

Cumberland Falls chondritic inclusions: III. Consortium study of relationship to inclusions in Allan Hills 78113 aubrite

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Abstract—We describe the mineralogy and report contents of Ag, Au, Bi, Cd, Co, Cs, Ga, In, Rb, Sb, Se, Te, Tl, U and Zn determined by RNAA in three primitive chondritic inclusions from the ALH A78113 aubrite. Comparison of these data with those for large, petrologic type 3 chondritic clasts from the Cumberland Falls aubrite and the discovery of small clasts in it like those in ALH A78113 indicate that all constitute a single chondritic suite. We also report thermoluminescence data for Cumberland Falls chondritic inclusions and achondritic host. These results, together with mineralogic, major, minor and trace element information, demonstrate that aubrite inclusions represent a different sort of type 3 chondrite, not an LL3 chondrite altered during equilibration with aubrite host. Instead, the aubrite inclusions represent a distinct chondrite class. These inclusions reflect nebular condensation/accretion over a broad redox range and at temperatures relatively high compared with those at which other type 3 chondrites formed. Limited metamorphism and reduction occurred during condensation/accretion, prior to incorporation into aubrite host. During the impact of the chondritic parent body with the aubrite parent body, chondrite fragments were strongly shocked and cooled rapidly. They then mixed with aubrite host, possibly in a regolith, so that these aubrites now represent impact breccias.

INTRODUCTION

THE CUMBERLAND FALLS METEORITE has long been a black and white example of a polymict breccia, consisting of chondritic inclusions in enstatite achondrite (aubrite) matrix. Even scattered early investigations of individual inclusions revealed them to be peculiar. In the first systematic study of Cumberland Falls inclusions, NEAL and LIPSCHUTZ (1981) reported that the mineralogy and petrology of 9 samples indicated them to be members of a unique primitive chondrite suite condensed from the nebula over a broad redox range. Their parent body had impacted the enstatite meteorite parent object, highly-shocked fragments being incorporated into the aubrite host. Volatile/mobile trace elements in these same Cumberland Falls inclusions indicate condensation/accretion temperatures somewhat higher than those at which other petrologic type 3 chondrites formed; abundances seem unaffected by post-accretionary processes (VERKOUTEREN and LIPSCHUTZ, 1983). Oxygen isotopic compositions (Clayton,

quoted in VERKOUTEREN and LIPSCHUTZ, 1983) resemble those of type 3 ordinary (H, L, LL) chondrites, in keeping with the highly unequilibrated nature of these Cumberland Falls inclusions. Type 3 ordinary chondrites exhibit siderophile element patterns that make it clear that the relationship between type 3 and higher petrologic type ordinary chondrites involves more than metamorphism alone (SEARS and WEEKS, 1986).

Whether Cumberland Falls inclusions are related to discrete meteorites is uncertain. Largely because of redox state similarities, GRAHAM *et al.* (1977) connected them with Kakangari, Mt. Morris, Pontlyfni and Winona, calling all forsterite chondrites though 3 of the 4 equilibrated meteorites exhibit no chondritic texture. Similarities in $\delta^{13}\text{C}$ /temperature-release patterns for some of these meteorites and Cumberland Falls inclusions support this linkage (GRADY and PILLINGER, 1986). On the other hand, volatile/mobile trace element abundances and oxygen isotope compositions (CLAYTON and MAYEDA, 1978a,b; CLAYTON *et al.*, 1976, 1983a,b; MAYEDA and CLAYTON, 1980; VERKOUTEREN and LIPSCHUTZ, 1983) indicate the distinctiveness of Cumberland Falls inclusions relative to known type 3 ordinary chondrites. VERKOUTEREN and LIPSCHUTZ (1983) thus suggested that the forsterite chondrite name be reserved for Cumberland Falls inclusions and for related ones in ALH A78113 aubrite.

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The abundance pattern of the only such inclusion studied (.38) generally resembled that of Cumberland Falls inclusions but exhibited some differences (VERKOUTEREN and LIPSCHUTZ, 1983). KALLEMEYN and WASSON (1985), in reporting data for five ungrouped meteorites and a Cumberland Falls clast, questioned the existence of a distinct forsterite chondrite group exemplified by these inclusions and conjectured that Cumberland Falls inclusions represent an LL chondrite precursor partly equilibrated by contact with aubrite. GRADY and PILLINGER (1986) reported that the $\delta^{13}\text{C}$ /temperature-release pattern of a Cumberland Falls inclusion is entirely different from that of a highly unequilibrated chondrite, like the LL3.0 chondrite, Semarkona.

In recent years, induced thermoluminescence (TL) properties have proven of value in exploring the metamorphic and shock histories of meteorites, especially type 3 ordinary chondrites. Ordinary chondrites as a whole show a 10^5 -fold range in TL sensitivity, whereas the range for type 3 chondrites alone covers a range of 10^3 (SEARS *et al.*, 1980). Decreasing amounts of igneous glass, and the appearance and coarsening of feldspar are important parameters in the petrologic (*i.e.*, metamorphic) VAN SCHMUS and WOOD (1967) classification. The TL sensitivity variation apparently reflects feldspar formation through metamorphic devitrification of glass (SEARS *et al.*, 1984a; DEHART and SEARS, 1985; GUIMON *et al.*, 1986). There are also metamorphism-related changes in the peak temperature (for maximum TL emission) and peak width (or temperature range for TL emission defined in terms of full width at half maximum, FWHM, *i.e.*, SEARS *et al.*, 1982). Laboratory annealing treatment has reproduced these changes (GUIMON *et al.*, 1985). The peak temperature change is very similar to that induced by analogous annealing of a terrestrial feldspar where changes are related to the onset of disordering in the Al, Si framework (PASTERNAK, 1978; HARTMETZ and SEARS, 1987).

Intense shock also decreases TL sensitivity by 1 to 2 orders of magnitude below the values observed for unshocked, equilibrated chondrites. The decrease appears to be associated with feldspar melting (SEARS *et al.*, 1984b). Below melting temperatures (and equivalent shock pressures), TL sensitivity decreases by about a factor of 2 by an unknown process with a very low activation energy (30 kJ/mol).

To gain further insight into the history of the Cumberland Falls and ALH A78113 chondritic inclusions, we have formed a mini-consortium to investigate three questions. (1) What relationship, if any, exists between black inclusions in Cumberland Falls and ALH A78113 aubrites? (2) How did these inclusions form? (3) Do they represent a unique chondritic group, or are they LL3 chondrites metamorphosed during contact with aubrite? To answer the first question, we decided to investigate mineralogically and petrologically as many inclusions as possible and determine Ag, Au, Bi, Cd, Co, Cs, Ga, In, Rb, Sb, Se, Te, Tl, U and Zn in aliquots of them. These data, bulk refractory, major, minor and trace element contents and TL results are then used to address the second and third questions.

EXPERIMENTAL

Samples

Inclusions in ALH A78113 are sparser and smaller than those in Cumberland Falls and the Antarctic sample is much smaller, 299 g

vs. 16 kg for Cumberland Falls. Hence, we could locate only 3 inclusions in ALH A78113 large enough to provide samples for a thin section (PTS) and for our radiochemical neutron activation analysis (RNAA) measurements. VERKOUTEREN and LIPSCHUTZ (1983) reported RNAA data for .38 (230 mg): its corresponding PTS (.31) was unfortunately lost in transit. However, we obtained another sample of the same inclusion (.51 of 228 mg mass) for RNAA study, its corresponding PTS being .41. Other inclusions sampled for RNAA were .43 (390 mg) and .45 (90 mg), with corresponding PTS .49 and .50. The aubrite matrix (.15) had been analyzed previously by RNAA (BISWAS *et al.*, 1980). Part of ALH A78113.38 (244 μg) and samples of Cumberland Falls 604-2 (764 μg) and 604-9 (198 μg)—representing the known extremes in redox state for Cumberland Falls inclusions—were also analyzed by instrumental neutron activation analysis (INAA). The aliquots were taken from batches of homogenized powder prepared from 100–200 mg chips of the inclusions. Numbers of Cumberland Falls inclusions for INAA and TL, and their PTS correspond with those in NEAL and LIPSCHUTZ (1981) and VERKOUTEREN and LIPSCHUTZ (1983).

Techniques

Three polished thin sections were studied using transmitted and reflected light microscopy. Mineral analyses were carried out using an ARL-SEMQ automated electron microprobe, with standards chosen for their compositional similarity to the phases being analyzed. All phases and standards were analyzed for 20 seconds on the peak and 10 seconds on backgrounds, and were corrected by BENCE-ALBEE (1968) methods. Modal analyses were determined by an automated method described by PRINZ *et al.* (1980) and DELANEY *et al.* (1983). For larger clasts, 500 points were analyzed; for smaller ones 100 points were measured. Bulk compositions were determined by broad-beam electron microprobe techniques, with standards and unknowns being analyzed with a beam 50 μm in diameter. Equally spaced points were analyzed within each clast for 20/10 seconds (peak/background) per spot, and each point was corrected by the BENCE and ALBEE (1968) method. All FeO was corrected for the amount present in the silicates by assigning the appropriate Fe to each of the sulfides and metallic phases modally present, the compositions of which were previously determined. The technique has been tested against materials that have been analyzed by wet chemistry and the results are very comparable. Although some error exists in using broad-beam microprobe techniques on heterogeneous samples, as discussed by ALBEE *et al.* (1977), the technique is relatively reliable and invaluable when applied carefully.

