

COMPOSITIONAL COMPARISONS OF METAMORPHOSED CARBONACEOUS CHONDRITES

Gregory W. KALLEMEYN

*Institute of Geophysics and Planetary Physics, University of California,
Los Angeles, California 90024, U.S.A.*

Abstract: Five carbonaceous chondrites (Allan Hills 82135, Coolidge, Karoonda, Pecora Escarpment 82500 and Yamato-693) thought to be metamorphosed chondrites of petrologic types 4 or 5 were analyzed by instrumental and radiochemical neutron activation analysis for 28 elements: Na, Mg, Al, K, Ca, Sc, V, Cr, Mn, Fe, Co, Ni, Zn, Ga, As, Se, Br, Ru, Cd, Sb, La, Sm, Eu, Yb, Lu, Os, Ir and Au. Coolidge and Y-693 are members of the CV clan based on refractory lithophile abundances. Coolidge has significantly depleted volatile element abundances relative to CV3 chondrites and is tentatively classified as CV4. Y-693 is compositionally indistinguishable from the oxidized subgroup CV3 chondrites, showing no significant depletion of volatile element abundances, in conflict with the petrographic data indicating type 5; the chondrite may be heterogeneous. Compositional and petrographic data for Karoonda and ALH82135 suggest they form a grouplet, part of a clan with refractory lithophile abundances intermediate between those of the CM-CO and CV clans. Compositional classification of the severely weathered PCA82500 is difficult because of the scatter of data. It is probably closely related to Karoonda and ALH82135.

1. Introduction

The study of metamorphosed carbonaceous chondrites can provide useful insights into certain aspects of the original parent bodies, such as constraints on their original sizes and structures. It is also important to know whether the composition of a metamorphosed chondrite has been significantly altered by an open-system metamorphism, or whether metamorphism occurred in a closed system leaving the premetamorphism composition essentially unchanged. Metamorphosed carbonaceous chondrites, *i.e.*, those of petrologic type >3 , are relatively rare with only about five or six specimens studied to any significant extent.

SCOTT and coworkers have recently made extensive petrographic studies of several metamorphosed carbonaceous chondrites, including four included in this study: Allan Hills 82135, Coolidge, Karoonda, Pecora Escarpment 82500 and Yamato-693. Coolidge and PCA82500 are of petrologic type 4 (SCOTT *et al.*, 1984; SCOTT, 1985; SCOTT and TAYLOR, 1985), while ALH82135, Karoonda and Y-693 are assigned to types 4 or 5 (VAN SCHMUS and HAYES, 1974; MASON, 1984; MCSWEEN, 1977a; SCOTT, 1985; SCOTT and TAYLOR, 1985). However, OKADA and coworkers (OKADA, 1975; OKADA *et al.*, 1975) describe Y-693 as an unequilibrated CV chondrite containing isolated areas of shock melting and deformation. CLAYTON *et al.* (1979) determined oxygen isotopes in separated magnetite and plagioclase from Y-693 and determined a

metamorphic temperature similar to that determined from mineral separates in Karoonda. Karoonda, PCA82500 and Y-693 are petrographically similar in their having abundant magnetite and pentlandite (except PCA82500 which has pyrrhotite as the abundant sulfide), little Fe-Ni metal and FeS, and a low chondrule/matrix ratio; olivine is homogeneous in composition, while plagioclase is heterogeneous (SCOTT and TAYLOR, 1985). ALH82135 has a very similar opaque mineralogy, but olivine and low-Ca pyroxene are more equilibrated suggesting a higher petrologic type (SCOTT, 1985). Coolidge is petrographically most dissimilar from the others, with Fe-Ni metal and FeS as the dominant opaques and a higher chondrule/matrix ratio (MCSWEEN, 1977b; SCOTT and TAYLOR, 1985). MCSWEEN (1977b) assigned Coolidge to the reduced subgroup and Y-693 to the oxidized subgroup of the CV chondrites, although he did not perform any petrographic studies on the latter.

Previous compositional studies show Coolidge and Y-693 to be members of the CV clan (KALLEMEYN and WASSON, 1982; SHIMA and SHIMA, 1975). The compositional classification of Karoonda is more controversial as it has been classified as a member of CV (TAKAHASHI *et al.*, 1978; FITZGERALD, 1979), as a single member of a new CK group (WILKENING, 1978) and as ungrouped (VAN SCHMUS and HAYES, 1974; KALLEMEYN and WASSON, 1982). On the basis of compositional data KALLEMEYN and WASSON stated that Karoonda was not a member of the CV clan; its refractory lithophile abundances are intermediate between those of CO and CV chondrites. Further controversy lies in whether Karoonda was subjected to open-system (MATZA and LIPSCHUTZ, 1977) or closed-system (TAKAHASHI *et al.*, 1978) metamorphism. Based on their petrographic studies, SCOTT and TAYLOR (1985) predicted ALH82135 and PCA82500 would have chemical compositions similar to those of Karoonda and Y-693. The present compositional study supports the chemical grouping of the first three chondrites, but shows Y-693 to be a normal member of the CV3 group.

