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Geochemistry of the ungrouped carbonaceous chondrite Tagish Lake, the anomalous CM chondrite Bells, and comparison with CI and CM chondrites

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Abstract–I have determined the composition *via* instrumental neutron activation analysis of a bulk pristine sample of the Tagish Lake carbonaceous chondrite fall, along with bulk samples of the CI chondrite Orgueil and of several CM chondrites. Tagish Lake has a mean of refractory lithophile element/Cr ratios like those of CM chondrites, and distinctly higher than the CI chondrite mean. Tagish Lake exhibits abundances of the moderately volatile lithophile elements Na and K that are slightly higher than those of mean CM chondrites. Refractory through moderately volatile siderophile element abundances in Tagish Lake are like those of CM chondrites. Tagish Lake is distinct from CM chondrites in abundances of the most volatile elements. Mean CI-normalized Se/Co, Zn/Co and Cs/Co for Tagish Lake are 0.68 ± 0.01, 0.71 ± 0.07 and 0.76 ± 0.02, while for all available CM chondrite determinations, these ratios lie between 0.31 and 0.61, between 0.32 and 0.58, and between 0.39 and 0.74, respectively. Considering petrography, and oxygen isotopic and elemental compositions, Tagish Lake is an ungrouped member of the carbonaceous chondrite clan. The overall abundance pattern is similar to those of CM chondrites, indicating that Tagish Lake and CMs experienced very similar nebular fractionations.

Bells is a CM chondrite with unusual petrologic characteristics. Bells has a mean CI-normalized refractory lithophile element/Cr ratio of 0.96, lower than for any other CM chondrite, but shows CI-normalized moderately volatile lithophile element/Cr ratios within the ranges of other CM chondrites, except for Na which is low. Iridium, Co, Ni and Fe abundances are like those of CM chondrites, but the moderately volatile siderophile elements, Au, As and Sb, have abundances below the ranges for CM chondrites. Abundances of the moderately volatile elements Se and Zn of Bells are within the CM ranges. Bells is best classified as an anomalous CM chondrite.

INTRODUCTION

Chondritic meteorites are the most primitive solar system objects available for detailed laboratory studies. As such, they allow cosmochemists to probe the formative processes that converted the solar nebula into the nascent solar system. Because of this, discovery of new chondrite types offers the possibility of revealing new, fundamental information on the formation of the solar system.

The Tagish Lake meteorite fell in British Columbia, Canada, in January 2000, and several pieces were rapidly recovered from the surface of the frozen lake and preserved frozen (Brown *et al.*, 2000). Initial petrographic and compositional data, and determination of its orbit, indicated that Tagish Lake was similar to, but distinct from, CI and CM chondrites, and was possibly linked with the low-albedo C, D and P asteroids that occupy the outer reaches of the asteroid belt (Brown *et al.*, 2000). Recently, spectrographic study of Tagish Lake has strengthened the possibility that it represents the first sample of a D asteroid (Hiroi *et al.*, 2001).

Here I report the results of my compositional study of a bulk sample of so-called pristine Tagish Lake, and comparative studies of Orgueil and several CM chondrites, including the anomalous CM chondrite, Bells.

SAMPLES AND ANALYTICAL METHODS

The sample of Tagish Lake was from a complete stone obtained by M. E. Zolensky from the finder, Mr. James Brook. The specimen was collected and kept frozen until sampled for compositional studies. Approximately 1 g of interior material was finely ground and homogenized, and a split of ~50 mg was taken for instrumental neutron activation analysis (INAA). Friedrich *et al.* (2002) analyzed a split of the same homogenized powder. Samples of Orgueil and several CM chondrites were obtained from the research collection of M. E. Zolensky. For Orgueil, interior chips massing ~242 mg were gently crushed and homogenized, and a split of ~40 mg was taken for analysis. Because the CM chondrite sample sizes were limited, interior chips massing between 23 and 30 mg were taken and crushed for analysis. An exception is Cold Bokkeveld. This was obtained from R. Hutchison in the form of a large thin slab with a brecciated structure showing distinctly darker and lighter clasts. The slab was broken to obtain material representative of the whole rock, and the dark and light lithologies. Masses of 108 to 241 mg for the three samples were ground and homogenized, and splits of 62 to 69 mg taken for INAA.

The samples were analyzed by INAA in three separate irradiations using standard Johnson Space Center (JSC) procedures (see Mittlefehldt and Lindstrom, 1993, and references therein). CI and CM chondrites can evolve gas caused by heating in the reactor during irradiation, resulting in rupture of the tubes, so these samples were heated in air to 400 °C for a few hours prior to sealing the silica glass irradiation tubes. Matza and Lipschutz (1977) have done heating experiments on Murchison to test for loss of volatile elements. They found that heating at 400 °C for 1 week under vacuum did not result in loss of even the most volatile elements they study, including four elements, Co, Zn, Se and Cs, that are determined in my analyses. Ngo and Lipschutz (1980) did similar heating experiments on Allende, and showed that there is no loss of As or Sb at 400 °C. Hence, I believe that my analyses were not compromised by the heat treatment. However, Br may be more volatile than any of the elements determined by Matza and Lipschutz (1977) and Ngo and Lipschutz (1980), and will have to be interpreted cautiously.

Subsequent to our normal INAA, I decided to obtain data for several elements not normally determined *via* our procedure. The original silica glass irradiation tubes were broken open, and the samples transferred to polyethylene vials for pneumatic-tube irradiation and INAA (pt-INAA) for Na, Mg, Al, Ca, V and Mn. The more volatile-rich samples, Tagish Lake, Orgueil and Bells, could not be quantitatively transferred from the silica vials, and new samples were prepared. Unfortunately, I had forgotten that there was a store of homogenized powder for Orgueil, and I took 58 mg of additional interior chips for the pt-INAA sample. The pt-INAA was performed by M. Glascock of the University of Missouri Research Reactor Center. Splits of USNM homogenized Allende powder were analyzed in all irradiations.