The RNAA methods and equipment used were those described by VERKOUTEREN and LIPSCHUTZ (1983). The INAA technique was similar to that used for the first 8 Murchison inclusions studied by EKAMBARAM *et al.* (1984). Portions of 6 Cumberland Falls inclusions and 4 adjacent matrix samples (each ~ 100 mg) were ground and, after removal of magnetic material, 4 mg aliquots were placed in Cu dishes and analyzed for TL using the equipment and techniques of SEARS and WEEKS (1983). Five samples each of similarly prepared Chainpur (LL3.4) and Dhajala (H3.8) samples were analyzed as reference standards. Both were analyzed when the chondritic inclusions were studied. The uncertainty quoted for each single Cumberland Falls analysis is one population standard deviation estimated from the replicate Dhajala data. Uncertainties quoted for Chainpur are estimated from its replicate analyses. After completing study of chondritic inclusions, analysis of achondritic host samples seemed worthwhile and a different Dhajala sample was used as the control for this series of measurements. We also performed annealing experiments on three inclusions using the techniques of GUIMON *et al.* (1985) to compare the results with similar ones for type 3 ordinary chondrites and to test predictions made on the basis of TL trends displayed by the inclusions.

RESULTS

Mineralogy/petrology

Each of the three black ALH A78113 inclusions, several millimeters across, is fine-grained with a dense black matrix and contrasts sharply with the light-colored aubritic host. The

large Cumberland Falls inclusions also appear black in hand specimen but have a light-colored crystalline matrix. Several newly discovered mm-sized clasts in Cumberland Falls 604-8 differ somewhat from the large chondritic clasts in that they have a dense black matrix resembling those in ALH A78113 inclusions. These inclusions are also included in this study, as they expand the range of materials known from Cumberland Falls and resemble chondritic clasts from ALH A78113.

Petrographically, ALH A78113 clasts are angular, sometimes coherent and, at times, intimately intermixed with aubrite host. Small olivine and pyroxene crystals are scattered in the black matrix: ALH A78113,41 has the largest percentage of visible crystals in a vaguely chondrule-like structure. The lost PTS (ALH A78113,31) had a more obvious, but unphotographed chondrule. Although no clear-cut chondrules are observed in the clasts, the mineralogy and general textures are chondritic. ALH A78113,41 contains several ultra-fine grained areas with distinctive and unusual mineralogy, including roederite and ureyitic pyroxene.

Modal analyses of the three chondritic ALH A78113 clasts, three small black matrix clasts in Cumberland Falls 604-8 and a large chondritic inclusion in Cumberland Falls 604-7 reveal broad similarities indicative of their being part of the same population. However, ALH A78113,41 has a very unusual mineral assemblage (Table 1). It contains a high percentage of homogeneous ureyitic pyroxene and Na-rich plagioclase glass, plus significant roederite (and merrihueite), djferfisherite, and phosphatic glass. The other two ALH A78113 clasts are modally more chondritic, although ,49 contains much clinopyroxene, some nepheline and schreibersite. Small black-matrix clasts in Cumberland Falls 604-8 have high clinopyroxene content but many minerals are too fine-grained to identify.

By broad-beam microprobe analysis, ALH A78113 chondritic inclusions and small black matrix clasts in Cumberland Falls 604-8 differ somewhat from large Cumberland Falls chondritic clasts (Table 2). Included in Table 2 are wet chemical analyses (JAROSEWICH, 1967; BINNS, 1969) to evaluate the broad-beam method. In general, analyses calculated as silicates generally agree quite well with wet chemical results—especially since bulk FeO varies from clast to clast in Cumberland Falls (NEAL and LIPSCHUTZ, 1981). There is a clear difference in the amounts of reduced metal and sulfides in the large Cumberland Falls clasts; this may be a sampling artifact or may have deeper significance.

Table 1. Modes (vol. pct.) of chondritic clasts in ALH A78113 and Cumberland Falls.

	ALH A78113			Small CF 604-8 Incl.			CF
	,41	,49	,50	1	2	3	604-7
Olivine	50.5	10.3	23.1	33.8	19.1	33.0	23.2
Orthopyroxene	17.4	49.7	55.8	39.7	52.5	42.0	47.9
Clinopyroxene	6.4	21.6	4.0	25.5	16.2	21.0	6.6
Plagioclase glass	15.9	5.1	9.3	*	7.8	*	10.6
Roederite	3.7	1.6	-	-	-	-	-
Chromite	0.2	-	-	-	-	-	-
Phosphate	tr	tr	-	-	-	-	0.1
Fe-Ni metal	2.2	3.4	5.3	-	2.0	2.0	8.5
Troilite	2.8	2.4	2.0	1.0	2.4	1.0	2.4
Djerfisherite	0.8	-	-	-	-	-	-
Daubreelite	0.1	tr	0.3	-	-	-	0.3
Schreibersite	tr	5.9	0.2	-	-	-	0.2
Alabandite	-	-	-	-	-	-	0.2
No. of points	500	503	507	102	102	100	494
Area (mm ²)	8.4	1.2	2.6	0.22	0.16	0.08	31.1

*Too fine-grained to be detected as separate phase.

Table 2. Broad beam bulk compositions (wt. pct.) of chondritic clasts in ALH A78113 and Cumberland Falls (CF) compared with literature data for the latter.

	ALH A78113			Small CF 604-8 Incl.			CF Inclusions*		
	,41	,49	,50	1	2	3	604-7	X [§]	†
SiO ₂	47.4	54.3	51.1	47.5	49.8	48.8	52.6	54.4	52.6
TiO ₂	0.18	0.13	0.15	0.18	0.13	0.16	0.16	0.14	0.23
Al ₂ O ₃	5.7	3.2	3.6	2.72	4.2	3.2	4.3	3.9	2.7
Cr ₂ O ₃	0.66	0.50	0.67	0.65	0.53	0.59	0.53	0.50	0.67
FeO	11.5	4.8	8.2	7.2	8.5	7.4	3.2	2.4	5.1
MnO	0.53	0.49	0.44	0.33	0.49	0.35	0.45	0.6	0.8
MgO	27.3	29.8	31.9	34.5	30.6	32.9	34.1	34.2	32.9
CaO	1.16	4.6	2.04	4.9	2.97	4.2	2.6	2.1	2.8
Na ₂ O	5.0	2.02	1.74	1.76	2.56	2.12	1.8	1.5	1.6
K ₂ O	0.53	0.16	0.10	0.27	0.24	0.26	0.2	0.1	0.2
Total	100.0	100.0	99.9	100.9	100.0	100.0	99.4	99.9	99.6
FeNi	7.0	14.0	4.2	-	-	1.4	6.0	15.7	12.0
FeS	4.2	4.3	4.7	0.8	1.5	0.5	2.3	5.2	7.8
(FeNi) ₂ S ₃	0.9	4.4	-	-	-	-	0.02	0.1	-
FeCr ₂ S ₄	-	-	-	-	-	-	0.1	0.11	-
MnS	-	-	-	-	-	-	-	0.16	-

*Literature data (Binns, 1969; Jarosewich, 1967) in the top portion are recalculated for silicates only.

A noteworthy property of all small clasts, whether from Cumberland Falls or ALH A78113 (especially ,41), is that they are generally FeO-enriched relative to large Cumberland Falls inclusions (Table 2). However, the small clast, ALH A78113,49, compositionally resembles the large chondritic inclusions in Cumberland Falls, thus suggesting a link between inclusions in these two aubrites. The generally higher FeO contents of ALH A78113 and small Cumberland Falls clasts may reflect sampling of a somewhat broader population. Clast ALH A78113,41 is also enriched in Na₂O, K₂O and Al₂O₃, and is low in SiO₂, indicative of its high olivine and plagioclase glass content, and the presence of ureyitic pyroxene and djferfisherite.

Major mineralogical characteristics of small ALH A78113 and Cumberland Falls chondritic clasts summarized in Table 3 are generally similar to those of large chondritic Cumberland Falls clasts. However, ALH A78113,41 is exceptional. Further mineralogic data are given in Table 4-6. ALH A78113,49 most resembles large Cumberland Falls inclusions, and clast ,41 differs strikingly; clast ,50 is intermediate.

Olivine. Olivine in ALH A78113,41 is homogeneous and FeO-rich (Fo₇₉), with high MnO (0.6-0.7%) and low CaO (0.02-0.04%). Olivine compositions in ALH A78113,49 and ,50 show some variability. Several olivine grains with severely reduced margins in clast ,49 were analyzed. Olivine in the small Cumberland Falls black matrix clasts is also magnesian. Thus, all olivines in ALH A78113 and in the small Cumberland Falls clasts are similar to that in the large Cumberland Falls clasts, except for the unique sample ALH A78113,41.

Pyroxene. Pyroxene in ALH A78113,49 and ,50 is compositionally variable and also similar to pyroxene in large

Table 3. Summary of mineralogic characteristics of chondritic clasts in ALH A78113 and Cumberland Falls (CF).

