Thermal metamorphism of primitive meteorites—VI.
Eleven trace elements in Murchison C2 chondrite
heated at 400–1000°C

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Abstract—We used neutron activation analysis to determine 11 trace elements in Murchison (C2) chondrite powder heated in a low-pressure environment (initially $\sim 10^{-5}$ atm H_2) for 1 week at 100°C increments from 400–1000°C. Cobalt seems unaffected by heating, 65% of Cs is lost only at 1000°C and losses of other elements progress with temperature to extremes of 25% for Se, 75% for Ga, and 96–99.6% for Ag, Bi, Cd, In, Te, Tl, and Zn. Treating elemental mobilization as kinetically-controlled by diffusion from spherical grains of uniform size, Cd, Ga, In, and Se are lost from a single site and/or process while Ag, Bi, Te, Tl, and Zn are lost from two sites and/or processes. Magnitudes of apparent activation energies for loss of Ga, In, and Se and, at low temperatures, Ag, Bi, Te, Tl, and Zn are consistent with volume diffusion; all other data suggest a low-energy process like desorption. Factor analysis indicates that only two factors account for the variability of all 11 elements whereas three factors appeared for six to ten elements in each of the four heated primitive chondrites studied previously. Comparison, where possible, between Allende (C3) and Murchison indicates differences in the genetic histories of these carbonaceous chondrites, possibly including a low-temperature sintering by mild, closed-system metamorphism of Allende parent material.

INTRODUCTION

PRIMITIVE CHONDRITES, i.e., those of petrologic grades 1–4, are thought to contain important clues to the origin of meteoritic parent bodies and, by extension, to the genesis of other solid objects in the solar system. Among these, carbonaceous chondrites loom especially large in significance. Cosmic abundance estimates for many elements are derived from C1 chondrites (e.g., Cameron, 1970) since there is a close compositional correspondence between these primitive meteorites and the solar photosphere. Furthermore, similarities between the surface spectral reflectance of many asteroids and carbonaceous chondrites (cf., McCord and Gaffey, 1974; Chapman, 1976) suggest that similar material proportionally may be much more abundant in the inner solar system at least, than in terrestrial meteorite collections.

Largely based upon trace element contents, Anders (1964) suggested that carbonaceous chondrites represent mixtures in varying proportions of components differing in thermal history—a low-temperature portion (identified with C1 chondrites and C2 and C3 matrix) containing volatile elements in "cosmic"

proportions and high-temperature material (now identified with chondrules, metal and Ca–Al-rich inclusions) containing none of these elements. Results from numerous subsequent studies generally accord with this view—e.g., volatile trace element atomic abundances (relative to Si) in C1 : C2 : C3 chondrites are in ratios of 1.00 : 0.51 : 0.2–0.3 (Krähenbühl *et al.*, 1973; Anders *et al.*, 1976)—but some data suggest the need for minor modifications (e.g., Case *et al.*, 1973; Kurimoto *et al.*, 1973) which can be incorporated in the mixing model (cf., Anders *et al.*, 1976).

Elements exhibiting these regular ratios in carbonaceous chondrites are less abundant in ordinary (H-, L-, and LL-group) chondrites—especially equilibrated ones (cf., Binz *et al.*, 1976)—their depletion factors or atomic abundances relative to C1 chondrites being in the range 0.001–0.25. Naturally, elements at ppm–ppb levels cannot form discrete chemical compounds (i.e., minerals) with established thermodynamic properties; thus their volatilities cannot be determined directly. Instead, the depletion factor in ordinary chondrites is taken as a qualitative index of its volatility under nebular conditions (Anders, 1964) although not necessarily under other conditions, e.g., in chondritic parent objects.

Ikramuddin and Lipschutz (1975)—hereafter denoted as Paper I—demonstrated substantial loss of Bi, In, and Tl and, to a lesser extent, of Ga and Se during week-long heating of the Allende C3 chondrite under temperature (400–1000°C) and pressure (initially $\sim 10^{-5}$ atm H_2) conditions reasonable for the ambient environment in primitive inner solar system objects. Similar studies conducted under these standardized conditions using Abee (E4), Krymka (L3), and Tieschitz (H3) demonstrated even greater loss of these elements and of Ag, Cs, Te, and Zn (Ikramuddin *et al.*, 1976a, 1977a,b—hereafter denoted as Papers II, III, and V, respectively). Such loss even occurred from similarly-treated terrestrial basalt BCR-1 (Ikramuddin *et al.*, 1976b—hereafter, Paper IV), an igneous sample radically different in composition and origin from primitive chondrites. These data demonstrate that progressive elemental loss with temperature is a general characteristic of geologic material and, together with results of Ikramuddin *et al.* (1975), that the loss is kinetically, rather than thermodynamically, controlled. We therefore distinguish between elemental mobility under our experimental conditions and elemental volatility by using the relevant specific term.