RESULTS

The results of my analyses of Tagish Lake, Orgueil, the CM chondrites and Allende are presented in Table 1. Included in this table are comparative literature data for Allende (Kallemeyn and Wasson, 1981) or a mean for CV chondrites (Wasson and Kallemeyn, 1988). One potential issue is sample representativeness for the CM chondrites, as for most of them, only small chips were available. M. Lipschutz has done a study of compositional homogeneity of Murchison by analyzing sets of four samples each in three mass ranges: ~5, ~32 and ~200 mg (Zolensky *et al.*, 1992). Five of the elements determined by these authors are also determined here: Co, Zn, Se, Sb and Au. They found that the standard deviation of the mean for the 32 mg samples for all of these elements except Sb was the same as for the 200 mg samples. They concluded that Murchison, and by inference other CM chondrites, are relatively homogeneous for most elements on the 32 mg sample size.

A second way to evaluate homogeneity is to compare my data with those of Kallemeyn and Wasson (1981), who used sample masses about an order of magnitude larger than mine. First I will compare my data on Orgueil with those of Kallemeyn and Wasson (1981) to evaluate inter-laboratory biases, as the sample sizes are comparable (assuming the split I analyzed is representative of the prepared powder). For the elements determined in common, my analyses fall within 1σ analytical uncertainty of the range of four replicates analyzed by Kallemeyn and Wasson (1981) except for Na, Ca, Cr, Co, Br and Sm. Bromine is typically variable in carbonaceous chondrites (*e.g.*, Kallemeyn and Wasson, 1981) so the disagreement between my datum (~17% low) and those of Kallemeyn and Wasson (1981) is not unexpected. However, the heat treatment may possibly have degassed some of the Br in my sample. My Sm datum is ~11% high relative to Kallemeyn and Wasson (1981), but within uncertainty of many estimates of mean CI chondrite (see Lodders and Fegley, 1998, Table 16.9). My Co datum is ~9% low, and outside the range of estimated CI chondrite means. However, the Ni content is at the low end of the range reported by Kallemeyn and Wasson (1981) and thus my sample may not have adequately sampled the siderophile element component. My Co data for Allende agree with those of Kallemeyn and Wasson (1981), indicating that there is not a problem with the analytical technique. My Cr datum is ~6% high, and outside the range of estimates of CI means. However, again my data on Allende lie within the range (albeit at the high end) of that of Kallemeyn and Wasson (1981), and my analyses for several international standard rocks agree with recommended values. My Na datum is ~13% high, and outside the range of estimates for CI chondrite means. Here again, my analyses of Allende agree with those of Kallemeyn and Wasson (1981), and my analyses of international standard rocks agree with recommended values. Finally, my Ca datum is ~18% low compared to Kallemeyn and Wasson (1981) and below the ranges of CI chondrite means. My Ca datum is a mean of analyses of two separate fractions taken from a single stone, and they agree within error. The analyses, one by normal INAA the other by pt-INAA, utilize different nuclides, so it is unlikely that analytical

TABLE 1. Major, minor and trace element compositions of Tagish Lake, Orgueil, CM chondrites and Allende determined by INAA.

Source†		Tagish Lake* finder	Orgueil* FMNH	Bells* ASU 122.68	Cochabama NMW	Cold Bokkeveld BM(NH) 1727			Mighei FMNH me 1456	Nogoya ASU 556.2	Pollen BM(NH) 1964.496	Allende USNM 3529 split 9, pos. 25				Allende Literature
Split						dark	light	wr								
Mass	(mg)	55.71	39.57	23.74	29.64	69.09	62.21	66.12	27.68	26.45	22.80	35.86	36.05	29.11	52.25	–
Na‡	mg/g	4.34	5.22	*2.58*§	4.40	5.53	4.26	3.99	4.87	5.45	2.87	3.36	3.38	3.45	3.40	–
Na	mg/g	5.03	1.49#	*2.23*§	4.62	–	–	–	5.09	5.95	3.04	3.33	3.30	–	3.18	–
mean	mg/g	4.47	–	*2.52*§	4.44	–	–	–	4.90	5.52	2.90	3.36	3.37	–	3.36	3.23–3.42
Mg	mg/g	91.0	97.1	114	110	–	–	–	115	116	110	128	130	–	120	144–152
Al	mg/g	9.64	8.96	9.21	11.2	–	–	–	10.9	11.6	21.0	27.1	28.0	–	10.1	17.1–17.8
K	µg/g	610	510	*320*§	370	–	320	330	420	550	460	310	320	–	–	283–305
Ca‡	mg/g	8.5	8.3	15.0	12.9	–	14.3	13.6	15.0	15.0	12.9	16.4	20.0	20.7	15.7	–
Ca	mg/g	9.8	8.0	11.1	12.6	–	–	–	13.1	14.3	14.1	17.8	18.0	–	10.3	–
mean	mg/g	9.7	8.0	11.3	12.6	–	–	–	13.1	14.4	14.0	17.6	18.1	–	10.5	17.8–20.1
Sc	µg/g	8.28	6.04	6.43	7.29	7.18	8.39	8.64	7.15	8.12	7.91	11.1	11.1	11.4	11.1	11.1–11.3
V	µg/g	59.2	50.8	58.8	59.9	–	–	–	64.8	74.6	74.3	91.2	88.2	–	60.2	97–101
Cr	mg/g	2.80	2.79	3.04	3.15	2.89	3.21	3.10	3.05	2.98	3.08	3.72	3.74	3.71	3.70	3.60–3.71
Mn	mg/g	1.38	1.77	1.59	1.74	–	–	–	1.69	1.72	1.71	1.30	1.32	–	1.39	1.40–1.52
Fe	mg/g	184	186	208	213	186	201	206	212	201	204	236	235	237	236	235–239
Co	µg/g	515	470	592	610	539	574	585	590	569	568	665	661	673	672	655–669
Ni	mg/g	11.7	10.0	12.8	12.9	12.1	12.6	12.8	12.8	12.6	12.3	14.2	14.1	14.7	15.0	13.0–13.7
Zn	µg/g	209	307	202	206	–	–	–	213	183	198	120	124	–	124	110–125
As	µg/g	1.54	1.89	1.36	1.82	1.57	1.77	1.83	1.72	1.80	1.94	1.70	1.56	1.90	1.53	1.51–1.64
Se	µg/g	14.6	21.3	14.2	14.0	13.8	12.7	13.5	14.2	13.0	13.2	9.5	8.5	8.7	8.8	8.1–8.3
Br	µg/g	*2.24*$	*3.08*$	*1.04*§,$	*4.01*$	*3.57*$	*2.43*$	*1.83*$	*2.32*$	*55.5*@	*1.86*$	1.43	1.46	1.76	1.63	1.5–1.6
Sb	ng/g	88	118	76	113	81	104	95	87	129	127	78	71	107	80	77–89
Cs	ng/g	150	200	–	–	–	–	–	–	–	–	–	–	–	–	–
La	ng/g	286	260	267	315	274	327	286	326	314	322	508	502	511	532	478–497
Sm	ng/g	177	153	167	197	181	216	211	189	203	219	324	329	339	327	288–309
Eu	ng/g	75	58	65	84	78	80	81	77	78	76	108	127	125	123	108–120
Tb	ng/g	52	–	51	–	–	–	–	44	50	48	–	–	140	78	65
Yb	ng/g	204	180	170	210	201	258	225	210	210	210	340	280	350	323	305–337
Lu	ng/g	33	34	29	33	30	35	37	40	51	31	42	61	52	47	44–49
Hf	ng/g	183	150	140	180	140	120	156	170	270	170	180	190	200	170	194
Ir	ng/g	644	470	574	714	505	489	584	641	757	590	781	941	779	780	762–805
Au	ng/g	158	140	141	198	154	175	173	202	171	198	149	161	165	160	142–149

