Labile Trace Elements in Some Antarctic Carbonaceous Chondrites: Antarctic and Non-Antarctic Meteorite Comparisons

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Dedicated to Professor Heinrich Wänke on the occasion of his 60th birthday.

We report data for Ag, Au, Bi, Cd, Co, Cs, Ga, In, Rb, Sb, Se, Te, Tl, U and Zn determined by radiochemical neutron activation analysis in consortium samples of Belgica (B) 7904, Yamato (Y) 82042, Yamato 82162 and Yamato 86720 carbonaceous chondrites. These trace elements cover a wide volatility/mobility range and give unique information on thermal histories of meteorites. The results indicate the unique nature of these carbonaceous chondrites. Y-82042 proves to have the volatile element pattern of a C2 (≡CM) chondrite and the petrologic characteristics of a C1 (≡CI) chondrite. These must be primary nebular condensation/accretion features, unaffected by post-accretionary processes. The other three meteorites were thermally metamorphosed in ≧2 parent regions over the 600–700 °C range, at relative temperatures B-7904 < Y-82162 < Y-86720. Before heating, B-7904 and Y-86720 had C2-levels of volatile elements: Y-82162 had uniquely high volatile element concentrations, at about C1-levels. The data require a new classification scheme for such chondrites. Belgica 7904 and Y-82162 and -86720 seem to be derived from one or more thermally altered carbonaceous asteroids, and their spectral characteristics should be compared with those of B-, F-, G- or T-asteroids. These results indicate substantial differences in the thermal histories of Antarctic and non-Antarctic C1 and C2 chondrite populations. In reviewing all that is known about the Antarctic and non-Antarctic meteorite populations, the overwhelming weight of evidence supports the view that these populations sample different extraterrestrial source materials, differing in thermal histories. It may be that over the extended collecting period of the Antarctic ice sheet, it has sampled a considerably greater proportion of near-Earth asteroids than do current falls.

Introduction

For many years, Wänke and co-workers have been exceedingly active in using neutron activation analysis to determine the chemical composition of extraterrestrial material. These multielement analyses, mainly of relatively refractory trace elements in evolved materials, have shed important light on the origin and evolution of their parent objects e.g. the Moon, Mars and probably Vesta (in the case of eucrites). It is to Prof. Dr. Heinrich Wänke, in honor of his 60th birthday, that we dedicate this study of volatile trace elements in primitive extraterrestrial materials.

Among non-Antarctic samples, C1 and C2 chondrites each have well-defined, precise patterns for labile trace elements that clearly distinguish between them (cf. [1, 2] and references in these). (We specifically use elemental "volatility" in referring to equilibrium processes during nebular condensation and accretion, and "mobility" to refer to non-equilibrium trace element loss during solid-state metamorphism in a parent body. "Lability" is used when either thermal process could have occurred. We do not use lability in discussing compositional alteration during Antarctic weathering.) Refractory elements can less easily distinguish between these and other carbonaceous chondrite groups. Kallemeyn and Wasson [3] proposed the terms CI and CM for C1 and C2, respectively, to emphasize that their petrologic and chemical characteristics, like the oxygen isotopic composition, are of primary nebular origin rather than reflecting secondary, parent-body alteration. Among non-Antarctic samples, these properties are consistent: a meteorite classified as CM petrographically will have an oxygen isotopic composition and a volatile trace element abundance pattern like those of other CM chondrites. As will be seen, data for Antarctic samples present a different picture, with part of the difference reflecting secondary (parent body) rather than primary (nebular) processes. As will be seen, some of the data reported here reflect primary processes, others

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Table 1. Comparison of numbers of carbonaceous chondrites.

Type	Non-Antarctic[a]		Antarctic		
	Falls	Finds	ANS-MET[b,d]	ANS-MET[b,e]	JARE[c,e]
C1	5	0	0	0	2
C2	18	5	19	76	17
C3O	5	2	4	7	7
C3V	6	4	5	7	3
C4	0	1	7	16	2
C5	1	1	1	1	2
C6	0	0	1	1	0

[a] Data from Graham et al. [36].
[b] U.S. Antarctic Search for Meteorites. One further-unclassified C3 chondrite is known [37].
[c] Japanese Antarctic Research Expedition. Numbers do not include 46 further-unclassified carbonaceous chondrites [13].
[d] Corrected for pairing [37].
[e] Uncorrected for pairing [36, 37].

result from secondary alteration. We will, therefore, use the CI-CM terminology to describe mineralogic-petrologic-refractory element-oxygen isotopic trends and the C1-C2 terminology to describe trends established from labile trace elements.