Furthermore, comparison of elemental abundances, correlation profiles (i.e., patterns of statistically significant interelement relationships), factor analysis and two-element correlation diagrams for heated Abee, Krymka, and Tieschitz with those for E3-6, L3-6, and H3-6 chondrites, respectively (cf., Binz *et al.*, 1974, 1976) indicates pronounced differences in chondritic genetic histories. In particular, E3-6 chondrites apparently reflect a substantial *open-system* thermal metamorphic episode in their parent object; L3-6 and probably H3-6 chondrites escaped such an event although modest mobile element losses could have occurred in the case of the H3-6 chondrites (Papers II, III, V). Mobile element trends in the C4 chondrite, Karoonda, are also consistent with open-system losses during mild thermal metamorphism (Matza and Lipschutz, 1977).

These facts indicate similar investigations on other primitive chondrites to be

clearly warranted. In particular, comparison of trends in heated Murchison C2 chondrite with those in Allende (Paper I) should help: establish similarities and/or differences in samples of two petrologic grades of the same chondritic group; test whether mobile elements are sited similarly in carbonaceous chondrites; establish boundary effects to be expected during thermal metamorphism of carbonaceous chondrite-like asteroidal material. In making this comparison we do not imply a direct genetic link between these two carbonaceous chondrites; indeed chemical data indicate a collateral relationship between C2 and C3 chondrites. Furthermore such comparison can only be partial at this time since we determined only a few mobile elements in our initial feasibility study of Allende (Paper I). Here we report data on 11 trace elements—Ag, Bi, Cd, Co, Cs, Ga, In, Se, Te, Tl, and Zn—in Murchison homogenized powder samples heated at 100°C increments under our standardized conditions and compare these with Bi, Co, Ga, In, Se, and Tl results for similarly-treated Allende.

EXPERIMENTAL

Through the kindness of Dr. E. Olsen of the Field Museum of Natural History we obtained 50 g of homogenized (<100 mesh) Murchison powder and an equal-mass chunk, both from sample Me 2682 from which he had previously removed potentially contaminated surfaces. As in Papers I–V, we analyzed replicate aliquots of unheated powder to establish initial trace element contents and to assess precision (Table 1). We irradiated all samples in the CP-5 reactor and determined all elements in each sample using chemical and counting techniques described in Paper II. Average chemical yields for all elements were at least as high as those listed in Paper II.

We prepared each heating run—consisting of two 0.3 g samples (for trace analysis and a reserve sample) and 0.7 g of chips (for mineralogy/petrology and other studies)—as described in Paper I using an initial ambient atmosphere of $\sim 10^{-5}$ atm H_2 (Papers I–V). In view of the volatile-rich nature of Murchison we feared that gases evolved during heating could affect trace element retentivity (Ikramuddin et al., 1975; unpublished data); hence we placed Linde type 3A or 5A molecular sieve into the cold trap (Paper II), the latter being used in runs 700B-900 when we anticipated high pressures. With this precaution, the ambient pressure varied normally with time, reaching final values (Table 2) which seemed very reasonable (Papers I–IV). As in Allende (Paper I) we observed visible amounts of yellow-white material—probably S_8—in the cold traps from heating runs ≥700°C; thus, of all primitive chondrites we studied so far, sulfur is mobile only in carbonaceous chondrites and, then, only a relatively small proportion vaporizes (Gibson, 1976).

As in Krymka and Tieschitz (Papers III, V), the sudden release of volatiles (probably water) from Murchison at temperatures ≥600°C caused some effervescence and loss of small amounts of powder from the vials. As before we minimized this by step-heating from 400°C and corrected the observed concentrations for material transport using Co as an internal "standard". Although these corrections are relatively small, 0.6–12% (cf., Papers III, V), their existence may cause relationships between Co and any mobile element to be questionable. We list both observed and corrected values in Table 2 but use only the latter to establish correlation profiles and two-element correlation diagrams and for factor analysis. We did not feel it worthwhile analyzing Murchison chips since Allende and Abee trace element retentivities in powder and chips are so similar (Papers I, II; Ikramuddin et al., 1975).

RESULTS AND DISCUSSION

We will discuss our results only in the context of comparison with trends in similarly-treated Murchison. Extrapolation of our laboratory studies to conditions in extraterrestrial parent objects is a long one and certain *caveats* must

be mentioned (cf., Papers I–V). First, we cannot reproduce geologic time although experimental conditions may compensate for this. Second, there need not be a 1:1 correspondence between laboratory and parent body heating temperatures; available data suggest that these are not grossly dissimilar, however. Third, it must be recognized that the composition and response of even the most primitive chondrite to heating may not be identical to those of primordial parent material since post-accretion processes conceivably could have occurred. Fourth, trace element mobility is affected by ambient atmospheric conditions (Ikramuddin et al., 1975; unpublished data) and it is by no means certain what conditions existed in meteoritic parent bodies or, indeed, whether these bodies were open or closed to loss of volatiles. Even with these uncertainties, results from such studies have proven very encouraging. Let us now consider the Murchison data.