2. Experimental

2.1. Samples and preparation

All chondrites except Karoonda are finds and all samples were from internal pieces. Both the Coolidge and PCA82500 samples looked severely weathered. Each had a generally rusty color, and PCA82500 had patches of white patina on the outer surface. The main mass of PCA82500 has numerous cavities that probably resulted in part from the severe weathering (MASON, 1984; SCOTT and TAYLOR, 1985). The Y-693 sample was generally grayish-black and appeared to be relatively fresh. The main mass of ALH82135 was almost completely covered by fusion crust and shows only minor weathering effects (MASON, 1984). Our sample appeared relatively fresh.

The ALH82135 and PCA82500 meteorites, which were supplied as chips, were believed to have been cleanly handled in the field and in the laboratory at Houston, therefore they were transferred directly to clean, polyethylene irradiation vials in a laminar flow hood to minimize the chance of contamination. The Coolidge and Karoonda specimens were cleaned with acetone and samples chipped from the interiors of larger pieces. The Y-693 sample had sawn faces which were cleaned with SiC paper and acetone. All INAA irradiations were performed at the UCLA Engineering

Reactor Facility with a neutron flux of 2×10^{12} n cm² s⁻¹, or the UCI TRIGA Reactor Facility with a flux of 1.8×10^{12} n cm⁻² s⁻¹. Sample replicate masses ranged from 275–300 mg. The samples were initially irradiated for two minutes and immediately counted in order to determine elements producing very short-lived radioactive species (Mg, Al, V and Ca). The samples were then irradiated for 3–4 h and counted several times over a period of ~6 weeks for determining elements producing longer-lived species (Na, K, Ca, Sc, Cr, Mn, Fe, Co, Ni, Zn, Ga, As, Se, Br, Sb, REE, Re, Os, Ir and Au). The INAA procedure is more explicitly described in KALLEMEYN and WASSON (1981). Samples analyzed by RNAA (for Cd) were irradiated for 25 h at the University of Missouri Research Reactor Facility following the INAA procedure. The RNAA procedure is described in SUNDBERG and BOYNTON (1977).

2.2. Data precision and accuracy

The relative standard deviations for each element determined in replicate samples of an Allende standard powder (split 3, position 18) are: Na, $\pm 2.2\%$; Mg, $\pm 1.8\%$; Al, $\pm 1.6\%$; K, $\pm 2.8\%$; Ca, $\pm 3.9\%$; Sc, $\pm 0.9\%$; V, $\pm 1.7\%$; Cr, $\pm 1.1\%$; Mn, $\pm 3.0\%$; Fe, $\pm 0.6\%$; Co, $\pm 0.8\%$; Ni, $\pm 1.9\%$; Zn, $\pm 4.3\%$; Ga, $\pm 1.4\%$; As, $\pm 3.2\%$; Se, $\pm 1.0\%$; Br, $\pm 3.5\%$; Cd, $\pm 4.4\%$; Sb, $\pm 6.1\%$; La, $\pm 1.4\%$; Sm, $\pm 2.7\%$; Eu, $\pm 3.8\%$; Yb, $\pm 3.9\%$; Lu, $\pm 4.7\%$; Re, $\pm 5.0\%$; Os, $\pm 2.1\%$; Ir, $\pm 2.2\%$ and Au, $\pm 1.8\%$. The mean concentrations of eight elements (Ni, Zn, Se, Br, Sb, Os, Ir, Au) reported by TAKAHASHI *et al.* (1978) for a different Allende standard powder agree with our values to within 10%. Data for seven major and minor elements (Na, Mg, K, Ca, Cr, Mn, Fe) in Y-693 reported by SHIMA and SHIMA (1975) agree to within 5% of our values.

3. Data and Results

Table 1 contains concentration data for 28 elements in an individual analysis of ALH82135 and replicate samples of PCA82500 and Y-693. Also included are mean elemental concentrations for replicate samples of Coolidge and Karoonda previously reported by KALLEMEYN and WASSON (1982). The PCA82500 and ALH82135 samples were not analyzed by RNAA so there are no Cd data.

Cl-normalized elemental abundances for each chondrite are plotted in Figs. 1–4. In Figs. 1 and 3 all elements are Mg-normalized and grouped according to lithophile and siderophile-chalcophile tendencies. In Figs. 2 and 4 siderophile and chalcophile elements are Ni-normalized to reduce the effect inhomogeneous distribution of siderophile-rich components, perhaps in part resulting from weathering. Elements in each grouping are generally ordered from left to right according to decreasing condensation temperature.