Similarities in the surface spectral reflectances of the numerous C asteroids and carbonaceous chondrites of petrographic types 1 and 2 have led to the consensus view that these chondrites are "ground truth" for these asteroids [4]. Other asteroid types exist, some of which (B, F, G and T-asteroids) may have surfaces representing altered or metamorphosed C1 and C2 material [5]. The 48 carbonaceous chondrite falls or finds ouside of Antarctica seem not to include any suitable example of such materal (Table 1). By and large, non-Antarctic C1 and C2 chondrites represent relatively simple assemblages which, if altered, were affected only by low-temperature hydrolysis [6] under conditions such that trace elements did not migrate over great distances.

Recently, an unofficial consortium organized by Dr. A. L. Graham [7] reported data for a peculiar carbonaceous chondrite from Queen Maud Land, Antarctica: Yamato (Y) 82042. This 376-gram sample exhibits the textural and petrologic properties of a C1 chondrite but the oxygen isotopic and major and minor element composition of a C2 chondrite [7]. Grady et al. [7] also report data for refractory and some moderately volatile trace elements. Where these data discriminate between C1 and C2 chondrites, they favor the latter: Na, K and Br seem peculiar, however, The only other Antarctic carbonaceous chondrite examined in much detail – Belgica (B) 7904, 1200 grams; Y-82162, 40 grams; Y-86720, 800 grams – exhibit unusual properties suggesting thermal metamorphism, and Prof. Y. Ikeda organized a Consortium to study these.

Our pleasure at being invited to join these Consortia and measure Ag, Au, Bi, Cd, Co, Cs, Ga, In, Rb, Sb, Se, Te, Tl, U, and Zn by radiochemical neutron activation analysis (RNAA) was exceeded only by our interest in studying these examples, the first Antarctic C1 and C2 chondrites in which labile elements have been determined. Part of our interest lay in determining the extents to which labile element contents of such chondrites reflect primary and secondary genetic processes. The other part of our interest lay in further examining the extent to which Antarctic and non-Antarctic meteorites differ and the reasons for these differences [8–10]. Here, we report our results.

Experimental

All Antarctic samples studied were received as individual pieces chipped from the interiors of the respective specimens. Samples of ~100 mg (B-7904,16 – 99.7 mg; Y-82042,50 – 94.1 mg; Y-82162,84 – 83.7 mg; Y-86720,83 – 97.2 mg) were irradiated at the University of Missouri Research Reactor for 2 days at a flux of 8×10^{13} n/cm^2 sec. Techniques for chemically processing samples and monitors and for data reduction are described elsewhere [11]. As is usual in our Laboratory, replicate portions of Allende Meteorite Reference Sample had previously been analyzed to assure the quality of our data.

Results

Allende

We list in Table 2 our results for Allende Meteorite Reference Sample powder together with the mean values from previous measurements in our Laboratory: there are no discrepancies. Lingner et al. [12] had previously compared means of slightly fewer data from our Laboratory with all other prior (and fewer) results and found no discrepancy. Since no Allende data from other groups have been published more recently, the comparison by Lingner et al. [12] serves to test our Laboratory's results with others.

Antarctic Carbonaceous Chondrites

We list our results in Table 3 together with some prior literature data for these elements in non-Antarctic C1 and C2 chondrites, for comparative purposes. (There is no evidence either from the literature [13–17] or from our data (Table 3) that results from carbonaceous chondrites of petrographic types ≧3 need be considered.) We selected these literature data because they were determined in general, comprehensive surveys of the respective carbonaceous chondrite groups.

Labile elements concentrations in C1 and C2 chondrites do not vary much, especially when contrasted with the 1–3 orders of magnitude variation evident in other meteorite groups. Data for C1 chondrites are illustrative of the analytical coherence. For 2 CI chondrites (6 analyses), Kallemeyn and Wasson [3] estimated relative standard derivations from the mean of 2–6% for 5 of 7 elements: the remaining 2 elements (Sb, Au) exhibited precisions of 13 and 17% (Table 3). In the compilation of Ebihara et al. [18] for data from many sources (10–39 analyses), 9 of 12 elements had estimated relative standard deviations from the mean of 3–10% (Table 3). Precisions for the remaining 3 elements – Au, Sb, Rb – were 16–18%: interestingly, these are among the least labile of the elements considered here. Hence it makes little difference which literature data we list. The sources of literature data for Ag, Bi, Co, Cs, Ga, Rb, Te, Tl and U are listed in Table 3. For other elements, we chose the data of Ebihara et al. [18] since these are the most recent and comprehensive. In Fig. 1, we depict our results from Table 3 in terms of C1-normalized abundance ratios.