Accuracy and precision

The analyses of unheated Murchison powder indicate that three data specifically marked in Table 1 are more than 4σ from the mean of the remaining values and can safely be ignored. Two occurred in the first irradiation; the third involves Cd, an element notorious as a contaminant in quartz irradiation vials (cf., Paper IV). The data generally are in excellent agreement with prior results (Table 1) except for Ga, where the X-ray fluorescence datum of Lovering et al. (1971) is ~20% lower than ours, and Bi, where the data of Santoliquido and Ehmann (1970) are nearly a factor of 2 lower than our results and that of Krähenbühl et al. (1973). We have no reason to suspect the accuracy of our measurements; moreover, for our purposes precision is more important than accuracy and in this regard our results are very satisfactory. Only in the case of Ga is the estimated standard deviation from the mean as high as 8%; all others are 3–5% (Table 1).

Retentivity pattern

Measurements on the two 700°C samples are generally in excellent agreement, the sole exception being Bi (Table 2). The major difference between these runs—the higher final ambient pressure in run 700A (Table 2)—coupled with the dependence of Bi upon atmospheric composition (Ikramuddin et al., 1975) suggests that the Bi value from run 700B is more reliable. The Cd results for both runs at 700°C are so high that they must be ascribed to contamination from the irradiation vials (cf., Paper IV). The trend of the remaining Cd data are such that either the result at 600°C is too high or that at 500°C is to low; we believe the former is more likely because of known Cd contamination problems.

As expected, many elements are vaporized and lost progressively over a broad temperature range during the heating of Murchison homogenized powder under our standardized conditions (Table 2). Temperatures of incipient elemental loss vary widely: Bi, Cd, Tl $\geqslant$ 500°C; In, Te, Zn— $\geqslant$ 600°C; Ag— $\geqslant$ 800°C; Ga, Se $\geqslant$ 900°C; Cs— $\geqslant$ 1000°C. Such variations are not unusual; for example, incipient loss temperature for Allende are: Tl— $\geqslant$ 400°C; Bi— $\geqslant$ 500°C; In, Se— $\geqslant$

Table 1. Comparison of trace element contents in unheated Murchison homogenized powder with prior data.

Sample	Co (ppm)	Ag (ppb)	Ga (ppm)	Se (ppm)	Cs (ppb)	Te (ppm)	Zn (ppm)	Cd (ppb)	Bi (ppb)	Tl (ppb)	In (ppb)
1	—	140	9.41	14.3	120	1.70	187	436	74.2	83.3	50.0[δ]
2	—	132	10.2	13.2	132	1.77	201[δ]	434	76.6	80.1	44.4
3	531	126	8.51	—	126	1.61	169	414	73.5	79.0	40.0
4	555	135	8.17	13.6	132	1.79	174	410	74.5	78.6	42.8
5	558	131	9.62	12.6	133	1.79	175	605[δ]	68.9	80.7	42.4
6	530	122	9.65	12.8	133	1.66	173	440	68.5	86.1	43.4
Mean*	543± 15	131± 6	9.27± 0.77	13.3± 0.7	129± 5	1.72± 0.08	176± 7	427± 14	72.7± 3.3	81.3± 2.9	42.6± 1.6
Lit.	502§f 590 d 650¶b	172 a	7.6§f	11.3 a	135 a	1.53§g 1.8 a	175 a 191§e 224†f	310†b 379 a 442§e	44.3†h 64 a	84 a 87 c	45†b 46 a

[δ]Omitted in computation of the mean since, in each case, the suspect datum lies more than 4σ from the mean of the remaining five analyses.
*Uncertainties are one estimated standard deviation from the mean calculated from the dispersion of our individual measurements.

References to literature data: (a) Krähenbühl et al. (1973); (b) Showalter et al. (1972); (c) Huey and Kohman (1972); (d) Ehmann et al. (1970); (e) Rosman and De Laeter (1974); (f) Lovering et al. (1971); (g) Smith et al. (1976); (h) Santoliquido and Ehmann (1972). Data indicated by symbols are averages of two values (§), three values (†), or six values (¶).

Table 2. Trace element contents in heated Murchison homogenized powder samples.

Heating temperature (°C)	Pressure initial (mtorr)	Pressure final (mtorr)	Co (ppm)	Ag (ppb)*		Ga (ppm)*		Se (ppm)*		Cs (ppb)*		Te (ppm)*		Zn (ppm)*		Cd (ppb)*		Bi (ppb)*		Tl (ppb)*		In (ppb)*	
400	40	50	572	*118*	112	*8.9*	8.5	*13.8*	13.1	*123*	117	*1.69*	1.61	*185*	176	*425*	404	*74.0*	70.4	*84.0*	79.9	*44.0*	41.8
500	15	35	528	*131*	135	*8.9*	9.1	*13.2*	13.6	*129*	133	*1.71*	1.76	*178*	183	*20.1*	20.7	*50.2*	51.7	*62.3*	64.2	*39.4*	40.6
600	35	210	497	*114*	125	*8.8*	9.7	*11.6*	12.7	*95.2*	104	*1.40*	1.53	*142*	155	*115†*	126†	*22.1*	24.2	*14.7*	16.1	*14.8*	16.2
700A	50	450	533	*128*	131	*8.9*	9.1	*12.5*	12.7	*127*	130	*1.26*	1.28	*9.48*	9.68	—	—	*5.51*	5.62	*5.04*	5.14	*10.7*	10.9
700B	30	32	537	*122*	124	*9.0*	9.1	*12.4*	12.6	*127*	129	*1.15*	1.16	*10.1*	10.2	—	—	*8.10*	8.21	*4.90*	4.96	*10.4*	10.5
800	50	125	517	*59.4*	62.5	*8.2*	8.6	*11.5*	12.1	*123*	129	*0.41*	0.43	*1.87*	1.97	*6.08*	6.40	*4.48*	4.71	*3.21*	3.38	*2.95*	3.10
900	40	50	485	*3.70*	4.15	*6.7*	7.5	*10.3*	11.6	*117*	131	*0.089*	0.10	*0.56*	0.63	*5.98*	6.71	*1.99*	2.23	*1.47*	1.65	*1.12*	1.26
1000	25	480	547	*2.28*	2.27	*2.3*	2.2	*10.4*	10.3	*44.1*	43.9	*0.072*	0.072	*0.75*	0.75	*8.45*	8.40	*1.70*	1.69	*1.26*	1.25	*0.92*	0.91