3.1. Yamato-693 and Coolidge

Y-693 has refractory lithophile abundances similar to CV, but refractory and common siderophiles are enriched by 10–15% (Fig. 1). Surprisingly, volatile abundances are generally at normal CV3 levels. The match is especially good among the lithophile elements, for which weathering effects tend to be most noticeable.

Table 1. Concentrations of 28 elements in the five carbonaceous chondrites. Data for Coolidge and Karoonda are mean values from KALLEMEYN and WASSON (1981).

	Na	Mg	Al	K	Ca	Sc	V	Cr	Mn	Fe	Co	Ni	Zn	Ga
	mg/g			$\mu\text{g/g}$	mg/g	$\mu\text{g/g}$		mg/g			$\mu\text{g/g}$	mg/g	$\mu\text{g/g}$	
ALH82135	3.27	144	15.5	302	17.5	8.79	97	3.24	1.44	215	618	12.1	98	5.6
Coolidge	1.89	150	19.8	145	19.6	12.0	106	4.35	1.17	193	561	12.2	60	4.0
Karoonda	3.08	152	16.7	324	17.7	10.9	100	3.77	1.43	242	681	13.8	91	5.4
PCA82500	3.22	146	15.1	240	16.2	7.87	92	3.20	1.36	219	495	10.2	65	5.2
	2.99	132	15.0	227	14.0	8.61	95	3.22	1.31	216	513	10.8	78	5.6
Mean	3.13	139	15.1	234	15.1	8.24	94	3.21	1.34	218	504	10.5	72	5.4
Y-693	3.12	143	15.6	300	18.3	11.2	94	3.87	1.47	242	745	14.3	104	5.8
	3.19	143	16.0	334	19.8	10.8	100	3.79	1.42	238	757	14.4	110	5.5
Mean	3.16	143	15.8	317	19.0	11.0	97	3.83	1.45	240	751	14.3	107	5.7

	As	Se	Br	Ru	Cd	Sb	La	Sm	Eu	Yb	Lu	Os	Ir	Au
	$\mu\text{g/g}$			ng/g										
ALH82135	1.32	8.0	0.4	1100	—	75	405	240	100	275	42	820	757	559
Coolidge	1.17	3.2	0.6	1170	39	45	505	311	118	329	52	866	779	115
Karoonda	1.32	7.3	0.7	1180	174	74	435	271	110	308	46	880	838	136
PCA82500	0.89	7.2	0.4	965	—	44	348	210	82	244	36	680	620	141
	1.19	7.8	0.4	940	—	57	350	218	96	240	35	750	621	134
Mean	1.04	7.5	0.4	953	—	51	349	214	89	242	36	715	610	138
Y-693	1.64	8.0	0.5	1150	295	76	480	295	110	322	45	870	810	60
	1.70	10.0	0.6	1350	242	70	485	301	120	300	48	1050	1030	180
Mean	1.67	9.0	0.6	1250	268	73	483	298	115	311	47	960	920	120