There are few prior data with which our results can be compared, and these exist only for Y-82042. For duplicate samples of Y-82042, Grady et al. [7] report 534 and 648 ppm Co, 160 and 162 ppm Au, 110 and 120 ppb Sb, 7.85 and 7.99 ppm Ga, 12.4 and 14.3 ppm Se and 176 and 200 ppm Zn. Our Co and Sb results for Y-82042 are clearly lower than these, Ga is slightly lower but Au essentially agrees (Table 3). Heterogeneous metal distribution is possible but it should be noted that, relative to the other chondrites found in this work to have a C2-like trace element pattern, Y-82042 contains lesser quantities of many of the least labile elements (U→Se). We believe that this effect is real and reflects primary differences.

Table 2. Trace element concentrations in Allende (C3V) Meteorite Reference Sample.

		This work[a]	Purdue Mean[b]
Ag	(ppb)	102 ±9(9)	99.0 ±9.5(59)
Au	(ppb)	147 ±5(3)	145 ±9(27)
Bi	(ppb)	49.5 ±0.8(3)	48.6 ±3.4(4)
Cd	(ppb)	518 ±26(8)	505 ±56(56)
Co	(ppm)	615 ±32(9)	614 ±39(66)
Cs	(ppb)	87.2 ±5.3(9)	86.9 ±5.3(60)
Ga	(ppm)	5.97 ±0.54(9)	6.21 ±0.55(47)
In	(ppb)	31.7 ±3.8(9)	30.3 ±3.4(52)
Rb	(ppm)	1.11 ±0.14(9)	1.11 ±0.13(54)
Sb	(ppb)	84 ±9(5)	84 ±14(38)
Se	(ppm)	8.44 ±0.69(9)	8.74 ±1.09(44)
Te	(ppm)	0.960 ±0.041(9)	1.02 ±0.09(65)
Tl	(ppb)	60.6 ±3.7(6)	61.0 ±4.7(68)
Zn	(ppm)	119 ±8(9)	116 ±7(65)

[a] Split 22, position 25. Mean value and one sample standard deviation are listed for the number of replicates analyzed (in parentheses).
[b] Mean value and one sample standard deviation are listed for the number of replicates shown in parentheses [9, 12 references cited therein, 32].

Table 3. Trace element concentrations in some Antarctic carbonaceous chondrites and mean concentrations for non-Antarctic C1 and C2 chondrites.

Meteorite and Reference	U (ppb)	Co (ppm)	Au (ppb)	Sb (ppb)	Ga (ppm)	Rb (ppm)	Cs (ppb)	Se (ppm)	Ag (ppb)	Te (ppm)	Zn (ppm)	In (ppb)	Bi (ppb)	Tl (ppb)	Cd (ppb)
Belgica 7904,16	13.3	495	177	120	9.29	1.9	140	14.7	148	1.61	171	35	17.9	5.56	1.86
Yamato 82042,50	9.6	422	155	47	7.50	1.5	117	11.5	133	1.33	196	48	68.0	84.9	403
Yamato 82162,84	11.7	490	102	140	13.2	3.2	211	27.8	291	3.12	364	39	23.4	3.37	≦1.4
Yamato 86720,83	11.1	483	178	72	9.74	1.6	143	20.1	128	1.68	29.2	16	3.88	6.65	0.85
CI [3]		510	140	153	9.8			21.3			311	87			638
		±13	±24	±20	±0.2			±0.8			±16				±41
C1 [18, 38]	8.1		137	160		2.03	185	18.4	214	2.35	305	79	113	140	670
			±23	±29		±0.33	±10	±0.7	±21	±0.24	±9	±5	±8	±13	±41
CM [3]		579	165	118	7.8			13.1			185	51			352
C2M [20, 21]	11		150	120		1.4	130	11	210	1.14	200	47	75	110	470
C2R [21, 39]	13		160	80		1.08	84	8.1	94	1.1	130	31	44	56	300