*A second sample of these meteorites was taken for pneumatic tube irradiation: Tagish Lake = 58 mg; Orgueil = 54 mg; Bells = 54 mg.

†Sample sources: Arizona State University (ASU); British Museum (Natural History) (BM(NH)); finder, Mr. J. Brooks; Field Museum of Natural History (FMNH); Naturhistorisches Museum, Wien (NMW); US National Museum (USNM); literature – range of Allende data from Kallemeyn and Wasson (1981), except Tb and Hf, which are mean CV chondrites from Wasson and Kallemeyn (1988).

‡Na and Ca were determined by both types of INAA. The first value listed determined by normal JSC INAA, the second value by pneumatic tube INAA, mean is a weighted mean.

§Some samples of Bells were recovered after rains, and these have low Na, K and Br contents (Kallemeyn, 1995). I do not know whether the sample I analyzed was collected before or after the rains. The Na, K and Br data for Bells should be treated with caution.

#The Na content of the pneumatic tube irradiation sample is anomalously low, and is not used.

$All samples except Allende were heated to 400 °C before sealing silica tubes. Bromine may have been lost.

@The Br content of Nogoya is more than 10× higher than any other CM value. Contamination is suspected, and the datum is discarded.

Typical analytical uncertainties: <3% – Na, Mg, Al, Sc, V, Cr, Mn, Fe, Co, Ni; 3–5% – Ca (pt-INAA), Sm; 5–10% – Se, La, Eu, Ir, Au; 10–15% – Zn, As, Br; 10–20% – Yb, Lu; 15–25% – Ca, Sb, Cs, Hf; 20–35% – K, Tb.

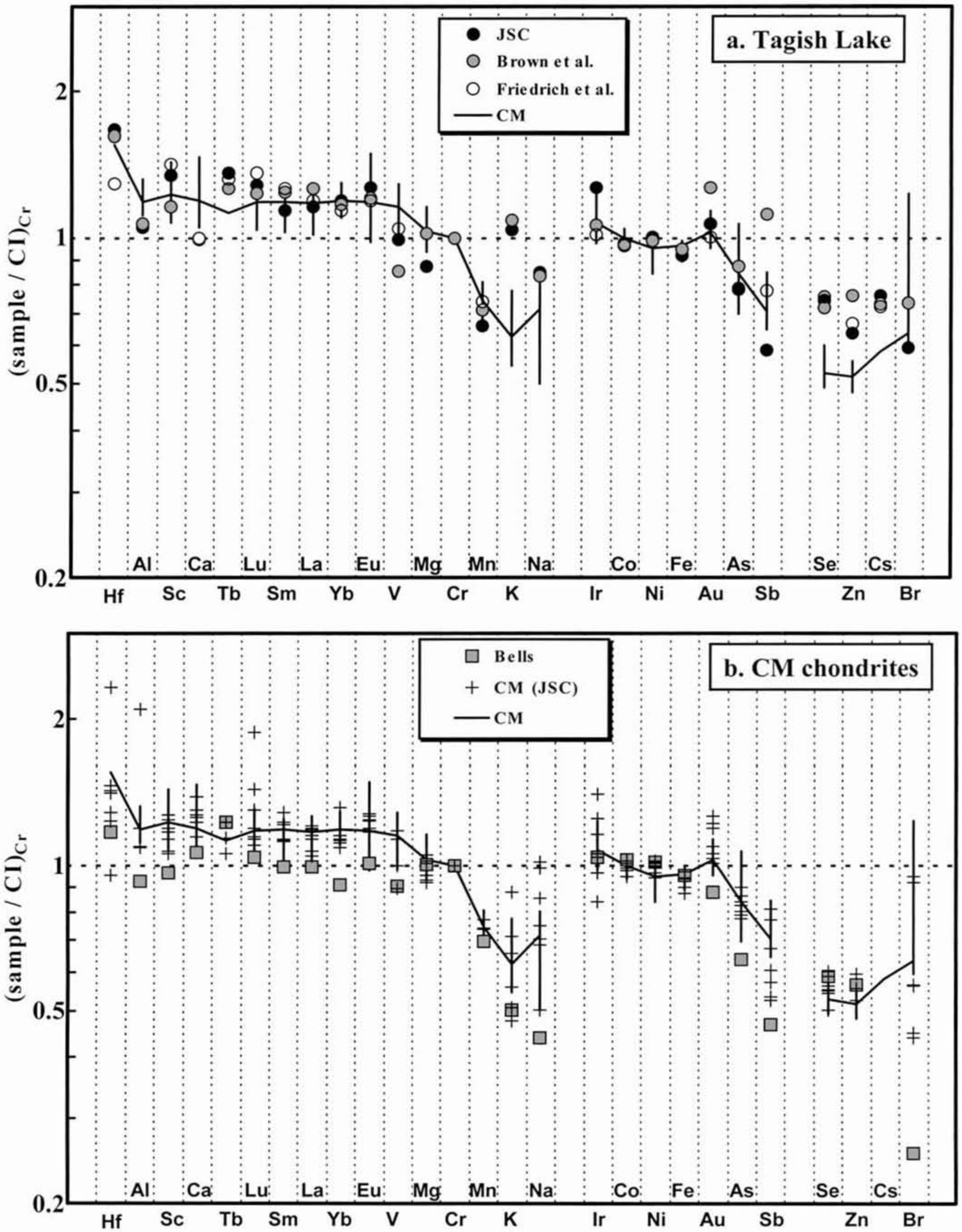
problems cause the data to be low. Gounelle and Zolensky (2001) have documented mobilization of $CaSO_4$ in samples of Orgueil during terrestrial residence. My Ca data for CM chondrites are not systematically low compared to literature data. Plausibly, the low Ca content of the Orgueil samples I analyzed reflect loss of $CaSO_4$ from the specimen I sampled. In summary, with the possible exceptions of Na and Br (see below), my analyses do not show systematic inter-laboratory biases with those of UCLA.