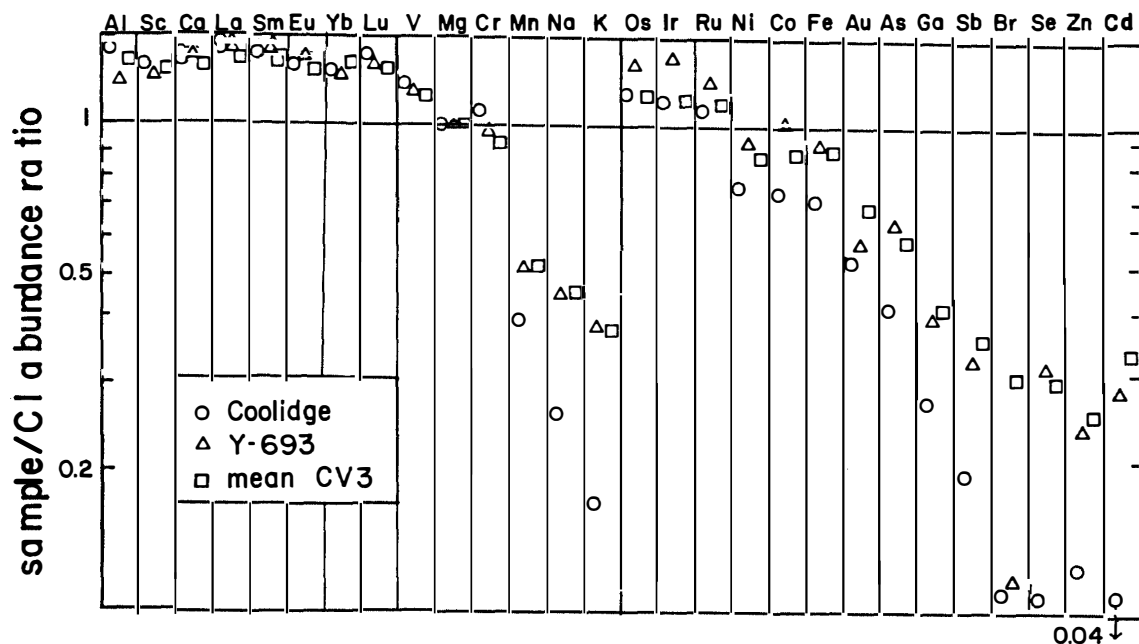


Fig. 1. Mg-normalized sample/CI abundance ratios are plotted for Coolidge, Y-693 and mean CV3 chondrites. Lithophile elements are grouped on the left half and siderophile and chalcophile elements are grouped on the right half of the diagram. Elements in each grouping are generally ordered from left to right according to decreasing condensation temperature. Coolidge and Y-693 both have CV levels of refractory lithophiles indicating placement in the CV clan. The abundances of volatile elements in Coolidge are significantly lower than those in mean CV3, supporting a petrologic designation of type 4. However, volatile element abundances in Y-693 are at CV3 levels, in conflict with a petrologic designation of type 5.

Our Y-693 replicates show large differences in their contents of refractory siderophiles and Au; assigning less weight to the replicate with high contents would improve agreement with CV abundances, but we use the arithmetic mean. Normalization to Ni reduces the discrepancy between CV3 and Y-693 for refractory siderophiles. These results show that refractory siderophiles are sited mainly in phases different from those for other siderophiles, and these phases are inhomogeneously distributed on the scale of our sample sizes (~ 300 mg).

Y-693 has a high Cd content as expected since petrographic data (OKADA, 1975) show it to belong to the oxidized subgroup of CV. Although the mean oxidized CV3 Cd abundance is $\sim 20\%$ higher than that of Y-693, this discrepancy is mainly due to a very high value for Allende; Y-693 falls within the range of the 3 oxidized CV3 chondrites studied by KALLEMEYN and WASSON (1981).

The large depletion of Br in Y-693 relative to CV3 is a mystery. Although low Br abundance is commonly found in weathered chondrites, it is usually accompanied by similarly low Na and K abundances (KALLEMEYN and WASSON, 1981, 1982). One likely site for Br in CV chondrites is probably sodalite which is found in some refractory inclusions (GROSSMAN and LARIMER, 1974), although some phosphate mineral or organic compounds are other possibilities. The low Br abundance might be explained by the shock effects which caused devolatilization loss in portions of the chondrite due to degradation of organic compounds.

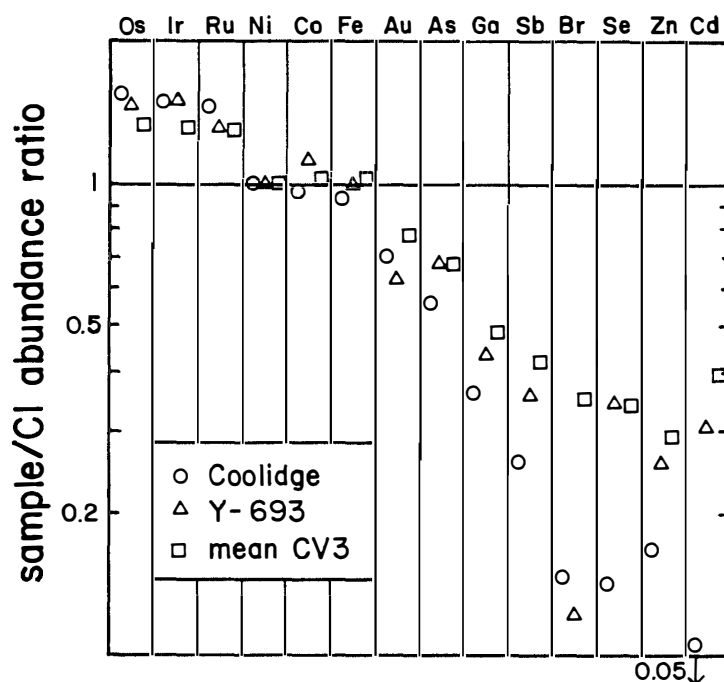


Fig. 2. Ni-normalized sample/CI abundance ratios for siderophile and chalcophile elements are plotted for Coolidge, Y-693 and mean CV3. Elements are generally ordered from left to right according to decreasing condensation temperature. Both Coolidge and Y-693 have enhanced levels of refractory siderophiles relative to CV3. Large depletions of volatile element abundances are still evident in Coolidge relative to mean CV3, thus, the low volatile abundances cannot be attributed to non-representative sampling of metal.

Coolidge has CV3 refractory element levels, but shows marked depletions of volatile elements and common siderophiles (Fig. 1). Low abundances of Na and K could be the result of weathering as these elements are often found 'depleted' in weathered chondrites (KALLEMEYN and WASSON, 1981, 1982), but this is probably not the reason for the low Mn.