	ALH A78113			Small CF 604-8 Incl.			Large CF
	,41	,49	,50	1	2	3	Incl. 4
Olivine (Fo)	79	93-98*	83-97	96-99	99	95	96-99
Orthopyroxene (En)	76-80	80-85	74-97	84-98	75-80	90-98	85-99
Clinopyroxene (Wo)	ureyitic	40	40	too small	41	42	
(En)	(Na,Cr)	58	55	small	54	57	
Plag. glass (% An)	0.6	6†	23	-	-	-	4-11
Kamachite (% Ni)	6.3	3.4	5.4	-	-	-	4.4-5.8
Troilite (% Ti)	<0.02	-	0.58	-	-	-	<0.02
Schreibersite (% Ni)	18	33	none	-	-	-	30-53
Phosphate	biannite	merr	none	-	-	-	-

*Some grains have reverse zoning at rims due to reduction.

†Also jadedite (Na-Al-rich) pyroxene.

‡Some nepheline also.

§Neal and Lipschutz (1981).

Table 4. Distinctive mineralogy of chondritic clast ALH A78113,41

	Ureyitic Pyroxene		Roedderite- Merrihueite*		Feldspathic Glass	
SiO ₂	53.2	50.1	71.2	62.4	59.9	67.9
TiO ₂	0.66	1.27	0.01	0.05	0.13	-
Al ₂ O ₃	1.39	0.89	1.19	0.39	0.71	19.2
Cr ₂ O ₃	4.7	11.4	-	-	-	-
FeO	4.9	7.4	0.97	7.7	9.1	0.64
MnO	0.15	0.02	-	-	-	-
MgO	15.0	9.7	18.8	18.3	21.9	0.29
CaO	16.3	11.5	0.26	0.31	0.68	0.13
Na ₂ O	2.8	6.1	3.6	9.1	6.3	12.0
K ₂ O	-	-	4.9	0.91	2.6	0.53
Total	99.2	98.6	100.9	99.1	101.4	100.7
Wo	34.4	24.4				
En	43.9	28.7				
Fs	8.1	12.3				
Ur	13.6	34.6				

*Also present in ALH A78113,49 but not in ,50.

Cumberland Falls clasts: grains in ,41 are more homogeneous and FeO rich. Fine-grained areas contain ureyite-rich pyroxene (Table 4), which is inhomogeneous due to the fine-grain size. Pyroxene grains in the Cumberland Falls small black matrix clasts are generally more Fe-rich than those in large Cumberland Falls chondrite clasts. However, these small clasts are similar to the large Cumberland Falls clasts in being consistently more Fe-rich than is co-existing olivine, another indication that all clasts are part of the same population.

Plagioclase. Plagioclase is present in the clasts only as a fine-grained or glassy component, or is too small to analyze. All analyses show some FeO and MgO, indicative of overlap with fine intergrown mafic minerals, or the presence of these components in the glass. Feldspathic glass in ALH A78113,41 is unusual in that it has very low CaO (0.1–0.4%), and high Na₂O (11–14%); K₂O is 0.4–1.9%. Feldspathic glass in ,49 is generally albitic, but some areas have the composition of nepheline: SiO₂, 45%; Al₂O₃, 32%; Na₂O, 16%; K₂O, 5%.

Roedderite-merrihueite. Roedderite is found in ALH A78113,41 (Table 4) and in ,49 but not in ,50. The crystals are very small (5–10 microns) and are enclosed in the black matrix so that optical properties are not visible. Those in ALH A78113,49 are all FeO-poor, as in the original roedderite (FUCHS, 1966), but some crystals in ,41 contain up to 9.1% FeO (Table 4) and therefore have some merrihueite component. Merrihueite was described by DODD *et al.* (1975), and it is generally assumed that complete solid solution exists between roedderite and merrihueite. These are the Al-poor members of the osumilite-type minerals, and K and Na mutually substitute as do Mg and Fe. The Al-rich members are osumilite and yagiite (BUNCH and FUCHS, 1969). The general structural formulae for roedderite-merrihueite found in ALH A78113 chondritic inclusions are (Na, K)₃Mg₂(Mg, Fe)_{2.5}Si₁₂O₃₀ and (Na, K)₂Mg₂(Mg, Fe)₃Si₁₂O₃₀. Roedderite is generally associated with enstatite chondrites, although OLSEN (1967) and PRINZ *et al.* (1983) reported roedderite in silicate inclusions in the IAB irons Wichita Co. and San Cristobal.

FeNi metal. Metal in ALH A78113 chondritic clasts narrowly ranges from 4.7–6.3% Ni, similar to metal in the host achondrite which averages 5.7% Ni. Si, Cr, and P are all below the 0.1 wt.% detection limit both in chondritic clasts and aubrite host of Cumberland Falls and ALH A78113. These Cumberland Falls data, which differ from earlier results by

Table 5. Metal in chondritic clasts and host aubrites of ALH A78113 and Cumberland Falls.

	ALH A78113			Cumberland Falls		
	Host	Clasts		Host	Large	Small
Fe	94.5	94.2	93.5	93.6	93.3	93.4
Ni	5.7	4.7	6.3	6.1	5.8	5.5
Co	0.45	0.52	0.77	0.42	0.33	0.44
Total*	100.6	99.4	100.6	100.1	99.4	99.30

*Si, Cr, P are all below detection.

WATTERS and PRINZ (1979) and NEAL and LIPSCHUTZ (1981), are preferred because they involve more precise determinations and compare metal with Si-free FeNi standard.

Thus, the ALH A78113 and Cumberland Falls aubrites have the lowest Si in metal of all aubrites, and the chondritic clasts in both are similar in this respect. The lack of Si presumably indicates somewhat more oxidizing conditions at the time of last equilibrium of the metal. In these two (and all aubrites), P cannot be detected in metal; it is solely present in schreibersite.

Troilite. Troilite in ALH A78113,41 and ,50 clasts and in host aubrite compositionally differ somewhat from one another (none was analyzable in ,49). Troilite in ,41 has 0.3% Ni, 0.06% Cr and <0.02% Ti, and that in ,50 has 0.2% Ni, 0.7% Cr and 0.6% Ti. Troilite in the host aubrite has 0.2% Ni, 0.4% Cr and 1.1% Ti, but Ti is somewhat variable.

Djerfisherite. Djerfisherite was found in the chondritic clast ALH A78113,41 and in the host aubrite. Both occurrences are compositionally similar and contain high Ni and low Cu compared with the original djerfisherite (Table 6). Ni in djerfisherite in the host is somewhat lower than that in the clast, and K is somewhat higher. The djerfisherite is associated with a large metal nugget in the aubrite, and is in the fine-grained area in ALH A78113,41 clast.

Schreibersite. Schreibersite was found in ALH A78113,41 and ,49 clasts but not in ,50. The schreibersite in ,41 has 18% Ni, whereas that in ,49 has 33% Ni; that in the host aubrite has 37%. Ni varies similarly in schreibersites in Cumberland Falls host aubrite and large clasts (NEAL and LIPSCHUTZ, 1981).

Phosphates. Merrillite was found in ALH A78113,49 chondritic clast and brianite-like phosphate in clast ,41; no phosphate was found in ,50. The merrillite is typical of that in many chondritic and achondritic meteorites. The brianitic

Table 6. Nickel-rich djerfisherite in chondritic clast and host of ALH A78113,41.

	Clast	Host	St. Marks†
Fe	48.9	51.4	50.7
Ni	5.3	3.1	0.8
Cr	0.15	0.56	-
Cu	0.19	0.26	4.2
S	33.9	34.1	33.8
Na	0.64	0.22	0.3
K	8.4	9.5	8.7
Cl	1.81	1.41	1.0
Sum*	99.4	100.6	99.5

*Mn and Ti are below detection.

†Data from Fuchs (1966).

Table 7. INAA data for two clasts from Cumberland Falls and ALH A78113 aubrites.

	Cumberland Falls		Allan Hills
	604-2	604-9	78113,38
Na ₂ O (wt)	0.307±0.001	1.17±0.01	3.31±0.01
MgO	3.8±0.1	40.1±0.3	5.5±0.1
Al ₂ O ₃	1.5±0.1	2.4±0.7	4.6±0.6
K ₂ O	<0.74	<0.52	<0.37
CaO	1.23±0.2	5.2±0.5	2.6±0.4
TiO ₂	<0.30	<0.05	<0.40
Fe	31.22±0.03	6.17±0.06	16.6±0.2
Sc (ppm)	3.76±0.04	6.58±0.02	8.79±0.03
V	18±2	35±2	49±6
Cr	1810±30	3500±60	3840±60
Co	1527±6	108±0	392±2
Ni	26200±700	2430±70	7900±200
Zn	<10	9±2	40±3
As	2.7±0.5	<1.7	<1.7
Se	13±1	7.2±0.5	11.2±0.4
Br	<2.8	<6	<6.6
Ru	<2.2	1.4±0.5	<2
Cs	0.33±0.12	0.15±0.04	<0.1
Ba	-	<31	<88
La	<0.09	<0.64	<0.65
Nd	<27	<21	<40
Sm	0.12±0.05	<0.17	0.29±0.12
Eu	0.07±0.02	0.19±0.02	0.14±0.01
Tb	<0.19	<0.09	<0.10
Dy	<0.27	<0.60	<0.41
Ho	<0.28	<0.71	<0.73
Tm	<0.12	0.095±0.040	0.11±0.04
Yb	<0.56	<0.40	<1.6
Lu	-	0.038±0.016	<0.07
Hf	0.38±0.15	0.26±0.09	<0.17
Os	<6.7	<3.1	<8.0
Ir	0.99±0.01	0.129±0.003	0.339±0.005

phosphate is fine-grained and, therefore, difficult to analyze. It contains high Na₂O, MgO and CaO, but FeO is also present as well as some overlap with silicate. The phosphate may be glassy. Compared with rare brianite occurrences in silicates of the IB San Cristobal iron (BILD, 1974) and the IIICD Dayton iron (FUCHS *et al.*, 1967), this brianitic phosphate is low in Na₂O and CaO, and higher in MgO perhaps because of solid solution with other phosphate minerals, or analytical error due to overlap with another mineral. Silicate inclusions in ALH A78113,41, as in the San Cristobal iron (PRINZ *et al.*, 1983), contain roedderite and brianite.