*Concentrations listed in normal type were calculated by normalizing measured concentrations (in italics) to the Co content of unheated samples, thus compensating for sample loss during heating.

†Cadmium in the 600°C run is higher than those in other runs at temperatures ≥500°C and may reflect very slight contamination by shards from the quartz irradiation vial.

600°C; Ga—$\geq$ 900°C (Paper I). It seems noteworthy that Ga is lost significantly at temperatures as low as 900°C only in carbonaceous chondrites, additionally Se seems unusually tightly held in Murchison since it is released significantly at substantially lower temperatures in other chondrites studied (Papers I-III, V).

As noted, elemental loss progresses with temperature; losses from Murchison at 1000°C are generally among the most extreme yet observed: 25% for Se (about the same as in all other primitive meteorites studied—cf., Papers I-III, V), 65–75% for Cs and Ga and 96–99.6% for all other mobile elements (Fig. 1). [The order in which we list elements in such places as Table 1 or Fig. 1 is by depletion
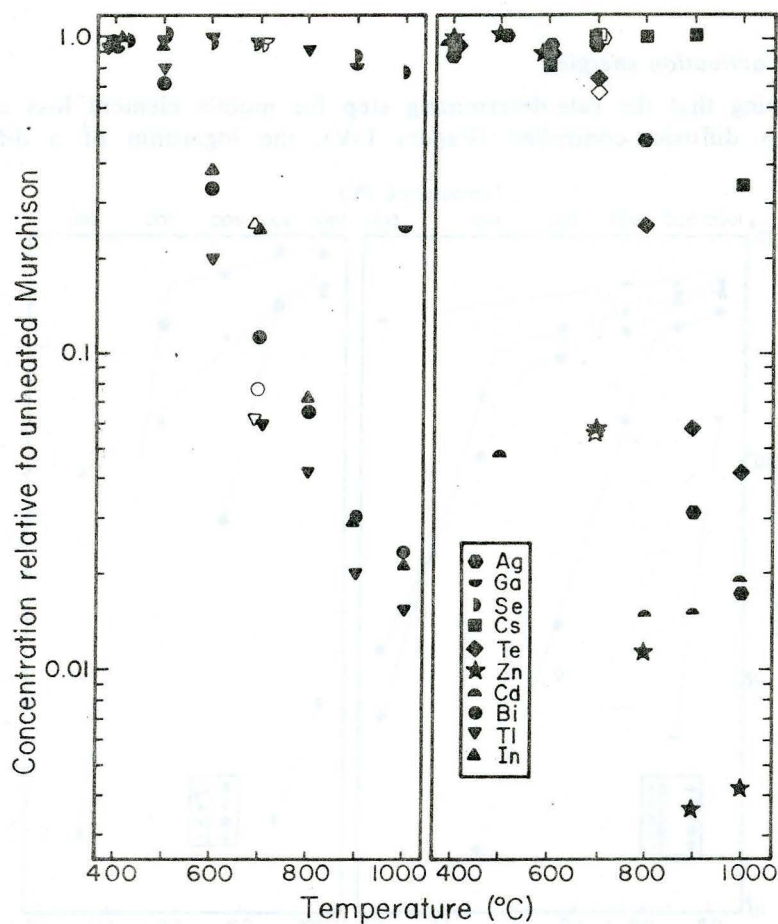

Fig. 1. Retentivities of mobile trace elements (left half—Bi, Ga, In, Se, Tl; right half—Ag, Cd, Cs, Te, Zn) as a function of temperature in homogenized Murchison (C2) powder aliquots heated for 1 week each in a low-pressure environment (initially $\sim 10^{-5}$ atm H$_2$). At 700°C, open symbols refer to run 700A, filled symbols to 700B. Elements are lost progressively over a broad temperature range, the maximum depletions being among the most extreme yet observed (see text).

factor, hence in presumed order of volatility *in the nebula*. As in all similar previous studies of primitive chondrites (Papers II, III, V) Ag mobility in Murchison resembles mobilities of Te, Zn, Cd, Bi, Tl, and In more than those of Ga, Se, or Co (Table 2); hence it should more properly be grouped with the former six elements.]