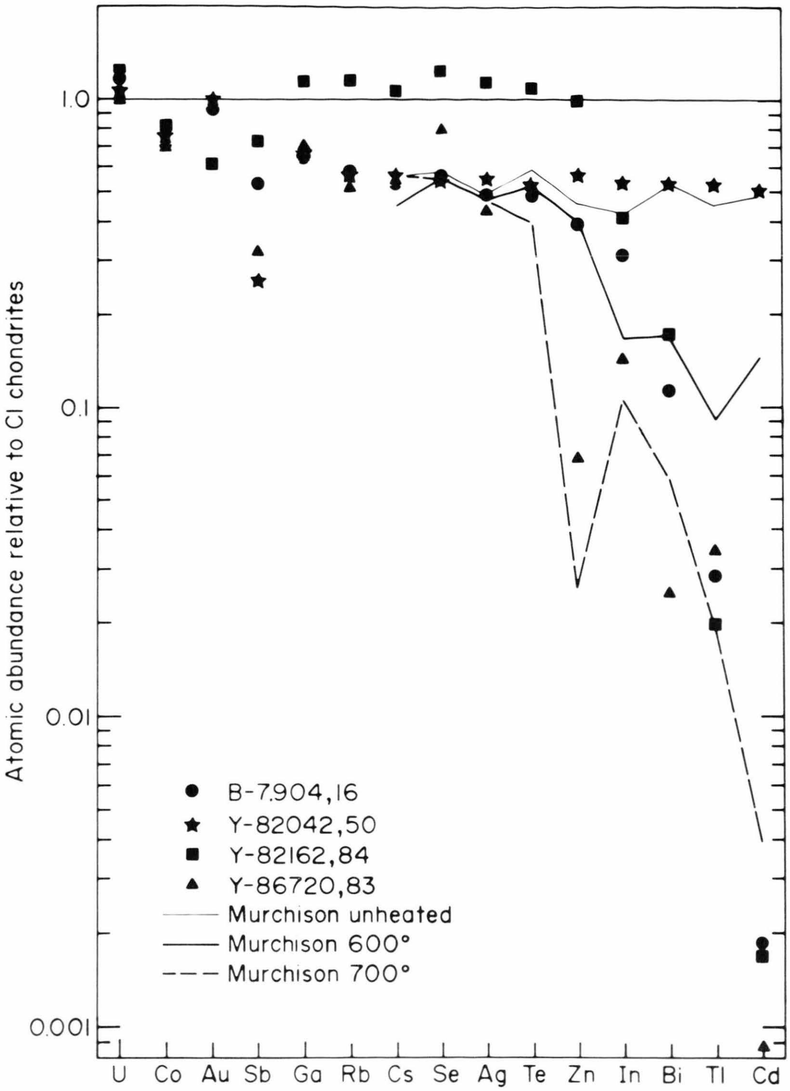

Fig. 1. Concentrations of 15 trace elements in four carbonaceous chondrites from Queen Maud Land, Antarctica, normalized to those in C1 chondrite falls [38]. Elements are ordered from left to right by increasing mobility (ease of vaporization and loss) in Murchison (C2) chondrite heated for 1 week in a low pressure (initially 10^{-5} atm H_2) environment at 600–700 °C [19]. Data for unheated Murchison [19] match those of Yamato 82042 very well, confirming that it is chemically C2 while being petrographically C1 [7]. Clearly, these features were established during primary nebular condensation and accretion. From comparison with data for heated Murchison [19], the other samples – Belgica 7904, Yamato 82162 and Yamato 86720 – experienced post-accretionary thermal processing in parent bodies at progressively higher temperatures in the 600–700 °C temperature range. Prior to metamorphism, Yamato 82162 parent material had about C1 levels (horizontal line at 1.0), possibly a bit higher, of mobile elements (judged from Ga→Zn). The other 2 metamorphosed chondrites had C2 levels of mobile elements. Because of differences in contents of less-mobile elements, Yamato 82162 must have originated in at least a different parent region than Belgica 7904 and Yamato 86720. These parent regions/bodies must have been similar to present-day B-, F-, G- or T-asteroids.

Discussion

To aid in our discussion, we have chosen to list the elements in Table 3 and Fig. 1 in order of increasing mobility at 600–700 °C, a temperature range consistent with petrologically-observable thermal alteration effects in Y-82162 [15, 16] and Y-86720 [17]. We assumed that the mobility order for elements in this temperature range would be similar in C1 and C2 chondrites and determined the order from data for Murchison C2 chondrite heated in a low-pressure environment (initially 10^{-5} atm H_2) at temperatures of 400–1000 °C [19]. In Fig. 1, we depict C1-normalized abundance trends for unheated Murchison and aliquants of it heated at 600 °C and 700 °C [19] together with the data for the 4 Antarctic carbonaceous chondrites (Table 3). In calculating atomic abundances for the Antarctic carbonaceous chondrites, we used Si data of Ikeda (pers. comm.).

