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ON VOLATILE/MOBILE TRACE ELEMENT TRENDS IN E3 CHONDRITES

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Abstract: Contents of 3 non-mobile trace elements (U, Co, Au) and 12 slightly-to-highly volatile ones (Rb, Sb, Ag, Ga, Se, Cs, Te, Zn, Cd, Bi, Tl and In) determined by RNAA in the Yamato (Y)-691 and Qingzhen E3 chondrites generally fall within ranges reported for E4 chondrite falls. Contents of most elements are similar in the two E3 chondrites: highly volatile Cd, Bi and Tl differ markedly, with the Y-691 data falling at C1 levels and those of Qingzhen near the bottom of the E4 ranges. Trace element abundances and interelement comparisons indicate that both E3 chondrites compositionally reflect only nebular condensation, with Y-691 parent material having condensed at lower temperatures than Qingzhen. Both escaped the post-accretionary metamorphic episode that compositionally altered other enstatite chondrites. For volatiles, E3, 4 chondrites differ markedly from E5, 6: for siderophiles, E3–5 differ markedly from E6. These trends could reflect enstatite chondrites' origin in 1 or 2 parent bodies: we interpret the data as indicating a single body.

1. Introduction

The enstatite chondrites exhibit a number of mineralogic and chemical peculiarities. Since they are the most highly reduced of all chondritic meteorites, it is reasonable to assume that their parent nebular material condensed and accreted closer to the proto-sun than that of any other meteorite type. In principle, then, the primitive members of this group should give unique information on nebular condensation conditions. The problem is that no consensus exists as to which, if any, of these meteorites experienced post-accretionary processing.

Considering the scientific importance of Antarctic meteorites, it is appropriate that the first of the modern discoveries, by the 10th Japanese Antarctic Research Expedition, Yamato (Y)-691, also proved to be the first known E3 chondrite. Prior to its discovery, known enstatite chondrites were of petrologic types 4–6. It had long been established that E4 and 5 chondrites have systematically higher contents of siderophile elements (including Fe) than do E6 samples. The difference must be nebular in origin and prompted classification of high-iron E4 and 5 chondrites as EH and low-iron E6 chondrites as EL (*e.g.* WEEKS and SEARS, 1985; KALLEMEYN and WASSON, 1986 and references

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in them). These authors postulate at least two E chondrite parents; one for EH, the second for EL.

Concentrations of labile trace elements—*i.e.* those considered volatile during nebular condensation or mobile (easily volatilized and lost) during heating of, say, chondritic parent material—form continua, with E4 values being higher, sometimes systematically so, than those of E5 or 6 chondrites (LAUL *et al.*, 1973; BINZ *et al.*, 1974; BISWAS *et al.*, 1980; HERTOGEN *et al.*, 1983). It is tempting to ascribe labile trace element trends to the same nebular process that fractionated siderophiles (SEARS *et al.*, 1982; KALLEMEYN and WASSON, 1986) but they differ: labile element contents in types 5 and 6 E chondrites are essentially equivalent, just as in ordinary chondrites (BINZ *et al.*, 1974; BISWAS *et al.*, 1980; HERTOGEN *et al.*, 1983).

Labile element trends in E4–6 chondrites have been attributed to solid state metamorphism of a single enstatite chondrite parent body, stratified in siderophiles but initially containing E4 ($\equiv$C1) levels of the labile ones (BINZ *et al.*, 1974; IKRAMUDDIN *et al.*, 1976; BISWAS *et al.*, 1980). In reporting their data, HERTOGEN *et al.* (1983) concluded that trends for refractory siderophiles indicate metamorphic fractionation into E chondrite metal but could not decide whether the condensation or the metamorphic model better accounts for labile element distributions.