Chemical compositions

INAA data for Cumberland Falls inclusions 604-2 and 604-9 and ALH A78113,38 are listed in Table 7 and RNAA results for ALH A78113 are in Table 8. In Figs. 1 and 2, we depict the data of Tables 7 and 9, respectively, the latter including ranges, arithmetic means and associated sample

standard deviations for Cumberland Falls inclusions (VERKOUTEREN and LIPSCHUTZ, 1983). INAA and RNAA data can be compared for five elements (As, Co, Cs, Se and Zn) and agreement is generally excellent for the two inclusions in Cumberland Falls. Only for Co is there a difference: the INAA datum for 604-2 is 3× higher and for 604-9, 4× lower than corresponding RNAA data. We attribute this to heterogeneities in metal distribution (*cf.* Table 2).

The large Allan Hills chondritic inclusion also shows some peculiar compositional features. Analysis by RNAA of another portion of the inclusion that had yielded ,38 produced essentially similar results (Table 8), including its uniquely high Ga and Zn contents relative to Cumberland Falls inclusions (VERKOUTEREN and LIPSCHUTZ, 1983). However, there are some differences between ,38 and ,51 for the RNAA determinations alone at the factor-of-2 level deemed significant for volatile/mobile elements: contents of Au and In are higher and Cd is lower in ,51 (Table 8). ALH A78113,51 contains systematically more normally siderophile elements (Au, Co, Sb, Ag and Ga), but these elements must be in some phase other than metal since its corresponding PTS (41) contains so little (Table 1). In view of these differences, it is not surprising that Se and Co results determined by INAA agree with RNAA data for ,38 and ,51, respectively, and disagree with the other determination for each; for Zn, where the RNAA results agree, the INAA datum is almost an average.

Thermoluminescence

TL glow curves (plots of TL vs. heating temperature) for Cumberland Falls inclusions closely resemble those of certain type 3 chondrites and are very different from those of the achondritic host (Fig. 3). The four host samples from Cumberland Falls produce glow curves with two very sharp peaks at 177 ± 5° and 293 ± 5°C, with indications of smaller peaks at ~110° and ~370°C. In contrast, glow curves for the inclusions and type 3 ordinary chondrites each consist of a broad peak—in fact, a composite of several unresolved peaks—with a maximum between 165–207°C.

The TL sensitivity, peak temperature and peak width for the Chainpur sample used as a control here (Table 9) agree well with values reported by SEARS and WEEKS (1983). Results for one Dhajala sample are similar to those reported by SEARS and WEEKS (1983) but another sample, analyzed in conjunction with the aubrite host samples, gave somewhat lower TL peak temperature and width values than normal

Table 8. Trace elements contents of chondritic inclusions from ALH A78113 and Cumberland Falls aubrites.

	U	Au	Co	Rb	Sb	Ag	Ga	Se	Cs	Te	Zn	Cd	Bi*	Tl*	In*
	(ppb)	(ppb)	(ppm)	(ppm)	(ppb)	(ppb)	(ppm)	(ppm)	(ppb)	(ppm)	(ppm)	(ppb)	(ppb)	(ppb)	(ppb)
ALH A78113															
,38†	16	116	404	6.19	58.8	23.3	64	8.01	71.4	0.33	41.0	15.3	0.36	2.06	1.40
,51	13	440	623	9.55	119	41.4	71.9	11.0	45.4	0.29	37.9	2.7	0.2±0.1	2.50	4.08
,43	9.7	73.8	256	5.39	69.8	17.8	12.6	7.96	55.9	0.43	9.25	0.66	0.4±0.3	0.8±0.2	0.9±0.2
,45	18	89.8	256	1.38	62.8	42.2	5.25	8.98	98.2	1.60	12.0	1.5	1.6±0.6	0.6±0.2	1.6±0.5
Cumberland Falls															
Range†	18–	80.9–	198–	2.50–	47.1–	8.9–	3.48–	3.94–	126–	0.91–	5.98–	3.9–	≤0.3–	0.10–	0.44–
	24	173	512	4.49	123	88.5	4.69	20.2	325	7.57	9.13	110	7.8	48.2	5.45
Mean†	20±	140±	400±	3.1±	90±	40±	3.8±	9±	190±	4±	8±	30±	3±	6±	1±
	2(5)	30(8)	100(9)	0.6(9)	20(8)	30(9)	0.4(9)	5(9)	60(9)	2(9)	1(9)	30(9)	3(9)	16(9)	2(9)

* Each uncertainty is one standard deviation based on counting statistics where this exceeds the uncertainty from replicate Allende analysis (Verkouteren and Lipschutz, 1983).
† Data from Verkouteren and Lipschutz (1983). Uncertainties shown are one standard deviation from replicate analysis of the number of analyzed Cumberland Falls chondritic inclusions shown in parentheses.

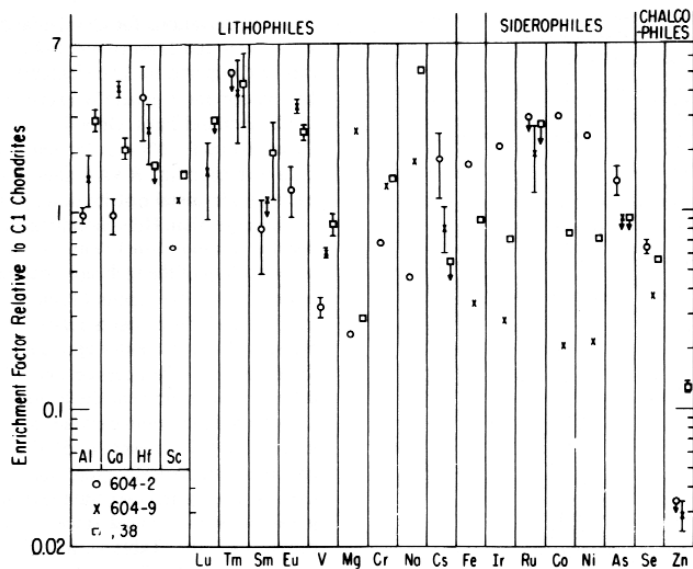


FIG. 1. Refractory major, minor and trace element contents determined by INAA in Cumberland Falls inclusions 604-2 and 604-9 and ALH A78113,38. Lithophile, siderophile and chalcophile elements are each listed in increasing order of nebular volatility. The pattern of these data (C1-normalized by weight) is unlike that of any known chondritic group and, like the volatile/mobile trace elements (Fig. 2), contents are highly variable. These variations indicate an unusually broad range of conditions during nebular condensation and/or accretion of the inclusions.

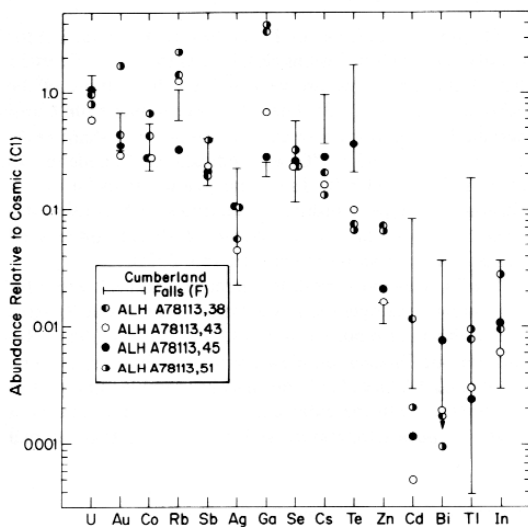


FIG. 2. Trace element abundances (normalized to those in C1 chondrites) for 3 ALH A78113 inclusions (individual points), and the range for 9 Cumberland Falls (CF) inclusions. Samples ,38 and ,51 are separate portions of the same large inclusion. Elements are listed from the left in order of putative nebular volatility. Data for ALH A78113 inclusions extend Cumberland Falls ranges and seem part of a single suite. Compared with other chondrites, elemental contents are quite variable, indicating an unusually large range of conditions during condensation and accretion of these primitive chondritic inclusions. Low contents of volatile elements argue for relatively high temperatures during the condensation/accretion process.

(Table 9). This may reflect a difference between the two Dhajala samples in the proportion of chondules with feldspar of high and low structure state (KECK *et al.*, 1986). The results of the annealing treatments on the inclusions are listed in Table 10.