Before discussing the Antarctic samples, we should briefly summarize the important points of similarity and difference in C1 (≡CI) and C2 (≡CM) abundance data for non-Antarctic samples. Refractory lithophiles, like U, are generally enriched in CM chondrites by 33% relative to CI chondrites [3]. Siderophiles, like Co and Au, are enriched in CM chondrites by 9%

relative to C1 chondrites [3]. Finally, for the 11 moderately-to-strongly volatile elements in Table 3 (Ga → Cd), concentrations in CM (≡C2M) chondrites are 0.55±0.11 of those in CI (≡C1) chondrites [18, 20, 21]. Antimony, an element with volatility intermediate between siderophiles and moderately-to-strongly volatile trace elements, has a similar CM/CI ratio, i.e. 0.60 [3, 18, 20, 21].

Antarctic Carbonaceous Chondrites

The picture presented by data for the 4 least labile elements, U→Sb, is much more clouded than that obtained from the more mobile ones. Three of these elements – U, Co and Au – form generally tight clusters in Fig. 1 centered at 1.1 × C1, 0.75 × C1 and 1.0 × C1, respectively. (Only one datum, Au in Y-82042, lies apart from the cluster, and that result is confirmed by other analyses.) These values are not those typical of CI or CM chondrites and may signal a real difference or a systematic analytical problem. Our Allende analyses (Table 2) argue against the latter. The Co discrepancy in Y-82042 argues for it but the Au agreement negates this. The large spread in Sb values and their substantial depletion relative to C1 chondrites suggest some difficulty with this element which exhibits poorer precision in its determination by any technique, including our own ([3, 18]; cf. Table 2). Fortunately, it is the more labile elements that are more crucial to our understanding of the Antarctic carbonaceous chondrites, and their trends are quite easily interpreted.

Yamato 82042

Data for Y-82042 define the simplest pattern, and we will discuss this chondrite first therefore. Normalized to C1 chondrites, abundances in Y-82042 decrease slightly from U to Ga or Rb and are virtually constant thereafter (Figure 1). Because of uncertainty associated with interpretation of data for the least volatile elements, we judge that the most significant qualitative trend exhibited by the Y-82042 data is the flat pattern of the volatiles. This is diagnostic of a primary, nebular effect, and no post-accretion event altered it.

Quantitatively, the data for Y-82042 fit the CM trace element pattern reasonably well. Relative to concentrations in C1 chondrites, the 11 volatile elements (Ga→Cd) have concentrations that vary little, averaging 0.55±0.05. (Even if data for the 4 least volatile and therefore most variable elements in Y-82042 are included, the mean C1-normalized abundances becomes 0.61±0.21.) From the volatile element perspective, Y-82042 is indistinguishable from a C2M chondrite. For example, as part of a heating study, Matza and Lipschutz [19] determined 11 trace elements, Co, Ga, and the 9 elements Cs→Cd, in unheated Murchison, a typical C2M chondrite. The mean C1-normalized abundances are 0.53±0.09 for the 10 elements Ga→Cd and 0.56±0.14 for all 11 elements, in excellent accord with the corresponding ratios of 0.55±0.05 and 0.57±0.08 for Y-82042. Figure 1 depicts the trend for the volatile elements Cs→Cd in unheated Murchison. As can be seen, it is quite similar to the corresponding results for Y-82042. Naturally, if Y-82042 had C1-levels of volatiles, its ratio would be exactly 1: such a line is also indicated in Fig. 1, and the deviation of the Y-82042 points from this is obvious. U, Co, Au and Sb data add little to the picture. While these data might be taken as indicating that Y-82042 deviates very marginally from CM chondrites in its component of less-volatile elements, the differences are so slight that we adopt the conservative view of regarding it as C2 chemically. On an element-by-element basis, differences between our data for Y-82042 and CM or C2M means exceed 10% only for Co, Sb, Ag, Te, and Tl. We have discussed the first two of these before: differences for the Ag and Tl reflect abnormally high values for 2 of 9 C2M chondrites measured by Anders and coworkers [20, 21].

Our data then confirm the earlier view [7] that Y-82042 is a unique meteorite, being CI texturally and CM or C2 chemically. We discuss below its further classification.