Returning now to CM chondrites, there are three meteorites, Cochabama, Mighei and Nogoya, for which I did analyses on ~25 mg chips that can be compared to the analyses of much larger samples by Kallemeyn and Wasson (1981), and I have analyzed splits of three large samples of Cold Bokkeveld that can be compared with the data of the latter authors. In general, agreement between my data and those of Kallemeyn and Wasson (1981) is good, and does not indicate that sample heterogeneity is a problem. One exception to this is the Mighei sample, for which my data for Fe, Co and Ni are all slightly above the ranges of three analyses by Kallemeyn and Wasson (1981). This most plausibly reflects slight enhancement in the siderophile element component in the sample I analyzed. Note that my Br data (excluding Nogoya which, with 55.5 μg/g Br, must have been contaminated) are lower than those of Kallemeyn and Wasson (1981) by 9–59%, possibly as a result of loss during the heat treatment. However, Kallemeyn and Wasson (1981) show that Br is anomalously high in CM chondrites compared to nebular volatility trends. Hence it is unclear whether my analyses are low, theirs are high, or Br is just too variable for useful comparison. Another exception is Na; my data are systematically high compared to those of Kallemeyn and Wasson (1981), and compared to estimates of CM chondrite means (see Lodders and Fegley, 1998, Table 16.10; Wasson and Kallemeyn, 1988). This, plus comparison of the data on Orgueil, suggest that my Na data may be systematically high. There are four possible ways for INAA data to be systematically high: (i) incorrect standardization, (ii) uncorrected interference, (iii) improper background calculation, and (iv) contamination. My Na analyses of Allende and international standard rocks agree well with literature data, indicating that there is no problem with standardization. Interference and background problems can be ruled out for a variety of reasons, not the least of which is that a spot-check manual verification of the data reduction was done and did not uncover any problems. Contamination is unlikely because I routinely analyze samples with much lower Na (diogenite orthopyroxenes; pallasite olivines) without problem. At present, the Na difference is an unsolved paradox.

The data are shown graphically in Fig. 1, plots of CI-normalized element/Cr ratios ordered by cosmochemical group and decreasing calculated condensation temperature. Typically, chondrite data are normalized to Si or Mg, but the JSC standard analytical technique does not include either element. Although I obtained Mg data on most of the samples, I will use Cr as the normalizing element as I have done previously (*e.g.*, Mittlefehldt and Lindstrom, 2001). Chromium has similar nebular volatility to Mg (see Lodders and Fegley, 1998, Table 2.3), so fractionation caused by segregation of condensates during cooling of the nebula should be a minimum. This is borne out by analyses (*e.g.*, Kallemeyn and Wasson, 1981; Wolf and Palme, 2001). Chromium is calculated to condense as a siderophile element (Lodders and Fegley, 1998, Table 2.3), leaving open the possibility of lithophile-siderophile element fractionation. However, ordinary chondrites, which show evidence for metal-silicate fractionation (Wasson, 1972) have decreasing CI-normalized Ni/Mg of 1.03–0.60 in the sequence H–L–LL, while Cr/Mg varies only from 0.97 to 0.91 (Wasson and Kallemeyn, 1988), plausibly within the uncertainties of the means. Among carbonaceous chondrite groups, CI-normalized mean Mg/Cr ratios are CM, 1.05; CO, 1.12; CR, 1.01; CV, 1.10 (Kallemeyn *et al.*, 1994; Wasson and Kallemeyn, 1988). Hence, to first order, Cr-normalized abundances are directly comparable to the more commonly used Mg-normalized abundances. Chromium is as precisely determined by INAA as is Mg. Thus, the analytical uncertainty of Cr does not increase the uncertainties of element abundance ratios over those when Mg is used. The only drawback of using Cr is that it is concentrated in the minor phase, spinel. Hence, sample heterogeneity problems can potentially shift all element/Cr ratios for a given sample. However, this would be easily identified from abundance patterns in Fig. 1—no such problems are present.

Figure 1a shows my results for Tagish Lake compared to those of Brown *et al.* (2000) and Friedrich *et al.* (2002), and to mean CM chondrites (Wasson and Kallemeyn, 1988). Friedrich *et al.* (2002) did not determine Cr or Mg in their sample. However, my analysis and that of Brown *et al.* (2000) have virtually identical Co/Cr ratios, so for the purpose of this plot, I calculated a Cr content for the Friedrich *et al.* (2002) data based on their Co datum. Also shown in Fig. 1a are the ranges in element/Cr ratios for CM chondrites from Kallemeyn and Wasson (1981). Tagish Lake matches well CM chondrite ranges and means for refractory and moderately volatile lithophile and siderophile elements, with the exceptions of K and Na. My K datum has a large uncertainty, and the K/Cr ratio thus overlaps the CM chondrite range. However, the K/Cr ratio of Brown *et al.* (2000) is resolvably higher than the CM range. The Na/Cr ratios of my analysis and that of Brown *et al.* (2000) are resolvably higher than the CM range of Kallemeyn and Wasson (1981). The Na/Cr ratios of my analyses of CM chondrites overlap that of Tagish Lake. Among the most volatile elements I determined, Tagish Lake has

FIG. 1. *(right)* Elemental abundance patterns for lithophile, siderophile and the most volatile elements Se–Br in Tagish Lake, Bells and CM chondrites plotted in order of decreasing nebular volatility within each subset. Data sources given in text; CI normalization from Anders and Grevesse (1989), except Se from Lodders and Fegley (1998). Vertical lines represent CM abundance ranges from Kallemeyn and Wasson (1981).