DISCUSSION

Modal, bulk chemical and mineralogic characteristics of chondritic clasts in ALH A78113 cover wide ranges, wider than those of large chondritic inclusions in Cumberland Falls

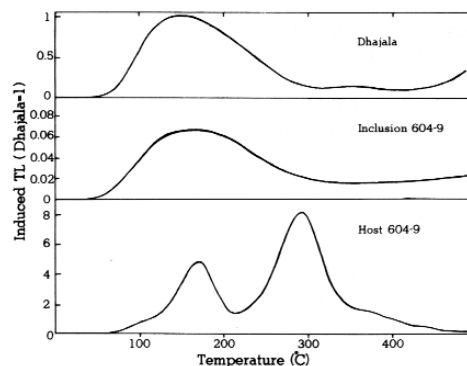


FIG. 3. Glow curves (or thermoluminescence emitted as a function of heating temperature) for the Dhajala H3.8 chondrite, and a chondritic inclusion and a sample of the achondritic host from Cumberland Falls. The glow curve of the host differs markedly from the other two. Glow curves for Dhajala and inclusion 604-9 are very similar.

Table 9. Thermoluminescence data for Cumberland Falls chondritic inclusions, associated achondritic host samples and controls (samples typically 100 mg).

Sample	TL Sensitivity*		Peak Temperature (°C)		FWHM (°C)†	
	Peak 1	Peak 2	Peak 1	Peak 2	Peak 1	Peak 2
Chondritic Inclusions and Controls‡						
Dhajala	(1.0)		175±6		162±4	
Chainpur	0.087±0.017		138±16		83±10	
604-2	0.21±0.02		207±8		239±6	
604-7	0.18±0.02		190±7		217±6	
604-5	0.16±0.01		196±7		200±5	
X	0.099±0.008		194±7		218±6	
2739-1	0.072±0.005		178±7		197±5	
604-9	0.067±0.005		165±6		183±5	
Achondritic Hosts and Control‡						
Dhajala	(1.0)		155±5		156±5	
604-8 host§	19±5	34±8	174±5	298±5	59±1	66±1
2739-1 host§	2.3±0.4	2.1±0.4	173±6	293±6	56±2	69±2
604-6 host§	9.2±1.7	13±2	169±5	289±5	58±2	67±1
604-9 host§	4.8±0.9	7.8±1.6	171±2	292±4	57±1	65±1

*Normalized to Dhajala.

†Full width of the peak at half its maximum intensity.

‡Uncertainties are one sample standard deviation from replicate Dhajala measurements.

§Uncertainties are one sample standard deviation from replicate analyses.

§Host samples taken: 3 cm from 604-6; 8 cm from 604-9; 5 cm from 2739-1; from fragments obtained when 604-8 was excavated.

(NEAL and LIPSCHUTZ, 1981). However, the newly-discovered small, black matrix clasts in Cumberland Falls 604-8 show many petrographic resemblances to chondritic inclusions in ALH A78113 (Tables 1–3). These, then, link the chondrite populations in the two aubrite breccias and increase the known range of petrographic characteristics of chondritic inclusions in aubrite breccias (NEAL and LIPSCHUTZ, 1981). These results suggest that the two aubritic breccias sampled a single chondritic population which, as a working hypothesis, we will take to represent debris from the projectile that disrupted the aubrite parent body (NEAL and LIPSCHUTZ, 1981; VERKOUTEREN and LIPSCHUTZ, 1983). Within this context, Cumberland Falls seems to have sampled a broader spectrum of the chondritic body than did ALH A78113—perhaps just because it is a larger meteorite or because of sampling, either by us or by the way in which the parent of the inclusions accreted. As noted, ALH A78113,41 is a unique inclusion and some olivine grains in .49 have reduced margins, which can arise in numerous ways including by nebular processes (PECK and WOOD, 1987). Otherwise, there is no petrographic evidence for interactions of the chondritic clasts with the aubrite host.

Differences in redox state during formation of Cumberland Falls inclusions observed petrographically (NEAL and LIPSCHUTZ, 1981) are also reflected by INAA data (Fig. 1). In 604-2, contents of lithophiles are 0.2–1.3× C1, whereas in 604-9 the values are 1–4× C1; for siderophiles, values are 2–3× C1 for 604-2 and 0.2–0.3× C1 in 604-9. Hence, from refractory major, minor and trace element contents, as from petrographic analysis (NEAL and LIPSCHUTZ, 1981), the reduced metal/silicate ratio is much higher in 604-2 than in 604-9, i.e., the latter was formed under more oxidizing, metal-poor conditions. Lithophile and siderophile element contents in ALH A78113,38 are 1.5–5.0× C1 and 0.7–0.8× C1, respectively, so that its metal/silicate ratio is intermediate to those of Cumberland Falls inclusions 604-2 and 604-9.

C1-normalized contents of most lithophile elements (including Ca and Al) are enriched relative to Mg by factors of 2–4 and 5–10 in 604-2 and ALH A78113,38 respectively; in the unique inclusion 604-9, lithophile/Mg ratios are essen-

tially chondritic, ranging from 0.3–1.6. Because most lithophiles determined by INAA are not readily hosted by olivine, these trends must reflect variable proportions of olivine to LIL (large ion lithophile)-hosts, i.e. clinopyroxene and plagioclase. In this event, LIL-host/olivine ratios must decrease in going from ALH A78113,38 to 604-2 to 604-9.

Siderophile/lithophile fractionation is evident in the three clasts, and refractory siderophiles are rather uniformly enriched or depleted in each of them (Fig. 1). More volatile Au, Co, Sb and As do not show as much variation (VERKOUTEREN and LIPSCHUTZ, 1983; Fig. 2), perhaps reflecting their thermal response or, possibly, the fact that RNAA determination of these elements involves analysis of a much more representative portion of each inclusion than do INAA measurements. What is clear from these data is that there are much wider refractory element variations and, at times, much greater enrichments than are exhibited by any known chondritic group, e.g., LL chondrites (LARIMER *et al.*, 1987; SEARS and WEEKS, 1986).

Volatile/mobile trace element contents of Cumberland Falls and ALH A78113 chondritic clasts also seem to form continua (Fig. 2). When normalized to atomic abundances in C1 chondrites, data for ALH A78113 chondritic clasts generally overlap those of inclusions from Cumberland Falls and extend their range, commonly in both directions. Ranges are extended upward for Ga and Zn (especially by results for .38 and .51 from the unique ALH A78113 inclusion) and downward for U, Cs, Te and Cd (Fig. 2). With these changes, the trace element pattern of chondritic inclusions remains different from those of other highly unequilibrated petrologic type 3 chondrites (*cf.* Fig. 2 of VERKOUTEREN and LIPSCHUTZ, 1983). The most volatile/mobile trace elements are underabundant in the chondritic inclusions—less abundant, in fact, than in equilibrated ordinary chondrites.

Petrologic characteristics indicate that Cumberland Falls and ALH A78113 chondritic inclusions are of petrologic type 3, despite their low volatile/mobile trace element contents. The Cumberland Falls inclusions exhibit evidence for very low metamorphic grades, but substantial shock (NEAL and LIPSCHUTZ, 1981). Textures (*i.e.* opaque fine-grained matrix and sharp chondrule outlines) and mineral compositions (*e.g.*

Table 10. Thermoluminescence data for Cumberland Falls inclusions X, 604-2, and 604-9 and after annealing.*

Inclusion	Annealing time (hr)	TL sensitivity (Dhajala = 1) (°C)	Peak temp. (°C)	Peak width† (°C)
X	unannealed	0.049±0.008	194±7	218±6
	100	0.13±0.02	203±3	209±9
	100	0.14±0.02	220±3	247±3
	100	0.13±0.02	207±3	245±2
	100	0.05±0.02	220±3	235±8
604-2	unannealed	0.21±0.02	207±8	239±6
	100	0.29±0.03	207±2	226±10
	100	0.14±0.03	211±4	241±3
	100	0.14±0.02	206±2	238±3
	100	0.094±0.007	223±2	225±7
604-9	unannealed	0.067±0.005	165±6	183±5
	100	0.36±0.06	175±4	172±5
	100	0.11±0.01	197±5	255±5
	100	0.064±0.008	184±3	231±3
	100	0.073±0.007	202±2	211±3

*Errors quoted are ±1σ based on replicate analyses of the Dhajala meteorite.

†Full width of the peak at half its maximum intensity.

Ni-bearing sulfides) indicate that the inclusions are of low type 3. The amount of microscopically visible feldspar might suggest higher type 3 grades of metamorphism. By comparison with type 3 ordinary chondrites (Figs. 4, 5), TL data from Cumberland Falls and ALH A78113 inclusions are entirely consistent with their also having experienced little metamorphism.