Belgica 7904 and Yamato 86720

These 2 chondrites also present a relatively simple picture, that of C2 chondrites altered by thermal metamorphism at 600–700 °C in parent bodies. The chemical evidence supporting this is straightforward and most easily seen in Figure 1. For the 10 elements to the left, U→Te, data for B-7904 and Y-86720 are very similar to those for Y-82042. (Sb is questionable for reasons discussed earlier.) To the extent that Y-82042 chemically represents C2 material for these elements, so too do B-7904 and Y-86720. The point of departure is Zn. This element and the 4 more mobile ones, In→Cd, are depleted in Y-86720 relative to the

C2 trend exemplified either by unheated Murchison [19] or Y-82042 (Table 3, Figure 1). In contrast, Zn and In are present at C2 levels in B-7904 but the 3 most mobile elements – Bi, Tl and Cd – are depleted in it. We attribute these depletions in B-7904 and Y-86720 to mobilization of these elements during thermal metamorphism of parent material initially containing C2-levels of Zn, In, Bi, Tl, and Cd.

Fortunately there exist appropriate experimental data [19] to test this suggestion. Trends for Murchison (C2M) chondrite material heated for 1 week at 600 °C and 700 °C plotted in Fig. 1 are very similar to those for B-7904 and Y-86720. Indium and the 3 elements to the right are significantly depleted from Murchison at 600 °C; Zn joins them at 700 °C (cf. Table 2). We interpret these results as indicating that Y-86720 was metamorphosed at ~700 °C, perhaps somewhat higher, while B-7904 was altered at somewhat lower temperatures, but still above 600 °C.

These conclusions generally accord with results obtained previously. Kallemeyn's [22] refractory element data for B-7904 group it with CM chondrites despite its oxygen isotopic composition which groups it with CI [14]. By comparison of 7 Å serpentine-type phyllosilicates in B-7904 with those in Murchison heated at 500 °C and 600 °C, Akai [23] concluded that B-7904 was thermally metamorphosed at a temperature higher than these. The refractory element data for Y-86720 "weakly group it with CM chondrites although it may be intermediate between CI and CM" [22]. Oxygen isotopic data for Y-86720 group it with B-7904 and Y-82162 at the high end of the CI distribution [24], but Tomeoka et al. [17] conclude that Y-86720 is a CM chondrite extensively affected by aqueous alteration and subsequently thermally metamorphosed preterrestrially. We concur with Tomeoka et al. [17] and suggest further that B-7904 represents a less thermally altered example. We believe that these 2 preterrestrially heated carbonaceous chondrites are not paired samples from different regions, in view of the distance between their find locations. At the least, they derive from different parent regions in the same parent body, because of the difference in their degree of thermal alteration.

Yamato 82162

While the trace element pattern for Y-82162 shows unambiguous evidence for loss of the most mobile of these elements, as in B-7904 and Y-86720, it shows some features that make Y-82162 unusual, perhaps unique (Figure 1). The 4 least mobile elements exhibit contradictory trends with U indicating CM, Cs and Sb indicating CI and Au indicating neither. The next 7 elements, Ga→Zn, are at about C1 levels, enriched by a small amount, 7%. The 4 elements of highest mobility at 600–700 °C are very significantly depleted in a manner strongly suggestive of thermal metamorphic loss for reasons discussed in connection with B-7904 and Y-86720. The data suggest that prior to this metamorphic episode, the contents of In, Bi, Tl and Cd were at or above C1 levels and that the metamorphic temperature was intermediate between those of B-7904 and Y-86720 (Figure 1).

Assuming the correctness of this interpretation, Y-82162 seems to represent pre-metamorphic material uniquely different from B-7904 or Y-86720. Yamato 82162 is a peculiar meteorite by any criterion. Its oxygen isotopic composition, like those of B-7904 and Y-86720 most closely resembles that of CI chondrites but all lie far away from normal, non-Antarctic CI chondrites [8, 24]. This also seems to be the case with data for refractory elements [22]. Tomeoka et al. [15] states that "this meteorite shows many mineralogical features that apparently differ from the known CI chondrites, suggesting that it has a unique formation history compared to other CI chondrites" [cf. 25]. In particular, Y-82162 seems to have largely escaped the late aqueous alteration stage that affected other CI chondrites [15, 25].

We concur with the conclusions of Tomeoka et al. [15, 25]. From our results, Y-82162 parent material apparently formed with volatile element concentrations at about C1 levels. Concentrations by weight are higher (by ~35%) than those in C1 chondrites but much of this difference reflects the lower water content of Y-82162. The primary, high levels of its 4 most mobile trace elements were subsequently lowered by thermal metamorphism in its parent body over the 600–700 °C temperature range. Despite the fact that B-7904, Y-72162 and Y-86720 (in order of increasing metamorphic temperature) were metamorphosed over a similar temperature range, this process must have taken place in at least 2 parent regions – perhaps on the same body, perhaps not – since chemical and petrological characteristics of Y-82162 differ so much from those of B-7904. We expect that the spectral reflectance characteristics of B-7904, Y-82162 and Y-86720 might well match those of B-, F-, G- or T-asteroids, minor planets suspected of being thermally metamorphosed C1 or C2 objects [5].