Analyses of relatively refractory trace elements indicate that Y-691 and Qingzhen—the only meteorites classified as E3 chondrites by GRAHAM *et al.* (1985)—and other possibly similar finds (including badly weathered ones), are of the high rather than low Fe sort (WEEKS and SEARS, 1985; KALLEMEYN and WASSON, 1986). Very little information was available on contents of highly labile trace elements in the two E3 chondrites. We were honored to participate in the Y-691 consortium and determine our suite of elements, which includes the most labile ones. We decided to include Qingzhen as well to determine how compositionally similar the Antarctic and non-Antarctic samples are (DENNISON *et al.*, 1986; DENNISON and LIPSCHUTZ, 1987) and what their labile element relationship is to E4 chondrites. Here, we report the results.

2. Experimental

We received a 406 mg chip of Y-691,90, which we subdivided into 2 aliquots, Y-691,90A (111 mg) and B (99.9 mg), to examine homogeneity for whole-rock samples. This can prove useful, particularly for volatile-rich samples, *e.g.* the lunar meteorite Y-791197 (KACZARAL *et al.*, 1986). We analyzed a single 210 mg Qingzhen chip.

Prior to measurement by radiochemical neutron activation analysis (RNAA), we chipped away all potentially contaminated surfaces of Y-691 and Qingzhen. Sample and monitor preparation, irradiation conditions, chemical treatment and data reduction techniques were as described by KACZARAL *et al.* (1986). Chemical yields and radiochemical purity for all monitors and nearly all samples were quite satisfactory. The sole exception was In in Qingzhen where we obtained only a 10% yield and we regard this datum with more than the usual suspicion.

3. Results

We list our results for Y-691 and Qingzhen in Table 1 together with data from Biswas *et al.* (1980) for one of the more volatile-rich E4 chondrites, Abee, and average siderophile element data for EH and EL chondrites (Kallemeyn and Wasson, 1986). [Elements are listed in Table 1 in increasing order of mobility during post-accretionary heating (Huston and Lipschutz, 1984).] The duplicate results for Y-691 are generally quite precise, 13 of the 15 elements having relative estimated standard deviations of

Table 1. Trace element data for Yamato-691 and Qingzhen E3 chondrites compared with some prior results for Abee E4 chondrite and siderophiles in enstatite chondrites.

	U (ppb)	Co (ppm)	Au (ppb)	Sb (ppb)	Ga (ppm)	Se (ppm)	Rb (ppm)	Cs (ppb)
Yamato-691,90A	8.8	900	289	140	16.1	23.8	2.78	180
B	9.5	872	282	160	15.9	22.2	2.92	200
mean	9.2±0.5	886±20	286±5	150±20	16.0±0.1	23±1	2.8±0.1	190±10
Qingzhen	8.2	684	244	180	15.6	22.3	2.98	210
Abee*		878±44			20.7±1.0	28.1±1.9		260±6
Mean EH falls†		833	325	195	15.9			
Mean EL falls†		665	224	90	10.6			

	Te (ppm)	Bi (ppb)	Ag (ppb)	In (ppb)	Tl (ppb)	Zn (ppm)	Cd (ppb)
Yamato-691,90A	1.74	160	188	64.6	215	320	1160
B	1.80	170	191	61.2	228	220	1140
mean	1.77±0.04	170±10	190±2	63±2	222±9	270±70	1150±10
Qingzhen	1.62	21	158	(84)	3.5	340	61.6
Abee*	2.46±0.06	112±9	289±20	96.4±2.7	93.9±7.4	419±10	825±41
Mean EH falls†							
Mean EL falls†							

* Data from Biswas *et al.* (1980).

† Data from Kallemeyn and Wasson (1986).

Table 2. Comparison of our trace element data for Yamato-691 and Qingzhen E3 chondrites with other results.