The low abundances of the common siderophiles could represent non-representative sampling of metal in our sample or also loss due to weathering. Even when the siderophile elements are Ni-normalized, though, large volatile element depletions are still evident (Fig. 2). It is unlikely that weathering could be the cause of the low values since the volatile abundance ratios decrease more-or-less monotonically with decreasing condensation temperature.

3.2. Allan Hills 82135, Pecora Escarpment 82500 and Karoonda

ALH82135 and Karoonda show very similar lithophile abundances except for Sc which has a 20% lower abundance ratio in ALH82135 (Fig. 3). The refractory lithophile abundance ratios are intermediate between CO and CV, and KALLEMEYN and WASSON (1982) used this fact to place Karoonda in its own chondrite clan. It appears that ALH82135 is a strong candidate as a second member of this clan. The severely weathered PCA82500 deviates from the others with 10–15% lower abundances of REE's, Ca and K. Two refractory lithophile elements well-determined by INAA, Al

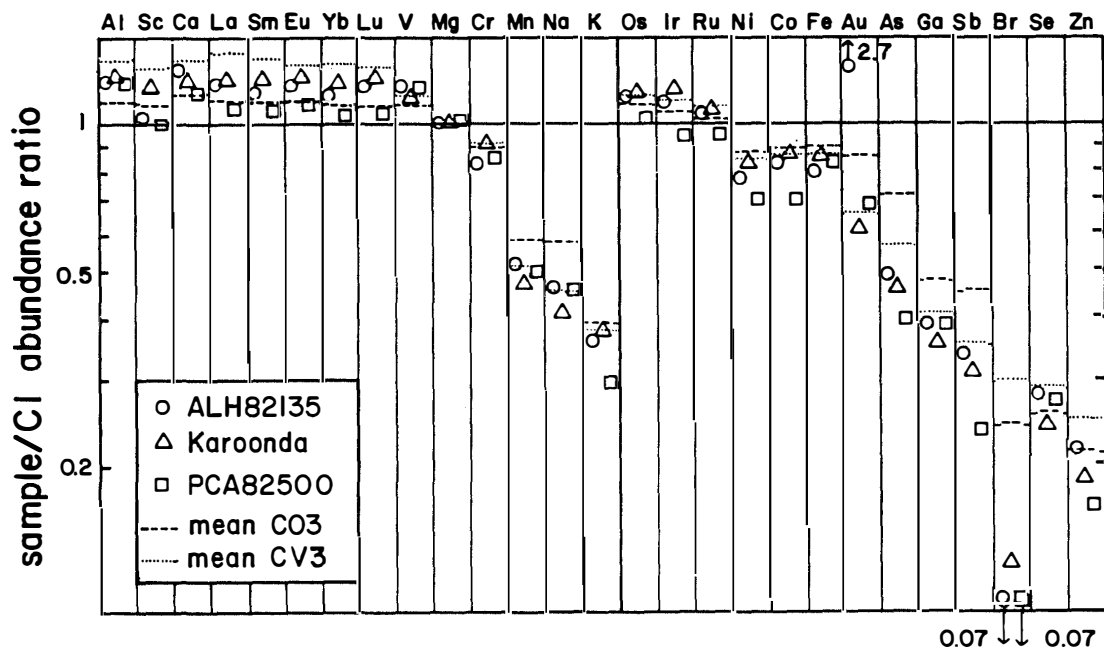


Fig. 3. Mg-normalized sample/Cl abundance ratios are plotted for ALH82135, Karoonda and PCA82500. Elements are grouped and ordered as in Fig. 1. Mean CO abundances are marked with dashed lines, while mean CV abundances are marked with dotted lines. The refractory lithophile abundance data suggest ALH82135 and Karoonda are members of a clan intermediate between the CM-CO and CV clans. Both chondrites appear very similar compositionally and probably form a grouplet. There is considerable scatter in the abundance data for PCA82500, probably a result of its severely weathered state, making compositional classification difficult. It is probably related to ALH82135 and Karoonda.

and V, show identical abundance ratios to Karoonda and ALH82135, giving support to the idea that PCA82500 is also of member of the clan. The lower abundance ratios for the REE's and Ca might result from the loss of a phosphate phase, which would not affect the other lithophile elements. However, in other samples loss of phosphate leads to rare-earth fractionations (KALLEMEYN and WASSON, 1985).

Both PCA82500 and ALH82135 have the same odd depletions of Sc, suggesting a weathering effect. Pyroxene is a likely site for Sc, but with loss of pyroxene one might also expect loss of Mn which is not seen. Furthermore, concurrent loss of Mg would mean that the Mg-normalization should eliminate part of the effect.

Refractory and common siderophile element abundance ratios are quite similar between ALH82135 and Karoonda, especially when Ni-normalized (Fig. 4). Unlike CV chondrites, the refractory siderophile abundance ratios of these two chondrites are at the same levels as those of the refractory lithophiles.