Could loss of the most labile trace elements in these 3 carbonaceous chondrites be an Antarctic weathering artifact? We think not. Trace elements are lost by leaching during alteration of Antarctic meteorites to form samples of the most heavily weathered type C [8]. However, these losses affect 10 elements (Co, Au, Sb, Cs, Bi, In, Tl, and possibly Rb, Zn and Cd), not merely the 3–5 most thermally labile ones and rarely exceed a factor of 3. The 4 Antarctic carbonaceous chondrites studied here appear essentially unweathered, and there is no evidence for trace element leaching from this sort of sample [8]. To invoke weathering as the loss mechanism for Bi→Cd in B-7904, In→Cd in Y-82162 and Zn→Cd in Y-86720 by amounts of up to 10^3 is to require a remarkable degree of coincidence. It would require that just those 3–5 elements be lost (to about the correct extent) from the 3 Antarctic carbonaceous chondrites) by leaching as by heating Murchison to 600–700 °C, a temperature range consistent with thermally-induced petrographic changes evident in the Antarctic samples. Such a degree of coincidence seems to us so unlikely that we discard this possibility.

The Murchison samples were heated in the laboratory under conditions and times [19] that probably differ vastly from those experienced by Antarctic carbonaceous chondrites during heating in their parent body. How quantitatively instructive then are the trace element data from heated Murchison to metamorphic temperatures in the parent bodies of B-7904, Y-82162 and Y-86720? Three sorts of data suggest that the Murchison results provide at least semi-quantitative information.

1. Temperatures estimated from trace element data for the 3 Antarctic carbonaceous chondrites and heated Murchison are consistent with thermometers provided by the petrography of the samples [15, 17, 23, 25].

2. Sulfide equilibration temperature ranges for non-Antarctic enstatite chondrites and achondrites are very similar to putative metamorphic temperatures estimated from labile trace element contents of these same meteorites and from Abee (E4) samples heated artificially under conditions like those used in heating Murchison [26–28].

3. Qualitatively, those elements mobilized by heating Krymka (LL3) under conditions like those used in heating Murchison are the elements whose contents in non-Antarctic L chondrites vary inversely with the degree of shock-loading as estimated petrographically or from contents of radiogenic ^{40}Ar [29–31].

Clearly additional petrographic work needs to be done to uncover mineralogic/petrologic thermometers in B-7904, Y-82162 and Y-86720 to establish their metamorphic temperatures definitively. At this point, we feel justified as estimating the range as 600–700 °C.

Carbonaceous Chondrite Classification

Three factors could be used to unambiguously classify carbonaceous chondrites into petrographic types – petrology, oxygen isotopic composition and volatile trace element content. Heretofore, for non-Antarctic samples, the classifications from them would be self-consistent so that, for example, the term CM unambiguously communicated the nature of a sample's petrographic properties and oxygen isotopic and volatile trace element contents.

As summarized in Table 4, the properties of the first 4 Antarctic C1/2 (CI/M) samples studied in detail are not self-consistent or unambiguous. B-7904, for example, exhibits the petrographic properties of a CM chondrite (including hydration of matrix) but the oxygen isotopic composition of a CI. Its trace element composition indicates that it accreted as a CM or C2 but this composition was then altered by heating in a parent body at a temperature near 600 °C.

We find it necessary to propose a more complicated classification scheme that will express all of these parameters. Our proposal is limited, for the time being, to those samples prompting the change. We propose something like

$$\text{Chemical Type} \; {}^{\text{Oxygen Isotopes}}_{\text{Petrography}} \; \text{Labile Trace Elements}$$

with an asterisk denoting post-accretion metamorphism. By this convention, B-7904, Y-82042, Y-82162

Table 4. Summary of properties of four Antarctic carbonaceous chondrites.

	Petrography	$^{18,17,16}O$	Labile Trace Elements
Belgica 7904	CM	CI	C2[a]
Yamato 82042	CI	CM	C2
Yamato 82162	CY	CI	C1[a]
Yamato 86720	CM	CI	C2[a]

[a] Thermally metamorphosed.

and Y-86720 would be described as $C^{I}_{M}2^{*}$, $C^{M}_{I}2$, $C^{I}_{Y}1^{*}$, and $C^{I}_{M}2^{*}$, respectively. Any sample not requiring this more elaborate scheme could still be denoted as e.g. C2, C2M or CM for Murchison.