	Yamato-691		Qingzhen	
	This work	Other results*	This work	Other results
Co (ppm)	872, 900	830(b), 840(b), 890(a)	684	824(b), 848(a), 917(a), 966(a), 970(a)
Au (ppb)	282, 289	279(b), 283(b), 286(a)	244	311(b), 355(b)
Sb (ppb)	140, 160	132(b), 162(b)	180	170(b), 190(b)
Ga (ppm)	15.9, 16.1	15.0(b), 15.1(b)	15.6	14.6(b), 16.4(b)
Se (ppm)	22.2, 23.8	22.2(b), 22.5(b)	22.3	18.6(a), 21.2(b), 21.7(b), 22.7(a), 25.5(a)
Te (ppm)	1.74, 1.80	1.8(b), 2.1(b)	1.62	2.1(b), 2.3(b)
Zn (ppm)	220, 320	212(b), 230(b)	340	144(b), 167(b), 182(a), 304(a), 318(a)

* References: (a) Weeks and Sears (1985); (b) Kallemeyn and Wasson (1986).

$\leq 6\%$. Such precision is very unusual for whole rock samples and is normally obtained only for homogenized powder samples as, *e.g.*, the Abee data in Table 1. Experimental precisions for the exceptions, Sb and Zn, in homogeneous powder are typically 2–3 × better (*e.g.* DENNISON *et al.*, 1986) than in Y-691 (Table 1) suggesting real chemical heterogeneity in this E3 chondrite.

Almost half of the elements we determined were previously measured in Y-691 and Qingzhen: these mainly include the less labile ones (Table 2). Agreement is generally excellent. Our Co and Au data for Qingzhen are about 30% lower than other results. The excellent agreement for these elements in Y-691 precludes any systematic difference and suggests that our Qingzhen sample contained somewhat less metal than the ones analyzed by WEEKS and SEARS (1985) and KALLEMEYN and WASSON (1986). Replicate Zn data for Qingzhen differ more than do our results for Y-691 (Table 2) suggesting that this element is somewhat heterogeneously distributed in E3 chondrites.

4. Discussion

Both WEEKS and SEARS (1985) and KALLEMEYN and WASSON (1986) classify Y-691 and Qingzhen as EH chondrites and our data for Co, Au, Sb, and Ga (Table 1) are generally consistent with that assignment. Our Co and Au data for Qingzhen appear low for EH falls but, as noted earlier, our sample may have contained less than a representative amount of metal (Table 1).

Our data for moderately and strongly mobile elements are more instructive. Most of the last 11 elements are essentially equally abundant in both E3 chondrites (Table 1). However, highly mobile Bi, Tl and Cd are exceptions, and, in each case, the concentration is 1–2 orders of magnitude lower in Qingzhen than in Y-691. This suggests that, at some stage in their histories, Qingzhen experienced higher time-temperature conditions than did Y-691. Concentrations of 2 elements, Tl and Cd, are higher in Y-691 than in the typical volatile-rich E4 chondrite, Abee; for other elements, concentrations are comparable or somewhat lower (Table 1).

When data for the two E3 chondrites are compared with all mobile element data for E4 falls (LAUL *et al.*, 1973; BINZ *et al.*, 1974; HERTOGEN *et al.*, 1983), the pattern becomes more distinct (Fig. 1). With a few exceptions, data for the E3 chondrite lie within the E4 ranges and Cd, Bi and Tl—which differ widely—Y-691 points are at C1 levels (at or above E4 values) while Qingzhen data are near the bottom of the ranges (Fig. 1). The elements are listed in Fig. 1 by increasing nebular volatility, not mobility (as in Table 1) and those discrepant elements are 3 of the 4 most volatile ones. (Note that the Qingzhen In datum is suspicious because of low chemical yield.) When normalized to data for C1 chondrites (ANDERS and EBIHARA, 1982) mean abundances of these 15 elements in Y-691 and Qingzhen are, respectively, 0.79 ± 0.25 and 0.60 ± 0.33. If comparison is limited to the 10 moderately and highly volatile elements (Ag to In), the values are lowered more or less: 0.74 ± 0.22 and 0.49 ± 0.33, respectively.