Peak temperature and peak width for Cumberland Falls inclusions increase with increasing TL sensitivity by about 35%, as in type 3 ordinary chondrites. There are differences, however. Peak temperatures for inclusions are comparable with those of type 3.5–3.9 ordinary chondrites, whereas peak widths are systematically higher than those of any unequilibrated ordinary chondrite. (Differences are $\sim 100^\circ\text{C}$ relative to ordinary chondrites of types 3.2–3.5 and are smaller, 30–40°C, relative to samples of types 3.5–3.9.) It is interesting that one type 3 ordinary chondrite that plots near inclusion 604-9 in Fig. 5 is an atypical chondritic clast in Quinyambie (B. MASON, pers. commun.; see SEARS *et al.*, 1982). TL sensitivities for inclusions are in the range observed for type 3.4–3.5 ordinary chondrites and from these sensitivities, can be ordered as 604-9 < 2739-1 < X < 604-5 < 604-7 < 604-2 (Table 9). This is precisely the order determined by mean Fe^{2+} contents of low-Ca pyroxene in the inclusions (NEAL and LIPSCHUTZ, 1981), suggesting a link (to be discussed shortly) between processes responsible for establishing TL sensitivity and Fe^{2+} content of ferromagnesian silicates. Ad-

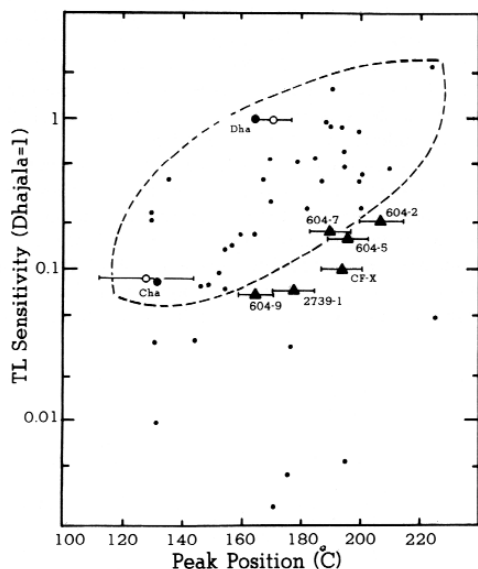


FIG. 4. Thermoluminescence (TL) sensitivity versus TL peak temperature (peak position) for Cumberland Falls chondritic inclusions (triangles) compared with type 3 ordinary chondrites (small dots). Large dots indicate control samples (open symbols, data from this study; closed symbols, literature data). For the TL sensitivity data, uncertainties (1 standard deviation of 3–5 replicate measurements on homogenized powder) are comparable with symbol size. Like comparable type 3 ordinary chondrites, TL sensitivity for the inclusions increase with increasing peak temperature, although the peak temperatures for the inclusions are displaced to higher values by about 30–40°C.

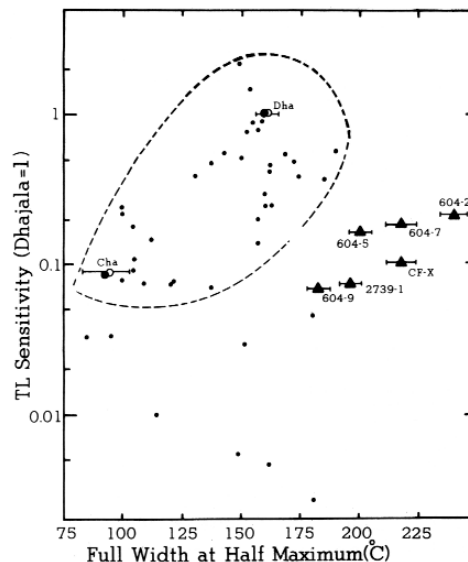


FIG. 5. Thermoluminescence (TL) sensitivity versus TL peak width at half its maximum intensity for Cumberland Falls (CF) chondritic inclusions compared with type 3 ordinary chondrites. Symbols and uncertainties as in Fig. 4. As with the type 3 ordinary chondrites of comparable TL sensitivity, peak width tends to increase with increasing TL sensitivity, but widths are systematically higher for Cumberland Falls inclusions by almost 100°C .

ditional aspects of TL are germane to the question of whether Cumberland Falls and ALH A78113 chondritic inclusions represent shock-metamorphosed LL3 chondrites, and we consider this now.

Achondrite—LL3 equilibration?

There seems little doubt that Cumberland Falls and ALH A78113 chondritic inclusions are now texturally and mineralogically of petrologic type 3. Furthermore, the oxygen isotopic composition is consistent with this assignment. If KALLEMEYN and WASSON's (1985) suggestion has any merit, these inclusions (which they consider to have been LL chondrite fragments originally) must thus have been of petrologic type 3 and at least as unequilibrated with respect to aubrite host as the most disparate inclusion found, *e.g.*, 604-2 (NEAL and LIPSCHUTZ, 1981). We cannot, therefore, understand their assumption that "the clasts originally had 'equilibrated' LL pyroxene and olivine compositions", since this seems contrary both to our observations and to the properties of their putative precursor, the LL3.0 chondrite Semarkona.

Since, in their discussion, KALLEMEYN and WASSON (1985) emphasized Cumberland Falls inclusions, we will focus upon these as well. Basically, their argument is that the varying degrees of reduction of the inclusions' oxidized phases represent different stages in the equilibration of highly unequilibrated LL3 material with totally equilibrated aubrite host. [KALLEMEYN and WASSON (1985) do not specify which, if either, material is the heat source, but WASSON (pers. commun.) indicates it as the chondritic material and we adopt

this as the basis of our discussion.] They would then explain the differing forsterite contents of the nine Cumberland Falls inclusions as representing Fe^{2+} diffusion out of chondritic olivine into the aubrite, and the higher Fe^{2+} content of the co-existing pyroxene (relative to olivine) as resulting from slower kinetics. KALLEMEYN and WASSON (1985) do not comment on the consistent heterogeneity of other phases or mutual correlations of mineral compositions of the inclusions except to note (quite correctly) that Si contents in kamacite (α Fe) are higher than those in the aubrite host (NEAL and LIPSCHUTZ, 1981) and needed re-checking. Several lines of evidence indicate that properties of the inclusions are not consistent with the proposal of KALLEMEYN and WASSON (1985).

The compositions and heterogeneity of minerals in Cumberland Falls inclusions are unusual (NEAL and LIPSCHUTZ, 1981). The mean Fe^{2+} content of pyroxene decreases in the inclusions, and there is a direct correlation with mean Ni contents in the low-Ni metallic α Fe and an inverse correlation with mean Ni contents of schreibersite, $(\text{Fe}, \text{Ni})_3\text{P}$. Mean Fe^{2+} contents of pyroxene also correlate directly with TL sensitivity so that the latter also correlates either directly or inversely, as appropriate, with these other compositional parameters (Fig. 6). For such correlations to be the result of

equilibration (KALLEMEYN and WASSON, 1985) of aubrite host with *e.g.* Cumberland Falls 604-2-like LL3 material requires virtually identical diffusion rates for Fe^{2+} in pyroxene, Ni in α Fe, and Ni in Fe_3P with matrix and other minerals. Furthermore, these rates must also be proportional to the formation rate of the TL phosphor, probably feldspar. (Identification of feldspar as the phosphor in Cumberland Falls inclusions is based upon similarities of: the TL sensitivity/peak width/peak temperature trends in inclusions and ordinary chondrites; glow curve shape for inclusions and Dhajala; and the response to annealing of the inclusions, terrestrial feldspars and type 3 ordinary chondrites.) Coincidences of all these rates during equilibration of LL3 or any other type 3 chondrite with aubrite host seems extraordinary. It would be less extraordinary to assume that the correlations generally reflect processes that occurred in the chondrite parent material before the inclusions were incorporated into the aubrite host.

In every Cumberland Falls inclusion, contents of Fe^{2+} in pyroxene, Ni in α Fe and Ni in Fe_3P are very heterogeneous. The absolute heterogeneity of each element is essentially constant in virtually all samples, so that as ferrosilite content decreases, for example, the percent mean deviation (PMD) of Fe^{2+} in pyroxene increases (NEAL and LIPSCHUTZ, 1981). This is not the expected trend if hot, highly unequilibrated LL3 material is equilibrating with aubrite host. In that event, one would expect that decreasing ferrosilite content would reflect increasing temperature or time and, in that case, absolute heterogeneity of pyroxene, α Fe and Fe_3P should decrease, not stay constant. The unique inclusion 604-9 shows an effect for pyroxene but not for α Fe and Fe_3P . Moreover, its ferrosilite content is so low that its PMD has the highest value of any Cumberland Falls inclusion studied. Finally, the mineralogy and texture of inclusion 604-9 are so peculiar (NEAL and LIPSCHUTZ, 1981) that its origin from a Cumberland Falls 604-2-like LL3 chondrite progenitor seems impossible.

Ignoring other factors, preservation of petrologic type 3 texture during reduction of hot, highly unequilibrated LL3 chondrite material by aubrite host is conceivable, but preservation of shock-produced jadeitic pyroxene seems very unlikely. The Cumberland Falls inclusions constitute the only known meteorite occurrence of jadeite component, identified by microprobe (NEAL and LIPSCHUTZ, 1981). Even heavily shocked L chondrites contain no such component (although some contain shock-produced ringwoodite and majorite), presumably because of its post-shock thermal decomposition (KUSHIRO, 1969) by contact with massive, heated ejecta (NEAL and LIPSCHUTZ, 1981; WALSH and LIPSCHUTZ, 1982; HUSTON and LIPSCHUTZ, 1984). Shock-formed jadeitic pyroxene would be preserved in Cumberland Falls inclusions only if they were *not* heated to any appreciable extent. TL data indicate this.