Refractory and common siderophiles in PCA82500 are very low compared to those in ALH82135 and Karoonda in Fig. 1, but the Ni-normalization in Fig. 2 eliminates the discrepancy, suggesting loss of siderophile-rich components (presumably metal before oxidation) as a result of weathering. Volatile element abundance ratios tend to be ~10% higher in ALH82135 than in Karoonda, except for Br which is lower. Whereas volatile abundances in Karoonda are consistently lower than those of CO

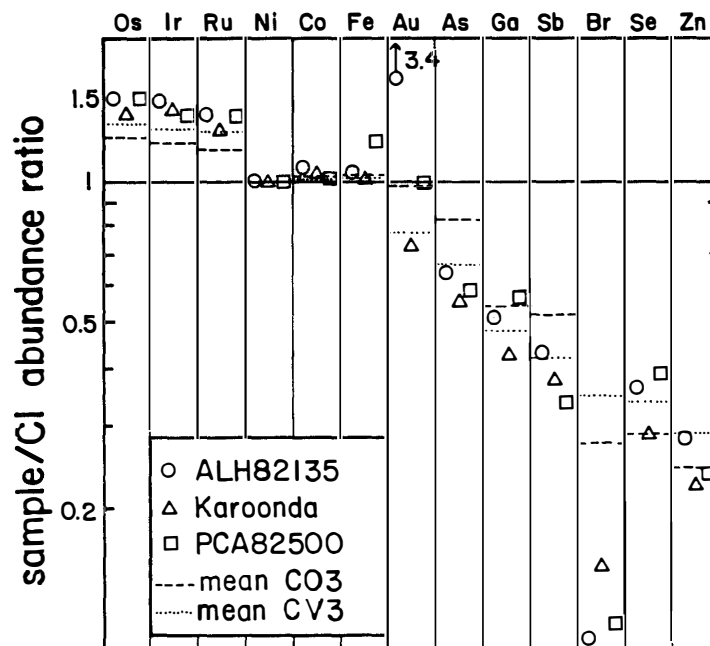


Fig. 4. Ni-normalized sample/Cl abundance ratios for siderophile and chalcophile elements are plotted for ALH82135, Karoonda and PCA82500. Elements are generally ordered from left to right according to decreasing condensation temperature. Mean CO abundances are marked with dashed lines, while mean CV abundances are marked with dotted lines. ALH82135 and Karoonda have generally similar abundance levels. PCA82500 shows better agreement with ALH82135 and Karoonda, suggesting that some of the scatter in Fig. 3 is due to loss of metal during weathering.

and CV chondrites, ALH82135 tends to plot near the mean CV values (except Br), especially when Ni-normalized (Fig. 4). ALH82135 has an anomalously high Au content. We suspect this to be a contamination problem, even though specimens are supposedly handled in the field and sampled under clean conditions (see experimental section). In summary the major deviations are shown by PCA82500 whose volatile abundances fluctuate around those of Karoonda (Fig. 3). The Ni-normalized volatile abundances tend to show a closer relationship between Karoonda and PCA82500 than between either of them and ALH82135.

4. Discussion

Based on compositional evidence KALLEMEYN and WASSON (1982) concluded that the Coolidge CV4 chondrite was originally CV3 material which later underwent open-system metamorphism. The compositional data clearly places Y-693 with the CV group, yet it clearly does not show the metamorphic effects in its composition and would seem better classified as CV3. SCOTT and TAYLOR (1985) report Y-693 to be of petrologic type 4, and to be petrographically similar to PCA82500 and Karoonda, based on the petrographic descriptions of OKADA (1975) and OKADA *et al.* (1975) and the oxygen isotope data of CLAYTON *et al.* (1979). SCOTT (1985) later suggested that Y-693 could be of type 5 since his own mineral composition data showed it to have

more equilibrated low-Ca pyroxenes.

Clearly, one must explain why the petrographic and compositional data for Y-693 appear to lead to opposite conclusions on its metamorphic state. One explanation could be that the low volatile abundances in Coolidge are a nebular effect and later metamorphism occurred in a closed-system (in this case Coolidge is, *sensu stricto*, not a CV chondrite). The high volatile element abundances in Y-693 would be an indication that CV3 material was subjected to closed-system metamorphism. Such a scenario would differ from that for ordinary chondrites, which show a distinct correlation of decreasing abundance with increase of petrologic type from 3 to 6 for elements as volatile as Cd (ZÄHRINGER, 1966; TANDON and WASSON, 1968; KEAYS *et al.*, 1971).