For elements of such lability, C1-normalized abundances are high and rather uniform when compared with those of other petrologic type 3 chondrites (BINZ *et al.*, 1976; LIPSCHUTZ *et al.*, 1983; ANDERS and ZADNIK, 1985). Only C3 chondrites show greater precision for such elements (ANDERS *et al.*, 1976). We interpret these data as indicating

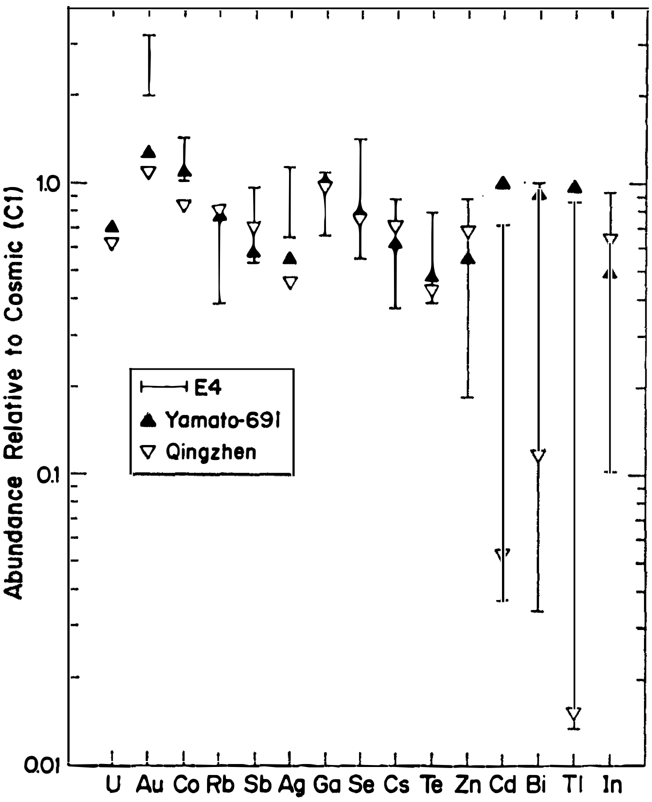

Fig. 1. Atomic abundances (normalized to cosmic or C1 values) in Y-691 and Qingzhen E3 chondrites compared with ranges for E4 chondrite falls. Generally, compositions of the 2 E3 chondrites are similar to each other and to E4 values. Differences for the most highly volatile elements (to the right)—Cd, Bi and Tl—seem to reflect nebular condensation of E3 chondrite parent material at different temperatures, with Y-691 having formed at a rather lower temperature than Qingzhen.

that labile element abundances in the two E3 chondrites were established during nebular condensation and accretion.

This conclusion is supported by consideration of Se/Te ratios (Fig. 2). Following a suggestion by PELLY and LIPSCHUTZ (1971). IKRAMUDDIN *et al.* (1976) and BISWAS *et al.* (1980) showed that the Se/Te ratios of enstatite chondrites closely matched ratios in Abee samples heated under simulated metamorphic conditions, *i.e.* 400–1000°C for 1 week in a low-pressure (initially 10^{-5} atm H_2) environment. On the appropriate diagram (Fig. 2), the E3 points essentially lie with unheated Abee, at the head of the putative metamorphic sequence. On analogous plots of Bi *vs.* Tl, In *vs.* Tl and In *vs.* Bi (not illustrated, to save space), the E3 chondrite points also lie at or near unheated Abee, emphasizing that Y-691 and Qingzhen are primitive E chondrites.

We interpret these data as indicating that labile element trends in these two E3 chondrites were established during nebular condensation and accretion of parent material, which escaped later heating. Volatile element contents in Y-691 and the E4 chondrites Indarch and Abee are essentially equal and suggest that the parent materials