a. Tagish Lake
● JSC
● Brown et al.
○ Friedrich et al.
— CM
(sample / CI)$_{Cr}$
2
1
0.5
0.2
Hf
Al
Sc
Ca
Tb
Lu
Sm
La
Yb
Eu
V
Mg
Cr
Mn
K
Na
Ir
Co
Ni
Fe
Au
As
Sb
Se
Zn
Cs
Br
b. CM chondrites
■ Bells
+ CM (JSC)
— CM
(sample / CI)$_{Cr}$
2
1
0.5
0.2
Hf
Al
Sc
Ca
Tb
Lu
Sm
La
Yb
Eu
V
Mg
Cr
Mn
K
Na
Ir
Co
Ni
Fe
Au
As
Sb
Se
Zn
Cs
Br

Se/Cr and Zn/Cr ratios resolvably higher than the CM ranges (Kallemeyn and Wasson, 1981; my analyses). The Cs/Cr ratio of Tagish Lake is higher than the CM mean (Fig. 1a), but the range for CM chondrites is poorly constrained. As mentioned, Friedrich *et al.* (2002) did not determine Cr, and the Se/Cr, Zn/Cr and Cs/Cr ratios for their sample are estimates. In Fig. 2a, I show $(Zn/Co)_{CI}$ *vs.* $(Se/Co)_{CI}$ for all three analyses of Tagish Lake compared to all available analyses for CM and CI chondrites that include these three elements. Tagish Lake lies in the gap between CI and CM chondrites, and is clearly distinct.

CM chondrite Cr-normalized abundances are shown in Fig. 1b. My data agree well with the CM mean compiled by Wasson and Kallemeyn (1988), although they scatter more about the mean than do the analyses of larger samples done by Kallemeyn and Wasson (1981). I have highlighted the data for Bells. This is an unusual CM chondrite (*e.g.*, Brearley,

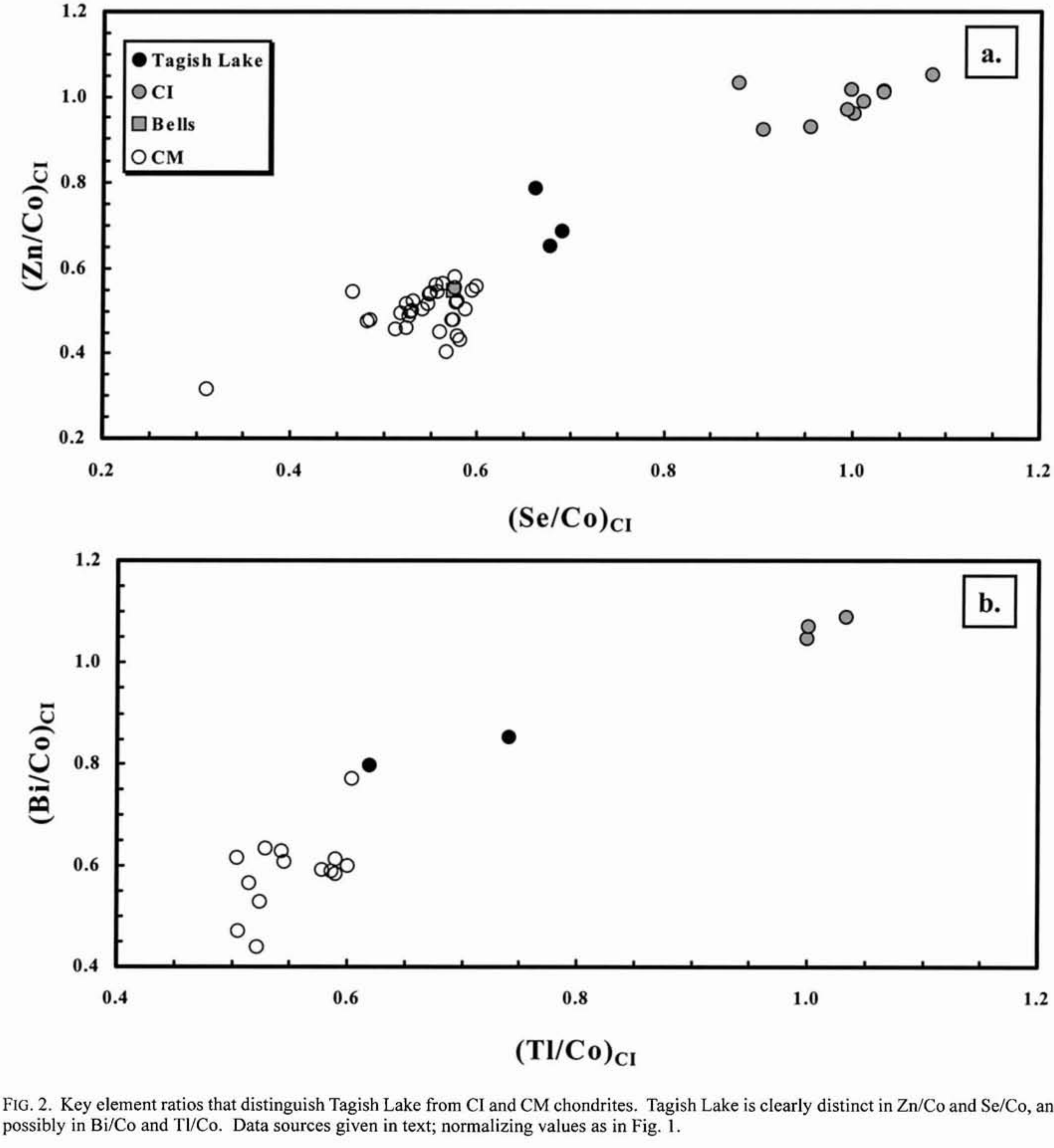


FIG. 2. Key element ratios that distinguish Tagish Lake from CI and CM chondrites. Tagish Lake is clearly distinct in Zn/Co and Se/Co, and possibly in Bi/Co and Tl/Co. Data sources given in text; normalizing values as in Fig. 1.

1995) for which there is no published bulk composition. Note that Bells has systematically lower refractory lithophile element abundances compared to the CM mean, and indeed has refractory lithophile element abundances like those of CI chondrites. However, siderophile, moderately volatile and volatile element abundances for Bells are similar to those of CM chondrites, although Na, Au, As, Sb and Br are lower than the CM ranges. Bells lies at the high end of the range of Zn/Co and Se/Co for CM chondrites (Fig. 2a).