It seems more likely that Y-693 has not suffered a general metamorphism but only localized shock-heating effects as noted by OKADA *et al.* (1975), which was not sufficiently strong enough to alter the chemical composition. CLAYTON *et al.* (1979) caution that metamorphic equilibrium has not been established throughout Y-693. SCOTT (1985) bases his suggestion that it is type 5 on the homogeneity of two pyroxenes each measured in chondrules and in matrix. Perhaps the materials in his thin section were not representative of the chondrite as a whole, but had been affected by a localized shock heating event. MCSWEEN (1977b) cautions against placing too much stock in measures of variability of mineral compositions in the CV chondrites as it is probably just a measure of the component in which the mineral is sited. Indeed, in his Table 3 the type 2 chondrite Al Rais shows a more 'equilibrated' pyroxene composition than the type 4 Coolidge. Further more, many of the criteria SCOTT and TAYLOR (1985) use to group Y-693 with Karoonda and PCA82500, *i.e.*, opaque mineral abundances and compositions, chondrule/matrix ratio, are criteria MCSWEEN uses to describe the oxidized subgroup of CV chondrites which is independent of petrologic type.

A macroscopic inspection of our INAA sample appeared to reveal chondrules larger (up to 2 mm) and more abundant than described by OKADA (1975) in his section. Based on this and the general description by OKADA *et al.* (1975) it appears Y-693 may be petrographically heterogeneous. It may also be compositionally heterogeneous, although bulk analysis (presumably on a larger sample than ours) of major and minor elements by SHIMA and SHIMA (1975) show good agreement for 7 mutually analyzed elements including moderately volatile Na and K. Y-693 should be petrographically reexamined in a more extensive manner using sections taken from different areas of the chondrite. It is not clear whether OKADA and coworkers examined more than one thin section, or whether the one used by SCOTT (1985) was studied by OKADA.

Based on refractory lithophile abundances ALH82135 appears to be ungrouped, the second member of a grouplet together with Karoonda, part of a clan intermediate between those of CV and CM-CO. As predicted by SCOTT and TAYLOR (1985) from petrographic similarities of the two chondrites, ALH82135 and Karoonda have very similar overall compositions. ALH82135 has higher Ni-normalized volatile-siderophile and chalcophile abundances (Fig. 4), but these could represent a minor degree of unrepresentative sampling. If real, this could indicate that ALH82135 is somewhat less metamorphosed than Karoonda, in disagreement with SCOTT (1985) who suggests ALH82135 could be type 5, as opposed to type 4 for Karoonda.

The compositional classification of PCA82500 is less clear. The severe weathering

it has suffered has obviously affected the concentrations of some elements. If the low abundance ratios of Ca and the REE's can be attributed to leaching associated with weathering, then PCA82500 could be more confidently placed in the same clan as Karoonda and ALH82135. The scatter in the siderophile-chalcophile data is reduced by using Ni-normalization which helps to eliminate some of the effects of metal loss due to weathering. A selective loss of Ca,Al-rich inclusions during weathering (PCA-82500 has numerous cavities) could result in a general lowering of refractory lithophiles without significantly affecting the concentrations of common lithophile, common siderophile and volatile elements, but this leaves the 'normal' Al and V levels unexplained. Alternatively, Al and V may be anomalously high, and Ca and the rare earths 'normal', in which case PCA82500 is not clearly related to Karoonda. Ni-normalized refractory siderophiles in ALH82135 are not depleted relative to CV as one might expect, but instead are somewhat enriched. Petrographic similarities with Karoonda and ALH82135 add support to the inclusion of PCA82500 into their group-let, although, as discussed above, members of the oxidized subgroup of the CV chondrites share several similar petrographic characteristics.

5. Conclusions

Compositional data place Coolidge and Y-693 in the CV clan and this is further supported by their similar petrographic characteristics (OKADA, 1975; SCOTT and TAYLOR, 1985) and their similar oxygen isotopic compositions (CLAYTON *et al.*, 1977, 1979). Coolidge shows a significant depletion in volatile abundances relative to CV3 chondrites, probably due to metamorphism, and is tentatively classified CV4.

Y-693 is compositionally and (mineralogically) indistinguishable from oxidized subgroup CV3 chondrites, although petrologic data which suggests it is type 4 or 5. This chondrite may be petrographically heterogeneous.

Compositional data for Karoonda and ALH82135 suggest they are members of the same clan with refractory lithophile abundances intermediate between those of the CM-CO and CV clans. The overall composition of the two are similar, which suggests along with petrographic similarities that they are also members of the same group-let.

The severely weathered state of PCA82500 makes compositional classification difficult; it is probably closely related to Karoonda and ALH82135.

Acknowledgments

Meteorite samples were kindly provided by K. YANAI and the Meteorite Working Group (Houston). The author is indebted to A. PANG and T. TANAKA for technical assistance and to J. T. WASSON for helpful discussions on the pater. Irradiations were handled by G. MILLER and P. ROGERS (UCI). This research is mainly supported by NSF grant EAR 84-08167.