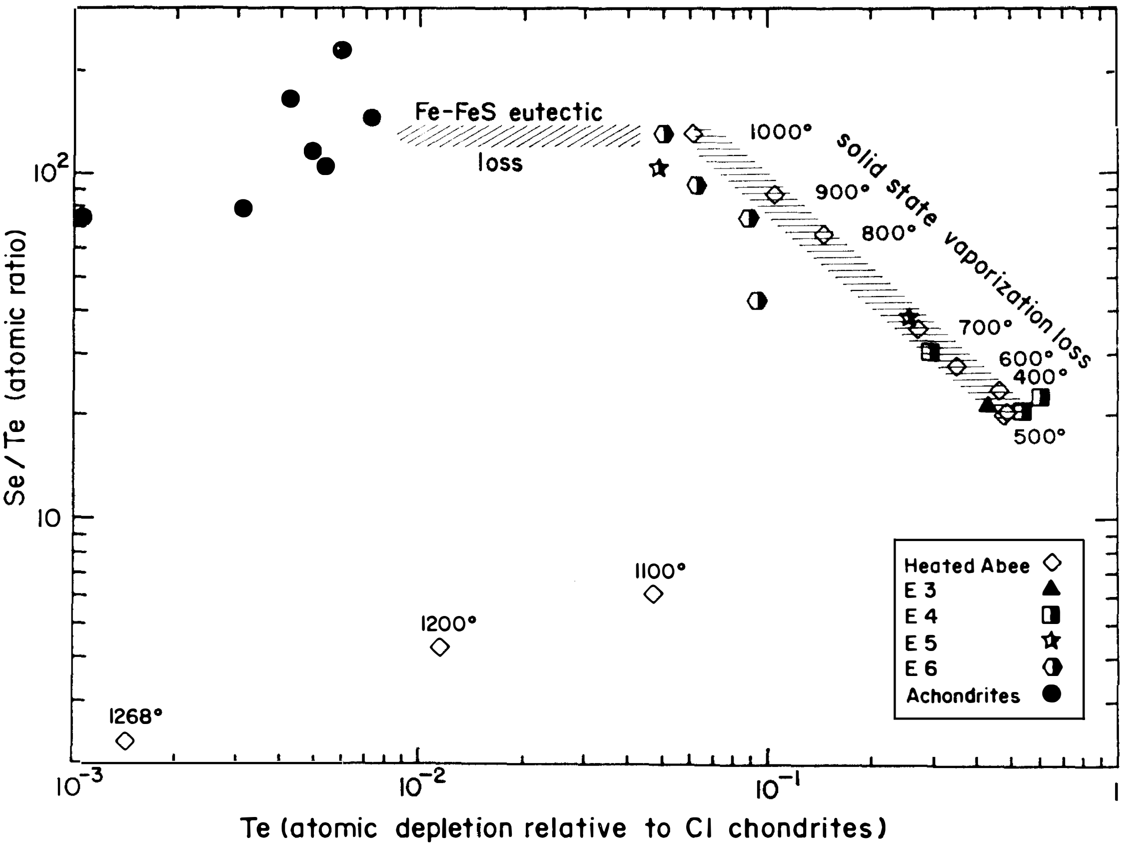

Fig. 2. Se/Te atomic ratios vs. Cl-normalized Te abundances for E3–6 chondrites and non-Antarctic enstatite achondrites compared with data for Abee samples heated for one week at temperatures of 400–1268°C in low pressure (initially 10^{-5} atm H_2). Both Y-691 and Qingzhen E3 chondrites are represented by the single filled triangle that lies at the origin of the putative chondritic metamorphic sequence. No evidence exists suggesting that E3 chondrites experienced post-accretionary heating. See BISWAS *et al. (1980) for a discussion of the thermal history of the enstatite meteorite parent body suggested by trands for Se, Te and other moderately and highly labile elements.*

of these 3 meteorites formed at temperatures lower than those of other enstatite chondrites. Qingzhen's parent material apparently formed at somewhat higher temperatures. The two E3 chondrites are not compositionally identical: whether this reflects chance or actual Antarctic/non-Antarctic population differences will require the discovery of additional compositionally-uncompromised E3 chondrites.