Chromite and apatite are common in ordinary chondrites, but are rare in Cumberland Falls or ALH A78113 inclusions, whereas other minerals (oldhamite, ferroan alabandite, daubreelite, Fe_3P) are common in most of the inclusions (including 604-2) but not in ordinary chondrites. It remains to be demonstrated what conditions would allow removal of two minerals (especially refractory chromite) and formation of four others in a hot LL3 chondrite during reduction by

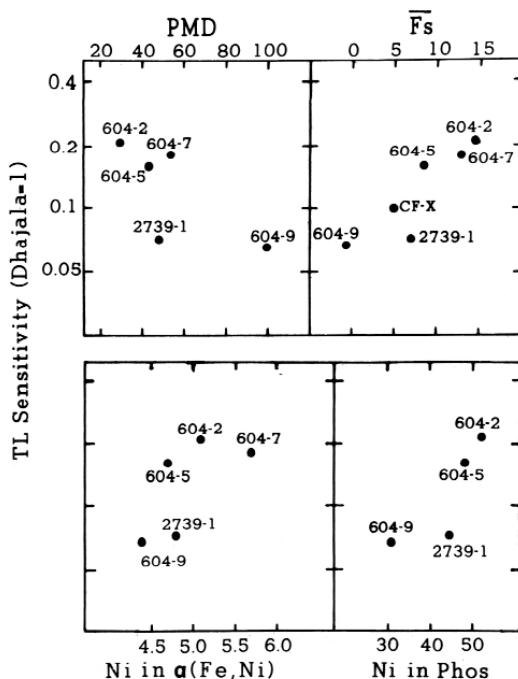


FIG. 6. Thermoluminescence (TL) sensitivity for the Cumberland Falls inclusions versus mineralogic data. Properties shown are percent mean deviation (PMD) and mean ferrosilite (Fs) contents of low-Ca pyroxene, Ni and α Fe and Ni in Fe_3P . These trends can reasonably be interpreted in terms of primary condensation/accretion and related metamorphism in a varied redox sequence. Inclusion 604-9 lies at the least oxidized, least metamorphosed end of the sequence and 604-2 is at the other end. Similar trends are observed for the type 3 ordinary and C30 chondrites.

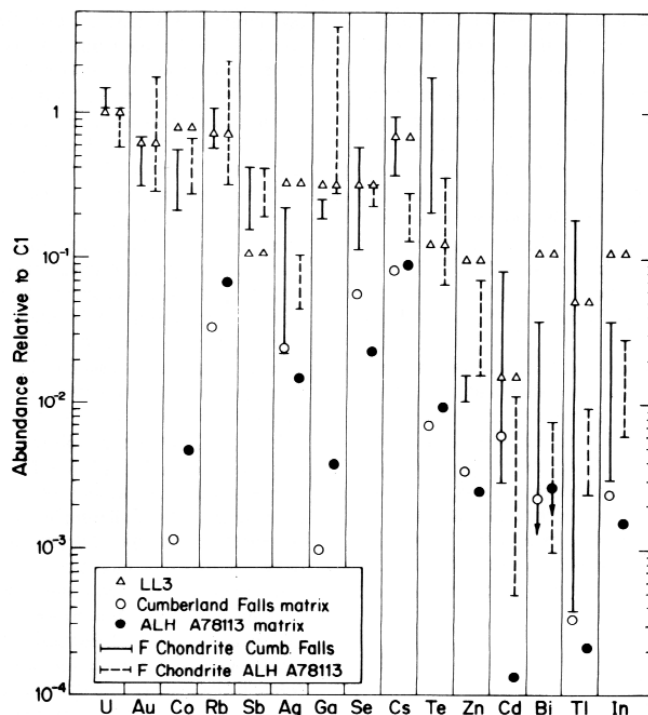


FIG. 7. Trace element abundance ranges (C1-normalized) for chondritic inclusions from ALH A78113 and Cumberland Falls (CF) aubrites. Relative abundance data for host matrix samples of each aubrite are shown as are mean contents in LL3 chondrites. If the inclusions compositionally reflect equilibration of LL3 chondrite with aubrite host, all compositional data would lie between the LL3 and aubrite points. Exceptions exist—especially Ga in ALH A78113, Te in Cumberland Falls inclusions and, very likely Sb in samples from both aubrites—where contents generally exceed those in LL3 chondrites (see text). Furthermore, data for the most mobile elements should be least variable and lie closest to the aubrite points. This is certainly not the case nor do mobile trace elements contents vary systematically with Fe^{2+} contents of low Ca pyroxene as do other mineralogic and thermoluminescence trends (see text). The inclusions seem to be a sample suite of unique primitive material.

contact with aubrite host (KALLEMEYN and WASSON, 1985), while still preserving chemical heterogeneity in minerals, jadeite component, TL sensitivity at the levels observed, etc.

The peculiar nature and variations of major, minor and trace elements in ALH A78113,38 and Cumberland Falls inclusions 604-2 and 604-9 (Fig. 1) argue strongly that these fragments do not represent any known chondritic group, equilibrated with aubrite host or not. These elements are very refractory: their redistribution between hypothetical hot LL3 precursor and achondrite would require temperatures and times sufficient to destroy chondritic textures, let alone existing, more heat-sensitive, properties, like TL.

If Cumberland Falls and ALH A78113 chondritic inclusions result from the reduction of an LL3 chondrite precursor (similar to inclusion 604-2) by aubrite host (KALLEMEYN and WASSON, 1985), trace element contents should parallel mean ferrosilite contents, but they do not (NEAL and LIPSCHUTZ, 1981; VERKOUTEREN and LIPSCHUTZ, 1983). Inclusion 604-2 should be uniformly richest in trace elements, particularly mobile ones, but it is not (VERKOUTEREN and LIPSCHUTZ, 1983). It is not surprising that contents of most volatile/mobile trace elements lie between LL3 values (which are among

the highest known) and those for aubrite hosts (which exhibit the low concentrations typical of achondrites). What is surprising is that contents of some volatile/mobile trace elements exceed those typical of LL3 chondrites, indeed, even of C1 chondrites. These data include U and Te in Cumberland Falls, Ga in ALH A78113 and Sb in both aubrites (Fig. 7).

These arguments, while convincing, are indirect. TL data for the Cumberland Falls inclusions and host aubrite provide direct evidence against KALLEMEYN and WASSON's (1985) hypothesis.

Aubrite host samples vary by $\sim 10\times$ in TL sensitivity (Table 9), probably because of chemical heterogeneity, but exhibit remarkably constant peak temperature and peak width values, indicating that all four contain the same phosphor. Glow curves for Cumberland Falls host samples are distinct from those for inclusions in it and for ordinary chondrites in that the aubrite exhibits two very sharp peaks (Fig. 3, Table 9). Glow curve shapes for the aubrite are very similar to those of the enstatite chondrites (SEARS, 1974) except that the latter exhibits a third major peak at $\sim 400^\circ\text{C}$. This is present only as an inflection in aubrite curves (Fig. 3). The TL phosphor in enstatite meteorites is enstatite (GEAKE and WALKER,

1967). Small amounts of Fe quench TL, and this may account for their lower TL and possibly also for the weakness of the 400°C peak of aubrites compared with the enstatite chondrites. Glow curve differences between aubrites and enstatite chondrites could also reflect minor and trace element differences; enstatite cathodoluminescence (and therefore TL) is highly dependent on minor and trace elements (GEAKE and WALKER, 1967; GRÖGLER and LIENER, 1968; LEITCH and SMITH, 1982).

Returning to the question of whether Cumberland Falls inclusions represent LL3 chondrites equilibrated with aubrite host, it is clear that TL peak temperature and width for ordinary chondrites (and shergottites and C30 chondrites, in which feldspar is the dominant phosphor) are related to their thermal history. Most reasonably, the TL is sensitive to whether the feldspar is in a "high" form (where it has a broad peak at high glow curve temperatures) or in a "low" form (where it has a narrow peak at low glow curve temperatures). In the H3.8 chondrite, Dhajala—and probably most meteorites—both forms are present (KECK *et al.*, 1986) so that the peak temperature and width reflect the relative proportions of the two forms. In the laboratory, annealing for 10 hr at 800°C reproduces the changes observed in glow curve shape, but longer times at slightly lower temperatures (but still above the phase-transition temperature) might also be as effective (GUIMON *et al.*, 1986). If simple conversion of low to high feldspar alone is responsible for the TL changes, X-ray diffraction data on the order-disorder transformation temperature place the phase change at 600–700°C.

Figure 8 depicts results of annealing experiments on three Cumberland Falls inclusions representing the full ferrosilite compositional range. If trends in peak temperature and peak width shown by all inclusions are due to the same processes as those responsible for trends in type 3 ordinary chondrites, rather specific results can be predicted. Inclusion 604-2, which contains the most Fe-rich ferromagnesian silicates, should show little or no change with annealing whereas samples from inclusion 604-9, containing the most Fe-poor (and, percentage-wise, most heterogeneous) ferromagnesian silicates, should show a peak temperature increase and peak broadening when annealed $\geq 600^\circ\text{C}$. Changes in Cumberland Falls inclusion X, an intermediate sample (NEAL and LIPSCHUTZ, 1981), should parallel but be less extreme than those in inclusion 604-9 after annealing. These predicted trends are observed. Samples annealed at 500°C for 100 hr show no significant change in induced TL properties, whereas samples of inclusions X and 604-9 annealed at 700°, 800° or 900° for 100 hr show increasing peak temperature and width. Ultimately, their peak shapes and positions resemble those of Cumberland Falls inclusion 604-2. These data demonstrate that inclusions X and 604-9 have not been heated at 700°C for 100 hr since formation of feldspar in them. These data further indicate similarities in the origin of aubrite inclusions and type 3 ordinary chondrites.