DISCUSSION

The focus of this paper is on Tagish Lake and Bells, two unusual carbonaceous chondrites, and how they compare to typical CM chondrites. Before launching into a discussion of them, I will first very briefly consider the typical CM chondrites to establish whether my data on them conform to expectations for CM chondrites.

Cochabama, Cold Bokkeveld, Mighei, Nogoya and Pollen are typical CM chondrites—I have found no petrologic descriptions indicating unusual properties (*e.g.*, Barber, 1981; Browning *et al.*, 1996; Metzler *et al.*, 1992; Zolensky *et al.*, 1993). Oxygen isotopic data for Cold Bokkeveld, Mighei and Nogoya (Clayton and Mayeda, 1999), and bulk compositional data for all but Pollen (*e.g.*, Kallemeyn and Wasson, 1981) exist and confirm that they are CM chondrites. My data for all five of these meteorites are consistent with this classification. Individual analyses scatter about the CM mean for the full range of lithophile and siderophile, refractory to volatile elements, but there are no systematic deviations from the CM mean, for example, depletions of all refractory lithophile elements, that would suggest that any of them are anomalous or improperly classified. Based on my data alone, I would conclude that all these meteorites are typical CM chondrites.

Tagish Lake

Based on the first analyses of Tagish Lake, Brown *et al.* (2000) noted the following: (i) this meteorite was recognized as being of unusual petrologic type, with characteristics similar to, but distinct from, those of CI and CM chondrites; (ii) the bulk composition of Tagish Lake has refractory lithophile element abundances like those of CM chondrites, while moderately volatile and volatile element abundances are between those of CI and CM chondrites; (iii) the oxygen isotopic composition of Tagish Lake plots near those of CI and some metamorphosed carbonaceous chondrites but is distinct from either of these, and is far removed from the O-isotope field of CM chondrites; and (iv) the bulk rock carbon isotopic composition is distinct from those of CI and CM chondrites, although the carbonates in Tagish Lake have isotopic compositions like those of the latter two meteorite groups. These characteristics suggest that Tagish Lake represents a new type of chondritic material (Brown *et al.*, 2000). However, further consideration of the O-isotopic composition of Tagish Lake shows that it lies on the CM chondrite alteration line, and may simply reflect alteration at a higher water–rock ratio (Clayton and Mayeda, 2001). With additional analyses now available, I will take a second look at comparing the bulk composition of Tagish Lake to those of CM and CI chondrites.

As mentioned, Tagish Lake has refractory lithophile element (Hf–V) abundances like those of CM chondrites (Fig. 1a). Based on my analyses, the weighted mean refractory lithophile element/Cr ratio for Tagish Lake is 1.14 ± 0.01, while the mean of the CM chondrites I analyzed, excluding Bells, is 1.13 ± 0.01, with a range of 1.03–1.25. Friedrich *et al.* (2002) did not determine Mg, Si or Cr for their sample of Tagish Lake, and used Sc as a normalizing element. They found that Tagish Lake was distinct from the Murchison CM chondrite fall they analyzed in refractory lithophile element/Sc ratios. Examination of their Fig. 1 indicates that most refractory lithophile elements in their sample of Murchison are at essentially the same element/Sc ratio. Thus, if they had normalized to almost any other refractory element (*e.g.*, Sm, rather than Sc), Murchison and Tagish Lake would have had similar refractory element abundances.

Moderately volatile lithophile element (Mn–Na) abundances in Tagish Lake are generally similar to those in CM chondrites, although there do seem to be distinctions (Fig. 1a). Both K and Na abundances are resolvably above the range of CM chondrites as determined by Kallemeyn and Wasson (1981) for large samples. The Cr-normalized abundances of Na and K in Tagish Lake are 0.84 and 1.08 compared to 0.50–0.80 and 0.55–0.79 for CM chondrites. Refractory and moderately volatile siderophile element abundances in Tagish Lake are identical to those in CM chondrites (Fig. 1a).

One distinction between Tagish Lake and CM chondrites is in the abundances of moderately volatile Se and Zn and in the volatile elements. Selenium and Zn are the two most volatile of the moderately volatile elements I determined. Cesium may be as volatile as or more volatile than Se and Zn, but at present, its condensation temperature is not well known (see Lodders and Fegley, 1998). Bromine is the most volatile element. The distinction between Tagish Lake and CM chondrites is most clearly shown by comparing CI-normalized Zn/Co and Se/Co ratios (Fig. 2a). There are numerous analyses of CM and CI chondrites that contain these three elements (Friedrich *et al.*, 2002; Kallemeyn and Wasson, 1981; Matza and Lipschutz, 1977; Xiao and Lipschutz, 1992; Zolensky *et al.*, 1992, 1996; my analyses), so the ranges for CI and CM chondrites are well constrained. Three analyses of Tagish Lake representing two separate samples are all clearly resolved from the CI and CM data and fall in a distinct gap between these two groups. (The sample analyzed by Friedrich *et al.*, 2002, is a split of the homogenized powder I analyzed.) Cesium is above the mean CM abundance, but there are relatively few analyses of CM chondrites that contain Cs and a suitable normalizing element. This makes it difficult to arrive at firm conclusions from this comparison. Cesium concentrations in CM chondrite falls

(74–139 ng/g, excluding an anomalous result of 254 ng/g on Haripura—Friedrich *et al.*, 2002; Krähenbühl *et al.*, 1973; Matza and Lipschutz, 1977; Xiao and Lipschutz, 1992; Wolf *et al.*, 1980; Zolensky *et al.*, 1992) are generally lower than those determined on Tagish Lake (135–153 ng/g—Brown *et al.*, 2000; Friedrich *et al.*, 2002; this work), although the ranges slightly overlap. Tagish Lake has a mean Cs/Co ratio of 0.76 ± 0.02, slightly above the range for CM chondrites: 0.39–0.74.

It is unclear whether the difference between Tagish Lake and the CM chondrites in Cs, Se and Zn abundances is due to nebular or parent-body processes. Possibly, the extensive aqueous alteration that affected Tagish Lake (Brown *et al.*, 2000; Zolensky *et al.*, 2002) may have redistributed the most volatile elements, although their potential susceptibility to mobilization during aqueous alteration is not known. One way to evaluate this is by comparing volatile siderophile element/Co ratios for the meteorites.