From the volatile element standpoint, E3 and E4 chondrites are rather similar as are E5 and E6 chondrites. This clearly differs from the trend for siderophile elements, where contents in E3–5 chondrites exceed those of E6. These trends differ from those in ordinary chondrites where volatile element contents in type 3 samples greatly exceed those in types 4–6 chondrites. There is no tendency for contents of highly volatile elements in H3 chondrites to exceed those of L3. This is certainly true for equilibrated H and L chondrites too: in fact, if anything, contents in the former are lower than those of unshocked, equilibrated L chondrites (LINGNER *et al.*, 1987; LIPSCHUTZ and WOOLUM, 1987). By analogy with ordinary chondrites, there seems no *a priori* reason to attribute higher volatile element contents in E3 and E4 chondrites to the nebular cosmochemical fractionation of siderophiles that caused these to be called EH. From the standpoint of highly labile elements, data for E6 chondrites are part of the continua defined by results for E3–5 chondrites and compositions and trends for these enstatite chondrites can be duplicated by heating Abee in the laboratory (IKRAMUDDIN *et al.*, 1976; BISWAS *et al.*, 1980). There seems no reason, then, to regard siderophile element content as more important than petrologic type, in categorizing the labile element contents of enstatite chondrites.

5. Conclusion

The results of this study indicate that, compositionally, the E3 chondrites Y-691 and Qingzhen are similar to E4 chondrites. Data for highly volatile elements indicate that both E3 chondrites reflect only primary nebular condensation, with no evidence for post-accretionary metamorphic heating that affected other enstatite chondrites. Differences in the Cd, Bi and Tl contents of the two E3 chondrites indicate that Y-691 parent material condensed at lower temperatures than did that of Qingzhen.

It has been argued that the higher siderophile element contents of E3–5 (EH) chondrites relative to E6 (EL) indicates derivation of these two sorts from different parent bodies. From their contents of moderately-to-highly labile elements, strong overlap exists between these 2 sorts of chondrites, with the E3,4 population being richer than the E5,6 population. With equal validity, one could hypothesize that E3,4 chondrites derive from one parent body and E5,6 from another. In fact, it seems more reasonable to ascribe derivation of all E3–6 chondrites (and, indeed, enstatite achondrites) from a single parent body, initially stratified by nebular processes with respect to siderophiles but containing C1-levels of volatiles.

According to latter view, described in more detail by BISWAS *et al.* (1980), the primitive chondrite parent body—in which the siderophile-poor material lay deeper (because of prior condensation/accretion)—was then altered by extended heating. Material of intermediate depth was metamorphosed in the solid state, vaporizing labile elements and forming E5,6 chondrites. Deeper material experienced higher temperatures and part, if not all, subsequently melted and cooled, forming an enstatite achondrite region and an iron core. The proto-achondrite region was intruded by an FeS-Fe eutectic melt (formed around 988°C) from the proto-E6 region, bringing with it small amounts of siderophiles and chalcophiles. Experimental verification of labile element trends expected for this model have been duplicated by laboratory heating of volatile-rich Abee under simulated metamorphic conditions (IKRAMUDDIN *et al.*, 1976; BISWAS *et al.*, 1980). If this picture is correct, both E3 chondrites are near surface material, Y-691 lying nearer the surface than Qingzhen.

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References

ANDERS, E. and EBIHARA, M. (1982): Solar-system abundances of the elements. Geochim. Cosmochim. Acta, **46**, 2363-2380.

ANDERS, E. and ZADNIK, M. G. (1985): Unequilibrated ordinary chondrites; A tentative subclassification based on volatile-element content. Geochim. Cosmochim. Acta, **49**, 1281-1291.

ANDERS, E., HIGUCHI, H., GANAPATHY, R. and MORGAN, J. W. (1976): Chemical fractionations in meteorites-IX. C3 chondrites. Geochim. Cosmochim. Acta, **40**, 1131-1139.

BINZ, C. M., KURIMOTO, R. K. and LIPSCHUTZ, M. E. (1974): Trace elements in primitive meteorites—V. Abundance patterns of thirteen trace elements and interelement relationships in enstatite chondrites. Geochim. Cosmochim. Acta, **38**, 1579-1606.

BINZ, C. M., IKRAMUDDIN, M., REY, P. and LIPSCHUTZ, M. E. (1976): Trace elements in primitive meteorites—VI. Abundance patterns of thirteen trace elements and interelement relationships in unequilibrated ordinary chondrites. Geochim. Cosmochim. Acta, **40**, 59-71.