Losses of mobile elements from Murchison certainly greatly exceed those for Allende—15% for Se, 10% for Ga, 87–93% for Bi, In and Tl (Paper I)—which so far is the most retentive meteorite studied. Thus, from the standpoint of elemental retentivity the two carbonaceous chondrites seem most extreme in behavior, a rather unexpected result.

Apparent activation energies

Assuming that the rate-determining step for mobile element loss can be treated as diffusion-controlled (Papers I–V), the logarithm of a diffusion
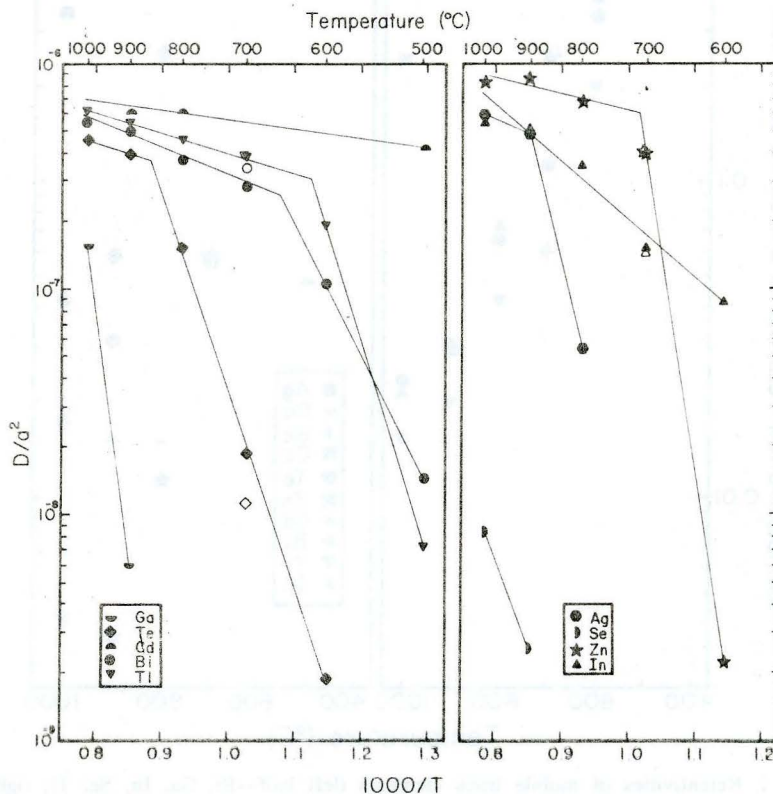

Fig. 2. Arrhenius plots for nine mobile trace elements in Murchison. Open and filled symbols at 700°C refer to runs 700A and 700B, respectively; we plot data only at those temperatures where significant ($>2\sigma$) loss occurred. In 5/9 cases, elements define lines of differing slope—hence differing apparent activation energies—at high and low temperature.

parameter (D/a^2)—calculated from elemental retentivity (cf., Eq. (1) of Paper I)—when plotted versus reciprocal absolute temperature, define a straight line for data obeying the Arrhenius equation (cf., Eq. (3) of Paper I). The slope of such a line then corresponds to the apparent activation energy, Q. (We examine underlying assumptions and other possibilities in a future paper in this series.)

Data for nine mobile elements (excepting Cs which is lost only at 1000°C) are plotted in Fig. 2; lines shown are visual fits. The accord seems generally good except perhaps for the In datum at 1000°C; a line of shallow slope could have been drawn between results at 900° and 1000°C. (We have conservatively chosen not to do this; experiments at temperatures >1000°C will indicate whether this choice was wise.) We list corresponding Q values for all elements in Table 3.

Results for a majority of elements—Ag, Bi, Te, Tl, and Zn—are each clearly consistent with differing Q values at high and low temperatures, the latter being greater than the former (Table 3). These trends are typical of those observed for all other primitive chondrites studied but Krymka and can be interpreted as indicating loss of Cd, Ga, Se and, probably, In from a single host site and/or by a single process and loss of Ag, Bi, Te, Tl, and Zn from two sites and/or two different processes, each functioning in a different temperature region (Papers I–III, V). Naturally, a given type of site could host two or more elements.

Numerical values for Q are generally similar to those observed previously (cf., Papers I–V). Results for Ga, In, Se and, at low temperatures, for Ag, Bi, Te, Tl, and Zn are consistent with those of solid-state volume diffusion while for the latter five elements at high temperatures and Cd, the Q values indicate a less

Table 3. Apparent activation energies (Q) for Ag, Bi, Cd, Ga, In, Se, Te, Tl, and Zn in Murchison homogenized powder.

