metamorphic Grade

McSween (1977a) suggested that the CO3 chondrites form a metamorphic sequence. He showed that with increasing metamorphism, textural features become more recrystallized, average olivine and low-Ca pyroxene compositions change from Fa_{12},Fs_3 to Fa_{34},Fs_{11}, olivine and low-Ca pyroxene compositional heterogeneity decreases, kamacite Ni contents increase, taenite Ni contents decrease and Fe/Mg exchange between matrix and chondrules plus inclusions increases.

Our petrologic data indicate that Colony is one of the least metamorphosed CO3 chondrites. These data include occurrence of many glass-bearing chondrules, unrecrystallized texture (Fig. 1), heterogeneous olivine and low-Ca pyroxene (Table 2; Fig. 3), and compositionally distinctive compositions of kamacite (low Ni and Co, high Cr; Table 3) and amoeboid inclusions (low MnO and FeO; Fig. 4). The extremely high FeO in the fine-grained matrix material of the Colony host and analyzed clast (Table 4) is indicative of negligible Fe/Mg exchange between matrix material and chondrules plus inclusions. This suggests that Colony may be the least equilibrated CO3 chondrite.

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This conclusion is consistent with the results of Scott and Taylor (1984), who analyzed olivines in type I and type II porphyritic olivine chondrules in Colony and other CO3 chondrites. They found that chondrule olivines in the least metamorphosed chondrites have lower Fa and higher CaO. Their data indicate that Colony and Allan Hills A77307 are less equilibrated than Kainsaz.

The TL systematics of CO chondrites are currently being explored (B.D. Keck and D.W.G. Sears, unpublished data) and there is an indication that TL sensitivity is related to metamorphic history. Thus, the low TL sensitivity of Colony appears to be consistent with the petrologic evidence of its very low metamorphic grade.

3. Nature of Brecciation

Several H-L-LL3, CV3 and CO3 chondrites may be accretionary breccias, containing chondritic clasts with similar (but not identical) lithologies to those of their hosts. For example, Piancaldoli (LL3) contains LL3 clasts with different modal abundances of opaque and recrystallized silicate matrix (Rubin *et al.*, 1982) and Leoville (CV3) contains, among its many clasts, one that is texturally similar to the host, but much finer-grained and richer in magnetite (Kracher *et al.*, 1982). Our unpublished petrographic observations of Isna (CO3) (section USNM 5890-5) indicate that it contains a small CO3 chondrite clast with a very recrystallized matrix. The brecciated texture of all of these meteorites was probably established during agglomeration.

Colony may also be an accretionary breccia. The three clasts visible in the slabs all appear similar to the Colony host (e.g., Fig. 2); the analyzed clast in section USNM 6264-1 is very similar to the host except for the appearance and composition of the fine-grained matrix (Fig. 1). The clast may have acquired its fine-grained matrix material from a slightly different compositional reservoir than that which supplied matrix material to the host. The slightly more pronounced undulose extinction of silicates in the clast attests to a somewhat more violent shock history. It is possible that the clast was mildly shocked during its incorporation into the host.

6. Acquisition of Amoeboid Inclusions by CO Chondrites

Figure 7 shows that there is an inverse correlation between olivine heterogeneity (expressed as percent mean deviation or %MD) and modal abundance of amoeboid inclusions in CO3 chondrites ($r = -0.742$, $n = 10$, $2\alpha = 0.02$). The least metamorphosed CO3 chondrites tend to have the fewest amoeboid inclusions and the most metamorphosed ones tend to have the most. If Colony and Allan Hills A77307 are omitted from Figure 7, the correlation is less strong ($r = -0.616$), but still significant at the $2\alpha = 0.15$ level.

We suggest two possibilities to explain the correlation: (1) The more metamorphosed CO chondrites initially agglomerated in a different region than the others, one that had a higher proportion of amoeboid inclusions (i.e., the correlation is a coincidence). (2) The more metamorphosed CO chondrites agglomerated earlier than the others and were buried (and metamorphosed) beneath additional accreting material (H.Y. McSween, personal communication, 1984). Meanwhile, the supply of amoeboid inclusions decreased; fewer were available when the least metamorphosed CO3 chondrites agglomerated.