BISWAS, S., WALSH, T., BART, G. and LIPSCHUTZ, M. E. (1980): Thermal metamorphism of primitive meteorites—XI. The enstatite meteorites; Origin and evolution of a parent body. Geochim. Cosmochim. Acta, **44**, 2097-2110.

DENNISON, J. E. and LIPSCHUTZ, M. E. (1987): Chemical studies of H chondrites—II. Weathering effects in the Victoria Land Antarctic population and comparison of two Antarctic populations with non-Antarctic falls. Geochim. Cosmochim. Acta, **51**, 741-754.

DENNISON, J. E., LINGNER, D.W. and LIPSCHUTZ, M. E. (1986): Antarctic and non-Antarctic meteorites; Different populations. Nature, **319**, 390-393.

GRAHAM, A. L., BEVAN, A.W.R. and HUTCHISON, R. (1985): Catalogue of Meteorites. 4th ed. London, British Museum (Natural History), 460p.

HERTOGEN, J., JANSSENS, M.-J., TAKAHASHI, H., MORGAN, J. W. and ANDERS, E. (1983): Enstatite chondrites; Trace element clues to their origin. Geochim. Cosmochim. Acta, **47**, 2241-2255.

HUSTON, T. J. and LIPSCHUTZ, M. E. (1984): Chemical studies of L chondrites, III. Mobile trace elements and ^{40}Ar/^{39}Ar ages. Geochim. Cosmochim. Acta, **48**, 1319-1329.

IKRAMUDDIN, M., BINZ, C. M. and LIPSCHUTZ, M. E. (1976): Thermal metamorphism of primitive meteorites—II. Ten trace elements in Abee enstatite chondrite heated at 400-1000°C. Geochim. Cosmochim. Acta, **40**, 133-142.

KACZARAL, P. W., DENNISON, J. E. and LIPSCHUTZ, M. E. (1986): Yamato-791197; A volatile trace element rich Lunar Highlands sample from Antarctica. Mem. Natl Inst. Polar Res., Spec. Issue, **41**, 76-83.

KALLEMEYN, G. W. and WASSON, J. T. (1986): Compositions of enstatite (EH3, EH4,5 and EL6) chondrites; Implications regarding their formation. Geochim. Cosmochim. Acta, **50**, 2153-2164.

LAUL, J. C., GANAPATHY, R., ANDERS, E. and MORGAN, J. W. (1973): Chemical fractionations in meteorites—VI. Accretion temperatures of H-, LL- and E-chondrites, from abundance of volatile trace elements. Geochim. Cosmochim. Acta, **37**, 329-357.

LINGNER, D. W., HUSTON, T. J., HUTSON, M. and LIPSCHUTZ, M. E. (1987): Chemical studies of H chondrites—I. Mobile trace elements and gas retention ages. Geochim. Cosmochim. Acta, **51**, 727-739.

LIPSCHUTZ, M. E. and WOOLUM, D. S. (1987): Highly labile elements. Meteorites and the Early Solar System, ed. by J. F. KERRIDGE and M. S. MATTHEWS. Tucson, Univ. of Arizona Press (in press).

LIPSCHUTZ, M. E., BISWAS, S. and MCSWEEN, H. Y., JR. (1983): Chemical characteristics and origin of H chondrite regolith breccias. Geochim. Cosmochim. Acta, **47**, 169-179.

PELLY, I. Z. and LIPSCHUTZ, M. E. (1971): Selenium (34). Handbook of Elemental Abundances in

Meteorites, ed. by B. MASON. New York, Gordon and Breach, 271–278.
SEARS, P. W., KALLEMEYN, G. W. and WASSON, J. T. (1982): The compositional classification of chondrites; II. The enstatite chondrite groups. Geochim. Cosmochim. Acta, **46**, 597–608.
WEEKS, K. S. and SEARS, D.W.G. (1985): Chemical and physical studies of type 3 chondrites-V; The enstatite chondrites. Geochim. Cosmochim. Acta, **49**, 1525–1536.

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