Element	Allende* (C3)		Murchison (C2)	
	Temp. range (°C)	Q (kcal/mole)	Temp. range (°C)	Q (kcal/mole)
Ag			800–900	55
			900–1000	5.8
Ga			900–1000	97
Se	600–900	4.4	900–1000	35
Te			600–800	41
			900–1000	4.3
Zn			600–700	88
			800–1000	3.3
Cd			500–1000	2
Bi	400–600	25	500–600	27
	600–1000	2.2	700–1000	5.4
Tl	400–600	29	500–600	44
	600–1000	2.2	700–1000	4.1
In	600–1000	22	600–1000	12

*Data from Paper I.

energetic process, perhaps desorption (Table 3). Naturally, these conclusions are model-dependent and will be re-examined in a future paper in this series.

Values of Q for Bi, In, and Tl in Allende and Murchison are quite comparable; but results for Se clearly differ (Table 3). It should be noted however that Allende Se data are consistent with a line of steeper slope from 900° to 1000°C (Paper I). Thus the major difference in behavior of Se in the two carbonaceous chondrites may be its loose bonding from 600° to 900°C in Allende; additional experiments above 1000°C now in progress should shed further light on this.

Correlation profiles

Patterns of statistically-significant (>95% confidence level) interelement relationships—all direct correlations—for heated Murchison and Allende are
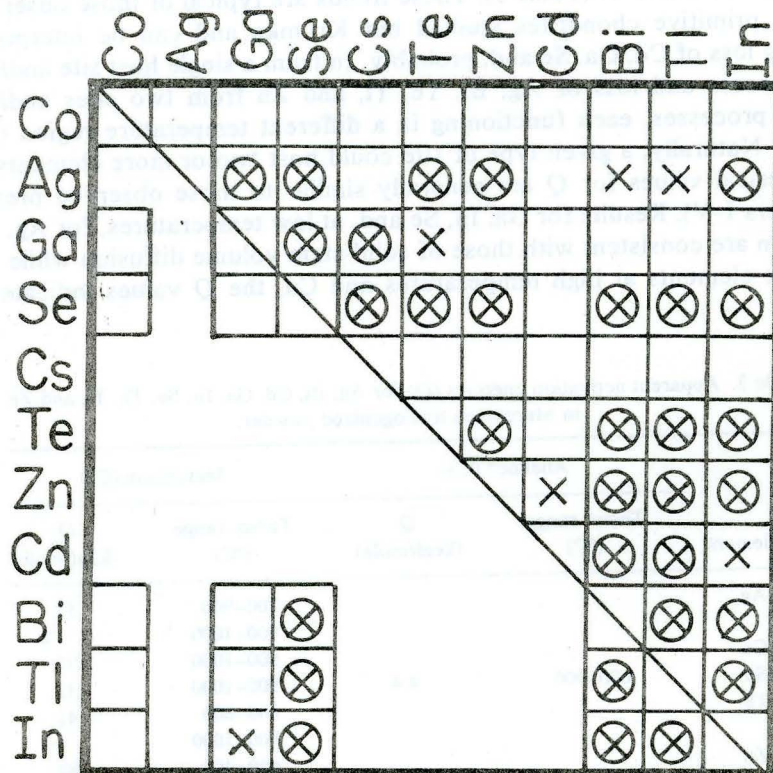

Fig. 3. Patterns of statistically-significant (>95%) interelement relationships in heated Murchison (portion right of diagonal) and Allende (portion left of diagonal) homogenized powder. Crosses and circles designate linear : linear and logarithmic : logarithmic correlations, respectively; elements are ordered left to right and top to bottom by greater depletion in (equilibrated) ordinary chondrites. Data for Allende (Paper I) are limited to six elements; we will profile the blank area after obtaining results for additional elements.

shown in separate halves of Fig. 3. The profile for Murchison is generally similar to those obtained previously (Papers II–V) with some noteworthy features. For the first time we succeeded in limiting the Cd contamination problem in heated primitive chondrite powder; the data indicate a substantial similarity in the behavior of this element, Bi, In, and Tl in *at least* this C2 chondrite. More importantly, the 30 related interelement pairs include substantially fewer Cs correlations and rather more Ga correlations than usual. This, we attribute primarily to the order of temperature of incipient loss; Cs and Ga are mobile only at relatively high temperatures (Tables 1, 2) and correlate only with elements of moderate or low mobility—themselves, Ag, and Se (Fig. 3). Selenium is somewhat puzzling; it is not very mobile yet, like Ag, it correlates with elements like Bi, In, Tl, and Zn which are lost at 500–600°C, reaching losses of 98–99.6% at 1000°C. We note that the 800°C Se datum is almost $1.6\,\sigma$ lower than the unheated mean and may indicate some loss even at this temperature.

Results for Allende are unfortunately sparse (Fig. 3) since our feasibility study for this series of studies involved determination of but six elements in this chondrite (Paper I). At present we can say only that in both Allende and Murchison, Bi, In, Se, and Tl mutually correlate in both linear and exponential fashions but there are differences in the behavior of Ga with In and Se (Fig. 3). We are now initiating a study of additional elements in Allende which will permit a more complete comparison.