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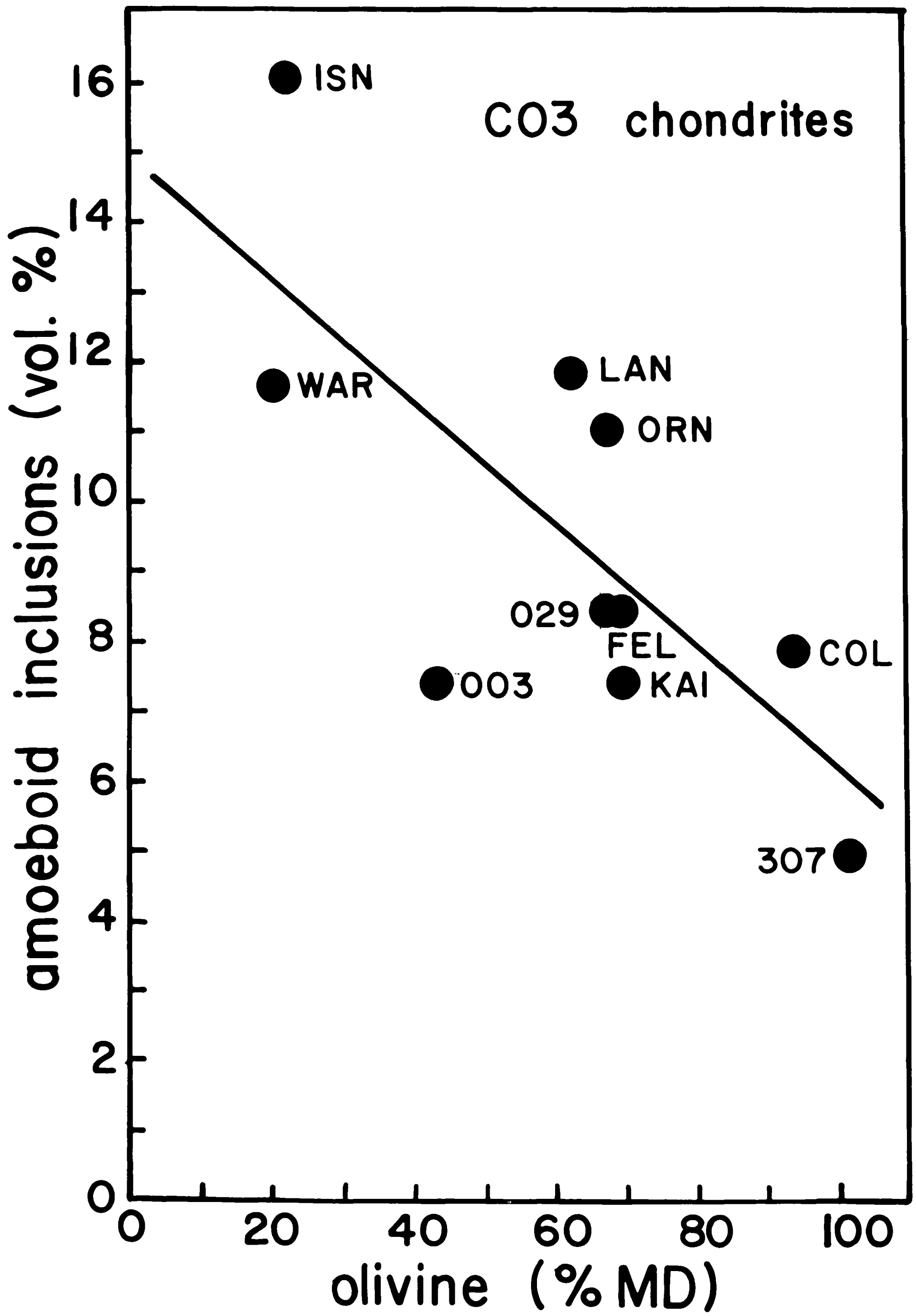

Fig. 7 Modal abundances of amoeboid inclusions versus olivine heterogeneity (expressed as %MD or percent mean deviation) for 10 CO3 chondrites (Allan Hills A77003, A77029 and A77307, Colony, Felix, Isna, Kainsaz, Lancé, Ornans and Warrenton). Olivine data are from this study, McSween (1977a) and E.R.D. Scott (personal communication, 1984); modal abundances are from McSween (1977a) and H.Y. McSween (personal communication, 1984).

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APPENDIX

Sources of Literature Data For the Composition of the Allende Meteorite

Element	Reference	Element	Reference	Element	Reference	Element	Reference
Na	1,2,12,13, 17,18	Sc	1,10,13, 17,18	Co	1,2,4,5, 7,10-18	La	1,12,18
Mg	1,2,10	V	1,18	Ni	1-3,8-11, 17	Sm	1,12,13, 18
Al	1,2,10,18	Cr	1,2,10,11, 17,18	Zn	1,3-10, 14,15,16	Eu	1,12,13, 18
K	1,2	Mn	1,2,11,12, 18	Ga	1,4,5,9, 14-16	Ir	1,3,8,9, 12,13,17
Ca	1,2,10,18	Fe	1,2,10,12, 13,17,18	Se	1,3-6,8, 14,15	Au	1,3,8-10, 13,15-18

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