Thallium and Bi are calculated to be siderophile elements in the nebular environment, and to be more volatile than Se or Zn (see Lodders and Fegley, 1998, Table 2.3). Figure 2b shows Bi/Co *vs.* Tl/Co for Tagish Lake (Brown *et al.*, 2000; Friedrich *et al.*, 2002) compared to the relatively few analyses of CI and CM chondrites available (Friedrich *et al.*, 2002; Matza and Lipschutz, 1977; Xiao and Lipschutz, 1992; Zolensky *et al.*, 1992). The Tagish Lake datum that plots nearer the CM data is that of Brown *et al.* (2000), which has relatively large analytical uncertainty for Bi. The other Tagish Lake point (Friedrich *et al.*, 2002) is more directly comparable to the CI and CM data as they were all determined by Lipschutz's group using radiochemical neutron activation analysis. This should be given more weight because inter-laboratory bias can be excluded. Hence, Figs. 1a and 2a,b *suggest* that it is the most volatile elements irrespective of geochemical behavior (lithophile—Cs; siderophile—Tl, Bi; chalcophile—Se; lithophile and chalcophile—Zn) in Tagish Lake that are at higher abundances than in CM chondrites. This is more likely a nebular signature.

(I have ignored the most volatile element, Br, in this discussion. Although Tagish Lake matches the CM chondrite abundance range for Br, this element is typically variable in CM chondrites, and the data of Kallemeyn and Wasson (1981) suggest that its abundance in CM chondrites is anomalously high for its estimated volatility. Hence, Br should not be used in comparisons.)

I suggest, however, that we should keep an open mind about the cause(s) of the slight compositional differences between Tagish Lake and CM chondrites. There are still only few analyses of Tagish Lake that contain precisely determined contents of these most volatile elements and suitable normalizing elements, and the same is true of CM chondrites for some elements. In fact, most of the CM data shown in Fig. 2b are analyses of Murchison. Thus, the variability especially of Tl/Co and Bi/Co in CM chondrites is poorly constrained. Although I *believe* that the differences in bulk composition are nebular in origin, it is premature to conclude this with confidence.

Although above I highlighted the distinctions between the abundance patterns of Tagish Lake and CM chondrites, these distinctions are nevertheless fairly small. The nebular fractionations embodied in the proto-CM chondrite material are very similar to those in the proto-Tagish Lake material. Thus, we can infer that the nebular process that formed these two chondritic materials were very similar, and differed only slightly in degree.

Bells

Bells is an unusual CM chondrite. The matrix contains a higher abundance of magnetite than typical CM chondrites, and the assemblage of matrix phyllosilicates is more similar to that in CI than CM chondrites (Brearley, 1995). The oxygen isotopic compositions of matrix silicates and magnetite in Bells are nevertheless like those of other CM chondrites (Rowe *et al.*, 1994). Browning *et al.* (1996) found that Bells suffered a slightly higher degree of aqueous alteration than Murchison, but that these two represented the least altered CM chondrites.

Little is known about the bulk composition of Bells. Kallemeyn (1995) briefly described the results of analyses of two samples of Bells, and mentioned that some stones were collected after heavy rains (see Monnig, 1963). Kallemeyn (1995) noted that Bells has (i) refractory lithophile element/Mg ratios like CI chondrites, (ii) moderately volatile and volatile lithophile element abundances like those of CM chondrites, (iii) refractory siderophile element abundances higher than those of CI chondrites, (iv) Fe, Co and Ni abundances at CI levels, and (v) depletion in Au relative to Fe, Co and Ni. Because Bells is unusual, and its composition has not been published, I compare the results of my measurements to CM chondrites in Fig. 1b.

My results agree with those described by Kallemeyn (1995) in showing that refractory lithophile element abundances are like those of CI chondrites; the weighted mean refractory lithophile element/Cr ratio for Bells is 0.95 ± 0.01 compared to 0.96 ± 0.01 for my analysis of Orgueil. Kallemeyn (1995) noted that the stone collected after rains was depleted in Na, K and Br, and possibly showed slight depletion in Ca. Unfortunately, I was unable to obtain information regarding the collection details of the sample I analyzed; however, the Na and Br contents are very low compared to the CM chondrite ranges, while K lies at the low end of the range (Fig. 1b). Because of this, I will assume my sample was from one of the latter collected stones and treat these elements as suspect and non-diagnostic. The moderately volatile lithophile element Mn is depleted in Bells relative to CI chondrites, and is similar in abundance to that of the CM chondrite mean. I find a siderophile element pattern for Bells very much like that of CM chondrites, although the most volatile siderophile elements, Au, As and Sb, are below the CM ranges (Fig. 1b). Selenium and Zn, the most volatile elements I determined, excluding Br, are at CM chondrite abundances (Fig. 1b, 2a).

Kallemeyn (1995) suggested that Bells may not be a CM chondrite. Based on my data, oxygen isotopic data, and petrography (Brearley, 1995; Rowe *et al.*, 1994), I rather concur with Brearley that Bells is best classed as an anomalous CM chondrite for the time being.

CONCLUSIONS

Tagish Lake has an abundance pattern for a wide range of elements very similar to those of CM chondrites. Moderately volatile Na and K are, at best, only slightly higher than those of mean CM chondrites, but there is overlap with the CM ranges. Tagish Lake is distinct from CM chondrites in the abundances of the most volatile elements. Considering available petrographic, isotopic and elemental data, Tagish Lake is an ungrouped member of the carbonaceous chondrite clan. The overall elemental abundance pattern is very similar to those of CM chondrites, indicating that Tagish Lake and CMs experienced very similar nebular fractionations.

The CM chondrite Bells has refractory lithophile element abundances like those of CI chondrites, and distinctly lower than those of CM chondrites. The moderately volatile siderophile elements, Au, As and Sb, have abundances below the ranges for CM chondrites. All other element abundances of Bells are within the CM ranges. Bells is best classified as an anomalous CM chondrite.

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REFERENCES

ANDERS E. AND GREVESSE N. (1989) Abundances of the elements: Meteoritic and solar. *Geochim. Cosmochim. Acta* **53**, 197–214.