Factor analysis

This statistical technique serves to cluster elements into a few factors such that elements loaded by a given factor are mutually highly correlated; in some cases such a factor can be identified with a specific physical process (Shaw and Harmon, 1975; cf., Binz *et al.* (1974) and Paper II). For every other heated primitive chondrite studied—Abee (Paper II), Krymka (Paper III), Tieschitz (Paper V), and, as will be seen, Allende—results of factor analysis indicate elemental variation to reflect three factors. We were astonished when only two factors emerged for Murchison irrespective of choices made in compiling the input data matrix. The lack of reliable Cd data at 600° and 700°C meant that we either had to omit this element entirely or all elements at these two temperatures. The results (Table 4) are those resulting from the latter choice; we note below specific differences when the former option is chosen.

Using either elemental abundances (i.e., atoms/10^6 Si atoms) or the logarithms of these, nine elements are loaded solely or partly by a single factor and the remaining two elements by the second factor (Table 4). Standard deviations for the linear case exceed 50% for the usual elements—Ag, Te, Zn, Bi, Tl, In (cf. Paper V), and, now, Cd—suggesting that logarithms of abundances might be preferable as input data. As can be seen (Table 4) this makes little difference, only Te being affected by the additional influence of factor 2. (Deletion of all Cd data and incorporation of 600° and 700°C results for all other elements produce little change. In the linear case, Te reflects both factors 1 and

Table 4. Rotated factor loadings (>0.3) or coefficients for elemental abundances and the logarithms of these in unheated and heated Murchison homogenized powder.

	Factors			
	Elemental abundance		Logarithms of abundance	
Element	1	2	1	2
Co	−0.85	0.43	−0.88	0.41
Ag	−0.80	−0.54	−0.70	−0.64
Ga	−0.30	−0.93		−0.96
Se	−0.65	−0.75	−0.63	−0.77
Cs		−0.98		−0.98
Te	−0.88	−0.45	−0.81	−0.57
Zn	−0.90	−0.37	−0.90	−0.40
Cd	−0.84		−0.89	
Bi	−0.94	−0.32	−0.88	−0.46
Tl	−0.94	−0.33	−0.89	−0.45
In	−0.91	−0.38	−0.87	−0.49

2. In the exponential case, Co is similarly loaded by both factors while Te is loaded only by factor 1.) Two eigen-values exceed 0.5; in the linear case these account for 94% of the variance with factors 1 and 2 contributing 75 and 19%, respectively, while in the exponential case the corresponding figures are 96%, 77%, and 19%. In either case, the communality of Cd is unusually low (0.71 in the linear and 0.81 in the exponential case) possibly indicating it is affected by a specific factor; all other communalities range from 0.91–0.99.

Evidence for two factors in the Murchison case may be contrasted with results for Allende where three factors are evident (Table 5). Irrespective of whether the linear or exponential case is considered Se, Bi, Tl, and In are loaded by factor 1, In and Ga by factor 2, and Co by factor 3. (In the linear case, standard deviations exceed 50% for Bi, Tl, and In and 98% of the total variance

Table 5. Rotated factor loadings (>0.3) or coefficients for elemental abundances and their logarithms in unheated and heated Allende homogenized powder.

	Factors					
	Elemental abundance			Logarithms of abundance		
Element	1	2	3	1	2	3
Co			0.96			0.95
Ga		−0.98			−0.97	
Se	−0.81	−0.40	0.41	−0.85	−0.38	0.36
Bi	−0.94			−0.93		
Tl	−0.97			−0.94		
In	−0.63	−0.71		−0.58	−0.79	

is accounted for with the three factors contributing 71, 15, and 12%, respectively. In the exponential case the corresponding percentages are 99%, 72%, 17%, and 10%. Communalities range from 0.95–0.999.)

Factor analysis results for mobile elements in Murchison seem to parallel temperatures of incipient release. Those elements exhibiting some loss at 500° or 600°C—Bi, Cd, In, Te, Tl, and Zn—are affected solely by factor 1; highly-mobile Ag which is lost at 800°C and above is affected more by factor 1 than by factor 2; the reverse is true for relatively invariant Se which, as noted, *may be* lost somewhat even at 800°C; Ga and Cs—which though lost only at 900° or 1000°C—are rather mobile and are affected solely by factor 2.

However, Co in Murchison does not fit this picture since it is loaded by factor 1 but is non-mobile (Papers I, II, IV). Indeed here and in Papers III and V Co is non-mobile by definition since it has been used to correct for effervescence of Krymka, Murchison, and Tieschitz during heating. One might argue that loading of Co in Murchison by factor 1 is spurious, merely reflecting material transport at temperatures ⩾600°C. However, Krymka and Tieschitz experienced similar decrepitation and in these cases Co is not loaded by the same factor that affects highly-mobile elements with low temperatures of incipient loss.

Thus, with due regard to the limited number of cases considered for each chondrite, results of factor analysis of Murchison differ from those obtained from any other primitive meteorite studied, including Allende.