Antarctic/Non-Antarctic Meteorite Populations

Several years ago, Dennison et al. [32] suggested that H chondrites and other meteorites recovered in Antarctica may represent an extraterrestrial population significantly different from that falling on Earth today. It is important to note in this connection that for differences to be observed, all Antarctic meteorites need not have thermal histories differing from non-Antarctic histories of the same type. It is sufficient if each population – Antarctic and non-Antarctic – of a given type contains contributions of material from $\geqq 2$ sources having different thermal histories, but in different proportions [32]. It turns out that Antarctic samples from every meteorite group studied to date differ in meaningful ways from their non-Antarctic siblings. Commenting on this suggestion, Wetherill [33] pointed out that this would imply the existence of "meteoroid streams", i.e. that meteoroids "remember" the launch parameters imparted to them during collisional ejection from their parent bodies. The idea that meteorite orbits are not randomized during their transit from parent body to Earth, i.e. during their cosmic ray exposure history, is at odds with the conventional orbital dynamic picture obtained by statistical, Monte Carlo-type calculations of meteorite derivation from the Asteroid Belt. Halliday et al. [34] recently reported direct evidence for numerous streams of meteorite-producing asteroidal fragments from photographic observations by the U.S. Prairie Network and Canadian Meteorite Observation and Recovery Project camera networks.

The different ensemble of properties exhibited by Antarctic and non-Antarctic carbonaceous chondrites as discussed above is one more example of the significant Antarctic/non-Antarctic meteorite population difference observed for every meteorite group studied to date. A detailed summary of these studies is beyond the scope of this paper and is presented elsewhere [35]. It is sufficient to note here that few of the long list of differences could conceivably be due to Antarctic weathering. Most, if not all, differences must reflect preterrestrial processes.

Conclusions

Trace element data, especially for volatile/mobile elements, confirm the uniqueness of the 4 carbonaceous chondrites from Queen Maud Land (Antarctica) studied here, relative to non-Antarctic falls. No fall has the peculiar combination of characteristics (CI petrology, CM oxygen isotopic composition and labile trace element chemistry) of Y-82042. These trends, which must have been established during primary nebular condensation and accretion, argue that Y-82042 derives from a source other than those which produced CI or CM falls. During primary formation of its parent material, Y-82162 acquired trace element contents similar to those of CI falls, but a lesser qantity of H_2O. Ironically, it was surrounded by (frozen) H_2O since it landed on Earth. The petrographic characteristics of Y-82162 led Tomeoka et al. [15] to conclude that "this meteorite may have come from a location distinct from other CIs, i.e. different locations in a parent body or different parent bodies". We concur. Furthermore, this meteorite and B-7904 and Y-86720 – both of which apparently derive from parent material containing CM-levels of volatiles – experienced open system thermal metamorphism at 600–700 °C in their parent bodies, a characteristic unknown among C1 and C2 falls. From chemical, isotopic and petrologic properties, B-7904 and Y-86720 must have come from different source region(s) or object(s) than that from which Y-82162 derives, despite the fact that B-7904 and Y-86720 apparently were metamorphosed at temperatures bracketing the metamorphic temperature of Y-82162. Possible parent asteroids for these 3 thermally altered carbonaceous chondrites include those of the B-, F-, G- or T-types.

This difference in the thermal histories of Antarctic and non-Antarctic carbonaceous chondrites, now requiring substantial modification of traditional classification schemes, adds to the preponderance of evidence arguing that the two overall sample populations derive from substantially different parent populations. We interpret the results as indicating that the near-Earth population of extraterrestrial material has changed with time on the 10^5–10^6 year scale. Such a temporal change in the meteoroid flux of extraterrestrial material is not consistent with the current picture of meteorite derivation from the Asteroid Belt, as deduced from statistical, Monte Carlo calculations. Another long-standing problem is that no Asteroid Belt object seems to have a spectral reflectance consistent with those of the overwhelming majority of meteorites, the ordinary chondrites [4]. Seemingly, both of these suggest a near-Earth origin with the Apollo, Amor or Aten asteroids having varied in their effectiveness as a meteorite source with time.

Whatever the ultimate answer to the question of the parent population(s) for Antarctic and non-Antarctic meteorites, it seems likely that Antarctic samples will continue to provide many more surprises [40].

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