BARBER D. J. (1981) Matrix phyllosilicates and associated minerals in CM2 carbonaceous chondrites. *Geochim. Cosmochim. Acta* **45**, 945–970.

BREARLEY A. J. (1995) Aqueous alteration and brecciation in Bells, an unusual, saponite-bearing, CM chondrite. *Geochim. Cosmochim. Acta* **59**, 2291–2317.

BROWN P. G. *ET AL.* (2000) The fall, recovery, orbit and composition of the Tagish Lake meteorite: A new type of carbonaceous chondrite. *Science* **290**, 320–325.

BROWNING L. B., MCSWEEN H. Y., JR. AND ZOLENSKY M. E. (1996) Correlated alteration effects in CM carbonaceous chondrites. *Geochim. Cosmochim. Acta* **60**, 2621–2633.

CLAYTON R. N. AND MAYEDA T. K. (1999) Oxygen isotope studies of carbonaceous chondrites. *Geochim. Cosmochim. Acta* **63**, 2089–2104.

CLAYTON R. N. AND MAYEDA T. K. (2001) Oxygen isotopic composition of the Tagish Lake carbonaceous chondrite (abstract). *Lunar Planet. Sci.* **32**, #1885, Lunar and Planetary Institute, Houston, Texas, USA (CD-ROM).

FRIEDRICH J. M., WANG M-S. AND LIPSCHUTZ M. E. (2002) Comparison of the trace element composition of Tagish Lake with other primitive carbonaceous chondrites. *Meteorit. Planet. Sci.* **37**, 677–686.

GOUNELLE M. AND ZOLENSKY M. E. (2001) A terrestrial origin for sulfate veins in CI1 chondrites. *Meteorit. Planet. Sci.* **36**, 1321–1329.

HIROI T., ZOLENSKY M. E. AND PIETERS C. M. (2001) The Tagish Lake Meteorite: A possible sample from a D-type asteroid. *Science* **293**, 2234–2236.

KALLEMEYN G. W. (1995) Bells and Essebi: To be or not to be (CM) (abstract). *Meteoritics* **30**, 525–526.

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., RUBIN A. E. AND WASSON J. T. (1994) The compositional classification of chondrites: VI. The CR carbonaceous chondrite group. *Geochim. Cosmochim. Acta* **58**, 2873–2888.

KRÄHENBÜHL U., MORGAN J. W., GANAPATHY R. AND ANDERS E. (1973) Abundance of 17 trace elements in carbonaceous chondrites. *Geochim. Cosmochim. Acta* **37**, 1353–1370.

LODDERS K. AND FEGLEY B., JR. (1998) *The Planetary Scientist's Companion.* Oxford Univ. Press, Oxford, U.K. 371 pp.

MATZA S. D. AND LIPSCHUTZ M. E. (1977) Thermal metamorphism of primitive meteorites–VI. Eleven trace elements in Murchison C2 chondrite heated at 400–1000 °C. *Proc. Lunar Planet. Sci. Conf.* **8th**, 161–176.

METZLER K., BISHOFF A. AND STÖFFLER D. (1992) Accretionary dust mantles in CM chondrites: Evidence for solar nebula processes. *Geochim. Cosmochim. Acta* **56**, 2873–2897.

MITTLEFEHLDT D. W. AND LINDSTROM M. M. (1993) Geochemistry and petrology of a suite of ten Yamato HED meteorites. *Proc. NIPR Symp. Antarctic Meteorites* **6**, 268–292.

MITTLEFEHLDT D. W. AND LINDSTROM M. M. (2001) Petrology and geochemistry of Patuxent Range 91501, an impact melt from the L chondrite parent body, and Lewis Cliff 88663, an L7 chondrite. *Meteorit. Planet. Sci.* **36**, 439–457.

MONNIG O. E. (1963) The Bells, Texas, meteorites (abstract). *Meteoritics* **2**, 67.

NGO H. T. AND LIPSCHUTZ M. E. (1980) Thermal metamorphism of primitive meteorites–X. Additional trace elements in Allende (C3V) heated to 1400 °C. *Geochim. Cosmochim. Acta* **44**, 731–739.

ROWE M. W., CLAYTON R. N. AND MAYEDA T. K. (1994) Oxygen isotopes in separated components of CI and CM meteorites. *Geochim. Cosmochim. Acta* **58**, 5341–5347.

WASSON J. T. (1972) Formation of ordinary chondrites. *Rev. Geophys. Space Phys.* **10**, 711–759.

WASSON J. T. AND KALLEMEYN G. W. (1988) Compositions of chondrites. *Phil. Trans. Royal Soc. Lond.* **A325**, 535–544.

WOLF D. AND PALME H. (2001) The solar system abundances of phosphorous and titanium and the nebular volatility of phosphorous. *Meteorit. Planet. Sci.* **36**, 559–571.

WOLF R., RICHTER G. R., WOODROW A. B. AND ANDERS E. (1980) Chemical fractionations in meteorites–XI. C2 chondrites. *Geochim. Cosmochim. Acta* **44**, 711–717.

XIAO X. AND LIPSCHUTZ M. E. (1992) Labile trace elements in carbonaceous chondrites: A survey. *J. Geophys. Res.* **97**, 10 199–10 211.

ZOLENSKY M. E., HEWIS R. H., MITTLEFEHLDT D. W., LINDSTROM M. M., XIAO X. AND LIPSCHUTZ M. E. (1992) Mineralogy, petrology and geochemistry of carbonaceous chondritic clasts in the LEW 85300 polymict eucrite. *Meteoritics* **27**, 596–604.

ZOLENSKY M. E., BARRETT R. AND BROWNING L. (1993) Mineralogy and composition of matrix and chondrule rims in carbonaceous chondrites. *Geochim. Cosmochim. Acta* **57**, 3123–3148.

ZOLENSKY M. E., IVANOV A. V., YANG V., MITTLEFEHLDT D. W. AND OHSUMI K. (1996) The Kaidun meteorite: Mineralogy of an unusual CM1 lithology. *Meteorit. Planet. Sci.* **31**, 484–493.

ZOLENSKY M. E., NAKAMURA K., GOUNELLE M., MIKOUCHI T., KASAMA T., TACHIKAWA O. AND TONUI E. (2002) Mineralogy of Tagish Lake: An ungrouped type 2 carbonaceous chondrite. *Meteorit. Planet. Sci.* **37**, 737–761.