References

CLAYTON, R. N., ONUMA, N., GROSSMAN, L. and MAYEDA, T. K. (1977): Distribution of the pre-

- solar component in Allende and other carbonaceous chondrites. *Earth Planet. Sci. Lett.*, **34**, 209–224.
- CLAYTON, R. N., MAYEDA, T. K. and ONUMA, N. (1979): Oxygen isotopic compositions of some Antarctic meteorites. *Lunar and Planetary Science X*. Houston, Lunar Planet. Inst., 221–223.
- FITZGERALD, M. J. (1979): The chemical composition and classification of the Karoonda meteorite. *Meteoritics*, **14**, 109–115.
- GROSSMAN, L. and LARIMER, J. W. (1974): Early chemical history of the solar system. *Rev. Geophys. Space Phys.*, **12**, 71–101.
- KALLEMEYN, G. W. and WASSON, J. T. (1981): The compositional classification of chondrites: I. The carbonaceous chondrite groups. *Geochim. Cosmochim. Acta*, **45**, 1217–1230.
- KALLEMEYN, G. W. and WASSON, J. T. (1982): The compositional classification of chondrites: III. Ungrouped carbonaceous chondrites. *Geochim. Cosmochim. Acta*, **46**, 2217–2228.
- KALLEMEYN, G. W. and WASSON, J. T. (1985): The compositional classification of chondrites: IV. Ungrouped chondritic meteorites and clasts. *Geochim. Cosmochim. Acta*, **49**, 261–270.
- KEAYS, R. R., GANAPATHY, R. and ANDERS, E. (1971): Chemical fractionations in meteorites-IV. Abundances of 14 trace elements in L chondrites: Implications for cosmochemistry. *Geochim. Cosmochim. Acta*, **35**, 337–363.
- MASON, B. (1984): Meteorite descriptions. *Antarct. Meteorites Newsl.*, **7**, 8–29.
- MATZA, S. D. and LIPSCHUTZ, M. E. (1977): Volatile/mobile trace elements in Karoonda (C4) chondrite. *Geochim. Cosmochim. Acta*, **41**, 1398–1401.
- MC SWEEN, N. Y. (1977a): Carbonaceous chondrites of the Ornans type: A metamorphic sequence. *Geochim. Cosmochim. Acta*, **41**, 477–491.
- MC SWEEN, H. Y. (1977b): Petrographic variations among carbonaceous chondrites of the Vigarano type. *Geochim. Cosmochim. Acta*, **41**, 1777–1790.
- OKADA, A. (1975): Petrological studies of the Yamato meteorites, Part 1: Mineralogy of the Yamato meteorites. *Mem. Natl Inst. Polar Res., Spec. Issue*, **5**, 14–66.
- OKADA, A., YAGI, K. and SHIMA, M. (1975): Petrological studies of the Yamato meteorites, Part 1: Petrology of the Yamato meteorites. *Mem. Natl Inst. Polar Res., Spec. Issue*, **5**, 67–82.
- SCOTT, E. R. D. (1985): Further petrologic studies of metamorphosed carbonaceous chondrites. *Lunar and Planetary Science XVI*. Houston, Lunar Planet. Inst., 748.
- SCOTT, E. R. D. and TAYLOR, G. J. (1985): Petrology of types 4–6 carbonaceous chondrites. *Proc. Lunar Planet. Sci. Conf.*, 15th, Pt. 1, C699–C709 (*J. Geophys. Res.*, **90** suppl.).
- SCOTT, E. R. D., TAYLOR, G. J. and KEIL, K. (1984): Petrology of metamorphosed carbonaceous chondrites. *Lunar and Planetary Science XV*. Houston, Lunar Planet. Inst., 740–741.
- SHIMA, M. and SHIMA, M. (1975): Cosmo-chemical studies on the Yamato meteorites—a summary of chemical studies on Yamato (A), (B), (C) and (D) meteorites. *Mem. Natl Inst. Polar Res., Spec. Issue*, **5**, 9–13.
- SUNDBERG, L. L. and BOYNTON, W. V. (1977): Determination of ten trace elements in meteorites and lunar materials by radiochemical neutron activation analysis. *Anal. Chim. Acta*, **89**, 127–140.
- TAKAHASHI, H., JANSSENS, M.-J., MORGAN, J. W. and ANDERS, E. (1978): Further studies of trace elements in C3 chondrites. *Geochim. Cosmochim. Acta*, **42**, 97–106.
- TANDON, S. N. and WASSON, J. T. (1968): Gallium, germanium, indium and iridium variations in a suite of L-group chondrites. *Geochim. Cosmochim. Acta*, **32**, 1087–1109.
- VAN SCHMUS, W. R. and HAYES, J. M. (1974): Chemical and petrographic correlations among carbonaceous chondrites. *Geochim. Cosmochim. Acta*, **38**, 47–64.
- WILKENING, L. L. (1978): Carbonaceous chondritic material in the solar system. *Naturwissenschaften*, **65**, 73–79.
- ZÄHRINGER, J. (1966): Primordial argon and the metamorphism of chondrites. *Earth Planet. Sci. Lett.*, **1**, 379–382.

(Received February 18, 1986; Revised manuscript received January 13, 1987)