Two-element correlation diagrams

We limit consideration of trends involving specific pairs of elements to those of Bi, In, and Tl (Fig. 4) because these are the only highly-mobile elements determined both in heated Allende and Murchison and because of their special importance as postulated cosmothermometers (cf., Anders, 1964; Anders *et al.*, 1976). Figure 4 represents the retentivities of pairs of these elements (relative to the respective unheated material) both in Allende (Paper I) and Murchison. Because of the greater retentivity of Allende, trends for Murchison are of broader scope. In all three cases, trends of the Murchison data suggest 1:1 variations, albeit with some curvature; the Bi/Tl trend for Allende is similar and, in fact, superimposable on that for Murchison (Fig. 4a). Clearly, however, In/Bi and In/Tl trends for the two chondrites differ (Figs. 4b, 4c), indicating differences in In host sites at least for Allende and Murchison.

If the volatile element host in carbonaceous chondrites is to be identified with some common phase, these trends point to differences in the genesis of this phase. In the two-component model, for example, where the host phase is postulated to be the matrix (Anders, 1964; cf., Anders *et al.*, 1976), one might postulate sintering of Allende parent material during a mild metamorphic episode subsequent to condensation and accretion. Such metamorphism could not occur under open conditions without loss of volatiles and thus, if metamorphism took place, it did so in a closed system.
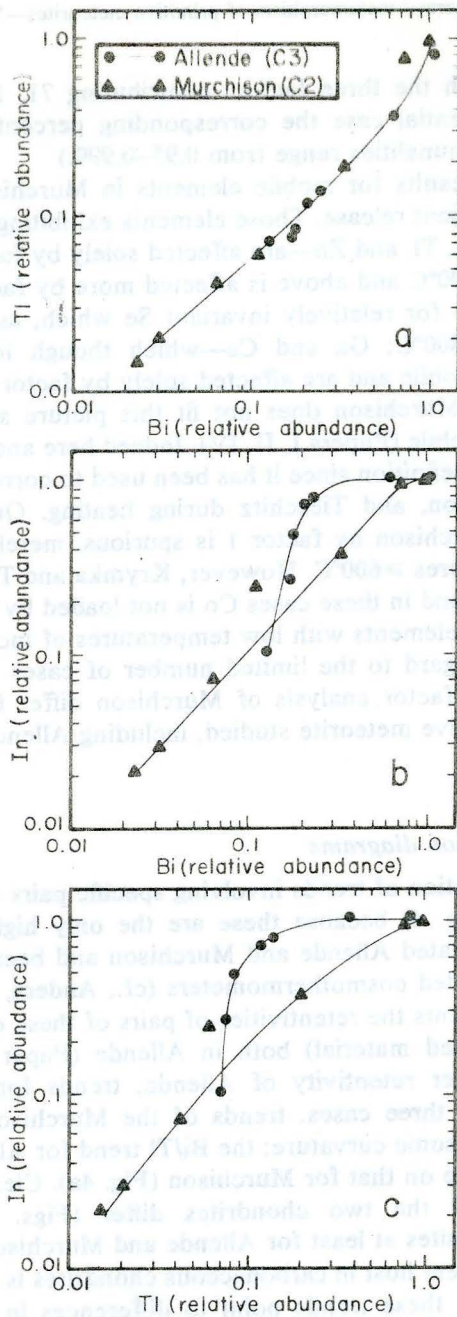
Fig. 4. Comparison of retentivities (relative to the respective unheated material) in heated homogenized powder samples of the Allende C3 chondrite (Paper I) and Murchison (C2) for highly-mobile element-pairs: (a) Tl/Bi; (b) In/Bi; (c) In/Tl. These elements clearly are more mobile in Murchison than in Allende and the host sites of In and Bi and Tl clearly differ in the two carbonaceous chondrites suggesting some variance in their genesis.

SUMMARY AND CONCLUSIONS

As in our other studies we found that ten trace elements are volatilized and lost progressively during open-system week-long heating of Murchison powder in a low-pressure environment (initially $\sim 10^{-5}$ atm H_2) at temperatures of 400–1000°C. In the extreme, losses from Murchison are at least as great as any yet observed, rivalling or exceeding those from Krymka—the least retentive meteorite studied previously. Of the nine elements lost over $\geqslant 100$°C temperature span, four—Cd, Ga, In, and Se—are lost from a single site or by a single process, and five—Ag, Bi, Te, Tl, and Zn—are each lost from two sites and/or by two processes at high and low temperature. Magnitudes of apparent activation energies suggest that loss of Ga, In, and Se and, at low temperatures, the latter five elements is controlled by diffusion: loss of Cd and Ag, Bi, Te, Tl, and Zn at high temperatures seemingly involves a less-energetic process such as desorption. Factor analysis indicates that two factors explain the variation of 11 elements in Murchison; three factors emerged from analysis of each of the five geologic samples studied previously even when we considered as few as six elements.

Where comparison of data for Allende and Murchison is possible, differences between these carbonaceous chondrites is no greater but no less than those of any two primitive meteorites heated under our standardized conditions. Considering that Allende and Murchison are members of the same chondritic group, differences to the extent observed in elemental retentivities, correlation profiles, factor analysis results in two-element correlation diagrams are rather surprising even in the light of the known mineralogic and chemical differences between C2 and C3 chondrites. These properties clearly indicate genetic variance; our results are consistent with such differences, including perhaps, mild closed system metamorphism of Allende parent material. To what extent these genetic differences extend to other carbonaceous chondrites will be the subject of future studies.

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