The peak temperatures indicate that in most Cumberland Falls inclusions, especially those with lowest TL sensitivity, a significant amount of the phosphor is in the low-form. Obviously, these inclusions have not been heated above the transformation temperature for more than a few hours; laboratory annealing experiments on Allan Hills 77011 (LL3.4)

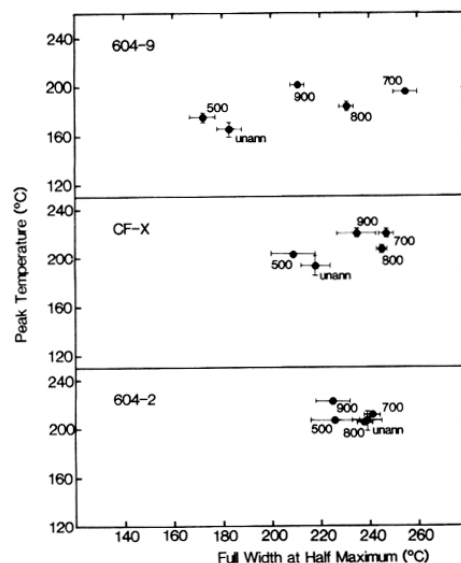


FIG. 8. Thermoluminescence (TL) peak temperature versus peak width for three unannealed (denoted unann) Cumberland Falls inclusions and after 100 hrs annealing at the temperatures indicated (in °C). Annealing at 500°C causes little or no change, whereas annealing at 700, 800 or 900°C causes peak broadening and an increase in peak temperature. The amount of change varies with the initial value. The TL sensitivities of the inclusions and the presumed level of auto- or metamorphism experienced increases along the series 604-9–X–604-2. In their TL properties, the inclusions do not resemble shocked chondrites.

and Dhajala (H3.8) have also shown that annealing at 800°C for 100 hr, or higher temperatures for shorter times, converts the low-form to the high-form (GUIMON *et al.*, 1985; KECK *et al.*, 1986). This effectively rules out production of the mineralogic trend by post-impact annealing. Non-Antarctic H chondrites show a trend in peak temperature with peak width similar to that shown by Cumberland Falls inclusions, but there is no relationship between shock history and position on the plot, implying that the trend also reflects differences in post-metamorphic cooling rates rather than shock-annealing temperatures or post-shock cooling rates (HAQ *et al.*, 1987). The TL and mineralogic trends in the Cumberland Falls inclusions are best interpreted, as with the type 3 ordinary chondrites, as reflecting pre-emplacement (probably metamorphic and possibly nebular) processes.

The results of annealing experiments are not consistent with the suggestion of KALLEMEYN and WASSON (1985) that inclusions X and 604-9 represent 604-2-like material heated at higher temperatures. In this event, annealing of the three inclusions should increase TL peak temperatures and peak width of 604-2 the most and of 604-9 the least, if at all. This is, in fact, opposite to what is observed.

Chondritic inclusions

The available evidence indicates overwhelmingly that Cumberland Falls and ALH A78113 chondritic inclusions

do not represent a known sort of primitive chondrite thermally and chemically equilibrated with aubrite host but, rather, some new type of chondritic material. Mineralogic and chemical parameters of the inclusions described by NEAL and LIPSCHUTZ (1981) are modified slightly by data for the chondritic inclusions in ALH A78113, now recognized as related to those in Cumberland Falls. All these inclusions seem to represent primitive fragments from the projectile that disrupted the aubrite parent body.

Differing degrees of nebular reduction are reflected by the inclusions' properties (NEAL and LIPSCHUTZ, 1981; VERKOUTERENE and LIPSCHUTZ, 1983) including the more magnesian nature of olivine coexisting with more Fe-rich pyroxene, and the reverse zoning observed in one clast from Cumberland Falls (KALLEMEYN and WASSON, 1985) and in some olivine grains in ALH A78113,41. The correlations of TL and mineralogic characteristics (Fig. 6) suggest that TL reflects primary condensation/accretion or nebular metamorphic processes rather than shock. Further support for this conclusion comes from comparison of peak temperature and peak width in ordinary chondrites and chondritic inclusions from aubrites (Fig. 9). Equilibrated ordinary chondrites fall in a region (that is also occupied by unequilibrated ordinary chondrites of types 3.5–3.9) separate from that of types 3.2–3.4. These two regions reflect high and low feldspar, respectively. When low feldspar is shocked ≥ 34 GPa, transformation to high feldspar occurs (OSTERTAG, 1983), so that peak temperatures are quantized at $130 \pm 10^\circ\text{C}$ and $230 \pm 12^\circ\text{C}$, respectively. (Peak width data cannot be obtained because of an interference from a peak at $380 \pm 10^\circ\text{C}$.)

The effect of shock loading high feldspar can be judged by

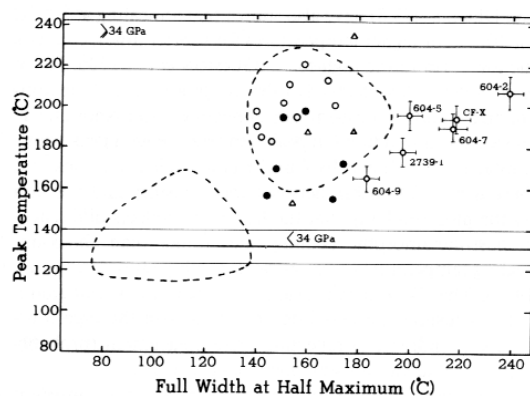


FIG. 9. Thermoluminescence (TL) peak temperatures *versus* peak widths for the Cumberland Falls inclusions (circles with 1 standard deviation error bars). Fields defined by broken lines indicate type 3 ordinary chondrites; types 3.5–3.9 occupy the upper field and types 3.2–3.4, the lower. Isolated points without error bars indicate equilibrated ordinary chondrites. Shock facies are indicated (facies a–c [<22 GPa], open circles; facies d–f [>22 GPa], filled circles; facies unknown, open triangles). Data for equilibrated chondrites were measured for this study from the glow curves of SEARS (1980). Horizontal lines indicate one standard deviation for the peak temperatures observed after shock-loading low-temperature oligoclase at pressures above and below 34 GPa (OSTERTAG, 1983).

comparing TL properties of heavily shocked (shock facies e and f) and mildly shocked ordinary chondrites (SEARS, 1980). Heavily shocked equilibrated ordinary chondrites have TL sensitivities $10\text{--}100\times$ lower than those of unshocked samples, but apparently unchanged peak widths (Fig. 9). There is some indication for a decrease of $\sim 40^\circ\text{C}$ in peak temperatures for heavily shocked samples (Fig. 9). The fact that the inclusions have a peak temperature range like that of equilibrated ordinary chondrites indicates that fine-grained feldspar formed before the shock event, probably by devitrification during accretion. The offset toward higher peak width for the chondritic inclusions merely indicates their distinctiveness relative to ordinary chondrites.

It appears that all members of a meteorite group normally formed under essentially identical redox conditions, hence have similar major element compositions. Iron may be an exception because the inclusions undoubtedly differ in amounts of reduced metal. Since this difference might also be a sampling artifact, this must remain an open question. However, Cumberland Falls and ALH A78113 chondritic inclusions clearly formed under a uniquely wide redox range and, consequently, vary widely in terms of mineral composition. The only other chondrites that reflect formation under a variety of redox conditions are the enstatite chondrites; there is some debate as to whether these come from 1 or 2 parent bodies. At this point we feel safe in stating that to the extent that enstatite chondrites can be regarded as a single meteorite group, so too can chondritic inclusions in aubrites be considered as a single chondritic group.

CONCLUSIONS

Direct and indirect arguments based on mineralogy, petrology, refractory major, minor and trace elements, volatile/mobile trace elements contents, and TL, indicate that chondritic inclusions in Cumberland Falls do not represent fragments of a known type of highly primitive chondrite thermally altered and reduced by the host achondrite. Instead, inclusions in Cumberland Falls and in ALH A78113 aubrite represent a primitive chondrite sample suite whose properties were established during primary nebular accretion and condensation over a broad redox range. In the absence of a better name, the previously proposed forsterite chondrites class seems an adequate descriptor for this group. Primary formation temperatures for this group seem to have been relatively high compared with those at which other petrologic type 3 chondrites formed—in some cases, enough for high feldspar to form—and some minor metamorphic changes, especially devitrification of glass, occurred during this period.

The parent body of these primitive inclusions was disrupted during collision with the aubrite parent body. During collision, the chondritic material was severely shocked and cooled rapidly, probably because of the fragments' small size. These were rapidly incorporated into the more massive aubrite debris, possibly in a regolith. We anticipate that other aubrites constitute similar impact breccias and that such chondrite fragments will be found in additional aubrites.

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